OCS Study
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Ecological Research Associates

EFFECTS OF NOISE ON MARINE MAMMALS

by

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prepared for

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Effects of Noise on Marine Mammals

by

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Although specific chapter authors are identified, the review was planned as an integrated document rather than a series of discrete papers. Chapters 9-11, in particular, depend on material from all preceding chapters. The chapter authors were as follows:

1. Introduction	*W.J. Richardson*
2. Acoustic Concepts and Terminology	*C.R. Greene Jr.*
3. Sound Propagation	*C.I. Malme*
4. Ambient Noise	*C.R. Greene Jr.*
5. Man-Made Noise	*C.R. Greene Jr. and S.E. Moore*
6. Marine Mammal Sounds	*D.H. Thomson*
7. Marine Mammal Hearing	*W.J. Richardson*
8. Documented Disturbance Reactions	*W.J. Richardson*
9. Zones of Noise Influence	*W.J. Richardson and C.I. Malme*
10. Significance of Responses and Noise Impacts	*W.J. Richardson and B. Würsig*
11. Conclusions and Data Needs	*W.J. Richardson*

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TABLE OF CONTENTS

GLOSSARY OF ACOUSTICAL TERMS

absorption. The process by which sound energy is converted into heat.

acoustic energy. The energy in an acoustic wave, measured in joules or watt-seconds. Acoustic energy is proportional to the product of pressure squared and time.

acoustic intensity. The acoustic power crossing a unit area. Generally the intensity varies with direction and is therefore a vector quantity. For a plane wave, the intensity is given by the pressure squared divided by the acoustic impedance (ρc, where ρ represents the density and c the sound velocity).

acoustic power. The energy per unit time, measured in watts. The acoustic power is proportional to acoustic pressure squared.

acoustic pressure. Pressure variations around an ambient static pressure (such as the hydrostatic pressure in water at some depth) at acoustic frequencies. These are very small pressures compared to the static pressure or compared to shock or blast wave pressures.

ambient noise. Background noise; noise not of direct interest during a measurement or observation. Excludes sounds produced by the measurement equipment, such as cable flutter.

auditory sensitivity. An animal's hearing sensitivity as a function of frequency.

auditory threshold. The minimum amplitude of sound that can be perceived by an animal in the absence of significant background noise. Auditory threshold varies with frequency and is inversely related to the animal's auditory sensitivity.

A-weighted level. A sound level measured by a method suitable for airborne environmental noise as perceived by man. Determined by integrating across all frequencies after weighting the frequency distribution (spectrum) by a weighting curve approximating the auditory sensitivity curve for human beings. Different airborne sounds can be compared on the basis of their "dBA" A-weighted levels.

bandpass filter. A filter with high- and lowpass cutoff frequencies to pass only a band of frequencies.

critical band. The frequency band within which background noise can affect detection of a sound signal at a particular frequency.

critical ratio. The ratio of power in a barely-audible tone to the spectrum level of background noise at nearby frequencies.

continuous wave. A sound whose waveform continues with time. *cf.* transient wave.

cylindrical spreading. Sound spreading for cylindrical waves. The transmission loss for cylindrical spreading is given by $10*\log_{10}(\text{Range}/R_0)$, where R_0 is some reference range. The received level diminishes by 3 dB when range doubles, and by 10 dB for a tenfold increase in range.

cylindrical wave. A sound wave whose fronts are cylindrically shaped. For a point source in shallow water, a cylindrical wave forms at distances large compared to the water depth because of the way reflected sound from the surface and bottom reinforces the direct wave.

decibel (dB). A logarithmically based relative measure of sound strength. A sound pressure P can be expressed in dB as a sound pressure level of $20*\log_{10}(P/P_{ref})$, where P_{ref} is a reference pressure (usually a standard pressure like 1 µPa). Note that $20*\log(X)$ is the same as $10*\log(X^2)$, where X^2 is the mean square sound pressure and is proportional to power, intensity or energy.

delay. The time in seconds by which one waveform lags behind another. For example, reflected sound will usually be delayed in reaching a receiver compared to directly traveling sound.

doppler shift. The change in the frequency of a received signal caused by motion of the source, the receiver, or both. The motion must have a radial component, i.e., there must be a component of motion aligned with the line between the source and receiver. The doppler shift will be a constant for constant radial speed. If the radial component of speed changes, such as occurs when the source moves past the receiver or vice versa, then the doppler shift changes and the received frequency will change.

duty cycle. The percentage of time a given event or activity occurs. The term is usually applied to a periodic activity, i.e., an activity in which the on-off cycle repeats with the same duration each cycle.

electrical noise. Noise generated by electronic circuits, as distinct from acoustic noise.

filter. An instrument or mechanism for restricting or altering the frequency range or spectral shape of a waveform.

frequency. The rate at which a repetitive event occurs, measured in hertz (cycles per second).

hertz. A measure of frequency corresponding to a cycle per second.

highpass filter. A filter passing sounds above a specified frequency.

hydrophone. A transducer for detecting underwater sound pressures; an underwater microphone.

infrasonic. A term used to refer to sound energy at frequencies too low to be audible to humans—generally, frequencies below 20 Hz.

intensity level. The acoustic intensity expressed in dB.

level. The term "level" is usually applied to sound amplitudes, powers, energies or intensities expressed in dB.

Lloyd mirror effect. The diminished pressure of a sound from an underwater source when it is received near the water/air boundary (the surface). The reflected sound wave is inverted (out of phase) with respect to the incident sound wave and their sum at the receiver approaches zero as the receiver approaches the surface.

lowpass filter. A filter passing sounds below a specified frequency.

masking. The obscuring of sounds of interest by stronger interfering sounds.

mean square pressure. The average of the pressure squared. The acoustic power, intensity, or energy is proportional to the mean square acoustic pressure.

microbar (μbar). A unit of pressure previously used as a reference pressure in dB level measurements. A μbar is equivalent to 1 dyne/cm^2 and to 0.1 pascal, or 10^5 μPa.

micropascal (μPa). The usual reference pressure in underwater sound level measurements.

octave band. A frequency band whose upper limit in hertz is twice the lower limit.

one-third octave band. A frequency band whose upper limit in hertz is $2^{1/3}$ times the lower limit. Three one-third octave bands span an octave band. Such bands have widths proportional to the center frequency; the center frequency is given by the square root of the product of the upper and lower limit frequencies, and the bandwidth is 23% of the center frequency. There is a standard set of one-third octave frequency bands for sound measurements.

particle velocity. A physical quantity used as a measure of sound. Particle velocity is a measure of the particle motion associated with the existence of sound energy. The dimensions of particle velocity are distance per unit time; common units are cm/second. A sound wave in a fluid can generally be detected with sensors sensitive to either pressure or particle motion. *cf.* pressure.

pascal. A unit of pressure equal to 1 newton per square meter.

peak level. The sound level (in dB) associated with the maximum amplitude of a sound.

period. The time between repetitions of a cyclic activity. In acoustics, the period is the reciprocal of the frequency. The dimension of period is time.

phase. An angular measure of the displacement in time of some periodic function with respect to a reference time. For example, a general expression for a sinusoidal waveform is

$A*\cos(\omega t+\theta)$, where A is the amplitude, ω is the radian frequency, t is time, and θ is the phase angle (in radians).

phase difference. See phase. The phase difference is the difference in phase of two waveforms. Generally the waveforms will be the same frequency. However, the term "180° phase difference" can be applied to arbitrary waveforms "out of phase" with each other, i.e., one waveform is inverted with respect to the other.

phase velocity. The velocity of a wavefront (points of constant phase) on a traveling wave. The phase velocity is commonly cited in acoustics for the speed of sound.

plane wave. For a plane wave, the wavefronts (points of constant phase) are planes rather than spheres, cylinders or some more complex shape.

point source. A hypothetical point from which sound is radiated. The concept is useful in describing source levels by a pressure level at unit distance. The concept is an abstraction; to describe a 300 m ship as a point source stretches the imagination, but at a distance of 10 n.mi. the received sound may as well have come from a point source radiator.

power density spectrum. The result of a frequency spectrum analysis to determine the distribution of power in a signal vs. frequency where continuously distributed sound (not tones) is the important component of the signal. Correct units of a power density spectrum are watts/Hz but the usual units in acoustics are $\mu Pa^2/Hz$, because the power is proportional to the mean square pressure and pressure is the commonly measured physical quantity.

power spectrum. The result of a frequency spectrum analysis to determine the distribution of power in a signal vs. frequency where tones are the important components of the signal. Correct units of a power spectrum are watts but the usual units in acoustics are μPa^2, because the power is proportional to pressure squared and pressure is the commonly measured physical quantity.

pressure. A physical manifestation of sound. (See also particle velocity.) The dimensions of pressure are force per unit area. The commonly used unit of acoustical pressure is the micropascal.

propagation loss. The loss of sound power with increasing distance from the source. Identical to transmission loss. It is usually expressed in dB referenced to a unit distance like 1 m. Propagation loss includes spreading, absorption and scattering losses.

proportional bandwidth filters. A set of filters whose bandwidths are proportional to the filter center frequencies. One octave and one-third octave filters are examples of proportional bandwidth filters.

pure tone. A sinusoidal waveform, sometimes simply called a tone. There are no harmonic components associated with a pure tone.

reflection. The physical process by which a traveling wave is returned from a boundary. The angle of reflection equals the angle of incidence.

refraction. The physical process by which a sound wave passing through a boundary between two media is bent. If the second medium has a higher sound speed than the first, then the sound rays are bent away from the perpendicular to the boundary; if the second medium has a lower sound speed than the first, then the sound rays are bent toward the perpendicular. Snell's law governs refraction: $c_2 * \sin \theta_1 = c_1 * \sin \theta_2$, where c is the sound speed, subscript 1 refers to the first medium and subscript 2 refers to the second medium, and the angles are measured from the perpendicular to the boundary. Refraction may also occur when the physical properties of a single medium change along the propagation path.

relative phase. The phase of a periodic waveform with respect to a reference waveform.

scattering. The physical process by which sound energy is diverted from following a regular path as a consequence of inhomogeneities in the medium (volume scattering) or roughness at a boundary (boundary scattering).

sound. A form of energy manifested by small pressure and/or particle velocity variations.

sound pressure. The pressure associated with a sound wave.

sound pressure density spectrum. The description of the frequency distribution of sound pressure in which the actual pressure at any frequency is infinitesimal but, integration over any non-zero frequency band results in a non-zero quantity. The correct dimensions of sound pressure density spectrum are pressure squared per unit frequency; a common unit is $\mu Pa^2/Hz$. *cf.* power density spectrum.

sound pressure density spectrum level. The measure in decibels of sound pressure density spectrum. A common unit is dB re 1 $\mu Pa^2/Hz$.

sound pressure level (SPL). The measure in decibels of sound pressure. The common unit is dB re 1 μPa.

sound pressure spectrum. The description of the frequency distribution of a sound pressure waveform consisting of tones. The dimension is that of pressure; a common unit is the micropascal.

source level. A description of the strength of an acoustic source in terms of the acoustic pressure expected a hypothetical reference distance away from the source, typically 1 m, assuming that the source is a point source. Source level may be given in units of dB re 1 μPa-m. Source level may vary with frequency (see source spectrum level) but it may be given for some band of frequencies.

source spectrum level. A description in decibels of the strength of an acoustic source as a function of frequency. The description is meaningful for sources of tones. Source spectrum levels are described in decibels referred to a unit pressure at a unit distance, such as dB re 1 μPa-m.

spherical spreading. Sound spreading for spherical waves. The transmission loss for spherical spreading is given by $20*\log_{10}(\text{Range}/R_0)$, where R_0 is some reference range. The received level diminishes by 6 dB when range doubles, and by 20 dB for a tenfold increase in range.

spherical wave. A sound wave whose fronts are spherically shaped. Such a wave forms in free space without reflecting boundaries or refraction. Typically, spherical waves are emitted by point sources and retain their sphericity until the influence of reflected waves or refraction becomes noticeable.

spreading loss. The loss of acoustic pressure with increasing distance from the source due to the spreading wavefronts. There would be no spreading loss with plane waves. Spreading loss is distinct from absorption and scattering losses.

threshold of audibility. The level at which a sound is just detectable. The threshold of audibility depends on the listener and varies with frequency.

time delay. A time difference between related events, such as the time between arrivals of a sound wave at two receivers, or the time between sound transmission and the reception of its reflection.

tone. A sinusoidal waveform, sometimes called a pure tone. There are no harmonics. A tone is distinct from waveforms consisting of components continuously distributed with frequency.

transducer. A device for changing energy in one form (say mechanical) into energy in another form (say electrical). An acoustic transducer might change a pressure waveform into an electrical waveform, or vice versa. Microphones, hydrophones, and loudspeakers are examples of transducers.

transient wave. A wave that starts and ends in a relatively short time. Transient waves contrast with continuous waves that are said to continue without stopping.

transmission loss. The loss of sound power with increasing distance from the source. Identical to propagation loss. It is usually expressed in dB referenced to a unit distance like 1 m. Transmission loss is includes spreading, absorption and scattering losses.

ultrasonic. A term used to refer to sound energy at frequencies too high to be audible to humans—generally, frequencies above 20,000 Hz.

waveform. The functional form, or shape, of a signal or noise vs. time.

wavelength. The length of a single cycle of a periodic waveform. The wavelength λ, frequency f and speed of sound c are related by the expression $c = f*\lambda$.

1. INTRODUCTION[1],[2]

This volume is a review of literature concerning the effects of man-made noise on marine mammals. Sound, unlike light and other potential stimuli, is transmitted very efficiently through water. Underwater noise created by ships and some other human activities can often be detected many kilometers away from the source, far beyond the distances where human activities would be detectable underwater (or even in air) by vision or other senses. Also, the efficiency of underwater sound propagation allows marine mammals to use underwater sounds as a primary method of communication with one another. In addition, toothed whales produce echolocation sounds to sense the presence and location of objects, including prey.

The long distances over which marine mammal calls and other natural underwater sounds can be detected are one reason why sounds are so useful and important to marine mammals. Marine mammals probably obtain much information about their environment by listening to the sounds from other natural sources, aside from members of their own species. Examples may include surf noise (indicating the presence and direction of a shoreline or shoal), ice noise, and sounds from predators such as killer whales.

Concern has arisen that sounds introduced into the sea by man could have deleterious effects on marine mammals. One way in which man-made noise could affect marine mammals is through interference with their ability to detect calls from conspecifics, echolocation pulses, or other important natural sounds. Any sound signal in the water or air is detectable only if the received intensity of sound exceeds a certain detection threshold. Detection thresholds are discussed in detail in Chapter 7, but in general are often roughly equal to the level of background noise in the corresponding frequency band. Thus, if the sound signal reaching an animal is appreciably weaker than the background noise, the signal probably will not be detected. Consequently, elevated background noise levels caused by man-made noise may prevent detection of other sounds important to marine mammals.

A second potential effect of man-made noise on marine mammals is to disturb their behavior. These reactions can range from brief alterations in behavior to short- or long-term displacement from areas where man-made noise is present.

A third concern, at least in man and other terrestrial mammals, is that strong sound can cause temporary reductions in hearing sensitivity. In man, exposure to very high sound levels for brief periods or to moderately high levels for prolonged periods (e.g. in the workplace) can sometimes cause permanent hearing impairment (Kryter 1985). There has been some speculation about the possibility of similar temporary or permanent hearing impairment in marine mammals exposed to high levels of man-made noise (Chappell 1980; Bohne et al. 1985, 1986).

Although most of the concern about noise effects on marine mammals has involved the potential effects of underwater noise, airborne sounds are important to marine mammals that

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[1] By W. John Richardson, LGL Ltd.

[2] Constructive comments on a draft of this chapter were provided by Drs. W.C. Cummings, R.A. Davis, R.H. Nichols and A.N. Popper.

emerge from the water into the air, i.e. pinnipeds and sea otters. Indeed, most of the available data on behavioral reactions of pinnipeds to man-made noise deal with responses of seals, sea lions and walruses hauled out on land or ice.

1.1 History of Relevant Research and Analyses

Many publications dealing with the natural history of marine mammals include brief anecdotal comments concerning observed reactions (or lack of reactions) of marine mammals to boats, aircraft, or other sources of underwater or airborne sound. In most of these cases it is not certain that the animals reacted to noise and not to visual stimuli or some other sensory modality. However, these anecdotal observations give some indications about the possible responsiveness (or lack of it) of various marine mammals to potentially disturbing human activities.

A considerable amount of research designed specifically to determine the ***behavioral responsiveness*** of marine mammals to noise has been conducted in the last several years. Much of this work was done because of concern that noise from the offshore operations of the oil industry might harm marine mammals in one or more of the ways mentioned above. The provisions of the U.S. Marine Mammal Protection Act and the U.S. Endangered Species Act, among other reasons, have led to much research on this topic. The U.S. Department of the Interior, through the Bureau of Land Management, the Minerals Management Service, and interagency agreement with the National Marine Fisheries Service, has funded much of this research. Their major objective has been to ensure that issuance of leases and permits for offshore hydrocarbon exploration would not significantly harm marine mammals. The oil industry and various state and local agencies have also funded several important studies. Concern about effects of noise from other human activities, e.g. vessel traffic associated with commerce and tourism, has led to considerable related research funded by the U.S. National Marine Fisheries Service, U.S. National Park Service, and other agencies.

During these recent studies, researchers have documented in a more or less quantitative manner the disturbance reactions of various species of whales and, less often, pinnipeds to several oil industry activities. These activities have included vessel and aircraft traffic, marine seismic exploration and construction, and various types of drilling operations. Study techniques have included either uncontrolled observations of the reactions of animals to actual oil industry activities or controlled experimental tests of reactions to simulated oil industry activities. In some of these studies the levels of noise near the animals have been monitored or predicted by acoustic modeling methods, thereby providing information about sound levels and frequencies that do and do not elicit behavioral reactions, i.e. "thresholds of responsiveness". This volume includes a detailed summary and review of these types of data.

A few of the recent studies of marine mammal disturbance have included specific measurements of the ***characteristics of oil industry sounds***. There is wide variation in the intensity, frequency composition and waveform of the sounds from different oil industry activities, and these variations are expected to lead to wide variability in the reactions of marine mammals. Additional valuable data on characteristics of vessel and aircraft noise have come from studies conducted for purposes unrelated to marine mammals, e.g. basic acoustical research, studies of ship noise conducted for military purposes, and studies of aircraft noise for purposes of reducing noise around airports. A detailed summary of these types of data is an important component of this review.

Data on natural background noise (***ambient noise***) are important in evaluating the detectability of other sounds, either natural sounds like marine mammal calls or the various types of man-made sounds. The stronger the natural background noise, the stronger a sound signal must be in order to be detected. Relatively few data on natural ambient noise have been collected during studies of marine mammals. However, work with other objectives has resulted in a large literature on ambient noise in the sea and air. This review provides a brief summary of some relevant aspects of ambient noise.

The ***attenuation of sound*** as it propagates through the water or air from its source to a receiver (e.g. a marine mammal) is a very important process insofar as effects on marine mammals are concerned. Sound attenuation rates are highly variable depending on environmental conditions. In situations where the rate of attenuation is large, effects on marine mammals are not expected to extend as far from the noise source as would occur in situations where the attenuation rate is small. A limited amount of research on sound propagation has been done during recent studies of the reactions of marine mammals to underwater noise. However, much information on underwater sound propagation has been obtained during basic and military research programs in various countries. Computer models that predict sound attenuation rates under different environmental conditions have been developed, in many cases for naval interests. Some of these publications and models are published or at least unclassified, but many are not available. This review summarizes the basic principles of underwater and airborne sound propagation, emphasizing aspects relevant to the present topic, but does not attempt to review all of the literature on sound propagation.

Another important area of research has been on the ***hearing abilities*** of various marine mammals. Hearing abilities of several species of toothed whales, hair seals and eared seals have been measured in at least a preliminary way. There are also a few data on hearing by manatees, but no direct information on hearing by baleen whales or sea otters. Such data are important because hearing abilities determine the detectability of natural and man-made noise under varying conditions, and the effects of man-made noise on detectability of natural sounds. Almost all of the direct studies of the hearing abilities of marine mammals have been conducted for purposes other than evaluation of the effects of industrial noise on hearing. However, the data that have been collected are very relevant to the present topic. This review includes a detailed summary of the relevant aspects of marine mammal hearing.

Similarly, over the past several decades much work has been done on the ***characteristics of sounds*** emitted by many species of marine mammals. Some of these data are relevant here because marine mammal sounds are undoubtedly important for communication or echolocation. The frequency content of these sounds is at least partly indicative of the frequencies that are important to the species involved. The intensities of the marine mammal sounds affect their susceptibility to interference by man-made noise. We do not attempt to provide a complete review of marine mammal sounds. However, we do review the relevant aspects and provide tables summarizing the sounds produced by many species occurring in and near U.S. waters.

A few workers have attempted to draw together several of these types of information in order to ***evaluate the potential effects*** of underwater noise on marine mammals. These evaluations involve consideration of

- the intensities and other characteristics of industrial noise,
- its rate of attenuation with increasing distance,
- natural ambient noise level as it affects the distance at which the industrial noise level attenuates below the ambient level,
- characteristics of marine mammal sounds that are to be detected in the presence of man-made and natural noise,
- hearing abilities of the species, and
- documented behavioral reactions of the species to noise.

The first publication to attempt an evaluation of this type was Payne and Webb (1971). Based on existing data, they evaluated the detectability of fin whale calls as a function of distance, and discussed the probable effects of increased shipping noise in recent decades. Fletcher and Busnel (1978) edited an important symposium on the effects of noise on wildlife, including a review by Myrberg (1978) on the effects of underwater noise. More recently, the Acoustical Society of America (1981) organized, on behalf of the Alaska Eskimo Whaling Commission, a discussion of the need for more specific data of the various types listed above. Several workers used existing data to evaluate the possible effects of noise from proposed liquefied natural gas (LNG) tankers on northern marine mammals (Peterson 1981).

Gales (1982) was one of the first investigators to make specific field measurements in support of an evaluation of noise effects on marine mammals. He measured sounds emitted by several drilling and production platforms and then used existing data on sound attenuation and hearing to estimate the distances within which the oil industry sounds might be audible.

Beginning in the early 1980s, a series of studies was conducted to obtain more specific and coordinated field data on industrial noise characteristics, sound propagation, and behavioral reactions of marine mammals as a function of distance and of received sound level. This work was summarized by Richardson et al. (1989) and Myrberg (1990), and is reviewed in detail in this volume. As more data of these types become available, detailed mathematical models of the potential radius of noise influence may become possible. Miles et al. (1987) and Malme et al. (1989) have made the most elaborate attempts to develop "***zone of acoustic influence***" models for marine mammals. However, as will be discussed in this review, even these comparatively elaborate models have major limitations. One of the most severe limitations of present data and models is that they deal primarily with short-term behavioral reactions to noise, on a scale of minutes or hours. The longer-term implications of these short-term effects are generally unknown.

1.2 Objectives and Scope of Review

The general objective of this literature review is to summarize available evidence concerning the effects of man-made noise on marine mammals. Emphasis is given to underwater noise, but some attention is given to airborne sounds. Strong emphasis is given to the effects of noise from offshore oil and gas exploration and development, but effects of related types of man-made noise are also taken into account. We deal primarily with effects of noise on marine mammals in U.S. coastal waters, but the worldwide literature is considered.

Formally published literature is reviewed in detail, but considerable efforts also were made to review the large body of relevant research reported in technical and contract reports.

To provide a comprehensive and logical review, several types of background information are presented in the early chapters. These chapters are followed by chapters summarizing the available information and hypotheses about specific noise effects on marine mammals. The initial background chapters include the following:

1. Introduction (this chapter)
2. Acoustic Concepts and Terminology
3. Sound Propagation
4. Ambient Noise
5. Man-made Noise
6. Marine Mammal Sounds
7. Marine Mammal Hearing

These background chapters are then followed by four chapters that deal more specifically with the effects of noise on marine mammals:

8. Documented Disturbance Reactions
9. Zones of Noise Influence
10. Significance of Responses and Noise Impacts
11. Conclusions and Data Needs

The review concludes with an extensive list of "Literature Cited", an Appendix showing the scientific names of all species of marine mammals mentioned in the text, other Appendices, and an Index. A Glossary of common acoustics terms is provided at the front of the volume.

As noted in section 1.1, the level of detail provided in different chapters varies in relation to the relevance of the material to the overall theme. The chapters on acoustic concepts and terminology, ambient noise, and sound propagation do not attempt to review the literature in detail; instead, they summarize the material that is necessary as background for later sections of this review. The chapter on marine mammal sounds is more detailed, but emphasizes relevant material and is not intended to be comprehensive. The chapters on man-made noise, marine mammal hearing, and documented disturbance reactions provide detailed reviews of the relevant literature. The zone of influence chapter explains currently used approaches and gives several specific examples--some from the literature and some based on new analyses.

Although this review is divided into separately-authored chapters, the reviews of all topics were closely coordinated. LGL was responsible for coordinating the effort and for preparing the biological chapters (6-8, 10, 11, and part of 9). C.R. Greene Jr. of subcontractor Greeneridge Sciences Inc., a company specializing in underwater acoustics research, prepared Chapters 2, 4 and 5, assisted by S.E. Moore. Subcontractor C.I. Malme of BBN Systems & Technologies Corp. prepared Chapter 3 and parts of Chapter 9 involving sound propagation models.

The work was greatly facilitated by the fact that all authors have been actively involved in one or more relevant field studies for at least several years. Thus, much of the necessary literature was already known to us. However, a detailed literature search was also done as part of this project. In addition to manual searches, we conducted a computer search of the National Technical Information Service (NTIS) database, which lists government reports, and of the BIOSIS database, which lists refereed biological publications. The work of LGL and Greeneridge was further facilitated by the fact that we had prepared a similar review in 1982-83 (Richardson et al. 1983). An updated second edition of that review (Richardson et al. 1989) was prepared simultaneously with early stages of the present effort, and some of the material in this volume appears in similar form there.

This review is believed to take into account most major sources of relevant data. However, much of the relevant information is available only in unpublished contract reports and similar sources, and some significant information no doubt has been missed. In anticipation of a future updated review, the authors and editor welcome comments and corrections.

Three consultants, Drs A. Popper, R. Schusterman and B. Würsig, assisted LGL by contributing to and reviewing several chapters. We are also grateful to three external referees who reviewed various chapters on behalf of the Minerals Management Service: Dr. W.C. Cummings, the late Dr. R.H. Nichols, and Dr. D. Ross. Each of these six reviewers, along with Dr. R.A. Davis of LGL and a number of anonymous MMS reviewers, provided many constructive comments, most of which have been taken into account. However, not all suggestions could be accepted; the interpretations and conclusions, along with any remaining errors and omissions, are the responsibility of the authors.

2. ACOUSTIC CONCEPTS AND TERMINOLOGY[1,2]

2.1 Introduction

Sound is what we hear. Waves of sound energy travel through air or water as vibrations of the fluid particles, reaching our ears to exert tiny push-pull pressures on our eardrums. We take sound for granted. We are familiar with a wide variety of sound sources, varying in strength from the weak hiss of air molecules moving randomly to the clap of thunder from a nearby lightning stroke. We know that many animals respond to sounds and that some use sounds for communication.

Before presenting a definition of sound by a physical acoustician, a few basic terms need to be defined. ***Frequency*** refers to the rate of oscillation or vibration, measured in cycles per second or Hertz. The pitch of a sound as perceived by a human is directly related to frequency. Humans are often said to be able to hear sounds ranging from 20 Hz to 20,000 Hz, although for most individuals the actual range of useful sensitivity is narrower. A ***tone***, sometimes called a ***pure tone***, involves a sinusoidal oscillation at a specific frequency.

The unit of frequency measurement is the ***Hertz***, which is one cycle per second. Frequency is the reciprocal of the ***period*** of the oscillation, which is the time (in seconds) required for one complete oscillation. The usual symbol for frequency is f. The concept of ***wavelength*** applies to periodic sounds and is the length of the fundamental oscillation in the medium of propagation.

To a physical acoustician,

> "Sound is a longitudinal mechanical wave motion propagating in an elastic medium. The waves comprise alternating compressions and rarefactions which propagate at a speed that depends on the relative compressibility of the medium... . The wavelength of a single tone is related to its frequency by the equation $c = f\lambda$, where c is the speed of sound, f is the frequency, and λ is the wavelength. Sound is the only form of energy that propagates to significant distances in the oceans. Hence, the emphasis on underwater sound for navigational as well as submarine detection systems. SONAR, SOund NAvigation and Ranging, is the underwater counterpart to radar." (D. Ross, pers. comm.)

Some fluctuations in fluid pressure are commonly called sounds even though they cannot be heard by man. These include ***ultrasonic*** sounds, whose frequencies are too high to be heard by man (>20,000 Hz), and ***infrasonic*** sounds, whose frequencies are too low to be heard (<20 Hz). Many animals (e.g. dolphins, bats and dogs) can detect certain ultrasounds. Some animals (e.g. elephants) can detect certain infrasounds.

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[2] Constructive comments on a draft of this chapter were provided by Drs. W.C. Cummings, R.A. Davis, R.H. Nichols, A.N. Popper and D. Ross.

A useful model of the acoustic process is the "***source-path-receiver***" model. This model recognizes that any hearing process involves

- a source of sound with particular characteristics,
- changes in sound characteristics as the sound propagates away from the source, and
- a receiver with specific detection capabilities.

As an example, consider a whale swimming near a drillship: the drillship is a source of underwater sound, the water (including the surface and bottom) is the path from the source to the whale, and the whale is the receiver. Using this general model, we can examine the character of sound sources; the influence of the sound propagation path, including the introduction of extraneous sounds or noise; and finally the characteristics of a particular receiver.

Source characteristics include the transient or continuous nature of the sound, the way in which the sound energy is distributed in frequency, and its strength. ***Transmission*** refers to the propagation of sound through the air, water or bottom from a source to a receiver. The ***transmission path*** is the route from source to receiver, and may include various combinations of air, water or bottom materials. The path often is not a straight line. Multiple transmission paths occur when there are reflecting surfaces along the path, such as the surface and (in underwater sound transmission) the bottom. Rough surface or bottom features cause sound to be scattered. Some of the underwater sound impacting the bottom is absorbed. Refraction (ray bending) can be important in either underwater or airborne sound transmission. In this review the ***receivers*** of interest are marine mammals. Important receiver characteristics include an animal's hearing sensitivity to sounds at different frequencies and the responsiveness of the animal to different types and levels of sounds.

In this chapter we introduce the terminology used by acousticians to describe the different elements of the source-path-receiver model. Our goal is to provide the reader with at least a basic knowledge of the terms and concepts necessary to interpret technical literature describing the influences of underwater sound on marine mammals. Familiarity with these concepts and terms will be essential to understand subsequent chapters of the review. Two important books about underwater sound, Ross (1976) and Urick (1983), and a good text on sound in general (Kinsler and Frey 1962), provide good discussions of acoustic concepts and terminology.

2.2 Sound Measurement Units

Most sound receivers are sensitive to ***sound pressure***, which is measured in units of ***micropascals (μPa)***. A pascal is a standard unit of pressure in the SI system of units: One pascal is the pressure resulting from a force of one newton exerted over an area of one square meter. Older reports use a different pressure unit, the ***dyne/cm²***, also called a ***microbar (μbar)***. A bar is the pressure of one standard atmosphere. The microbar and micropascal are directly related and interconvertible:

$$1 \text{ micropascal} = 10^{-5} \text{ microbar} \qquad (2.1)$$

Acoustic intensity is rarely measured directly but is often discussed. It is important because it is a fundamental measure of propagating sound. It is defined as the ***acoustical power*** per unit area in the direction of propagation; the units are watts/m^2. The intensity, the power and the energy of an acoustic wave are proportional to the average of the pressure squared (the

mean square pressure). Acoustics researchers often refer to the ratio of intensities or powers. However, they derive this from the ratio of pressures squared, since measurement instruments normally sense pressure rather than intensity or power. This practice is legitimate for ratios of measurements *in the same medium* (i.e. in water or in air), where the constants of proportionality between intensity or power and pressure are the same. This discussion will be augmented later in this review when decibels are defined and discussed.

In presenting sound measurements acousticians use ratios of pressures, or pressures squared, requiring the adoption of a standard reference pressure for use in the denominator of the ratio. Early acousticians working on problems in air acoustics adopted a standard pressure of 0.000204 μbars, which is the pressure in air corresponding to an intensity of 10^{-12} watts/m^2. This reference intensity was chosen because it is the approximate minimum sound intensity detectable by man (Table 2.1). At first, underwater sound researchers used the same reference (rounded to 0.0002 μbar). However, this reference pressure was arbitrary and inappropriate for underwater sound, and the reference pressure for underwater sound was redefined as 1 μbar. Finally, when the SI system became accepted throughout physics, the underwater sound community adopted 1 μPa as the reference pressure (Table 2.1). For airborne sound it is conventional to use 20 μPa as the reference pressure; that is the open ear threshold of human hearing at 1 kHz (Table 2.1).

For humans, sounds that are faint and barely perceptible have intensities near 10^{-12} watts/m^2, whereas those that are painful are near 10 watts/m^2. The ear is able to span this wide range of intensities by means of a complicated nonlinear response (Kinsler and Frey 1962). In fact, in judging the relative loudness of two sounds, our ears respond to the ratio of their intensities, meaning our hearing behaves logarithmically. Because of this, and to keep numbers within reasonable ranges, acousticians adopted a logarithmic scale for sound intensities and denoted the scale in ***decibels***. In decibels, the ***intensity level*** of a sound of intensity I is given by

$$\text{Intensity Level (dB)} = 10 \log (I/I_0) \tag{2.2}$$

where I_0 is the reference intensity, e.g. 1 watt/m^2. Because intensity is proportional to pressure squared, ***sound pressure level*** (SPL) of a sound of pressure P is given by

$$\text{Sound Pressure Level (dB)} = 20 \log (P/P_0) \tag{2.3}$$

where P_0 is the reference pressure, e.g. 1 μPa. The phrase "sound pressure *level*" implies that a reference pressure has been used as the denominator of the ratio.

In underwater sound studies we rarely measure intensity; pressure is the physical quantity of interest, and we use the reference pressure units cited earlier for P_0. In summary, the reference pressure currently used is one micropascal (μPa), but earlier publications used one microbar (μbar) or, even earlier, 0.0002 μbar. Sound pressure levels referred to these units are related as follows:

$$\text{SPL (dB re 1 μPa)} = \text{SPL (dB re 1 μbar)} + 100 \tag{2.4}$$

$$\text{SPL (dB re 1 μPa)} = \text{SPL (dB re 0.0002 μbar)} + 26 \tag{2.5}$$

For example, an SPL of -40 dB re 1 μbar is also 60 dB re 1 μPa. Table 2.1 shows the interrelationships of various scaling procedures for sound levels.

Table 2.1. Interrelationships of various scales for acoustic measurements. Adapted from Kryter (1985:8). Standard reference units are underlined.

dB re 1 µPa	Pascals	Dynes /cm^2	Bars	dB re .0002 µbar	Typical airborne sounds
220	100,000	1,000,000	1	194	
200	10,000	100,000	.1	174	
180	1,000	10,000	.01	154	Some military guns
160	100	1,000	.001	134	Sonic booms
140	10	100	.0001 = 100 µ	114	Discomfort threshold, 1000 Hz steady tone
120	1	10	10 µ	94	500 m from jet airliner
100	.1	1	1 µ	74	15 m from auto, 55 km/h Speech in noise, 1 m from talker
80	.01	.1	.1 µ	54	Speech in quiet, 1 m from talker
60	.001	.01	.01 µ	34	
40	.0001	.001	.001 µ	14	
32	40 µ	400 µ	.0004 µ	6	Audiomet. thrhold,1 kHz
26	20 µ	200 µ	.0002 µ	0	Open ear thrhold, 1 kHz
20	10 µ	100 µ	.0001 µ	-6	Open ear thrhold, 4 kHz
0	1 µ	10 µ	.00001 µ	-26	

Acoustical researchers are not uniformly conscientious about citing their reference units, and readers will encounter many reports with confusing graph scales simply labeled "dB". Often the caption or text will clarify what is meant. The recommended practice is to cite the reference unit. Occasionally authors abbreviate, e.g. dB//1μPa instead of dB re 1 μPa.

A sound ***waveform*** represents the amplitude variations of the sound with time. In general, sound from a particular source may have power distributed over a wide range of frequencies. Some of the sound components may be periodic, consisting of a repeated waveform whose power is concentrated at specific frequencies. The waveform of a pure tone is a simple sinusoid. However, other components of sounds from most sources are ***continuously distributed*** across frequency; such sound may have a hissing quality at higher frequencies or a rumbling quality at lower frequencies. The waveforms of these more complex sounds are erratic, particularly if tones are present. If a general sound is passed through a ***bandpass*** filter, which permits only the sound components between two specific frequencies to pass the filter, the filter output will contain the power, or the mean square pressure, in the sound within the filter passband. In the case of a continuously distributed sound, if the filter bandwidth is decreased, the output power will decrease.

To describe continuously distributed sounds, acousticians use the concept of ***power density spectrum***. This is a graph plotting power per unit frequency vs. frequency. Because measurements are usually in terms of pressure rather than power, a more common graph is the ***sound pressure density spectrum***--the mean square pressure per unit frequency in units of $\mu Pa^2/Hz$ (e.g. Fig. 2.1). To measure the sound pressure density spectrum, one could use one narrow filter whose passband is adjustable and whose output is recorded as the passband sweeps across the frequency band of interest. A better approach is to use a set of contiguously-spaced narrow filters that span the frequency band of interest. By using a set of filters, all frequency bands can be analyzed simultaneously. The mean square pressure density spectrum is obtained by dividing the mean square pressure for each filter band by the filter width. The result is a set of data showing the sound pressure density as a function of frequency, with units $\mu Pa^2/Hz$. These data become ***sound pressure density spectrum levels*** when the pressure density per hertz is converted to decibels referred to a unit pressure density (e.g., dB re 1 $\mu Pa^2/Hz$).

Consider the effect of a constant amplitude, continuous tone in a sound so analyzed. Such a pure tone has all its power at a single frequency. As the filter bandwidth is decreased, the output from the filter containing the tone remains constant. A filter of infinitesimally narrow width, but including the tone, would indicate the power in the tone. Furthermore, the ratio of the finite output power to the infinitesimally narrow filter width would be an infinitely large mean square pressure density. Thus, it is inappropriate to cite a pressure *density* for a tone, yet it is inevitable that tones will be present in many general sounds.

The effective width of the analysis "filters" is always greater than infinitesimal, and tones appear in the resulting density spectrum graphs as vertical spikes above the background noise continuum (Fig. 2.1). The heights or amplitudes of these spikes depend not only on their width and strength but also on the characteristics of the analysis--the narrower the filter, the taller the spike above the background (provided the filter is wider than the tonal spike). Ideally, researchers reporting a sound pressure spectrum will also report the width of the analyzing filter. This information permits readers to compute the power in the tone for themselves by

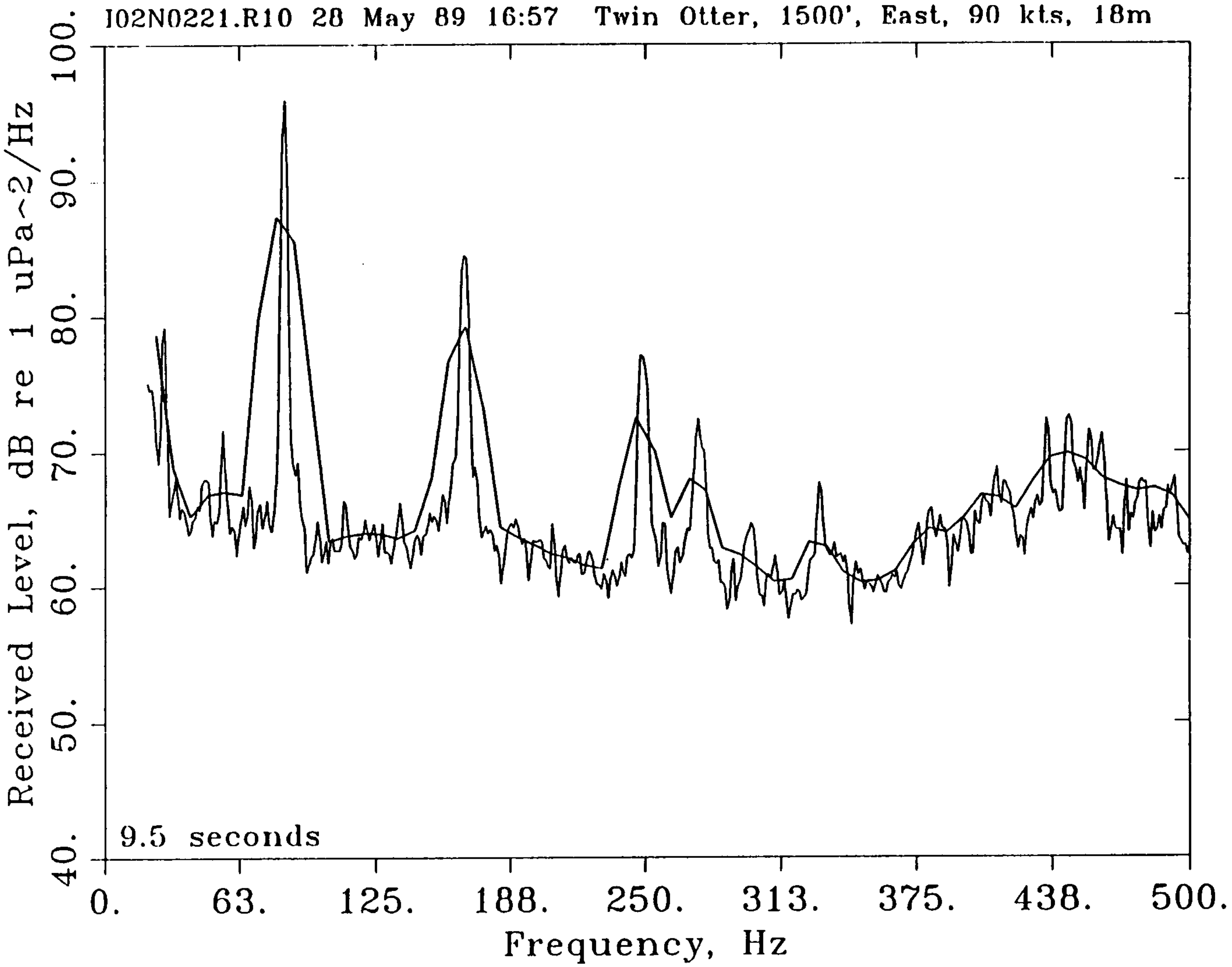

FIGURE 2.1. Effect of analysis bandwidth on sound pressure density spectra. Each line is a computed spectrum for sounds received by a hydrophone at depth 18 m during an overflight by a deHavilland Twin Otter aircraft (altitude 460 m; speed 157 km/h; 9.5 s of recording analyzed). The more-variable line shows sound components based on an analysis bandwidth of 1.7 Hz. The smoother line shows results with analysis bandwidth 13.7 Hz. "Spectrum levels" of the tones appear stronger with the narrower analysis bandwidth. However, after allowance for analysis bandwidth, the calculated levels of the tone at 83 Hz were the same (see text).

compensating for the divisor used to compute the density spectrum. For example, if a strong, pure-tone spike shows an apparent amplitude of 110 dB re 1 μPa²/Hz on a pressure density spectrum graph and the reported analyzer bandwidth is 4 Hz, the tone level is actually 110 + 10 log(4) = 116 dB re 1 μPa.

The foregoing discussion applies strictly to pure tones or to tones whose widths are less than the analyzing filter width. Two common sources of non-zero width in tones are (1) variations in the rotation rate of the source of the tone, and (2) ***doppler shift*** due to a change in the radial velocity of the source with respect to the receiver. For example, the frequencies of tones from an aircraft decrease as it passes over and starts moving away. At any one time, a tone may be at a single frequency, but the frequency may change within a typical analysis interval of a few seconds.

An example of a sound analyzed with two spectrum analysis widths is presented in Figure 2.1. The sound was from a deHavilland Twin Otter aircraft flying at altitude 1500 ft (460 m) over a hydrophone at depth 18 m. When the sound was decomposed into analysis cells 1.7 Hz wide over the frequency range 10-500 Hz, numerous tones were evident, the strongest at 83 Hz with a "spectrum level" of 96 dB re 1 μPa²/Hz. When this level was corrected by adding 10*(analysis bandwidth), i.e. 10*log(1.7) or 2.3 dB, the resulting sound level was 98 dB re 1 μPa. For comparison, the same sound was decomposed into analysis cells 13.7 Hz wide. The 83 Hz tone was included in the filter bin centered at 80 Hz, with a "spectrum level" of 87 dB re 1 μPa²/Hz. When corrected by adding 10*log(13.7) or 11.4 dB, the level was again 98 dB re 1 μPa, as expected.

Nowadays, spectra are usually obtained by computerized analysis techniques rather than through the use of analog filters; however, the concept is unchanged. After being digitized for computer processing, an acoustic waveform may be "filtered" mathematically into its power density spectrum by means of the ***discrete Fourier transform***, usually implemented with a ***Fast Fourier Transform*** algorithm.

Sound pressure density spectrum levels (SPSL) are cited in decibels with reference unit 1 μPa²/Hz. Some authors prefer to use a reference unit of 1 μPa/(Hz)$^{1/2}$, which is read as 1 micropascal per square root Hz. Either method is correct, and SPSL values referenced in either way are numerically the same.

The concept of a sound spectrum is important because we use it to describe the distribution of sound power as a function of frequency. An animal's sensitivity to sounds varies with frequency, and its response to a sound may be expected to depend strongly on the presence and levels of sound in frequency bands to which it is sensitive.

Some spectrum analyzers in common use are designed specifically to measure ***power spectra***. That is, they are designed to compute the frequency distribution of sound waveforms in which the tones are of primary interest, and therefore the levels are not corrected for the filter bandwidth. For such sound pressure spectrum levels, the units are dB re 1 μPa. The levels for the tones are correct. They are the sound power levels at the tonal frequencies, if the filter bandwidth is wider than the tone and if the tone is strong compared to the continuously-distributed background sound power (i.e. >10 dB above it). However, with this type of analysis the continuously distributed sound power is not correctly presented (as sound power density spectrum levels, dB re 1 µPa²/Hz), as that requires correcting for the filter bandwidth. This is admittedly confusing, to acousticians as well as others. Readers of the literature are cautioned to pay close attention to the units presented with any data describing the distribution of sound with frequency, as the presentation could be either ***sound power density spectrum level***, in dB re 1 µPa²/Hz, correct for continuously distributed sounds but not tones, or ***sound power spectrum level***, in dB re 1 µPa, correct for tones.

Sound pressure density spectrum levels, representing mean square sound pressure per unit of frequency, can be integrated over a range of frequencies--a ***frequency band***--to obtain the mean square pressure expected in the band. That is, if we applied a perfect ***bandpass*** filter with infinitely sharp lower and upper frequency "cutoffs" to a sound, the filter output would have the same mean square pressure as the integral of the density spectrum over the same range of frequencies. Two types of ***proportional bandwidth*** filters have been adopted as standards: ***one-third octave*** and ***octave*** band filters. In each case, the filter bandwidth is proportional to the filter center frequency.

An octave is a factor of two in frequency. For example, middle C on the music scale is at 256 Hz; the next higher C on the scale, an octave higher, is at 512 Hz. The bandwidth of a 1-octave band is 70.7% of the center frequency of that band, i.e. for center frequency x, a 1-octave band extends from $x(2^{-1/2})$ to $x(2^{1/2})$, or from $0.707x$ to $1.414x$.

The bandwidth of a one-third octave filter is 23% of its center frequency, i.e. from $x(2^{-1/6})$ to $x(2^{1/6})$, or from $0.891x$ to $1.122x$. Standard center frequencies (in Hz) for more-or-less adjacent 1/3-octave bands include the following:

50 63 80 100 125 160 200 250 315 400 500 Hz

as well as other frequencies lower or higher by factors of 10.

The sound power in a one-octave band is, of course, at least as high as that within any of the three 1/3-octave bands within that octave. Indeed, it is the sum of the sound powers within the three 1/3-octave bands. Similarly, the sound power in a 1/3-octave band is the sum of that within all 1-Hz bands within the 1/3 octave. Thus, a 1/3 octave level will equal or exceed the spectrum levels for all frequencies within that 1/3 octave (Fig. 2.2). When interpreting any quoted sound level, it is essential to be aware of the bandwidth over which that level was measured. Unfortunately, it is sometimes difficult or impossible to find this critical information in published accounts.

The terms ***phase***, ***phase difference***, ***relative phase*** and ***phase angle*** are sometimes used in describing periodic waveforms. These terms imply the existence of a reference waveform with the same period; phase is a measurement of the difference in time, or the offset, between the two waveforms. If the difference is equal to the period, or any integer multiple of the period, the two waveforms look the same and the phase difference is zero. Thus, it is possible to describe the phase as an angle in the range ±180°. For example, if the phase difference is one quarter of the period, the phase angle is ±90° (the sign depends on whether the waveform of interest is "ahead of" or "behind" the reference waveform).

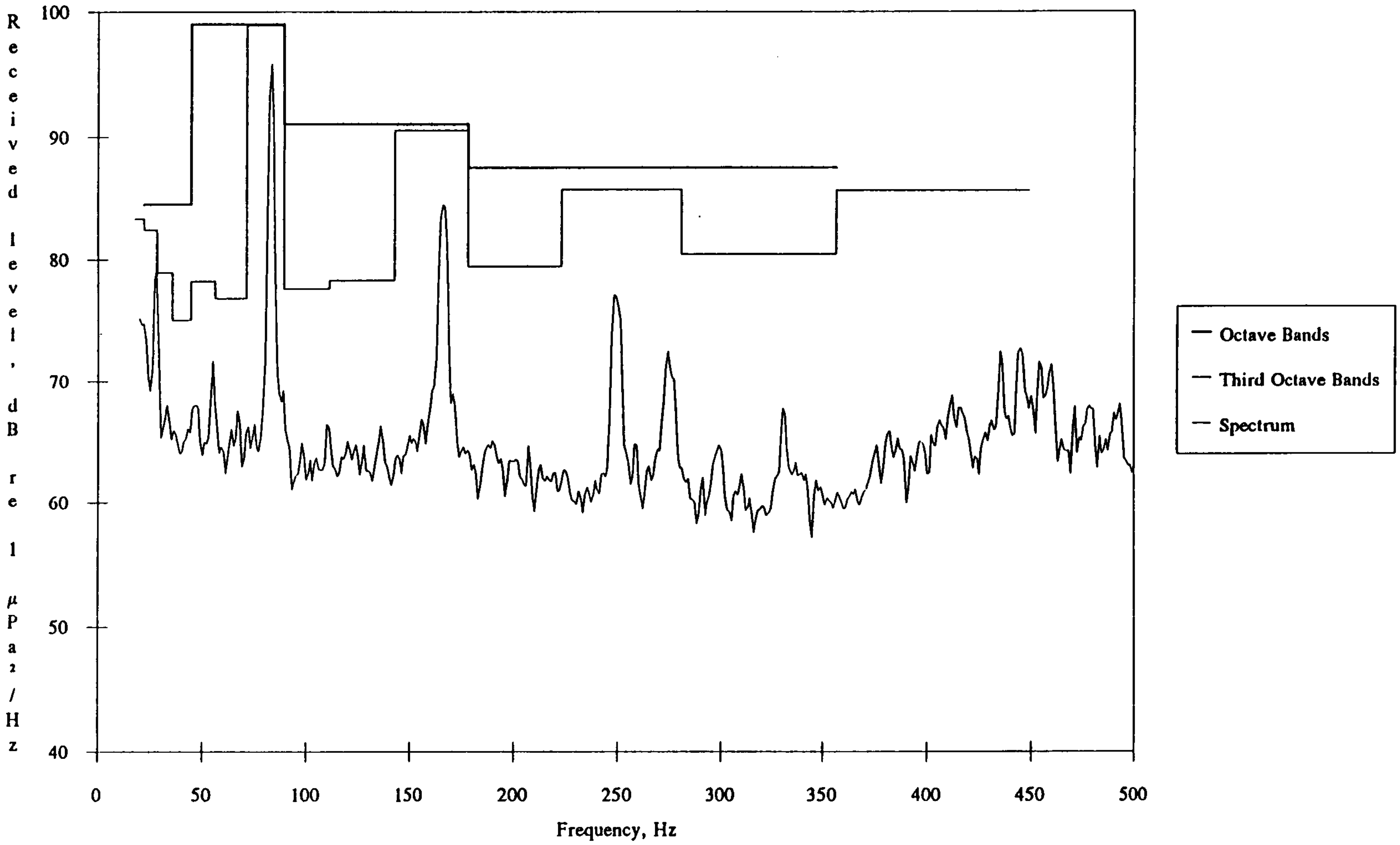

FIGURE 2.2. Comparison of spectrum levels, 1/3-octave band levels, and one-octave band levels for an example of Twin Otter sound. Spectrum levels represent the sound power in each 1-Hz band, and hence are lower than 1/3-octave levels, which represent the sound power in bands whose widths are 23% of the center frequency. Similarly, one-octave band levels are higher than 1/3-octave levels, since an octave band is three times as wide as a 1/3-octave band at the same center frequency. (Note that the ordinate legend applies to the spectrum levels; for the 1/3-octave and one-octave band levels the correct units are "dB re 1 µPa".)

For continuous waveforms that are random or non-periodic, the concept of phase generalizes to one of ***time delay***, or simply ***delay***, to describe the time offset of a waveform and its replica.

2.3 Terms Describing Sound Sources

2.3.1 Temporal Properties

A sound may be ***transient***, of relatively short duration having an obvious beginning and ending, or it may be ***continuous***, seeming to go on and on. Sources of transient underwater sounds include impulsive seismic survey devices that emit brief sound pulses every few seconds, and pile drivers that use an impact hammer. These are examples of transient but often-repeated sounds. The sound beneath an overflying aircraft is also transient. However, the aircraft sound would not be repeated as regularly or as often as the seismic or piledriver pulses. An example of a continuous sound source is a ship underway. Most sounds are not purely transient or purely continuous; most are a combination. For example, on a drillship, generators and pumps operate essentially continuously, but there are occasional bangs and clanks from various impacts during operations.

In describing a transient sound it is useful to present the ***peak level*** as well as some description of how the sound varies with time, *viz.* its waveform. The peak level may be described as being a particular pressure, or it may be described as a mean square pressure where the average was based on a relatively short length of time. The latter approach allows more reasonable comparisons with mean square pressure measurements of continuous sounds. Some transient sounds, like airgun impulses, occur periodically. For such sources it is helpful to describe the ***duty cycle***, or the fraction of time during which the transients are significant.

A continuous sound may be described by its mean square pressure. Generally it is useful to describe the distribution of sound power vs. frequency. For this purpose, the mean square pressure density spectrum is appropriate (e.g. Fig. 2.1). It may also be useful to show the corresponding levels in various 1/3-octave and one-octave bands (e.g. Fig. 2.2).

2.3.2 Amplitude Properties

Two primary terms used to describe sound source amplitudes are ***source level*** and ***source spectrum level.***

> "*Source level* is defined as the pressure level that would be measured at a reference distance of one foot, one yard or one meter from an ideal point source radiating the same amount of sound as the actual source being measured." (Ross 1976)

Thus, the concept of source level is based on replacing the actual source with "an ideal point source". With a point source, all of the energy emanates from a single point, rather than from a large or distributed object. Actual sources radiate sounds differently in different directions, and therefore source level is a function of direction.

The concept of source level introduces the dimension of distance into the description of the sound. In general, sound level decreases with increasing distance from the source. In order to compare different sound sources, it is necessary to adopt a standardized reference distance at which source levels will be determined. Normally, field measurements are made at distances different from the standard reference distance, and the source level must be determined by taking into account the known or expected change in level (propagation loss) between the reference and actual distances. For underwater sounds, a reference distance of 1 m (or 1 yard in older reports) is usually cited. However, in some reports on ship noise the reference distance may be cited as 100 m or 100 yards. Whatever the reference distance, the effect of transmission loss from the reference range to the range where the sound was measured is removed from the measured levels to produce a source level. Only in this way can the source levels of various sounds be compared. Units for source level are μPa-m for a reference range of 1 m. Many authors state the reference range explicitly, as in "*x* dB re 1 μPa at 1 m".

The units for source spectrum level are $(\mu\text{Pa-m})^2/\text{Hz}$. This format indicates that the distance dependence of the sound power is an inverse square function of distance, and that frequency dependence is direct with bandwidth. Authors may cite an equivalent unit of "1 μPa at 1 m in a 1 Hz band", or they may even fail to indicate the density spectrum nature of their sound description. In comparing different source level measurements, readers must be on the alert for inconsistencies in reference distances and reference units. Source levels at a reference distance of 1 yard can be converted into source levels at 1 m by subtracting 0.8 dB. Levels at a reference distance of 100 m or 100 yd cannot always be converted to levels at 1 m using a similar simple "rule of thumb", since propagation losses between 1 m and 100 yards or 100 m are somewhat variable. However, levels at 100 m will typically be about 40 dB lower than those at 1 m, since the spherical spreading concept (sect. 2.4) usually applies--to a first approximation--at ranges up to 100 m. However, this approximation may not apply in very shallow water or at very low frequencies.

2.4 Terms Describing Sound Propagation

Discussions of sound propagation include two all-inclusive terms, generally equivalent: ***transmission loss*** and ***propagation loss***. Chapter 3 discusses this topic in greater detail, but some introductory material is necessary in order to understand parts of that and other chapters. Conceptually, a sound wave traveling from point A to point B diminishes in amplitude, or intensity, as it spreads out in space, is reflected, and is absorbed. If the source level (at 1 m) is 160 dB re 1 μPa-m, the received level at range 1 km may be only 100 dB re 1 μPa; in this case the transmission loss is 60 dB. This illustrates the fact that transmission loss is generally expressed in dB, representing a ratio of powers, intensities or energies of a sound wave at two distances from the source. The distance at which the denominator measurement was taken is the reference distance for the transmission loss. Because dB scales are logarithmic, and log (ratio) equals log(numerator) minus log(denominator), propagation loss can be expressed as the difference, in dB, between the levels at the two distances. Transmission loss is a positive quantity that is plotted downward, as in Figure 2.3. A person viewing a transmission loss graph can visualize the way in which a sound diminishes with increasing distance.

A major component of transmission loss is ***spreading loss***. If a sound wave had ***plane wave*** fronts, it would propagate without spreading and the same power levels would be expected at different positions along the propagation path. However, plane waves would be unusual in the ocean or air. ***Spherical waves*** radiate outward from a ***point source*** when there is no ***reflection*** or ***refraction***. (Refraction is ray bending; it occurs as a consequence of changes in the sound velocity with position along the propagation path.) **Spherical spreading** implies

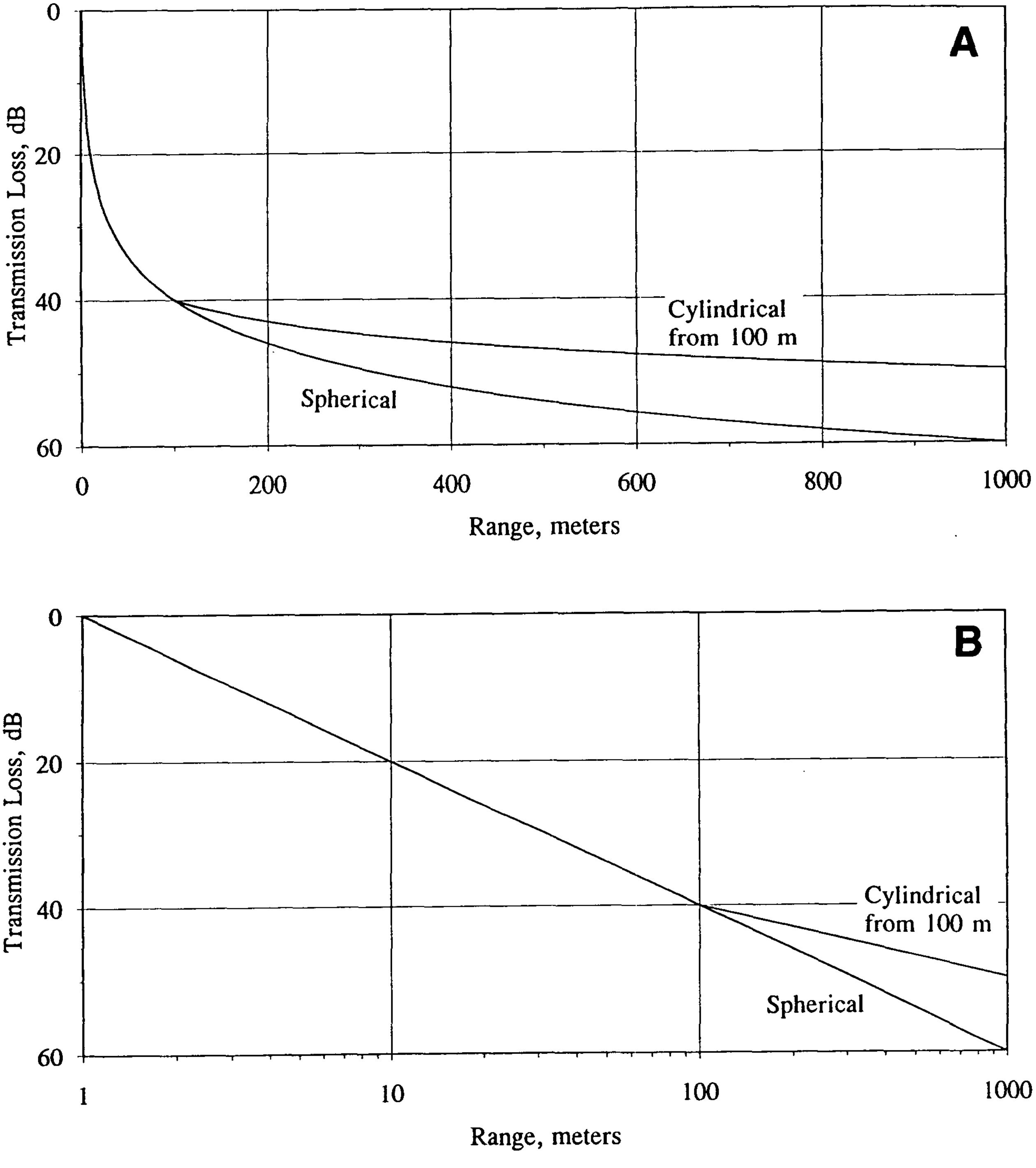

FIGURE 2.3. Sound transmission loss in relation to distance when (a) pure spherical spreading or (b) spherical spreading to 100 m and cylindrical spreading beyond 100 m applies. Upper panel shows results on a linear distance scale; lower panel shows results on a logarithmic distance scale.

that the intensity, or the mean square pressure, varies inversely with the square of the distance from the source. Thus, transmission loss due to spherical spreading is given in dB by 20 log (R/R_0), where R_0 is the reference range, normally 1 m. With spherical spreading, sound levels diminish by 6 dB when the distance is doubled, and by 20 dB when the distance increases by a factor of 10 (Fig. 2.3). Spherical spreading is inverse square law spreading.

In shallow water, sound is reflected from the surface and the bottom. At some distance from the source that is long compared to the water depth, the various reflected waves combine to form a ***cylindrical wave***. Such a wave may be imagined by picturing a short tuna fish can. The top of the can corresponds to the water surface, the bottom corresponds to the ocean bottom, and the curved outer surface is the cylindrical wavefront. In ***cylindrical spreading***, the sound power varies inversely with the distance from the source. A useful but oversimplified equation for transmission loss with cylindrical spreading is given (in dB) by

$$\mathrm{TL} = 20 \log R_1 + 10 \log (R/R_1) \tag{2.6}$$

where R_1 is the range at which spherical spreading stops and cylindrical spreading begins. The range R must be $>R_1$; for shorter ranges the transmission loss is spherical (Fig. 2.3). The equation for cylindrical spreading can be rewritten in the form

$$\mathrm{TL} = 10 \log R_1 + 10 \log R \tag{2.7}$$

With cylindrical spreading, sound levels diminish by 3 dB when the distance is doubled, and by 10 dB when the distance increases by a factor of 10. Thus, sound levels diminish much more slowly with increasing distance when cylindrical spreading is occurring than when spherical spreading occurs.

As sound travels, some power is absorbed by the medium, giving rise to ***absorption losses***. In dB, such losses vary linearly with the distance traveled, and absorption loss can be described as x dB/km. Absorption losses are strongly frequency dependent, becoming greater with increasing frequencies. ***Scattering losses*** vary linearly with distance in the same way as absorption losses. However, they result from different physical mechanisms (see Chap. 3). These absorption and scattering losses are in addition to the spherical, cylindrical or other spreading losses mentioned above.

2.5 Terms Describing Ambient Noise

Ambient noise is the background noise. There is no single source, point or otherwise. In the ocean, ambient noise arises from wind, waves, surf, ice, organisms, earthquakes, distant shipping, volcanoes, fishing boats, and more (see Chap. 4). At any one place and time, several of these sources are likely to contribute significantly to the ambient noise. In the source-path-receiver model, ambient noise is present in the medium (water or air) along the path, and it is present at any receiver location. At any such location, its level adds to that of the sound of interest (generally called the signal).

When the ambient noise level is x dB and there is a sound signal with level y dB, the total noise level is determined as follows:

$$\mathrm{L}_{x+y} \text{ (in dB)} = 10 \log (10^{x/10} + 10^{y/10}) \tag{2.8}$$

Thus, if the signal level and background noise level both equal z dB, the total noise level is (z+3) dB. For example, 100 dB + 100 dB = 103 dB. When two levels differ by at least 6 dB, their sum is less than 1 dB greater than the higher of the two component levels, e.g. 106 dB + 100 dB = 106.97 dB. These seemingly non-intuitive summation relationships are a consequence of the logarithmic nature of decibel scales.

Ambient noise varies with season, location, time of day, and frequency. It has the same attributes as other sounds, including transient and continuous components, tones, hisses and rumbles. It is measured in the same way that sounds received from sources of interest are measured, except that--in referring to ambient noise--it makes no sense to use a reference distance from the "source". There is no one source.

2.6 Terms Describing Sound Reception

What are the attributes of sound receivers? Some sound is received by instruments that extract properties of the sounds and present them in some transformed manner, e.g. a sound spectrum or a waveform on an oscillograph. In this volume we usually are not concerned with such mechanistic receivers. Two exceptions are ***hydrophones*** and ***microphones***. They are ***transducers*** that transform received acoustic pressures into electrical voltages or currents, which may be amplified and conditioned for application to meters, tape recorders, speakers or earphones. These transducers are characterized by their ***sensitivities***, which vary with frequency, by the ***electrical noise*** they add to the received sound, and by their ***distortion*** properties. Hydrophone sensitivities generally are described in volts per micropascal or in dB re 1 V/μPa.

Animals, including people, have complicated sound reception capabilities. We discuss only a few terms from psychoacoustics here. Additional terminology needed to define mammalian hearing processes is introduced in Chapter 7, "Marine Mammal Hearing". Sonn (1969) compiled a comprehensive lexicon. Other valuable sources include Kryter (1985) and Fay (1988).

The **threshold of audibility** of a sound is the minimum received sound level at which a sound with particular frequency properties can be perceived in the absence of significant background noise. The animal can hear a fainter sound if the threshold is low than if it is high. The concepts of ***auditory threshold*** and ***auditory sensitivity*** are inversely related. A low threshold is indicative of high sensitivity; a high threshold is indicative of low sensitivity.

Auditory thresholds vary with frequency; a graph of thresholds vs. frequency typically is U-shaped. Thresholds generally are high (poor sensitivity) at low frequencies. From there, thresholds generally diminish (improve) with increasing frequency, up to some frequency of optimal sensitivity. There may be a range of frequencies where thresholds are similarly low. Above that range, thresholds increase with a further increase in frequency. The frequency of optimal hearing varies from one species of animal to another. The graph relating hearing threshold to frequency is called the ***audiogram***. Section 7.2 includes underwater and in-air audiograms of all marine mammal species for which audiograms have been measured; the human in-air audiogram is also shown (Fig. 7.3). Similar data for many other vertebrates can be found in Fay (1988).

Two additional terms requiring discussion are ***critical ratio*** and ***critical band***. These terms deal with the detectability (audibility) of a pure tone in the presence of background noise.

People and animals have varying abilities in this regard. The critical ratio is the ratio of power in a barely-audible tone to the spectrum level of surrounding noise. Because of the logarithmic nature of dB scales, a critical ratio can be derived by subtracting the spectrum level of the background noise from the tone level. For example, if a tone must be 100 dB re 1 µPa in order to be detected in the presence of a background noise whose spectrum level is 80 dB re 1 $\mu Pa^2/Hz$ at frequencies near that of the tone, then the critical ratio is 20 dB (i.e. 100 minus 80). Critical ratios tend to increase with increasing frequency (sect. 7.5.1).

Critical bands can be defined in different ways (sect. 7.5.2), but in general the critical band around a particular frequency is the band within which background noise can affect detection of a sound signal at that frequency. Except when their levels are very high, background noises at frequencies outside the critical band have little effect on detectability of a sound within that band. The process by which background noise can prevent detection of sound signals at nearby frequencies is called "***masking***". These topics are discussed in Chapter 7. All published data on critical ratios, critical bands, and masking in marine mammals are summarized there.

The detection of natural sound signals in the presence of man-made noise is an important issue in relation to the possible effects of industrial noise on marine mammals. Likewise, the maximum radius of detectability of a man-made noise in the presence of natural background noise is an important issue. In order to address these topics, one must have information about the sound sources (industrial and marine mammals themselves), propagation losses between sources and receiver, ambient noise near the receiver, and hearing capabilities of the receiving animal. These background topics are discussed in Chapters 3-7, and the information is then drawn together in Chapter 9, "Zones of Noise Influence".

3. SOUND PROPAGATION[1,2]

3.1 Introduction and Relevance

The audibility or apparent loudness of a noise source is determined by the radiated acoustic power (source level), the transmission path efficiency, and the hearing sensitivity of the subject species. This chapter focuses on propagation effects.

The noise levels produced by industrial activities in underwater and terrestrial environments are determined not only by their acoustic power output but, equally important, by the local sound transmission conditions. A moderate-level source transmitting over an efficient path may produce the same received level at a given range as a higher level source transmitting through an area where sound is attenuated rapidly, i.e. over a "lossy" path. Likewise, a given noise source operating in different areas, or in the same area at different times, may be detectable for greatly varying distances, depending on regional and temporal changes in sound propagation conditions among other factors.

Transmission loss measurements in representative shallow water regions show that large regional and temporal differences in sound transmission conditions exist. As a result, the zone of acoustic influence for a given industrial source can vary in radius as much as ten-fold, depending on the operating site and on seasonal changes in water properties. Hence, sound transmission measurements, analyses and model predictions are necessary to estimate the potential zone of acoustic influence of planned offshore industrial activities.

Site-specific data on underwater or airborne propagation of sound are often lacking when a potentially noisy industrial activity is planned. It is often not feasible to obtain site-specific measurements of sound transmission properties for use in predicting how intrusive the new noise will be. However, predictions can often be made even in the absence of site-specific propagation data. These predictions are based on propagation models that have been developed for both airborne and underwater sound. These models provide procedures for estimating the received noise level as a function of distance, assuming that the source level and characteristics are known. These propagation models may be either purely analytic, based on physical principles; or semi-empirical, using both physical principles and the results of field measurements.

Although predictions obtained using sound propagation models can be useful for planning and for preparing environmental impact statements, it is advisable to obtain as many relevant empirical data as possible in order to help confirm the accuracy of the model predictions. Empirical confirmation is important because of the highly variable and site-specific nature of airborne sound transmission near the ground and underwater sound transmission in shallow water.

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[1] By Charles I. Malme, BBN Systems & Technologies Corp.

[2] Constructive comments on drafts of this chapter were provided by Drs. W.C. Cummings, R.H. Nichols and D. Ross.

This chapter contains a description of some sound propagation concepts relevant to the problem of noise impact prediction. The discussion begins with an overview of the theoretical aspects of sound transmission. The basic features of both deep-water and shallow-water propagation are then discussed. A summary of airborne sound transmission is included, together with a discussion of transmission through the air-water and water-bottom interfaces. The discussion concludes with a summary of some general sound transmission equations. Non-acousticians who have not read Chapter 2, "Acoustic Concepts and Terminology", should read that section before reading this one.

3.2 Theoretical Aspects

Efforts to develop theoretical models for computing received sound level as a function of range have been underway for several decades. A number of related approaches have been taken. This subsection mentions some of the most common approaches without attempting to explain the actual formulation of the equations. Later subsections include examples of some types of models mentioned here. In order to apply most of these models to actual situations, large numbers of calculations must be done. Thus, all but the simplest models must be implemented as computer programs before they can be applied to practical acoustical problems.

The differential equation relating the space and time variables in an acoustic field, the "wave equation", is difficult to solve for real-world situations. The method of ***normal modes*** can be applied in the common case where the sound velocity structure in the water column is horizontally stratified (i.e. changes vertically but not horizontally) and where the boundary conditions at the surface and bottom can be specified. The normal-mode method, developed by Pekeris (1948), is useful in calculating the sound field in shallow water where the water column acts as a waveguide for a limited number of propagating modes. The combinations of wavelength and incidence angle that match the boundary conditions of the water column determine the most efficient modes of propagation. Normal-mode theory has been expanded to take account of (1) sound speed gradients that vary with depth and (2) bottom layer properties that require both fluid and solid-layer models (Tolstoy 1955, 1960). Alternatively, bottom effects can be included by using plane-wave reflection coefficients, which can be obtained experimentally without requiring detailed knowledge of the bottom layer composition (Brekhovskikh 1960).

The problem of solving the wave equation for range-dependent conditions such as sloping or irregular bottoms and range-varying sound speed gradients has been overcome by using an approximation called the ***parabolic equation*** (Tappert 1977). Computer-implemented solutions to this equation use small incremental steps in range and depth to accommodate changes in propagation parameters without developing large errors. However, in deep water where many modes are propagating, a large number of increments must be used to obtain a valid solution. In this situation the method becomes computationally cumbersome.

In water deep enough to allow propagation of 10 or more modes, another wave equation approximation called ***ray theory*** may be used. This approximation requires only that the properties of the medium do not change very much over a distance equal to an acoustic wavelength. The sound field is calculated by tracing the paths of rays started from the source at uniformly spaced angular increments. For each increment in range, each path direction is determined by the ray equations and the local sound speed gradient. The sound intensity is determined by the ray density relative to the starting density. Ray calculations of intensity must be modified whenever rays predict infinite intensity such as in focussing regions (caustics) or in regions with an abrupt change in intensity (shadow zones).

Ray theory is useful in deep water where a small number of rays transmit most of the acoustic energy from a source to a receiver, where there is a direct path from source to receiver, and where only a limited number of surface- and bottom-reflected paths contribute. In water that is shallow but sufficiently deep to permit application of ray theory, the large number of reflected paths involved in most transmission geometries makes it impractical to calculate transmission loss by summation of individual ray contributions. For this application, analytic and semi-empirical transmission models have been developed. These models incorporate the principles of ray theory together with measured or theoretical bottom and surface loss parameters. These models typically incorporate one or more spreading loss terms, boundary reflection and scattering loss terms, and a volume absorption term. Specific examples are included in the following discussion of deep and shallow water propagation.

3.3 Deep Water Sound Propagation

In a discussion of sound propagation theory, the distinction between deep and shallow water concerns primarily the wavelength/water depth ratio rather than depth *per se*. At frequencies of a few hertz, wavelengths are hundreds of meters in length and even abyssal depths must be considered shallow water. In contrast, in the kilohertz range much of the continental shelf as well as abyssal areas may be considered deep. In deep water, water depths are typically >100 times the acoustic wavelengths and sound transmission generally involves few or no bottom reflections. In shallow water, in contrast, bottom and surface reflections are usually dominant components of sound transmission. It must be recognized, however, that the usual practice in classifying underwater sound data is to consider depths <200 m as shallow and depths >2000 m as deep.

In a uniform medium with no nearby boundaries and no absorption loss, sound from an omnidirectional source spreads uniformly outward with a spherical wavefront. Intensity decreases as the area of the wavefront expands. At distances that are large compared with the source dimensions, the sound intensity varies inversely as the square of the range from the acoustic center of the source. Since sound intensity is proportional to sound pressure squared (sect. 2.2), sound pressure is inversely proportional to range. In logarithmic terms, this is called a ***20 log R spreading loss*** or ***spherical spreading***:

$$L_r = L_s - 20 \log R \tag{3.1}$$

where L_r is the received level in dB re 1 µPa (underwater) or dB re 20 µPa (in air),
L_s is the source level at 1 m in the same units, and
R is the range in m.

When sound becomes trapped in a sound duct between horizontal refracting or reflecting layers, it is constrained to spread outward cylindrically rather than spherically. ***Cylindrical spreading*** also occurs when sound is trapped between the surface and bottom in shallow water. In these cases, sound intensity decreases in proportion to the increase in area of the expanding cylindrical wavefront. As a result, sound intensity varies inversely as the range from the source location, i.e. as $1/R$, in contrast to the $1/R^2$ that applies under spherical spreading. Sound pressure varies inversely as the square-root of the range, i.e. as $1/R^{0.5}$, in contrast to the $1/R$ that applies under spherical spreading. This is the ***10 log R spreading loss*** of cylindrical sound transmission, i.e.

$$L_r = L_s - 10 \log H - 10 \log R \tag{3.2}$$

where H is the effective channel depth. The "- 10 log H" term is related to the fact that cylindrical spreading does not begin at the source; spreading is usually more or less spherical from the source out to some distance, and then may transition to cylindrical (sect. 2.4; Fig. 3.1).

Sound attenuates much more rapidly with increasing distance when spherical spreading applies than when there is cylindrical spreading (Fig. 3.1). Thus, a given source can be heard farther away when there is cylindrical spreading (10 log R loss) along much of the path from source to receiver than when there is spherical spreading (20 log R loss) along most or all of the path.

Simple spherical or cylindrical spreading are important theoretical concepts and apply at least approximately to many real-world situations. However, the ocean is not a uniform medium. Variations in temperature and salinity with water depth affect the rate of propagation loss. The speed of sound increases with increasing temperature, salinity and pressure. This results in distortion of the wavefront as it propagates in the usual oceanic environment. This distortion of the wavefront is equivalent to bending (***refraction***) of the sound rays that trace the paths of points on the wavefront. Refraction causes the rays to be bent toward the direction of slower sound speed, since the portion of the wavefront traveling in the region of higher sound speed advances faster than the remaining portion. Refraction is a dominant feature of deep water sound transmission because the variation of sound speed with depth (sound speed gradient) controls the ray paths. As a result, the decrease of sound intensity with range is influenced not only by spreading loss but also by concentration or reduction in the ray density due to refraction.

Typically, the sound-speed profile can be divided into several horizontal layers (Fig. 3.2A, from Urick 1983).[3] Characteristics of the surface layer and seasonal thermocline are strongly influenced by solar radiation and by fresh water input from rain and river outflow. These factors cause seasonal and geographic variations in the sound speed profile. Seasonal variation in sound speed profiles at mid-latitudes is illustrated by Figure 3.2B, showing data from the Atlantic Ocean. In winter, surface cooling forms a thin ***surface duct*** where sound generated near the surface, such as from ship traffic, propagates well. Under these conditions, some sound energy from a near-surface source is refracted upward, trapping it within the surface duct. In contrast, during spring and summer the surface warms up, developing a thin upper layer which causes most sound from a surface source to be refracted downward. This results in increased transmission loss for sound propagating near the surface.

Details of surface-layer transmission can be shown in a ray diagram (Fig. 3.3). In this example, turbulence from wave action has resulted in a mixed layer of uniform temperature and salinity extending down to a depth of 200 ft (61 m). The increasing pressure with increasing depth causes sound from a source in the surface layer to be alternately refracted upward and

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[3] A variety of non-metric units are used in this and several subsequent diagrams taken from other sources. Conversion factors are supplied in the Figure captions.

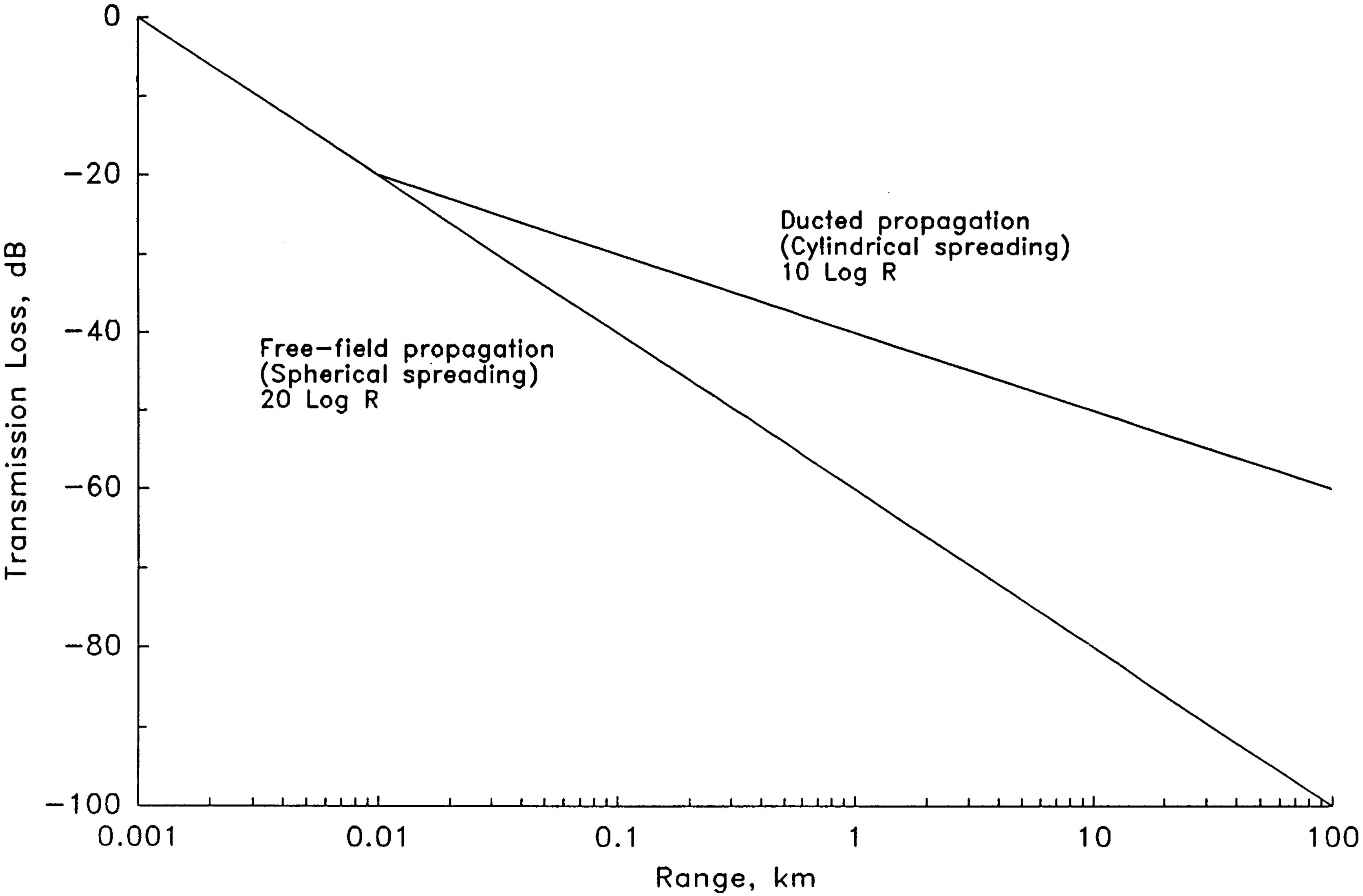

FIGURE 3.1. Sound transmission loss as a function of range for free-field (spherical) and ducted (cylindrical) propagation conditions. In this case, cylindrical spreading is assumed to begin 10 m from the source.

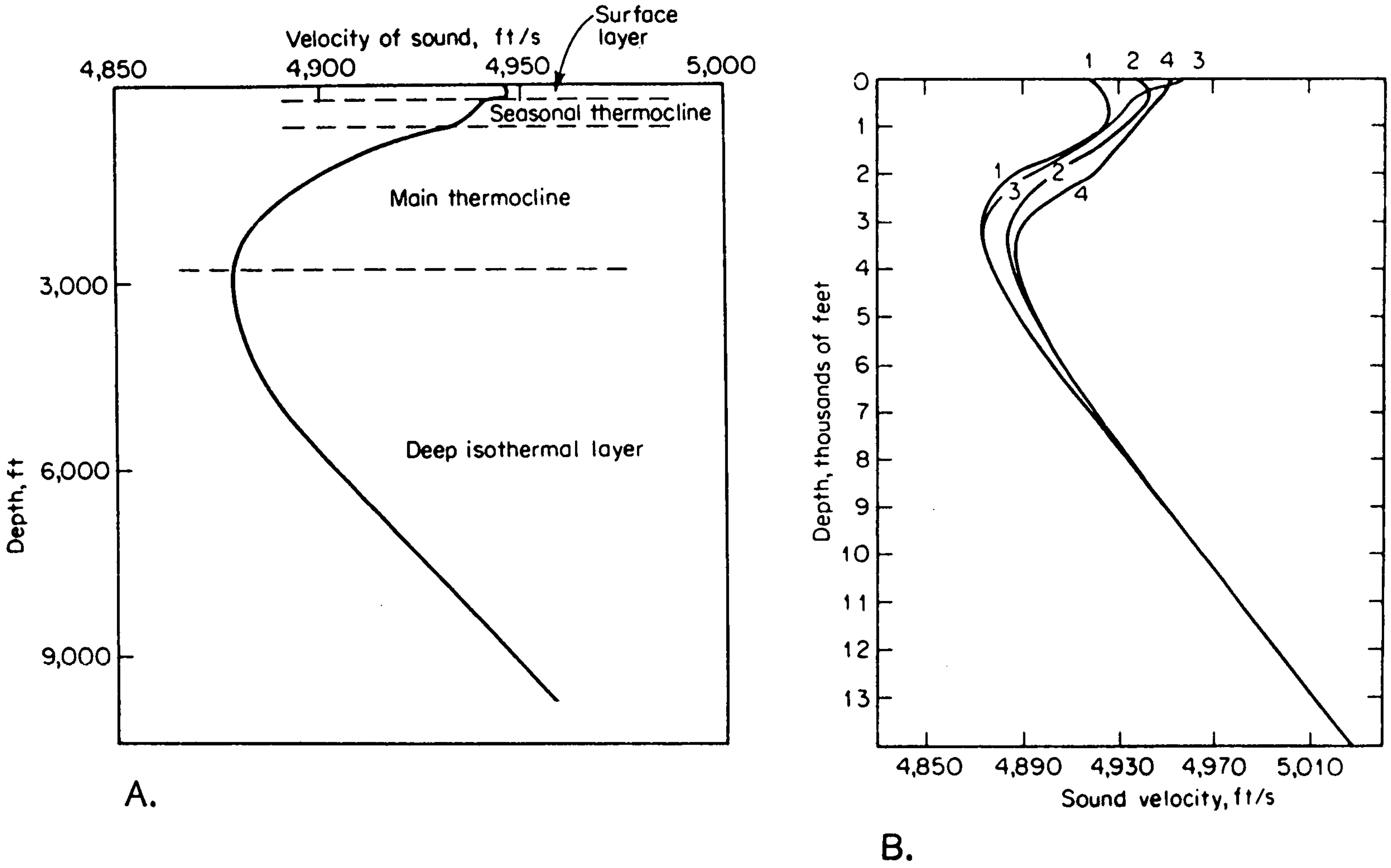

FIGURE 3.2. Typical deep-sea sound-speed profiles. (A) Profile showing layer structure (from Urick 1983). (B) Average sound-speed profiles in different seasons in an area halfway between Newfoundland and Great Britain: (1) winter, (2) spring, (3) summer, (4) autumn (from Urick 1983, based on U.S. Navy data). Unit conversions: 1000 ft = 305 m; 4920 ft/s = 1500 m/s.

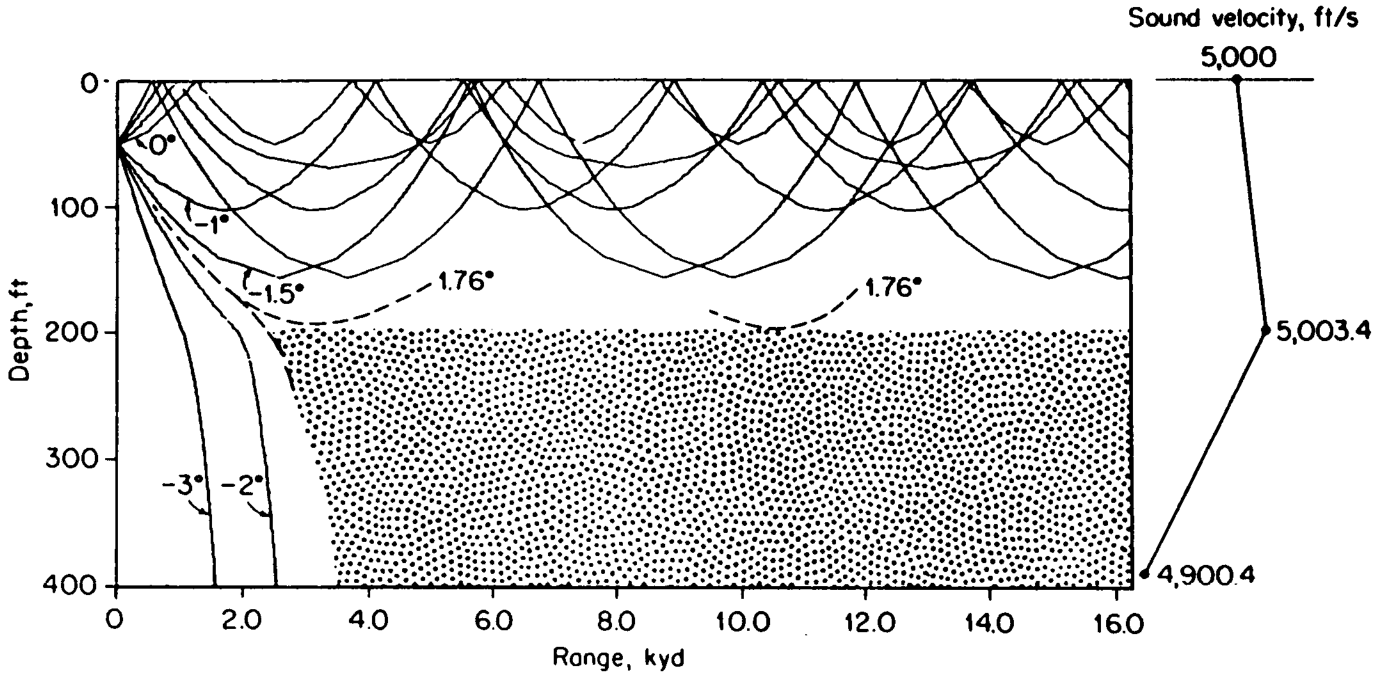

FIGURE 3.3. Ray diagram for sound transmission from a source at a depth of 50 ft (15 m) in a 200-ft (61 m) mixed layer (from Urick 1983). Sound speed profile at right. Rays are drawn at 1° intervals except as noted. Stippled area is a shadow zone. Unit conversions: 100 ft = 30.5 m; 4920 ft/s = 1500 m/s; 10 kyd = 9.1 km.

then reflected back downward from the surface. Sound trapped in a surface duct propagates with approximately cylindrical spreading. However, there is some additional loss due to surface scattering and ***leakage*** of sound energy out of the duct. In the case illustrated, rays propagating downward at angles steeper than -1.8° below the horizontal are not trapped but are refracted downward. This causes a ***shadow zone*** in the region below the mixed layer (Fig. 3.3). Received sound levels in this shadow zone are low but not zero. Some sound energy does reach this region by the scattering and leakage processes.

When there is no mixed layer near the surface, or when it is very thin, a negative sound speed gradient may exist at very shallow depths. In this case there is a downward-refracted sound field, and a near-surface shadow zone may result. This shallow shadow region often has higher attenuation values than found in a deeper shadow zone of the type shown in Figure 3.3. Sound levels at 24 kHz in the shadow zone are 40 to 60 dB lower than expected at the same range in the free-field (Urick 1983:135).

One of the better known features of deep water propagation is the ***deep sound channel,*** also known in some older literature as the ***SOFAR*** channel. The axis of this channel is at the point of minimum sound-speed in the sound speed profile; at mid-latitudes this occurs at depths 600-1200 m (2000 to 4000 ft; Fig. 3.2A,B). The focusing effect of this channel causes sound rays from sources within the channel to be trapped, avoiding the losses that would result from bottom and surface reflections (Fig. 3.4).

Special cases of the sound-channel effect also occur for near-surface sources in deep water when the surface layer is thin or becomes downward refracting. In this situation, sound from the surface source can become trapped in the sound channel and refracted so as to be concentrated near the surface in narrow annuli or ***convergence zones.*** These zones of elevated sound level are typically spaced at intervals of 30 to 35 n.mi. (56 to 65 km) in temperate and tropical latitudes (e.g. Fig. 3.5). At high latitudes the depth of the sound channel decreases and the range interval between successive convergence zones becomes smaller. The sound levels in convergence zones are typically about 10 to 15 dB above the level expected at that range based on simple spherical spreading and absorption.

Another special case of sound channeling in deep water occurs in arctic regions, where the axis of the sound channel is at or near the surface. This occurs because of the cold temperature at the surface, which causes the minimum sound speed to occur there. As a result, all sound rays in the ***arctic surface channel*** are refracted upward and are then reflected from the under-ice surface (Fig. 3.6). A major source of low-frequency loss in the arctic is conversion of acoustic waves into flexural waves of the ice-sheet. At higher frequencies under-ice roughness becomes an important factor affecting sound propagation. Smooth annual ice may enhance propagation as compared with open water conditions. However, with increased cracking, ridging and other forms of roughness, sound transmission losses generally become higher than in open water of the same depth.

In summary, in deep water with uniform properties, spherical (20 log R) spreading is an important mode of sound transmission. However, water properties are usually horizontally stratified (e.g. Fig. 3.2). As a result, for propagation over long distances, sound ducting and sound shadows often occur. When there is a duct, spreading losses may be as low as 10 log R

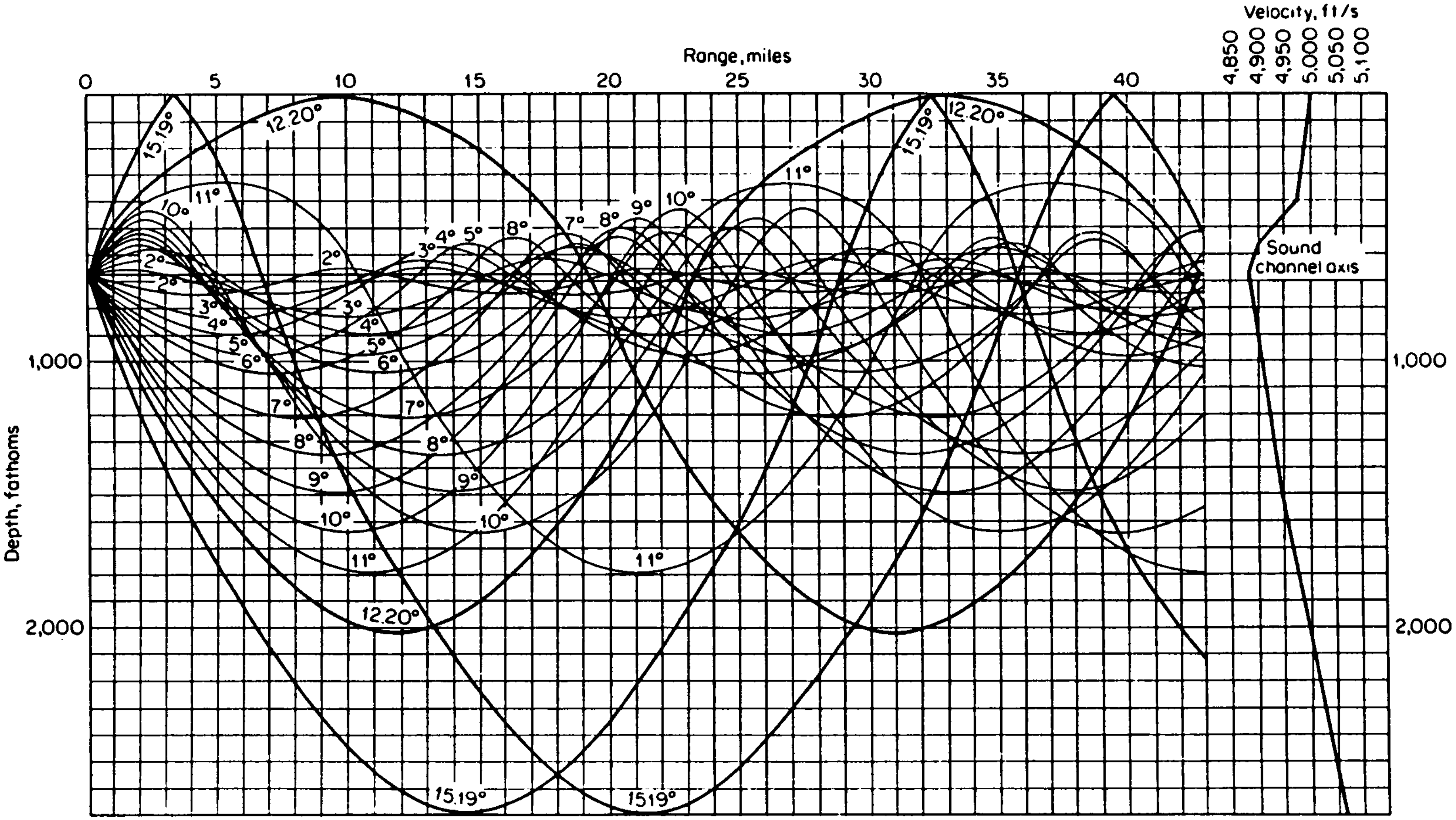

FIGURE 3.4. Ray diagram for the deep ocean sound channel when the source is on the axis (from Urick 1983). Unit conversions: 1000 fathoms = 1829 m; 10 mi = 16 km.

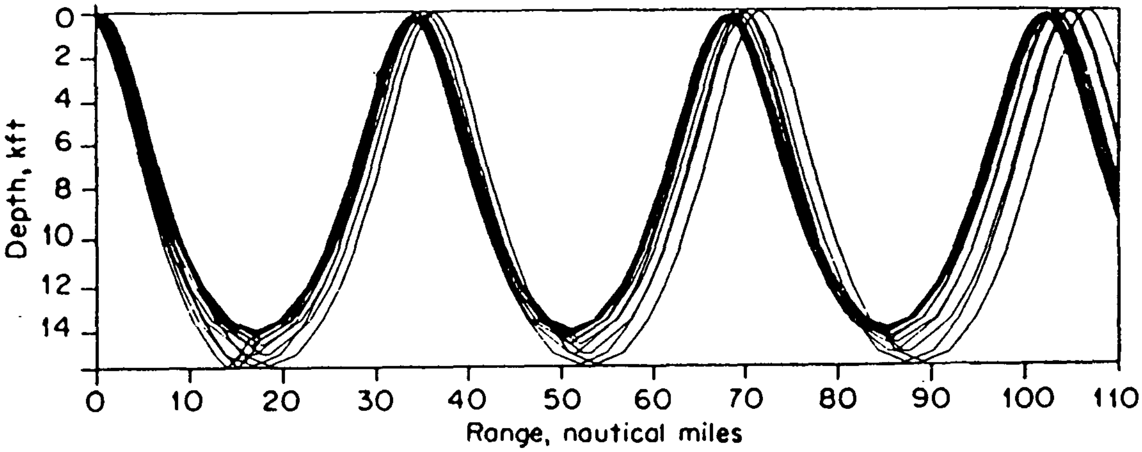

FIGURE 3.5. Ray diagram for convergence zone propagation in deep water; source at depth 300 ft (91 m) (from Urick 1983). Unit conversions: 10 kft = 3050 m; 35 n.mi.= 65 km.

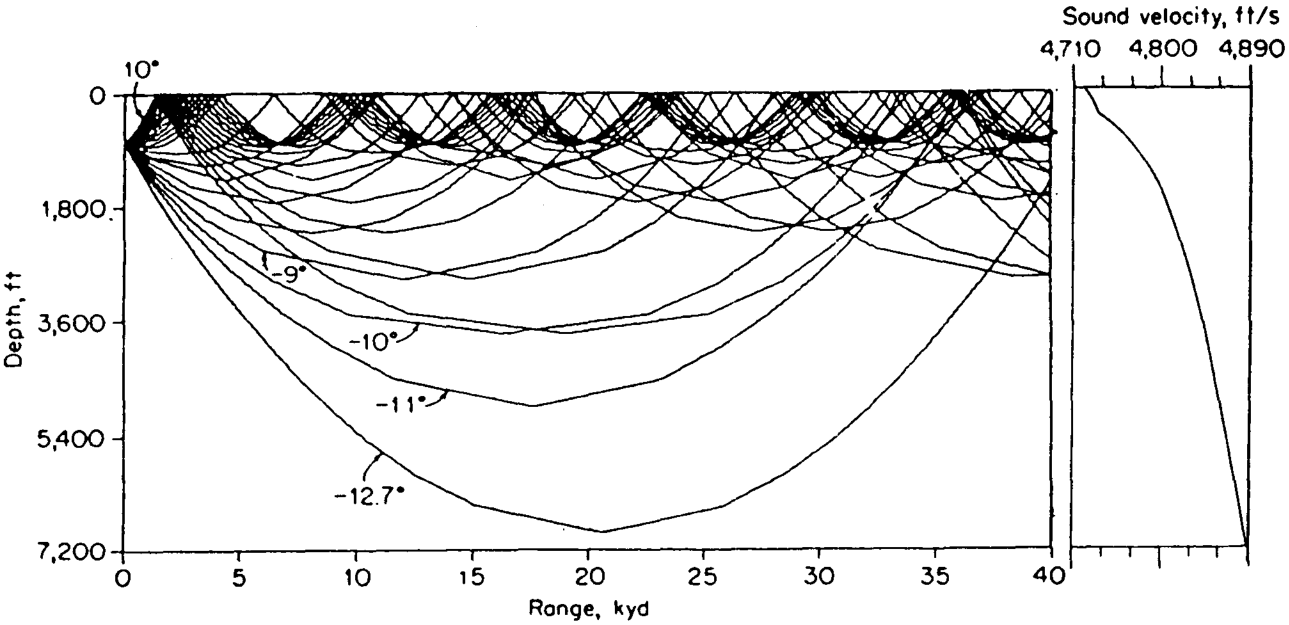

FIGURE 3.6. Ray diagram for deep-water sound transmission in the arctic (from Urick 1983). Ray interval 1°, with 12.7° ray added. Sound-speed profile at right. Unit conversions: 1000 ft = 305 m; 10 kyd = 9.1 km; 4920 ft/s = 1500 m/s.

(cylindrical spreading) when range from the source exceeds a transition range related to duct thickness.

3.4. Shallow Water Propagation

Sound transmission in shallow water is highly variable and site-specific since it is strongly influenced by the acoustic properties of the bottom material, bottom roughness, and surface conditions, as well as by variations in sound-speed within the water column. As in deep water, variations in temperature and salinity with depth cause sound rays to be refracted downward or upward. However, the shallow depth does not allow most types of sound channeling effects noted above for deep water. Refraction of sound in shallow water can result in either reduced or enhanced sound transmission. In upward refraction conditions, bottom reflections and the resulting bottom losses are reduced; in downward refraction conditions the opposite occurs. As a result of these and other processes, sound transmission conditions in continental shelf areas can vary widely. For example, based on the data shown in Figure 3.7, a given source of 40-Hz sound over the Scotian Shelf would be detectable much farther away than the same source over the Grand Banks.

The many environmental factors that influence shallow-water sound transmission make it difficult to develop adequate analytical models. It is necessary to combine analyses with site-specific empirical data in order to obtain reliable propagation predictions. In recent years, questions about military sonar operation in shallow seas have motivated many field studies. Although many of these data are unavailable, some of the unclassified results have been published in the *Journal of the Acoustical Society of America* and in various symposium proceedings (e.g. Kuperman and Jensen 1980; Akal and Berkson 1986).

When the water is very shallow, with sound wavelengths (λ) comparable to the water depth (H), i.e. where $0.25 < H/\lambda < 2$, sound propagation may be analyzed using mode theory or modified mode theory involving solutions of the parabolic wave equation. Mode theory predicts that, if the effective water depth is less than $\lambda/4$, waves are not matched to the duct and very large propagation losses occur. In many cases, however, the bottom consists of water-saturated sediment and is not a discrete reflecting boundary for all of the sound energy. In these conditions, propagation of low-frequency energy extends downward into the bottom material. If the composition and layer structure of the bottom are known, or can be estimated, this information, when incorporated into the modal analysis procedure, will permit calculation of shallow water sound transmission losses with good accuracy.

An example of the use of a model based on mode theory is shown in Figure 3.8, where sound propagation data from the Mediterranean Sea are compared with model results (Ferla et al. 1980). Transmission loss was considerably higher during summer than during winter. During summer there was a downward-refracting surface layer caused by enhanced surface heating.

Mode theory predicts the frequency dispersion effects that are observed when broadband impulsive sources are used in shallow water (e.g. airgun arrays or explosives). With some types of bottom material, signals propagate as two waves: a ground wave and a water wave. Theory predicts that the ground wave will begin to arrive first, and that it will increase in both amplitude and frequency over the duration of arrival of the pulse. The water wave arrives

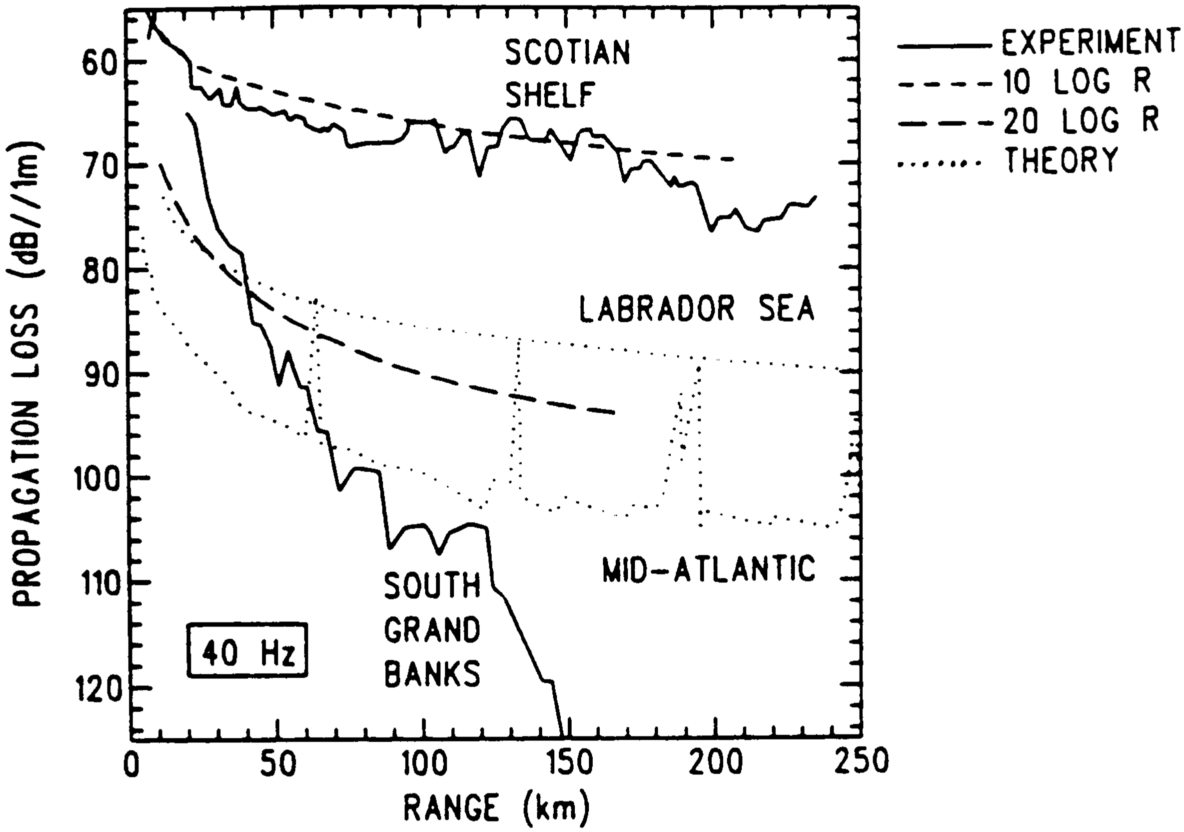

FIGURE 3.7. Propagation loss versus range for 40 Hz sound traveling in deep and shallow waters of the Atlantic Ocean (from Staal 1985). The two sets of measurements from shallow-water areas (solid lines) illustrate the large differences that can occur as a result of different environmental conditions. The dotted lines are theoretical predictions for deep-water sites.

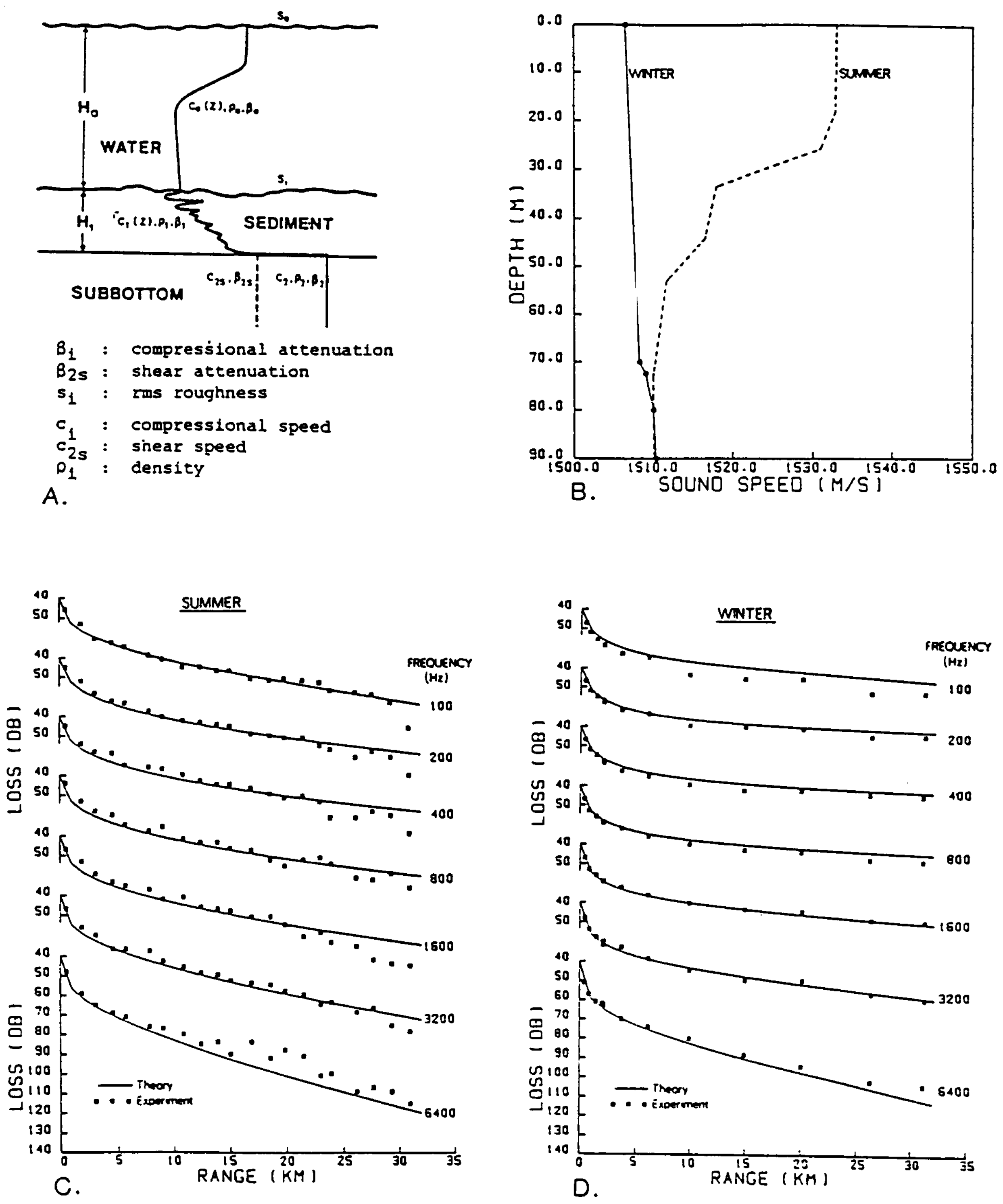

FIGURE 3.8. Comparison of sound transmission data obtained in the Mediterranean Sea with normal-mode model predictions using the SACLANTCEN SNAP model (from Ferla et al. 1980). Water depth = 90 m. *(A)* Environmental input to the SNAP Model. *(B)* Sound-speed profiles from shallow-water area in the Mediterranean. *(C)* Model/data comparison of depth-averaged losses for summer. Source depth = 50 m. *(D)* Model/data comparison of depth-averages losses for winter. Source depth = 50 m.

slightly later; it increases in amplitude but decreases in frequency through the duration of its arrival. Both waves terminate concurrently at a common amplitude and frequency called the ***Airy phase***. The ground wave is usually attenuated more rapidly than the water wave. Hence, impulsive underwater sounds such as those from distant seismic exploration sources are usually dominated by the water wave, and their predominant frequency tends to decrease during the period of arrival of the pulse (sect. 5.3.3).

The recent development of efficient computer-implemented solutions of the parabolic equation (Lee and Botseas 1982) provides advantages over conventional normal-mode solutions. The new methods can work with range-dependent conditions such as sloping bottoms and spatial variations in the sound speed profile. For accurate solutions, these methods typically require computation of the acoustic field using increments of $\lambda/4$ in depth and $\lambda/2$ in range. Solutions involving high frequencies, deep water, or long ranges are computationally intensive and require a fast computer or a patient analyst.

When the water depth becomes large compared to the longest wavelength of propagating sound energy ($H/\lambda > 5$), acoustic ray theory may be applied. Ray theory represents the sound field as a sum of ray contributions with each ray following a direct, refracted, or reflected path from the source to a receiving point. In shallow water it is convenient to represent the reflected paths as arrivals from a set of image sources, which are geometric reflections of the source in the planes of the bottom and surface. The strengths of the image sources are determined by amplitude and phase changes produced by reflection losses. At the receiving point the sound pressure is calculated as the vector sum of all pressure contributions from the images. When many images are involved and when the bottom reflection losses can be expressed as an analytic function, a closed-form solution for transmission loss can be obtained using an integral to represent the image summation process (Smith 1974). Analytic models developed in this way provide convenient methods for predicting shallow water transmission loss. Unfortunately, the variability of the water and bottom parameters often restricts the usefulness of these analytic models.

To accommodate the variability of real-world data, semi-empirical propagation models have been designed for application to shallow water. One of these, developed by Marsh and Schulkin (1962) and summarized in Urick (1983:178), was based on a large number of shallow-water measurements from 100 Hz to 10 kHz. This model includes three basic equations covering different spreading loss conditions. *(1)* Near the source, sound energy spreads spherically outward at the "20 log *R*" rate (eq'n 3.1). *(2)* At intermediate ranges a "15 log R" loss rate is assumed:

$$L_r = L_s - 20 \log R_0 - 15 \log (R/R_0) \tag{3.3}$$

R_0 is the transition range ($R_0<R$) where spherical spreading changes to "15 log *R*" spreading. This equation is a useful approximation when the bottom reflection loss is proportional to the grazing angle of the sound ray with the bottom. This has been called ***mode stripping*** because the higher order modes with steeper grazing angles are attenuated more quickly than the lower order modes with shallow grazing angles. *(3)* As a result of this process, only low order modal energy remains at ranges beyond a second transition range. This propagates as the lowest mode with a cylindrical "10 log *R*" loss rate. Marsh and Schulkin give criteria based on water depth and mixed layer depth for determining the ranges where each loss rate applies.

It is possible to make reasonable propagation predictions from simple formulas of these types under certain conditions, *viz.* if sound speed is nearly independent of water depth and if the bottom either is flat or slopes uniformly and gradually. This procedure has been developed by Weston (1976). Weston's formulas divide the shallow water transmission path into four regions rather than the three used in the Marsh and Schulkin model. These regions are, in order of increasing range,

1. a spherical-spreading zone, where directly transmitted rays contribute most of the sound energy (20 log *R*);
2. a transitional, cylindrical-spreading region where bottom- and surface-reflected rays contribute more energy than the directly transmitted rays (10 log *R*);
3. a mode-stripping region where the rays propagating at steep grazing angles are attenuated more rapidly than rays at low grazing angles (15 log *R*); and
4. the lowest-mode region (10 log *R*).

Weston's formulas have been modified by P.W. Smith, Jr. (Malme et al. 1986a) and incorporated into a short computer program that calculates transmission loss when given parameters of frequency, water depth at the source, bottom slope, and two parameters describing the bottom reflection loss. An example of the composite transmission-loss curve produced by this model is shown in Figure 3.9A. This ***Weston/Smith Model*** does not incorporate refraction effects and is appropriate for conditions where sound-speed gradients are small. Within this limitation, comparisons of model predictions with field measurements have shown that the model provides good predictions in shallow water (e.g. Fig. 3.9B). The empirical data in that comparison are from the direct field near the source (within the 20 log *R* area) and from the transition region where bottom-reflected energy begins to dominate (10 log *R*). Weston/Smith model results have also been compared with empirical propagation data from Alaskan waters, and used to estimate potential radii of noise influence on whales in those regions (Malme et al. 1986b; Miles et al. 1987; see sect. 9.6-9.11).

3.5 Absorption and Factors Affecting Spreading Losses

Several additional factors can have important influences on sound propagation in both deep and shallow water. These include molecular absorption and interference effects associated with shallow sources or receivers. The presence of a sloping bottom or of special types of sub-bottom layers can also affect propagation, especially in shallow water.

3.5.1 Absorption

When sound energy is transmitted through water, a small portion of the energy is absorbed by the water molecules. Sea water absorbs considerably more sound energy than does distilled water (Liebermann 1949). Viscosity effects are responsible for sound absorption by pure water (Mason 1965). Various chemicals contained in sea water--some in very small amounts--cause the additional absorption. Magnesium sulfate is the main cause of absorption from about 10 to 100 kHz. The mechanism involves a process in which molecules distort if stressed too long by the sound wave. This "relaxation" process absorbs energy, which is converted to heat. A second relaxation absorption process occurs at frequencies below 5 kHz. Small amounts of boric acid may be the cause (Yeager et al. 1973).

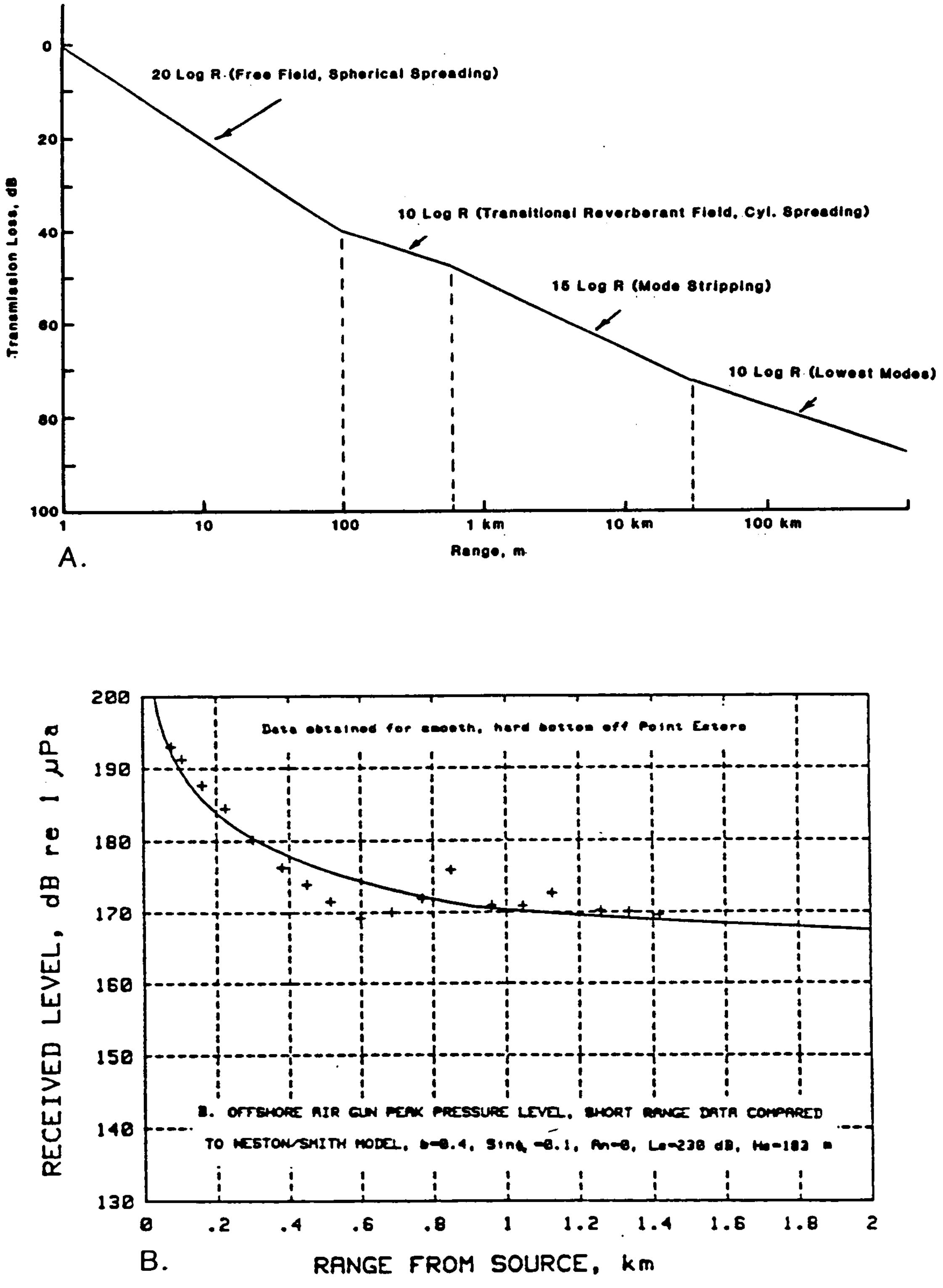

FIGURE 3.9. Weston/Smith shallow-water sound propagation model (from Malme et al. 1986a). *(A)* Example of theoretical transmission loss (depth = 100 m, freq. = 100 Hz). *(B)* Comparison of predicted results with empirical data obtained using an airgun source off the California coast (source depth = 8 m, water depth = 183 m).

Sound energy loss due to absorption is directly proportional to range and is usually given in terms of dB/km or, in earlier literature, db/kyd (1 dB/kyd = 1.09 dB/km). Absorption of sound by seawater increases with increasing frequency; the energy loss is approximately proportional to the square of frequency. Absorption is also weakly influenced by water temperature (Fig. 3.10A). Furthermore, there is a relatively strong pressure dependence, with absorption coefficients being reduced with increase in depth (Fig. 3.10B). At frequencies above 5 kHz, absorption causes significant (>2 dB) transmission loss if the range is >10 km. At frequencies below 1 kHz, absorption is not significant at ranges <40 km. Several empirical formulae have been published to calculate absorption as a function of frequency (Urick 1983). One that gives reasonable agreement with data over a wide range of frequencies (D. Ross, pers. comm.) is as follows:

$$a = 0.036\, f^{1.5} \qquad (3.4)$$

where f is frequency in kHz, and a is absorption in dB/km.

3.5.2 Shallow Source Effects

When the source and/or receiver are very close to the surface, the surface reflection of the sound (image source) interacts strongly with direct sound radiation. The reflected sound is out of phase with the direct sound. If the source has strong tonal or narrow-bandwidth noise components, this phenomenon produces an interference pattern. It may be observed as range-dependent fluctuations in the sound level at receiving locations along a horizontal radial line from the source. This phenomenon, known as the ***Lloyd mirror effect***, is strongest with low frequency tones and in calm sea conditions.

When the source is much closer to the receiver than to its surface image, the received level is determined by spherical spreading loss along a direct path. However, when range from source to receiver is long enough such that the direct and reflected path lengths are comparable, an interference field develops with alternating maxima and minima in received level. The boundaries of the interference region are determined by

$$2(d_1 d_2)^{0.5} < R < 4 d_1 d_2 / \lambda \qquad (3.5)$$

where d_1 and d_2 are the source and receiver depths in meters, R is the range from the acoustic center of the source (m), and λ is the wavelength of sound (m) at the frequency of interest (adapted from Urick 1983:132). Theoretically, with a pure tone source and a smooth surface, pressure doubling could occur at the maxima and complete cancellation of sound at the minima. However, because of wave roughness and finite bandwidth effects, variations in received level are more commonly <6 dB from maxima to minima for narrow band components.

Beyond the interference zone, spreading loss may be as much as 40 log R for a shallow source and shallow receiver in deep water (Fig. 3.11a). The rate of propagation loss is higher than normal when the source is close to the surface, i.e. when its depth is less than ¼-wavelength for the dominant output frequencies. With a shallow source, the source and its reflected image become effectively a dipole source with a vertical directionality (Urick 1983:134).

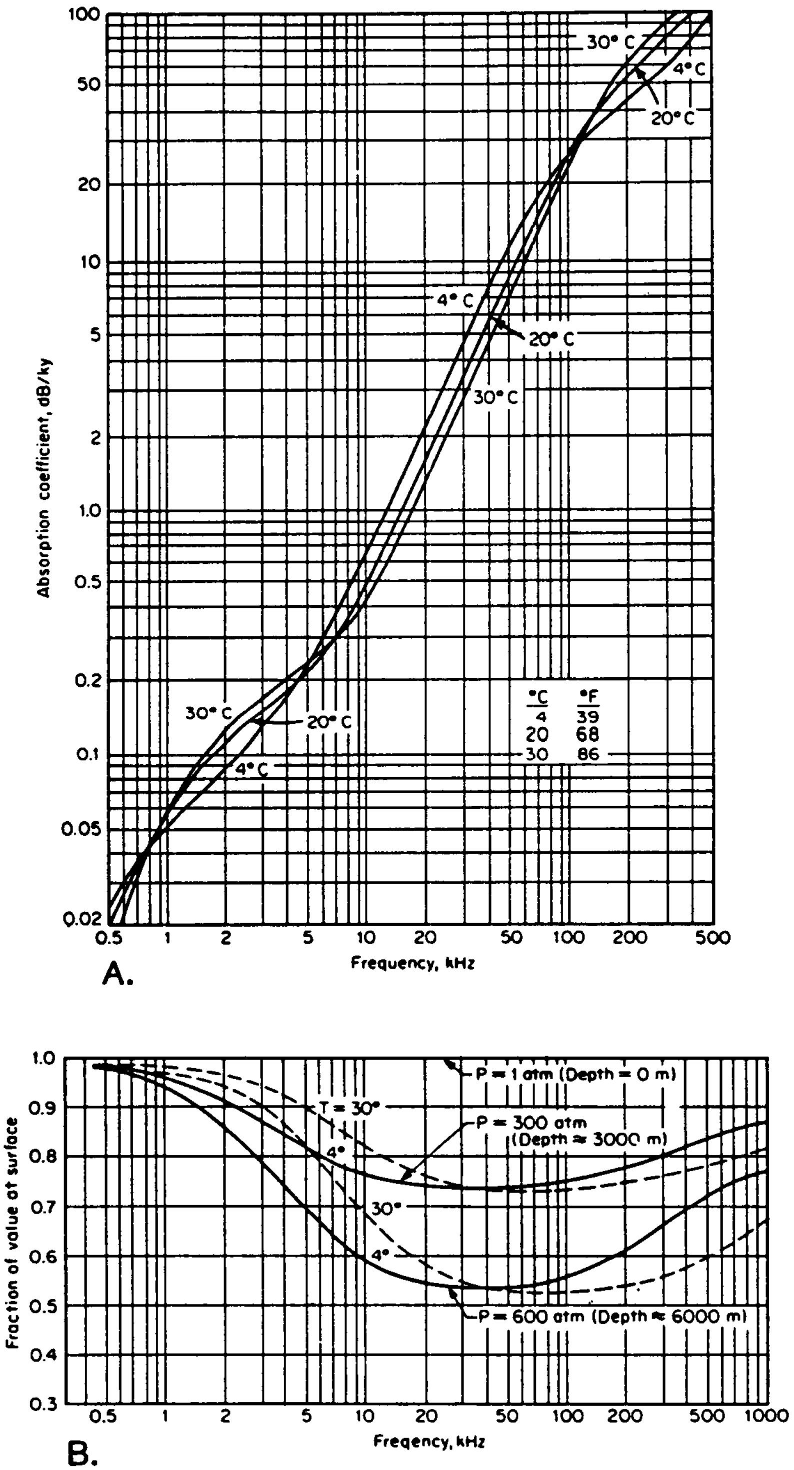

FIGURE 3.10. Absorption of sound energy by seawater in relation to *(A)* frequency and temperature at zero depth, and *(B)* pressure (35 ppt salinity, pH = 8; from Fisher and Simmonds 1977).

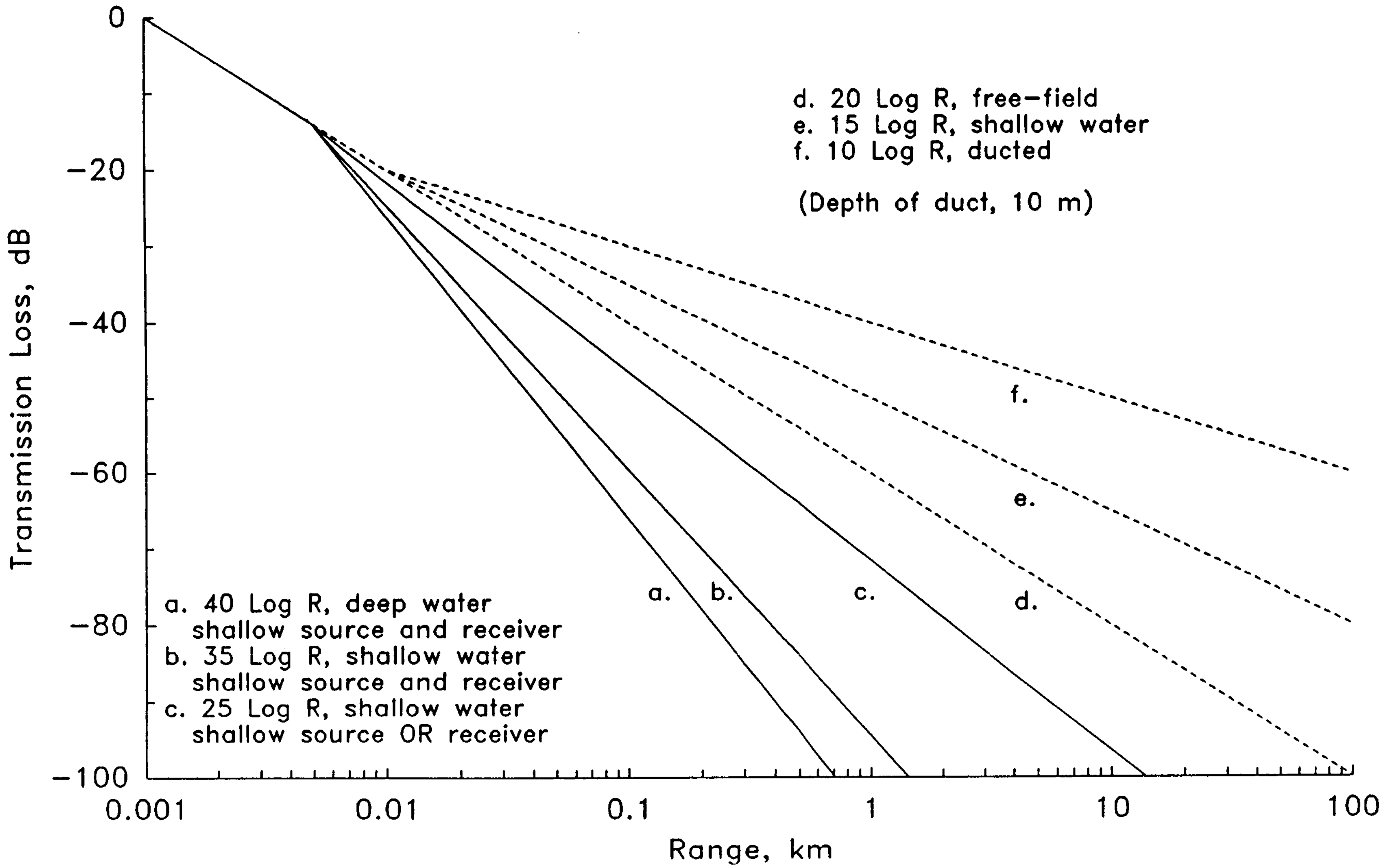

FIGURE 3.11. Theoretical underwater transmission loss when the source and receiver are within ¼ wavelength of the surface (a, b, c) as compared with transmission loss rates for greater source and receiver depths (d, e, f).

In shallow water, where propagation loss is typically at a 15 log *R* rate (Fig. 3.11e), the effect of the dipole directivity for shallow sources is to introduce an additional 10 log *R* spreading loss (Grachev 1983). As a result, propagation from a shallow source to a relatively deep receiver in shallow water may involve ~25 log *R* spreading loss (Fig. 3.11c). A similar interference effect occurs when the receiving location is within ¼-wavelength of the surface. Thus, an additional 10 log *R* spreading loss is present with a shallow receiver, and propagation from a shallow source to a shallow receiver will show ~35 log *R* spreading loss (Fig. 3.11b).

These types of effects have been reported for several oil industry sounds. Noise pulses from distant seismic exploration are typically several decibels weaker when received at 3 m depth than when received at 9 or 18 m (Greene and Richardson 1988). Similar depth-related differences in received levels were found for low-frequency components of dredge sounds (Greene 1987b).

3.5.3 Bottom Slope Effects

The slope of the bottom has a strong influence on sound transmission in shallow water. For sound transmission from a shallow region into deeper water, the increasing depth permits the sound energy to spread out into a larger volume than would have been available if depth had remained constant. This tends to result in a reduction in sound level. On the other hand, the sloping bottom causes the sound incidence angle to change with each reflection. Consequently, for a downward slope (increasing depth with increasing range from source), the incidence angle tends toward the horizontal. This results in fewer bottom and surface reflections and thus less energy loss per kilometer. For most bottom types, the reduction in reflection loss has the strongest influence.

Hence, the net effect of a downward slope along the propagation path often is lower transmission loss. This effect is most pronounced when neutral or upward refracting sound speed gradients exist. With these conditions, increasing depth may allow sound transmission to become ducted, in which case it is no longer influenced by the bottom (sect. 3.3). Thus, spreading loss is initially high in shallow water near the source, but may diminish to ~10 log *R* when the energy reaches deeper water.

Conversely, for sound transmission upslope into shallower water, the decrease in available volume for the sound energy would theoretically result in higher sound pressure and lower transmission loss. However, an upward slope causes the sound incidence angle to become steeper with each reflection. Consequently, there are high losses associated with high angles of incidence. These result in a net increase in transmission loss rate as sound enters shallower water, unless the bottom loss is very low. As propagation continues upslope, a depth is reached where a transition from multimode to single-mode propagation occurs. This results in a shift from a 15 log *R* to a 10 log *R* rate of spreading loss. Although spreading loss is reduced, the attenuation from bottom loss may be high because of the many reflections that occur in shallow water. Eventually, depth is reduced to the point where modal transmission is not supported and the remaining sound energy is attenuated very rapidly.

3.5.4 Transmission over Fast Sub-bottom Layers

Recent studies of low-frequency sound transmission in the Beaufort Sea have reported very low loss rates in shallow areas where high losses normally would be expected (Greene 1985a, 1987b; Miles et al. 1987). The observed transmission loss data typically have an overall trend showing 10 log *R* spreading loss with some additional losses at the longer ranges. However, there sometimes are intermediate regions where the trend of the data becomes flat or even positive.

These results may be explained by an analysis showing that certain types of bottom material where the sound speed is high may permit incident sound to penetrate the bottom and be refracted back out with low loss (Spofford et al. 1983). This type of "reflection" process does not depend on a large impedance mismatch such as occurs when sound encounters a rocky bottom. Subsea permafrost or overconsolidated clay layers, which are known to exist in parts of the Beaufort Sea, may have this type of low-loss bottom reflectivity.

3.6 Airborne Sound Transmission

Airborne sound transmission needs to be considered for two reasons. First, sound from some sources, especially aircraft, travels through air before entering water, and is attenuated along the airborne portion of the propagation path. Second, some marine mammals--especially pinnipeds--commonly haul out onto land or ice, where they hear airborne sounds and may themselves emit aerial calls.

Sound transmission from an omnidirectional source in an unbounded uniform atmosphere is attenuated only by spherical spreading of the sound energy (20 log *R*) and by absorption of sound energy by air molecules. However, sound transmission from a source near the ground is affected by additional factors. The ground is usually non-rigid and permeable, and propagation near this surface is influenced by reflections and wave transmission along the surface. Interference between the direct, reflected, and ground wave paths causes fluctuations in received level and in frequency composition for near-ground transmission. In addition, refraction caused by wind and temperature gradients produces shadow zones with very poor sound transmission in the upwind direction, and often produces enhanced sound transmission downwind.

3.6.1 Atmospheric Absorption

Atmospheric absorption of sound at frequencies below 30 kHz is produced by oxygen and nitrogen molecules. The dominant absorption mechanism is a relaxation process similar to that involved in sound absorption underwater (sect. 3.5.1). The amount of absorption depends on frequency, temperature, relative humidity, and to a small degree on atmospheric pressure. The physical relationships between these parameters and absorption are not easily expressed mathematically, but an empirical computer algorithm has been developed to calculate absorption coefficients in relation to the four parameters listed above (American National Standards Institute 1978).

In the mid-frequency range, sound absorption has a greater influence on sound transmission in the atmosphere than in the ocean. For example, at 1 kHz the underwater sound absorption coefficient is ~0.06 dB/km, whereas a typical value for in-air attenuation is ~4 dB/km. The absorption coefficient increases rapidly with frequency and becomes about 130 dB/km at 10 kHz, depending on temperature and humidity conditions. As a result, only low frequency sound is transmitted well in the atmosphere (Fig. 3.12).

3.6.2 Gradient Effects

The atmosphere near the ground is influenced by wind and temperature conditions, which vary with altitude. Vertical gradients of wind and temperature cause upward or downward refraction of wavefronts and corresponding variations in sound transmission. For downwind transmission, some sound enhancement occurs because the wind speed, which increases with height because of the drag of the ground, is added to the sound speed; hence ray paths are bent downward. For upwind transmission, the higher wind speed aloft acts to reduce the sound speed and sound rays are bent upward. This usually results in a near-surface shadow zone at some distance upwind from the source. This distance is determined by the strength of the vertical gradient in wind speed and by the heights of the source and receiver.

During a sunny day, the air near the ground becomes warmer than that at high altitudes, resulting in a ***temperature lapse*** condition. Since sound speed increases with temperature, sound rays from a source near the ground are bent upward. If the wind speed gradient is weak, a shadow zone surrounding the source is formed. In contrast, with ***temperature inversions***, which often occur at night when the ground cools off, the air near the ground is colder than that at altitude and sound rays are bent downward. This results in enhanced sound transmission along the ground in all directions from the source.

Under the usual daytime conditions, wind and temperature gradients interact to produce a shadow zone which partially surrounds the source (Fig. 3.13A). The day-night change in the shadow boundary illustrates the effect of a typical day-night change in temperature under a constant wind condition. The location of the shadow zone and the degree of ***excess attenuation*** within that zone change with changes in the angle between the wind direction and sound propagation direction (Fig. 3.13B). The amount of excess attenuation (i.e. in excess of spreading loss and absorption) is limited to a maximum of about 28 dB because of sound scattering from turbulence and ground wave transmission.

3.6.3 Ground Effects

Sound propagation near the ground is influenced by the acoustic properties of the surface in addition to the atmospheric refraction effects described above. Together with the direct and reflected paths, a ground wave path also contributes a significant amount of energy at low frequencies. Few studies of ground effects on airborne sound propagation have been reported for habitats likely to be occupied by marine mammals (but see Cummings and Holiday 1983). However, data from urban areas illustrate some of the general principles that are involved.

Interference between sounds arriving via different paths causes transmission irregularities (Fig. 3.14A,B). For propagation over asphalt, irregularities are greater with receiver height 1.2 m than for receiver height 0 m (Fig. 3.14A vs. B). Irregularities are minimized if the source or receiver is located near a hard surface where there is pressure doubling. For a

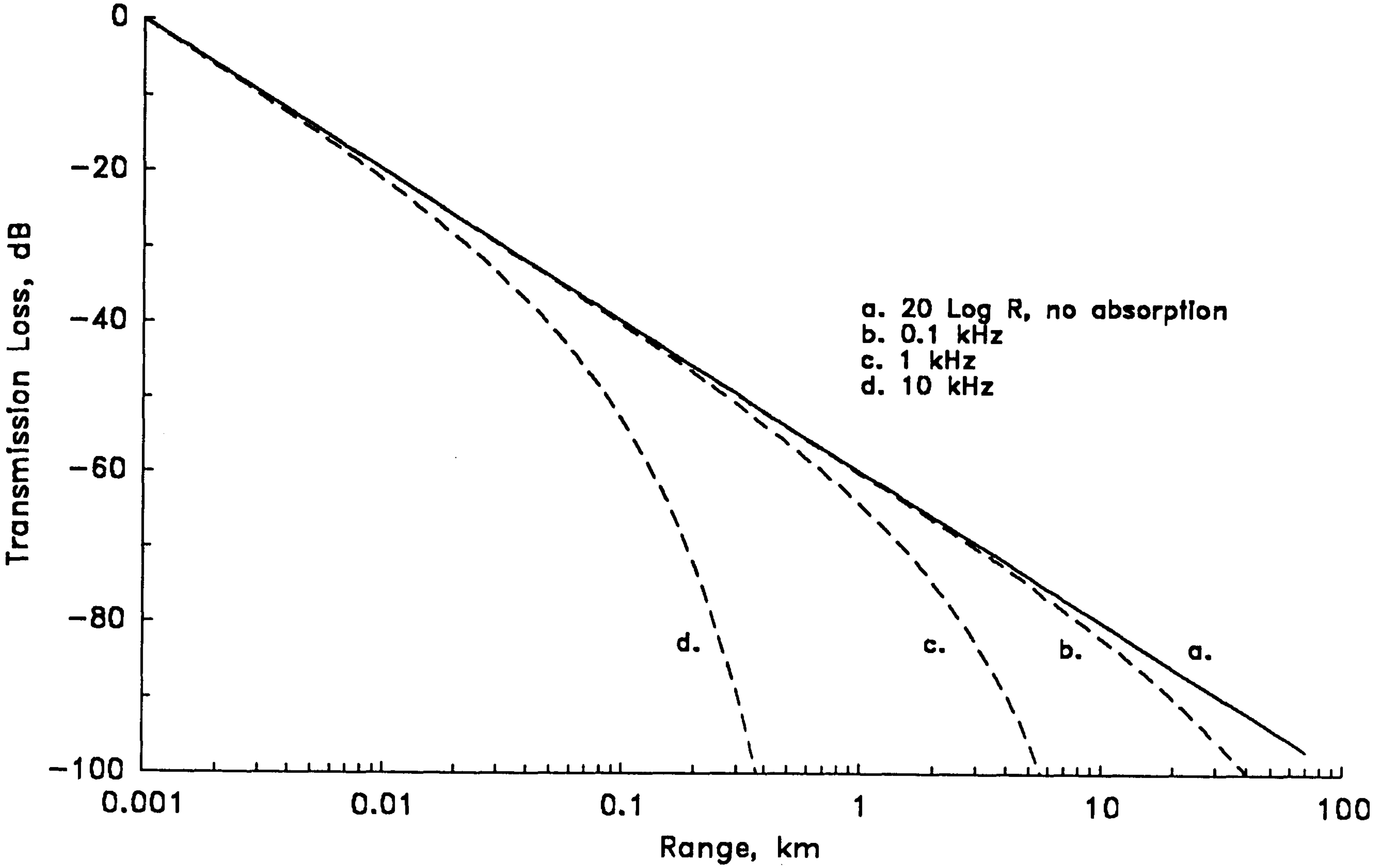

FIGURE 3.12. Atmospheric propagation loss based on spherical spreading plus additional absorption loss at 0.1, 1 and 10 kHz.

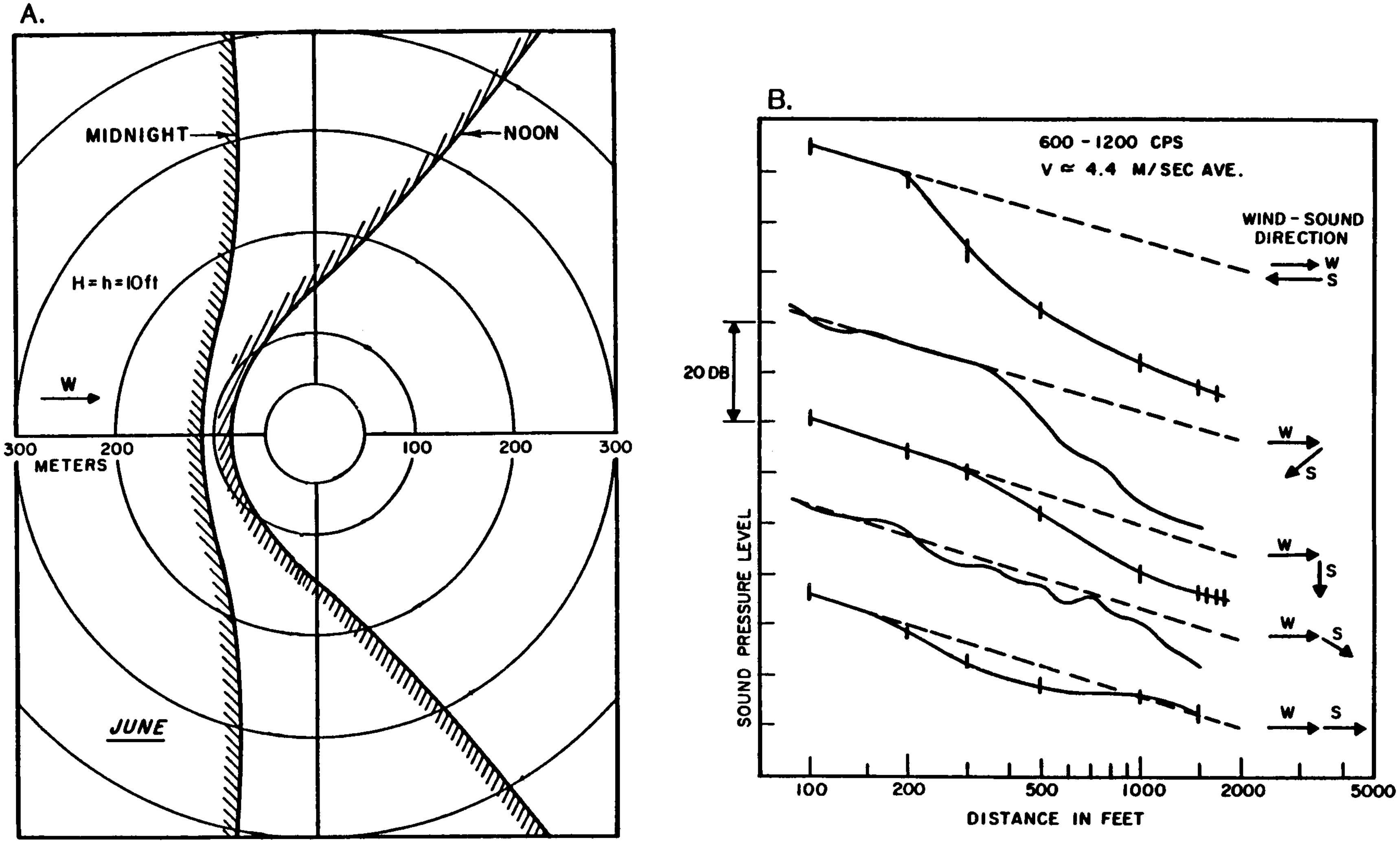

FIGURE 3.13. Effects of temperature and wind on airborne sound propagation (from Wiener et al. 1954). (A) Location of sound shadow near a source during the day and night. A constant wind is blowing from left to right. The sound shadow is to the left of the hatched boundary. (B) Variations in measured sound pressure levels in relation to wind speed and direction.

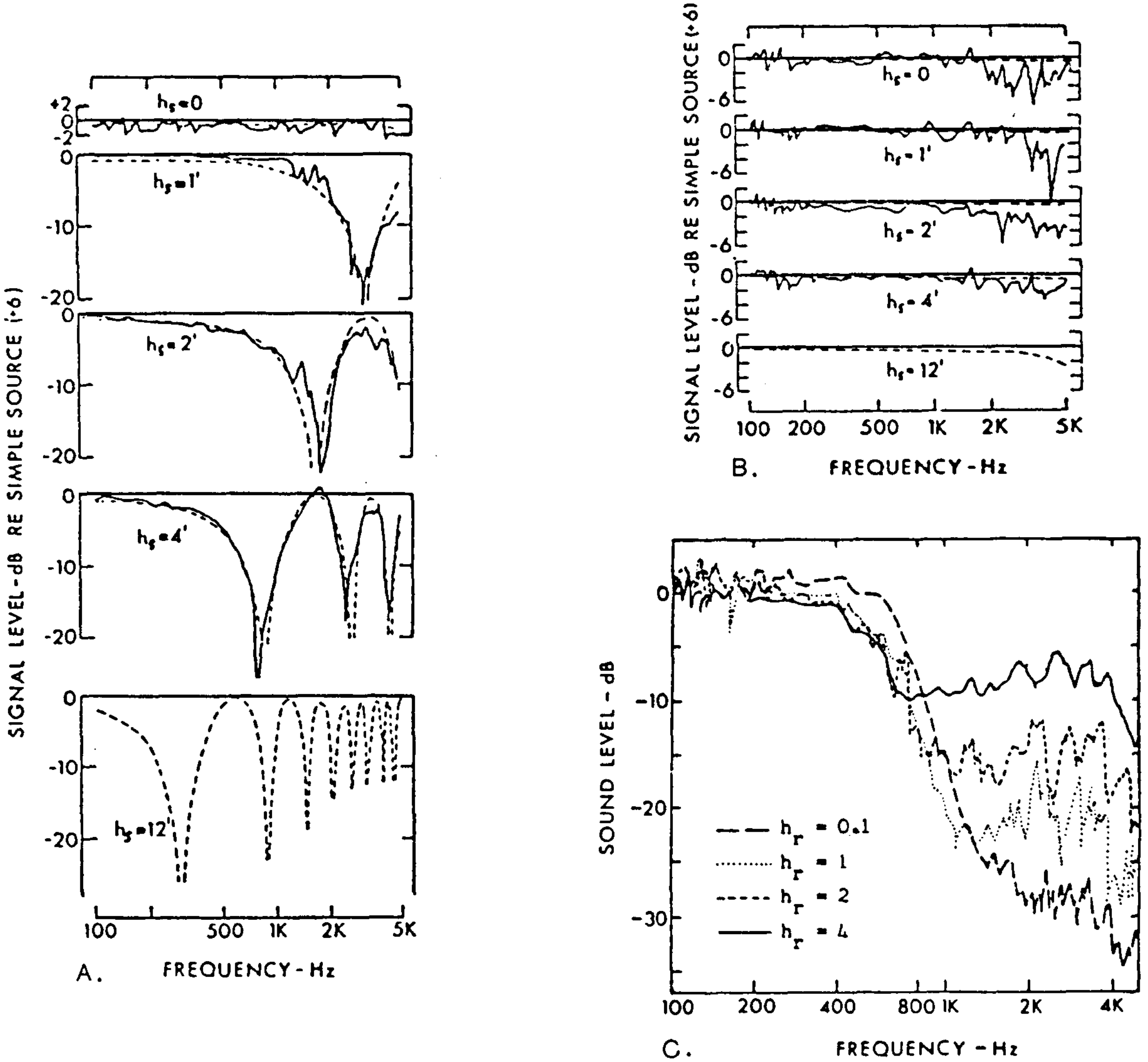

FIGURE 3.14. Sound level characteristics for propagation measurements with various source-receiver geometries over soft and hard surfaces. (A) Effects of source height h_s on measured (——) and calculated (- -) spectra for propagation over asphalt; receiver height h_r=1.2 m, horizontal distance 15 m (Piercy and Embleton 1974). (B) Same as (a) but h_r=0 (Piercy and Embleton 1974). (C) Sound level spectra for propagation at various heights over grass from a source on the ground; h_s=3 cm, horizontal distance 15 m; reference is expected free-field sound level (Embleton et al. 1976).

receiver near an asphalt surface, transmission is not affected appreciably by frequency for frequencies up to ~2 kHz and source heights up to 12 ft (3.7 m) (Fig. 3.14B).

Measurements over grass at a constant range of 15 m are shown in Figure 3.14C. Here the source is located near the ground and receiver height is varied. While the received level data are somewhat irregular, no pronounced interference pattern is observed. The low-frequency response below 500 Hz is nearly independent of receiver height, with the exception of the lowest height of 0.1 ft (3 cm). However, at higher frequencies the received level depends on receiver height (Fig. 3.14C). At longer ranges and higher frequencies, transmission is not as good over grass as over asphalt or concrete.

The propagation effects described above show that sound transmission in the atmosphere depends on the site and on weather conditions. Airborne propagation losses, especially near the ground, cannot be predicted accurately with a general model. Information on path geometry and local conditions is needed in order to use available transmission models successfully. However, to predict the *maximum potential* sound exposure for a given source and range, a simple model including only spherical spreading and atmospheric absorption (Fig. 3.12) is adequate, especially when the source is well above ground level. This model is appropriate for aircraft, which are the sources of airborne industrial noise to which marine mammals are most often exposed.

3.7 Transmission Through the Air-Water Interface[4]

Sound traveling from a source in air to a receiver underwater propagates in four ways: (1) via a direct refracted path; (2) via direct refracted paths that are reflected by the bottom; (3) via a "lateral" (surface-traveling) wave; and (4) via scattering from a rough sea surface (Fig. 3.15; Urick 1972). The types of propagation vary in importance depending on local conditions, the depth of the receiver, and bottom depth. The direct refracted path is important when the receiver is nearly under the aircraft. Snell's law predicts a critical angle of 13° from the vertical for the transmission of sound from air to water. Under calm-sea conditions, sound is totally reflected at larger angles and does not enter the water. However, it is possible for airborne sound to penetrate water at angles >13° from the vertical when rough seas provide water surfaces at suitable angles.

Air-to-water sound propagation has been documented using wave theory (e.g. Weinstein and Henney 1965; Medwin and Hagy 1972) and ray theory (Hudimac 1957; Urick 1972; Waters 1972; Young 1973); see also Chapman and Ward (1990). Young (1973) presented an equation predicting the received level of underwater sound from an airborne source. His equation considers a virtual (assumed) sound source situated under the actual source at height h', where $h' = (c_a/c_w)h$; c_a is the sound speed in air, c_w is the sound speed in water, and h is the actual height of the source. The predicted received level in the water, L_r, is as follows:

$$L_r = L_s - 7 + 20 \log (\cos \Theta) - 20 \log (r/r_s) \qquad (3.6)$$

where L_s is the source level at reference range r_s (not necessarily 1 m), r is the slant range from the virtual source to the receiver, and Θ is the angle between the vertical and the ray from the

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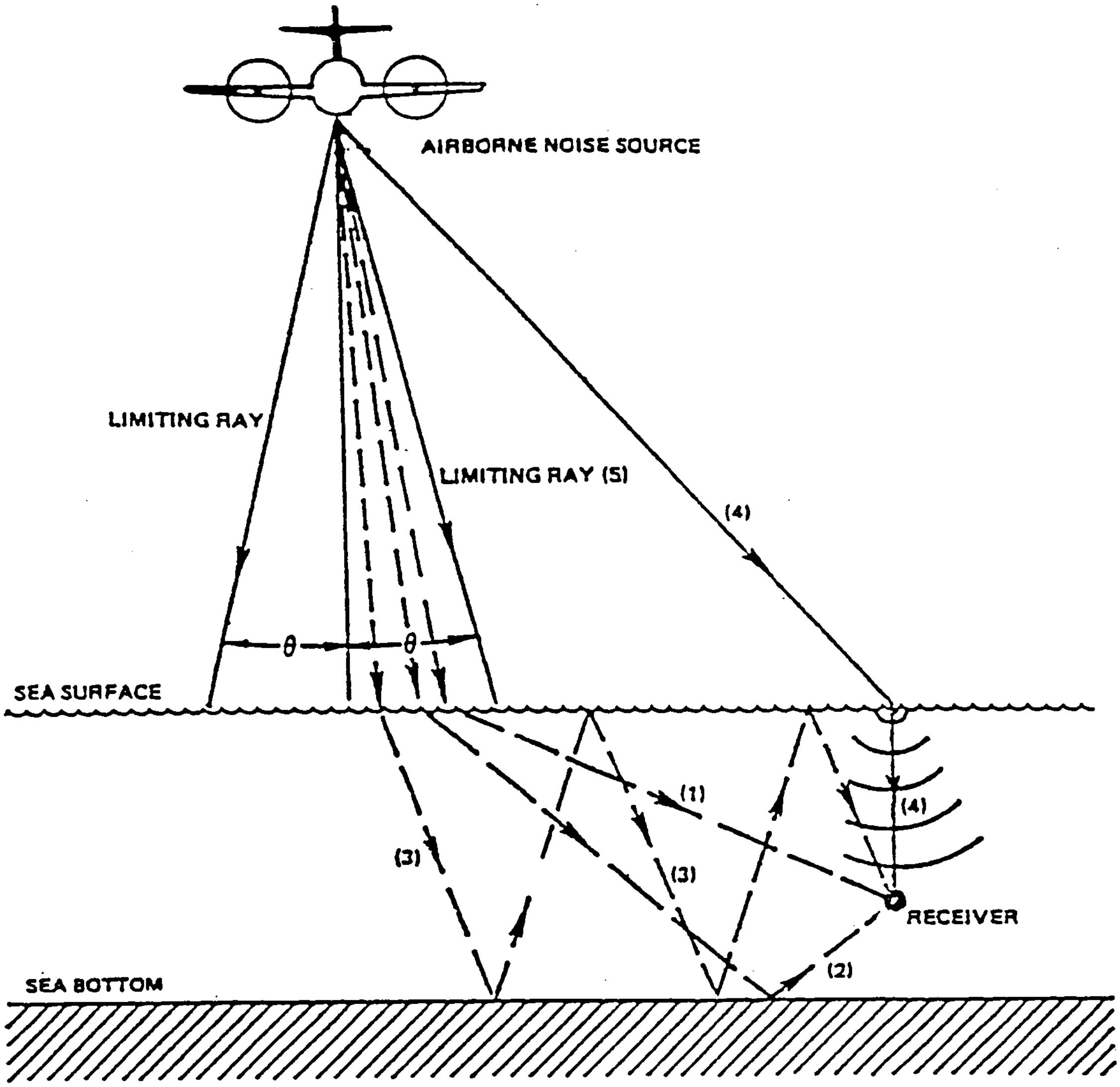
[4] Section 3.7 was prepared by C.I. Malme (BBN Systems & Technologies Corp.) and C.R. Greene Jr. (Greeneridge Sciences Inc.).



1. DIRECT PATH SHOWING BENDING AT SEA SURFACE
2. BOTTOM REFLECTED PATH
3. MULTIPLE BOTTOM-SURFACE REFLECTED PATH
4. SURFACE SCATTERED PATH
5. LIMITING RAY FOR CRITICAL ANGLE θ, BEYOND WHICH, RAYS ARE TOTALLY REFLECTED ($\theta = 13^\circ$)

FIGURE 3.15. Ray-path diagram showing various air → water propagation paths for aircraft noise (from Urick 1972).

virtual source to the receiver. This equation can be used to derive source levels from measured received levels for different types of aircraft.

Sound traveling from air to water along the direct refracted path passes through three phases: through air; across the air-water surface; and from the surface to the underwater receiver (Fig. 3.15). To a first approximation, propagation loss of sound traveling through air can be described by simple spherical spreading--6 dB decrease per distance doubled (sect. 3.6). At the surface, the great difference in acoustic properties of air and water results in most acoustic energy being reflected. However, the sound pressure transmitted to the water is actually enhanced because of the pressure-doubling effect of the water interface. Hence, sound pressure at the surface directly beneath the source is twice what the pressure would be in air at the same distance if there were no water surface. From the surface to the underwater receiver, sound propagation includes both geometrical spreading and the effects of the divergence of sound energy as it passes through the surface. This results in a complicated distribution of underwater sound pressure that depends upon the height of the source, the location of the receiver, the water depth, and the temperature-salinity profile of the water column.

To facilitate estimation of underwater sound levels produced by an airborne source over shallow water, an air → water sound transmission model was recently developed using eq'n 3.6 together with shallow water transmission theory (Malme and Smith 1988). Figure 3.16, based on this model, shows the difference between the sound level underwater and the "incident" sound level in air. The incident sound level is defined as the level that would be measured at the surface directly under the airborne source if the surface were not there. This point on the surface is defined as the subsource point. A constant source altitude of 300 m and a constant receiver depth of 5 m have been used for all curves shown in Figure 3.16. The values chosen for the bottom loss parameter *b* are representative of soft mud (*b*=2) and hard basalt (*b*=0.2).

The highest curve in Figure 3.16 shows the relative sound level in air just above the surface as a function of lateral distance from the subsource point. When the source is overhead, the sound level is 6 dB higher than the free field incident pressure because of the boundary reflection. The lowest curve shows the relative sound level in deep water, where only the direct sound field is present. The intermediate dashed and dotted curves show the influence of bottom-reflected sound in shallow water. With a hard bottom, the predicted sound level near the subsource position is influenced by water depth; higher received levels occur in 20 m (—·—) than in 200 m (—∘—) water. However at lateral distances beyond a few hundred meters in this example, predicted L_r is similar with water depths 20 and 200 m. With water 20-200 m deep and a hard bottom, sound levels underwater are expected to be only 10 dB less than those at the corresponding lateral distance just above the surface (Fig. 3.16). In comparison, in deep water, levels 1 km from the subsource point are much lower--35 dB less than those in air. With a soft bottom, levels underwater away from the subsource point are intermediate between those with a hard bottom at 20-200 m and those in deep water.

The model results are consistent with empirical data (e.g. Urick 1972; Greene 1985a). Empirical data show that, in deep water, there are high transmission losses between a source in air and an underwater receiver distant from the subsource point. Underwater received levels away from the subsource point are higher in shallow than in deep water. This difference occurs because, in shallow water, sound is transmitted horizontally away from the subsource point by

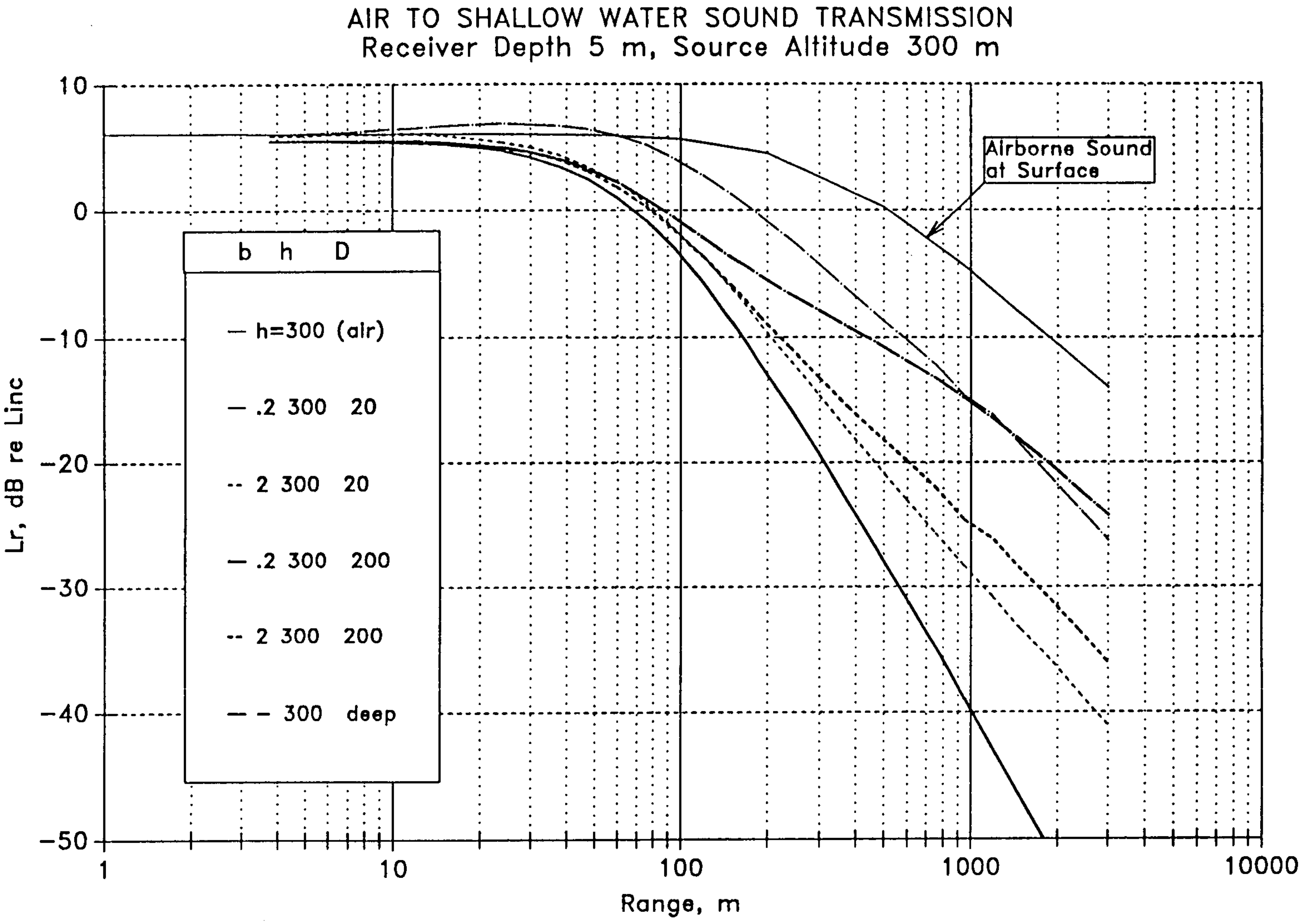


FIGURE 3.16. Theoretical air → shallow-water sound transmission for receiver depth 5 m and source altitude 300 m. Received levels just above the surface (top curve) and received levels underwater are expressed in dB with respect to the incident level 300 m directly below the source if the water surface were not there (from Malme and Smith 1988).

multiple reflections from the bottom and surface. This process is more efficient for hard bottom conditions. Even with a hard bottom, however, underwater noise diminishes more rapidly with increasing distance from the subsource point than does airborne noise (Fig. 3.16). Consistent with this, under typical ambient noise conditions, an approaching aircraft can be heard in the air well before it is audible underwater (Greene 1985a).

Waves affect air → water sound transmission. With sea states of two or higher and frequencies >150 Hz, surface roughness enhances air → water sound transmission at shallow grazing angles (Urick 1972; Barger and Sachs 1975). This results in a 3 to 7 dB increase in the underwater sound levels in the direction of wave travel. In directions perpendicular to the direction of wave travel, the increase is about 2 dB less. In the underwater region near the subsource point, which normally has the highest sound level, the wave scattering effect reduces sound intensity by 3 to 5 dB.

Transmission of sound energy from air through an ice layer and into water involves generation of several different types of waves in the ice in addition to the sound waves transmitted through the ice and into the water. The inhomogeneous nature of salt water ice makes this process a formidable theoretical modeling problem. At frequencies <500 Hz, where most acoustic energy from aircraft (sect. 5.2.1) and surface vehicles is concentrated, the ice layer is acoustically thin and causes little attenuation of sound (H. Kutschale, pers. comm.). Direct use of the air → water transmission model for transmission of low frequency sound through ice would provide slight overestimates of underwater sound levels from aircraft overflights. Transmission of noise from surface vehicles on the ice into the water is a more difficult problem. This topic is now being investigated, but many of the results are classified. Sound entering the water through ice cover is an important source of man-made noise since numerous species of cetaceans and pinnipeds inhabit regions with varying degrees of ice cover.

3.8 Summary

The potential effects of noise on marine mammals are determined by radiated sound power levels (Chap. 5), sound propagation characteristics, and the auditory and behavioral sensitivity of the mammals (Chap. 7, 8). The general description of sound propagation in this chapter is intended to assist biologists and naturalists in evaluating noise effects. Sound propagation in the sea has been the subject of much theoretical and empirical research. The open literature is extensive, and there is much additional unpublished and classified information. For specific applications, the general information provided above should be augmented by a more detailed review of the most directly relevant references.

Sound propagation research has made considerable progress in recent years. Field measurements of sound levels in relation to distance, frequency, and environmental parameters have been obtained in many areas and situations. Based on these data and on theoretical considerations, efficient computer algorithms have been developed that permit the use of models with sufficient detail to account for many of the propagation processes occurring in the real world. However, most of these models are designed for specialized applications (often classified) and are not easily generalized for use in predicting potential noise impact ranges for industrial sources. Fortunately, some simple and general relationships can be used for both underwater and airborne sound transmission to make estimates of the expected relationships between received level and range for many source and location situations.

The spherical spreading law with an added absorption loss term can be applied in the cases of (1) air-to-ground transmission from aircraft or other sources at elevation angles greater than 10°, and (2) non-ducted, direct-path underwater transmission:

$$L_r = L_s - 20 \log R - \alpha R - 60 \tag{3.7}$$

where L_r is the received level at range R (km) in dB re 1 μPa (underwater) or dB re 20 μPa (in air),
L_s is the source level in the same dB units at range 1 m,
α is the molecular absorption coefficient in dB/km (from a table), and
-60 is a conversion factor related to the change in range units from L_s at 1 m to L_r at R km; it represents spherical spreading (in dB) between 1 m and 1 km.

At frequencies below a few kilohertz, where most industrial noise energy is concentrated, the absorption coefficient is very low in water but higher in air. Thus the absorption term is generally negligible for underwater propagation of industrial noise over the limited ranges where spherical spreading applies. However, the absorption term can be significant for underwater propagation of high-frequency sounds, e.g. echolocation sounds from toothed whales, or for airborne propagation of industrial or animal sounds. For broadband sources, calculations should be made at several frequencies since the absorption coefficient, and usually also the source level, are frequency dependent. If an overall broadband received level is required, it can then be obtained by summing (via equation 2.8) the results for the various narrower bands.

For very shallow water or ducted underwater transmission beginning at a distance R_0 from the source, equation 3.7 is modified to use cylindrical spreading beyond range R_0 plus an additional linear loss factor:

$$L_r = L_s - 20 \log R_0 - 10 \log (R/R_0) - \alpha R - (A)R - 60$$

which is equivalent to

$$L_r = L_s - 10 \log R_0 - 10 \log R - \alpha R - (A)R - 60 \tag{3.8}$$

where R_0 is the range (in km) where the transition from spherical to cylindrical spreading occurs, and
(A) is a loss factor representing duct leakage or modal attenuation in dB/km (Urick 1983:152).

The transition range R_0 depends on the acoustic reflection properties of the bottom or on duct refraction conditions. In the absence of site-specific data, it is often defined as being equal to the water depth or duct width.

For underwater transmission in shallow water where the depth is greater than 5 times the wavelength, 15 log R spreading loss may occur beyond range H:

$$L_r = L_s - 5 \log H - 15 \log R - \alpha R - At[(R/H)-1] + Kl - 60 \tag{3.9}$$

where H is the water depth in meters,
At is an empirically determined factor related to scattering and other losses not accounted for in the mode stripping process, and

Kl is an anomaly term related to the reverberant sound field developed near the source by surface and bottom reflected energy. This causes an apparent increase in source level.

Relationship (3.9) is from the Marsh and Schulkin model (Urick 1983:178). Values for *At* and *Kl* may be obtained from tables based on their measurements or may be determined from empirical data obtained at the specific site. When site-specific data are available, this model is capable of providing good predictions of received levels for general locations in the area. This model will work for sloping bottom conditions if the depths at the source and receiver locations are averaged to determine the value of *H*.

For transmission loss predictions that require greater accuracy than provided by the simple relationships listed above, various more elaborate models mentioned in this chapter may be appropriate. The reader is referred to the cited sources to obtain the necessary detailed descriptions. If propagation losses and received levels at long range must be predicted, especially in shallow water conditions, site-specific empirical data on bottom conditions and water properties will be needed. Ideally, direct measurements of propagation loss should be made in order to validate site-specific propagation models.

4. AMBIENT NOISE[1,2]

4.1 Introduction

Ambient noise is background noise present in the environment. It is generally unwanted sound, sound that clutters and masks other sounds of interest. Ambient noise includes only the sounds that would exist if the sensor were not there; noise created by the measurement process, including any vessel or vehicle used to deploy the sound sensor, is usually excluded (Ross 1976). Ambient noise is a real phenomenon; it does not result from instrumentation disturbances caused by the hydrophone or microphone mounting or cable, or from the electronics used to amplify the signals. When present to a significant degree, those are called system noises, not ambient noise. Ambient noise may have directional properties, being stronger from some directions than others. Surf sounds coming from a shore, or distant shipping sounds coming generally from a shipping lane, are examples of directional ambient noise. Vertical directionality occurs at deep water sites.

In determining how far away a given sound source can be detected, the level and spectral characteristics of the ambient noise are two of the primary controlling factors, along with the source level of the sound of interest and the rate of sound transmission loss around the source. As a first approximation, a sound signal is detectable only if it is stronger than the ambient noise at similar frequencies. If the background noise level changes, the distance from the source at which the signal level diminishes below the ambient noise level also changes in an inverse fashion. The lower the background noise, the farther a sound signal will travel before its level diminishes below the background noise level. In a specific ocean area, a given sound source may be detectable several times farther away on one day than on the next as a consequence of a change in background noise. Similarly, "zones of acoustic influence" attributed to an industrial sound source (see Chap. 9) may be influenced strongly by the levels and types of background noise.

Ambient noise requires the same descriptors as other kinds of sounds. Basic qualities include the following: What is the temporal pattern of the sound--is it continuous or does it start and stop? What is its duration and frequency of occurrence? What are its frequency characteristics--is it concentrated at low or high frequencies, and does it contain tones (sinusoidal components)? Or is it relatively broadband, rumbling at low frequencies and hissing at high frequencies? Does it contain significant energy at frequencies that human beings cannot hear, either at very low frequencies (infrasonic, <20 Hz) or at very high frequencies (say above 15-20 kHz)? What are the directional properties, both horizontally and vertically, of the ambient noise at a specified location? What are its sources?

This chapter provides a brief introduction to ambient noise in the sea, including its sources, variability, and characteristics in shallow and deep water. Airborne ambient noise is

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[1] By Charles R. Greene, Jr., Greeneridge Sciences Inc.

[2] Constructive comments on drafts of this chapter were provided by Drs. W.C. Cummings, R.A. Davis, A.N. Popper and D. Ross.

mentioned briefly. The chapter emphasizes topics relevant to later sections concerning noise effects on marine mammals.

The published literature on ambient noise is far more extensive than it is practical or necessary to cover here. Most papers on underwater ambient noise appear in the *Journal of the Acoustical Society of America.* A particularly important review paper was written by Gordon Wenz (1962). An important predecessor paper that is still widely cited is Knudsen et al. (1948). Ross (1976) wrote a definitive book on underwater noise, including a discussion of ambient noise. Urick (1986) published a monograph on oceanic ambient noise that expands on the ambient noise material in his more general text on underwater sound (1983). Zakarauskas (1986) reviews literature on ambient noise in shallow water, and provides information on ambient noise in deep water as well.

4.2 Sources of Ambient Noise

Wind and waves are common and interrelated sources of ambient noise in all the world's oceans. The spectrum of sound from wind and waves is distributed smoothly with frequency; there are no "spikes" (tones). Ambient noise levels tend to increase with increasing wind speed and wave height, other factors being equal. Table 4.1 presents definitions and relationships among wind speeds, the Beaufort Wind Force scale, and the Sea State scale (see also Kennish 1989).

Knudsen et al. (1948) provided summary spectra showing typical sound level vs. frequency for sea states 0-6 (Fig. 4.1A, from Urick 1986). The data were taken at frequencies above 500 Hz from oceanic sites outside harbors and are probably appropriate for depths on the order of 200 m (Ross 1976). However, the Knudsen curves are widely used to characterize deep water ambient noise. The dashed lines at frequencies from 100 to 1000 Hz (Fig. 4.1A) indicate that it is appropriate to be skeptical about the accuracy of the spectra at the lower frequencies, particularly below 500 Hz.

The Knudsen curves for spectrum level ambient noise have slopes of -5 dB per octave. Sound pressure spectrum levels corresponding to the Knudsen curves can be calculated from the following equation and table:

$$\text{SPSL (dB re 1 }\mu\text{Pa}^2\text{/Hz)} = A - 16.6 \log (f) \qquad (4.1)$$

where f is the frequency in hertz (above 500 Hz) and A is a constant related to the sea state:

Sea State	0	1	2	4	6
Wind Force	1	2	3	5	8
Constant A	94.2	102.0	106.6	114.3	119.6

Thus, for each doubling of frequency above 500 Hz, the intensity of ambient noise in a 1 Hz band typically decreases by 5 dB. This is equivalent to a 0.67 dB decrease in the band level of ambient noise for each successive 1/3-octave band, or 2 dB/octave (Fig. 4.1B). In other words, the slope is shallower for 1/3-octave bands than for 1 Hz bands (spectrum levels). This occurs because 1/3-octave bands are progressively wider with increasing frequency (width = 23% of center frequency; see sect. 2.2). In comparing Figures 4.1A and 4.1B, note that the ordinate

Table 4.1. Interrelationships of sea state, Beaufort wind force, and wind speed.

Wind Speed Knots	Wind Speed m/s	Beaufort Wind Force	World Meteorol. Org. Terms	Sea State	Wave Heights (m)	Description
< 1	< 0.5	0	Calm	0	0	Glassy
1 - 3	0.5 - 1.5	1	Light air	½	< 0.1	Ripples
4 - 6	2.1 - 3.1	2	Light breeze	1	0 - 0.1	Small wavelets
7 - 10	3.6 - 5.1	3	Gentle breeze	2	0.1 - 0.5	Smooth wavelets
11 - 16	5.7 - 8.2	4	Moderate breeze	3	0.5 - 1.2	Slight; small whitecaps
17 - 21	8.7 - 10.8	5	Fresh breeze	4	1.2 - 2.4	Moderate waves, some spray
22 - 27	11.3 - 13.9	6	Strong breeze	5	2.4 - 4	Rough, larger waves
28 - 33	14.4 - 17.0	7	Near gale	6		
34 - 40	17.5 - 20.6	8	Gale	6	4 - 6	Very rough
41 - 47	21.1 - 24.2	9	Strong gale	6		
48 - 55	24.7 - 28.3	10	Storm	7	6 - 9	High
56 - 63	28.8 - 32.4	11	Violent storm	8	9 - 14	Very high
> 64	> 33	12	Hurricane	9	> 14	Phenomenal

in Fig. 4.1A is in units appropriate for spectrum level data (dB re 1 $\mu Pa^2/Hz$) whereas that in Fig. 4.1B is appropriate for broader bands (dB re 1 μPa).

There is strong evidence that wind speed at the surface is directly related to noise production at the sea-surface (e.g. Wille and Geyer 1984). Their data, from water 30 m deep, indicated that wave height is not as directly relevant to noise levels. Use of wave heights to infer noise levels may lead to errors because the sea state is not always fully developed for the existing wind conditions (sect. 4.4).

Ross (1976) also developed generalized spectra relating spectrum level ambient noise in deep water to wind force and sea state (Fig. 4.1C). He indicates that, above 500 Hz, the Knudsen models tend to overestimate the levels at each sea state by a few dB. This may be related, at least in part, to the fact that Knudsen's data came from moderately shallow water. More importantly, below 500 Hz the spectra for wind-generated ambient noise in deep water tend to flatten out at values considerably lower than would be predicted by extrapolation of the

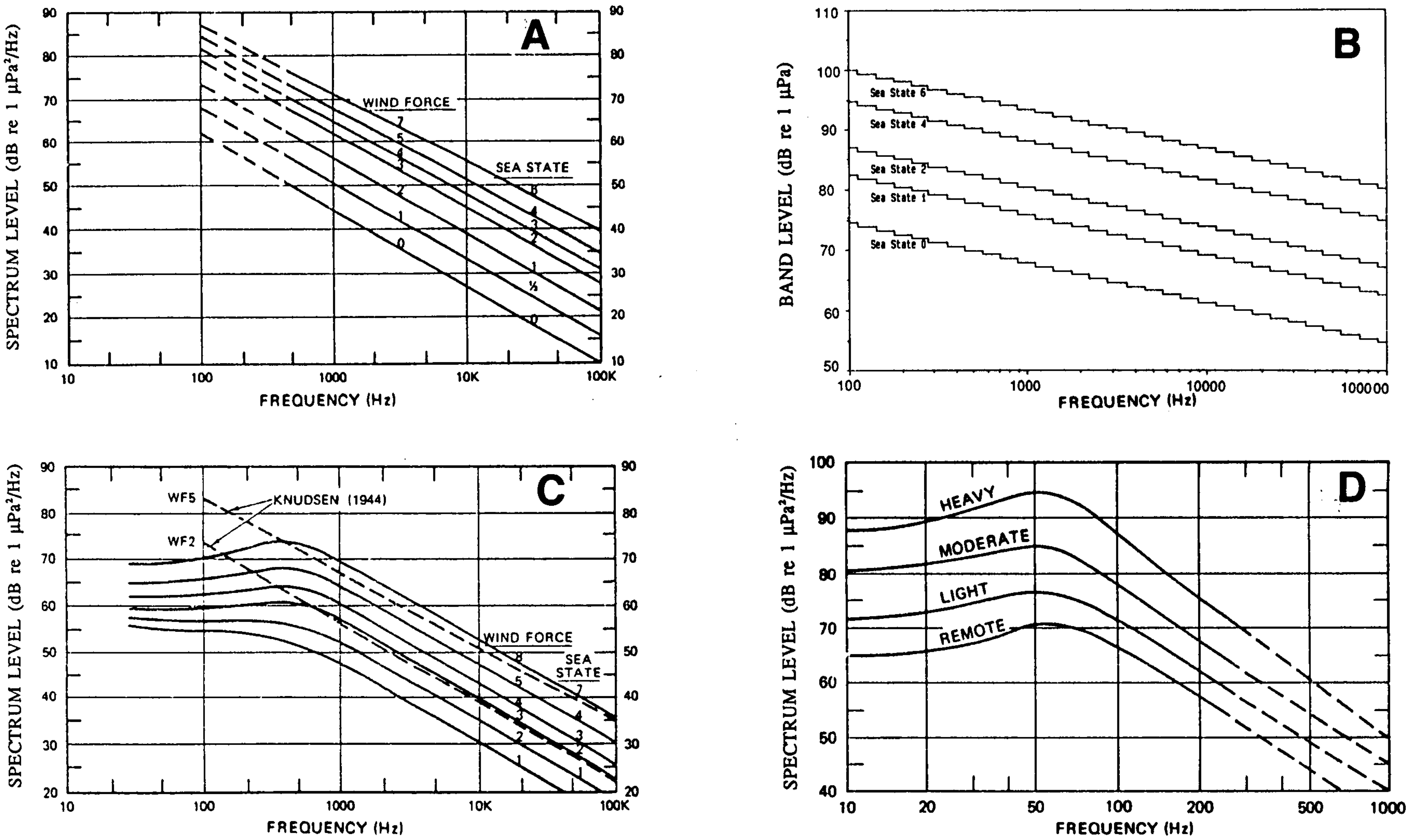

FIGURE 4.1. Four representations of typical ambient noise spectra in the sea. (A) Spectrum levels of ambient noise vs. sea state (adapted from Knudsen et al. 1948). Dashed line segments span frequencies for which the curves are extrapolated and may be inaccurate. (B) One-third octave band levels for the Knudsen sea state noise curves. (C) Spectrum levels of wind-generated ambient noise in deep water (from Ross 1976). (D) Shipping noise contribution to deep water ambient noise spectra (from Ross 1976).

Knudsen curves to frequencies <500 Hz (Ross 1976). Note that Figure 4.1C considers only wind-generated noise in deep water. When other sources are considered (see below), typical levels at frequencies <500 Hz are higher than in Fig. 4.1C, and closer to the extrapolated Knudsen curves of Fig. 4.1A.

Buckingham (1990) presents an assessment of the contributions of random wind-pressure fluctuations on infrasonic ambient noise. He points out that "it is well established" that there is at least one component of the ambient noise below 20 Hz that varies with wind speed. He cites work by Kibblewhite and others (1985, 1988, 1989a,b) demonstrating that a strong noise peak between 0.1 and 1.0 Hz "is due to the nonlinear interaction between opposing surface waves". Buckingham investigates the hypothesis that infrasonic ambient noise between 2 and 10 Hz may be due to random pressures on the sea surface from turbulent fluctuations in the atmospheric boundary layer. His conclusion is that "wind turbulence makes an insignificant contribution to the infrasonic ambient noise in the ocean".

Wenz (1962) presented an empirical "rule of fives" as an approximation for spectrum levels of wind-dependent ambient noise. We state his rule below, rephrasing it using units in current use:

> In the frequency band between 500 Hz and 5 kHz the ambient sea-noise spectrum levels decrease 5 dB per octave with increasing frequency, and increase 5 dB with each doubling of wind speed from 2.5 to 40 knots (4.6-74 km/h); the spectrum level at 1 kHz in deep water is equal to 51 dB re 1 $\mu Pa^2/Hz$ when the wind speed is 5 knots, and is 5 dB higher in shallow water.

Wenz stated that this generalization was fairly accurate up to a frequency of 20 kHz. However, he also cautioned "...that considerable departure may sometimes be expected, since wind speed is not a precise measure of the actual surface agitation..., nor are estimates of sea state". Varying bottom conditions may also introduce considerable variability from site to site.

Surf noise is another form of wave noise, localized at the land-sea interface. During heavy surf conditions in Monterey Bay, California, Wilson et al. (1985) made directional measurements at several distances from shore. At distance 8.5 km, in water 90 m deep, they noted that the received noise level in the 100-700 Hz band was about 10 dB higher from directions toward the beach. Surf noise may be prominent near shore even in calm wind conditions.

Thermal noise, resulting from molecular agitation, was described by Mellon (1952). Thermal noise is important at frequencies above 30 kHz. It limits the sensitivity of hydrophones, and it probably also limits the effective echolocation range for toothed whales that use very high frequency echolocation calls (Johnson 1979, 1980). Its spectrum level increases 6 dB/octave with increasing frequency. It is shown as the dashed line in the lower right corner of Wenz's graph of generalized ambient noise spectra (Fig. 4.2).

Seismic noise from volcanic and tectonic activity can contribute significantly to ambient noise at low frequencies, especially in the vicinity of the geological activity (Fig. 4.2; Wenz 1962). Such sounds are usually transient. Energy from earthquakes on land or below the sea bottom couples into the water to propagate as low frequency, locally-generated "T phase" waves. In contrast, seismograph records show pressure "P" and shear "S" waves that propagate over

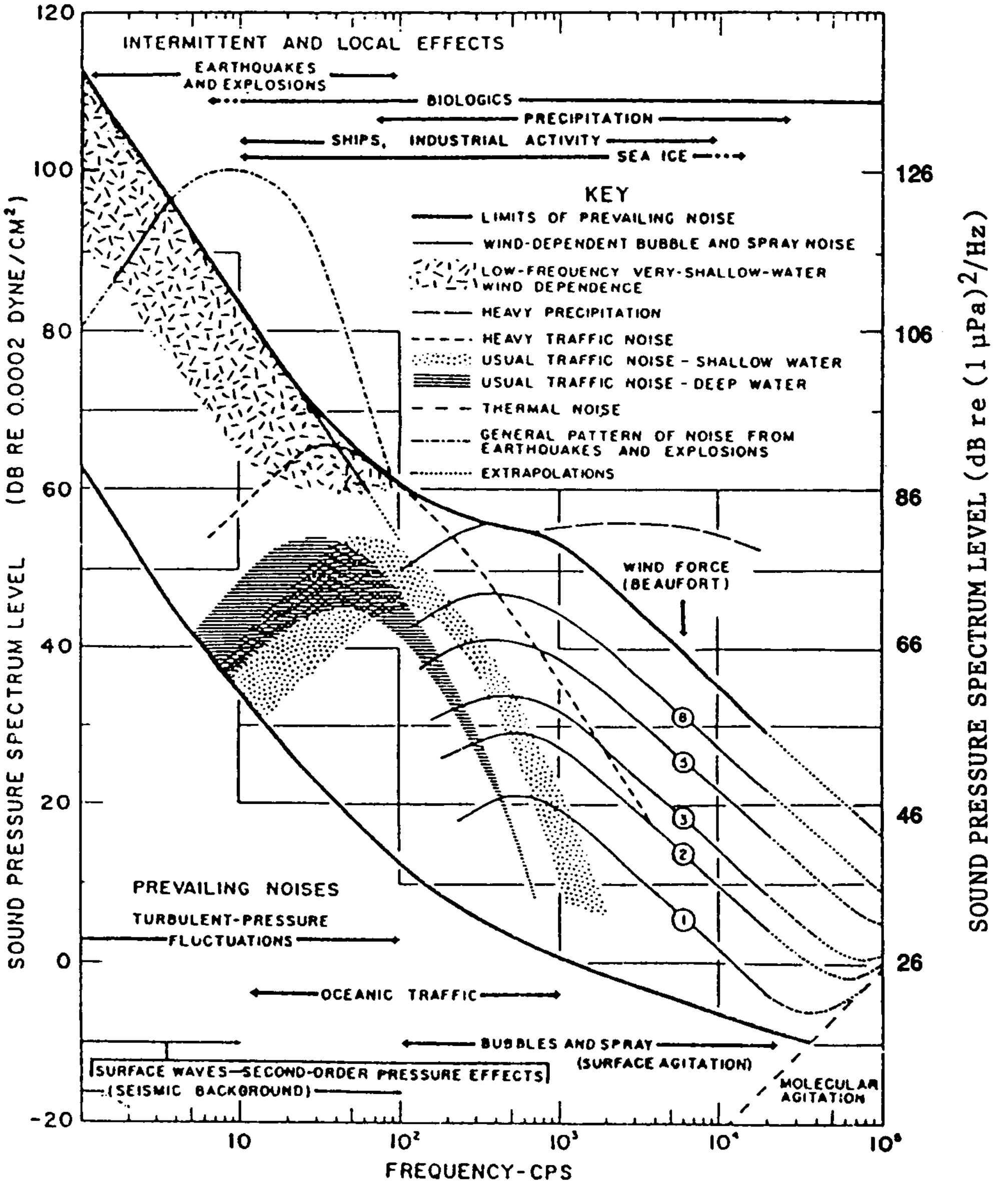

FIGURE 4.2. Generalized ambient noise spectra attributable to various sources, compiled by Wenz (1962) from many references. The scale on the right shows spectrum levels in currently-used units, dB re (1 μPa)^2/Hz.

longer distances. Energy from man-made explosions generates the same types of waves. Seismic sources and explosions emit energy at frequencies up to 500 Hz, although maximum spectrum levels occur between 2 and 20 Hz, with most energy below 100 Hz.

Biological noise arises in all oceans from a variety of sources. Marine mammals are noted for the wide range of sounds they make (Chap. 6), but certain fish and shrimp can also be significant contributors to ambient noise (e.g. Myrberg 1978; Dahlheim 1987). The frequency range of biological noise extends from 10 to over 100,000 Hz. Depending on the situation, biological noise can range from nearly absent to dominant over narrow or even broad frequency ranges.

Sea ice noise can be very significant in ice-covered waters, but its levels are highly variable. There are two important noise-making mechanisms: thermal stress, in which temperature changes induce cracking; and mechanical stress, in which ice deformation under pressure from differential wind and current forces causes significant noise at low frequencies. Milne and Ganton (1964) reported significant thermal cracking noise in landfast ice (ice frozen firmly to the shoreline and sometimes also to the bottom) during winter and spring. The spring noise spectra peaked at about 90 dB re 1 $\mu Pa^2/Hz$ at infrasonic frequencies (0.5-2 Hz). Above 2 Hz, spectrum levels decreased with increasing frequency up to about 20 Hz, above which the levels remained essentially constant up to 8 kHz. In contrast, during quiet times the spectrum levels remained below the extrapolated Knudsen spectrum for sea state zero. The winter noise spectra included wind-induced noise as well as thermal cracking sounds.

Ice deformation noises were measured by Buck and Greene (1979); see also Greene (1981). A pressure ridge active over a 3-day period produced tones at frequencies from 4 to 200 Hz. Source levels for 4 and 8 Hz tones ranged from 124 to 137 dB re 1 μPa-m.

Melting icebergs contribute "seltzer" noise to the background (Urick 1971). Urick estimated that the spectrum level of the iceberg noise was flat at about 62 dB re 1 $\mu Pa^2/Hz$ at range 180 m from the iceberg, decreasing to about 58 dB at 10 kHz, the upper frequency limit of the measurement system. The noise was attributed to tiny exploding air bubble cavities in the ice or, at deep depths, to imploding cavities.

Although sea ice often creates considerable noise, certain types of stable sea ice can dampen the total ambient noise. With 100% ice cover, noise from waves and surf is absent or dampened. Under these conditions, total ambient noise level can be considerably less than expected under calm open-water conditions (Greene and Buck 1964; Milne and Ganton 1964). Greene, *in* Richardson et al. (1989), provided a more extensive review of ice effects on ambient noise.

Precipitation noise from rain and hail is another important naturally-occurring source of ambient noise. Generally such noise is an important component of total noise at frequencies above 500 Hz during periods of precipitation. However, it may be noted at frequencies down to 100 Hz during otherwise quiet times (Fig. 4.2; Wenz 1962).

Man-made noises result from many human activities and are the subject of the following chapter. Noise from specific, identifiable ships and other human activities is generally not considered part of the background ambient noise. However, the aggregate *traffic noise*, arising from the combined effects of all shipping at long ranges, is considered part of the background noise. This traffic noise certainly originates from farther than 10 km away, and in deep water may sometimes include low frequency components from up to 4000 km. Shipping generally dominates ambient noise at frequencies from 20 to 300 Hz. The slope of the spectrum level of shipping noise typically diminishes at -9 dB per octave (Fig. 4.1D, 4.2, 4.3B).

Figure 4.1D presents Ross's (1976) estimate of the contribution of four levels of shipping activity to deep water ambient noise spectra. At low frequencies, noise levels from distant shipping usually exceed the levels of wind-related noise (*cf.* Fig. 4.1C). As indicated by the dashed lines in Fig. 4.1D, above 300 Hz shipping sounds may or may not be significant depending on the level of wind-dependent ambient noise (see also Fig. 4.2).

In coastal regions, the aggregate noise from many distant *fishing boats* may contribute significant sound. Because fishing boats have higher-speed engines and propellers than occur on ships, noise spectra from fishing boats peak around 300 Hz (sect. 5.2).

Other sources of man-made sound include industrial plants or construction activities on shore, and oil platforms and vessels at sea (Chap. 5). Geophysical surveys employing strong transient acoustic sources, e.g. airgun arrays, can be very significant contributors to the ambient noise, even at very long ranges (sect. 5.3).

As noted above, these man-made noises may or may not be considered part of the ambient noise. If they are not the main subject of interest, they are normally treated as part of the ambient noise. The characteristics of underwater noise from various specific man-made sources are discussed in detail in Chapter 5.

4.3 Deep Water Ambient Noise

Urick (1983, 1986) summarizes deep water ambient noise. Figure 4.3A, from Urick (1983), identifies the spectral slopes expected in five frequency bands extending from below 1 Hz to above 100,000 Hz.

Deep water noise from 1 to 20 Hz is of great importance because it contains the fundamental frequency components of the propeller blades used on oceangoing ships. At these infrasonic frequencies, noise levels depend only slightly on wind speed. Besides shipping, oceanic turbulence is an important source of noise in the 1-20 Hz band (Wenz 1962; Urick 1983). This turbulence takes the form of "irregular random water currents of large or small scale" (Urick 1983). At frequencies below about 20 Hz, ambient noise levels are difficult to measure accurately because of cable strum from water currents and bounce motion associated with hydrophone suspension systems and surface waves. Many studies do not include data from this frequency range. Below 1 Hz the noise arises from seismic sources, tides and waves.

Many data are available on deep-water ambient noise levels at frequencies above 20 Hz. From 20 to 500 Hz, the noise is most often dominated by sounds from distant shipping. From 500 to 50,000 Hz, the wind and wave noise dominates. Above 50,000 Hz thermal noise is the primary source. Fig. 4.3B summarizes typical deep-water ambient noise spectra for three categories of distant shipping and four ranges of wind speed. The distant shipping data came from measurements in the North Atlantic Ocean.

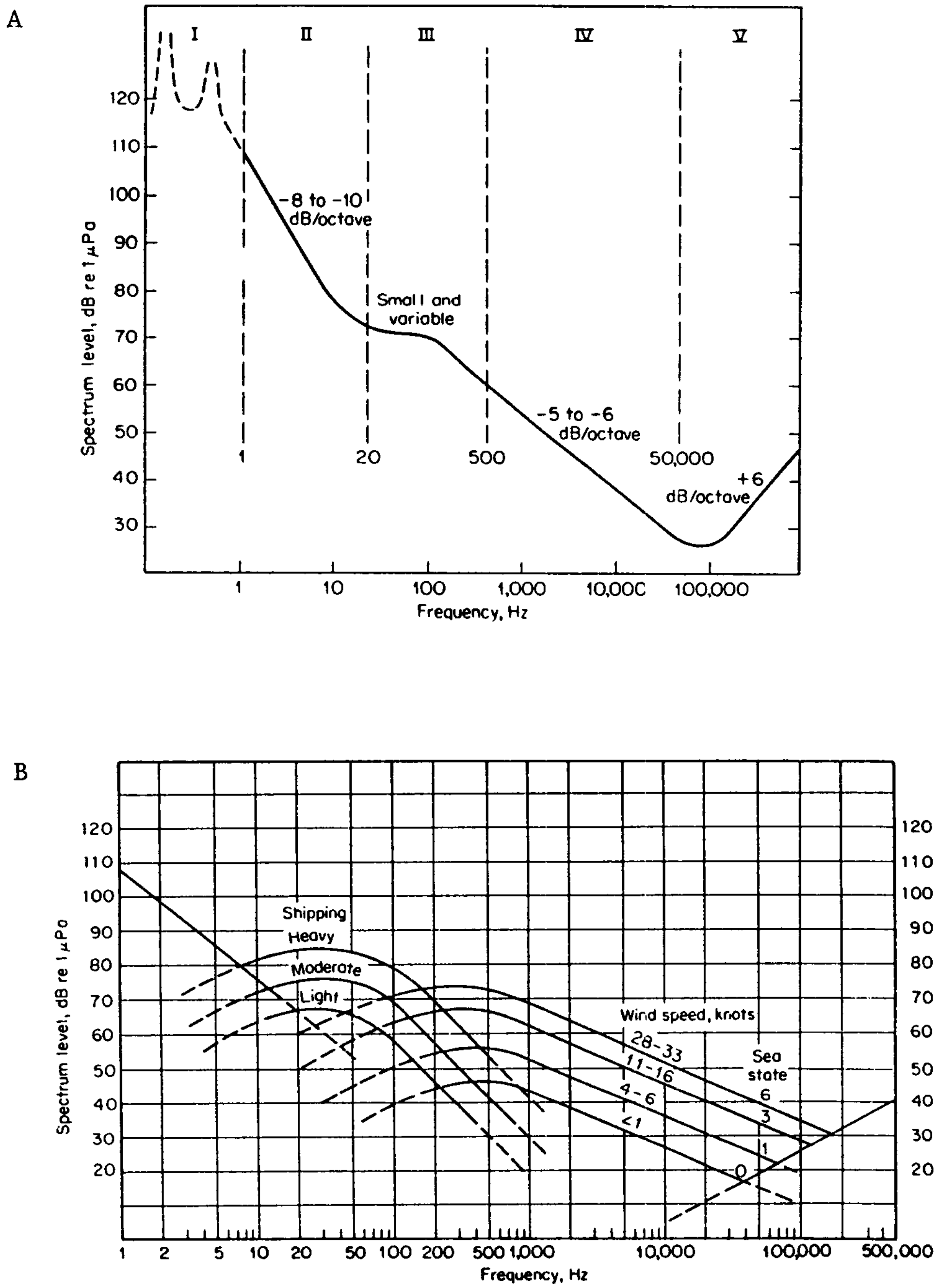

FIGURE 4.3. Two models of spectra for ambient noise in deep water. *(A)* A sample spectrum of deep-sea noise, showing typical spectral slopes in five frequency ranges. *(B)* Average deep-water ambient noise spectra as a function of sea state and relative amount of shipping in the region. Both diagrams were compiled by Urick (1983).

4.4 Shallow Water Ambient Noise

Shallow water is often defined as water less than 200 m deep. Zakarauskas (1986) characterized a shallow water environment as one in which the acoustic wavelength is of the same order of magnitude as the water depth. Noise in shallow water is subject to wide variations in level and frequency distribution, depending on time and location. The three primary sources of ambient noise in most shallow water regions are (1) shipping and industrial noise, (2) wind and wave noise, and (3) biological noise. In the Arctic, ice noise or geophysical exploration noise sometimes replace shipping and industrial noise as the dominant component at low-moderate frequencies.

A wider range of ambient noise levels occurs in shallow than in deep water under corresponding wind and wave conditions. The highest levels in shallow water can be higher than those in deep water, and the lowest levels can be lower. For frequencies above about 500 Hz, Urick (1983) suggests that typical levels are 5-10 dB higher in coastal than in deep water with corresponding wind speeds. However, when shipping and biological noise are absent, low-frequency noise levels (<300 Hz) in shallow water can be lower than expected in deep ocean waters (Urick 1983). Differences in sound transmission conditions between shallow and deep regions (Chap. 3) account for these observations.

As noted earlier, ambient noise levels in shallow waters are directly related to the wind speed but only indirectly related to sea state (Wille and Geyer 1984). Their measurements were obtained 1.8 m above the bottom in water 30 m deep about 75 km offshore in the North Sea, and they excluded data "contaminated" by shipping sounds. For frequencies 50-20,000 Hz and wind speeds above ~9 km/h, they found that ambient noise level was better predicted by wind speed than by wave height. Some of the variation in noise level at a given wind speed was attributable to changing wind profiles caused by temperature stratification of the atmosphere. Other references that show the correlation between wind speed and ambient noise level in shallow waters include Worley and Walker (1982) and Zakarauskas et al. (1990).

Ambient noise levels can be more variable in shallow than in deep water in the arctic as well as in temperate regions. In November 1975, an ambient noise measurement buoy drifted into the shallow water of the north Chukchi Sea WNW of Barrow, Alaska. An identical buoy drifted farther north in deep water. For almost nine months the two buoys returned data on ambient noise at 10, 32, and 1000 Hz every 8 h (Greene 1981). The median levels were lower in shallow water, but their variability was greater (Fig. 4.4). The depth effects were not as pronounced at 1000 Hz as at the two lower frequencies. The depth effects were attributed to higher low frequency acoustic transmission losses in shallow water (*cf.* Chap. 3).

Bottom conditions have a large influence on shallow water ambient noise (Urick 1983). Bottom conditions are important because of their strong and complex effects on sound propagation in shallow water (sect. 3.4, 3.5). Other factors being equal, ambient noise levels in a particular frequency range tend to be higher in areas where the bottom is highly reflective, and lower where it is absorptive.

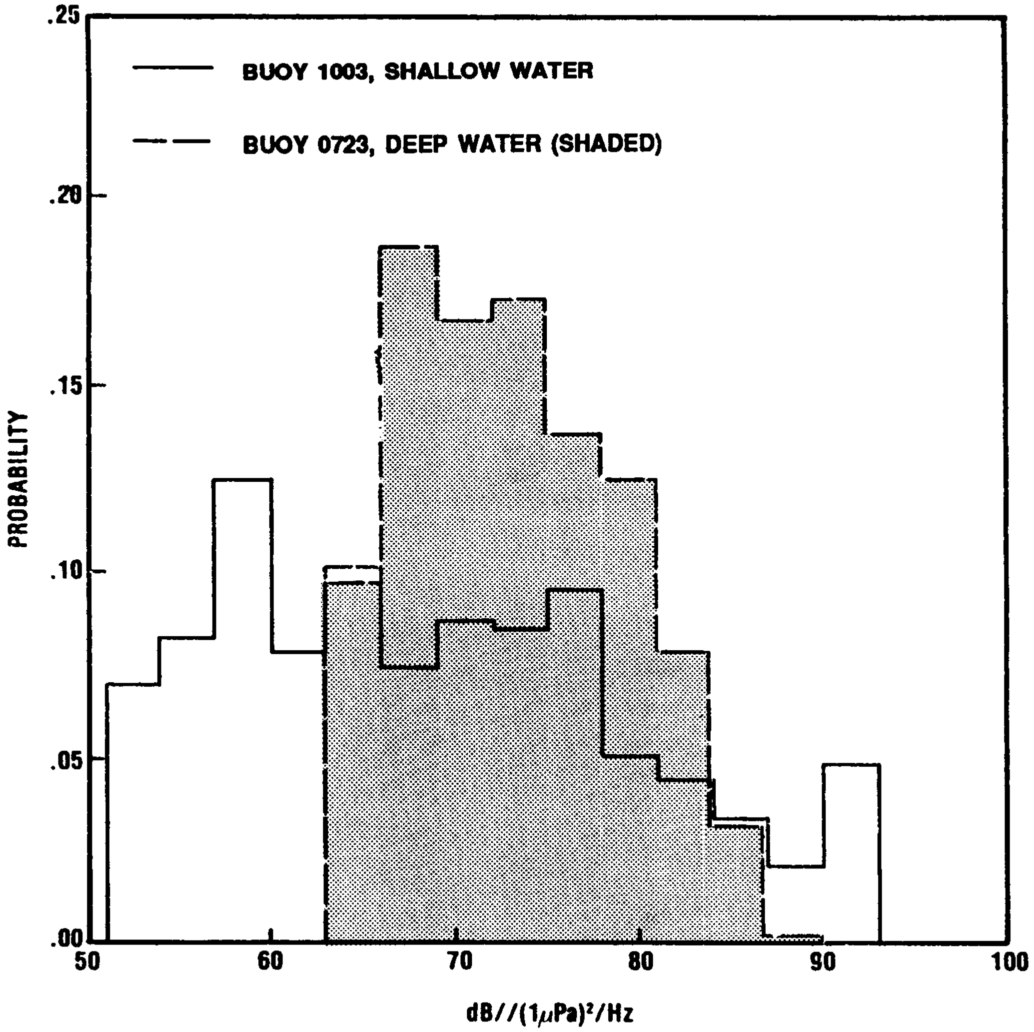

FIGURE 4.4. Comparison of the frequency distributions of 32-Hz ambient noise in deep and shallow arctic waters over nine months (November-July), based on telemetered data from drifting buoys (from Greene 1981). Note the wider range of noise levels in shallow water.

4.5 Variability of Underwater Ambient Noise

Variability in ambient noise in the sea is due mostly to variations in the sounds associated with various noise sources. For example, changes in wind speed and wave action have a direct effect on ambient noise, as does variation in the amount of distant human activity and in the rate of precipitation. There is strong hour-to-hour or seasonal variability in the sounds from some biological sources. For example, in much of the arctic, calls from bearded seals dominate the ambient noise at frequencies near 1 kHz during spring, but are rarely heard during other seasons (sect. 6.3.1).

The wide variability in ambient noise levels is shown in the generalized noise spectra of Figures 4.1-4.4. Ambient noise levels at a given frequency typically vary by 10 or even 20 dB from one day to the next. Even wider variation occurs under certain conditions. These changes in ambient noise level can have dramatic effects on the detectability of other sounds--an important consideration in some later chapters.

Some of the variation in ambient noise levels is due to variations in sound transmission conditions rather than changes in emitted sound. Ambient noise is expected to be stronger when sound attenuates slowly with increasing distance, and weaker when it attenuates rapidly. For example, the better propagation conditions on the Scotian Shelf than on the Grand Banks (Fig. 3.7; Staal 1985) are probably partly responsible for the higher average ambient noise levels on the Scotian Shelf (Zakarauskas et al. 1990). At a given location, transmission conditions vary from day to day when the vertical profile of temperature and salinity changes, and when wave and ice conditions change (Chap. 3). This can contribute to the day-to-day changes in ambient noise level.

In deep water, depth in the water column has relatively little effect on the level of wind and wave noise. This is largely attributable to the fact that wind and waves are not point sources of sound. As the distance from the surface increases, the surface area from which noise is reaching the receiver increases, countering the effect of transmission loss.

Anyone contemplating studies of the reactions of marine mammals to industrial noise at a specific site is well advised to consider the likely sources and characteristics of the ambient noise at the site during the period of the study. For example, noise studies off the coast of Florida may encounter the cacophony of snapping shrimp mixed with the sounds of fishing boats. Studies off the north coast of Alaska during May will doubtless encounter choruses of bearded seals, but there probably will be no vessel sounds. Continental shelf areas often are subject to geophysical surveys using powerful impulsive signal sources like airgun or Vibroseis arrays, but at other times there will be no such surveys.

The aggregate ambient noise from these and other sources strongly affects the distance to which mammal calls, specific industrial noises, and other sounds can be detected. Even within the range of detectability, variation in background noise levels greatly affects the prominence (signal-to-noise ratio) of sound signals. Chapter 7, on the hearing abilities of marine mammals, summarizes the available auditory data on masking of sound signals by ambient noise. Chapter 9 discusses the effects of ambient noise levels on the distances from industrial sources within which marine mammals may hear or react to those sources.

4.6 Airborne Ambient Noise

Readers will be familiar with airborne ambient noises through their personal experiences. Wind, thunder, aircraft, road and rail traffic, and biological sources all contribute to the background noise level. Kinsler et al. (1982, Ch. 12, p. 279-312) provide a useful overview of environmental acoustics, including its sources and measurements. Airborne noise measurements are often expressed as ***A-weighted sound levels*** (L_A), expressed in dBA. The reference pressure is 20 μPa, which is 26 dB above the usual underwater sound reference pressure of 1 μPa. The term "A-weighting" refers a frequency-dependent weighting applied to the sound in accordance with the sensitivity of the human ear to different frequencies. Figure 4.5 shows the weighting factor as a function of frequency for A-weighting and for the less-common C-weighting. With A-weighting, sound energy at frequencies below 1 kHz is increasingly attenuated, as is sound energy at frequencies above 6 kHz. To determine the sound level in dBA, the sound power in the weighted spectrum is integrated over frequency. Thus, information about the frequency spectrum of airborne noise is not available in the single dBA number resulting from A-weighting, but different noises can be compared (Table 4.2).

Table 4.2. A-Weighted sound levels for some commonly encountered airborne sounds (from Kinsler et al. 1982, Table 12.2).

A-Weighted Sound Level, dBA		
re 20 μPa	*re* 1 μPa	Source of Noise
110-120	136-146	Discotheque, rock-n-roll band
100-110	126-136	Jet flyby at altitude 300 m (1000 ft)
90-100	116-126	Power mower[1]; cockpit of light aircraft
80-90	106-116	Heavy truck at 64 km/h at 15 m; blender[1]
70-80	96-106	Car at 100 km/h at 7.6 m; clothes washer[1],
60-70	86-96	Vacuum cleaner[1]; airconditioner at 6 m
50-60	76-86	Light traffic at 30 m
40-50	66-76	Quiet residential--daytime
30-40	56-66	Quiet residential--nighttime
20-30	46-56	Wilderness area

[1] Measured at operator's position.

In a marine environment, wave and surf noises can be important contributors to the airborne ambient noise. Figure 4.6 shows one-third octave band levels measured near beaches. The A-weighted levels corresponding to the three noise spectra in Figure 4.6 were as follows:

Surf (BBN 1960)	90 dBA re 1 μPa	64 dBA re 20 μPa
Surf (Abrahamson 1974)	87 dBA re 1 μPa	61 dBA re 20 μPa
Offshore (BBN 1960)	72 dBA re 1 μPa	46 dBA re 20 μPa

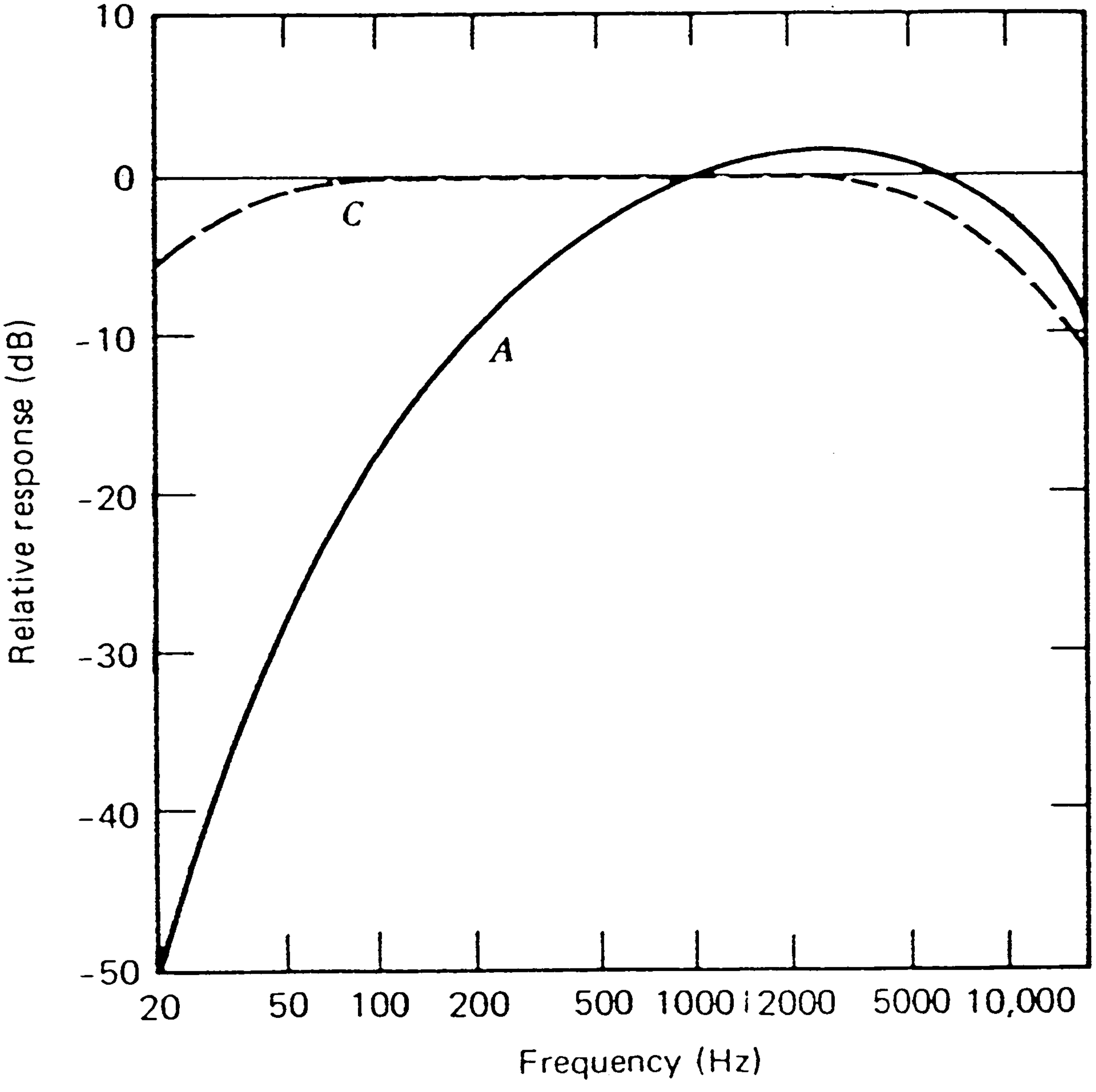

FIGURE 4.5. Filter characteristics for A- and C-weighted sound levels (from Kinsler et al. 1982). The curves show the number of decibels to be added to octave, one-third octave or other band levels before the band levels are integrated to obtain the overall A-weighted level.

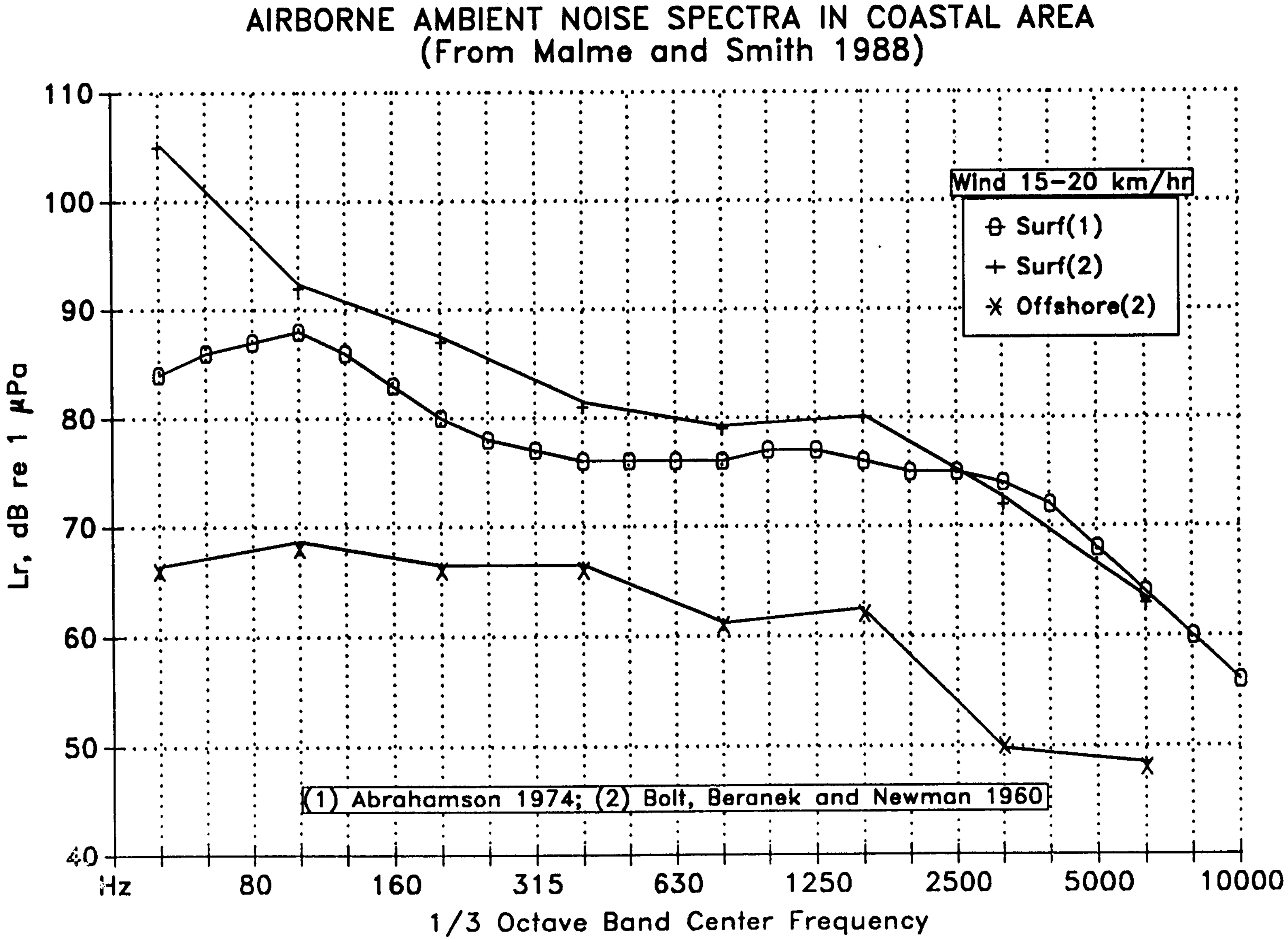

FIGURE 4.6. One-third octave band levels of airborne ambient sounds measured near seacoasts during two studies (from Malme and Smith 1988). Expressed in dB re 1 μPa for consistency with underwater sound levels; subtract 26 dB to convert to dB re 0.0002 μbars.

Comparison with Table 4.2 indicates that the two measurements of surf noise were comparable in level to vacuum cleaner noise as perceived at the operator's position, while the quieter noise recorded offshore was comparable to quiet residential noise during the daytime.

Airborne sounds from ships, boats, helicopters and industrial sites can contribute significantly to the airborne ambient noise to which marine mammals are exposed when at the surface or hauled-out. Aside from the data summarized in Figure 4.6, we are unaware of any published data on the levels of the overall ambient noise near coasts and at sea. The characteristics of noise from specific aircraft are discussed in section 5.2.1, and the propagation of those sounds is discussed in section 3.6. Mechanisms by which airborne sounds are transmitted into water are discussed in sections 3.7 and 5.2.1.

5. MAN-MADE NOISE[1],[2]

5.1 Introduction

Sources of industrial noise that could affect marine mammals include fixed-wing aircraft and helicopters, vessels of a variety of classes, icebreakers, hovercraft, transducers and machinery associated with geophysical surveys (e.g. Vibroseis, tracked vehicles, snowmobiles, airguns and explosions), marine dredging and construction, drilling, and production. The cumulative noise associated with industrial activities is often the result of the simultaneous operation of two or more of these sources.

Sound travels efficiently in water. The sound source is the initial element in the source-path-receiver model used to estimate the range to which a sound may be detected. Three inter-related parameters used to describe a source are level, frequency and time (see Chap. 2, "Acoustical Concepts and Terminology"). Briefly, source level refers to the intensity of radiated sound at a particular frequency and distance, usually 1 m, and is expressed in dB re 1 μPa-m (i.e. dB re 1 μPa at 1 m). Sources are categorized as "transient" if their duration is brief, as in the case of pulses from airguns or explosions; or "continuous" if they persist for long times, such as the sounds of ships underway. Except for frequency-specific tones, noise measurements usually are presented as spectrum levels, which depict sound intensity per unit frequency and are expressed in dB re 1 $\mu Pa^2/Hz$. However, noise levels also can be determined for bands of frequencies; levels in one-third octave bands are commonly presented (see sect. 2.2). Because 1/3 octave bands considered here always exceed 1 Hz in width,[3] levels expressed on this basis exceed spectrum levels. Spectra of transient sources are often determined from short segments of sound recorded at the times when their source levels are highest. Noise from continuous sources may be averaged over a longer time period.

The source level of a specific source of man-made noise is rarely measured at the reference distance (e.g. 1 m). Instead, more distant measurements of received sound level are converted to a source level by assuming or measuring the acoustic propagation loss from 1 m to the actual measurement distance. Such calculations may be in error because they often rely on simplifying assumptions about propagation loss that may be invalid for any particular measurement site (see Chap. 3). The importance of specifying the assumptions used to derive source level estimates cannot be overstated.

This chapter provides a comprehensive summary of the characteristics of sounds associated with offshore oil and gas development activities. Sources of these sounds can be divided into three types (Fig. 5.1): sounds generated during *transportation* in air, on the water, or over ice; sounds associated with *geophysical (=seismic) surveys* that seek out oil and gas reserves; and sounds associated with the *exploration and recovery* of hydrocarbons once promising areas are

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[2] Constructive comments on a draft of this chapter were provided by Drs. W.C. Cummings, R.A. Davis and D. Ross.

[3] The bandwidth of a 1/3-octave band is 23% of its center frequency, and we rarely consider frequencies below 10 Hz in this review.

found. To date, studies of underwater industrial noise have not focused equally on all sources, nor have they been conducted in all geographic regions where OCS activities are ongoing. Several fairly comprehensive studies have been undertaken in arctic waters (e.g. Greene 1985a, 1987a,b; Miles et al. 1986, 1987), but few similar projects have been carried out in temperate or tropical seas. However, computation of the free-field source levels reduces or eliminates the significance of the measurement site. If source levels are known, they can be used to predict zones of acoustic influence around any site provided that the sound propagation and ambient noise conditions are known. A review of published accounts for each type of sound source is presented in this Chapter, followed by a summary and comparison of all sources.

TRANSPORTATION

- aircraft
- vessels
- icebreakers
- hovercraft
- on-ice vehicles

MARINE GEOPHYSICAL SURVEYS

- vibroseis
- airgun arrays
- sleeve exploders
- explosives
- other techniques

EXPLORATION AND RECOVERY

- dredging
- construction
- drilling
- production

Figure 5.1 Industrial noise sources associated with transportation, marine geophysical surveys, and oil and gas exploration and recovery.

5.2 Transportation

5.2.1 Helicopters and Fixed-wing Aircraft

Introduction.--Helicopters are used routinely to ferry personnel and supplies to offshore sites. Helicopters account for most offshore flights associated with oil and gas development. Small twin-engined fixed-wing aircraft are also commonly used, e.g. for reconnaissance. Larger fixed-wing aircraft are primarily used to bring personnel and gear to coastal airstrips near drilling or production operations. The level of underwater sound from any type of aircraft depends upon receiver depth and the altitude, aspect and strength of the noise source.

Underwater sounds from passing aircraft are necessarily measured far beyond the 1 m distance for which source levels are normally determined. Indeed, the concept of a 1-m source level for underwater noise from an aircraft is not a very meaningful one. It is impossible to isolate the concepts of source level and propagation loss when considering underwater noise from aircraft. Hence, this subsection necessarily contains considerable information about the received levels of aircraft noise as a function of aircraft altitude, water depth, and hydrophone depth.

The angle at which a line between the aircraft and receiver intersects the water's surface is important. If it is more than 13° from the vertical, much of the incident sound is reflected and does note penetrate into the water. Hence, the received level underwater is greatly reduced. This is especially true with calm seas, deep water, or shallow water with a non-reflective bottom (sect. 3.7). It is possible for airborne sound to penetrate water at angles >13° from the vertical when rough seas provide water surfaces at suitable angles. However, the acoustic wavelengths of the low frequencies (<50 Hz) that dominate helicopter noise are much longer than typical ocean wavelengths, making the sea surface effectively flat for acoustic purposes at these frequencies.

Water depth and bottom conditions have strong influences on the propagation and levels of underwater noise from a passing aircraft. Lateral propagation of underwater sound from a passing aircraft is better in shallow than in deep water, especially when the bottom is reflective. Many reflected paths are possible in shallow water. As a result, the 13° critical angle does not limit air → water sound transmission in shallow water to the same extent that it does in deep water. The time during which an airborne source passing overhead can be received underwater is lengthened in shallow water by multiple reflections of the signal. Sections 3.6 and 3.7, on "Airborne Sound Transmission" and "Transmission Through the Air-Water Interface", provide background material necessary for interpreting empirical data on aircraft noise.

In summary, underwater sounds from aircraft are transient events. In deep water, strong underwater sounds are detectable for a period roughly corresponding to the time the aircraft is within a 26° cone above the receiver. The zone of ensonification enlarges in rough seas, and with surface and bottom reflections in shallow water. At least in deep water, an aircraft usually can be heard in air long before and after the brief period while it passes overhead and is heard underwater. Sound pressure in the water below an aircraft is greatest at the surface and diminishes with increasing receiver depth and/or aircraft altitude.

Frequency Composition of Aircraft Sounds.--Aircraft are powered by either reciprocating or turbine engines driving propellers, rotors or jets. We do not consider turbojet noise in this review, although there are airports (e.g. J.F. Kennedy on Long Island; Los Angeles International) from which departing turbojet-powered aircraft can be relatively low over ocean areas and might present disturbing sounds to marine mammals. Appendix 2 summarizes some basic descriptive information about the various types of aircraft mentioned in this section.

Reciprocating engine sounds are dominated by the cylinder firing rate, which causes an harmonic family of tones to appear in the sound spectrum. The fundamental frequency of this tone is

$$f\ (\text{Hz}) = (\text{rpm}/60) \times (\text{no. cyl.})/(\text{no. revolut./firing/cyl.}) \qquad (5.1)$$

Four cycle engines turn twice per cylinder firing. Thus, a six cylinder reciprocating engine turning at 2400 rpm would produce a tone at 120 Hz, with harmonics at 240 Hz, 360 Hz, etc. (***Harmonics*** are tones at integer multiples of the fundamental frequency; the fundamental is the first harmonic.)

Turbine engine sounds are characterized by the whine of the blades within the different stages of the engine; tones occur at frequencies from several hundred hertz to well above one kilohertz. For example, the power turbines of the Bell 212 helicopter turn at 33,000 rpm (550 Hz) and the turbine ***blade-rate tone*** is the number of blades x 550.

The primary sources of sound from aircraft, aside from those powered by turbojet or turbofan engines, are their propellers or rotors. The rotating blades produce tones with fundamental frequencies that depend on the rotation rate and number of blades, i.e.

$$f\ (\text{Hz}) = (\text{no. blades}) \times (\text{rpm}/60) \qquad (5.2)$$

For example, a three-bladed propeller turning at 3000 rpm results in a tone at 150 Hz. A two-bladed helicopter rotor turning at 330 rpm results in a tone at 11 Hz. A helicopter tail rotor with two blades turning at 1650 rpm results in a tone at 55 Hz. Harmonics are likely in all three examples.

Tones in the underwater sounds from three types of helicopters and three fixed-wing aircraft commonly used in offshore operations are shown in Figure 5.2. Dominant frequencies and the corresponding mechanical sources are listed in Table 5.1. In general, when helicopter sound is recorded close to the machine, the dominant tones are related to the blade rotation rates of the main and tail rotors. However, other tones associated with the engines and other rotating parts may also be present, leading to a potentially large number of tones at many frequencies.

Table 5.1. Aircraft noise: characteristics and frequencies of dominant tones for various helicopters and fixed-wing aircraft used offshore. Sources: Urick (1972), Moore et al. (1984), Greene (1985a) and Richardson et al. (1990a:87*ff*). See Appendix 2 for descriptions of aircraft listed here.

A. HELICOPTERS

Model	Main Rotor Speed (rpm)	No. Rotor Blades (Main/ Tail)	Frequencies of Tones (Hz)
Bell 212	324	2/2	10.8 + harmonics
Bell 214ST	354 (calc.)	2/2	11.8 + harmonics
Sikorsky 61	?	5/5	68 and 102

B. FIXED-WING AIRCRAFT

Model	Type	No. Blades /Propeller	Frequency of Tones (Hz)	
			Propeller	Engine
Britten-Norman Islander	Piston	2	68 - 74	102
de Havilland Twin Otter	Turboprop	3	82 - 84	
Grumman Turbo Goose	Turboprop	3	100	
Lockheed P-3	Turboprop	4	68	

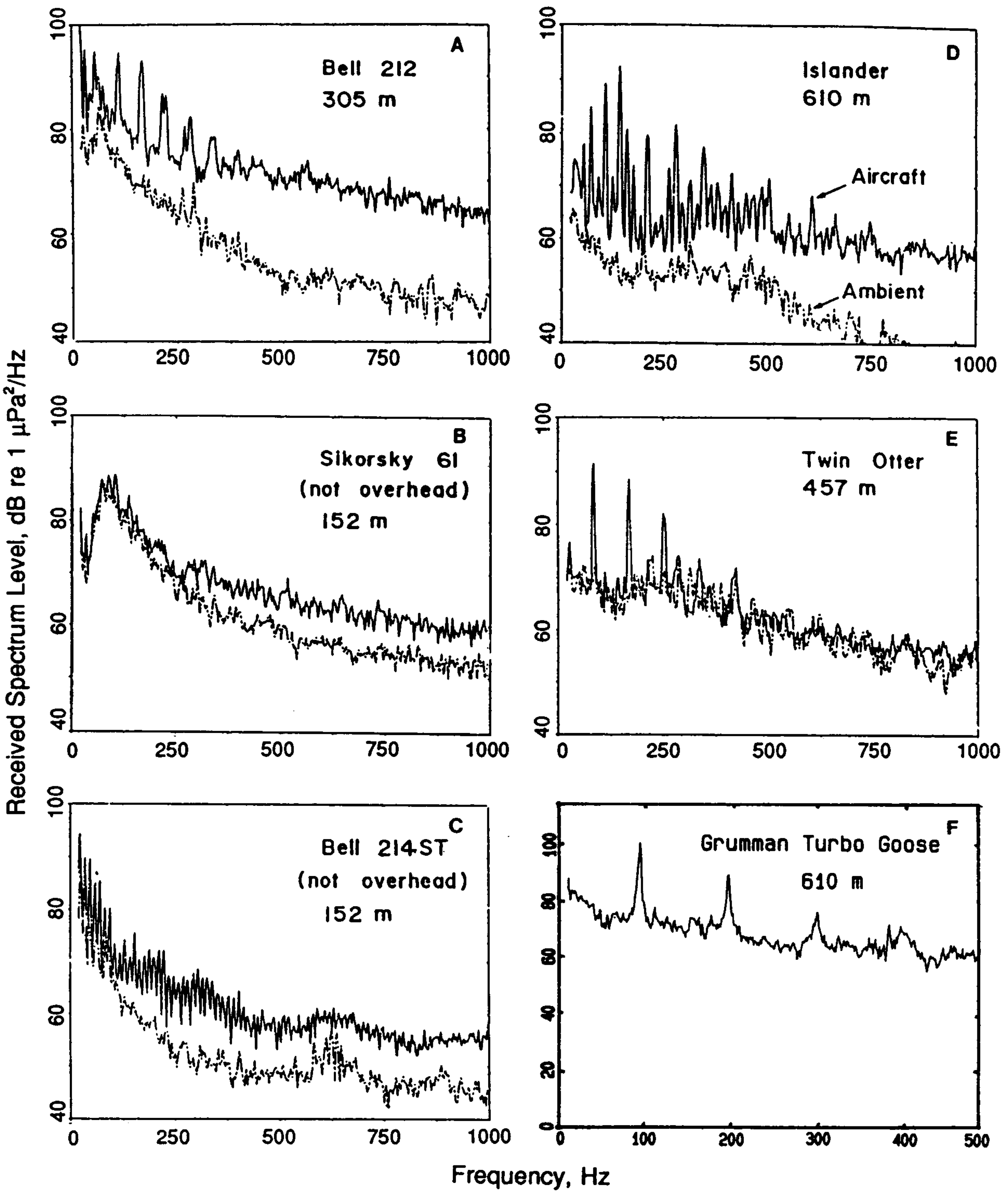

FIGURE 5.2. Aircraft noise spectra: received levels of underwater sound during flyovers by *(A-C)* three helicopters and *(D-F)* three fixed wing aircraft. Tones occur at frequencies related to piston firing rate (D) and propeller or rotor blade rate (A-F). Lower (dashed) spectrum in A-E is the ambient noise before or after the overflight. A-E from Greene (1985a) with analysis bandwidth 1.7 Hz; F from Moore et al. (1984), with analysis bandwidth 1.25 Hz.

Because of doppler shift effects, the frequencies of the tones as received at a stationary receiver diminish somewhat when an aircraft passes overhead. The apparent frequency isincreased somewhat when the aircraft is approaching and reduced somewhat when it is moving away (e.g. Richardson et al. 1990a:91).

Levels and Durations of Aircraft Sounds.--Levels and durations of sounds received underwater from a passing aircraft are largely dependent upon the altitude and aspect of the aircraft, the receiver depth, and the water depth. Data for three aircraft flying at various altitudes over different water depths are presented in Table 5.2.

In general, the peak received level of aircraft noise in the water as an aircraft passes directly overhead decreases with increasing altitude (Urick 1972). For example, the peak received level of Bell 212 helicopter sounds at a hydrophone depth of 9 m decreased from 111 dB re 1 µPa during a pass at 305 m altitude to 108 dB when the helicopter was at 610 m.

Table 5.2. Aircraft noise: received level (dB re 1 µPa) and duration of audibility (seconds) for noise from three types of aircraft at altitudes from 152 to 610 m. All received level measurements represent energy in the 20-1000 Hz band during the 4 s of peak sound level (i.e. when the aircraft was essentially overhead). The sea state was 0-1; the hydrophone depth was 3 or 9 m; "-" signifies no data were available. Data from Greene (1985a).

Aircraft Type	Aircraft Altitude (m)	Water Depth (m)	Ambient Noise (dB) (9 m)	Received Level (dB)		Duration (s)	
				3 m	9 m	3 m	9 m
Helicopter							
Bell 212	152	25	100	-	-	-	16-21
(straight,	305	25	100	-	111	-	18-27
cruise pwr)	610	25	100	-	108	-	26
Fixed-wing							
B-N Islander	457	15	86	119	106	Cont.[a]	58-75
(circling,	610	15	86	105	104	84-110	66-78
low power)							
B-N Islander	152	15	86	120	114	72-87	52-60
(straight,	305	15	86	122	111	53-76	49-75
cruise pwr)	457	15	86	116	105	44-58	34-42
	610	15	86	109	108	59-84	39-52
Twin Otter	152	22	95	-	-	-	33-36
(straight,	305	22	95	-	113	-	29
cruise pwr)	457	22	95	-	104	-	37
	610	22	95	-	105	-	

[a] Cont. = continuous.

Received level also diminishes with increasing hydrophone depth when the aircraft is directly overhead (Urick 1972). For example, the peak level from a Britten Norman Islander circling at 457 m was 119 dB re 1 μPa at 3 m depth and 105-106 dB at 9 m.

The effects of aircraft altitude and receiver depth on the length of time that aircraft noise is audible underwater are also relevant in assessing noise effects on marine mammals. In general, duration of audibility is expected to be higher at shallow rather than at deep depths because aircraft sounds diminish with increasing depth (Urick 1972). Urick found that sounds from a Lockheed P-3 Orion flying at altitude 305 m were detectable for 50 s at depth 244 m but <5 s at depth 4300 m. Results from shallow water also tend to show a somewhat reduced duration of audibility at 9 m depth than at 3 m depth (Table 5.2). Duration of audibility would also be expected to increase with increasing aircraft altitude because the aircraft would be within the 26° cone longer when it is higher. There is little evidence of this in Table 5.2, but this trend was observed by Richardson et al. (1990a).

In general, sounds from approaching aircraft are detectable far longer in air than in water. For example, an approaching Bell 214ST became audible in air over 4 min before it passed the hydrophones, but it was audible underwater only for total times of 38 s at 3 m depth and 11 s at 18 m (Greene 1985a). There are few additional data on the duration of aircraft audibility in air and underwater, as this is not often a primary concern of researchers. Stewart et al. (1982) comment on the brief duration of audibility (<30 s) of a Bell UH-1 (Bell 204) helicopter passing 30 m over a hydrophone about 2 m below the surface in water 4-8 m deep. Most of the sound energy was between 50 and 100 Hz.

The source level of aircraft noise can be estimated based on levels received underwater by applying equation 3.6 (in sect. 3.7, from Young 1973). Received levels decrease with increasing source altitude, but estimated source levels are essentially independent of measurement altitude, as expected (Table 5.3). In general, source levels vary with the size and type of aircraft. Large aircraft are usually noisier than small ones, and helicopters are generally ~10 dB noisier than small fixed-wing aircraft; helicopters tend to produce a larger number of tones and higher broadband levels (Greene 1982).

It is not surprising that the source level estimated for the P-3, a rather large 4-engined aircraft, was at least 10 dB higher than that for any of the smaller aircraft. The strongest *observed* tone from the Bell 212 helicopter was close in estimated source level to the dominant tones from the two smaller fixed-wing aircraft. However, the Bell 212's fundamental rotor blade-rate tone at 11 Hz was not measured. Also, at 1000 Hz, broadband noise from the Bell 212 helicopter was 6 to 9 dB stronger than that from the two smaller fixed-wing aircraft (Table 5.3).

Noise levels in 1/3-octave bands may be especially useful in interpreting noise effects on animals. Based on measurements by Greene (1985a) and BBN (unpubl.), Malme et al. (1989) derived 1/3-octave "source" levels for two helicopters and three fixed-wing aircraft (Fig. 5.3, 5.4). Aircraft sound levels were estimated for a receiver at the water's surface directly below an aircraft at altitude 300 m under standard temperature, humidity, and pressure conditions. The estimated 1/3-octave spectra are not source-level spectra in the usual sense, because of the

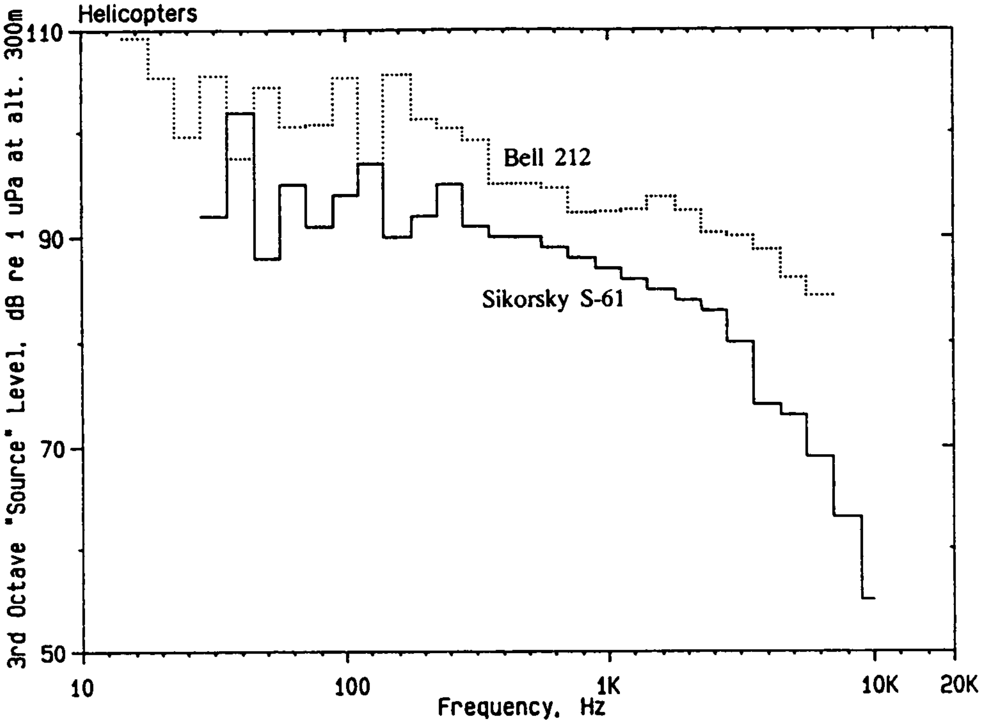

FIGURE 5.3. Helicopter spectra: estimated one-third octave levels at the water's surface for two helicopters at 300 m altitude. The Sikorsky did not fly directly overhead; the actual source levels may be higher than shown. Calculated by Malme et al. (1989) from data of Greene (1985a).

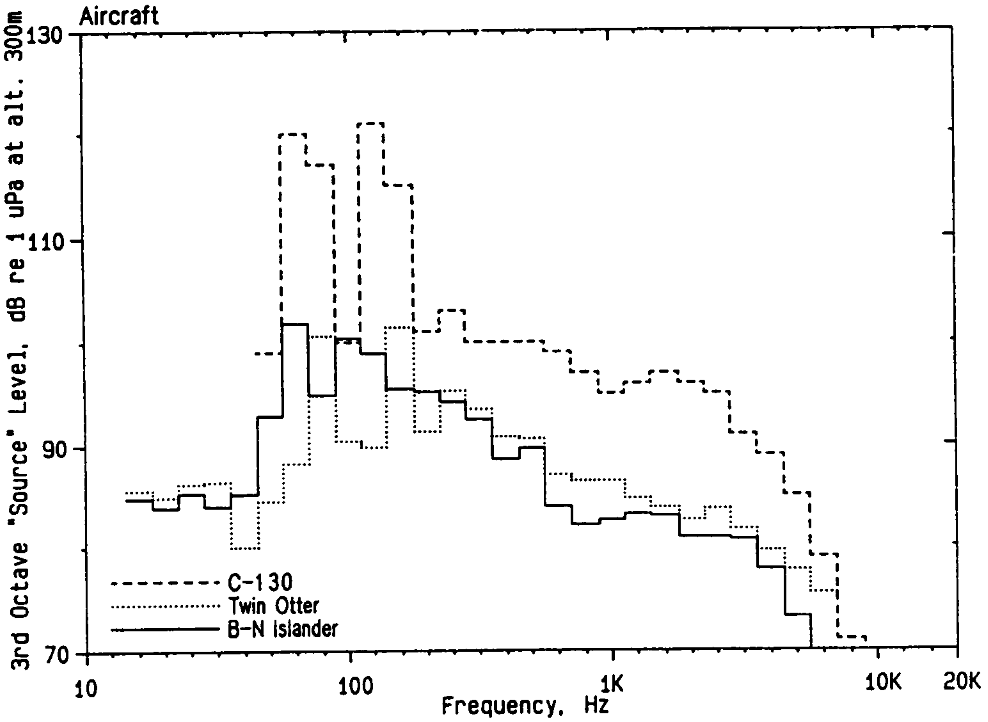

FIGURE 5.4. Fixed-wing aircraft spectra: estimated one-third octave levels at the water's surface for three fixed-wing aircraft at 300 m altitude. Calculated by Malme et al. (1989) from data of Greene (1985a) and BBN (unpubl.).

Table 5.3. Aircraft noise: Estimated source levels. This table shows estimated source levels for dominant tones or frequency bands, plus spectrum levels of broadband noise at selected frequencies. Young's equation (sect. 3.7) was used to estimate source levels based on measured received levels. Hydrophone depth was 3-18 m for all aircraft except the P-3, for which there were hydrophones at both 17 and 93 m; the respective levels are both given below, separated by "/". Data from Urick (1972) and Greene (1985a); calculations from Greene (1985a).

Aircraft Type (Freq.)	Aircraft Altitude (m)	Received Level (dB re 1 μPa)	Estimated Source Level (dB re 1 μPa-m)	Estimated source spectrum level, in dB re 1 $(\mu\text{Pa-m})^2$/Hz, at frequency (Hz)			
				1000	2000	4000	8000
Helicopter							
Bell 212 (22 Hz)	152	109	149	111	107	101	93
	305	107	151				
	610	101	151				
Fixed-Wing							
B-N Islander (70 Hz)	152	101	142	102	97	91	75
Twin Otter (82 Hz)	457	107	147	105	98		
	610	100	150				
P-3 Orion (56-80 Hz)[a]	76	124/113	162/161				
	152	121/112	162/161				
	305	114/105[b]	160/156[b]				
(890-1120 Hz)	76	112/111[b]	150/159[b]				
	152	107/99	148/148	124[c]			

[a] Most energy in this band was from a tone at 68 Hz.
[b] Inconsistent estimates (see text).
[c] Computed from the 148 dB source level for the 1/3-octave band at 890-1120 Hz.

300 m range. However, they are directly comparable with one another, and depict received levels in a situation of practical interest.[4]

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[4] Assuming spherical spreading as a rough approximation, levels at a hypothetical 1-m range would be about 50 dB higher (20 log 300) than those estimated by Malme et al. (1989). Their data are not directly comparable with those in Table 5.3 partly for this reason, and partly because most data in Table 5.3 refer to tones or spectrum levels (1 Hz bandwidth) whereas Malme et al. give estimates for 1/3-octave bands.

The Bell 212 helicopter sound levels are higher at frequencies below 50 Hz and above 500 Hz than are the sound levels from either the Twin Otter or the Islander (Fig. 5.3, 5.4). The helicopter main rotor is noisier than the small-plane propellers, accounting for the higher levels at frequencies below 50 Hz, and the helicopter's turbine power plant contributes the higher sound levels at frequencies above 500 Hz. Sound levels from the C-130, a rather large 4-engined transport, are notably higher at most frequencies than are the sound levels of the small aircraft.

Summary.--Underwater sounds from aircraft reach their highest levels just below the surface directly under the aircraft. When the aircraft is overhead, levels decrease with increasing aircraft altitude or increasing receiver depth. The sounds contain many tones related to the rotor or propeller blade rate, with most energy at frequencies below 500 Hz. Helicopters tend to be noisier than similar-sized fixed wing aircraft, and large aircraft tend to be noisier than smaller ones. The underwater noise from a passing aircraft is generally brief in duration, especially when compared with the duration of audibility in the air. Although received levels diminish with increasing receiver depth directly below the aircraft, aircraft noise levels can be stronger at mid-water than at shallow depths when the aircraft is not directly overhead and the water is shallow.

For any given situation, the amount of noise that an aircraft transmits to the water depends primarily on its altitude and the resultant "26° cone" predicted by Snell's law, and secondarily on sea surface conditions. Once the sound has entered the water, its level, frequency content, and duration are primarily affected by water depth and bottom conditions, and secondarily by the physical properties of the water column. The lateral distance at which aircraft noise becomes undetectable will vary with local ambient noise conditions and can only be estimated for a specific set of conditions. However, as a general rule this distance is less than the corresponding distance in the air.

5.2.2 Vessels: Boats, Ships and Supertankers

Numerous small vessels, classified as boats, are used in the petroleum industry to ferry work crews and small supplies to offshore sites. Vessels of this class are variously described as workboats, tugboats, or crewboats, and range from roughly 12 to 30 m in length. In addition, smaller craft (<12 m) equipped with outboard engines are sometimes used by the oil industry for utility purposes and are very widely used by other operators.

The distinction between boats and ships becomes arbitrary when considering larger exploration, support and supply vessels used in offshore industrial operations. Geophysical survey vessels are usually 30 to 60 m long. Supply and icebreaking support ships generally range from 55 to 85 m in length and perform a variety of operations related to oil recovery and transportation. Tugs and stand-by safety vessels used by the oil industry range widely in size. Commercial vessels, container ships and supertankers are used to transport oil products over long distances and are the largest vessels associated with the oil and gas industry. Commercial vessels include freighters and tankers, and generally range from 100 to 200 m in length and displace 8,000 to 15,000 tons. Container ships and supertankers are generally >200 m long and displace 20,000 to over 200,000 tons.

Vessels of all classes generate sound in much the same way. The primary sources of ship-radiated noise are propeller cavitation, propeller singing, and propulsion machinery. ***Propeller cavitation*** noise results from two types of vortex cavitation, tip-vortex and hub-vortex, and two types of blade surface cavitation, back and face. Propeller cavitation is usually the dominant noise source for any single marine vehicle (Ross 1976). ***Propeller singing*** arises when vortex shedding frequencies reinforce a resonant vibrational frequency of a propeller blade. The result is the emission of a strong tone between 100 and 1000 Hz. Propeller singing is exacerbated if a propeller is damaged or if propellers on a multiple-propeller vessel are operating asynchronously. Cavitation bubbles on a propeller blade absorb vibrational energy, and therefore singing commonly ceases when cavitation is strong. Unlike propeller cavitation and singing, which originate outside the hull of a vessel, noise from ***propulsion machinery*** originates inside the vessel and is coupled to the water via the vessel hull. Sources of machinery noise include rotating shafts, gear reduction transmissions, reciprocating parts, gear teeth, fluid flow turbulence, and mechanical friction. Typical noise sources include pumps, engines, generators, ventilators, and compressors. ***Other sources*** include flow noise from water dragging along the hull and bubbles breaking in the wake. Ross (1976) provides a comprehensive review of the mechanics of vessel noise.

As with aircraft noise, vessel noise is a combination of narrowband "tonal" sounds, with energy concentrated at specific frequencies, and "broadband" sounds, with energy spread continuously over a band of frequencies. For medium to large vessels, tones dominate vessel noise spectra at frequencies up to about 50 Hz. These tones are related to the propeller blade rate and secondarily to the rates of engine cylinder firing and shaft rotation. Broadband components, caused primarily by propeller cavitation and flow noise, may extend to 100 kHz with a peak between 50 and 150 Hz. In addition, auxiliary machinery such as pumps and compressors can generate tones at frequencies up to several kilohertz. Propellers on smaller vessels tend to rotate faster than those on large vessels, and this results in a concentration of noise energy at higher frequencies.

Ross (pers. comm.) has pointed out that medium- and high-speed diesel engines, which are built with simple connecting rods, are very noisy; their noise may overshadow propeller cavitation. Slow-speed diesel engines (<250 rpm) have articulated connecting rods and are relatively quiet. The latter are used for most large tankers, freighters and container ships; hence, cavitation noise dominates the radiated noise from these modern large ships.

There are many published data on vessel noise, including the book by Ross (1976) and specific measurements by Buck and Chalfant (1972), Cybulski (1977), Leggat et al. (1981), and Thiele and Ødegaard (1983). Many of the post-1945 measurements of ship sounds have been of naval vessels; most of these data are in classified reports that are not available for review. Some data from World War II vessels are available, but these data do not describe the sounds from today's large supertankers, bulk carriers and container ships. These large vessels have been estimated to radiate noise 5 to 8 dB greater than that from typical 1945-vintage ships (Ross 1976).

Differences between noise generated by various classes of vessels are related to ship size. Although sound levels emitted by a vessel can be strongly affected by its design and speed, there is a rough correlation between sound levels and vessel size. Small vessels typically have small propellers with high rotation rates; the small propellers result in cavitation noise at higher frequencies, and the high rotation rates result in blade rate noise at relatively high frequencies. Large vessels create stronger and lower-frequency sounds due to their greater power, large drafts, and slower-turning engines and propellers. They also have large hull areas that efficiently couple the machinery sound to the water. The following summary of vessel noise is organized by vessel size to facilitate comparison of emitted noise for vessels of comparable sizes.

Boats.--Small boats equipped with outboard engines are common in coastal waters, yet there are few published measurements of sound levels produced by them. Outboard engines can produce overall free-field source levels on the order of 175 dB re 1 μPa-m. In general, larger outboards emit stronger sounds at lower frequencies than smaller engines. Available data are summarized in Table 5.4, which presents some sound level measurements and estimated levels for a standardized range of 50 m.

Somewhat larger boats commonly involved in offshore oil and gas activities include small tugboats and crewboats. Noise levels associated with such craft are very dependent on their operating status. Table 5.5 presents some estimates of source levels (at 1 m); received levels at range 50 m would be about 34 dB lower.

The differing frequency ranges considered by various authors make the data in Table 5.5 difficult to compare and interpret. However, smaller boats tend to produce sound spectra whose peak levels are at higher frequencies as compared to the sounds from larger boats (Fig. 5.5). The spectra from boats in this class contain strong tones at frequencies up to several hundred Hertz (Fig. 5.6).

Table 5.4. Outboard motorboat noise: summary of measured received levels, dominant frequency bands, and estimated band levels at 50 m range from small outboard-powered boats.

Outboard Size	Speed (km/h)	Range (m)	Received Level (dB re 1 μPa)	Est. Level @ range 50 m (dB re 1 μPa)	Frequency Band (Hz)
18 hp[a]	9	30	89-103	85-99	100-8000
18 hp[b]	7-9	(1)[b]	(145-150)	111-116	wideband
35 hp[c]	"fast"	20	119	111	3000-10000
70 hp[c]	"medium"	100	136	142	400-4000
2x90hp[d]	"accel"	~500	82	97-102	Tone @ 1850

[a] Young and Miller (1960), 1/3-octave band levels in 100-8000 Hz range.

[b] Evans (1982); actual measurement range unknown; gave free-field source levels.

[c] Stewart et al. (1982).

[d] Moore et al. (1984), bimodal spectrum with peaks 50-100 Hz and 300-410 Hz.

Table 5.5. Estimated source levels (1 m) of noise from small vessels, including small tugs and crewboats. For comparison with Table 5.4, subtract 34 dB for estimated levels at range 50 m.

Vessel (length)	Frequency Range (Hz)	Source Level (dB re 1 µPa-m)	Description
MS Sparton[a] (25 m)	37, tone	166	Tug pulling empty barge
Arctic Fox[b]	1000, 3rd oct.	170	Tug pulling loaded barge
" "	1000, 3rd oct.	164	Tug pulling empty barge
" "	5000, 3rd oct.	161	Tug pulling loaded barge
" "	5000, 3rd oct.	145	Tug pulling empty barge
MV Sequel[c] (12 m)	250 - 1000 Hz	151	Fishing boat, 7 knots
Imperial Adgo[c] (16 m)	90 Hz tone	156	Crewboat, 2nd harmonic of prop blade rate
Zodiac[d] (5 m)	6300, 3rd oct.	152	Outboard engine
Outboard Drive[d] (7 m)	630, 3rd oct.	156	Same level: 400, 500, 630 & 800 Hz 3rd oct.
Trawler[d]	100, 3rd oct.	158	Same level: 100, 125, 160, 200, 250 3rd oct.
Twin Diesel[d] (34 m)	630, 3rd oct.	159	

[a] Buck and Chalfant (1972)

[b] Miles et al. (1987)

[c] Greene (1985a)

[d] Malme et al. (1989)

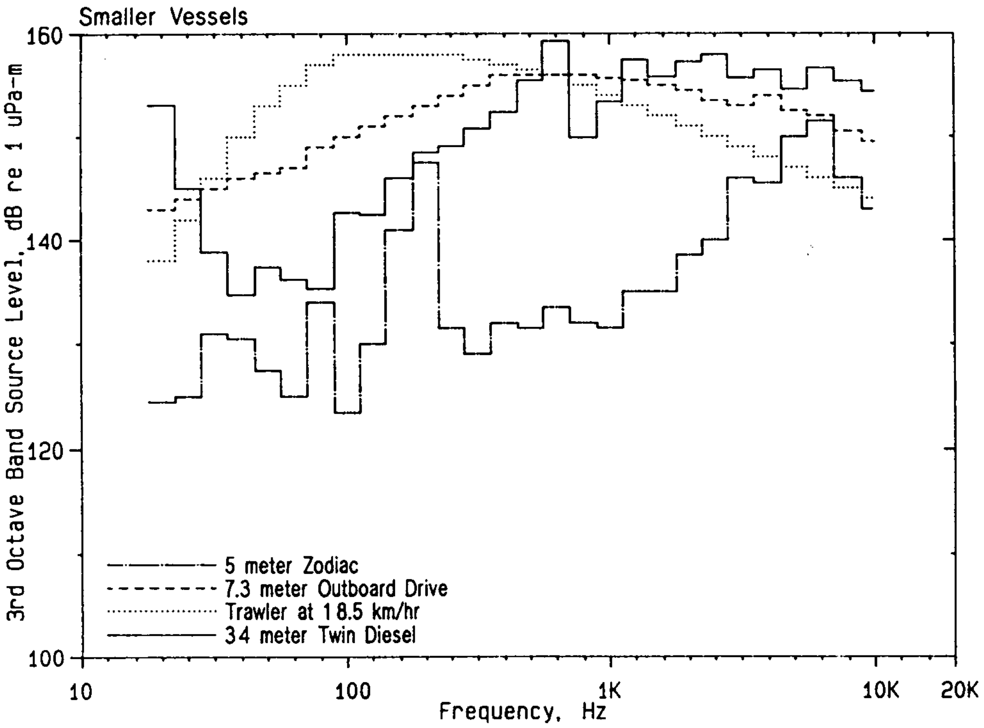

FIGURE 5.5. Estimated one-third octave source levels of underwater noise (at 1 m) for four boats. Data from Malme et al. (1989).

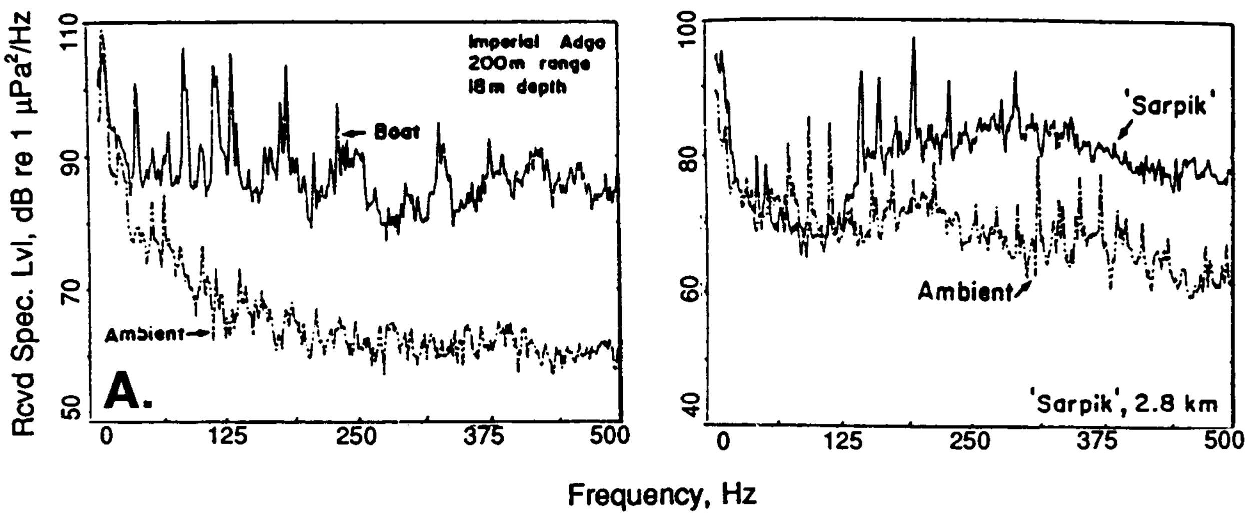

FIGURE 5.6. Received underwater sound spectra for two diesel-powered crew boats: *(A) Imperial Adgo* at range 200 m, and *(B) Imperial Sarpik* at 2.8 km. Dotted lower spectrum is ambient noise. Analysis bandwidth 1.7 Hz. From Greene (1985a).

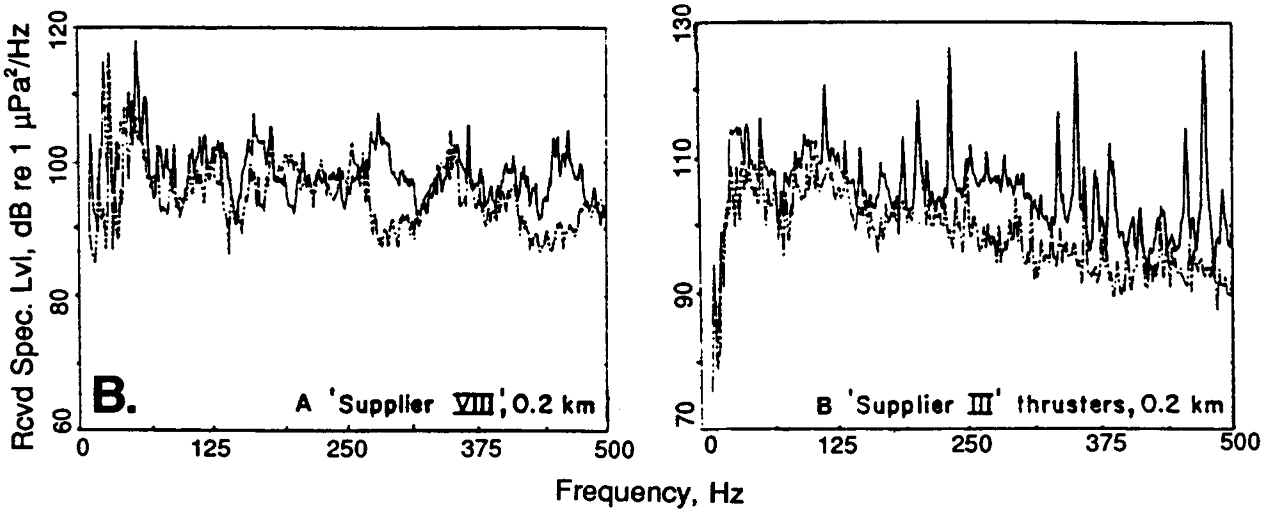

FIGURE 5.7. Received underwater sound spectra from two supply ships: *(A) Canmar Supplier VIII* underway at 0.2 km, and *(B) Canmar Supplier III* during start up of 450 hp bow thrusters at 0.2 km. Dotted lower spectrum is ambient noise. Analysis bandwidth 1.7 Hz. From Greene (1985a).

Small Ships.--Support and supply vessels, ranging in length from roughly 55 to 85 m, are used extensively in all open-water areas with offshore oil industry operations. The larger geophysical survey vessels are in this size range. Noise levels from ships underway are summarized here. Later sections describe noise from icebreakers (sect. 5.2.3) and special geophysical survey devices (sect. 5.3).

Support and supply ships are generally diesel-powered with two propellers. These ships have larger slower-rotating propellers than the smaller vessels discussed above. Typical small-ship propellers have four blades, diameter 3 m, and turn at 160 rpm. The fundamental blade-rate tone is therefore around 10-11 Hz. Often the propellers are in nozzles, which protect the propellers and help to direct the thrust and improve maneuverability. There is some evidence that nozzles reduce radiated noise from the propellers, at least for some aspects and some frequencies.

Greene (1987a) presented 1/3-octave sound levels for three icebreaking supply ships operating in the arctic with water depth 35 m. The measurement range was 0.37 km for the three ships. However, for improved comparability with sound levels presented for other sized vessels, the levels for range 50 m have been estimated assuming spherical spreading (Table 5.6). Radiated sound levels were higher for *Canmar Supplier IV* than for *Supplier VII* or *Robert Lemeur*. The higher levels were thought to be due to the lack of nozzles around the propellers of *Supplier IV*. Although *Lemeur* is larger than the other two supply ships, the nozzles apparently limited radiated propeller noise to levels comparable to those from the smaller *Supplier VII*.

Supply ships commonly have one or two hydraulic- or electric-powered bow thrusters to enhance maneuvering capability while conducting operations requiring close positioning accuracy. A bow thruster creates a strong harmonic family of tones with a relatively high fundamental frequency that corresponds to the high rotation rate of the thrusters. For example, the received noise spectrum of *Canmar Supplier III* shown in Fig. 5.7B exhibits a harmonic family of tones with fundamental frequency 118 Hz. These sounds were generated by a 450 hp transverse bow thruster. The first nine harmonics were prominent, extending to 1064 Hz. For comparison, the spectrum from *Supplier VIII* without operating bow thrusters does not contain any similar family of tones (Fig. 5.7A). A significant increase in radiated noise with the onset of bow thrusters was also evident in spectra from *Robert Lemeur* (Fig. 5.8). Received level in the 20-1000 Hz band increased from 130 to 141 dB when the bow thrusters began operation at range 0.56 km.

Figure 5.9 presents received sound levels in the 20-1000 Hz band as a function of range for a number of boats and small ships. The larger vessels radiated higher overall noise levels. An exception is *Canmar Supplier IV*, which lacks propeller nozzles and is noisier than *Robert Lemeur*, a larger ship that does have nozzles.

Commercial Vessels and Supertankers.--Commercial vessels and supertankers are used to haul crude oil and petroleum products over long distances. Although they are clearly associated with oil and gas development, their operation is not specifically confined to offshore production sites. Their large size and high power imply high sound levels at low frequencies. Their propellers are large and relatively slow-turning, on the order of 80-110 rpm.

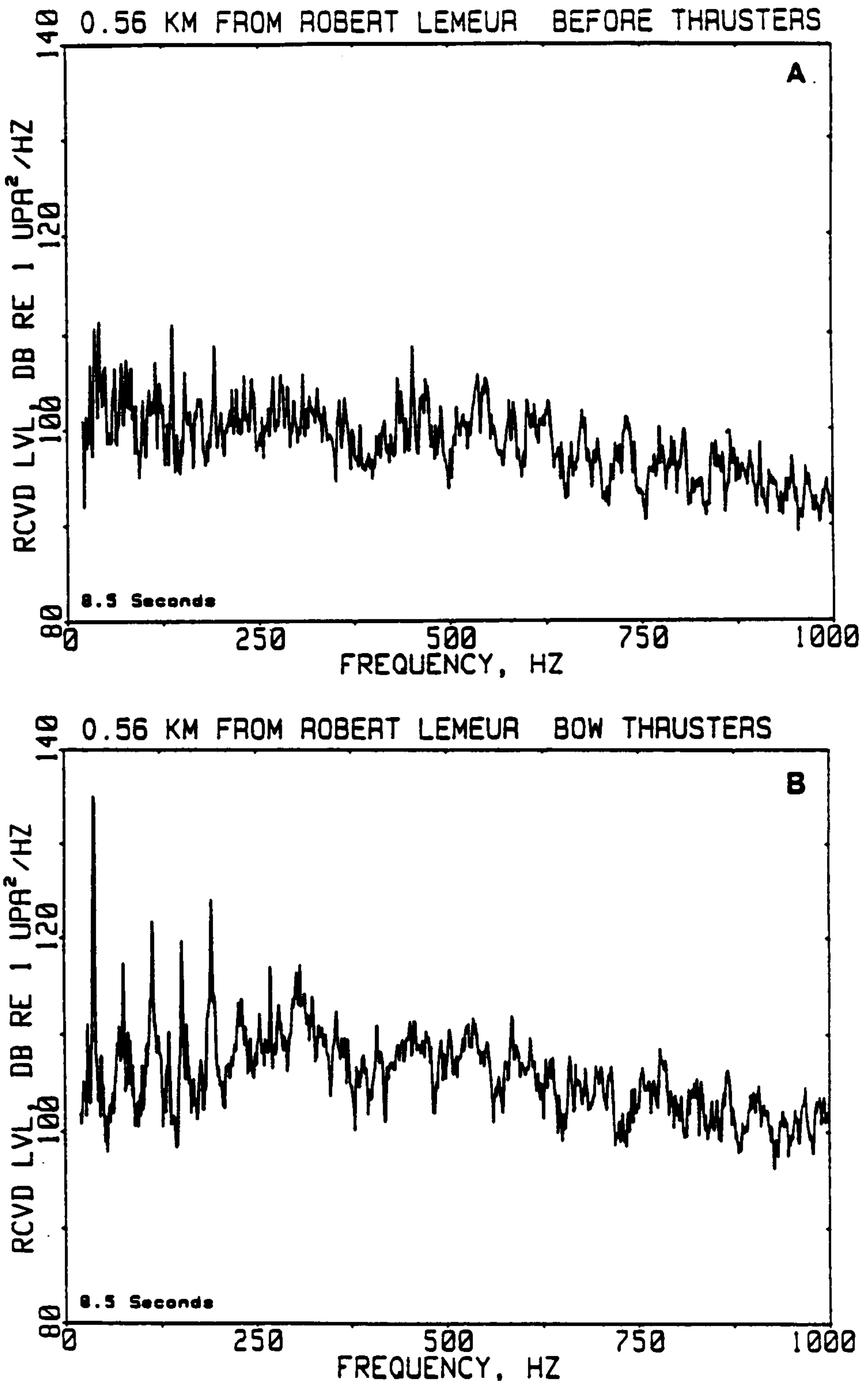

FIGURE 5.8. Received underwater sound spectra from supply ship *Robert Lemeur* *(A)* without and *(B)* with bow thruster operation; range 0.56 km. Broadband (20-1000 Hz) levels were 130 dB (A) and 141 dB (B). Analysis bandwidth 1.7 Hz. From Greene (1987a).

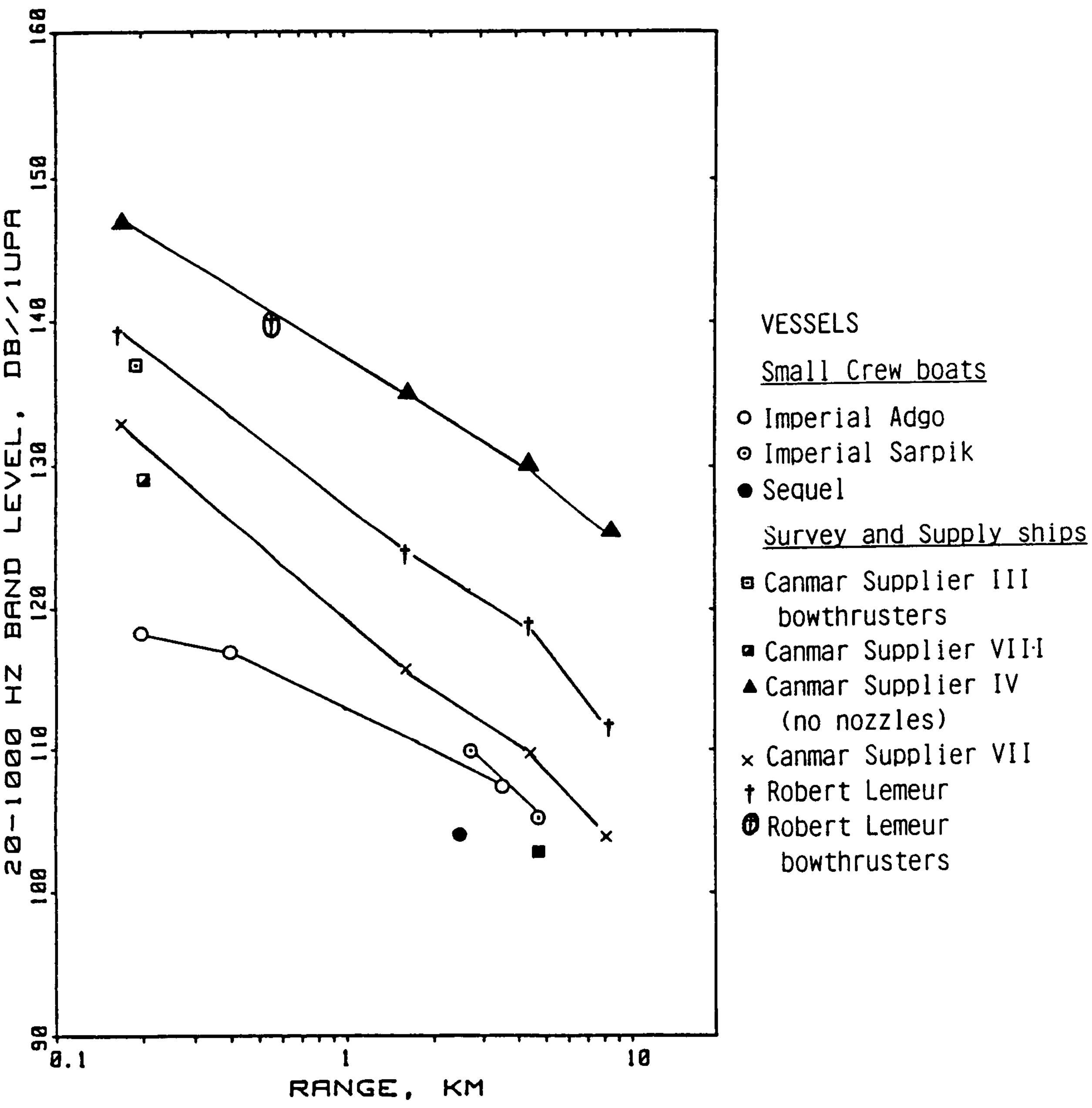

FIGURE 5.9. Vessel noise vs. range: received underwater sound levels (20-1000 Hz) for selected boats and ships in relation to range. Vessels are underway except for the one *R. Lemeur* measurement noted as "bowthrusters". Data from Greene (1985a, 1987a).

Table 5.6. Supply ship noise: 1/3-octave sound levels for three supply vessels estimated for range 50 m from measurements at range 370 m. *Robert Lemeur* (length 83 m, 9600 bhp) and *Canmar Supplier IV* (62 m, 7200 bhp) were underway in open water at 22 km/h; *Canmar* Supplier VII (56 m, 5280 bhp) was underway at 18.5 km/h in open water amidst 3/10 pack ice. Hydrophone depth 18 m in water 29-42 m deep. Data from Greene (1987a).

1/3-octave band	Estimated received Level at 50 m (dB re 1 µPa)		
center freq. (Hz)	*Supplier VII*	*Supplier IV*	*R. Lemeur*
20	103	127	132
25	113	139	129
31.5	116	143	126
40	120	136	126
50	128	139	132
63	130	143	132
80	132	145	134
100	123	139	134
125	120	141	130
160	123	137	126
200	126	136	126
250	125	134	128
315	127	135	127
400	128	134	130
500	129	135	129
630	127	136	130
800	125	134	129
Broadband, 20-1000 Hz	139	152	142

Buck and Chalfant (1972) recorded radiated noise from four commercial vessels in the shipping lanes of Santa Barbara Channel off California. Source levels at 1 m were estimated for the strongest tones, based on measurements at ranges of 366 to 914 m and assuming spherical spreading loss (Table 5.7). The authors associated the *Bryant*'s 428 Hz tone (source level 169 dB re 1 µPa-m), and a second component at 484 Hz, with a singing propeller. Although *Houston* and *Hawaiian Enterprise* were comparable in size and had tones at comparable amplitudes (180-181 dB re 1 µPa-m), *Enterprise* produced broadband noise (80-1000 Hz) about 8 dB higher than that from *Houston.*

Several authors have reported noise data for supertankers and a large container ship (e.g. Table 5.7; Fig. 5.10). Ross (1976) reviewed measurements made by Morris (1975, not seen) for the supertanker *Chevron London.* Tones with a fundamental frequency of 6.8 Hz were evident in noise measured 139-463 km away. The strongest elements were at frequencies 40-70 Hz; their source levels were estimated to be as high as 190 dB re 1 µPa-m. Leggat et al. (1981), based on Cybulski (1977), reported source level spectra (2-80 Hz) for *Mosteles* and *World Dignity,* two fully laden supertankers underway in deep water. Transmission loss corrections included surface reflection effects (Lloyd-mirror) so source levels at frequencies down to 2 Hz should be valid. Noise levels were highest at the lowest frequencies (down to about 2 Hz) for both supertankers. Levels decreased with increasing frequency at -9 dB per

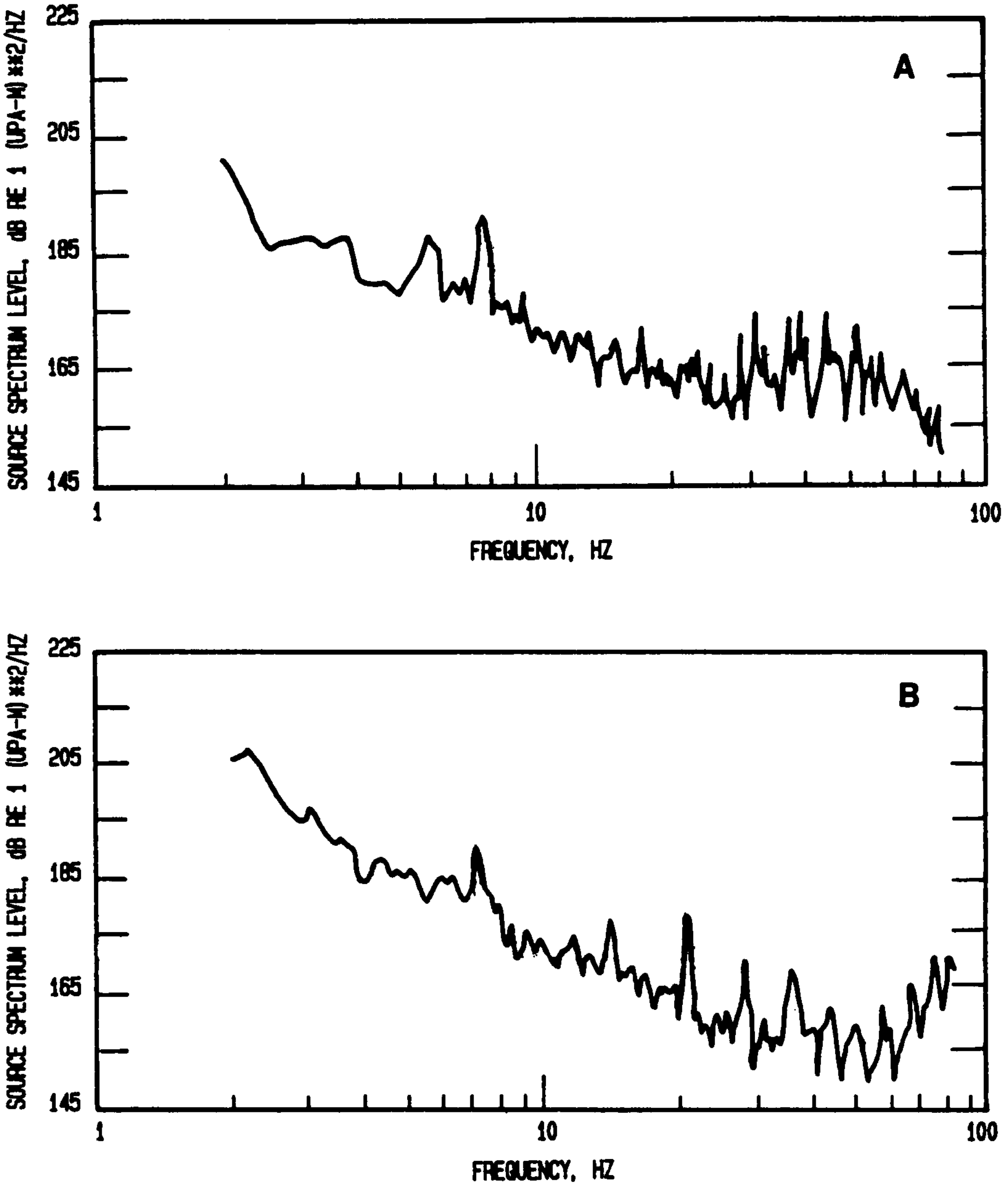

FIGURE 5.10. Low-frequency source level spectra for supertankers: *(A) Mosteles*, 103 ktons, 266 m LOA, speed 15.5 knots; and *(B) World Dignity*, 271 ktons, 337 m LOA, speed 16 knots. Analysis bandwidth 0.32 Hz. Data from Leggat et al. (1981), based on Cybulski (1977).

octave up to about 30 Hz. The spectrum for each ship included strong broadband components attributable to propeller cavitation. These were centered at 40-50 Hz for *Mosteles*, which had a propeller 6.3 m in diameter, and near 100 Hz for *World Dignity*, with a 9 m propeller. Ross (1976) states that noise power from propeller cavitation is expected to be proportional to the total number of blades cavitating and to propeller diameter, but the dependence on tip speed is strongest.

The strongest radiated noise from the triple-screw container ship *M/S Jutlandia* (274 m LOA, 75 khp) consisted of a family of 7.7 Hz tones from the center propeller when all three propellers were working during full power operation (Thiele and Ødegaard 1983). Their measurements for the container ship were made 600 m ahead of the ship. Cybulski (1977) noted the importance of aspect in determining received noise level from supertankers. In one case, he found that the level of a fundamental blade-rate tone was 7 dB higher at bow than at stern aspect. He suggested that longitudinal hull resonance may have enhanced forward sound radiation.

C.I. Malme (BBN, pers. comm.) provided one-third octave source levels for a large tanker and a cruise ship (Fig. 5.11). The levels are about 20 dB higher than those estimated in the same way for several smaller vessels (*cf.* Fig. 5.5).

Table 5.7. Sounds from large commercial ships underway: fundamental frequency, estimated source level of that tone, and measured spectrum level of broadband noise at the specified frequency. Data from Buck and Chalfant (1972), Ross (1976), Brown (1982b) and Thiele and Ødegaard (1983).

Vessel Name	Ship Length (m)	Source Level of Dominant Tone		Spectrum Level (dB re 1 µPa^2/Hz at 1 m)
		Freq. (Hz)	(dB re 1 µPa at 1 m)	
MS Thor I (Freighter)	135	41.0	172	
SS F.S.Bryant (Tanker)	135	428.0	169	
SS Houston (Tanker)	179	60.0	180	
SS Hawaiian E. (Container ship)	219	33.0	181	
K. Maru (Bulk carrier)	-	28.0	180	173 @ 100 Hz
		36.0	180	
Chevron London (Supertanker)	340	6.8	190	-
Mosteles (Supertanker)	266	7.6	187[a]	158 @ 40-50 Hz
World Dignity (Supertanker)	337	7.2	185[a]	161 @ 100 Hz
M/S Jutlandia (Container ship)	274	7.7	181	-
Third harmonic:		23.0	198	
Fifth harmonic:		38.3	186	

[a] The actual levels are several decibels lower than apparent levels for the corresponding tones in Fig. 5.10. Levels of tones are not accurately displayed in spectrum graphs like Fig. 5.10 if the analysis bandwidth is not 1 Hz (see sect. 2.2). Actual levels of tones can be estimated from apparent levels shown on spectrum graphs by adding 10 log (analysis bandwidth)--in this case 10 log (0.32) = -5 dB.

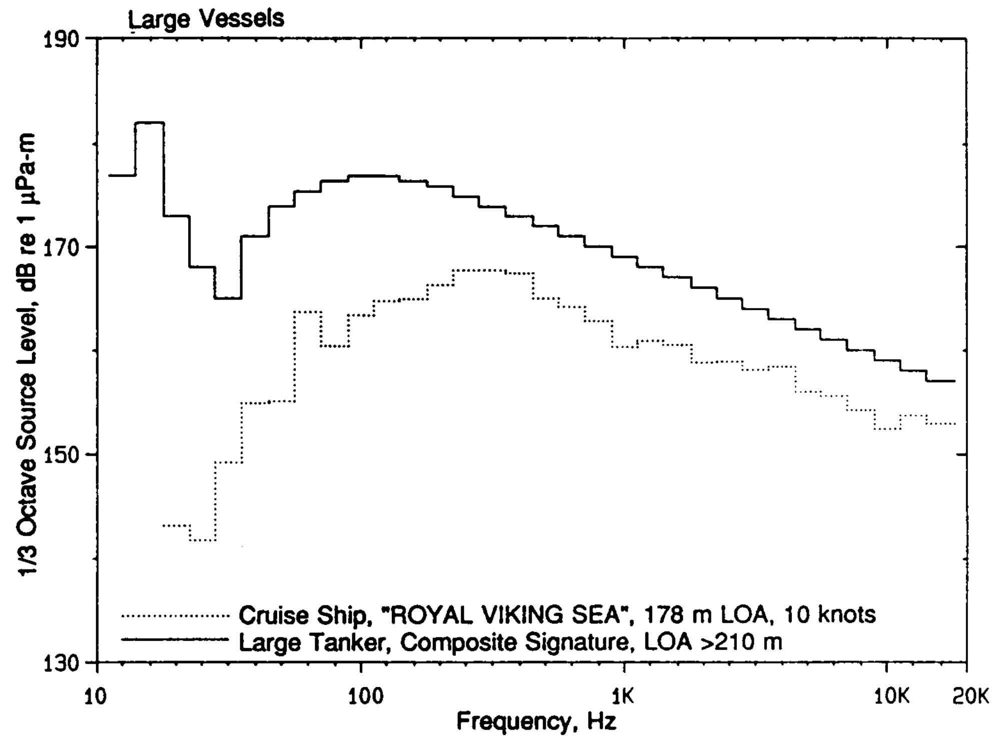

FIGURE 5.11. Estimated one-third octave source levels of underwater noise (at 1 m) for a composite supertanker (LOA >210 m) and the cruise ship *Royal Viking Sea*. Data from C.I. Malme, BBN (pers. comm.). The cruise ship levels at low frequencies are unexpectedly low.

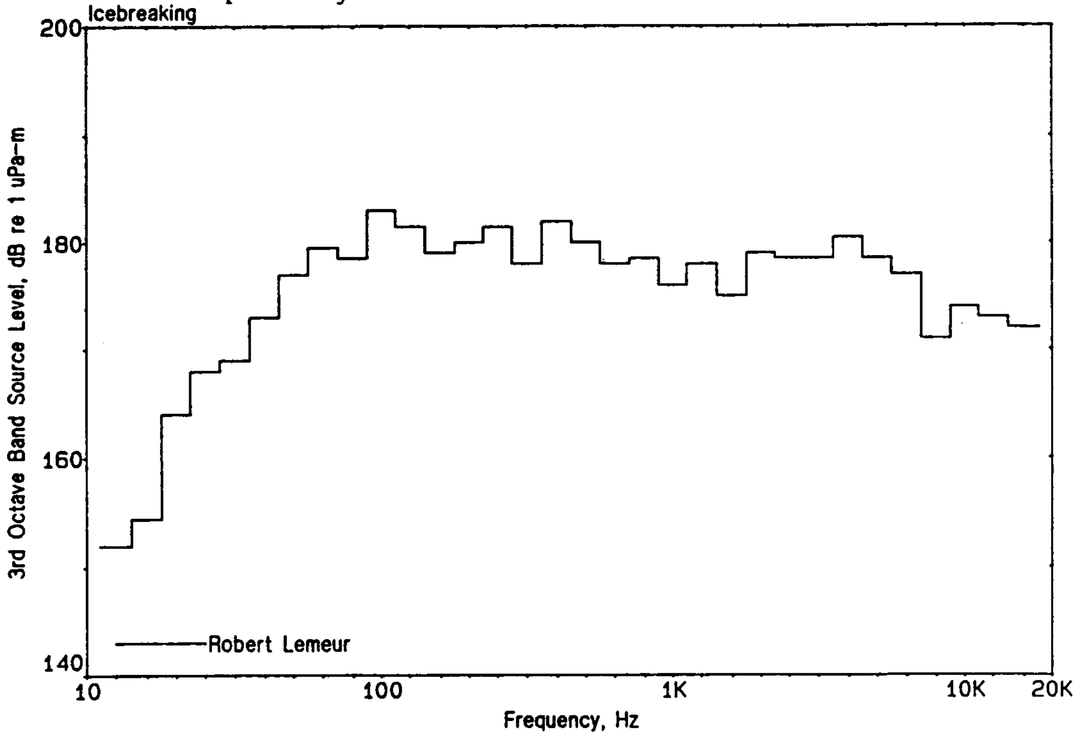

FIGURE 5.12. Estimated one-third octave source levels of underwater noise (at 1 m) for icebreaking supply ship *Robert Lemeur* engaged in icebreaking. Data from Malme et al. (1989). The levels at low frequencies are unexpectedly low.

In general, vessels produce noise in the same ways. Propeller cavitation produces most of the broadband noise, with dominant tones arising from the propeller blade rate. Propellers create considerably higher noise levels if they are damaged, not operating synchronously, or operating without nozzles. Propulsion and auxiliary machinery can also radiate significant noise. Radiated noise can be roughly related to ship size, speed, and mode of operation. Large ships tend to be noisier than small ones, and ships underway with a full load (or towing or pushing a load) produce more noise than unladen vessels. Noise also increases with a ship's speed. The general condition of a ship and its state of maintenance also influence radiated sound level. Ships with old auxiliary machinery (e.g. generators and compressors) tend to radiate more noise than newer or well-maintained vessels.

5.2.3 Icebreaking

Icebreaking vessels produce some of the strongest sounds associated with oil and gas operations. A typical icebreaking operation involves ramming the ship forward into the ice until momentum is lost, followed by backing astern in preparation for another run at the ice. Such operations result in highly variable levels of radiated noise. Strong cavitation sounds occur when the ship reverses direction from astern to forward, and when it is stopped by the ice after ramming. When the ice is thinner, continuous forward progress may be possible. For example, *Canmar Kigoriak*, a 91-m oil-industry icebreaker, is capable of breaking through 1.5 m of smooth ice while underway at 5.5 km/h (Alliston 1980). Even when a ship can make steady forward progress through ice, more power is required than when the same ship is underway in open water; hence more noise is generated.

The effect of icebreaking on radiated ship noise is demonstrated clearly by comparing sound spectra from the same ship underway in open water vs. icebreaking at the same distance (Fig. 5.13). During icebreaking, received sound levels in the 20-1000 Hz band increased by 14 dB in the case of *Supplier VII* and by ~12-13 dB for *Robert Lemeur*. The differences in received noise levels for a ship underway vs. icebreaking tended to decrease as distance from the ship increased (Fig. 5.14B). The steeper slope during icebreaking (Fig. 5.14B) indicated more rapid attenuation of sound in the heavy ice condition. Even so, the elevation in noise levels attributable to icebreaking was substantial out to at least 5 km.

The increases in noise level during icebreaking vary over time (Fig. 5.15, from Miles et al. 1987; see also Thiele 1988:40*ff*). For example, when *Robert Lemeur* was icebreaking near an offshore drillsite, noise levels increased during ice-pushing episodes. This was caused by propeller cavitation noise, which included some energy at frequencies above 5 kHz. In that case, icebreaking sounds were detected >50 km away.

Malme et al. (1989) computed the 1/3-octave source levels of *Robert Lemeur* icebreaking (Fig. 5.12). Compared to the source levels for the large tanker (*cf.* Fig. 5.11), the peak levels from cavitation noise were about 7 dB higher for the icebreaker; in both cases the peak 1/3-octave levels were near 100 Hz.[5] Also, levels of icebreaking noise did not fall off nearly as rapidly with increasing frequency. The high level of cavitation during icebreaking accounts for this.

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[5] The low frequency blade-rate tones from the tanker were not included in this comparison.

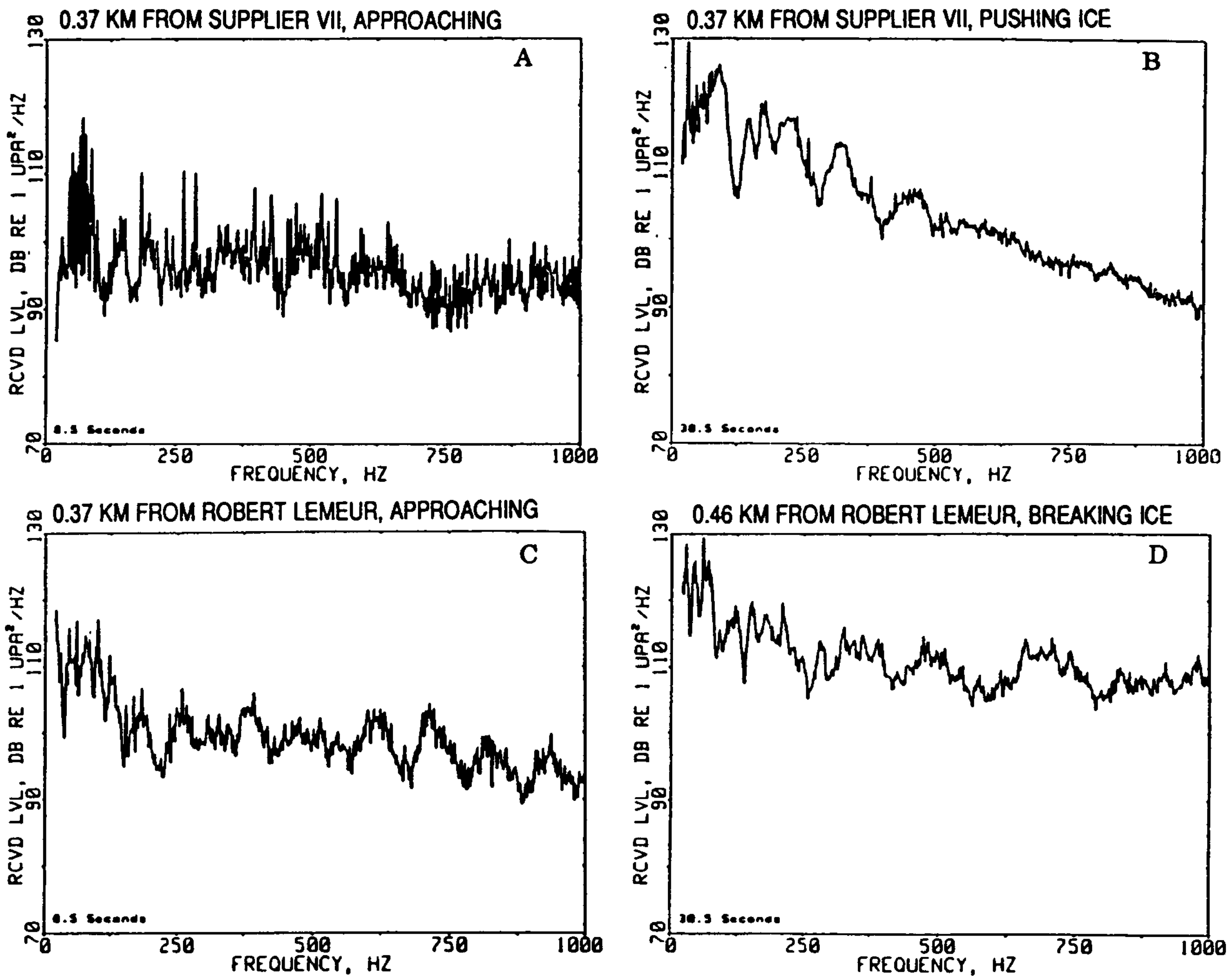

FIGURE 5.13. Icebreaker noise spectra: received underwater sound pressure spectra for two icebreaking supply vessels underway in open water (left) and icebreaking (right). Broadband (20-1000 Hz) received levels for *Supplier VII* were 130 dB in open water (A) and 144 dB while pushing ice (B). Broadband levels for *R. Lemeur* were 133 dB in open water (C) and 144 dB while pushing ice (D). A-C were at range 0.37 km whereas D was at 0.46 km; hence levels in D should be increased by 1-2 dB to make them comparable to A-C. Analysis bandwidth 1.7 Hz. From Greene (1987a).

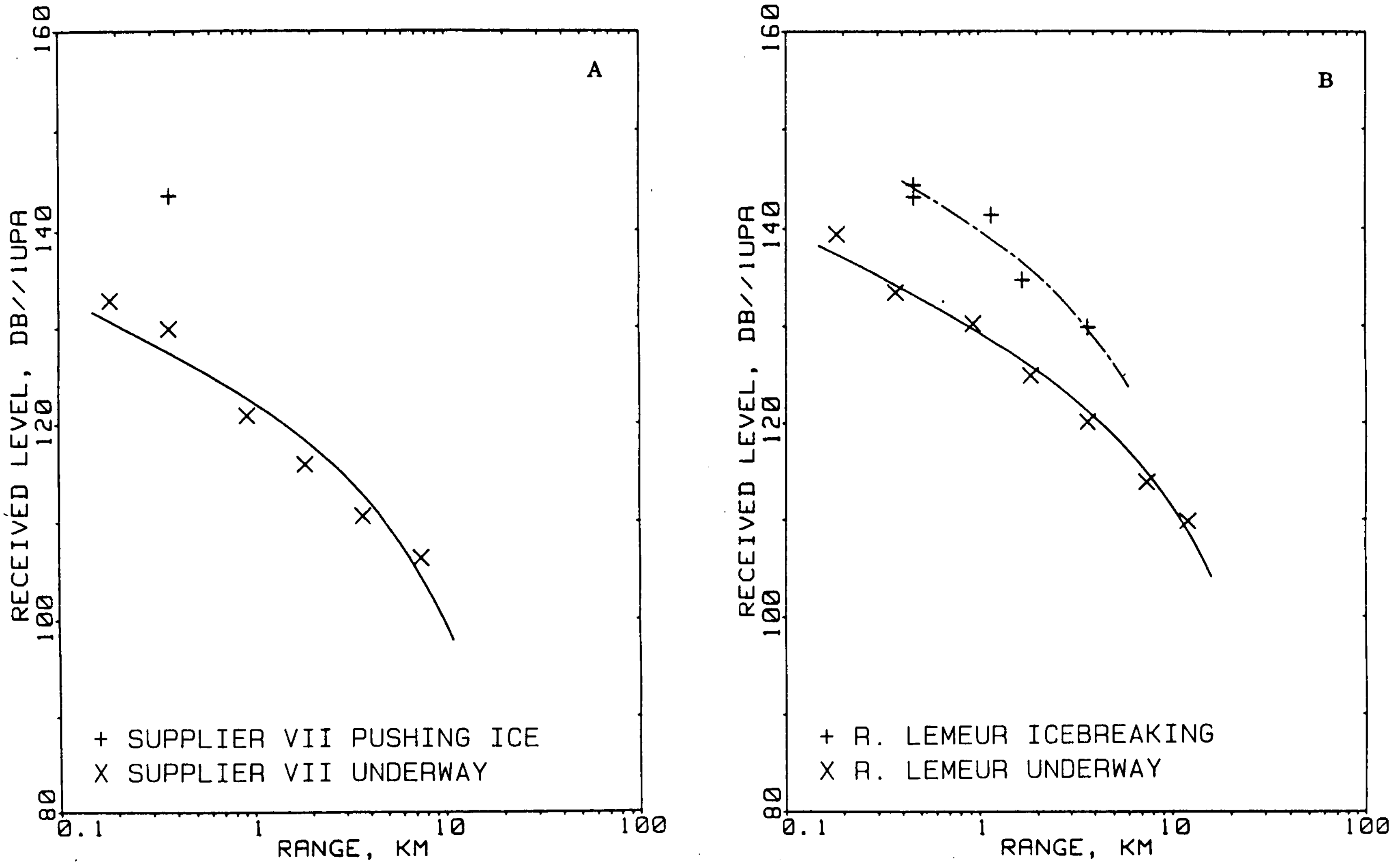

FIGURE 5.14. Icebreaker noise vs. range: received underwater noise levels (20-1000 Hz) for ***(A)*** *Canmar Supplier VII* and ***(B)*** *Robert Lemeur* while (**x**) underway and (**+**) pushing against or breaking ice. From Greene (1987a).

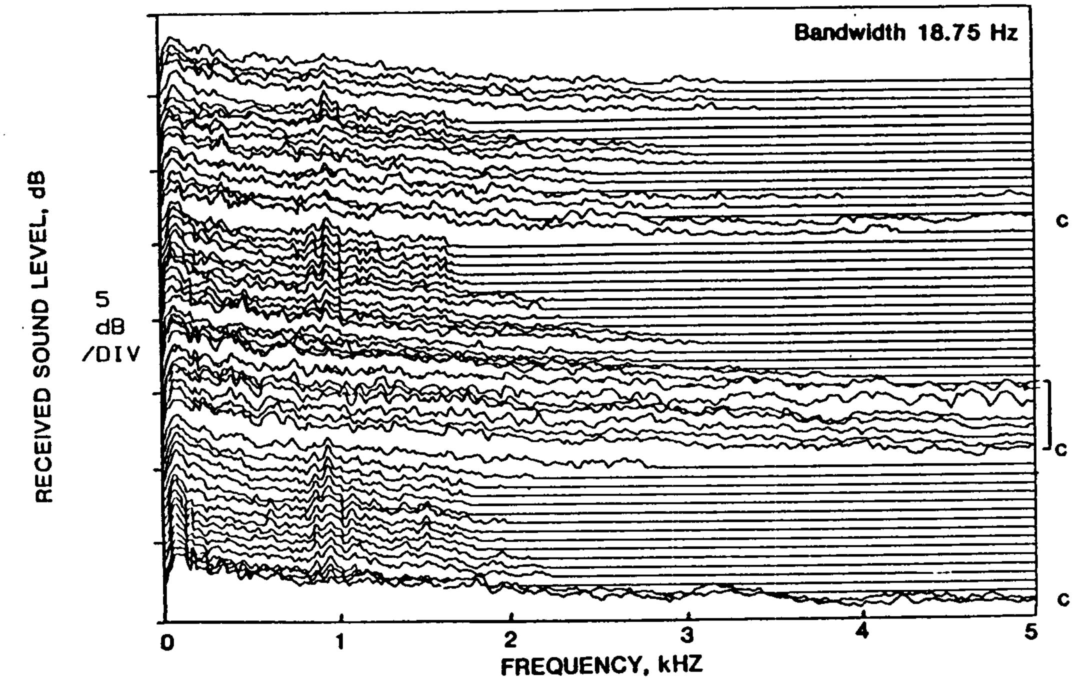

FIGURE 5.15. Icebreaker noise vs. time: sequence of received underwater noise spectra over a 10-min period of icebreaking by *Robert Lemeur*. Periods of increased noise were due primarily to propeller cavitation (marked "c") during icebreaking. The dB scale is not calibrated with respect to a reference. Spectrum interval = 10 s; analysis bandwidth 18.75 Hz. From Miles et al. (1987:97).

A report by Thiele (1981) on noise from the *M/S Voima* described one of the earliest field studies of icebreaker noise (Table 5.8). *Voima* is an 83.5 m Finnish icebreaker outfitted with four propellers, two in front and two astern. Thiele concluded that radiated noise level increased by about 5 dB from open water to icebreaking at the 50 to 60% power level, and by an additional 10 dB for icebreaking at full power. There were no strong tones associated with icebreaking or ship stopping.

There has been speculation about whether physical crushing of ice contributes to the overall increase in noise level during icebreaking. Thiele (1984, 1988) evaluated this by placing accelerometers in the bow of the icebreaker *John A. MacDonald* to sense icebreaking vibration, and in the stern to sense to propeller vibration. Signals from the accelerometers were correlated with underwater noise received at a remote hydrophone while the ship was icebreaking and traveling in open water. There was a clear correlation between propeller cavitation and underwater noise, but little correlation between icebreaking vibration and radiated noise. Thus, the increased noise during icebreaking is primarily due to the propellers.

Studies of the icebreakers *M/S Voima* and *John A. MacDonald* and of the icebreaking ore carrier *M/V Arctic* have all shown that noise levels during icebreaking are highest during the full astern phase (Table 5.8). The increase ranges from 5 to 10 dB (Finley et al. 1983a, 1984; Thiele 1981, 1988).

Table 5.8 Estimated source levels (at 1 m) for icebreaker noise. The source levels for the strong tones from *M/V Arctic* are in the "Broadband" column because the dB reference units there are correct. For *John A. MacDonald* the 1/3-octaves with strongest source levels were centered at 50 Hz for all three operating conditions. Data from Finley et al. (1983a, 1984) and Thiele (1981, 1988).

Description	Frequencies (Hz)	Source Levels	
		Broadband (dB re 1 µPa-m)	Spectrum (dB re (1 µPa-m)^2/Hz)
MS Voima			
icebreaking full astern	broadband	190	
icebreaking full ahead	broadband	180-185	162 @ 100 Hz
open water, 50-60% pwr	broadband	177	
MV Arctic			
icebreaking ahead	10-1000	184	
icebreaking astern	10-1000	191	
icebreaking ahead	Tones @ 53 & 205	Tones 171	
icebreaking astern	Tone @ 79	Tone 177	
MV John A. MacDonald			
idle	1/3 Oct. Band		160 @ 50 Hz
icebreaking ahead	1/3 Oct. Band		172 @ 50 Hz
icebreaking astern	1/3 Oct. Band		181 @ 50 Hz

Thiele (1988) describes icebreaking noise from the icebreaker *John A. MacDonald* under two conditions of ice cover. *MacDonald* is 96-m 3685-tonne icebreaker with maximum total power is 11,200 kW (15,000 shp). In Baffin Bay during June in an area of 1-m ice floes, 50-80% ice coverage, the ship ran ahead essentially unhindered by the ice. In Lancaster Sound, ice cover was 100% shore fast ice, and the ship made only slow progress backing and ramming. Comparative levels for 1/3-octave bands were as follows:

Location	Condition	rpm	Power, kW	1/3 Octave Freq., Hz	Source Level, dB re 1 µPa-m
Baffin Bay	Ahead	140	5,500	31.5	177
" "	Astern	-	-	50	~187
Lancaster S.	Ahead	140	10,000	50	172
" "	Astern	140	"	50	181

As usual, source level was higher during movement astern than ahead. It is not known why the estimated source levels were higher in the lighter ice condition (Baffin Bay). It is possible that there were aspect differences between the two measurement areas. Thiele (1988) noted that the low-frequency underwater sounds of backing and ramming in Lancaster Sound were occasionally audible 55 km away. Thiele's analysis included infrasonic frequencies. He found several strong tones below 20 Hz, including one at 2.4 Hz. These tones were the fundamentals and harmonics of the propeller shaft and blade rates.

Based on their icebreaker sound measurements, Thiele et al. (1990) prepared a computer model for noise exposure from shipping in Baffin Bay and Davis Strait. Source strength, transmission loss and ambient noise are taken into account. Thiele et al. stressed the importance of site-specific transmission loss measurements or model predictions.

In ***summary***, the alternating periods of ice ramming and backing that are common during icebreaking cause variations in radiated noise levels. Icebreaking vessels pushing ice radiate noise about 10 to 15 dB stronger than that when not pushing ice. The higher noise levels are due primarily to strong propeller cavitation. There are tones at frequencies related to the propeller blade-rate below 200 Hz, including some strong tones below 20 Hz, and lesser components extending beyond 5 kHz. On a third-octave basis, levels can be high even at frequencies above 5 kHz (Fig. 5.12). The duration of a single episode of strong cavitation noise is generally about one minute, followed by several minutes of less intense noise as the icebreaker repositions itself. However, increased noise levels can also occur at times during repositioning, primarily because of intermittent propeller cavitation while the ship is moving astern and reversing direction. Measured noise levels for two icebreakers were 7 to 8 dB higher when going astern than when moving ahead. When present, nozzles around the propellers significantly reduce radiated propeller noise during all phases of a ship's operation, but especially during icebreaking.

5.2.4 Hovercraft and Other Vehicles

In addition to aircraft and vessels, other vehicles are sometimes used in the course of offshore oil and gas development. Hovercraft ride on a self-generated air cushion and can operate over open water or ice. Snowmobiles, rolligons, trucks, Sno-Cats, and ordinary construction equipment often operate on ice. In general, although noise generated on ice is transmitted into the water directly below, it does not propagate well laterally. There are relatively few published measurements from such sources. The following is a summary of published accounts of noise measured underwater from "other vehicular" sources, with the exception of seismic profiling noise which is covered in sect. 5.3.2.

Slaney (1975) measured underwater noise from a Bell Voyageur hovercraft during a "flypast" over open water at a lateral range of 46 m. The Voyageur is equipped with 2.7 m diameter propellers centered 3.7 m above the water and with tip speed 246 m/s. The operating hovercraft is an airborne sound source, like an aircraft, and the sounds will couple into the water best at steep angles (less than 13°; see sect. 5.2.1). Therefore, only a brief transient sound is expected under water as the hovercraft "flies" past. However, duration of audibility was not reported by Slaney (1975). At receiver depth 1.8 m, the received levels in the 1/3-octave bands from 80 to 630 Hz were about 110 dB re 1 µPa; the 50-2000 Hz band level was 121 dB.

Large hovercraft are routinely used as ferries across the English Channel, and the U.S. Marine Corps uses them as "Landing Craft Air Cushion" (LCAC). We are not aware of any published underwater noise measurements from these operational hovercraft. It is possible that hovercraft could be used to ferry personnel and material to offshore sites in arctic regions when ice cover restricts shipping, but as yet no under ice noise measurements are available.

Several other types of vehicles are used for various purposes on the sea ice. The mechanism of sound transmission through ice to water is complicated by the fact that multiple

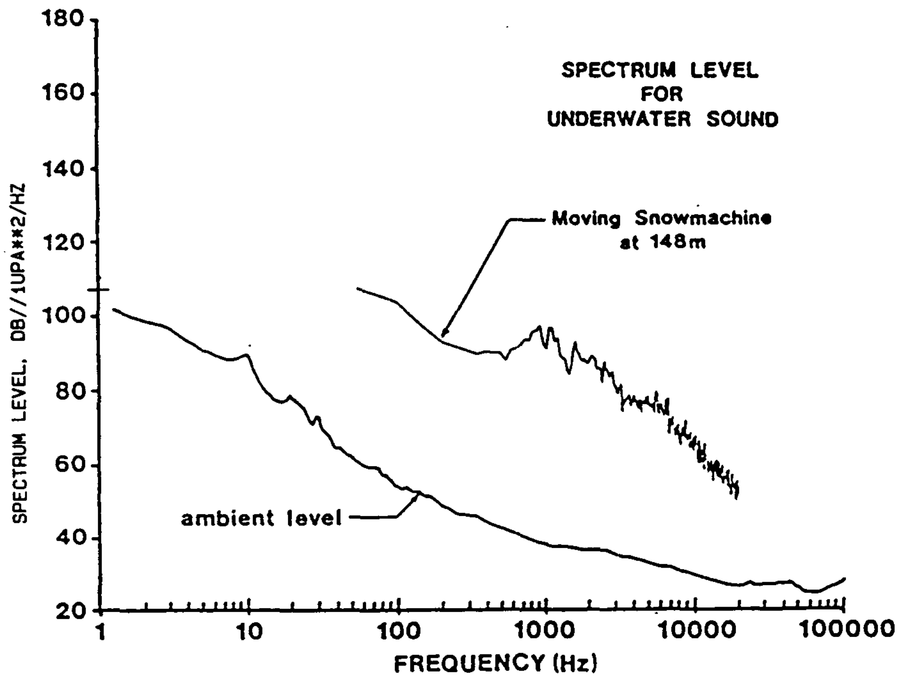

FIGURE 5.16. Snowmobile noise: underwater sound spectrum for a small snowmobile traveling over unplowed ice at a horizontal distance of 148 m. Analysis bandwidth 1.25 Hz. From Holliday et al. (1984:89).

types of sound waves are imparted to the ice layer. In general, noise transmitted into the water is affected by the condition of the ice surface. Snow cover absorbs airborne sound and dampens structure-borne sound. Low temperature ice supports better sound and vibration coupling to the water (Holliday et al. 1980).

Snowmobiles are often used along trails or over unplowed ice to transport personnel and light loads. The high-speed two-cycle engines used in small snowmobiles would be expected to create sounds at higher frequencies than larger, slower machinery. Holliday et al. (1980) described noise from snowmobiles moving over an established trail on ice 1.3 m thick covered with 1 cm of crusty snow. The hydrophone was about 200 m from the trail in water 31.8 m deep. Noise spectra showed broadband maxima at about 1.25 kHz, with received spectrum levels 55-60 dB re 1 $\mu Pa^2/Hz$ for speeds 16-48 km/h. These are low levels. The spectrum of underwater noise from a snowmobile traveling at 20 km/h over unplowed ice 148 m to the side of a hydrophone also showed peaks near 1 kHz, but received levels were higher--about 90 dB near 1 kHz (Fig. 5.16; Holliday et al. 1984).

Holliday et al. (1984) measured underwater noise from several large vehicles moving on ice. These vehicles were all involved in geophysical survey operations using the Vibroseis technique (sect. 5.3.2). Spectrum levels of underwater sound measured 148 m from a drill truck (drilling and idling), a bulldozer, an idling Vibroseis truck, and a fuel truck were all well above measured ambient levels, with energy maxima generally below 2 kHz (Fig. 5.17). Drilling noise averaged 13 dB higher than idling drill truck noise in the 1 to 30 kHz band (Fig. 5.17A).

Sound levels associated with road-building on ice were measured by Greene (1983). To build an ice road thick enough to support heavy equipment, a rolligon equipped with a large auger drilled holes through the ice near the center of the road alignment. Then pumps were used to flood the surrounding area with seawater, which then froze. Seawater pumping noises were measured 0.37 km from the center of the road in water 5 m and 10 m deep, with the hydrophone at mid-depth below ice 1.3 m thick. Except for an 83 dB tone at 26 Hz, sounds recorded in very shallow (5 m) water were well below expected ambient levels for calm seas (Fig. 5.18A). The received level of pumping noise was stronger at the deeper (10 m) site, with prominent tones from 58 to 254 Hz (Fig. 5.18B); the strongest tone was 97 dB re 1 µPa at 86 Hz, measured at range 0.37 km in water 10 m deep.[6] The difference in spectrum structure during the two measurements suggests that different sources were operating at the two times.

de Heering and White (1984) reported noise levels of a Bombardier SV 301 D tracked vehicle stationary on ice and traveling at 15 km/h. Measured underwater noise levels at 125-600 Hz were ~5-10 dB less with the vehicle standing on snow than on bare ice. However, when the tracked vehicle was traveling, noise levels during movement over snow-covered and bare ice were similar in the 125-4000 Hz band; above 4 kHz the snow attenuated the sound.

Cummings et al. (1981b) reported that the strongest received spectrum level for a Caterpillar tractor operating on ice at range 3.7 km was 66 dB re 1 $\mu Pa^2/Hz$ at about 800 Hz, with an "overall" level of 77 dB re 1 µPa.

In *summary*, vehicles on ice can transmit significant noise into the water. However, levels are affected by the condition of the ice (temperature, snow cover) and are generally much lower than noise levels generated by vessels in water. Snow absorbs sound. Running vehicles standing on ice blanketed by snow transmit much less noise to water than the same vehicles standing on bare ice. Water depth also significantly affects sound transmission from vehicles, although these effects on measured noise level for vehicles operating on ice have not been studied extensively.

5.3 Marine Geophysical Surveys

The purpose of geophysical surveys is to locate geologic structures associated with petroleum deposits, and in this way identify drilling sites with the greatest potential for recovery of oil and gas. Marine geophysical surveys use high energy sources of sound or vibration to create seismic waves in the earth's crust. High-energy low-frequency sounds, usually in the form of short-duration pulses, are created along survey grids to map the geologic features of a particular area. Sub-surface geologic structures are located and characterized by receiving and processing the sequence of refracted and reflected signals.

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[6] The apparent levels of tones in the Figure are 5 dB lower than the corrected values quoted here, for the reason explained below Table 5.7. The correction here is +5 dB, i.e. 10 log (3.4 Hz bandwidth).

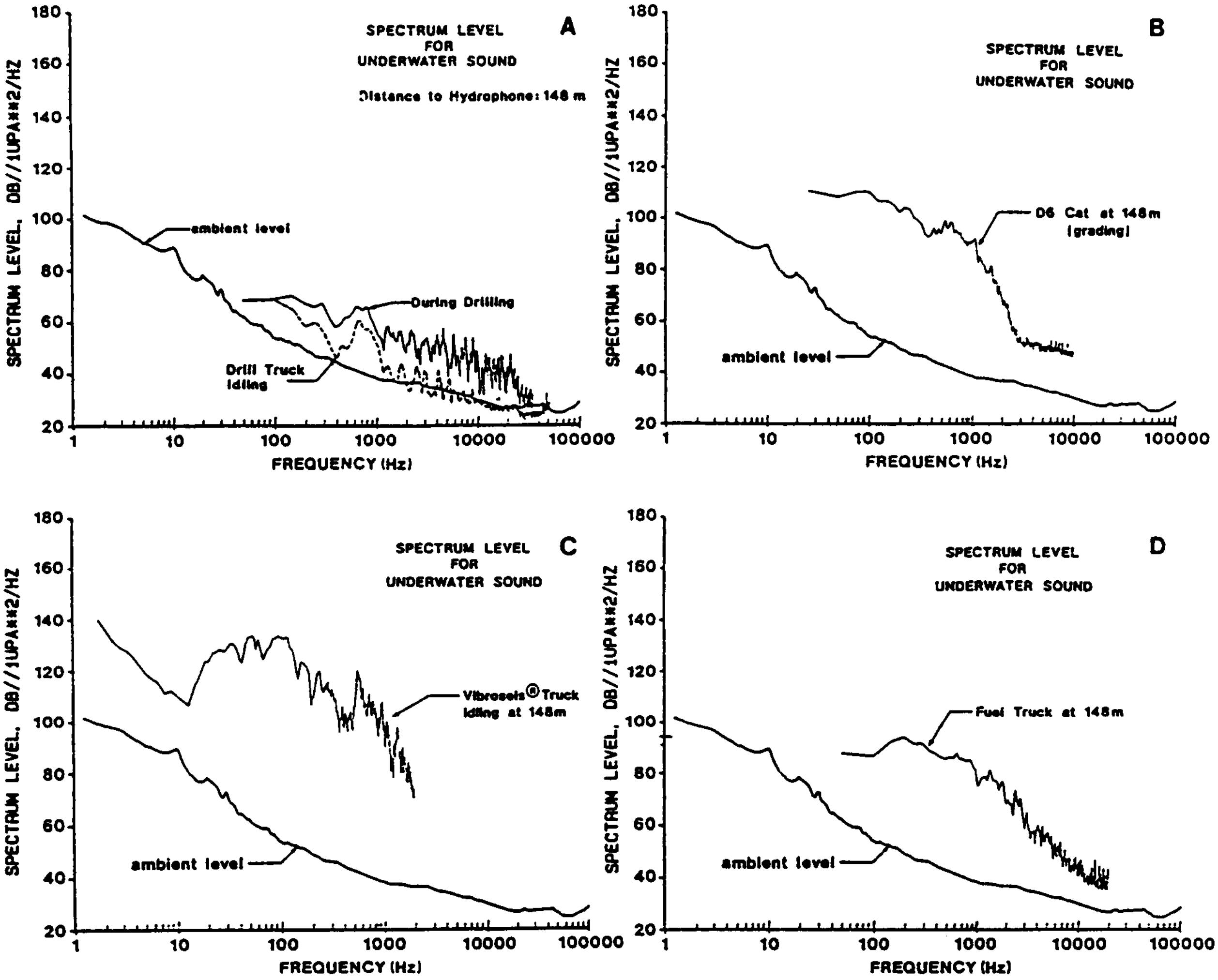


FIGURE 5.17 Underwater noise spectra for large vehicles associated with a Vibroseis convoy measured at 148 m: *(A)* drill truck; *(B)* bulldozer; *(C)* idling Vibroseis truck; and *(D)* fuel truck. Analysis bandwidth 1.25 Hz. From Holliday et al. (1984).

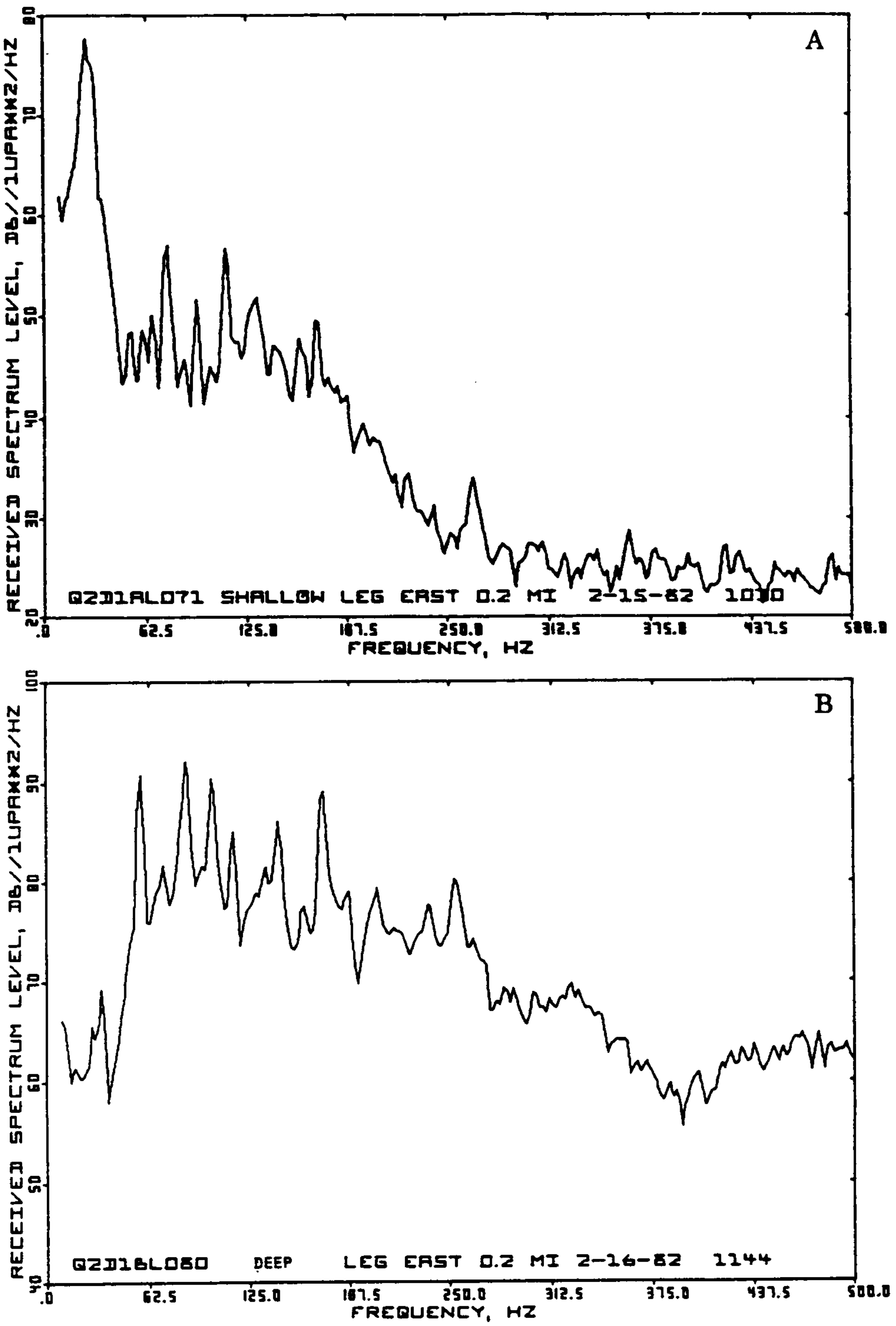


FIGURE 5.18. Underwater noise spectra from ice road construction. ***(A)*** 0.37 km from the road, water depth 5 m. ***(B)*** 0.37 km from the road, water depth 10 m. Analysis bandwidth 3.4 Hz. From Greene (1983:128).

Kramer et al. (1968) prepared a useful review of marine seismic survey techniques. Johnston and Cain (1981) updated their work. Two of their tables present a concise summary of seismic sources: Table 5.9 describes sources in use up until about 1977, and Table 5.10 describes more recent sources. The strongest of these is listed as "GECO Array 3100 + 1640", an airgun array at depth 25 ft (7.6 m) yielding 106 kiloJoules/m^2 in the 0-125 Hz band. Its peak-to-peak pressure is 82.4 bars at 1 m, representing a peak pressure of 41.2 bar-m or 252 dB re 1 µPa-m in the same band. Peak-to-peak pressures in bar-meters (P_s), a common unit in the seismic survey literature, can be converted to source levels in dB re 1 µPa-m as follows:

$$L_s \text{ (dB re 1 µPa-m)} = 20 \log (10^6 P_s/2) + 100 \qquad (5.3)$$

Other airgun arrays listed in Table 5.10, with volumes 1050-4440 in^3, have peak-to-peak pressures of 25.2-80.0 bar-m (Table 5.10), or source pressure levels of 242-252 dB re 1 µPa-m.

Following a short subsection on noise from underwater explosions, we review non-explosive seismic survey sources, which represent the types of sources currently in use by the geophysical industry in U.S. waters.

5.3.1 Explosions

Early seismic surveys were conducted on land. Surveys expanded into shallow waters of the continental shelf in the mid-1940s. Chemical explosives, primarily dynamite and TNT, were used almost exclusively until the mid-1960s. Such surveys relied on refraction techniques requiring two ships; one ship fired a series of explosive charges as it moved away from a second vessel equipped with hydrophones to measure the arriving seismic signals refracted within the geologic structures (Fig. 5.19). Charge sizes ranged from 0.5 to 140 kg of dynamite

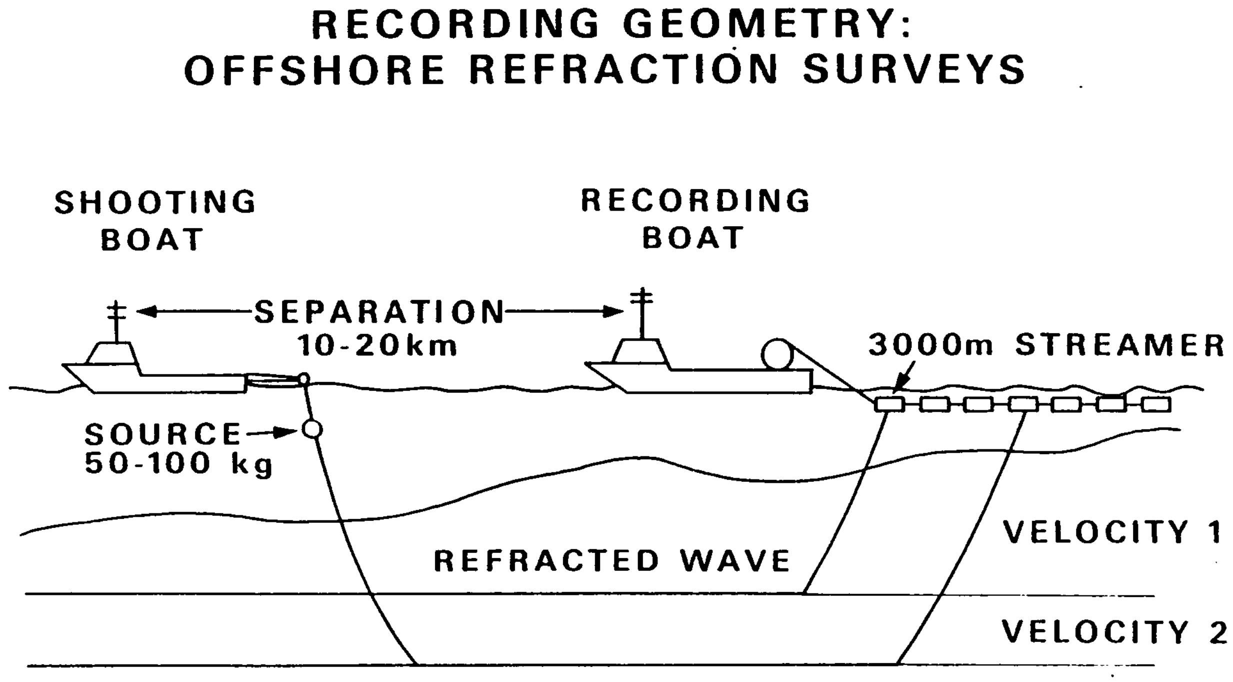
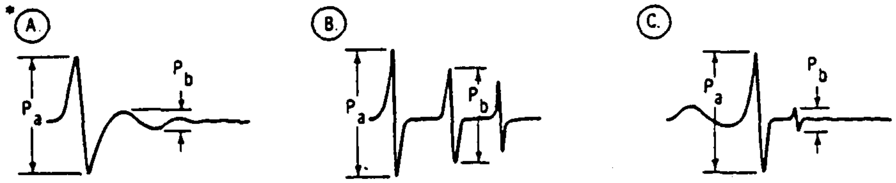


FIGURE 5.19. Geometry of geophysical survey vessels using explosives and relying on refraction survey techniques. From Campbell (1985).

Table 5.9 Characteristics of some marine seismic energy sources in use up to about 1977 (from Johnston and Cain 1981)

SOURCE	DESCRIPTION	P_a* (bar-m) (p-p, 0-125 Hz)	P_a/P_b* (0-125 Hz)	SIGNATURE TYPE*	COMMENTS
2000-CU. IN. AIR GUN ARRAY	31 GUNS (20-240 CU. IN.) 2 EA 150-FT LINE ARRAYS	69	12	A	
1450-CU. IN. AIR GUN ARRAY	25 GUNS (20-100 CU. IN.) IN 5 SUBARRAYS SPACED 30 m APART (ALSO USED WITH 15-m AND 60-m SUBARRAY SPACING)	52.6	6.3	A	CALCULATED RESULTS, DESIGNATED AS "LONG" ARRAY IN TEXT
4170-CU. IN. AIR GUN ARRAY	20 GUNS (60-360 CU. IN.), 1 GUN (1645 CU. IN.), 4 EA 15-FT LINE ARRAYS	49.5	16.7	A	
1450-CU. IN. AIR GUN ARRAY	25 GUNS (5-200 CU. IN.) 2 EA 80-FT LINE ARRAYS	48.3	8.4	A	DESIGNATED AS "STANDARD" ARRAY IN TEXT
24-LITER (1465 CU. IN.) AIR GUN ARRAY	24 GUNS [.16-2.5 LITER (10-150 CU. IN.)] IN "U-ARRAY"	43	12 (0-248 Hz)	A	
0.59-KG (1.3-LB) MAXIPULSE	0.59-KG NITROCARBONITRATE CHARGE FIRED AT 40-FT DEPTH	42	1.4	B	DEBUBBLE PROCESS REQUIRED, WESTERN GEOPHYSICAL TRADEMARK
3150-CU. IN. AIR GUN ARRAY	5 SUBARRAYS OF 5 GUNS EACH (630 CU. IN.) SPACED 20-56 m APART	41.5	5.1	A	SHELL CANADA LICENSEE
1200-CU. IN. AIR GUN ARRAY	26 GUNS (10-300 CU. IN.), 2 EA 65-FT LINE ARRAYS	40.5	9.2	A	
FLEXICHOC	200 CM D x 30 CM H EVACUATED CAVITY THAT IMPLODES WHEN "FIRED"	40	2.6	C	IFP TRADEMARK
1440-CU. IN. WATER GUN ARRAY	18 GUNS (80 CU. IN. EA), 3 EA 35-FT LINE ARRAYS	36	3	C	CALCULATED, P_a = 2.0 BAR-M FOR ONE GUN
0.27-KG (0.6-LB) MAXIPULSE	0.27-KG NITROCARBONITRATE CHARGE FIRED AT 40-FT DEPTH	35	1	B	DEBUBBLE PROCESS REQUIRED
1222-CU. IN. AIR GUN ARRAY	7 GUNS (67-410 CU. IN.) IN TRIANGULARLY-SHAPED ARRAY (52-FT BASE x 45-FT HEIGHT)	20.1	10.3	A	CALCULATED RESULTS
700-CU. IN. AIR GUN ARRAY	20 GUNS (10-80 CU. IN.), 2 EA 65-FT LINE ARRAYS	18	8	A	P_a/P_b IS ESTIMATED
1341-CU. IN. AIR GUN ARRAY	7 GUNS	12	12	A	GUN SIZES UNKNOWN
VAPORCHOC II	2-KG (4.4-LB) STEAM AT 60 BAR AND 400°C EXHAUSTED THROUGH EIGHT JETS	32	5	C	DEBUBBLE PROCESS REQUIRED, CALCULATED, CGG TRADEMARK
VAPORCHOC I	SAME STEAM CONDITIONS AS VAPORCHOC II EXHAUSTED THROUGH ONE JET	8	5	C	DEBUBBLE PROCESS REQUIRED
ONE SLEEVE EXPLODER	PROPANE/OXYGEN ACTUATED, 1.25 SEC FILL, 11 IN. D x 7-FT L	0.74 (o-p, SCOPE PHOTO)	3.2	A	NEAR FIELD SIGNATURE FROM 1969 OTC PAPER NO. 1120

NOTE: ALL AIR GUNS AND WATER GUNS CHARGED TO 2000 PSI



The peak pressure in bars at 1 m equals $P_a/2$, since P_a is a peak-to-peak value. The peak pressure in dB//1 μPa at 1 m is $100 + 20 \log \left(\frac{P_a}{2} \times 10^6 \right)$

Table 5.10 Characteristics of some marine seismic energy sources in recent use (from Johnston and Cain 1981)

SOURCE DESCRIPTION	P_c (PSI)	V_c (CU IN.)	d (FT)	P_a (BAR-M) (P-P, 0-125 HZ)	P_a/P_b (-)	E_t (J/m^2 @ 1 m) (0-125 HZ)
GECO ARRAY 3100 + 1640	2000	4740	25	82.4	9.7	106
GSI ARRAY 4000 PNU-CON	2000	4075	20	80.0	10.0	92
GECO ARRAY 3100	2000	3100	25	76.3	9.7	99
SSL ARRAY 4440	2000	4440	28	73.4	11.5	77
GSI ARRAY JONSSON 2000	2000	2000	20	55.0	13.0	46
GECO ARRAY 1985 + 1640	2000	3625	25	49.4	9.5	48
WESTERN ARRAY 1050	4500	1050	20	42.0	5.9	41
GECO ARRAY 1985	2000	1985	25	41.9	8.4	30
WESTERN MAXIPULSE	0.27 kg CHARGE @ 40 FT DEPTH			35.0	1.1	35
SSL ARRAY 1460	2000	1460	25	25.3	8.7	
WESTERN ARRAY 555	4500	555	20	25.2	4.6	11
GECO 594 SUBARRAY	2000	594	27	11.9	6.4	3
FLEXICHOC ARRAY 16 ea FHC-50	—	—	13	10.6	7.5	1.1
WATER GUN HWG-57	3000	57	10	2.3		0.09
SPARKER 30 kJOULE	12 kV	294 μF (21 kJ)	10	2.2 (0-248 HZ, NEARFIELD)	1.3	0.07
SODERA WATER GUN	2600			2.2	4.1	0.08

* P_c = Pressure within guns before release; V_c = total volume of guns; d = depth of guns below surface; P_a = source strength = acoustic pressure (peak-to-peak) at reference distance 1 m; P_a/P_b = ratio of initial to first bubble pulse (see Table 5.9); E_t = energy flux. P_a in bars at 1 m can be converted to dB//1 μPa as explained below Table 5.9.

or similar chemical explosive; 14-23 kg charges were most common. Charges were fired at relatively shallow depths so the initial bubble created by the explosion could be vented to the atmosphere to avoid a phenomenon called bubble pulse oscillation. If a charge was fired sufficiently deep, hydrostatic pressure caused the bubble to oscillate, creating a pulse of sound with each oscillation. These multiple pulses caused a prolonged and "noisy" return signal from the geologic structures. This was avoided by setting off a relatively large charge at shallow depth. The bubble vented, causing a geyser of water but no oscillation.

Various problems, including concern about the damage to fish and other marine life caused by underwater explosions, led to the development of "non-explosive" seismic techniques by the mid-1960s (Table 5.11). Various methods were developed to suppress or eliminate the bubble pulse without the need to vent to the atmosphere. Thus, less intense pulses produced at depth could achieve the same seismic efficiency as a strong explosion near the surface (Table 5.11). In addition, the non-explosive sources developed at this time were relatively small in size, could be fired repeatedly, and could be configured in arrays with appropriate time control to focus a beam of acoustic energy downward. These new seismic energy sources led to survey techniques that relied almost exclusively on seismic reflection, permitting both source and receiver to be operated from a single vessel.

Explosives are now rarely used in marine seismic surveys, especially in U.S. waters. The proceedings of a workshop entitled "Effects of Explosives Use in the Marine Environment" present a relatively current review of explosive sources and their effects on marine life (G.D. Greene et al. 1985).

5.3.2 Vibroseis

Portions of the Alaskan Outer Continental Shelf (OCS) are ice-covered for much of the year. Vibroseis is a method of seismic profiling conducted on shore-fast ice. This allows offshore seismic surveys to be carried out during the latter part of the winter, when the ice is thick enough to support heavy equipment. Vibroseis involves energizing the ice by vibrating it with powerful hydraulically-driven pads mounted beneath trucks called "vibrators". A typical Vibroseis convoy consists of four such vibrators accompanied by a drill truck to test ice thickness, a bulldozer to scrape the ice smooth to aid coupling between the vibrator pad and the ice, a truck to lay the sensor cable, a recording van, and a fuel truck.

Prior to the onset of vibrations, each vibrator truck is jacked up to put much of the vehicle's weight on the pads. The vibrations of the four vehicles are synchronized. A typical Vibroseis signal sweeps from 10 to 70 Hz, with harmonics extending upward to about 1.5 kHz (Fig. 5.20A). The sweep is repeated 10 times before the convoy moves along the shot line about 70 to 100 m to repeat the process (Holliday et al. 1984). Each sweep lasts 5 to 20 s. Vibroseis is the one seismic technique considered in this review that does *not* involve short sound pulses.

Although several estimates of the source levels of Vibroseis signals have been reported, the effective source levels for horizontal propagation are uncertain. Holliday et al. (1984) estimated the source level of a four-vibrator array to be 187 dB re 1 μPa-m at 50 Hz during a 5-s sweep between 10 and 65 Hz. This estimate was based on horizontal beam-aspect prop-

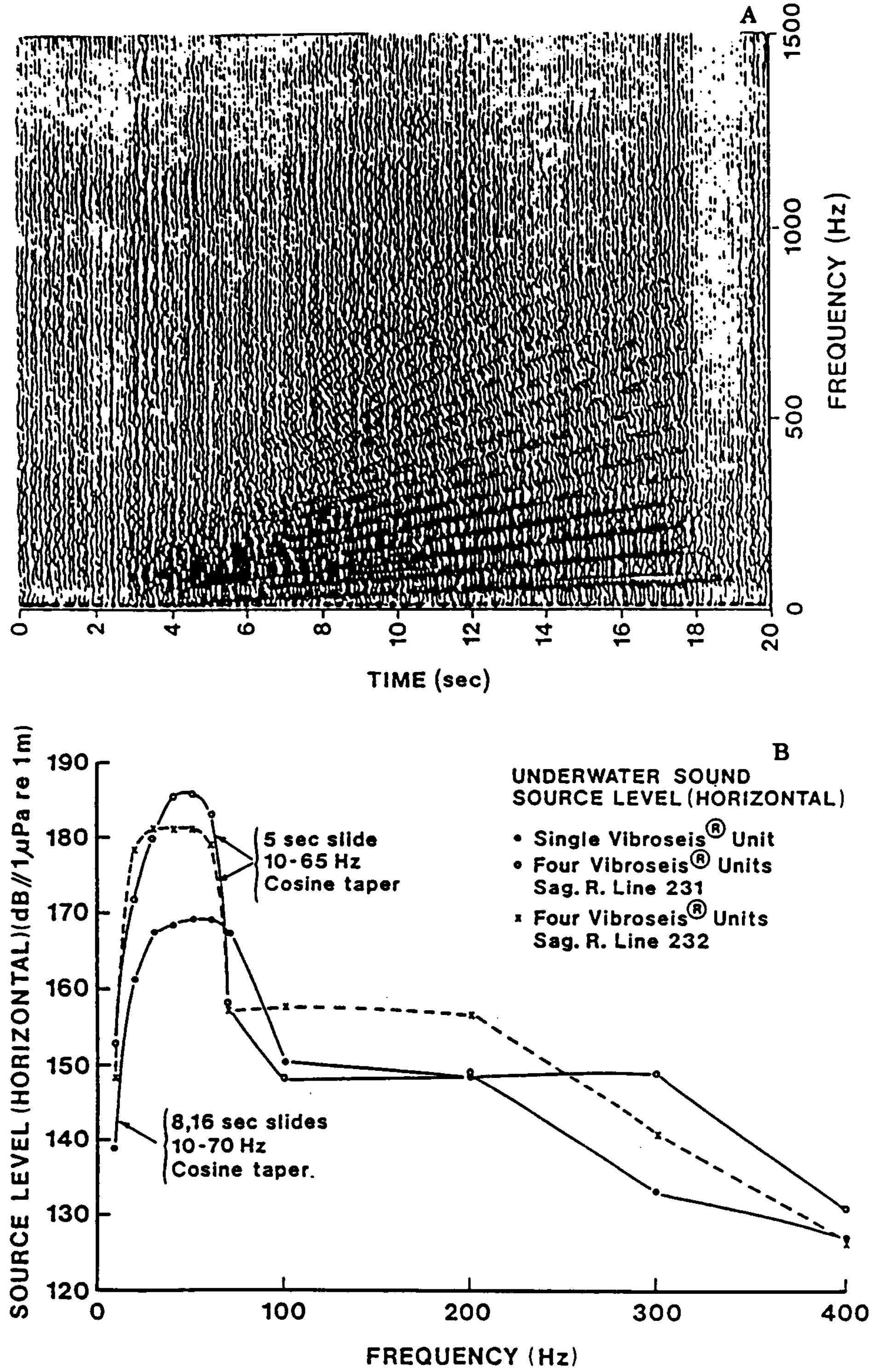


FIGURE 5.20. Vibroseis sounds: *(A)* Spectrogram of underwater noise from Vibroseis sweep; fundamental sweeps from 10 to 70 Hz, with harmonics to 1200 Hz. *(B)* Underwater sound source levels in the horizontal plane for four Vibroseis units and for a single unit. The spectrum analyzer was set for bandwidth 1.25 Hz and "peak hold", meaning that the peak level seen in each frequency bin was retained for plotting. From Holliday et al. (1984).

Table 5.11. Seismic energy sources, method of energy generation, and estimated source level (dB re 1 µPa-m). Vibroseis source levels were based on lateral measurements; other source levels were based on total energy. Data (except Vibroseis) from Appendix A.2 in Malme et al. (1984).

Source	Method	Size	Estimated Source Level (dB re 1 µPa-m)
EXPLOSIVE			
TNT	Chemical	0.5 kg	267
		14 kg	277
Black Powder	Chemical	0.5 kg	246
NON-EXPLOSIVE			
Vibroseis	Continuously driven piston with variable frequency waveform	4 units	230[a] 187[b]
Airgun	Compressed air discharged into piston assembly	1.6 L	226[c]
Airgun array	" " "	33 L	239
Gas Sleeve Exploder	Ignition of gas mixture in a plastic sleeve	1 sleeve	217[c]
Sparker	Electric discharge of a capacitor bank across electrodes	30 k-joule	221
Boomer	Electric discharge of a capacitor across two metallic plates	500 joules	212
Water Gun	High pressure water to solenoid-triggered piston	0.9 L	217[c]

[a] Acoust. Soc. Am. (1981) [b] Holliday et al. (1984)
[c] Usually employed in arrays with higher total source level.

agation in very shallow (<9 m) water. Holliday et al. reported a level 20 dB lower for endfire (ahead or behind) aspects. The downward radiation was thought to be as much as 30 dB stronger. Cummings et al. (1981b), also based on measurements of a four-vibrator array, cited a source level of 185 dB re 1 µPa-m in the overall frequency band to 2 kHz. This estimate was based on a received level of 144 dB at a horizontal distance of 328 m. Given the shallow water and a source on the surface, the transmission loss from the source to 328 m might be expected to be more than the assumed 41 dB, i.e. the source level for horizontal propagation might have exceeded 185 dB. Given this possibility, Malme et al. (1989) estimated a considerably higher source level based on the Cummings et al. (1981) data. However, C. Malme (pers. comm., 1991) believes that there are too many uncertainties about the transmission conditions to permit reliable estimates of the source level. Thus, the source level for horizontal propagation from a four-vibrator Vibroseis array can be said to be at least 185 dB, and probably more.

Propagation losses for underwater Vibroseis noise generally increased with frequency, and were larger in shallower water for a given frequency. Propagation losses were related to distance in a roughly linear fashion, and ranged from 22.5 dB/km at 10 Hz to 31.2 dB/km at 60 Hz (Holliday et al. 1984). This linear relationship to distance indicates that a high proportion of the attenuation was due to absorption into the bottom and overlying ice cover, and to scattering due to local boundary roughness (Chap. 3; Urick 1983). Under these environmental conditions, Holliday et al. (1984) estimated that a Vibroseis source level of 190 dB re 1 μPa-m would diminish to the ambient noise level (about 70 dB) at distances of 3.5-5 km.

5.3.3 Airguns

Airgun arrays are now the most common energy sources used to conduct marine geophysical surveys. They produce the highest underwater sound levels regularly associated with oil and gas development. Broadband source levels of 248 dB re 1 μPa-m are typical of a full-scale array (Barger and Hamblen 1980), and source levels as high as 255 dB have been reported (Greene 1985b). The geophysical literature contains information about the effects of array design on the characteristics of the sound pulses that propagate vertically (Barger and Hamblen 1980; Kramer et al. 1968). The 248 and 255 dB source levels quoted above, and those listed in Tables 5.9-5.10, refer to downward propagation.

Of greater interest here are the characteristics of the sound pulses that propagate horizontally in the water. The effective source level of an array for horizontal propagation will often be less than that for vertical propagation, and will also depend on aspect relative to the long axis of the array. Even with these allowances, the effective source levels of airgun arrays for horizontal propagation are extremely high. Because of this, and the frequent use of airgun arrays in continental shelf areas, horizontal propagation of airgun signals has been investigated in numerous studies (e.g. Malme et al. 1983, 1984, 1985, 1986a,b; Greene 1985a,b; Richardson et al. 1986; Miles et al. 1987; Pearson et al. 1987; Greene and Richardson 1988; Ljungblad et al. 1988b).

Airguns all function in much the same way. A container of high pressure air is vented suddenly into the water. This produces an air-filled cavity that expands violently, then contracts, and re-expands; sound is created with each oscillation. Although a single airgun is sometimes used, seismic surveys are usually conducted by towing an array of airguns at a depth of 4 to 8 m (Barger and Hamblen 1980; Hoff and Chmelik 1982). To locate deep structures, large arrays containing 12-24 airguns are common. In other applications, only a few airguns may be used. A 3000 to 3600 m cable containing up to 24,000 individual hydrophones is towed behind the airgun array to receive the reflected signals from beneath the sea floor (Fig. 5.21A).

The level, duration and frequency content of pulses received from an airgun array depend upon numerous factors, including the aspect of the receiver with respect to the array alignment; the sizes, number, and spatial pattern of airguns in the array; the air pressure; local transmission loss characteristics; and receiver range and depth.

The airgun array directs most but not all sound energy downward. One important result of this is that, analogous to Vibroseis signals, sound levels directly ahead of and behind the seismic ship (bow and stern aspect) are roughly 20 dB less than levels directed downward or to the side (Fig. 5.21B). These nulls in sound level represent a 10:1 reduction of sound

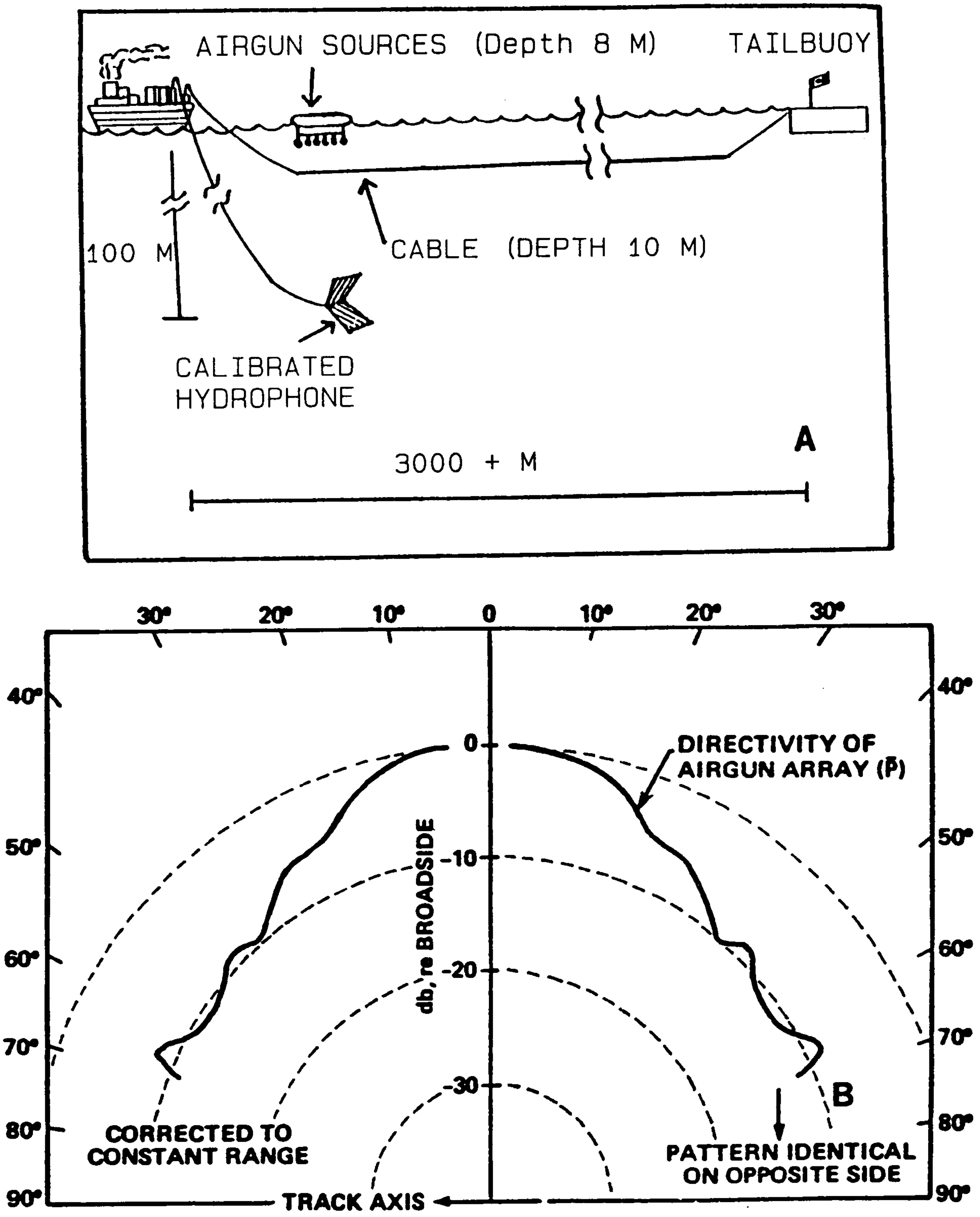


FIGURE 5.21. Schematic representation of *(A)* a towed airgun array, and *(B)* the horizontal directivity pattern of underwater noise from a 66 L airgun array. The pattern is almost the same forward and aft of the ship (left and right sides of graph, respectively). The dB levels are to be read radially from the origin. Adapted from (A) Duncan (1985) and (B) Malme et al. (1983).

pressure (Malme et al. 1984). They noted that sound levels from an airgun array at bow or stern aspect may be no higher than those received from a single airgun. However, despite the fact that geophysicists attempt to direct as much sound energy as possible downward, strong sound pulses are projected horizontally into the water in certain directions, and these can be detected many kilometers away (Fig. 5.22; Malme et al. 1983; Greene and Richardson 1988). Figure 5.23 shows the estimated third-octave source-level spectrum for horizontally-propagating pulses from a representative airgun array. Source levels are estimated as being near 210 dB re 1 μPa-m in several 1/3-octave bands (from Malme et al. 1989).

Signals from airguns originate as short, sharp pulses, typically emitted every 10 to 15 s although shorter intervals are sometimes used. By design, most of the energy is at low frequencies, 40-120 Hz. Energy at higher frequencies would be wasted for geophysical survey purposes because it would be rapidly attenuated when propagating vertically in the bottom sediments. However, the pulses do contain some energy at frequencies as high as 500-1000 Hz. This is insignificant when compared to the very strong low frequency energy but very significant when compared to ambient noise levels in shallow water. As the pulses propagate horizontally in shallow water, the low frequencies attenuate rapidly, leaving only the higher frequency energy (Fig. 5.22B vs. 5.22C).

During horizontal propagation, the initially short pulse is elongated by the combination of multiply-reflected sound rays bouncing between the surface and the bottom. After traveling some distance in shallow water (normally >5 km), the pulse can extend to ¼-½ s or more in duration.

After propagating several kilometers the now-elongated pulse also tends to develop a particular pattern of frequencies. In shallow water, it tends to include a downward sweep in frequency (Fig. 5.22). The predominant frequency at the leading edge of the pulse is usually between 200 and 400 Hz, dropping to 100-200 Hz at the end of the pulse (Greene 1985a). The once-sharp signal then sounds like a downward "chirp". Such a downward chirp signal is characteristic of the geometrical dispersion of sounds undergoing multiple reflections between the surface and bottom in shallow water (sect. 3.4). In deeper water with upward refraction of sound rays, such as is often found in icy waters, the combination of multiply-refracted, surface-reflected sound rays forms a frequency upsweep (Officer 1958; Richardson et al. 1987b:340).

In some areas the low frequency energy may travel long distances through the bottom sediments, re-entering the water far from the source. Sound speeds through the bottom are generally faster than those in water. Hence, at a distant receiver there may be an initial low frequency pulse, resulting from the bottom-traveling energy, followed an instant later by a higher frequency pulse resulting from the water-traveling energy.

Differences in sound attenuation rate can have a strong effect on the received levels of airgun signals. For example, Malme et al. (1986a) describe the differences for pulses traveling upslope toward shallower water versus downslope toward deeper water or along shore at constant depth. For sand or rock bottoms, seismic pulses traveling upslope are attenuated faster than those traveling alongshore or downslope. Further, Malme et al. (1986a) found that received levels of sounds from a single airgun decreased by 15 log (range) but sounds from an airgun array decreased by 25 log (range) in the same area off central California. This difference in

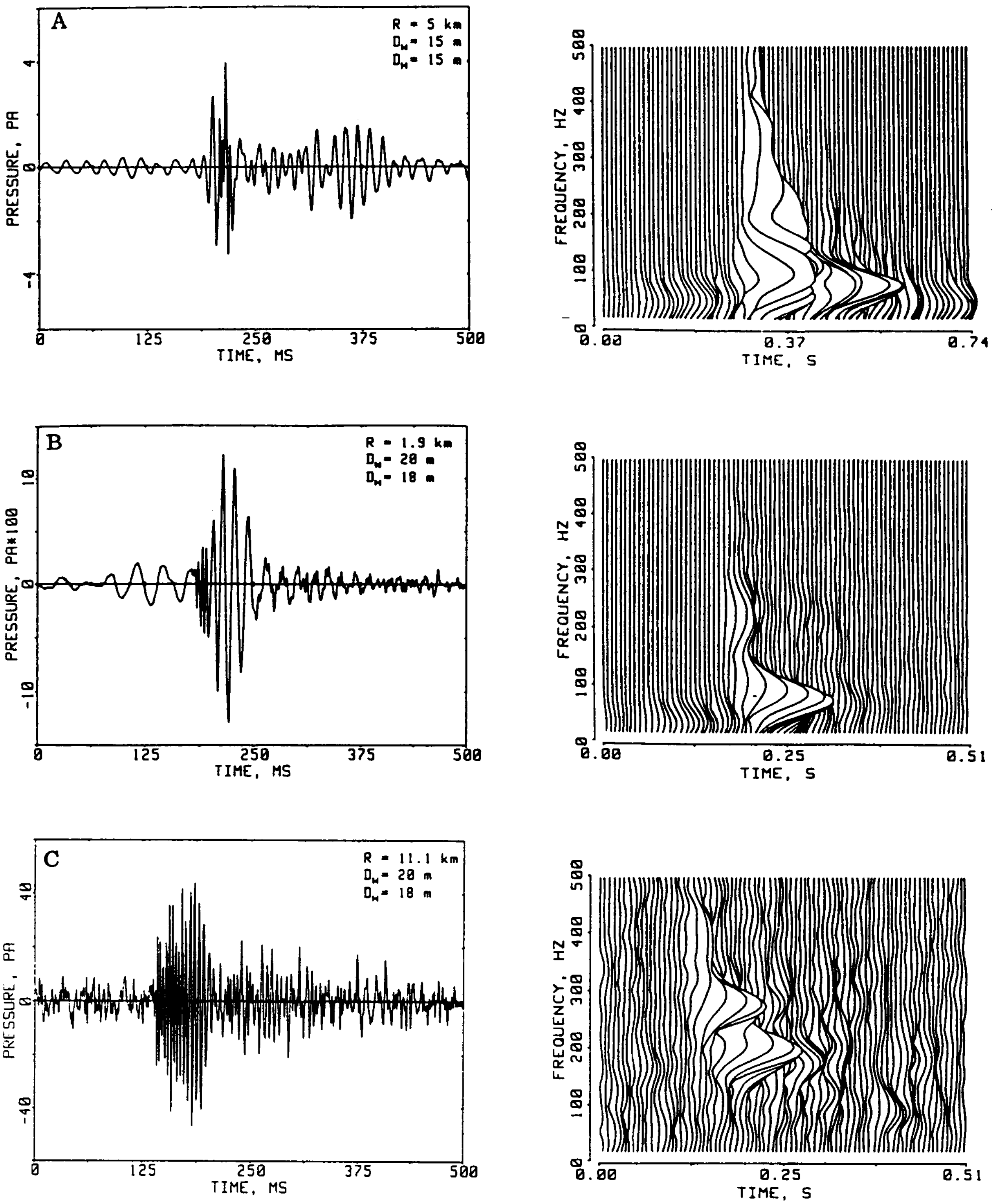


FIGURE 5.22. Airgun pulse characteristics: pressure waveforms (left) and waterfall spectrograms (right) for *(A)* a pulse from a single 40 in^3 (0.66 L) airgun received underwater 5 km away, and for a pulses from a 28-L airgun array at *(B)* 1.9 km and *(C)* 11.1 km. From Greene and Richardson (1988).

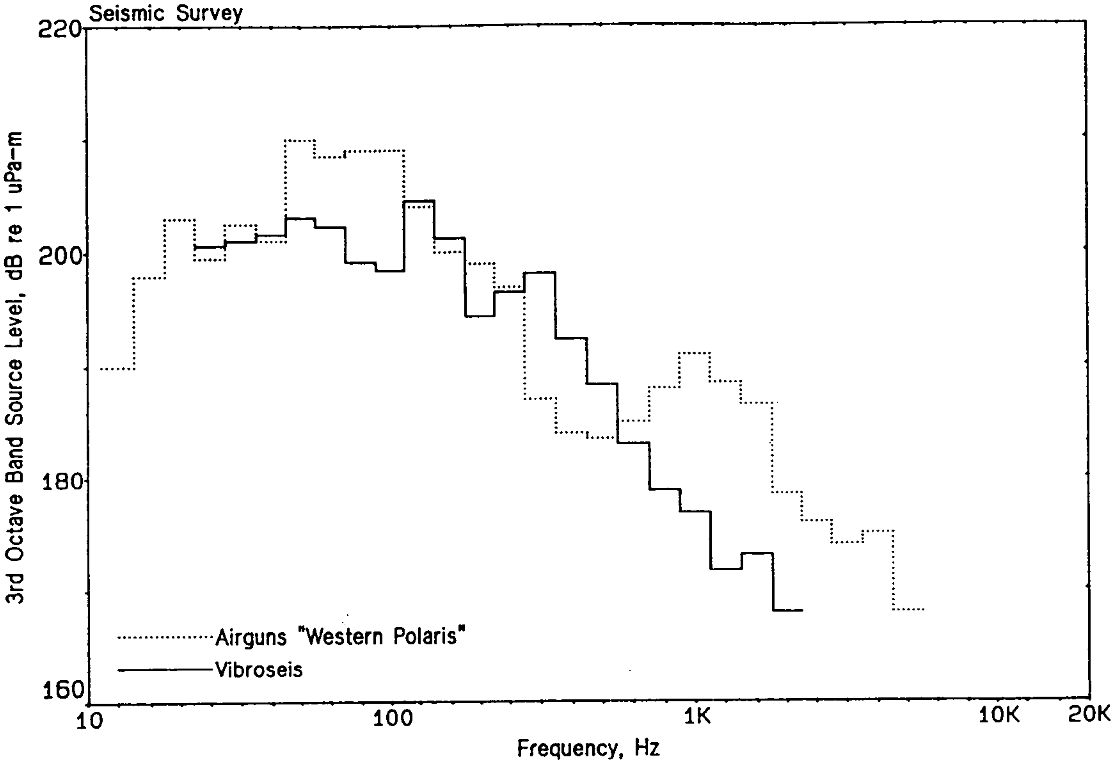


FIGURE 5.23. Estimated peak one-third octave source levels (at 1 m) for horizontal propagation of Vibroseis signals and of airgun array pulses from a 32-gun array on *Western Polaris*. Data from Malme et al. (1989). **Note**: the estimates for Vibroseis are subject to considerable uncertainty (see sect. 5.3.2).

propagation loss was thought to be due to surface reflections that depend on array aspect. A similar hypothesis was presented by Grachev (1983) for signal attenuation in shallow seas.

Received levels of seismic signals, like other underwater sounds, diminish with increasing range (see Fig. 5.25, later). To a first approximation, the decrease in the received level of airgun signals often can be described by spherical or cylindrical spreading loss (i.e. 20 or 10 log range) plus a linear range term for losses due to absorption and scattering (Greene and Richardson 1988). In their study, the linear coefficients for airgun levels ranged from -0.61 dB/km for water 20 to 110 m deep to -0.97 dB/km for water <20 m deep. For water depths on the order of 25-50 m, operating airgun arrays are often audible to ranges of 50-75 km; detection ranges can exceed 100 km during quiet times with efficient propagation.

The received level of airgun pulses at a specific range is reduced just below the surface relative to the levels at deeper depths. In one case, received levels for a geophysical vessel operating 9-17 km away were 1-4 dB less at 9 m depth than at 18 m (Greene 1985a).

Similarly, signals received from a 3-airgun array at ranges 3-10.4 km averaged ~7 dB less at depth 3 m than at 9 and 18 m (Greene and Richardson 1988). This phenomenon is accounted for by the "Lloyd Mirror Effect" (Urick 1983:131) in which sound incident on a "pressure-release boundary" (water-air interface) interferes with its reflection, depending on angle of incidence, frequency and depth (sect. 3.5.2).

In ***summary***, airgun arrays (along with other seismic sources) are by far the strongest sources of underwater noise associated with oil and gas exploration and development. However, the extremely short duration of each pulse limits the total energy. With increased distance from the source, received pulses from airgun arrays generally decrease in level but increase in duration. The elongated pulses received at ranges beyond a few kilometers sound "chirp"-like, with higher frequencies usually arriving before lower frequencies. Levels vary dramatically with horizontal aspect; the strongest levels are directly abeam of the array and the weakest are along the axis of the tow line. Pulses traveling upslope along rock or sand bottoms are attenuated faster than those radiated alongshore or downslope. Pulses from an airgun array may attenuate more rapidly than those from a single gun, depending on the array aspect. However, received levels from arrays are normally higher than those from a single airgun because of the stronger source level of the array. Received levels at a specific range are generally several decibels lower near the surface (e.g. 3 m depth) than at deeper depths (e.g. 9-18 m).

5.3.4 Sleeve Exploders and Gas Guns

Although airguns are the most widely used sources for geophysical surveys, arrays of sleeve exploders and open bottom gas guns are also common sources of noise pulses. These devices are charged with a mixture of oxygen and propane, which is exploded to produce the sound pulse. The sleeves expand but do not oscillate, producing shorter bursts than airguns of comparable energy. The resulting pulsed signals are quite similar to those from airguns in numerous respects, including the fact that they propagate horizontally through the water for many kilometers.

Pulses from sleeve exploders and gas guns, like those from airguns, become elongated and "chirp"-like with increasing horizontal range (Fig. 5.24; Greene and Richardson 1988). In one case, received signals from a sleeve exploder array were roughly 250 ms in duration at 8 km and over 400 ms at 28.7 km. The downward frequency sweep of the elongated signal was clearly evident (Fig. 5.24A,B). A more complex case, involving gas gun signals, is shown in Fig. 5.24C,D. At 0.9 km, the pulses were 200 ms long with most energy concentrated near 72 Hz (Fig. 5.24C). At 14.8 km, the signal was roughly 250 ms long, with the strongest components occurring, in temporal sequence, near 270 Hz, 500 Hz, 370 Hz and 250 Hz (Fig. 5.24D). These changes may have been related to a geological discontinuity known to exist in the area.

The received levels of pulses from a sleeve exploder array operating in shallow water were 148-153 dB re 1 μPa at 8 km and 115-117 dB at 25-29 km (Greene and Richardson 1988). Received levels for the open bottom gas guns operating in even shallower water ranged from 177 dB at 0.9 km to 123 dB at 14.8 km. There was no specific information on the aspect or configuration of the open bottom gas gun array. Regression equations describing the measured transmission loss (Fig. 5.25) included a cylindrical spreading loss term (i.e. 10 log range) plus a linear term with coefficients -1.39 dB/km for sleeve exploder signals in water 15-30 m deep,

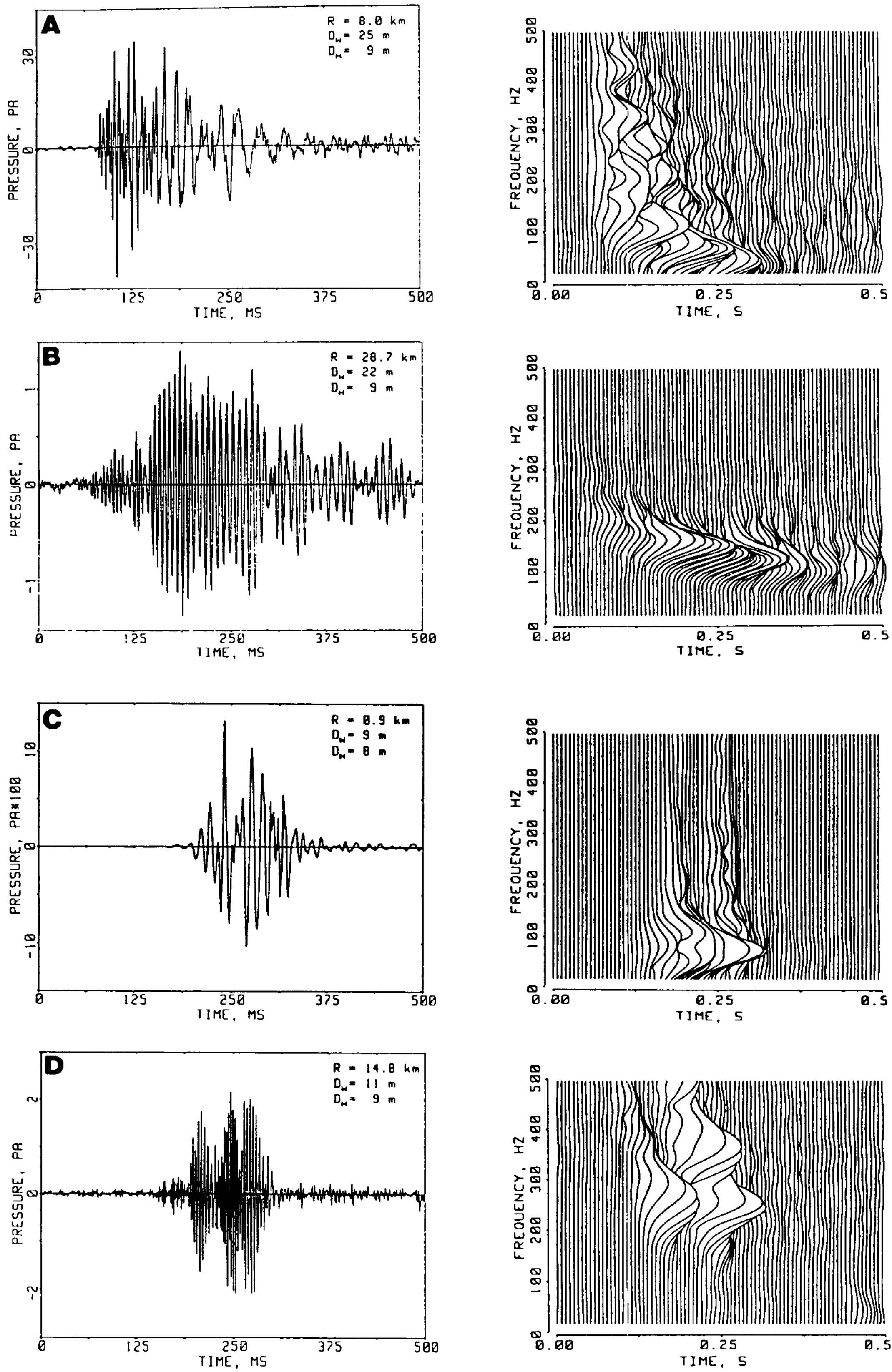


FIGURE 5.24. Sleeve exploder and gas gun pulse characteristics: pressure waveforms (left) and waterfall spectrograms (right) for underwater pulses from an array of sleeve exploders at range *(A)* 8 km and *(B)* 28.7 km, and from an array of open bottom gas guns at *(C)* 0.9 km and *(D)* 14.8 km. From Greene and Richardson (1988).

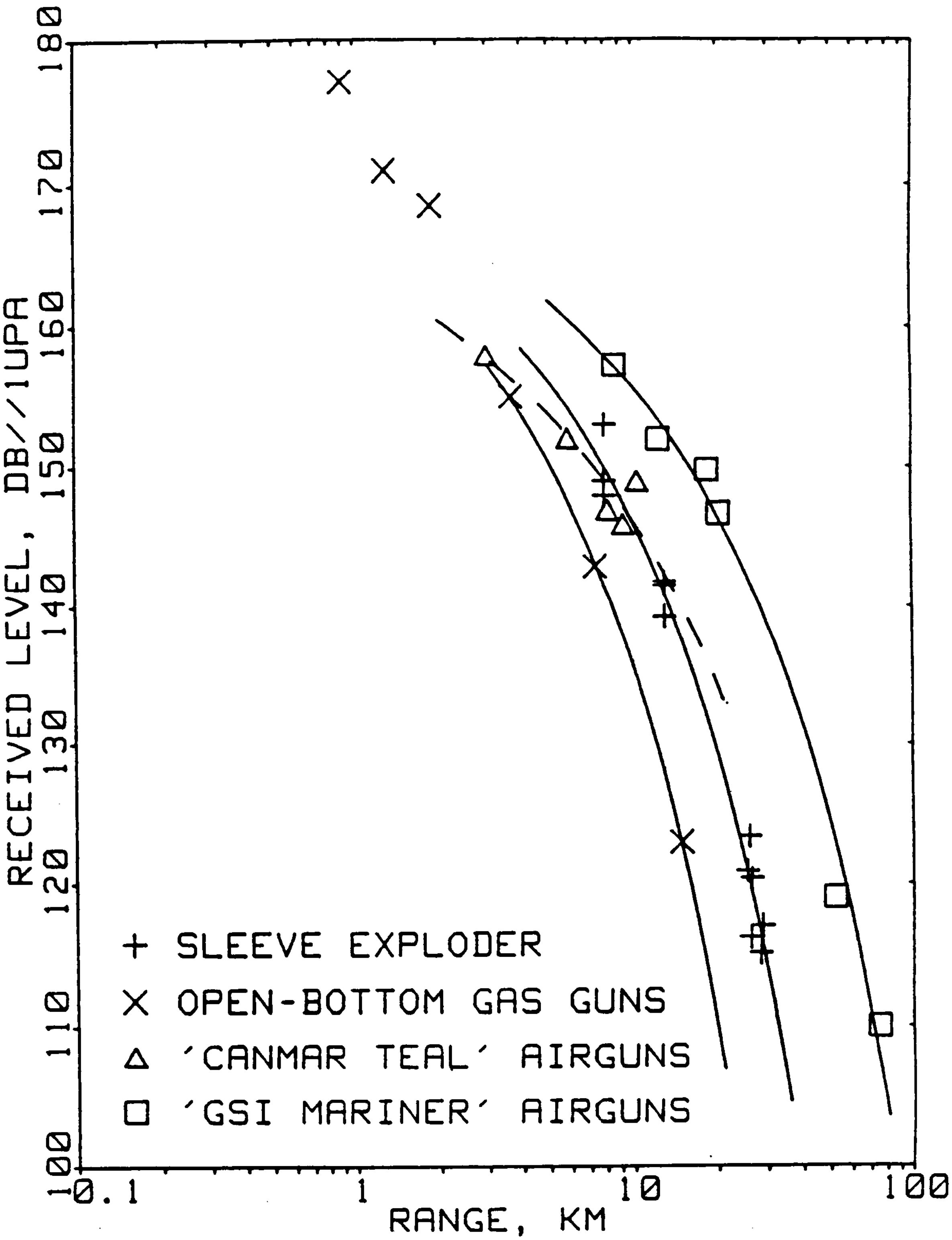


FIGURE 5.25. Seismic noise vs. range: received underwater levels of seismic signals vs. range, with best-fit regression curves. From Greene and Richardson (1988).

and -2.33 dB/km for gas gun signals in water 9-11 m deep. The difference is related to the differing sound propagation conditions at the two sites, rather than to differences between the source.

In ***summary***, sleeve exploders and open bottom gas guns produce high energy pulses with levels and propagation characteristics very similar to those of airgun signals. As with airgun signals, received levels generally decrease, and signal duration increases, with increasing range. In shallow water, higher frequencies (~200 Hz) usually arrive before lower frequencies (~70 Hz) at ranges of several kilometers. This results in a downward sweeping "chirp"-like sound.

5.3.5 Lower-Energy Techniques

Lower-energy devices of several types are sometimes used as sources of noise for seismic surveys (Table 5.11). A boomer or sparker produces a sound pulse by the sudden discharge of electrical energy stored in a bank of capacitors. Water guns discharge a solenoid-triggered piston with high pressure water. Kramer et al. (1968) review such sources. Although some of these sources have been used for many years, we are not aware of any measurements documenting lateral sound transmission from them. However, the characteristics of the initial energy discharge have been reported (e.g. Kramer et al. 1968; Malme et al. 1986a).

The pressure waveform from spark sources has a characteristic double peak. The spark discharge forms a steam bubble and initial pressure pulse; the bubble then collapses to produce a large secondary pulse (Fig. 5.26). The second large peak is followed by a number of smaller pulses from bubble pulse oscillations. Pulse characteristics vary with power level and operating depth. Spark sources are used less frequently now because the results are somewhat difficult to interpret. Also, the sparker is less efficient than some alternative sources.

Water guns produce pulses by creating a large void in the water similar to a cavitation bubble, after which the void collapses. An initial low-amplitude pulse associated with the release of high pressure water is followed by a major pulse that occurs with the collapse of the water cavity (Fig. 5.27A). Relative to comparably-sized airguns, the spectrum of water gun pulses has a higher proportion of energy above 200 Hz. This occurs because there is no significant gas-filled bubble, and thus little low-frequency bubble-pulse energy (Hutchinson and Detrick 1984). As a result, water guns are often used for high resolution seismic profiling.

In ***summary***, although lower-energy seismic sources such as sparkers and water guns are commonly used in marine geophysical surveys, their horizontal transmission properties have not been reported insofar as we know. Pressure waveform signatures for such sources differ from one another, and from those of higher energy sources such as airguns or Vibroseis. Thus their transmission properties are likely to be different as well. Their signal characteristics as a function of horizontal range cannot be determined without field measurements.

5.4 Oil and Gas Exploration and Production

Offshore drilling is usually conducted from man-made islands or platforms, or from drillships accompanied by a variety of support vessels. When recoverable deposits are found, further offshore construction may be necessary in advance of production. All of these offshore activities produce underwater noise. In addition, they require extensive aircraft and vessel

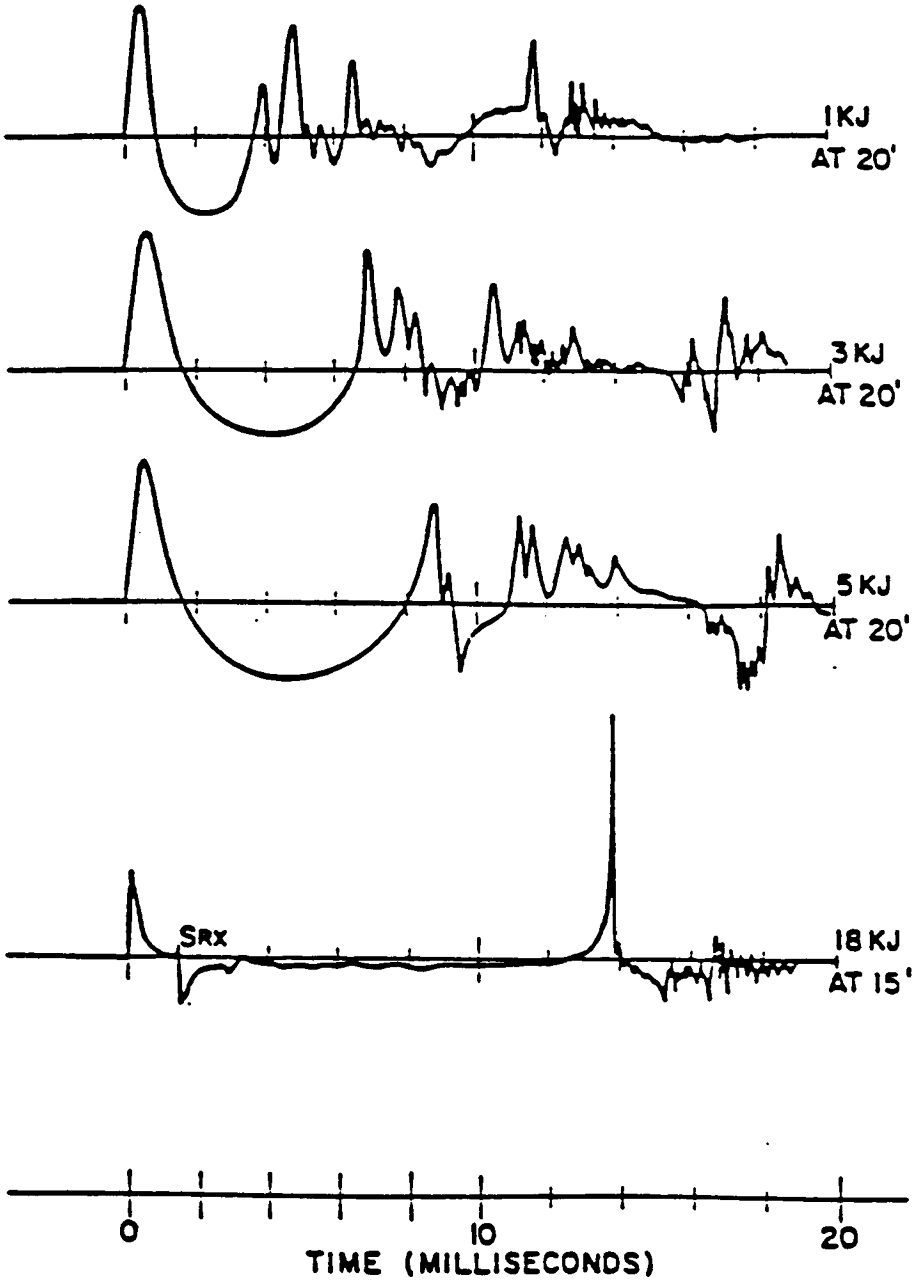
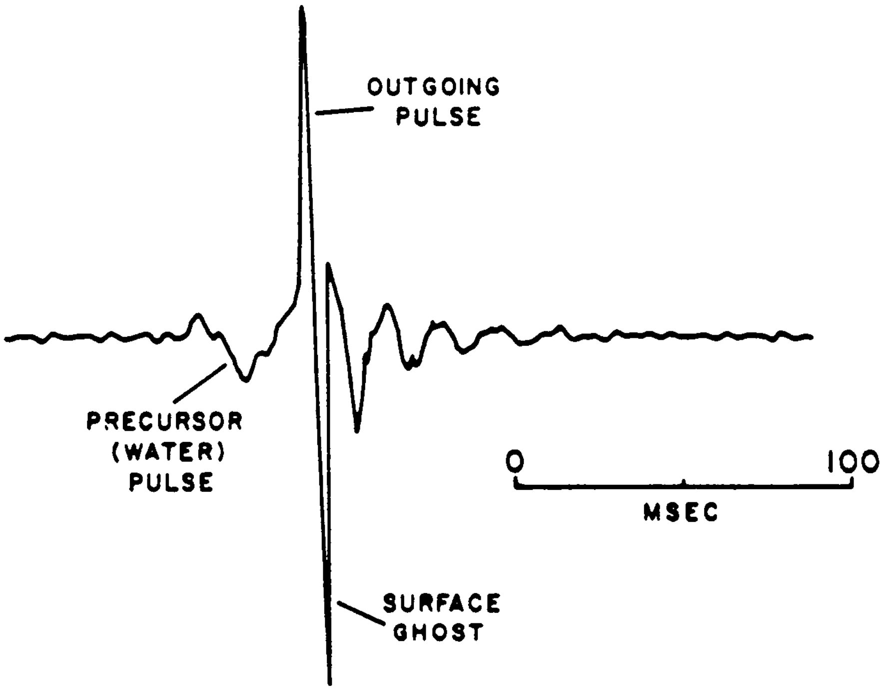


FIGURE 5.26. Spark sources: pressure waveform signatures at various power levels and depths as measured close to the source. From Kramer et al. (1968).



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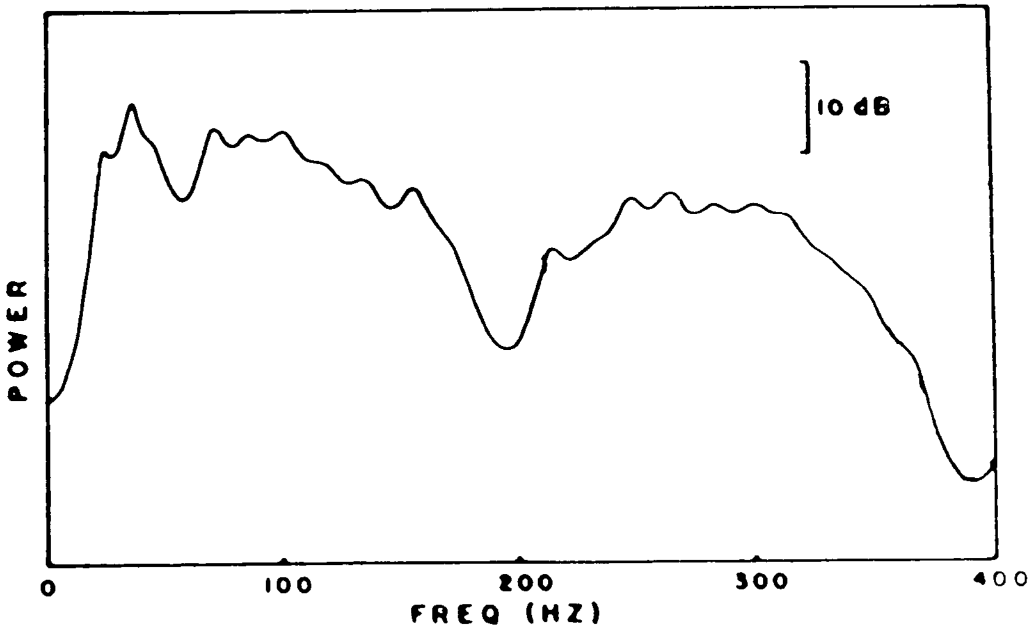


B. SPECTRUM

FIGURE 5.27. Water guns: *(A)* pressure waveform and *(B)* source power spectrum (from Hutchinson and Detrick 1984).

support that may further ensonify relatively broad areas around the offshore drillsite. Thus, offshore drilling and production facilities involve a variety of activities that produce a composite underwater noise field.

Four comprehensive studies of underwater noise associated with offshore oil and gas exploration have been conducted to date. Gales (1982) measured noise near platforms and man-made islands where drilling or production were occurring. Recordings were made off Santa Barbara, California; in Cook Inlet, Alaska; and in Atlantic waters off New Jersey. Gales presents the only comprehensive work to date on spectral characteristics of underwater noise from drilling and production operations in temperate waters. In the arctic, three studies examined radiated noise levels, spectral characteristics, and propagation near various industrial activities at drillsites in the Beaufort Sea (Greene 1985a, 1987b; Miles et al. 1986, 1987; Greene 1987a). In addition, several other studies of narrower scope have provided relevant data on specific offshore drilling activities.

Industrial noise sources associated with hydrocarbon exploration and recovery are reviewed here in the order of their likely occurrence, i.e. dredging and construction, offshore drilling, and offshore production. Noises from transportation sources and geophysical surveys, which often are present near exploration and production operations, were discussed earlier in this chapter.

5.4.1 Dredging and Offshore Construction

Offshore dredging and construction are often associated with offshore exploration and production. Underwater noise associated with these activities has been studied only in the Beaufort Sea. Hence, the types of marine construction activities whose noise has been documented are those usable in the arctic.

Offshore drilling in the arctic is often done from man-made islands or from caisson structures placed on the bottom or on sub-sea berms. These techniques are used when the drillsite is in water sufficiently shallow to permit their construction. Construction can be either in winter or summer. In winter, ice roads are built on the sea ice and trucks are used to haul gravel to the site (e.g. Greene 1983). In summer, dredges and sometimes barges are required to pile gravel onto the site. Three types of dredges are commonly used: cutter-suction transfer dredges, clamshell dredges, and hopper dredges. The transfer dredge is moored and extends suction pipes to the sea floor and discharge pipes to a barge or construction site. A cutter head loosens gravel which is pumped as a slurry through a pipe to the discharge site. The clamshell dredge pulls up large scoops of gravel within opposing buckets that clamp together; barges are commonly used to transfer this dredged material to the construction site. In contrast, the hopper dredge is mobile. It moves over a dredging site and fills its hoppers, and then transits to the construction site to offload the material either by pumping it out as a slurry or by dumping the load through gates in the bottom of the ship.

Dredging Operations.--Greene (1985a, 1987b) found that two cutter suction dredges produced quite different sound levels, and that hopper dredges were at least as noisy as the noisier of the two suction dredges at comparable ranges (Fig. 5.28). Broadband (20-1000 Hz) underwater sounds from these dredges would normally diminish below the typical broadband ambient noise level (about 100 dB re 1 μPa) within 25 km of the dredges. However, some dredges emit strong tones, and these would be detectable at ranges >25 km in some situations.

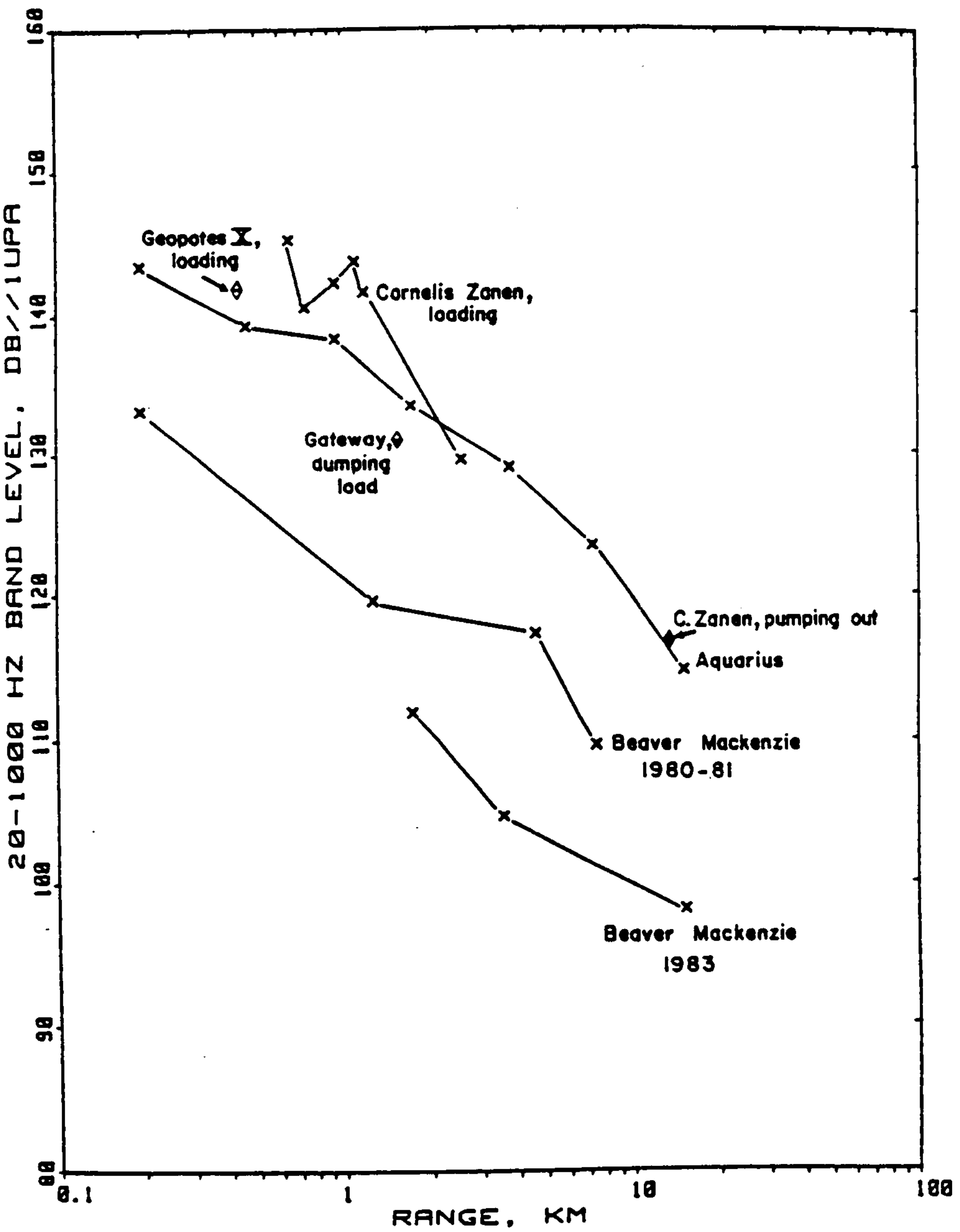


FIGURE 5.28. Dredge noise vs. range: received underwater sound levels (20-1000 Hz) of hopper and transfer dredges in relation to range. Hopper dredges are *Cornelis Zanen*, *Geopotes X* and *Gateway*; transfer dredges are *Beaver Mackenzie* and *Aquarius*; all operating in the Beaufort Sea. Hydrophone depths 9-18 m. From Greene (1985a).

Underwater noise levels from hopper dredges fluctuated with operating status. The highest levels occurred during loading. During all operations, low frequency energy predominated (Fig. 5.29), although sounds recorded at longer ranges showed the expected strong attenuation of low frequency energy in shallow water (Fig. 5.29B,D). Only *Geopotes X* loading produced a strong tone, at 480 Hz (Fig. 5.29C).

The strongest underwater sounds from two cutter-suction transfer dredges studied by Greene (1985a, 1987b), like those from the hopper dredges, were primarily at low frequencies (Fig. 5.30). However, high-frequency tones were also present. Their absolute levels were lower than the levels of low-frequency sounds, but the high-frequency tones were conspicuous against the lower levels of broadband dredge noise and ambient noise found at high frequencies. In the case of *Beaver Mackenzie*, tones were evident both at low frequencies and at the relatively high frequencies of 1604 and 1678 Hz. However, the high-frequency tones were absent after the dredge had been drydocked for overhaul (Greene 1987b). In the case of *Aquarius*, whose overall noise level was higher, tones were present at frequencies up to at least 6700 Hz (Fig. 5.30).

Miles et al. (1986, 1987) measured underwater noise from a clamshell dredge operating in the Beaufort Sea. The "dominant sound" was that of the motor that drove the winch pulling the loaded clamshell back to the surface. This noise had many harmonics with a fundamental at 125 Hz (Fig. 5.31A). Computed source levels ranged from 150 to 162 dB re 1 μPa-m in the 1/3-octave band centered at 250 Hz (Fig. 5.31B). A short transient "clank" sound was associated with the closing of the clamshell, but this sound contained little acoustic energy.

Malme et al. (1989) computed 1/3-octave source levels (at 1 m) for the two cutter suction dredges studied by Greene (1987b) and for a tug towing a barge during the clamshell dredging operation (Fig. 5.32). Dredge *Aquarius* was significantly noisier--by ~17 dB in the strongest bands. Dredge *Beaver Mackenzie*'s strongest 1/3-octave band was about 6 dB above the strongest band for the tug and barge. *Aquarius*'s source levels appear to be comparable to those for a large tanker (*cf.* Fig. 5.11).

Other Construction Operations.--Greene (1983) measured underwater noise from wintertime construction of an artificial island in water 12 m deep near Prudhoe Bay, Alaska (Seal Isl.; see sect. 5.2.4). These recordings were made through shorefast ice. At distances ≥3.6 km there was no evidence of noise components above 1000 Hz, and little energy below 1000 Hz. Construction-related sounds did not propagate well in shallow water under the ice during winter. This conclusion was consistent with the results of Malme and Mlawski (1979) concerning propagation of drilling sounds in the same area during winter.

Summary.--Dredges represent some of the strongest sources of continuous noise associated with the offshore oil industry. Dredge noises are strongest at low frequencies. Because of the rapid attenuation of low frequencies in shallow water, dredge noise normally is undetectable underwater at ranges beyond 20-25 km. Tones may appear in the spectra of dredge noise, even at frequencies above 6 kHz. Although noise levels from icebreakers or supply vessels can exceed those from dredging, icebreakers and ships usually do not produce strong noise in one area continuously for a prolonged period. In contrast, dredging often continues in one area for days or weeks at a time.

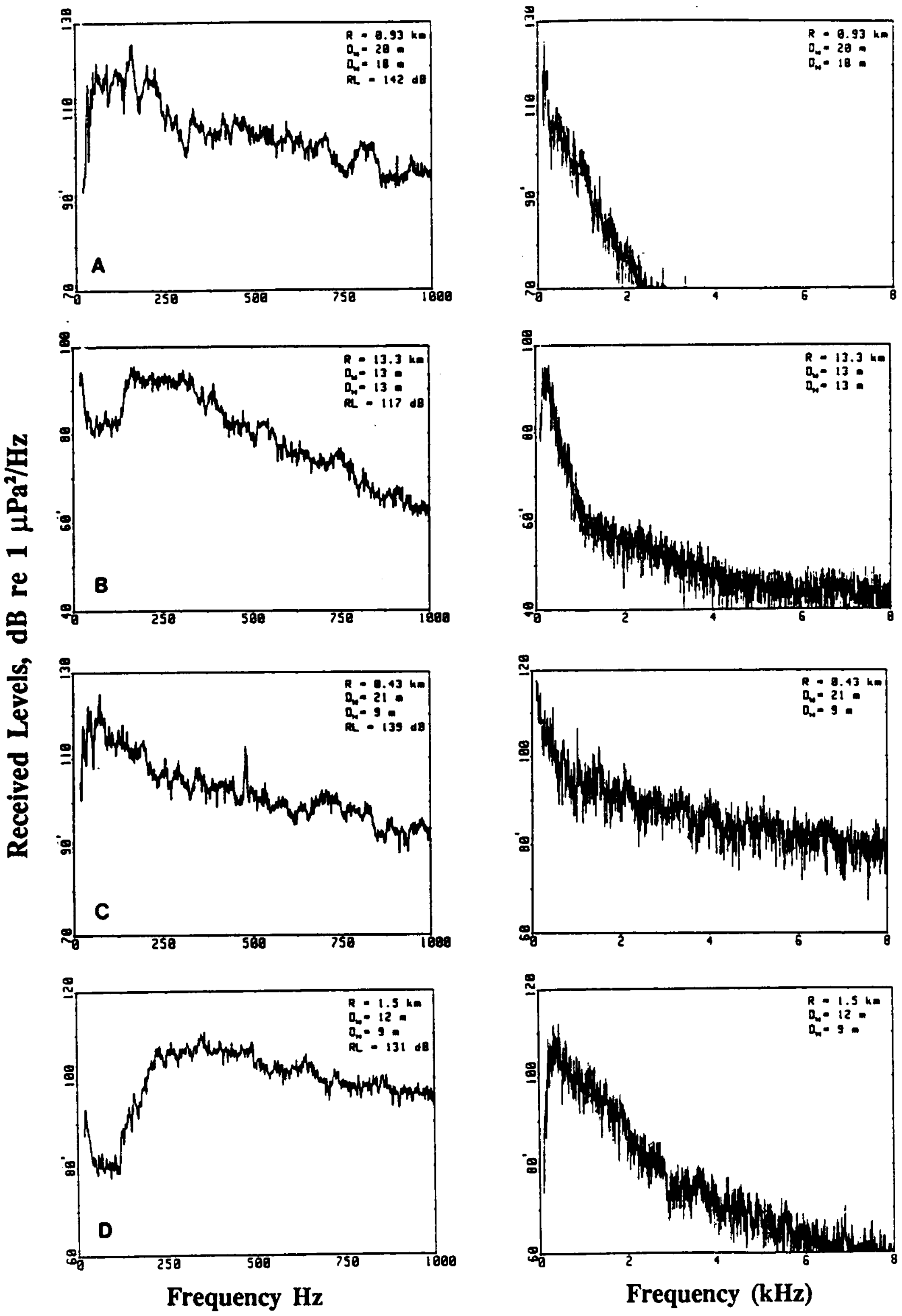


FIGURE 5.29. Received spectrum levels of hopper dredge noise for frequencies 20-1000 Hz (left) and 100-8000 Hz (right). *(A) Cornelis Zanen* during loading at range 0.93 km; *(B) Cornelis Zanen* pumping out at 13.3 km; *(C) Geopotes X* loading at 0.43 km; and *(D) Gateway* dumping a load at 1.5 km. RL is the overall received level in the 20-1000 Hz band. Analysis bandwidth 1.7 Hz (left) and 3.4 Hz (right). From Greene (1987b).

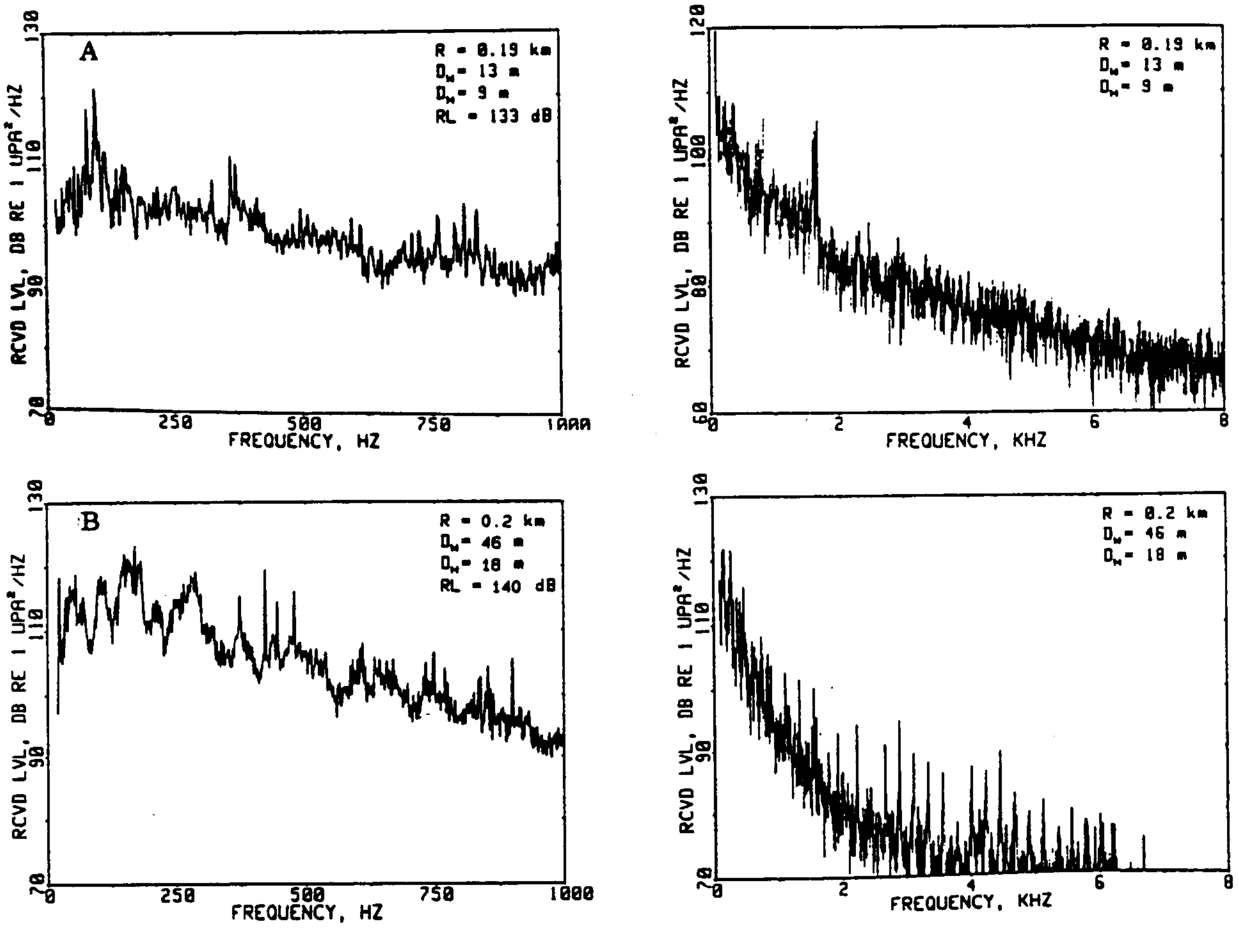
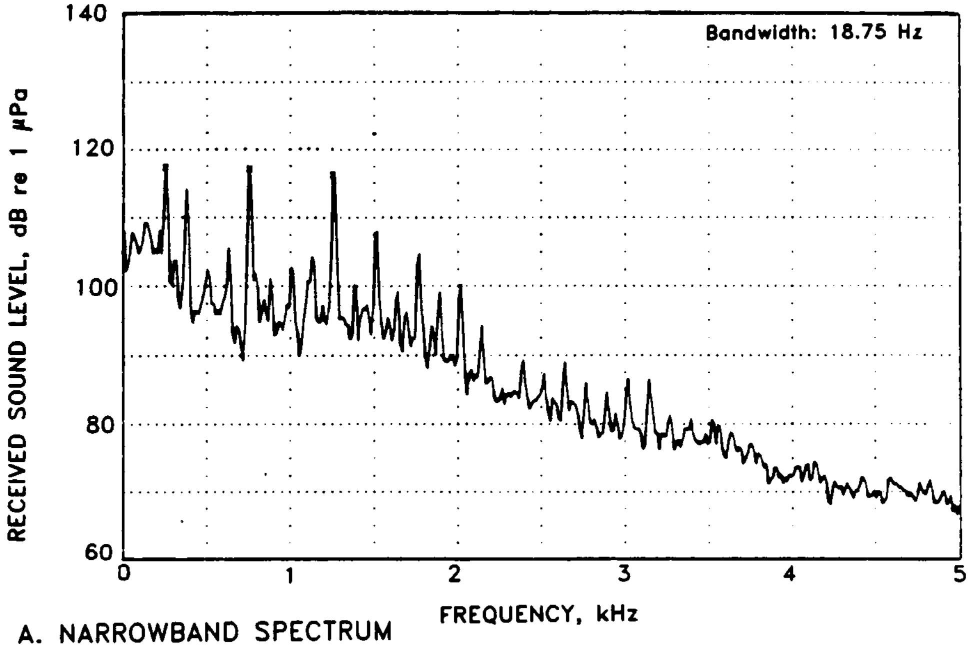
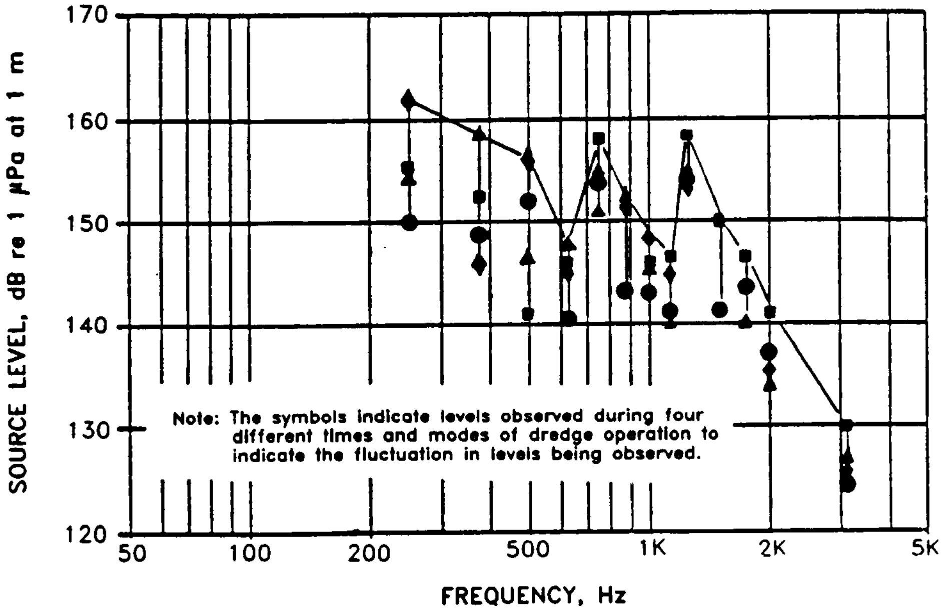


FIGURE 5.30. Received spectrum levels of transfer dredge noise for frequencies 20-1000 Hz (left) and 100-8000 Hz (right). *(A) Beaver Mackenzie* dredging at range 0.19 km; *(B) Aquarius* dredging at 0.2 km. Analysis bandwidth 1.7 Hz (left) and 3.4 Hz (right). From Greene (1987b).



A. NARROWBAND SPECTRUM



Note: The symbols indicate levels observed during four different times and modes of dredge operation to indicate the fluctuation in levels being observed.

B. SOURCE LEVEL 1/3 OCTAVE SPECTRUM

FIGURE 5.31. Clam-shell dredging noise. *(A)* Received spectrum levels during clam-shell retrieval; range unspecified (1-2 km) and analysis bandwidth 18.75 Hz. *(B)* Fluctuations in estimated source level (at 1 m) in certain one-third octave bands during various stages of the clam-shell retrieval operation; the curve shows the estimated peak source level at any stage of the operation. From Miles et al. (1987).

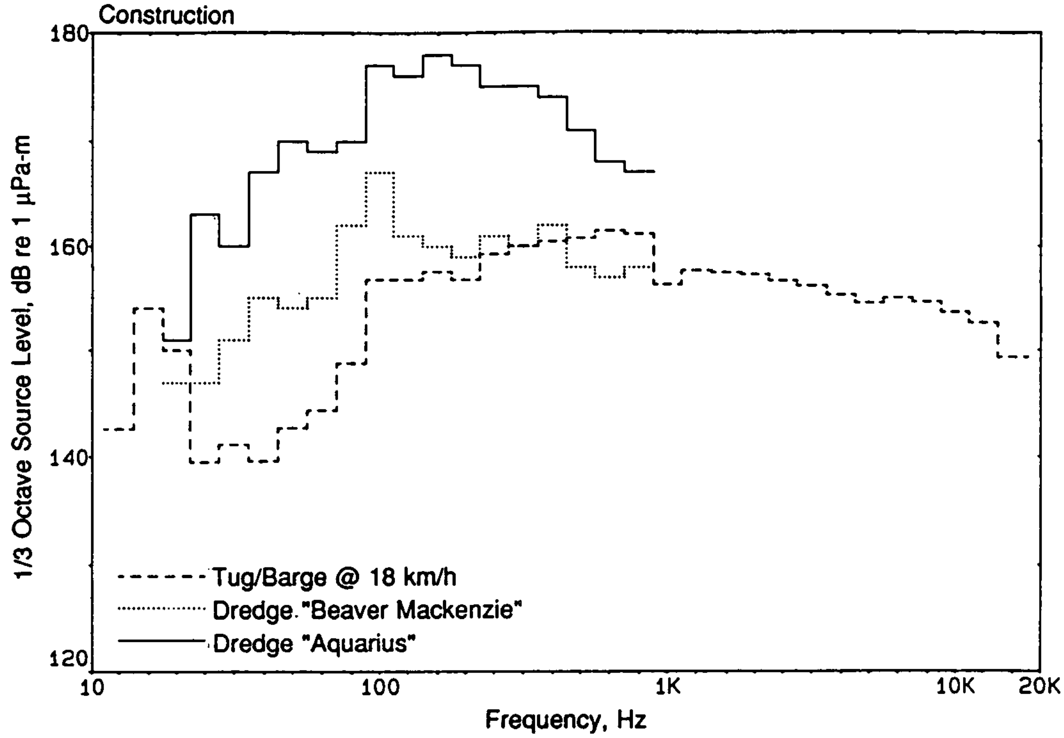


FIGURE 5.32. Estimated one-third octave source levels (at 1 m) for two operating transfer dredges and a tug towing a barge during a clamshell dredging operation. From Malme et al. (1989) based on data of Greene (1987b) and Miles et al. (1987).

Construction of artificial islands in winter, involving construction of an ice road and hauling gravel to dump through a hole in the ice, was found to be relatively quiet underwater. Such activities are most likely in shallow water, through which the sounds do not propagate well. In summer, construction involves barges or dredges and boats, with the attendant noises made by such vessels.

5.4.2 Drilling from Islands and Caissons

Offshore drilling is done from three types of facilities: (1) natural, man-made and caisson islands; (2) bottom-standing platforms set on legs; and (3) drilling vessels including semi-submersibles and drillships. The type of facility used depends upon water depth, ice conditions, other site-specific environmental and geologic features, and available resources. Information on underwater noise from some of these types of facilities has been obtained during the past decade.

Drilling from Islands.--Offshore islands, either natural or man-made, provide stable structures for drilling. Drilling from offshore islands has been conducted for many years but few measurements of noise from such drilling sites have been reported. In general, underwater noise levels expected near natural and artificial islands are low because noise is transmitted very poorly from the drillrig machinery through land into the water. In contrast, drilling sounds from caisson islands may be more efficiently transmitted into water.

Noises associated with drilling rigs operating on two icebound gravel islands, one a natural barrier island and one a man-made island, were recorded in March near Prudhoe Bay, Alaska (Malme and Mlawski 1979). Spectrum levels and shapes from the two rigs were similar, with noise primarily restricted to frequencies below 200 Hz. Broadband noise decayed to ambient levels within about 1.5 km. Low frequency tones were measurable only to ~9.5 km even under low ambient noise conditions, and drilling noise was essentially undetectable beyond about 1.5 km during high ambient noise conditions. Drilling on the natural island produced fewer tones than did drilling on the artificial island, but broadband noise levels were somewhat higher in the 0 to 160 Hz band near the natural island.

Turl (1982) estimated source levels from some of the data reported in Malme and Mlawski (1979), but the accuracy of his estimates is doubtful. In general, drilling noise from icebound conventional islands is expected to be confined to low frequencies, occurs at low levels, and would not be audible at distances of 10 km except during unusually quiet periods. The usual audible range would be about 2 km.

In very shallow arctic water, drilling is sometimes done from pads of ice resting on the bottom. Water is sprayed into the air to form ice granules, which settle onto the ice; the ice gradually thickens until its undersurface contacts the bottom. Noise from a rotary-table drillrig on one such ice pad was almost entirely below 350 Hz. It attenuated rapidly with increasing distance in very shallow water (6-7 m deep with 2 m of ice cover; 31 log *R* loss rate), and was detectable only within ~2 km (Greene, *in* Richardson et al. 1990a).

Cummings et al. (1981a) also recorded drilling sounds from offshore islands. They reported an overall received level of 86 dB re 1 μPa, with many tones between 10 and 160 Hz, at range 480 m from a rig drilling on an unspecified ice-bound base 1.5 m thick, with 1.2 m of water below.

Noise measurements have also been made with partially open water near two man-made islands off Prudhoe Bay. These data were obtained in early autumn in water 12 to 15 m deep (Davis et al. 1985 re Seal I.; Johnson et al. 1986 re Sandpiper I.). In general, noise levels at distances as close as 450 m were quite low, comparable to median ambient levels expected for sea state one with no shipping. At *Seal I.*, operations included well-logging, rig maintenance and housekeeping but not drilling. The only underwater noise associated with Seal Island was a 468 Hz tone produced during well-logging. Sound propagation from the logging equipment appeared to involve the air as well as the water, as levels were 4-5 dB higher at 3 m than at 9 m depth at ranges 500-700 m. In the absence of any active work by the rig, maintenance and power generation sounds were even weaker, and were not detectable at range 2.3 km. Based on these data, underwater sounds from artificial islands that are manned but not drilling are apparently quite weak, and generally not audible beyond 2-3 km (Davis et al. 1985).

At *Sandpiper I.*, median broadband (20-1000 Hz) levels of underwater noise received at range 0.5 km were 8 to 10 dB higher during drilling than without drilling (Johnson et al. 1986). The most obvious components were tones at 20 and 40 Hz, attributed to power generation on the island (Fig. 5.33A,B). The 20 Hz tone was 6 to 11 dB higher during drilling, and the

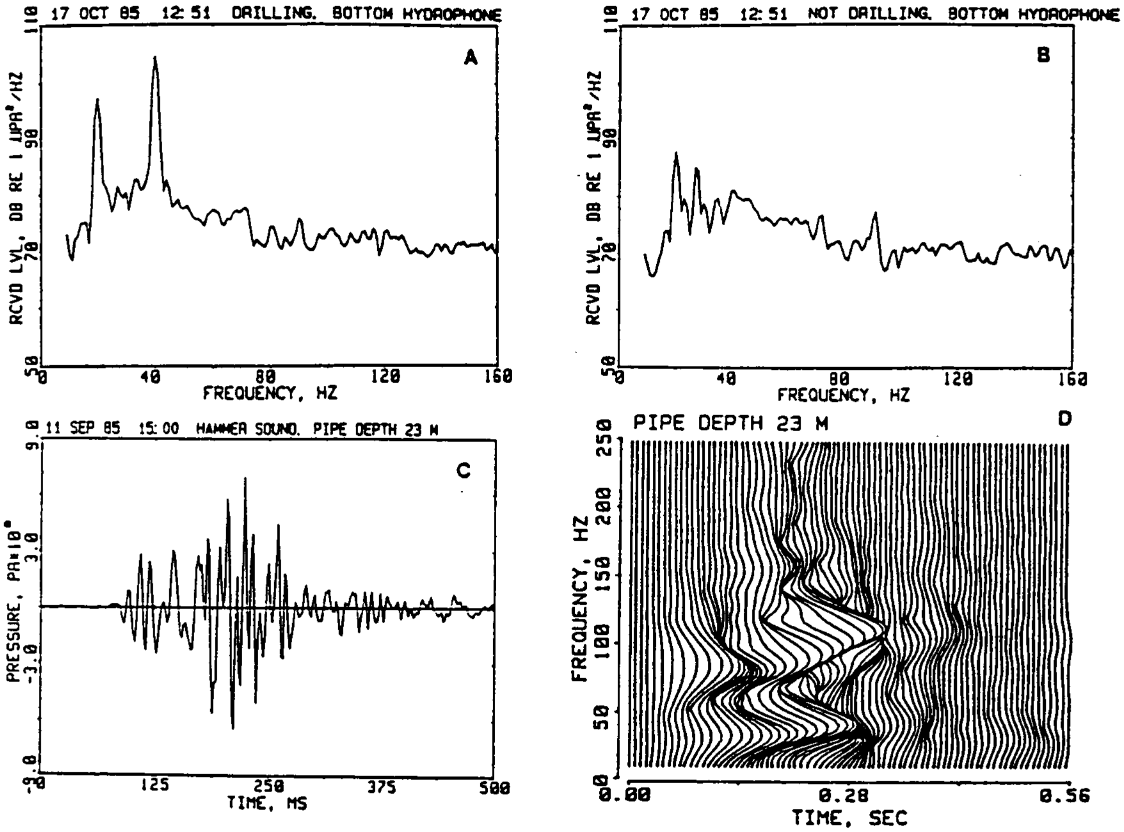


FIGURE 5.33. Underwater noise near Sandpiper artificial island, Alaskan Beaufort Sea, *(A)* with vs. *(B)* without drilling, and *(C,D)* in the presence of hammering. Range 0.5 km for the received spectrum levels in A and B, and 1 km for C and D. Analysis bandwidth 1.7 Hz in A and B. From Johnson et al. (1986).

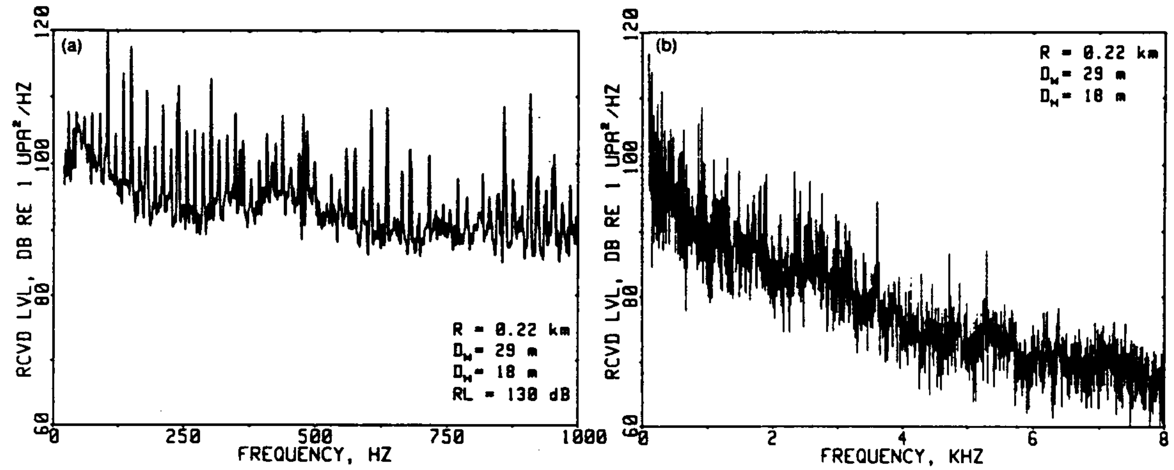


FIGURE 5.34. Received spectrum levels of underwater noise during drilling on a caisson-retained island (Amerk); frequencies 20-1000 Hz (left) and 100-8000 Hz (right), range 0.22 km. Analysis bandwidth 1.7 Hz (left) and 3.4 Hz (right). From Greene (1987b).

40 Hz tone was 15 to 24 dB higher then. However, these tones often were weakly detectable at range 0.5 km in the absence of drilling. Drilling sound levels received 3.7 km away were 24-30 dB less than levels at 0.5 km, and no drilling sounds were detected 9.3 km from the island (Johnson et al. 1986). Miles et al. (1987) estimated the effective source level of the 40 Hz tone to be 145 dB re 1 μPa-m, which is a relatively low value.

Impulsive hammering sounds associated with installation of a conductor pipe on Sandpiper I. were as high as 131 to 135 dB re 1 μPa at a distance of 1 km when pipe depth was greater than 20 m below the island. In contrast, broadband drilling noise at this distance would be expected to be only about 100-106 dB. During hammering, blows occurred about every 3 s, signal duration was 0.2 s, and the transient signals had strongest components at 30 to 40 Hz and near 100 Hz (Fig. 5.33C,D). Similarly, Moore et al. (1984) reported that received levels for transient pipe-driving bangs recorded 1 km from a man-made island near Prudhoe Bay were 25-35 dB above ambient levels in the 50 to 200 Hz band. Such sounds might be received as far as 10-15 km from the source.

Drilling from Caissons.--Caissons have been used extensively for offshore drilling in the Beaufort Sea. At least three types of caissons have been used, each likely to have different sound transmission properties: *(1)* Ring caissons like Canmar's Tarsiut Island and Esso Resources Canada's mobile Caisson-Retained Island (CRI). These are steel ring-shaped structures that are floated into place, ballasted down onto the bottom or onto a sub-sea berm, and then filled with sand or gravel. The drillrig and support facilities are set up on this sand or gravel as they would be on a conventional island. *(2)* Self-contained floating concrete rigs like Glomar's *CIDS* and BeauDril's *Molikpak*, which are floated into place and ballasted down onto a sub-sea berm. *(3)* A section of a ship with a drillrig mounted on it, like Canmar's Steel Sided Drilling Caisson (*SSDC*), which is ballasted down with water onto a sub-sea berm or ancillary support structure.

The underwater sounds from drilling on the three types of caissons are expected to differ in intensity, but few measurements exist. The ring-retained caisson is likely to be the quietest, as the gravel or sand should serve to dampen the vibrations from the rig machinery, as on conventional islands. There might be some differences as a consequence of the near-vertical caisson walls. In the absence of ice, these are exposed directly to the water and would be expected to radiate sound levels intermediate between those from drillships and from conventional shallow-sloping sand or gravel islands. Sounds from self-contained caisson-based rigs of types (2) and (3) would be expected to be more directly transmitted into the water. Limited measurements of underwater sounds have been reported for drilling and other activities on ring-caissons (type 1) and the concrete caisson *CIDS* (type 2); we know of no such data for the *SSDC* (type 3).

An important feature of caissons is the presence of standby vessels during open-water conditions and, in the arctic, into the freeze-up period. Such vessels contribute significant sound to the water, just as they do around floating drillrigs.

Greene (1985a, 1987b) measured underwater sounds during widely diverse activities at three ring-caisson sites (Table 5.12). The small difference (4 dB) between the two Amerk measurements, which were obtained at nearly the same time at ranges differing by a factor of

Table 5.12. Received sound levels near three caisson-retained islands supporting oil industry activities (from Greene 1985a, 1987b).

Range (km)	Source	20-1000 Hz band level (dB re 1 μPa)	Description
1.8	Tarsiut I.	113	General maintenance
1.8	Kadluk I.	119	CRI, installation
1.8	Amerk I.	126	CRI, drilling
0.22	Amerk I.	130	CRI, drilling

eight, may have occurred because the 0.22 km location was within the near-field or because of contamination by standby vessel noise. At all three sites, received sound levels varied with activities of the surrounding support vessels. The 130 dB level in the last line of the table is 4 dB less than the level found at the same distance (0.2 km) from a drillship (Greene 1985a; Fig. 5.34A, *cf.* Fig. 5.37B).

Sounds from the Glomar *CIDS*, a concrete caisson, were first reported by Miles et al. (1986). Their measurements were made during testing of previously drilled wells. Test tones at 2 and 4 kHz and frequency-modulated sweeps from 200 to 900 Hz were noted.

Hall and Francine (1990) measured underwater sounds near *CIDS* under open water conditions when it was not drilling and in November when it was drilling while surrounded by thin (50-90 cm) sea ice. The open water recordings were done with a conventional analog tape recorder; the November recordings also employed a digital recorder usable to below 1 Hz. In the absence of drilling, radiated levels of underwater sound were relatively low, at least at frequencies above 30 Hz (Hall and Francine 1990).[7] When *CIDS* was drilling in early winter, radiated sound levels above 30 Hz were again relatively low (~89 dB re 1 μPa at range 1.4 km). However, when lower frequency components were considered (based on the digital recordings), the received level was 112 dB at the 1.4 km range. Hall and Francine noted that more than 99% of the sound energy received at 1.4 km was at frequencies below 20 Hz. Levels at ranges 222-259 m were 121-124 dB, depending on aspect. There were strong infrasonic tones from 1.375 to 1.5 Hz. These tones corresponded to the rotation rate of the drilling turntable on *CIDS*.

Summary.--Underwater noise associated with drilling from natural barrier islands or man-made islands is generally weak, and inaudible at ranges greater than about 1 km. Drilling noise from caisson-retained islands (ring caissons) is much stronger. This was to be expected because, at least during open-water conditions, noise is conducted more directly into the water at CRI sites than at natural or man-made island drillsites. Noise associated with drilling activ-

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[7] Hall and Francine (1990) estimated the source level of *CIDS*, in the absence of drilling, as 131 dB re 1 μPa-m, excluding any infrasonic components. This estimate was based on a regression analysis of received levels vs. $\log_{10}$(range) over an unstated range of distances. The data suggested an attenuation rate of only 8.7 $\log_{10}$ (range). The actual attenuation rate close to the source was presumably higher, so the source level was presumably underestimated.

ities at both island and CRI sites varies considerably with ongoing operations. The highest documented levels were transient pulses from hammering to install conductor pipe. No data are available on characteristics of drilling noise from icebound CRI sites.

Data from self-contained concrete caissons indicate that they may be relatively quiet at frequencies above 10-20 Hz. However, the one available measurement of drilling sounds from a concrete caisson indicated that there was a strong tone near 1.4 Hz.

5.4.3 Drilling from Bottom-founded Platforms

Noise associated with conventional drilling platforms is relatively unstudied. Gales (1982) recorded noise from one drilling platform and three combined drilling/production platforms offshore from Santa Barbara, California. Continuous recordings were made over 5 days at the drilling-only platform using a hydrophone suspended from the platform. Gales reported that platform noise was so weak that it was nearly undetectable even alongside the platform during sea states of 3 and higher. However, source level computations were not possible because of the close measurement ranges relative to the sizes of the platforms.

Although only stylized noise spectra were reported, the strongest tones from all four platforms were at very low frequencies, near 5 Hz (Table 5.13). Received levels of these tones ranged from 119 to 127 dB at nearfield measurement locations. The highest frequency tone was at 1.2 kHz. These near-field measurements are not directly comparable with the results of other studies, but they suggest that conventional bottom-founded drilling platforms may not be especially noisy. However, additional data are needed.

Table 5.13. Summary of near-field noise levels for one drilling (FD) and three drilling/production (FDP) platforms in the Santa Barbara Channel. Levels approximated from stylized spectra and Table 1 of Gales (1982).

	Platform			
	FD-1	FDP-1	FDP-2	FDP-3
Activity	drilling	drill/prod	drill/prod	drill/prod
Water depth	258 m	61 m	49 m	40 m
Power source	diesel	diesel & shore	diesel & shore	gas turb. & shore
Tones (dB re 1 µPa)				
Strongest	124 dB at 4.5 Hz	119 dB at 5 Hz	127 dB at 5 Hz	125 dB at 5 Hz
Highest Freq.	4.5 Hz (90 dB)	850 Hz (94 dB)	1.2 kHz (85 dB)	70 Hz (112 dB)
Peak broadband spectrum level (dB re 1 µPa^2/Hz)	73 dB (at 300Hz)	85 dB (at 350 Hz)	89 dB (at 200 Hz)	98 dB (300 Hz)

5.4.4 Drilling from Vessels

Vessels used for offshore drilling are of two types: semi-submersibles and drillships. Both types are anchored firmly in place and are accompanied by various supply vessels and, where needed, by icebreakers. All of these vessels produce underwater noise. The machinery on semi-submersibles is mounted on decks raised above the sea on risers supported by submerged floatation chambers. Significantly, all machinery is above the water. Sound and vibration paths to the water are either through the air or the risers, in contrast to the direct paths through the hull of a drillship. Semi-submersibles should, therefore, be quieter than drillships during comparable activities.

Semi-submersibles.--Noise from semi-submersible vessels has been recorded by several researchers in a variety of locations. Greene (1986) measured sounds from *SEDCO 708* drilling in water 114 m deep in the Bering Sea. Broadband levels did not exceed local ambient levels beyond about 1 km, although weak tones were received as far as ~18 km away. Estimated source levels in relation to frequency were as follows:

	----Broadband-----		-------Tones--------		
Frequencies (Hz):	10-500	80-4000	60	181	301
Estimated Source Levels: (dB re 1 μPa-m)	154	154	149	137	136

These are rather low source levels compared with those of many oil industry sources discussed earlier. Furthermore, support boats may have contributed significantly. There was substantial variability in both the sound levels and in the frequencies of tones received. Figure 5.35 presents the measured sound spectrum levels from *SEDCO 708* at range 0.19 km, hydrophone depth 30 m.

Buerkle (1975) measured sounds from the semi-submersible *SEDCO J* drilling in the Bay of Fundy, accompanied by a 56-m twin-propeller support vessel, the *Janie B.* Calculated spectrum level 100 m from the *SEDCO J* drilling in water 63 m deep was 32 dB above the "upper limit" of prevailing ambient noise at 125 Hz. The maximum level for tripping was 39 dB above ambient at 315 Hz; for high-level tripping, the maximum difference was 42 dB at 200 Hz. (***Tripping*** is the process of running the drillstring into or out of the hole.) Maximum level for the *Janie B* was 32 dB above ambient at 200 Hz.

Turl (1982) presented estimated source level data from Kramer and Wing (1976, not seen) for a semi-submersible platform drilling in deep water off the east coast of the U.S.A. "Diesel" drilling was described as noisier than "non-diesel" drilling by about 10 dB. Assuming that spherical spreading (20 log R) was occurring, estimated source levels ranged from 130 to 150 dB, with a median of 143 dB for the 10 to 200 Hz band. However, it was unclear whether these estimates were for tones or broadband noise. These levels are even lower than Greene's estimates for *SEDCO 708* by about 10 dB.

Gales (1982) measured noise from two diesel-powered semi-submersibles with unmuffled exhaust stacks. Measurements were made in the near-field 12 to 15 m from the rigs, with the result that far-field and source levels could not be predicted reliably. Many tones were evident in the spectra from both rigs. The spectrum for one rig drilling in Cook Inlet, Alaska, peaked

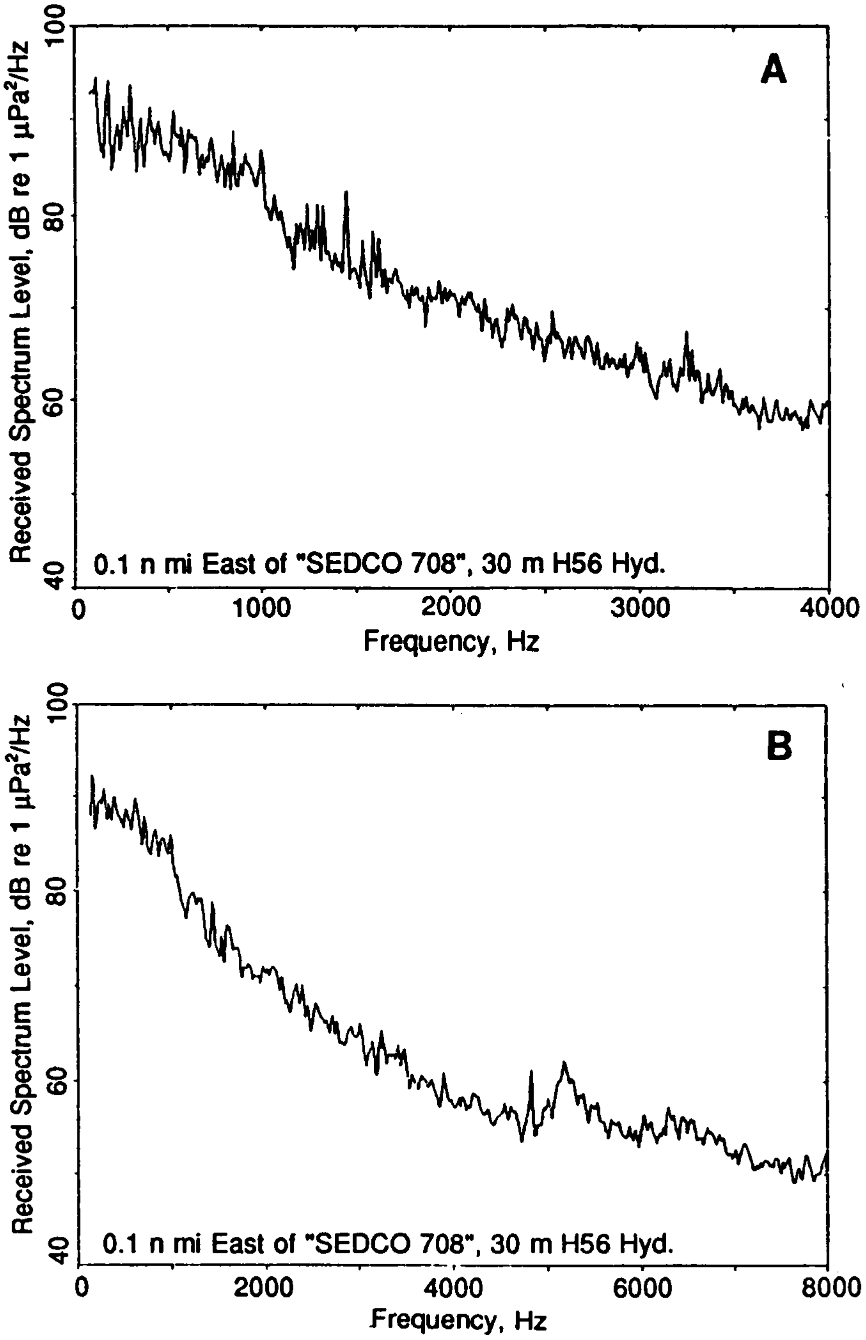

FIGURE 5.35. Semi-submersible drillrig noise: *SEDCO 708* at range 0.19 km, analysis bandwidth (A) 13.6 Hz and (B) 27.2 Hz. From Greene (1986).

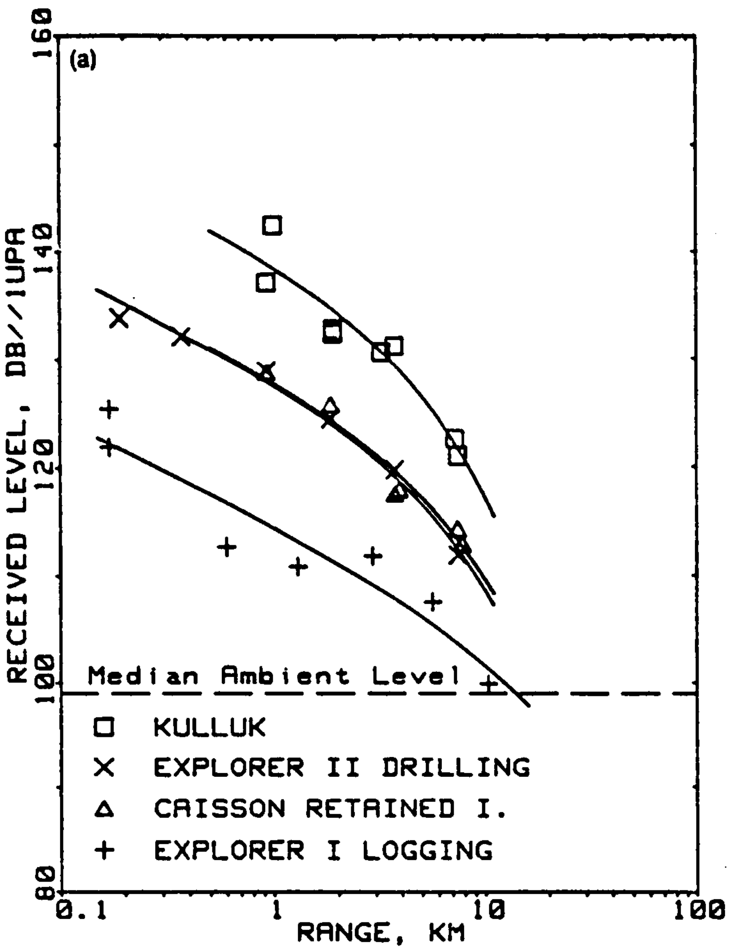

FIGURE 5.36. Received broadband levels of four sounds related to drilling, plotted in relation to range. Bandwidth 20 to 1000 Hz. From Greene (1987b).

between 50 and 100 Hz, with tones between 7 and 250 Hz. The spectrum for a rig drilling off New Jersey contained many tones between 16 and 1500 Hz. The strongest tones were at 62 Hz for the Cook Inlet rig and at 28 Hz for the New Jersey rig.

Drillships.--Noise levels associated with drilling from drillships are generally somewhat higher than those from semi-submersibles. The drillship hull contains the rig generators in addition to other machinery and the rig itself. The hull is well coupled to the water, in contrast to the semi-submersibles whose power generators and rig machinery are well above the water.

Greene (1987b) measured noise from two drillships (*Canmar Explorer I* and *Canmar Explorer II*) and from the ice-strengthened "Circular Drilling Unit" (CDU) *Kulluk*. The *Explorer* drillships are converted Liberty freighters with some ice strengthening. *Kulluk* was by far the strongest of these sound sources; the 20-1000 Hz broadband level was several decibels higher than that for *Explorer II* drilling at corresponding ranges (Fig. 5.36). Levels for *Explorer II* engaged in drilling were similar to those during drilling on a caisson retained island, but higher than those for *Explorer II* engaged in well-logging operations at a different site (Fig. 5.36).

Drillship spectra often contain prominent tones (Fig. 5.37). *Explorer II*'s spectrum was dominated by strong tones at 254 and 277 Hz (Fig. 5.37B). These were attributable to

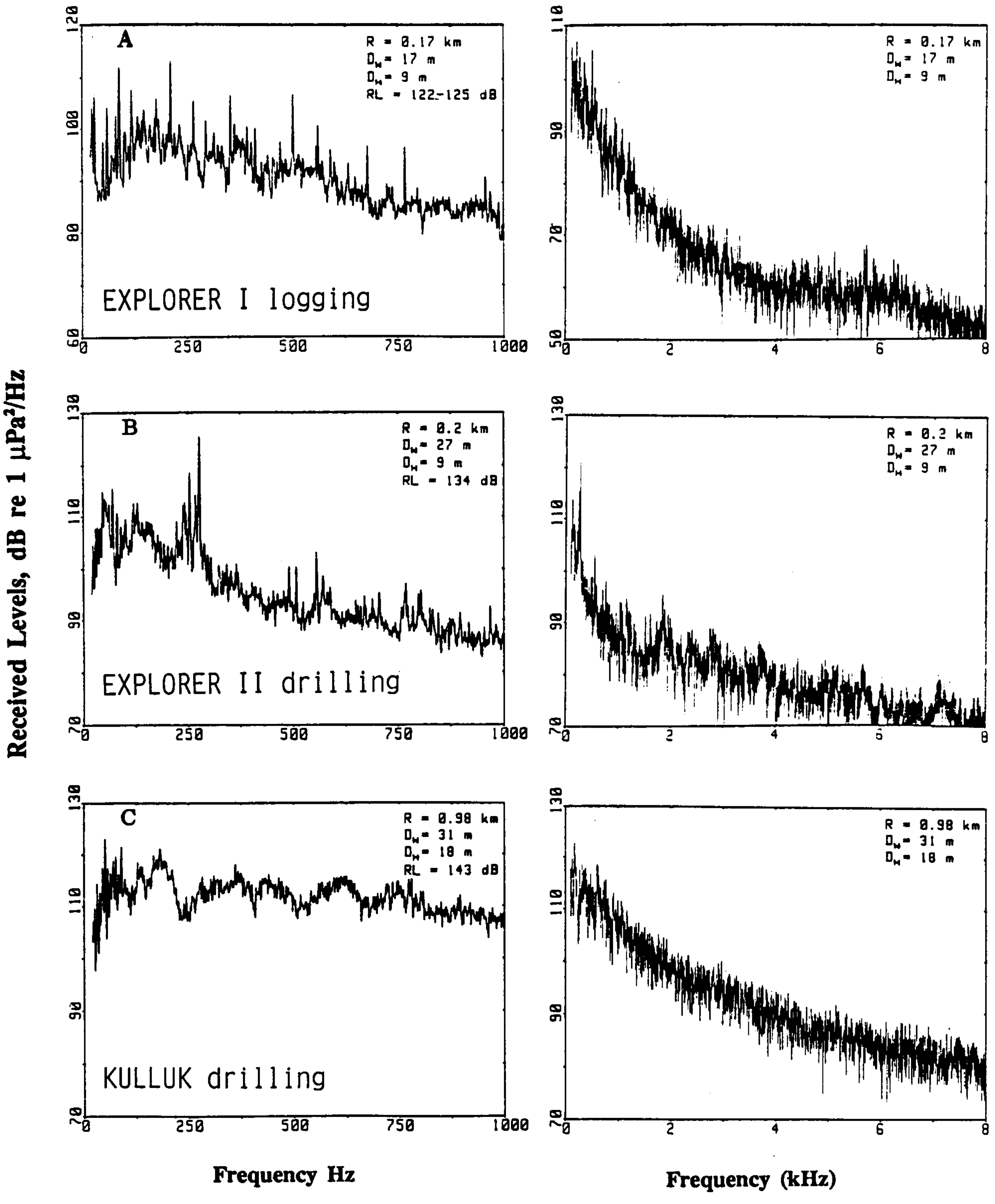

FIGURE 5.37. Received spectrum levels of drillship noise for frequencies 20-1000 Hz (left) and 100-8000 Hz (right). *(A)* Drillship *Explorer I* well-logging, *(B)* drillship *Explorer II* drilling, and *(C)* drilling barge *Kulluk* drilling. Analysis bandwidth 1.7 Hz (left) and 3.4 Hz (right). From Greene (1987b).

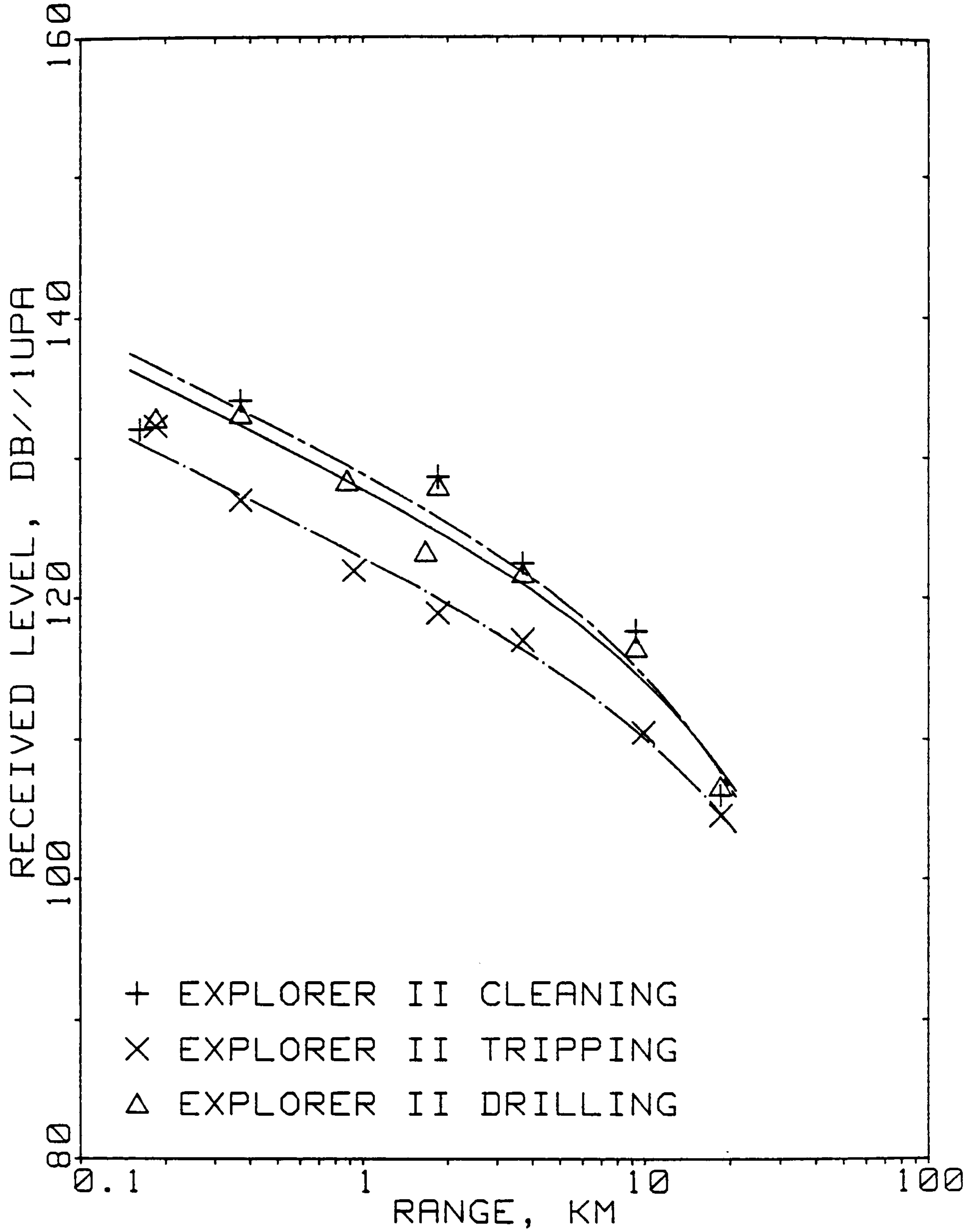

FIGURE 5.38. Drillship noise vs. range: received broadband levels of *Explorer II* drillship sounds vs. range. Bandwidth 20-1000 Hz. From Greene (1987a).

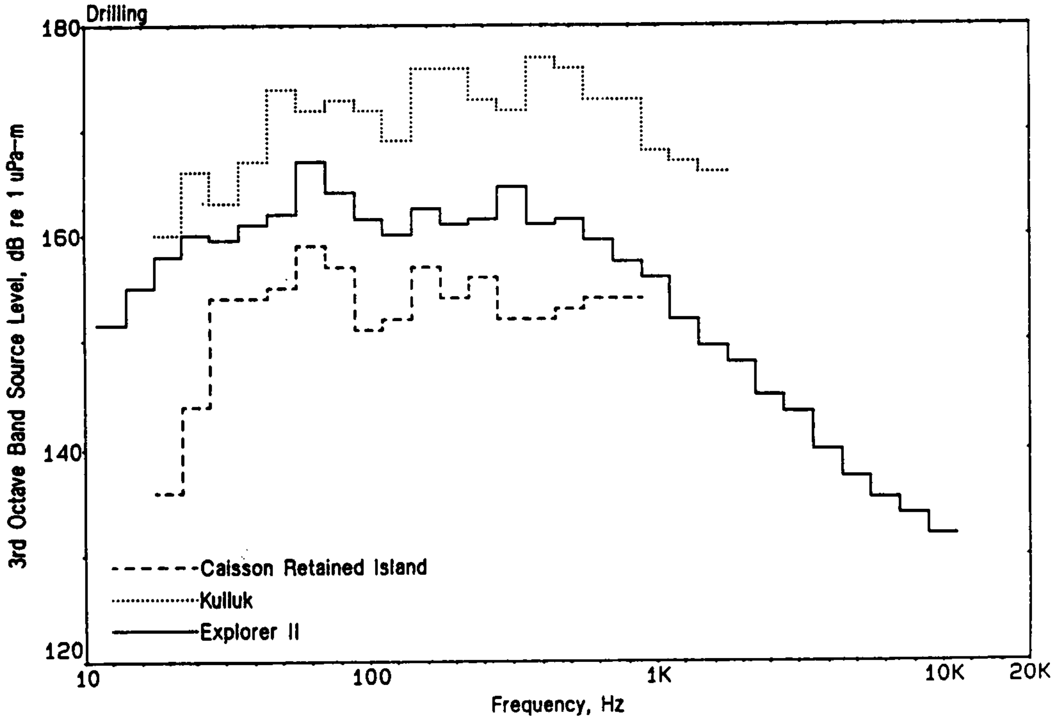

FIGURE 5.39. Estimated one-third octave source levels (at 1 m) for drilling from a caisson retained island (ring-caisson) and two drillships. From Malme et al. (1989).

turbochargers on the Caterpillar D-399 diesel electric generators. These tones changed frequency with the generator load and disappeared with light loads, as expected. Thus, measurements taken at different times may show a different spectrum, depending on the total electric load and the number of generators operating. A similar turbocharger tone was noted in the sounds from Sandpiper Island (Johnson et al. 1986), whose rig also was powered by D-399s.

Further investigation of *Explorer II* sounds has shown that, close to the ship, noise levels seem somewhat lower at bow and stern aspects than at beam aspects (Greene 1987a). Noise from well cleaning activities, including circulating mud, washing and reaming, was comparable to that from drilling and somewhat stronger than that from tripping (Fig. 5.38). In contrast, well-logging operations aboard *Explorer I* produced weaker sounds (Fig. 5.36, 5.37). Miles et al. (1987) estimated source levels of drilling sounds from *Explorer II* based on their 1986 measurements. They compared their results with Greene's data for the same ship in earlier years, and concluded that the ship's noise changes from year to year, probably because of changes in operating machinery.

Malme et al. (1989) estimated 1/3-octave source levels for drilling from *Explorer II*, *Kulluk* and a caisson-retained island (Fig. 5.39). The largest drilling vessel, the conical drillship *Kulluk*, was the strongest source for all 1/3-octave bands between 20 and 1600 Hz (the measurement limits). The caisson retained island was slightly weaker than *Explorer II*. A significant portion of the noise from the CRI probably came from the standby vessels idling nearby rather than from drilling *per se*.

Summary.--Offshore drilling is usually conducted from natural, man-made or caisson-retained islands, from platforms, or from specially designed vessels. In general, more sound is radiated underwater during drilling operations from drillships than from semi-submersibles. Noise from drilling on islands radiates very poorly to water, making such operations among the quietest major activities associated with offshore oil and gas exploration. Noise levels from drilling platforms and certain types of caissons have not been well documented, but are apparently intermediate between those from vessels and islands. Drilling operations often produce noise that includes strong tonal components at low frequencies.

5.4.5 Offshore Oil and Gas Production

Offshore oil and gas production activities are usually carried out from bottom-standing metal platforms or from islands. To date, there has been only one published study of the levels and characteristics of noise from these sources (Gales 1982). In general, one might expect that platforms standing on metal legs might introduce relatively weak sounds into the water because of the low surface area exposed to the water and the placement of machinery on decks well above the water. Sounds from production on islands are also likely to be strongly attenuated before they enter the water, as has been documented for drilling operations on natural and artificial islands (sect. 5.4.2).

Noises from eleven production platforms and one man-made island were summarized by Gales (1982). His measurements were in the near-field and were not suitable for source level computations. The platforms were bottom-standing steel structures with multiple steel legs. The strongest tones from four production platforms were at very low frequencies, between ~4.5 and 38 Hz, when measured at ranges 9-61 m. Two platforms powered by gas turbines produced more tones than did two that had at least partial shore power. Two platforms had peak sound spectrum levels at 50-200 Hz or 100-500 Hz, while sound levels fell with increasing frequency near the other two platforms.

In contrast, noise levels were very low near the man-made Rincon production island, made of sand protected by outer rock in water 14 m deep (Gales 1982). The major source of underwater noise was a submerged firewater pump, which was not run continuously. Tones at 30-120 Hz had received levels of only 89-94 dB when measured only 34 m from the island. The author rated production noise from the man-made island as "very quiet" relative to that from metal-legged production platforms. Gales surmised that the low noise levels from the production equipment were probably the result of an onshore power supply, poor conduction of sound across the rock and fill composition of the island, and poor conduction of low frequency sound in shallow water.

These results are generally consistent with the expectations noted at the start of this section. However, additional measurements of the noise around production platforms and islands are needed before a quantitative analysis of production sounds will be possible.

5.5 Overview and Summary

Underwater noise associated with the offshore oil and gas industry radiates from a variety of sources. Noise sources have been reviewed here within three broad categories: transportation, marine geophysical surveys, and oil and gas exploration and production. It is emphasized that underwater noise associated with any particular offshore site is usually the result of a combination of specific sources. For example, at an exploratory drillsite there are sounds from the drillship, platform, island or caisson itself, plus sounds from helicopters and support ships. In addition, there may be sounds from any other drillsites within several kilometers, and from any geophysical survey vessels operating within 50-100 km.

5.5.1 Transportation

Aircraft transmit significant noise to the water within a "cone" beneath them; the angular width of this cone is about 26°. The noise is generally dominated by frequencies below 500 Hz, and contains many tones related to propeller or rotor blade rate. The highest underwater noise levels occur just below the surface directly under the aircraft. Sound level decreases with increasing aircraft altitude and, directly beneath the aircraft, with increasing receiver depth. An aircraft can often be heard in air long before and after it passes above the receiver and is heard underwater. In fact, an aircraft over deep water probably will not be heard underwater unless it passes nearly overhead. Even in shallower water, where underwater noise from aircraft is detectable farther to the side, the noise is not detectable as far away in the water as it is in the air. Thus, underwater noise from aircraft is a highly transient phenomenon.

Vessel noises often dominate the underwater sound fields near offshore lease sites. All types of vessels from outboards to supertankers produce significant underwater noise, although the dominant frequencies tend to decrease and the overall source levels tend to increase with increasing vessel size. The primary sources of noise from all vessel classes are propeller cavitation, propeller "singing", and propulsion machinery. Most of the broadband noise is the result of propeller cavitation; tones are emitted at the propeller blade rate and from auxiliary machinery. Propellers radiate higher noise levels if they are damaged, operating asynchronously, or operating without nozzles. Propulsion and auxiliary machinery can also contribute significant noise. To a first approximation, radiated ship noise increases with ship size, speed and load.

Icebreaking produces some of the highest noise levels associated with oil and gas activities. In heavy ice, icebreakers alternately ram the ice until all forward momentum is lost, and then back up in order to ram the ice again. This sequence causes irregular variations in radiated noise levels. As a result of propeller cavitation, vessels pushing heavy ice radiate noise at levels about 10 to 15 dB higher than when not pushing ice, and vessels going astern to reposition radiate noise about 7 to 8 dB stronger than when going ahead. When nozzles are present around the propellers, propeller noise is reduced significantly during both open water and icebreaking activities. Icebreaker noise is strongest at low frequencies, in the tens or hundreds of Hertz, but extends above 5 kHz.

In the arctic, vehicles such as snowmobiles, trucks and heavy machinery often operate on shorefast ice during winter, and hovercraft are occasionally used over ice or water. Noise levels transmitted to water from vehicles operating on ice are generally not very high. Levels received underwater decrease with increasing snow cover on the ice and with increasing receiver depth.

5.5.2 Marine Geophysical Surveys

Marine geophysical surveys employ strong energy sources to create seismic waves below the sea floor. Although explosives such as TNT and black powder were commonly used from the 1940s to the 1960s, non-explosive techniques have essentially replaced explosives as sound sources since the 1960s. The two most common sources for geophysical surveys are airgun arrays towed by geophysical vessels and, in the arctic, Vibroseis vehicles used on landfast ice in winter. The horizontal propagation of sounds from these sources, along with sounds from sleeve exploders and gas guns, has been studied in some detail. A variety of other geophysical survey techniques with lower source levels are employed for special purposes, such as high-resolution and geotechnical surveys, but their horizontal propagation properties have not been well documented.

Airgun arrays generate high-amplitude noise pulses lasting a fraction of a second and separated by 4-15 s. Pulses from airgun arrays are often detectable in the water 50-100 km away from the survey ship, and received levels within a few kilometers typically exceed 160 dB re 1 µPa. Most of the energy in the pulses is below 100 Hz. However, this is often attenuated rapidly such that the dominant energy at horizontal ranges beyond a few kilometers is at 100-250 Hz. Vibroseis generates a series of transient high-energy sweeps lasting several seconds. The fundamental sweeps from about 10 to 70 Hz, and harmonics extend up to at least 1500 Hz.

The estimated effective source levels for horizontal propagation are about 220-230 dB re 1 µPa-m for pulses from a typical airgun array and at least 185 dB re 1µPa-m for the longer-duration sweep signals from Vibroseis. Sound levels directly ahead (bow aspect) and directly behind (stern aspect) of Vibroseis or airgun arrays can be as much as 20 dB lower than beam-aspect levels at corresponding distances. In shallow water, signals from impulsive seismic sources like airguns are elongated when received at ranges of at least a few kilometers; they are often ¼-½ s in duration, and sound "chirp"-like. The received signals are generally lower by 1 to 7 dB near the surface (depth 3 m) than at deeper (≥9 m) depths.

5.5.3 Oil and Gas Exploration and Production

Offshore dredging and construction activities commonly precede exploratory drilling for oil and gas. Dredges represent some of the strongest sources of continuous noise, although vessel or icebreaking noise may at times be stronger than dredging sounds. Drilling activities radiate the strongest noise into water when conducted from drillships, somewhat less when done from caisson-retained islands or semi-submersibles, and far less when conducted from natural or man-made islands. Drilling-related activities, such as driving conductor pipe or well-cleaning, often produce noise levels that exceed those from drilling *per se*. Noise from conventional metal-legged drilling platforms and concrete caissons has not been well documented, but levels are apparently less than those of drillships and stronger than those of drilling from islands. At least some types of drilling platforms radiate strong infrasonic sounds (<20 Hz).

Underwater noise from offshore production activities has not been studied extensively, but production seems to radiate more noise underwater when conducted from metal-legged platforms than when conducted from islands. Platforms powered by gas turbines generally produce stronger sounds than those with shore power.

5.5.4 Comparison of Noise Sources

The potential effects of industrial noise on wildlife will be partially dependent on whether the sounds are transient or continuous. An animal's response to a pulse of sound with a particular peak level may be quite different than its response to a continuous sound at the same level. For this reason, the following summary and comparison of noise sources (Table 5.14) is organized into two categories depending on whether the source is transient or continuous in nature.

Most previous studies of noise from oil-industry operations have not considered frequencies below 10-20 Hz, although ships, icebreakers and some drilling platforms are known to emit strong tones at very low frequencies (sections 5.2.2, 5.2.3, 5.4.2, 5.4.3). It is not known whether any marine mammals can detect such infrasounds. Baleen whales are the marine mammals most likely to have this ability (sect. 7.6). There is little information, at least in the open literature, about the attenuation of very low frequency sounds in shallow continental shelf waters. Hence, it is uncertain how far away from the sources these infrasonic components might be detectable above the often-high ambient noise levels at corresponding low frequencies.

Table 5.14. Summary and comparison of source levels of noise sources associated with offshore oil and gas exploration and production. The data are taken from the 1/3-octave band level summaries tabulated in Malme et al. (1989) for 45-7070 Hz. Note that some sources also emit strong sounds at lower frequencies, not considered here.

	Source Levels, dB re 1 µPa-m							Highest Level	
	Broadband	1/3-Octave Band Center Freq.						1/3 Oct Band	
Sound Source	(45-7070 Hz)	50	100	200	500	1000	2000	Freq.	Level
TRANSIENT									
Seismic Survey									
Air Gun Array (32 guns)	216	210	209	199	184	191	178	50	210
Vibroseis on Ice	210	203	198	194	188	177	168	125	204
Icebreaking, *R. Lemeur*	193	177	183	180	180	176	179	100	183
Aircraft Flyover[a]									
C-130 (4 turboprop)	175	149	150	151	150	145	146	63	170
Bell 212 helo.	162	154	155	151	145	142	142	16	159
B-N Islander (2 prop.)	157	143	150	145	140	133	131	63	152
Twin Otter (2 turboprop)	156	134	140	141	141	136	133	160	151
CONTINUOUS									
Vessels Underway									
Tug and Barge, 10 kts.	171	143	157	157	161	156	157	630	162
5-m Zodiac	156	128	124	148	132	132	138	6300	152
Supply Ship (*Kigoriak*)	181	162	174	170	166	164	159	100	174
Large Tanker	186	174	177	176	172	169	166	100+125	177
Snowmobile (224-7070 Hz)	130	-	-	-	114	118	122	1600	124[b]
Drilling									
Kulluk (45-1780 Hz)	185	174	172	176	176	168	-	400	177[b]
C. Explorer II	174	162	162	161	162	156	148	63	167
Dredging									
Aquarius (45-890 Hz)	185	170	177	177	171	-	-	160	178[b]
Beaver Mackenzie 45-890 Hz)	172	154	167	159	158	-	-	100	167[b]

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[a] Aircraft flyover source levels were computed by Malme et al. (1989) for a standard altitude of 1000 ft (305 m). For consistency with other sound sources, those values were changed to a reference range of 1 m by adding 50 dB.

[b] The sound sources for which data are incomplete are nevertheless well represented by the levels given, as the frequency bands not analyzed generally contained little energy, with the likely exception of infrasonic frequencies for some sources.

6. MARINE MAMMAL SOUNDS[1,2]

Sound, unlike light, propagates efficiently in the sea. For long distance, rapid communication under conditions of darkness or poor visibility, sound is a far better means of communication than light or odorants. Thus, it is not surprising that sound and hearing are very important to marine mammals. They use sound for communication via simple calls composed of one or a few sounds and, in at least a few species, more complex repetitive vocalizations. Some of the latter have been termed "songs". As in other animals, calls can be used to convey information of many types, e.g. about the presence of a conspecific or other animal in a particular area, the identity of the caller, feeding opportunities, imminent danger, reproductive status, and territoriality. Odontocete cetaceans also use specialized sounds and special hearing processes for echolocation, a phenomenon of extreme importance in the localization and identification of both animate and inanimate underwater objects.

Terrestrial animals communicate with one another by vocal and visual means. However, vision is restricted in the sea. During their evolutionary history, marine mammals have developed acoustic signaling capabilities that may substitute for some of the visual displays of their terrestrial ancestors.

All pinnipeds give birth and nurse their pups on a solid substrate of land or ice. Initially, airborne vocalizations are important in the bonding between mother and pup. Later, in some species, underwater calling by the pup may signal a need for maternal attention (Renouf 1984). When males compete intensely for females and mating occurs on land, airborne vocalizations and visual displays are used in ways similar to those of terrestrial mammals (e.g. Peterson 1968). However, pinnipeds and cetaceans that mate in the water apparently use underwater calls to coordinate mating (Ray et al. 1969; Silber 1986; Watkins et al. 1987). In at least some species, when animals are in close proximity, they may use visual and other non-acoustic forms of communication (Pryor 1986).

Species of marine mammals that use echolocation emit brief sound pulses, and then sense, process and interpret the echoes received from nearby objects (Popper 1980a). Although some terrestrial mammal species, including man, possess at least a rudimentary echolocation ability, two groups--toothed whales and bats--are highly specialized for echolocation. Their specialized echolocation signals are used to detect, localize and characterize nearby objects (Au and Snyder 1980; Au et al. 1987).

Marine mammals produce sounds with widely-varying frequencies, durations, and repetition rates. Sounds may be amplitude modulated, frequency modulated, or both. They can be produced either as smooth continuous sounds or with segments or pulses. Individual sounds are sometimes combined to form a *doublet* (two different sounds produced one after the other, e.g. Cummings et al. 1986), *stereotyped phrase* (a specific sequence of several sounds produced repeatedly, e.g. Cummings and Philippi 1970), or a *song* or *coda* (a long series of sounds

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[1] Denis H. Thomson, LGL Ltd.

[2] Constructive comments on drafts of this chapter were provided by Drs. W.C. Cummings, R.A. Davis, P.L. Edds, R.H. Nichols, A.N. Popper, R.J. Schusterman, and B. Würsig.

always produced in the same sequence, e.g. Payne and McVay 1971; Watkins and Schevill 1977b). The complex stereotyped sounds of a species sometimes differ among stocks inhabiting widely spaced regions, among groups in adjoining areas, and among individuals within a group (Hafner et al. 1979; Awbrey et al. 1982; Ford and Fisher 1983; Payne and Guinee 1983).

Many species of marine mammals produce a large number of different sounds and combinations of sounds, as may particular individual animals. Only a few species have been studied in detail. Documentation of the full acoustic repertoire of a species may be close to impossible for species that call almost continuously, such as white whales and bottlenose dolphins. The sounds of the long-finned pilot whale and southern right whale have been described as continua (Taruski 1979; Clark 1982). Caldwell and Caldwell (1970,b) and Tyack (1986a) believe that, in some species, small differences in sounds may convey much information at the individual or group level, and that each individual of some species may have a unique signature call. Other bioacousticians differ as to the interpretation of these small differences among vocalizations.

Many recent studies have attempted to correlate the occurrence of specific kinds of sounds with specific behaviors or situations (e.g. Watkins 1981b; Clark 1983; Hoelzel and Osborne 1986). Some cetaceans and seals are easy to train, capable of mimicry, and adaptable. Consequently, some results obtained from captive animals may not apply wild animals. Because of difficulties in observing wild animals and in ascribing a given sound to a particular animal, it has been possible to study only the general relationships between vocalizations and behavior of free-ranging animals, and then only for a few species. When all data are combined, some preliminary conclusions regarding the behavioral significance of sound production can be drawn. However, for most species, specific functions of most sounds are unknown.

This section summarizes the types of sounds produced by various marine mammals. Detailed information about the sounds of particular species are given in tables. The text discusses the general categories of sounds produced by each major group of species. Emphasis is placed on data that may be important in evaluating potential interference by man-made noises. Acoustic characteristics that are important in this respect include the dominant frequencies (Hz), source levels, effective distances, and functions of the marine mammal sounds.

6.1 Baleen Whale Sounds

Nine of the eleven extant species of baleen whales (mysticetes) occur off the coasts of the United States. They are the blue, fin, minke, sei, Bryde's, humpback, northern right, bowhead and gray whales (see Appendix 1 for scientific names). Because of the paucity of data on the sounds of the northern right whale, information for the closely-related southern right whale is also reviewed below. The pygmy right whale inhabits the southern hemisphere and is not considered.

Baleen whales characteristically produce low frequency tonal moans and grunt-like sounds that are mostly below 1 kHz (Table 6.1). The durations of most sounds are relatively long--0.5 to 1 s in the Balaenidae and over 1 s in the Balaenopteridae (Watkins and Wartzok 1985). In addition to low frequency sounds, sounds with frequencies above 1 kHz are produced by the humpback whale (Winn et al. 1979; Thompson et al. 1986) and have also been attributed to other species including the gray whale (Fish et al. 1974), bowhead whale (Clark and Johnson

Table 6.1. Characteristics of underwater sounds produced by baleen whales.

Species	Signal type	Frequency Range (Hz)	Dominant Frequencies (Hz)	Source Level (dB re 1 μPa at 1 m)	References
Fin whale	moans, downsweeps	14–118	20	160–186	Watkins 1981b; Watkins et al. 1987; Edds 1988
	constant call	20–40	-	-	Edds 1988
	moans, tones, upsweeps	30–750	-	155–165	Watkins 1981b; Cummings et al. 1986; Edds 1988
	rumble	10–30	-	-	Watkins 1981b; Edds 1988
	whistles?, chirps?	1500–5000	1500–2500	-	Thompson et al. 1979
	clicks?	16,000–28,000	-	-	Thompson et al. 1979
Blue whale	moans	12–390	20–30, 50–60	188	Cummings and Thompson 1971a; Edds 1982
	clicks?	6,000–8000 21,000–31,000	6,000–8,000 25,000	130, 159	Beamish and Mitchell 1971; Beamish 1979
Bryde's whale	moans	70–245	124–132	152–174	Cummings et al. 1986
	growl	400–800	-	-	Edds and Odell 1989
Minke whale	down sweeps	60–130	-	165	Schevill and Watkins 1972
	moans, grunts	60–140	60–140	151–175	Schevill and Watkins 1972; Winn and Perkins 1976
	ratchet	850–6,000	850	-	Winn and Perkins 1976
	clicks	3,300–20,000	<12,000	151	Beamish and Mitchell 1973; Winn and Perkins 1976
	thump trains	100–2,000	100–200	-	Winn and Perkins 1976
Sei whale	Not recorded	-	-	-	Cummings 1989
Gray whale	moans	20–1,200	20–200, 700–1,2000	185	Cummings et al. 1968; Fish et al. 1974; Swartz and Cummings 1978
	pulse modulated	80–1,800	225–600	-	Dahlheim et al. 1984
	FM up-down sweep	100–350	300	-	Dahlheim et al. 1984
	pulses	100–2,000	300–825	-	Dahlheim et al. 1984
	clicks (calves only)	100–20,000	3,400–4,000	-	Fish et al. 1974; Norris et al. 1977
Humpback whale	song components	40–8,000	100–4,000	144–174	Thompson et al. 1979
	shrieks	-	750–1,800	179–181	Thompson et al. 1986
	horn blasts	-	410–420	181–185	Thompson et al. 1986
	moans	10–1,900	25–360	175	Thompson et al. 1986
	grunts	25–1,900+	-	190	Thompson et al. 1986
	pulse trains	25–1250	25–80	179–181	Thompson et al. 1986
	underwater blows	100–2,000	-	158	Beamish 1979
	fluke & flipper slap	30–1,200	-	183–192	Thompson et al. 1986
	clicks	2,000–8,200	-	-	Winn et al. 1970b; Beamish 1979
Bowhead whale	tonal moans	25–900	100–400	129–178	Ljungblad et al. 1982a; Cummings and Holliday 1987; Clark et al. 1986
	pulsive	25–3,500	-	152–185	Würsig et al. 1985; Clark and Johnson 1984; Cummings and Holliday 1987
	song	20–500	<4,000	158–189	Cummings and Holliday 1987
Right whale	tonal	30–1,250	160–500	-	Cummings et al. 1972; Clark 1983
	pulsive	30–2,200	50–500	172–187	Cummings et al. 1972; Clark 1983
				181–186	C. Clark (in Würsig et al. 1982)

? Infrequently recorded, and/or questionable correlation of sound with species.

1984; Cummings and Holliday 1987), and southern right whale (Cummings et al. 1972). Some high-frequency sounds have been called chirps or cries. Pulsed sounds of short duration, high frequency, and with short intervals between pulses are termed clicks. Click sounds above 1 kHz have been reported from humpback whales and a gray whale calf. The highest frequency sounds, perhaps as high as 31 kHz, have been attributed to blue, minke and fin whales (Beamish and Mitchell 1971, 1973; Fish et al. 1974; Thompson et al. 1979; Winn et al. 1979). The specific sources of high frequency clicks recorded near some baleen whales have been disputed. There is insufficient evidence concerning the possible emission of high frequency chirps and cries by the fin whale and click sounds by the fin and minke whales (e.g. Watkins 1981b).

There is no standard nomenclature for baleen whale sounds. The same sound is often given different names by different authors. The names of the sounds listed in Table 6.1 are those used by the authors cited, and most names are based on subjective aural interpretation. In some cases, one description may be used by different authors to refer to dissimilar sound types.

It has been very difficult to study the context and functions of baleen whale sounds. Large whales have not been kept in captivity for prolonged periods. In field studies, it has rarely been possible to relate specific baleen whale sounds to specific animals whose activities were under observation. Much research effort has been expended on the sounds of fin, humpback, gray, bowhead, and southern right whales. Much has been learned about the acoustical characteristics and (to some extent) the functions of fin, humpback and right whale sounds. Gray and bowhead whale sounds have been well documented, but less is known about their functions. The sounds of the blue, minke and Bryde's whales have been described, but the significance of these sounds is largely unknown. Sounds of the sei whale have not been described.

Demonstrated functions of baleen whale sounds include

- long range sexual display (humpback whales, Winn and Winn 1978; fin whales, Watkins et al. 1987),
- contact calls (southern right whales, Clark 1983; humpback whales, Thompson et al. 1986),
- short distance communication to display aggression among males; may be related to dominance and proximity to females (humpbacks, Silber 1986),
- general sexual activity (southern right whales, Clark 1983), and
- signalling between whales, including two way communication, or to announce group activities (fin whales, Watkins 1981b).

The vocalization rate for social sounds increases with group size in humpbacks (Silber 1986) and with the general activity level of southern right whale groups (Clark 1983).

6.1.1 Bowhead Whale

Most sounds emitted by bowhead whales are tonal frequency-modulated (FM) sounds at frequencies between 50 and 400 Hz (Würsig et al. 1982; Clark and Johnson 1984). Most single-note tones last ~1 s, but they may be as short as 0.4 s or as long as 3.7 s (Ljungblad et al. 1982a; Würsig et al. 1985). Most of these sounds have little or no energy above 400 Hz, but a few contain energy up to 1200 Hz (Würsig et al. 1985). FM upsweeps and downsweeps seem to exhibit limited directionality, with sounds being somewhat stronger in front of the animal than behind (Clark et al. 1986).

Source levels of simple low-frequency moans have been estimated as 129-178 dB (median 159 dB) on a spectrum level basis, i.e. dB re (1 µPa-m)^2/Hz (Cummings and Holliday 1987) and, in a different year, ~128-178 dB (mean 151 dB) on a broadband basis, i.e. dB re 1 µPa-m (Clark et al. 1986). Some of this apparent variation in estimated source levels is undoubtedly artifactual. The estimates depend on unverified assumptions about site-specific propagation losses between the whales and the receiving hydrophones. The actual range of source levels is unknown. This is a general problem affecting source level estimates for all species of marine mammals studied in field conditions.

There is no concrete evidence of associations between specific sounds and behaviors for bowhead whales. Based on parallels with his more intensive work on the closely-related southern right whale, C.W. Clark has drawn some general inferences (Clark and Johnson 1984; Clark *in* Würsig et al. 1985; Clark et al. 1986). High pitched sounds and pulsatile sounds were interpreted as indicative of excitement and aggression, respectively, in the southern right whale. These types of sounds sometimes (not always) are proportionally more common near socializing bowheads than near other bowheads (Würsig et al. 1982, 1985). The FM upsweep sound is similar to an "up" sound used by the southern right whale to establish contact. Clark has speculated that bowhead whales may also use the "up" sound as a contact call.

Mother and calf baleen whales apparently use acoustic communication to maintain contact and to rejoin if they become separated. Würsig et al. (1985) obtained evidence that sounds facilitated rejoining by a mother and calf after the mother had been feeding at a distance from the calf.

Bowhead whales "sing" during spring migration through ice leads around northern Alaska. Cummings and Holliday (1987) recorded "trumpet-like" sounds repeated in phrases to form songs that lasted a mean of 66.3 s. There were 3 to 20 phrases per song with a mean interval of 7 s between phrases. The first phrase of a song was higher in frequency and more pulsatile, and had less frequency modulation, than did the following phrases (Cummings and Holliday 1987). Frequencies generally were less than 4 kHz, but some energy was detected as high as 5 kHz. Peak spectrum source levels for songs were estimated as 158-189 dB re 1 µPa-m (median 177 dB). Generally, only one bowhead whale could be heard singing at a time, even though several were within range of the hydrophone; when one whale stopped singing, another often began (Cummings and Holliday 1987). Bowhead songs have also been heard off Point Barrow during other spring seasons (Clark and Ellison 1987), but songs have not been noted during summer or autumn in the Beaufort Sea. The function of bowhead song is unknown.

Table 6.2. Major categories of southern right whale sounds recorded during winter (from Clark 1982).

Call Type	Description	Major Energy (Hz)	Duration (s)
Up	low frequency tonal FM upsweeps	50-200	0.5-1.5
Down	low frequency tonal FM downsweeps	100-200	0.5-1.5
Constant	Tonal with little FM	50-500	0.5-6
High	High frequency tonal FM sweeps	200-500	0.5-2.5
Hybrid	Mixture of FM sweep and AM	50-500	0.5-2.5
Pulsatile	Complex AM of noise or FM	50-200	0.5-3.5
Blows	Noisy broadband	100-400	0.5-26
Slaps	Sharp onset noisy	50-1000	0.2

Marine mammal sounds are usually recorded with a single omnidirectional hydrophone. However, hydrophone arrays can be used to measure the distance and bearing to a calling animal. Source locations for bowhead whale sounds have been determined with hydrophone arrays in several studies (e.g. Cummings and Holliday 1985; Davis et al. 1985; Clark et al. 1986; LGL and Greeneridge 1987). A few calling bowheads have been detected and localized at distances as great as 20 km. However, with high ambient noise, calling bowheads can only be localized at shorter distances. The distance at which bowhead sounds can be detected with instruments can be reduced by high background noise levels attributable to ice, other marine mammals and industrial noise as well as the usual water and wind contributions to natural ambient noise (Cummings et al. 1983; Cummings and Holliday 1985, 1987; Clark et al. 1986; LGL and Greeneridge 1987).

6.1.2 Southern Right Whale

The southern right whale uses an "up" sound (a simple tonal FM upsweep) for long distance contact and as an aid in bringing groups together (Clark 1983). This sound is 0.5 to 1.5 s in duration and between 50 and 200 Hz in frequency. Calling ceases after groups join. Single whales also use the "up" call to establish contact prior to joining. A "down" call is used to maintain acoustic but not physical contact. It is a low-frequency tonal FM downsweep of 0.5 to 1.5 s duration at 100-200 Hz. Similarly, northern right whales summering in the Bay of Fundy use low-frequency sounds as contact calls (Spero 1981). Source levels of right whale calls have been estimated as 172-187 dB re 1 μPa-m (Table 6.1).

Clark (1983) observed and recorded a southern right whale mother/calf pair that became separated by 75 m. Because of suspended material in the water, this distance was beyond underwater visual range. Both mother and calf made the "up" sounds described above and rejoined.

Other sounds of the southern right whale include tones with little frequency modulation, high frequency tonal FM sweeps, complex amplitude-modulated pulsatile sounds, mixtures of amplitude and frequency modulation, noisy broadband blows, and impulsive slaps (Table 6.2; Clark 1983). These sounds have their major energy at 50-1000 Hz and durations of 0.5-3.5 s

(0.5-26 s for blows). The types of sounds produced are related to the activity, size, and sexual composition of the right whale group (Clark 1983). Variable complex sounds were associated with actively socializing animals (Clark 1983). As the activity level of a group increased from resting through active swimming to sexual activity, the numbers of sounds increased and there was a change in the kinds of sounds (Clark 1983). Resting whales made few calls and some long blow sounds. Whales in small mildly-active groups mostly made the "up" and "down" sounds in addition to slaps. Whales in larger or more active groups mostly made "high", hybrid and pulsatile sounds, sometimes with slaps and blows. Based on his observations, Clark speculates that the "high" sounds indicate excitement and that hybrid and pulsatile sounds signify aggression.

6.1.3 Gray Whale

The most common sounds made by the gray whale are knocks and pulses with frequencies from <100 Hz to 2 kHz with emphasis between 327 and 824 Hz. A series of 2 to 30 pulses lasts an average of 1.8 s (Dahlheim et al. 1984; Dahlheim 1987). The source level for knocks was estimated as 142 dB re 1 µPa-m (Cummings et al. 1968)--not an especially high level. Moore and Ljungblad (1984) found that these knocks were the most common sounds recorded in the presence of feeding whales in summer. They could not make reliable associations between sounds and surface behaviors. However, Bogoslovskaya (1986) believes that, in summer, gray whales feed in stable groups and that individuals within the group keep in acoustic contact when separated by distances >800 m.

The rate of sound production in gray whales may be related to the general level of social activity (Dahlheim 1987). Gray whales are relatively silent when dispersed on their summer feeding grounds, slightly more vocal when migrating, and most vocal when on their winter breeding/calving grounds (Dahlheim 1987). Group size is small when on the summering grounds and larger when migrating. The whales are most concentrated when on the winter grounds. They make seven distinct types of sounds there, but the significance of these sounds to the species is unknown (Dahlheim 1987).

6.1.4 Humpback Whale

Humpback whales produce three kinds of sounds: (1) "songs" that are produced in late fall, winter and spring by solitary individuals, (2) sounds made by whales within groups on the winter grounds, and (3) sounds made while on the summer feeding grounds.

Songs.--The humpback whale produces a stereotyped song associated with reproduction (Winn et al. 1970a; Payne and McVay 1971; Tyack and Whitehead 1983). The humpback song is complex. Many components are at relatively high frequencies for a baleen whale: from 40 Hz or lower to 4 kHz, with occasional sounds up to 8 kHz (Thompson et al. 1979). High and low frequency sounds tend to alternate within some parts of the song (Winn and Winn 1978). Humpback songs have been described, often with an element of presumed onomatopoeia, as moans, cries, chirps, yups, ratchets, grunts, frequency sweeps, snores, etc. (Winn et al. 1970a; Payne and McVay 1971; Winn and Winn 1978). It is possible that the alternating frequency pattern might, through differential attenuation of high and low frequency sounds, give range information to listening whales (Winn and Winn 1978).

Low frequency components of humpback whale songs have been estimated to have source levels well above 160 dB re 1 μPa-m. Thompson et al. (1979) state that source levels of songs average 155 dB re 1 μPa-m and range from 144 to 174 dB. Thompson et al. (1986) imply that source levels of songs recorded off Hawaii were ~170 dB. As usual for source level estimates obtained in the field, these values depend on uncertain assumptions about sound propagation loss.

The complex humpback whale songs last as long as 30 min in bouts up to 22 h long (Payne 1970; Winn et al. 1970a; Payne and McVay 1971; Winn and Winn 1978; Tyack 1981). These songs have been recorded on various wintering grounds at low latitudes in the Atlantic, North Pacific, and South Pacific, and during late autumn on northern feeding grounds (Winn and Winn 1985; Mattila et al. 1987). Humpbacks also produce songs while on the southeast Alaskan feeding grounds (McSweeney at al. 1989). Within each of these large areas, the songs are similar at any one time, but songs differ markedly between areas (e.g. Cape Verde, Africa, vs. West Indies; Winn et al. 1981). In any given year all whales in an area sing similar songs, but over the course of several years the song in a given area changes (Payne and Guinee 1983; Payne and Payne 1985). These changes appear to occur gradually as individuals "update" their song to conform to songs being sung by the rest of the group (Guinee et al. 1983). Though songs from different whales in an area are similar, Hafner et al. (1979) believe that each whale may have unique renditions of song components.

Almost all humpback songs are produced by males (Winn and Winn 1978; Glockner-Ferrari and Ferrari 1981; Silber 1986; Mattila et al. 1987), and singers are almost always alone (Winn and Winn 1978; Tyack 1981). Singing whales seem to avoid one another, but they may pursue or be joined by silent whales. Singing ceases when whales join (Tyack 1981). Although the exact function of the song is still unclear, it appears to be most important as an advertisement display by males during the breeding season (Tyack and Whitehead 1983).

Humpbacks breed in tropical coastal waters (Dawbin 1966). Off the West Indies, male humpbacks usually sing over a flat bottom in shallow (<40 m) isothermal water. The concentration of singing males in these areas causes such a high background noise level that the effective range of an individual's song is decreased (Whitehead and Moore 1982). They speculate that the humpback males congregate and display with song near areas used by females. In the West Indies, song could be detected with a hydrophone at distances up to 13 km (Winn et al. 1975).

Off Hawaii, humpbacks occupy an area 130 by 50 km in extent and occur over water depths less than 200 m (Herman and Antinoja 1977). However, most whales occur in several smaller subareas within this larger area. Tyack (1983) played recorded songs through an underwater sound projector and observed reactions of Hawaiian humpbacks. All playbacks were at distances ≤3 km and at a source level of 155 dB re 1 μPa-m, slightly less than typical observed source levels for song. Most whales moved away from the boat during playback of song. These results were consistent with earlier observations that singers were generally separated by distances of 5 km (Tyack 1981). Tyack speculated that song may function to maintain this distance. Lone singing humpbacks reacted to groups from distances as great as 9 km (usually a maximum of 7.5 km; Tyack and Whitehead 1983). In general, humpback song appears to have an effective range of ~10 to 20 km. This range may correspond to the relatively small extent of each subarea occupied by humpbacks in winter.

"Social" Sounds Produced in Winter.--Humpback whales within groups produce sounds that are very different from the songs of solitary animals. These group or "social" sounds are most often associated with agonistic behavior among males (Silber 1986). The sounds are heard from groups of three or more whales but rarely from solitary whales, cow/calf pairs, or adult pairs (Silber 1986). These sounds, which are often associated with aggressive behavior, may be made by males as they compete for dominance and proximity to females (Tyack 1983; Silber 1986). The sounds extend from 50 Hz to 10 kHz (or higher), with most energy in components below 3 kHz. Durations are 0.25 s to over 5 s; most are single frequency-modulated upsweeps followed by a period of silence (Silber 1986). Sounds produced in series generally are of short duration and have short inter-call periods (Silber 1986). These sounds, or the associated impact noises, can elicit a reaction from humpbacks at distances up to 9 km (Tyack and Whitehead 1983).

Sounds Produced on the Summer Grounds.--On high latitude summer feeding grounds, humpbacks are less vocal than when on their winter range. In southeast Alaska, their sounds are at ~20-2000 Hz and have median durations 0.2-0.8 s; source levels have been estimated as 175-192 dB re 1 µPa-m (Table 6.3; Thompson et al. 1986). Thompson et al. noted that low-frequency pulse trains were associated with generation of bubbles during "bubble net" feeding, and an associated broadband noise at 40-1250 Hz occurred as the bubbles rose to the surface. Some grunts were also associated with feeding. Shrieks and trumpet-like sounds occurred when two or more whales converged.

Table 6.3. Sounds made by humpback whales in Alaska (from Thompson et al. 1986).

	Fundamental Freq. (Hz)	Frequency Range (Hz)	Median Duration (s)	Source Level (dB re 1 Pa at 1 m)
Simple moans	25-30	20-1800	0.8	.175
Complex moans	35-360	10-1900	0.8	-
Grunts	-	25-1900+	0.2	.190
Low-frequency Pulse Trains	25-80	25-1250	0.3-0.4/pulse	179-181
Blowhole-associated				
Shrieks	750-1800	-	0.42	179-181
Trumpet-like	410-420	-	0.55	181-185
Fluke and flipper slaps	-	30-12,000	-	183-192

Nilson at al. (1989) studied the sounds made by feeding humpback whales. They determined that the whale leading the feeding pod uttered vocalizations during 97% of successful feeding lunges. The calls apparently serve for prey manipulation and as assembly calls for feeding, and probably not for coordination of feeding. A prolonged bout of vocalization can attract whales from distances up to 10 km.

6.1.5 Fin Whale

The fin whale produces 20 Hz sounds that vary in duration from 1 s pulses to 20 s moans (Thompson et al. 1979). In spring, summer and fall these sounds are uttered singly or in a series of two to five pulses (Watkins 1981b; Watkins et al. 1987). However, in winter 20 Hz pulses are heard in repeated stereotyped patterns and have been recorded in most ice-free oceanic waters (Watkins et al. 1987). Pulse intervals typically are 7-26 s. Bouts of vocalizations continue for 1 to 33 h, but are suspended for an average of 2 min when the whale surfaces to breathe and for 20 min to 2 h when the whale is approached by another whale or is disturbed by a boat or underwater noise (Watkins et al. 1987). Sound production rate is similar by day and by night. The typical "20 Hz" sound generally has a downward sweeping frequency, starting at ~23 Hz and dropping to ~18 Hz over 1 s (Watkins 1981b). The bandwidth is generally ~3-4 Hz (Payne and Webb 1971). Most 20 Hz sounds have source levels estimated as 160 to 186 dB re 1 µPa-m, with a maximum of 200 dB and a minimum of ≤140 dB (Patterson and Hamilton 1964; Northrop et al. 1968, 1971; Watkins 1981b; Watkins et al. 1987).

The 20 Hz signals apparently are emitted by fin whales primarily during their reproductive season from autumn to early spring. This led Watkins et al. (1987) to speculate that the repetitive stereotyped 20 Hz signals are an acoustic display associated with reproduction; they may be similar in function to the songs of the humpback whale. Only one fin whale in a group produces this song. When more than one whale sings, the singers are separated by ≥1 km (Watkins 1981b). While singing, fin whales exhibit shallow dives (Watkins 1981b).

Payne and Webb (1971) speculated that 20 Hz sounds from fin whales might be heard at distances of 81 km, assuming spherical spreading, and as great as 1300 km if the deep sound channel is used. This speculation was based on the high intensity and low frequency of fin whale sounds, and the fact that these sounds have been recorded in a deep-water sound channel (SOFAR, see sect. 3.3). However, fin whales do not dive to the depth of the SOFAR channel and probably do not purposefully use it for communication (Watkins 1981b). In practice, the 20 Hz fin whale sounds have been detected using underwater listening stations located up to 180 km from the source whale (Cummings and Thompson 1971a). This 180 km estimate involved sound localization via widespread hydrophones and triangulation. In the upper 50 m of the water column, practical distances for detection of these sounds with a hydrophone are 8-10 km in shallow water, and 25 km in deep water (Watkins 1981b). In apparent response to faint received sounds from fin whales 20-25 km away, one fin whale reacted by swimming toward the group (Watkins 1981b). Watkins believes that most fin whales respond to singers that are nearby (<15 km).

Fin whales also produce sounds at frequencies higher than 20 Hz. These include 34-75 Hz tones, a 129-150 Hz tone preceding more intense 20 Hz sounds, and generally downward-sweeping pulses with frequencies of 118 to 14 Hz and levels of 155 to 165 dB re 1 µPa-m (Patterson and Hamilton 1964; Schevill and Watkins 1972; Watkins 1981b; Cummings et al. 1986; Edds 1988). Sounds recorded by Cummings et al. (1986) were heard only when the whales were at depth and not while whales were breathing at the surface. Watkins (1981b) heard these sounds mostly during interactions of two or more whales, particularly when several whales were feeding near the surface or during long dives. Because of their relatively low source levels, Watkins (1981) speculates that these sounds are used for communicating with nearby whales. In summer, 82% of sounds recorded in the St. Lawrence estuary by Edds (1988) were downsweeps with initial frequencies of 14-118 Hz. Most downsweeps were of 0.5-1 s duration and most had an initial frequency of 40 Hz or less. Vocalizing fin whales are generally less than 1 km, and usually not more than 15 km, from other fin whales (Watkins 1981b). Whales that are alone (>15-20 km from other whales) do not utter these high frequency sounds (Watkins 1981b).

A low frequency broadband rumble with energy concentrated at 30 Hz may signify surprise, e.g. in response to a close encounter with a ship, and may also be associated with agonistic behavior between whales (Watkins 1981b; Edds 1988). The data base is weak and the significance of these presumed short-distance sounds is not well known.

6.1.6 Blue and Minke Whales

Blue whales in the southern hemisphere, off Chile, produced low frequency moans with frequencies between 12.5 and 200 Hz. Moan duration can be up to 36 s (Cummings and Thompson 1971a). A short, 390 Hz pulse is also produced during the moan. The overall source level of the sounds was estimated to be as high as 188 dB re 1 µPa-m, with most energy in the 1/3-octave bands centered at 20, 25 and 31.5 Hz, as well as secondary components near 50 and 63 Hz (Cummings and Thompson 1971a). Each sound was uttered as a 3-part sequence. Cummings and Thompson (1971a) recorded these sounds from two solitary blue whales. While recording one of these whales, similar but weak sounds were heard from whales beyond the visual horizon. Because of the nature of their sounds, these distant whales were presumed to be blue whales.

Thompson et al. (1987) recorded low frequency (<110 Hz) sounds from at least six blue whales spread over 6 km^2 in the Gulf of Mexico. Four of these, possibly subadults, were traveling in separated pairs. Almost half the sounds were recorded as stereotyped doublets, unlike the sounds recorded by Cummings and Thompson in the southern hemisphere and others recorded off California and Oregon (W.C. Cummings, pers. comm.).

Edds (1982) recorded narrowband moans sweeping from 20 to 18 Hz and lasting ~16 s near a lone blue whale. Six of seven sounds from that whale were followed by faint sounds, presumably from a distant blue whale. Functions of these blue whale sounds are unknown, but they may represent long distance communication. Cummings (pers. comm.) believes that regional differences in the protracted, low-frequency moans of blue whales represent regional dialects.

Minke whales produce sounds described as downsweeps, upsweeps, grunts, clicks, thump trains, and ratchets (Winn and Perkins 1976; Thompson et al. 1979). Thump trains may contain individual signature information (Thompson et al. 1979). They lasted over 1 min and are composed of 50 to 70 ms thumps, mainly at frequencies 100-800 Hz (Winn and Perkins 1976; Thompson et al. 1979). Minke whales in coastal waters may have individual home ranges (Dorsey 1983; Edds and Macfarlane 1987). One function of humpback whale songs appears to be to maintain spacing among individuals (Tyack 1981). Minke whales could also use sounds with identification information to maintain spacing.

6.1.7 High Frequency Sounds and "Echolocation"

Some workers have recorded high frequency clicks in the presence of baleen whales (Table 6.1). Some workers have speculated that these clicks are used in echolocation. Other researchers refute this claim and do not believe that there is any evidence of echolocation by baleen whales.

Fin whales may occasionally make high frequency sounds classified as chirps and whistles at frequencies from 1500 to 2500 Hz, with some energy as high as 5000 Hz (Thompson et al.

1979). High frequency clicks up to 28 kHz have also been attributed to fin whales that were close to a hydrophone (Thompson et al. 1979). The small sample of high frequency clicks recorded from fin whales suggests that these sounds are uttered infrequently. Watkins (1981b) has listened to many fin whales with equipment capable of detecting high frequency sounds without encountering frequencies higher than several hundred Hz.

High frequency calls with relatively low source levels have been attributed to blue whales on two occasions by Beamish and Mitchell (1971) and Beamish (1979). However, the sources of these sounds are uncertain. Watkins (1981b) and Norris (1981) do not believe that blue whales make these kinds of high frequency sounds.

Clicks with peak energy at 2.0-8.2 kHz have been recorded near humpback whales by Beamish (1979). Winn et al. (1970a) also recorded clicks at 2-7 kHz, as well as a white noise blast with energy up to 14 kHz. The functions of click sounds produced by humpback whales remain unknown.

Beamish and Mitchell (1973) recorded clicks at principal frequencies of 4 to 7.5 kHz near a minke whale. The clicks had regular repetition rates of ~7 clicks per second and a relatively low source level of 151 dB re 1 μPa-m.

Some baleen whales may make high frequency click sounds (Table 6.1). However, click production in itself does not constitute proof of echolocation abilities. The evidence suggests that if baleen whales produce click sounds, they do so very infrequently. Although baleen whales do not have a well-developed echolocation system similar to that of toothed whales, baleen whales may use their low-frequency calls to obtain some information about their surroundings. Ellison et al. (1987) have speculated that differential reverberation patterns from calls could be used to distinguish pack ice from smooth ice or open water. They speculate that these sounds could be used to make a rough estimate of the nature of the ice ahead of migrating whales. This hypothesis is not proven.

6.2 Toothed Whale Sounds and Echolocation Signals

Numerous species of toothed whales (odontocetes) are found off the coasts of the United States. Toothed whales were the first marine mammals whose sounds received much attention from biologists. Recordings of white whale sounds were made as early as 1949 (Schevill and Lawrence 1949).

Many odontocetes are very social. They sometimes form stable groups of various sizes, and individuals within these groups interact continually with one another. Social interactions include mating and sexual activity, play, dominance interactions, and maternal behavior (Herman and Tavolga 1980; Tyack 1986a). Many species are very vocal when in groups and when interacting with one another.

Odontocete sounds can be classified into three general categories: tonal whistles, pulsed sounds of very short duration used in echolocation, and less distinct pulsed sounds such as cries, grunts and barks (Table 6.4).

Many data on odontocete sounds have been obtained from captive animals. Caution is necessary in interpreting data on waveforms, frequencies and source levels of sounds recorded in captivity. Sounds recorded from odontocetes in the wild and in captivity may differ because of real differences in the sounds emitted by captive vs. free-ranging animals, or because of recording artifacts in small tanks (Cummings et al. 1975; Watkins 1980b; W.C. Cummings pers. comm.).

6.2.1 Kinds of Toothed Whale Sounds

Many odontocete species produce whistle vocalizations (Table 6.4). The white whale and Atlantic spotted dolphin produce both whistles and pulsed sounds (Table 6.4; Caldwell and Caldwell 1971b; Sjare and Smith 1986a). In general, whistling species of toothed whales are very social and assemble in herds of dozens to thousands of individuals (Tyack 1986a). Non-whistling species are generally found alone or in small groups (Herman and Tavolga 1980). There are at least two notable exceptions to this apparent relationship. *(1)* Sperm whales are quite social but produce clicks, not whistles (Watkins and Schevill 1977a; Watkins et al. 1985a,b). *(2)* Killer whales form very stable groups but usually use pulsed sounds to communicate; however, they do produce whistles (Ford and Fisher 1982). The harbor porpoise produces relatively low frequency clicks (2 kHz) and other pulsed sounds (Busnel and Dziedzic 1966a). Dall's porpoise also utters rather low frequency clicks (0.4-12 kHz) and apparently does not whistle often (Evans 1973; Awbrey et al. 1979).

Whistles.--Most whistles emitted by odontocetes are narrowband sounds--sometimes pure tones. Whistles typically have most of their energy below 20 kHz (Table 6.4). A large variety of whistles can be produced. Basic kinds of whistles include those whose frequency pattern is unmodulated, trilled, ascending, descending, ascending-descending, descending-ascending, or slowly wavering. A whistle can consist of one of these sounds, a series of sounds of one type, or a series of sounds of several types. Over the duration of a whistle, the amplitudes of the ascending and descending portions can vary. Whistles can be continuous or have a variable number of breaks and segments within one whistle. For any one species, initial, final, maximum and minimum frequencies may vary, as can the duration and intensity. The bottlenose dolphin can combine basic kinds of whistles into more complex phrases (see Dreher and Evans 1964). Taruski (1979) has shown that the whistles of the long-finned pilot whale form a continuum in which no mutually exclusive types could be recognized.

Clicks and Pulsed Sounds.--Most vocalizations recorded in the presence of sperm whales are clicks. Watkins (1980a) and Watkins et al. (1985a) did not believe that these clicks were suitable for echolocation. However, recent evidence suggests that they may be used for echolocation (e.g. Mullins et al. 1988). Sperm whale clicks have a frequency range from <100 Hz to 30 kHz with most energy at 2-4 kHz and 10-16 kHz. Clicks are repeated at rates of 1-90 per second (Backus and Schevill 1966; Watkins and Schevill 1977b; Watkins et al. 1985a). Source levels of clicks for sperm whales at sea can be near 180 dB re 1 µPa-m (Watkins 1980a). Dunn (1969) reported a source level of 173 dB in a 1/3-octave band centered at 1 kHz. Levenson (1974) recorded source levels of 163-175 dB (mean 171, s.d. 3 dB) for 13 discrete sperm whale sounds.

Killer whales are very gregarious and social groups (pods) of some populations are stable for many years. Hoelzel and Osborne (1986) identified 38 discrete call types from three pods

Table 6.4. Characteristics of underwater sounds produced by odontocete whales.

Species	Signal type	Frequency Range (kHz)	Dominant Frequencies (kHz)	Source Level (dB re 1 µPa at 1 m)	References
Physeteridae					
Sperm whale	clicks	0.1-30	2-4, 10-16	160-180	Backus and Schevill 1966; Levenson 1974; Watkins 1980a
Pygmy sperm whale	echolocation	<2	-	-	Caldwell et al. 1966a; Caldwell and Caldwell 1987
	clicks	60-200	120	-	Santoro et al. 1989
Monodontidae					
White whale	whistles	0.26-20	2-5.9	-	Sjare and Smith 1986a,b
	pulsed tones	0.4-12	1-8	-	Sjare and Smith 1986a,b
	noisy vocalizations	0.5-16	4.2-8.3	-	Sjare and Smith 1986a,b
	echolocation	40-120	variable	160-222	Au et al. 1985, 1987
Ziphiidae					
Northern bottlenose whale	whistles	3-16	-	-	Winn et al. 1970a
	clicks	0.5-26+	-	-	Winn et al. 1970a
Blainville's beaked whale	chirps/short whistles	<1-6	-	-	Caldwell and Caldwell 1971a
Mesoplodon sp.	clicks	to 80+	0.875	-	Buerki et al. 1989; Lynn and Reiss 1989
Delphinidae					
Killer whale	whistles	1.5-18	6-12	-	Steiner et al. 1979; Ford and Fisher 1983;
	pulsed tones	0.5-25	1-6	160	Awbrey et al. 1982; Ford and Fisher 1983; Schevill and Watkins 1966
	echolocation	0.1-35	12-25	180	Diercks et al. 1971, 1973; Wood and Evans 1980
False killer whale	echolocation	-	20-65	-	Thomas et al. 1988
	whistles	-	4-9.5	-	Busnel and Dziedzic 1968
Pygmy killer whale	echolocation?	-	-	-	Pryor et al. 1965
	growls, blats	-	-	-	Pryor et al. 1965
Long-finned pilot whale	whistles	1-8	1-5[1]	-	Steiner 1981; Taruski 1979; Busnel and Dziedzic 1966a
	echolocation	1-18	-	-	Busnel and Dziedzic 1966a
Short-finned pilot whale	whistles	0.5-20+	2-14	180	Fish and Turl 1976; Caldwell and Caldwell 1969
	echolocation	0.1-100	-	180	Evans 1973

Continued...

Table 6.4. Concluded.

Species	Signal type	Frequency Range (kHz)	Dominant Frequencies (kHz)	Source Level (dB re 1 μPa at 1 m)	References
Bottlenose dolphin	echolocation	10-200	110-130	220	Au et al. 1974; Au and Penner 1981; Au et al. 1982
	whistles	4-18	9-12	-	Lilly and Miller 1961
	rasp, grate, mew, bark, yelp	-	-	-	Wood 1953
Northern right-whale dolphin	clicks	1-40+	40+?	180	Fish and Turl 1976
	whistles	?-16+	-	-	Leatherwood and Walker 1979
	tones	1-4	1.8,3	-	Leatherwood and Walker 1979
Common dolphin	whistles	-	2-18	-	Caldwell and Caldwell 1968
	chirps	-	8-14	-	Caldwell and Caldwell 1968
	barks	-	<0.5-3	-	Caldwell and Caldwell 1968
	echolocation	0.1-150	20-100	180	Evans 1973; Fish and Turl 1976
Risso's dolphin	whistles	-	3.5-4.5	-	Caldwell et al. 1969
	clicks	<1-8	-	-	Watkins 1967b
	rasp/pulse burst	0.1-8+?	2-5	-	Watkins 1967b
Atlantic spotted dolphin	whistles	-	6-13	-	Caldwell et al. 1973a; Steiner 1981
	clicks	1-8	-	-	Caldwell and Caldwell 1971b
	squealy-squawk	0.1-3	-	-	Caldwell and Caldwell 1971b
	squawk	<1	-	-	Caldwell and Caldwell 1971b
	barks	0.1-3	-	-	Caldwell and Caldwell 1971b
	growls	-	-	-	Caldwell et al. 1973a
	chirps	4-8	-	-	Caldwell et al. 1973a
Striped dolphin	whistles	-	8-12.5	-	Busnel et al. 1968
Spinner dolphin	clicks	-	-	85-95?	Watkins and Schevill 1974
	whistles (= squeals?)	1-20	9-14[1]	109-125?	Watkins and Schevill 1972; Steiner 1981
	pulse bursts	-	2-3	108-115	Watkins and Schevill 1972
Atlantic white-sided dolphin	whistles	-	8-12	-	Steiner 1981
Pacific white-sided dolphin	whistles	2-20+	4-12	-	Caldwell and Caldwell 1970b, 1971c
	echolocation	0.2-150	60-80	170	Evans 1973
Rough-toothed dolphin	clicks	16-100+	-	-	Norris and Evans 1967
	whistles	-	4-7	-	Busnel and Dziedzic 1966b
Phocoenidae					
Dall's porpoise	clicks	0.04-12, 125-135	-	120-148	Evans 1973; Evans and Awbrey 1984
Harbor porpoise	clicks	100-160	130	132-149	Dubrovskii et al. 1971; Møhl and Andersen 1973
	clicks	2	-	100	Busnel and Dziedzic 1966a; Schevill et al. 1969

[1] Maximum and minimum frequencies.
? Questionable data.

resident in the Puget Sound area of western North America. Ten of these calls were monosyllabic frequency modulations or constant tones, 18 were 2 or 3 syllable tonal calls, and 10 were multisyllabic calls that were most often rapid alternations of a constant tone or frequency modulation. The 10 most common calls represented 85% of the phonations recorded. Each pod tends to have a characteristic dialect (Ford and Fisher 1982, 1983). Some of the variability in vocalizations within pods may be due to individual differences in call rendition (Ford and Fisher 1983). Pods that frequently socialize or travel together may share many discrete types of calls, whereas other pods, often found nearby, exhibit no overlap in calls. Pods with no overlap in calls do not associate socially.

Seventy to ninety-five percent of killer whale social sounds are pulsed (Ford and Fisher 1982). The pulsatile calls have been described as "screams" (Schevill and Watkins 1966), or as being "harsh and metallic" (Steiner et al. 1979). Pulsed calls are extremely complex with energy at 600 Hz to 25 kHz and pulse repetition rates up to 5000 per second (Ford and Fisher 1982). Pulsed calls differ from echolocation clicks in that the pulse repetition rate is much higher. Pulse repetition rate for echolocation clicks is 6 to 18 clicks/s (Schevill and Watkins 1966). Durations of pulsed calls range from 0.05 to 10 s, but most are 0.5-1.5 s long (Ford and Fisher 1982).

6.2.2 Possible Functions of Toothed Whale Sounds

Most toothed whales are gregarious. Depending on the species, they often travel and feed in groups of three to thousands. Some researchers believe that certain odontocete sounds may serve an individual-identification function, but the evidence for this is controversial. When feeding, odontocetes often cooperate to maximize feeding opportunities, e.g. by herding prey. There is indirect evidence that this coordination is effected through acoustic contact.

There continues to be a good deal of research on the communicative functions of whistles and other sounds, the establishment of correlations between specific sound types and behaviors, and the existence and use of "language" by odontocetes (e.g. Dreher and Evans 1964; Taruski 1979; Morton et al. 1986; Schusterman et al. 1986; Sjare and Smith 1986b). This work has shown that some sound types are produced under specific behavioral circumstances. However, results obtained in the wild are often ambiguous, and the applicability of results obtained in captivity to animals in the wild remains unknown. Important functions of the sounds may include communication of information about the location, sex, reproductive status, emotional state and individual identity of the whale (Evans 1987). In the following discussion, comments about functions of various sounds are based on reports of general associations between specific sounds and behaviors--often not replicated. This discussion is, therefore, highly speculative.

Signature Calls.--Several researchers believe that some species of odontocetes use "signature calls" to convey information about the specific identity of the sender. They present evidence showing that calls are recognized and sometimes mimicked by other individuals. Most odontocetes use whistle vocalizations for this purpose. However, Watkins and Schevill (1977a) believe that click sounds of sperm whales can be used for individual identification. Sperm whale clicks may also convey information about the age and sex of the sender (Weilgart and Whitehead 1988). Pulsed sounds of each killer whale pod are distinct from those of other pods (Ford and Fisher 1982, 1983).

In many odontocete species, whistles may serve as identification calls and for other forms of communication (Caldwell and Caldwell 1977; Tyack 1986b). Originally the Caldwells suggested that the main purpose of whistles was identification; that is, each dolphin in a social group would have a unique stereotyped way of modulating the frequency of its whistles (Caldwell and Caldwell 1965). They found that 90% of the whistles made by each individual were this single type of signature call. The bottlenose dolphin can recognize the signature calls of other individuals within its group, as well as those of some individuals of other species (Caldwell et al. 1971, 1973b; Caldwell and Caldwell 1985).

Caldwell and Caldwell (1977) conceded that, in the bottlenose dolphin, a very limited amount of other information may be transferred via whistles, but concluded that whistles are primarily signature calls. Whistles may, however, function in other forms of communication provided that the receivers recognize the identity of the sender; whistles of a captured male Atlantic spotted dolphin elicited flight reactions from members of his own herd (Herman and Tavolga 1980). However, when played back to conspecifics in another area the same whistles caused approach and investigation. Tyack (1986b) has shown that bottlenose dolphins mimic each other's signature whistles. These whistles may be used as contact calls to establish or maintain contact between individuals (Tyack 1987).

Whistles that could be signature whistles have been recorded from the bottlenose dolphin, common dolphin, Atlantic and Pacific white-sided dolphins, Atlantic spotted dolphin, spinner dolphin, and long-finned pilot whale (Caldwell and Caldwell 1965, 1968, 1971c; Caldwell et al. 1973a; Steiner 1981). The white whale also has a very extensive repertoire of whistle sounds (Sjare and Smith 1986a). Whistles of the rough-toothed dolphin are similar to those of bottlenose dolphins and pilot whales (Busnel and Dziedzic 1966b). Whistles of the false killer whale are similar to those of the pilot whale and common dolphin (Busnel and Dziedzic 1968). However, research to establish whether white whales, rough toothed dolphins and false killer whales use signature calls has not been done.

Some types of sperm whale clicks may be used for individual identification, since unique stereotyped click sequence "codas" have been recorded from individual whales over periods lasting several hours (Watkins and Schevill 1977b; Adler-Fenchel 1980; Watkins et al. 1985b). The internal pulse structure of each click may also differ among individuals (Norris 1969). Slow clicks with an inter-click interval of ~6 s and frequencies <4 kHz may convey some information about the sex and reproductive status of the sender (Weilgart and Whitehead 1988). Production of these slow clicks appears to be restricted to maturing or mature males.

Coordination of Activity.--Foraging killer whales are often dispersed over distances of 2 km. Vocalizations may be important in coordinating pod foraging and other activities (Hoelzel and Osborne 1986; Ford 1989).

Off Hawaii, spinner dolphins feed in large schools dispersed over distances as great as 3 km (Norris and Dohl 1980). However, these schools move and reverse course together, and all members dive and surface within 1-2 min of each other. Thus, movements are coordinated but not fully synchronized. Norris and Dohl (1980) speculate that spinner dolphins probably use acoustic communication to pass information across the school.

The dusky dolphin (not a U.S. species) is closely related to the Atlantic and Pacific white-sided dolphins. Dusky dolphins in the South Atlantic forage in small groups of 6 to 15 individuals, with 20 to 30 such groups spread over an area of 100 km^2 (Würsig and Würsig 1980). The distance between adjacent foraging groups is ~1 km, which may be about the average range of audibility of their sounds (Würsig and Würsig 1980). Würsig and Würsig speculate that spacing is maintained by listening for the vocalizations of other groups. When a school of fish is found, the dolphins coordinate their activities to herd the fish against the sea surface. This activity is accompanied by much leaping by the dolphins into the air. The initial group is often joined by other groups. Birds are attracted to the feeding site. Würsig and Würsig (1980) speculate that vocalizations and noise associated with leaping attract dolphin groups from ½-1 km distance, and that groups >1 km away use visual cues (leaping and the overhead birds) to locate the feeding area.

In the North Atlantic, the complexity of long-finned pilot whale whistles is positively correlated with complexity of overt behavior (Taruski 1979; Weilgart and Whitehead 1990). Simple whistles were heard most often when pilot whales were milling or resting on the surface. Many sound types, especially complex whistles, were associated with presumed feeding activity. Greater numbers of most whistle types were produced when the whales were dispersed over a large area or when more than one group was present (Weilgart and Whitehead 1990).

Sperm whale clicks may function to maintain herd integrity during foraging in darkness at great depths or when the pod is scattered at the surface (Watkins and Schevill 1977a,b; Watkins et al. 1985a; Whitehead and Weilgart 1990). While under water, sperm whales may be ≥1 km apart but remain in contact with one another through clicking. Animals sometimes regroup just prior to surfacing, or surface independently several kilometers apart, whereupon they begin swimming in the same direction. Click series lasting ½-5 s and with a repetition rate of 1-3 clicks/s appear to be used for this type of long distance contact (Watkins et al. 1985a). Lone sperm whales are generally silent (Watkins 1980a).

6.2.3 Directionality and Effective Range of Sounds

Ranges at which toothed whale sounds are audible depend on a number of factors including sea state (i.e. the ambient noise level), the source level and directionality of the sounds, and the sensitivity of the receiver.

Although all echolocation clicks appear to be directional (see sect. 6.2.4), little information is available on directionality of other sounds. The pulse bursts of the Hawaiian spinner dolphins are probably omnidirectional (Watkins and Schevill 1974), as are the 2 kHz clicks used for communication by the harbor porpoise (Møhl and Andersen 1973). Fish and Turl (1976) report that sounds made by a herd of 200 common dolphins were 10-15 dB higher in intensity when the herd approached the hydrophone than when it moved away. However, echolocation clicks may have been the dominant sounds recorded. A sperm whale's click series showed little variation as a whale approached a hydrophone and then swam away, indicating that sperm whale clicks are not highly directional (Watkins 1980a).

Estimates of the ranges over which odontocete sounds can be detected by other animals can be made by examining the ranges at which the sounds can be detected with a hydrophone. There have been few attempts to determine maximum range of detection with hydrophones.

Fish and Turl (1976) recorded sounds of common dolphins, bottlenose dolphins, short-finned pilot whales, and northern right whale dolphins 200-1000 m from the animals. These sounds included the full range of sounds known for animals in the wild. Fish and Turl (1976) did not estimate maximum ranges for detection of the sounds. Pilot whale whistles were audible via hydrophone at distances of 400-1600 m (Busnel and Dziedzic 1966a; Taruski 1979). Echolocation signals from northern right whale dolphins were detected by hydrophone at a distance of 730 m (Leatherwood and Walker 1979). Evans and Dreher (1962) detected bottlenose dolphin echolocation signals at a distance of 450 m, with whistles audible at ~370 m.

Watkins (1980a) has detected sperm whale sounds at distances of 10 km and he estimates that sounds made in deep water can be detected with a hydrophone at 15 km (Watkins and Moore 1982). However, sperm whales apparently can vary the intensities of their sounds. At some times they were barely audible via hydrophones at distances of a few hundred meters (Watkins 1980a).

Pulsed sounds emitted by Peale's dolphin, a South American species, had very low source levels: only ~80 dB re 1 μPa-m. These sounds, which were at relatively low frequency (1 to 5 kHz), were not detectable at ranges exceeding 10-20 m (Schevill and Watkins 1971). Because of its low source level, the low frequency (2 kHz) click of the harbor porpoise would only be audible over short distances (Møhl and Anderson 1973).

In summary, there are insufficient data to determine the effective range at which odontocete sounds can be detected. A few circumstantial observations indicate that most odontocete sounds may be detectable by humans with hydrophones over ranges no greater than hundreds of meters, and perhaps up to a maximum of 1 km. Species that produce only low frequency sounds with low source levels may be detectable only within a few tens of meters. Sperm whales can be detected at distances >1 km.

6.2.4 Echolocation

Echolocation has been demonstrated in several species of odontocetes (Table 6.5). Numerous other species produce clicks of types used in echolocation but have not been proven to echolocate (Table 6.5). There is no proof that the sperm whale echolocates; however, it likely does so (Mullins et al. 1988).

Echolocating odontocetes produce highly-directional forward-projecting pulsed sounds of high intensity and frequency. In most but not all cases, pulses are spaced so an echo from the target is received before the next pulse is emitted. Pulse duration, frequency, inter-click interval, and sound level are adjusted by the animal to maximize detection under different conditions of ambient noise, reverberation, and distance to the target. The echolocation capabilities of the bottlenose dolphin and of the white whale are well documented; abilities of other species are much less well studied. The following section describes characteristics of echolocation

Directionality of Echolocation Signals.--Echolocation clicks are projected from an odontocete's head in a highly directional beam (Table 6.6). However, the beam does not have sharply defined edges. The peak intensity is at the center of the beam and intensity decreases

Table 6.5. Frequencies and source levels of odontocete echolocation clicks for species with demonstrated echolocation abilities and for similar clicks by other species.

Species	Frequency (kHz)	Source Level (dB re 1 μPa at 1 m)	Reference
Echolocation Demonstrated			
White whale	40–60, 100–120	206–222	Au et al. 1985, 1987
Killer whale	12–25	180	Diercks et al. 1971; Evans 1973; Wood and Evans 1980
Short-finned pilot whale	0.1–100	180	Evans 1973
Pacific white-sided dolphin	60–80	170	Evans 1973
Common dolphin	20–100	140	Evans 1973; Wood and Evans 1980
Bottlenose dolphin	100–130	218–228	Au et al. 1974
Atlantic spotted dolphin	-	-	Caldwell and Caldwell 1971b
Commerson's dolphin	130	135–142	Yeh et al. 1982
Harbor porpoise	110–150	132–149	Busnel et al. 1967; Møhl and Anderson 1973
Amazon River dolphin	60–80 95–105	166 -	Evans 1973 Kamminga et al. 1989
Echolocation type clicks			
Narwhal	20–60	to 218	Møhl et al. in press
Pygmy sperm whale	clicks	-	Caldwell et al. 1966a; Caldwell and Caldwell 1987
Bottlenose whale	8–12	-	Winn et al. 1970b
Long-finned pilot whale	6–11	-	McLeod 1986
Rough toothed dolphin	16–100+	-	Norris and Evans 1967
Tucuxi (*Sotalia*)	8–20+ 95–100	-	Caldwell and Caldwell 1970a Kamminga et al. 1989
Risso's dolphin	<1–8	-	Watkins 1967b
Spinner dolphin	clicks	85–95	Watkins and Schevill 1974
N. right whale dolphin	1–40+?	170	Fish and Turl 1976
Dalls' porpoise	125–135	120–148	Evans and Awbrey 1984
Indus susu	0.1–150	140	Herald et al. 1969
Franciscana	.6–.9, 1.4–1.7, 16–24	-	Busnel et al. 1974

Table 6.6. Directionality of odontocete echolocation clicks.

Species	Directionality	References	
Pygmy Sperm Whale	Directional	E	Caldwell and Caldwell 1987
White whale	3 dB beamwidth 6.5°	E	Au et al. 1987
Killer whale	4-6 dB loss at 90° at 3-4 kHz.	E	Schevill and Watkins 1966
Rough-toothed dolphin	6 dB beamwidth 10-12°	E	Norris and Evans 1967
Bottlenose dolphin	3 dB beamwidth 10-11.7°	E	Au et al. 1978; Au 1980
Hawaiian spinner dolphins	probably directional	F	Watkins and Schevill 1974
N. right whale dolphin	signal clearest when animal pointed directly at hydrophone.	F	Leatherwood and Walker 1979
Commerson's dolphin	3 dB beamwidth 16°	T,E	Yeh et al. 1982
Harbor porpoise	>27 dB loss at 90°	E	Møhl and Andersen 1973
Amazon river dolphin	clicks strongest when directed at hydrophone.	E	Caldwell and Caldwell 1970a

E = Based on experiments with captive animals.
F = Based on field observations.
T = Based on theoretical calculations.

with increasing angular distance off-center. Beamwidth is commonly expressed as the angle between the center of the beam and the off-axis point where the level is 3 dB lower than that at the center. In the bottlenose dolphin, the 3 dB beamwidth is 10 to 11.7° on either side of the center line of the animal at an angle 5° above its major axis (Au et al. 1978; Au 1980). In the white whale, the 3 dB beamwidth is only 6.5°, also at an angle of 5° above the major axis (Au et al. 1987). High frequency energy is especially strongly concentrated in the center of the beam; lower frequency components are distributed more broadly (Schevill and Watkins 1966).

Because the transmitting beam is highly directional, the effective source level within the beam is much higher than it would be if the beam were omnidirectional with the same total power. Directivity index, a measure of this apparent increase in source level due to directionality, is 25-27 dB in the bottlenose dolphin and 32 dB in the white whale (Au et al. 1986, 1987). Such extreme directionality helps provide a good target localization ability and intense echo returns from targets. Directionality and shape of the sonar fields for some other species have been calculated on theoretical grounds (Evans et al. 1964; see Pilleri et al. 1982a,b; Table 6.6).

The extreme directionality of the echolocation beam causes difficulties in documenting the frequency content and source levels of echolocation clicks produced in the wild. This occurs because, in uncontrolled field conditions, the orientation of the animal with respect to the hydrophone is usually unknown. The high frequency components may only be detectable when the beam is directed at the hydrophone. Also, the effective source level is underestimated when the beam is not directed at the hydrophone.

Source Levels.--Echolocation clicks have the highest source levels of any recorded marine mammal sounds. Average source levels for captive bottlenose dolphin echolocation clicks are ~220 to 222 dB re 1 µPa-m, with a maximum of 228.6 dB (Au et al. 1974). In a captive white whale, the source level increased from 206 to 218 dB re 1 µPa-m as range to the target increased (Au et al. 1987). A maximum source level of 218 dB re 1 µPa-m was recorded from a narwhal in the wild (Møhl et al. in press).

The white whale compensates for interfering ambient noise by emitting clicks at higher frequencies and higher intensities than under conditions of low ambient noise (Au et al. 1985). The source level of echolocation clicks increased from 204 db re 1 µPa-m under conditions of low ambient noise to 222 dB with strong noise (Au et al. 1985). This adjustment would increase the signal-to-noise ratio commensurately. Au et al. point out that higher intensities may be a by-product of sound emission at higher frequencies.

Source levels of echolocation clicks recorded from bottlenose dolphins and white whales under controlled experimental conditions are considerably higher than those of most other species (Table 6.5). Most of the low values reported for other species represent measurements made under less than ideal conditions. Many field measurements probably are erroneous because of difficulties in identifying the echolocating animal, estimating its range, and determining its heading relative to the hydrophone. Also, animals probably do not emit their most powerful pulses unless required. The only echolocation clicks recorded in the wild whose levels approach those of captive white whales and bottlenose dolphins are those of the narwhal (Møhl et al. in press).

Sound Frequencies Used in Echolocation.--Under conditions of low ambient noise, a white whale emitted echolocation pulses with peak energy at 40-60 kHz (Au et al. 1985). It adapted to higher ambient noise levels by emitting signals at higher frequencies (100 to 120 kHz; Au et al. 1985). The bottlenose dolphin usually produces echolocation clicks with peak energy at 120 to 130 kHz (Au et al. 1974; Au and Penner 1981; Au et al. 1982). However, Evans (1973) reported bottlenose dolphin echolocation clicks with peak energy at 30-60 kHz. This difference may have been related to differences in ambient noise level (Popper 1980a), but the situation is unclear.

Most species in which echolocation has been demonstrated or suspected emit clicks at relatively high frequencies (Table 6.5). However, the killer whale is an exception. Its echolocation clicks contain most energy at frequencies below 25 kHz (Wood and Evans 1980). Consistent with this, the upper hearing limit for the killer whale is only 32 kHz (Hall and Johnson 1972), a value considerably lower than that of the other toothed whale species whose hearing has been tested (see sect. 7.2.1).

Repetition Rate in Echolocation.--Two general types of echolocation click trains are emitted by odontocetes. "Orientation clicks" with relatively long inter-click intervals are used to scan the environment. "Discrimination clicks", often at briefer intervals, are used to obtain detailed information about a target (Airapet'yants et al. 1973; Popper 1980a). The inter-click interval (and thus the click repetition rate) is normally a function of the range being scanned, i.e. the two way sound travel time to and from the target.

In the bottlenose dolphin, the inter-click interval is generally greater than the two way travel time to the target (Au et al. 1974, 1982; Turl and Penner 1989). Thus, there is a brief lag between receipt of the echo from one click and emission of the next click. This lag time may be a function of the nature of the echolocation task and can range from 7 to 50 ms (Au 1980; Au et al. 1982). The inter-click interval increases with increasing distance to the target, from 10-25 ms at 1 m range to 120-160 ms at 73 m (Au 1980; Au et al. 1974, 1982). In contrast, the two-way travel time for a sound pulse is ~1.3 ms at 1 m range and 130 ms at 100 m. Click duration is 35-45 µs (Au et al. 1974).

In the white whale, the inter-click interval often is less than the two way travel time, at least for targets at distances >40 m (Turl et al. 1987; Turl and Penner 1989). The white whale's echolocation performance is superior to that of the bottlenose dolphin in several respects. One reason for this may be that the shorter inter-click intervals allow the white whale to process more information per unit time and thus gain greater accuracy (Turl et al. 1987).

Echolocation Ranges.--With a 7.62 cm sphere as a target, the maximum detection range (50% correct response) for a trained bottlenose dolphin under controlled experimental conditions was 113 m (Au and Snyder 1980). Under similar conditions, a trained white whale had good echolocation capabilities at distances as great as 80 m (Au et al. 1987). Maximum detection range for white whale echolocation is unknown. An experiment conducted with untrained bottlenose dolphins in open water showed that they may have detected a large target at a range of 360 m (Evans and Dreher 1962).

Many echolocation experiments have been conducted in rather small tanks where background noise and beam propagation are known or expected to differ from those in typical natural conditions. Such results cannot be used to estimate maximum detection ranges.

Echolocation Functions.--Echolocation has been demonstrated in various odontocete species, and similar impulses have been recorded from a number of other species (Table 6.5). Further work probably will show that all dolphins and porpoises can echolocate. In most cases, echolocation has been demonstrated through the use of trained animals. The functions of echolocation in the wild are not well known, but they are suggested by the needs of wild animals known to possess this capability.

Odontocetes echolocate for obstacle avoidance (Moore 1980). Evans and Dreher (1962) performed a simple experiment demonstrating scouting and obstacle avoidance by wild bottlenose dolphins. A penetrable barrier that was a good acoustic reflector was strung across a channel used by the animals. Five animals approached the barrier, but at a distance of 360 m they moved off to a shoal and formed a tight group. One at a time, 3 or 4 animals detached themselves from the group, made sonar runs (detected with a hydrophone) toward the barrier, and then rejoined the group. After this investigation, the entire group passed the barrier.

Captive Amazon River dolphins (boutus) appeared to use passive listening and vision to investigate their surroundings and to feed. Echolocation was also used, especially when visibility was poor, but vision was the preferred sensory modality (Caldwell et al.1966b). They speculated that young animals may have to learn how to echolocate.

Bel'kovich and Yablokov (1963) and Norris and Møhl (1983) suggested that intense "echolocation" signals may be used to stun prey at close ranges. However, sound pressure intensities of sufficient magnitude to stun prey have not been reported. The maximum sound intensity recorded for a bottlenose dolphin was 228.6 dB re 1 µPa-m (Au et al. 1974). The threshold causing disorientation in 50% of very small experimental fish was 236 dB re 1 µPa (Zagaeski 1987). Dolphins apparently do use echolocation-type clicks to disorient schools of fish, to extricate individual fish from a school, and even to break up a school (Hult 1982; Norris and Møhl 1983). Odontocetes may use echolocation-type sounds as an aid in feeding (e.g. Marten et al. 1989), but the extent to which these signals are used to debilitate prey remains unknown. Norris and Møhl speculated that the morphology of sperm whales was consistent with production of very intense sound pulses that might be suitable for debilitating prey, but this suggestion remains controversial and unproven.

6.3 Phocid Seal Sounds

Phocid (hair) seals found off the coast of the United States are diverse in habits and habitats. Bearded and ringed seals spend most of their time in the water or on ice, and penetrate far into arctic waters--wherever there is open water. Ringed seals maintain access holes in areas without open water. The ribbon seal hauls out on the ice but not on land, and migrates into arctic waters. The harp seal is not found off the coast of the U.S.; however, it is similar in habits to the ribbon seal and is included in the discussion because it has been one of the most studied of the phocids. Harbor, spotted, monk, gray, and northern elephant seals haul out on land. Because most phocid seal calls seem to be associated with mating, mother-pup interactions, and territoriality, underwater calls may not be very important for species such as the gray seal and elephant seal that perform these activities on land.

Some phocid seals produce intense underwater sounds that may propagate for great distances (Burns 1967; Ray et al. 1969; Watkins and Ray 1977), whereas other species produce faint and infrequent sounds (Schevill et al. 1963). Underwater sounds of the bearded, harp, ribbon, spotted, and ringed seals are thought to be associated with reproduction and territoriality since they are heard predominantly in the mating season (Ray et al. 1969; Terhune and Ronald 1976a; Watkins and Ray 1977; Beier and Wartzok 1979; Stirling et al. 1983). Phocids probably hear underwater sounds at frequencies up to ~60 kHz (sect. 7.2.2). Vocalizations between 90 Hz and 16 kHz have been reported (Table 6.7), but it is possible that other high frequency sounds were missed. The acoustic source level has been estimated for ribbon, harp, and ringed seals (Table 6.7). However, it is difficult to determine the range to a seal calling underwater, especially under ice, so reliable estimates of source levels are rare.

6.3.1 Ringed Seal and Bearded Seal

The ringed seal and bearded seal spend much of the time in the water, and calls presumed to be associated with territoriality and courtship are produced underwater. Because most of the relevant behaviors occur under water or under ice, it has not been possible to associate specific behaviors with specific call types. Arctic seals haul out on the ice in spring, but their in-air vocal behavior at this time has not been studied. The underwater calls of ringed and bearded seals are quite different.

Table 6.7. Characteristics of underwater sounds produced by pinnipeds and sirenians.

Species	Signal type	Frequency Range (kHz)	Dominant Frequencies (kHz)	Source Level (dB re 1 µPa at 1 m)	References
Phocids[a]					
Bearded seal	song	0.02-6	1-2	178	Ray et al. 1969; Stirling et al. 1983; Cummings et al. 1983
Ribbon seal	frequency sweeps	0.1-7.1	-	160 (estimated)	Watkins and Ray 1977
Harp seal	15 sound types	<0.1-16+	0.1-2	130-140	Møhl et al. 1975; Watkins and Schevill 1979; Terhune and Ronald 1986
	clicks	-	30	131-164	Møhl et al. 1975
Ringed seal	barks, clicks, yelps	0.4-16	<5	95-130	Stirling 1973; Cummings et al. 1984
Harbor seal and Spotted seal	social sounds	0.5-3.5	-	-	Beier and Wartzok 1979
	clicks	8-150+	12-40	-	Schevill et al. 1963; Cummings and Fish 1971; Renouf et al. 1980; Noseworthy et al. 1989
Gray seal	clicks	0-30	-	-	Schevill et al. 1969; Oliver 1978
	hiss	0-40	-	-	Oliver 1978
Otariids[a]					
California sea lion	barks	<3.5	<8	-	Schusterman et al. 1967
	whinny	<1-3	-	-	Schusterman et al. 1967
	clicks		0.5-4	-	Schusterman et al. 1967
	buzzing	<1-4	<1	-	Schusterman et al. 1967
Northern fur seal	clicks, beats	-	-	-	Poulter 1968
Steller sea lion	clicks, growls	-	-	-	Poulter 1968
Walrus	bell tone	0.4-1.2	-	-	Schevill et al. 1966
	clicks	0.4-10	-	-	Ray and Watkins 1975
Florida Manatee	squeaky	0.6-16	0.6-5	10-12 dB above ambient at 3-4 m	Schevill and Watkins 1965

[a] Underwater sounds of monk and elephant seals, and of Guadalupe fur seals, have not been described.

Bearded seals commonly produce distinctive trills whose dominant feature is a series of prolonged frequency downsweeps (Ouellet 1979). Bearded seals from various arctic areas appear to have identifiable geographic dialects (Cleator et al. 1987, 1989). In Alaskan waters, the trill generally starts at ~2.5 kHz, after which there is a short warbling upsweep to 3 kHz with frequency modulations of up to 1 kHz around the center frequency (Ray et al. 1969). The center frequency then descends, with modulations, to <1 kHz. Below 1 kHz the downsweep may be interrupted by an upsweep to ~2 kHz, after which the downsweep is resumed. There may be several downsweeps and upsweeps during a call. The call ends when a downsweep ends in a pause lasting up to 30 s, after which there is a 3-s pure tone moan that descends from 500 to 200 Hz. The duration of the bearded seal call is highly variable, but usually is at least a minute (Ray et al. 1969).

Bearded seal sounds are most common in spring and may be heard on recordings of other arctic marine mammals (e.g. Ljungblad et al. 1982c; Clark and Johnson 1984; Cummings and Holliday 1987). Bearded seal sounds constitute a dominant component of the ambient noise in many parts of the arctic during spring (e.g. Thiele 1988). The song is thought to be a territorial advertisement call or a mating call of the male bearded seal (Ray et al. 1969). Inuit hunters detect bearded seals from "great distances" by listening through paddles dipped in the water (Burns 1967). Source levels up to 178 dB re 1 µPa-m have been estimated (Cummings et al. 1983). The extreme frequency modulation and repetition of downsweeps in the bearded seal song may function to contrast with ambient noise. Cleator et al. (1989) estimated, based on time of arrival differences at two hydrophones, that some sounds from bearded seals up to 25-30 km away were detectable. Stirling et al. (1983) found that the overall rate of vocalization increased between late winter and early summer; however, they were unable to determine if this was due to an increase in the numbers of seals present or in vocalization rate per seal.

Ringed seal sounds are less complex and much lower in source level than those of the bearded seal. Ringed seal sounds include 4 kHz clicks, rub sounds (peak energy 0.5 to 2 kHz, durations 0.08 to 0.3 s), squeaks that are shorter in duration and higher in frequency, "quacking barks" (0.4 to 1.5 kHz, 0.03 to 0.12 s), yelps, and growls (Schevill et al. 1963; Stirling 1973; Cummings et al. 1984). Ringed seal calls appear to have most energy below 5 kHz (Stirling 1973; Cummings et al. 1984). It is possible that ringed seals produce sounds at higher frequencies, given that their most sensitive band of hearing extends up to 45 kHz (Terhune and Ronald 1975b; sect. 7.2.2) and that most recordings have been made with equipment unsuitable for frequencies >15 kHz. Cummings et al. (1984) note that the source levels of ringed seal vocalizations, 95 to 130 dB re 1 µPa-m (peak source spectrum levels), are low compared to most other marine mammals.[3] These low levels imply that detection ranges of those sounds for humans are only ~1 km (Cummings et al. 1984). The relatively low source levels of ringed seal sounds, at least in the human hearing range, may explain Stirling's (1973) observation that Inuit hunters (who can hear bearded seal calls through the ice) believe ringed seals to be silent. In addition, ringed seals make sounds infrequently and their sounds may be masked by bearded seal sounds.

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[3] The source spectrum levels (dB re 1 µPa at 1 m in 1 Hz band) reported by Cummings et al. (1984) are not directly comparable to broadband source levels. Broadband levels of ringed seal calls would be higher by an unknown amount.

No ringed seal calls associated solely with the reproductive season have been reported, but relative frequencies (Hz) of barks and yelps differ between seasons (Stirling 1973). The number of vocalizations increases markedly at the onset of the breeding season in April (Stirling et al. 1983; Cummings et al. 1984). Later in spring and during summer, ringed seals seem much less vocal (Stirling et al. 1983). Functions of sounds produced under the ice are unknown.

6.3.2 Ribbon Seal and Harp Seal

Ribbon seals and harp seals are seasonal migrants into arctic waters and do not remain in areas of landfast ice. Ribbon seals haul out and breed on the pack ice at or near the ice edge in the Bering Sea; much of their social behavior occurs in the water (Watkins and Ray 1977). Many of the underwater calls of both ribbon and harp seals may be associated with territoriality or reproductive behavior (Terhune and Ronald 1976a; Watkins and Ray 1977; Watkins and Schevill 1979).

The ribbon seal produces downward frequency sweeps and puffing sounds (Watkins and Ray 1977). Unlike the bearded seal call, the downsweep does not waver and it does exhibit several harmonics. Sweep sounds vary in duration as well as in start and end frequency. Long sweeps last 4-4.7 s and sweep from ~7100-3500 Hz down to 2000 Hz. Medium-length sweeps last 1.3-1.8 s and sweep from ~5300-2000 Hz down to 100 Hz. Short sweeps last <1 s and sweep from ~2000-1750 Hz down to 300 Hz. Source levels have been estimated to be near 160 dB re 1 μPa-m (Watkins and Ray 1977). In addition to the downsweeps, a broadband "puff" lasted <1 s with energy below 5 kHz (Watkins and Ray 1977).

Harp seals do not occur in U.S. waters but are numerous off the Canadian east coast and in the eastern arctic. Harp seals are dispersed over a wide area prior to mating. They then aggregate into large herds near the ice edge in March. They may use underwater sound to find each other, to find the main herd, and to locate mates (Terhune and Ronald 1986). They are very vocal at this time of year and may be relatively quiet at other times (Møhl et al. 1975). During the breeding season, Møhl et al. (1975) identified 16 types of harp seal sounds. Maximum source levels of most sound types were on the order of 135 to 140 dB re 1 μPa-m (Watkins and Schevill 1979; Terhune and Ronald 1986). Terhune and Ronald (1986) estimated that, under quiet conditions, a strong harp seal sound would be detectable by another harp seal at a distance of 2 km. Because of the large numbers of animals present, a vocalizing herd could be detected with hydrophones at 30-60 km (Watkins and Schevill 1979; Terhune and Ronald 1986).

Harp seals produce clicks that may have source levels up to 164 dB re 1 μPa-m (Møhl et al. 1975). However, given the reduced hearing sensitivity of seals to brief clicks relative to longer-duration sounds (sect. 7.2.4), clicks may not be detectable more than 1 km away (Terhune 1989b).

6.3.3 Harbor and Spotted Seals

Harbor and spotted seals spend much time hauled out on land. Many social interactions and vocalizations occur on land as well as in water.

A pair of captive ***spotted seals*** was relatively silent during most of the year. The male vocalized 2.5 times as much as the female (Beier and Wartzok 1979). The rate of underwater vocalization increased two weeks before mating in the male and one week before mating in the female. Both were most vocal on the first day of attempted mating, and rate of vocalization remained high for two weeks after mating. Underwater sounds produced by the mating pair included growls, drums, snorts, chirps, barks and a "creaky door" sound, with frequencies 500-3500 Hz and durations 19-400 ms (Beier and Wartzok 1979).

In-air vocal activity of captive male ***harbor seals*** was high within a group, but males were silent when alone or with pups (Ralls et al. 1985). Rate of vocalization in captive males increased as they reached sexual maturity, and sexually mature males were more vocal than females. The male reproductive display includes repeated trains of relatively low frequency (<4 kHz) 20-ms underwater pulses produced by long episodes of underwater bubble blowing. These were typically preceded by fore-flipper slaps on the water surface, which produced strong click sounds (Noseworthy et al. 1989). In the wild, in-air vocalizations coupled with visual signals are used to establish dominance and to defend individual space on the haul-out site (Sullivan 1982). These displays are typically initiated when animals are one body length apart, and are usually of short duration (Sullivan 1982).

Calls of the harbour seal pup are transmitted simultaneously in-air and underwater when the pup's head is in air (Renouf 1984). Both the airborne and underwater calls are individually distinct, can be recognized by the mother, and are used by the mother to recognize and maintain contact with her pup (Renouf and Perry 1983; Perry and Renouf 1985, 1988). As the pup becomes more distressed, its call rate increases (Renouf 1984). The fundamental frequency of the airborne calls is 350 Hz and mean duration is 0.81 s (Ralls et al. 1985). Underwater calls are similar; however, the lower harmonics are absent and there is a shift to higher frequencies (Renouf 1984; Perry and Renouf 1988). On average, calls are initiated when the pup is 1 m from its mother (Perry and Renouf 1988). Calls made by pups <2 m from their mothers were different from calls by pups >2 m away (Perry and Renouf 1988).

6.3.4 Monk Seal

The monk seal, an endangered tropical species occurring in some Hawaiian waters, is polygynous. Mating occurs in the water and whelping occurs on shore. Monk seal sounds have been described by Kenyon and Rice (1959), Kenyon (1981) and Miller (1985a). Sounds made in air include a throaty bubbling (belch) sound that is a threat display when made with the mouth open, or a sign of alarm when made with the mouth closed. It is audible to humans at a range of 15 m. Bellowing calls ("grunting bawl") are uttered when the mother is defending her pup from an intruder, when a non-receptive female is approached by a male, or when a seal drives another from the beach. On land, courting male monk seals may utter a bellow and snort when approaching a female. In the water, courting males may utter a coughing snort (in air). In the presence of her pup, a mother utters low moans or growls. Pups bleat. Mothers and pups use these sounds to remain in contact. Underwater sounds have not been studied.

6.3.5 Elephant Seal

The elephant seal mates on land. Threat displays and fighting are used to establish dominance among males and almost all mating is done by dominant males. The social behavior of mating and competing elephant seals is more similar to that of the otariid (eared) seals than to that of other phocids. In-air sounds are complex and have been the subject of a good deal of study. Aggressive males make three types of calls: *(1)* Snoring is produced by the inhalation of air and is a low intensity threat. *(2)* The snort, produced by exhaling air through the deflated proboscis, is used by a dominant male when approached by a sub-dominant male. The snort has fundamental frequencies of 0.2-0.6 kHz. *(3)* The clap threat, with most of its energy below 2.5 kHz, may contain signature information at the individual level (Sandegren 1976; Shipley et al. 1981, 1986). Leboeuf and Peterson (1969) originally believed that there were regional dialects in the clap threat calls; however, the dialects may be disappearing because of expansion and intermingling of local populations (Leboeuf and Petrinovich 1974; Shipley et al. 1981).

The female also vocalizes in the air. She responds to encroachment or disturbance with aggressive behavior and a belch roar vocalization that has most of its energy below 0.7 kHz (Bartholomew and Collias 1962). The pup-attraction call used by the female is a bark with a fundamental frequency of 0.5 to 1 kHz (Bartholomew and Collias 1962). Pups call when separated from the mother, restrained, bitten, or unable to feed. Fundamental frequencies of pup calls are <1.4 kHz, but harmonics reach 6 kHz or higher; the main function of the pup's call apparently is to maintain contact with its mother (Bartholomew and Collias 1962). Mother and pup vocalizations are individually distinctive (Insley 1989) and the female can recognize the call of her own pup (Petrinovich 1974).

Most elephant seal calls have most of their energy below 2 kHz (Bartholomew and Collias 1962; Sandegren 1976; Shipley et al. 1981, 1986). However, pup, yearling and female sounds can extend above 5 kHz. Underwater sounds of the elephant seal have not been reported.

6.3.6 Gray seal

The gray seal also breeds on land. This species is polygynous, but agonistic behaviors are not nearly as intense as in elephant seals (Bonner 1981a). There are no boundary displays and fighting is minimal (Cameron 1967; Bonner 1981a). In the gray seal, vocalizations are important in establishing and maintaining the mother-pup bond (Fogden 1971), but this bond does not appear to be as strong as in some other phocids or in otariids. On crowded beaches, mother and pup gray seals may become permanently separated, to the detriment of the pup's health (Fogden 1971).

Underwater, the gray seal mainly utters isolated clicks and, less frequently, clusters of clicks (Schevill et al. 1963; Oliver 1978). Clicks are broadband with a frequency range of 0-30 kHz. The inter-click interval between isolated clicks appears to be random. Oliver also recorded broadband (0-40 kHz) hisses. Underwater vocalizations of the gray seal are not very complex. For both the elephant and the gray seal, social activity with much vocalization occurs on land, and underwater sound apparently is not very important.

6.3.7 Echolocation by Phocids?

Both harbor and spotted seals emit faint clicks centered at 12 kHz (Schevill et al. 1963; Cummings and Fish 1971). Renouf et al. (1980) and Renouf and Davis (1982) recorded similar clicks, with most energy at 7 to 16 kHz. Renouf and colleagues have suggested that the harbor seal echolocates, based on its ability to catch live fish in a dark tank. The harbor seals that they tested produced clicks while catching fish. However, source levels of these sounds are unknown, and their suitability for echolocation is uncertain.

A blindfolded gray seal never detected inanimate objects at greater than chance level, thus failing to demonstrate an ability to echolocate (Scronce and Ridgway 1980).

Prey capture by seals in dark waters may depend on passive listening by the seal for prey noises (e.g fish swimming noises, as described by Moulton 1960) rather than echolocation. For example, the bottlenose dolphin, which has excellent echolocation abilities, can catch live fish while blindfolded without emitting any sound pulses (Wood and Evans 1980). The predominant view is that echolocation by seals has not been demonstrated unequivocally (Schusterman 1981a; Wartzok et al. 1984).

6.4 Eared Seal Sounds

Sea lions and fur seals defend territories, and they mate and give birth on traditional terrestrial rookeries. In-air vocalizations are parts of the displays used to establish and defend territories, attract females, and establish and maintain the mother-pup bond. California sea lions also use underwater calls to establish territoriality and dominance. The underwater sounds of other species have not been studied extensively.

6.4.1 Underwater Sounds

The most common sound of California sea lions is a bark. Barks made when the seal is in the water, with its head above the surface, are transmitted into the water and have similar acoustic characteristics in water and air (Schevill et al. 1963). Most of the energy is at frequencies below 2 kHz. These barks are accompanied by clicks that are also audible in air and water.

When California sea lions are submerged, their sounds include barks, whinny and buzzing sounds, and click trains (Schusterman et al. 1966). All sounds produced by California sea lions have most of their energy below 4 kHz and are associated with social situations (Schusterman et al. 1966, 1967). The underwater barks are directed at conspecifics in aggressive situations and may be territorial and dominance displays (Schusterman and Balliet 1969). Barks produced underwater with the mouth closed have the same structure as those produced in air with the mouth open (Schusterman and Balliet 1969). Clicks occur in response to a novel stimulus such as a mirror (Schusterman et al. 1966).

Sonograms of fur seal and Steller sea lion calls were published by Poulter (1968). Underwater clicks and bleating sounds have been attributed to northern fur seals (Poulter 1968; Cummings and Fish 1971). Schevill et al. (1963) attempted to record sounds from a captive fur seal but were unable to find purely underwater sounds. Sounds such as clicks, growls, snorts and bleats have been attributed to the Steller sea lion (Poulter 1968).

Poulter (1963, 1966) and Shaver and Poulter (1967) suggested that California sea lions may possess echolocation abilities, but this was rebutted by Evans and Haugen (1963) and Schevill (1968a). Further evidence for the lack of active sonar in this species was provided by

Gentry (1967), Moore (1975), and Moore and Au (1975). They showed that the California sea lion was not particularly good at localizing pure tones and click sounds at 1-4 kHz. California sea lion clicks have most of their energy at 0.5-4 kHz (Schusterman et al. 1967). Gentry (1967) states that, if the California sea lion uses echolocation, it would have to use frequencies above 3.5 kHz, because its ability to localize sound decreases below that frequency. There is no evidence that California sea lions produce high frequency clicks.

6.4.2 Airborne Sounds

California sea lions haul out to breed in late spring and summer. Males defend territories, non-continuously, for a period of four months. Bulls on territories bark incessantly (Peterson and Bartholomew 1967). The rate of vocalization of a territorial male increases if an intruder approaches. Males also bark during courtship. Females with pups bark at intruders. Females also squeal, belch and growl. Immediately after birth, mother and pup conduct a vocal interchange that lasts ~15-20 min (Peterson and Bartholomew 1967). These interchanges are repeated during the first several hours after birth. The female makes a bawling, trumpet-like pup-attraction call. The pup makes a bleat and a mother-response call. The vocalization occurs prior to suckling after a separation. These vocalizations probably help establish mutual recognition (Peterson and Bartholomew 1967). Females have individually distinctive calls that exhibit little within-individual variation (Hudson et al. 1989). Mother and pup are able to recognize one another by their calls (Trillmich 1981).

Peterson and Bartholomew (1969) analyzed California sea lion sounds. Male barks are highly directional, have a duration of 200-300 ms, have most of their energy below 1 kHz, and are very intense. Barks of young males are mostly below 1 kHz, but harmonics extend to 3 kHz. The female belch and growl are mainly at 0.25-4 kHz; the pup-attraction call is mainly at 1-2 kHz with harmonics to 5 kHz and a duration of 1-2 s. The mother-response call made by the pup is similar in structure to the pup-attraction call. The bleat appears to be a pulsed call with harmonic structure, mostly at 0.25-6 kHz.

During the non-breeding season, California sea lions that aggregate on land have no stable social organization (Peterson and Bartholomew 1967). At this time, they are highly gregarious and have size-related dominance relationships without sustained aggressive behavior.

Steller sea lion males remain on their terrestrial breeding territories in June and July. Well-defined territorial boundaries are defended by threat displays (including airborne vocalizations) and to a lesser extent by fighting. The threat displays include a roar and a hiss (Schusterman 1981b). Females defend a birthing territory with vocal and visual signals. Vocal exchanges between mother and pup begin soon after birth and may be significant in the maintenance of the mother-pup bond (Schusterman 1981b).

Northern fur seal sounds at haul-out locations, and their behavioral correlates, were described by Peterson (1968). Between May and July, males fight to establish breeding territories but use vocal and visual displays to maintain their well-defined territories. A trumpeted roar advertises existence of the territory when a potential intruder is seen. A low roar is uttered when defending the territory from an intruding bull, and a puff is uttered when lunging at an intruder. A click-like vocalization is made while patrolling and reaffirming the territory boundary. Intruders are silent when attacking but may utter a high pitched whine when retreating. Males use clicks and low roars as part of the display to entice/force females into their territories. While courting, males utter a low roar and females hiss. Females use a bawl-type sound to establish vocal communication with the pup soon after birth. Pups respond with the same type of sound. Vocalizations of both mother and pup are individually distinctive (Insley 1989). Vocal cues may be one of the means by which females, upon their return from feeding trips, find and recognize their pups (Peterson 1968). Females hiss when other females come too close to them or to their pups.

Guadalupe fur seal behavior and vocalizations during haul-out were studied by Peterson et al. (1968). It establishes territories in caves, recesses and other shady spots on land. In the breeding season, females form small, loosely organized groups of a few individuals. Adult males on territories utter a bark more often than any other call. Males on adjacent territories utter harsh, rasping puffs. When approached by man, Guadalupe fur seals roar. Females with pups make a bawl sound. Barks and bawls have most of their energy below 2 kHz and roars are mainly below 4 kHz. Some sounds are audible to humans from a distance of 25 m. In other species of *Arctocephalus*, the whimper or bark is the most common call and is associated with sexual arousal, affirmation of territory, social status and recognition; the puff sound is a challenge; the low pitched growl is a low-intensity threat; whines or moans are used by the female as a pup-attraction call; and bawls are used by pups as a cow-attraction call (Bonner 1981b).

6.5 Walrus Sounds

Walruses are known to produce three types of underwater sounds: clicks, rasps, and a bell-like tone (Schevill et al. 1966; Ray and Watkins 1975). Clicks have a base frequency at 400 Hz with additional energy and harmonics to 10 kHz. Rasps also have most energy at 400-600 Hz. The bell tone may have a frequency between 400 and 1200 Hz, and tones at two different frequencies are often produced in sequence (Ray and Watkins 1975). The tone is always preceded by a click, thought to be an artifact of tone production. The pharyngeal pouches are thought to be resonators for the tone sound (Schevill et al. 1966).

The bell tone probably is an underwater acoustic display of the male walrus, given that the pharyngeal pouches are poorly developed in females and juveniles (Schevill et al. 1966). Ray and Watkins (1975) have interpreted stereotyped click sequences in combination with bell tones as constituting a display song of the male walrus. In the Atlantic walrus, Stirling et al. (1987) found that the sounds of an individual walrus were consistent with one another, and different from those of other individuals. The context in which the song is used, and its acoustic source level, are unknown.

Walruses are very vocal on land or sea ice. Roars, grunts and guttural sounds are associated with agonistic behavior (Miller 1985b). Calves use barks as distress calls, and possibly to inform the mother of the calf's location. In older animals, barks are often used as a gesture of submission (Miller 1985b). Barks may be important in maintaining herd organization and in coordinating behavior (Miller 1985b). As walruses age, barks tend to have a lower fundamental frequency, merge into long utterances, have a lower harmonic richness, and become more pulsed (Miller 1985b). Most airborne sounds recorded by Miller (1985b) had fundamental frequencies below 0.5 kHz and most of their energy was below 2 kHz.

6.6 Sea Otter Sounds

Sea otters spend most of their time in the water. During rest periods, they may gather together and raft at the water's surface. In areas with no disturbance, they may rest on a beach. Mating occurs in the water over a period of several days (Kenyon 1981). Airborne sounds of adults include whines, whistles, deep-throated growls, soft cooing sounds, chuckles and snarls (Kenyon 1981). When stressed, they may utter a harsh scream (Kenyon 1981). Underwater sounds have not been studied.

Kenyon (1981) believes that territoriality is not strongly expressed and that fighting among males is rare. However, Calkins and Lent (1975) describe an Alaskan sea otter patrolling his territory with a highly audible and visible display of vigorous kicking and splashing. Females with pups initiate aggressive encounters with other sea otters when attempting to place their pups in protected locations during windy weather (Sandegren et al. 1973).

All maternal care occurs at sea. Airborne vocalizations are important in maintaining contact between mother and pup (Sandegren et al. 1973). The mother leaves her offspring at the surface when she dives for food. The pup vocalizes until she reappears. If the female cannot locate her pup immediately on surfacing, she vocalizes; the pup responds immediately. The pup also vocalizes in the presence of the mother, leading to nursing, grooming or comforting. Most energy in mother's and pup's vocalizations is at 3-5 kHz, but there are higher harmonics. Sandegren et al. (1973) recorded these sounds from a distance of 50 m in air and claimed that the sounds can be heard by humans at long distances, even over the sound of heavy surf.

6.7 Manatee Calls

Manatees spend all of their lives in water, but little is known about the importance of acoustic communication to manatees. Underwater sounds of the Florida (=West Indies) manatee included high pitched squeals, chirp-squeaks and screams (Hartman 1979). Manatees were usually very quiet and made sounds only under conditions of fear, aggravation, protest, and male sexual arousal (Hartman 1979). Information may have been conveyed by varying the duration and intensity of the calls rather than by varying the frequency and harmonics (Hartman 1979). Calves made sounds even when undisturbed. These calls were usually answered by the mother (Hartman 1979).

Underwater calls of the Florida manatee generally had fundamental tones at 2.5-5 kHz, but some were as low as 0.6 kHz (Schevill and Watkins 1965). The sounds were not very intense--only 10 to 12 dB above ambient at distance 3-4 m (Schevill and Watkins 1965). Duration was short, usually 0.15-0.5 s. Steel and Morris (1982) found that this species produced 10 types of sounds of short duration (0.06-0.4 s) and with average frequency 1-12 kHz. Rapid amplitude and frequency modulation was common. Adult female sounds were lower in frequency than adult male sounds. There were three types of sounds by neonates.

Sounds of the Amazon manatee are similar to those of the Florida manatee, but the fundamental frequencies (6-8 kHz) are higher (Evans and Herald 1970).

6.8 Summary

Underwater sounds of ***baleen whales*** (sect. 6.1) are primarily at frequencies below 1 kHz and have durations from ~0.5 s to over 1 s (sometimes much longer). Some have fundamental frequencies as low as 20 Hz. Thus, the dominant frequencies in baleen whale sounds overlap broadly with the dominant frequencies in many industrial sounds (*cf.* chap. 5). Many baleen whale sounds are uncomplicated tonal moans or sounds that have been described onomatopoeically as knocks, pulses, ratchets, thumps, and trumpet-like. Humpback whale sounds are more complex, and include extended songs. Source levels of most baleen whale sounds are in the range 150-190 dB re 1 µPa-m, apparently with much within-species variation.

Some ***odontocete whales*** communicate underwater with whistles at frequencies below 20 kHz; most of their energy is typically near 10 kHz (sect. 6.2). Source levels for whistles may be 100-180 dB re 1 µPa-m. The killer whale produces whistles but most sounds are pulsed sounds at frequencies 1-6 kHz; source levels range up to 160 dB re 1 µPa. Most calls by the sperm whale and the phocoenid porpoises are clicks, some of which may be used for communication. Most odontocete sounds are detectable to humans with hydrophones at distances within no more than 1 km. However, sperm whale clicks may propagate well to distances >1 km. Most components of odontocete social sounds are above the low frequency range where most industrial sounds are concentrated.

The echolocation capabilities of the odontocetes that have been studied are very well developed (sect. 6.2.4). Echolocation pulses are generally at high frequencies--30 to 100 kHz or higher. However, killer whale echolocation signals have most energy at 12-25 kHz. The echolocation signals are projected forward of the animal in a narrow beam extending several degrees on either side of the animal's center line. Source levels can be over 200 dB re 1 µPa-m. The effective range of odontocete sonar may be up to 350 m, depending on ambient noise levels, size and reflectivity of the target, species, and numerous other factors. Although the capabilities of echolocation systems have been studied in much detail in a few species held in captivity, the specific functions of echolocation sounds in nature have not been well demonstrated.

Pinnipeds that mate and breed on land typically use airborne vocalizations as well as visual displays to establish and defend territories, compete with other males for access to females, mate, and establish and maintain the mother-pup bond. Underwater vocalizations appear to be limited to barks and clicks with frequencies ranging from <1 kHz to 4 kHz (sect. 6.3). In contrast, pinnipeds that mate in the water are often quite vocal during the breeding season. Most underwater sounds have frequencies ranging from <1 kHz to 10 kHz. Source levels for three phocid species that mate in the water are ~95-160 dB re 1 µPa-m.

All pinnipeds, the sea otter, perhaps the manatee, and at least some cetaceans use sound to establish and maintain the mother-offspring bond. The calls appear to be especially useful when mother and pup are attempting to reunite after a separation.

Evidence for associations between specific underwater sounds and specific functions is, for most species, weak or non existent. Many marine mammals are gregarious, often coordinate activities, and often have to find one another in a visually-limited environment. It is assumed but only occasionally demonstrated that these phenomena are mediated, in part, by calls. *(1)*

Some sounds appear to be used for long distance communication. In whales, sounds produced while individuals are far enough apart to be out of visual contact may be associated with announcement of reproductive intentions, establishment of territory or spacing between animals, coordination of foraging and other activities, and maintenance or establishment of group structure. *(2)* Over short distances, sounds may be used in social interaction situations involving aggression between individuals and establishment of dominance, for individual identification, and for establishment and maintenance of the mother-pup bond.

Sounds of many species of marine mammals have been described in varying levels of detail, but the source levels, directionality, and maximum detection distances of most sound types are unknown or poorly documented. Many of the source level data that do exist were obtained from captive animals. In most cases it is unknown whether these data are representative of source levels in free-ranging animals. For species in which data of these types are lacking, it is not possible to estimate the maximum detection distances of the sounds either in natural conditions or in the presence of industrial noise.

7. MARINE MAMMAL HEARING[1,2]

7.1 Introduction

The hearing ability of a marine mammal, and indeed any mammal, is a complex function of several specific abilities and processes:

1. ***Absolute threshold:*** The intensity of sound that is barely audible in the absence of significant ambient noise is the absolute hearing threshold. More precisely, this threshold is the lowest sound level that can be detected during a specified percent of experimental trials. Different authors have used various percentages in the 50 to 75% range. A statistical definition is necessary because, even for a single animal, there is temporal variability in the minimum detectable sound level. Furthermore, threshold varies with frequency (Hz). The graph relating threshold intensity to frequency is called the **audiogram** (see Fig. 7.1-7.3, later in this section). The **best frequency** is that where sensitivity is highest and threshold is lowest. The best frequency varies among species. Some species are more sensitive than others at their respective best frequencies.

2. ***Individual variation:*** The auditory sensitivity of different individuals varies. Published audiograms for most marine mammal species are based on data from only one or two animals. Animal-to-animal variation is to be expected around these values.

3. ***Motivation:*** Even in a quiet environment, sensitivity of a particular animal--as measured by standard psychoacoustical methods--varies depending on motivation. As a result, it is necessary to use a statistical definition of absolute threshold, as noted in (1), above.

4. ***Masking***: One of the main auditory tasks of any animal is to detect sound signals in the presence of background noise. Natural ambient noise was discussed in Chapter 4; it includes contributions from waves, precipitation, other animals, and (in some areas) ice. The background noise can also include sounds from human activities, many of which are discussed in Chapter 5. In an animal that is highly dependent on sound, such as most marine mammals, the ability to recognize sound signals amidst noise is important in communicating, detecting predators, locating prey, and (in toothed whales) echolocation. The signal-to-noise (S/N) ratio required to detect a pure tone sound signal in the presence of background noise is called the **critical ratio**. Critical ratios vary with frequency.

5. ***Localization:*** Sound source localization is the ability to detect the bearing of a sound source, i.e. to determine the direction from which a sound is arriving. Localization is important in detecting and responding appropriately to predators, prey, and other sound sources. Good sound localization ability is also related to good ability to

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[1] By W.J. Richardson, LGL Ltd. This chapter is an extensively revised version of reviews prepared for the American Petroleum Institute in 1983 by J.P. Hickie and WJR, and in 1989 by WJR (Richardson et al. 1983, 1989).

[2] Constructive comments on drafts of this chapter were provided by Drs. R.A. Davis, R.H. Nichols, R.J. Schusterman and especially W.C. Cummings and A.N. Popper.

detect a sound signal in the presence of background noise. When a sound signal arrives from a very different direction than does the dominant component of the background noise, the signal may be detectable even if the background noise is stronger. However, if they are arriving from similar directions, the signal will normally need to be at least as strong as the noise at similar frequencies in order to be detected.

6. ***Intensity and Frequency Discrimination:*** The ability to discriminate sounds of different frequencies and intensities is important to marine mammals in several ways: in distinguishing various types of sounds made by conspecifics, including individual signature whistles of toothed whales, and in distinguishing sound signals from background noise. In general, the ability to detect a sound signal is affected primarily by components of the background noise whose frequencies are similar to those of the sound signal, i.e. within the **critical band** around the signal's frequency. Noise at frequencies outside the critical band has little effect on detectability of the sound signal unless the noise is very intense.

An understanding of these factors is necessary to evaluate the ability of a marine mammal to detect industrial sounds in various circumstances. This understanding is also needed to evaluate its ability to detect communication signals, echolocation sounds, or other sounds of interest in the presence of natural ambient noise and industrial sounds.

Various aspects of marine mammal hearing have been reviewed by several authors in recent years. Some of the most comprehensive and useful reviews are those of Popper (1980a,b), Fobes and Smock (1981), Schusterman (1981a), Ridgway (1983), Watkins and Wartzok (1985), Johnson (1986), Nachtigall (1986), and Moore and Schusterman (1987), plus the review of the Russian literature by Bullock and Gurevich (1979). Fay (1988) has tabulated and graphed many of the relevant marine mammal data, and has shown these data in relation to corresponding data from other vertebrates.

The present review covers many of the topics considered in the above-cited papers, and includes some references not available to earlier reviewers. We emphasize aspects of hearing that are especially relevant to the question of industrial noise effects on marine mammals, e.g. sensitivity as a function of frequency, frequency and intensity discrimination, sound localization abilities, and masking. Some other fundamental topics that are not directly related to our concerns are not discussed here, e.g. the anatomical and physiological bases of sound detection; neural processing of auditory data; and temporal discrimination of closely-spaced sounds. Those topics are discussed in several of the above-cited reviews.

Underwater hearing ability has been studied in some odontocetes (toothed whales), phocids (hair seals), and otariids (eared seals). A few relevant data are available for sirenians (manatees). Baleen whales, walruses and sea otters have not been tested. Almost all of the available data on marine mammal hearing deal with frequencies of 1 kHz or above. Many of the data relate to frequencies above 20 kHz. Unfortunately, little information is available about hearing processes below 1 kHz, the frequencies of most industrial sound energy. The few data that are available for low frequency hearing by marine mammals[3] suggest that--as in other animals--sensitivity becomes poorer with decreasing frequency below the "best" frequency. This is probably, in part, an adaptation to the typically high levels of natural background noise at low frequencies (Chap. 4). However, it is not known how closely baleen whales follow this trend. They emit low-frequency sounds, and presumably have good hearing sensitivity at low frequencies.

In most marine mammal species tested for hearing abilities, only one or two individuals have been studied. Thus, little is known about intraspecific variability. The most extensive data on individual variation in marine mammal hearing have come from the bottlenose dolphin and white whale: *(1)* Seeley et al. (1976) used a neurophysiological method to determine the high-frequency audiograms (5-200 kHz) of five dolphins. Results from four individuals were similar to one another and to other data for this species. However, one elderly animal had much poorer sensitivity. *(2)* Behavioral audiograms of six white whales have been determined; results were quite consistent (White et al. 1978; Awbrey et al. 1988; Johnson et al. 1989). Terhune (1981) suggested that enough data may be available to talk of general odontocete, phocid and otariid hearing abilities. However, even the limited data presently available show differences in hearing abilities among species of toothed whales and among seals.

7.2 Audiograms: Frequency Range and Sensitivity

Sensitivities of marine mammals to sounds of different frequencies are shown by audiograms, which are normally obtained by behavioral experimentation. However, electrophysiological methods also can be used to obtain data on hearing sensitivity vs. frequency. Some workers prefer to restrict the term audiogram to data obtained by behavioral methods; others use the term more loosely and refer to **electrophysiological audiograms** and **behavioral audiograms**.

In the behavioral method, pure tones of various intensities and frequencies are presented to a trained test animal. If the animal hears a sound stimulus, it usually responds positively; if the tone is not heard or if no sound was presented, as in a control trial, no positive response is expected. An individual animal's audiogram depicts, for various frequencies, the minimum detectable sound level, which is the level to which the animal responds during 50-75% of the trials. (Different researchers have used differing criteria.)

In this review we emphasize results from behavioral testing methods, but electrophysiological studies are also mentioned. Behavioral methods give data concerning sounds that are both detectable and effective in eliciting specific behavioral responses. Depending upon the way in which electrophysiological methods are applied, they provide data concerning the response of the ear, brainstem or auditory cortex. A sound that elicits a neurophysiological response may or may not be sufficient to elicit a behavioral response. Thus, electrophysiological methods are valuable in revealing the *relative* sensitivity of a defined part of the nervous system to different sounds, but these methods may not provide useful information about *absolute* sensitivity.

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[3] For white whales and bottlenose dolphins, data are available at frequencies as low as 40 and 75 Hz, respectively. For sea lions and harp seals, there are a few data down to 250 and 760 Hz, respectively (sect. 7.2).

7.2.1 Toothed Whales

Behavioral audiograms have been determined for six species of toothed whales (Fig. 7.1). Those tested can hear sounds over a wide range of frequencies. The hearing range extends at least as low as 40-75 Hz in the white whale and bottlenose dolphin, the only two species tested at low frequencies (Johnson 1967; Awbrey et al. 1988; Johnson et al. 1989). The hearing range extends up to 105-150 kHz in 5 of the 6 species tested (Fig. 7.1). However, sensitivity is poor at these extreme low and extreme high frequencies (Fig. 7.1). The one killer whale tested differed from other odontocetes in that its upper hearing limit was only about 31 kHz (Hall and Johnson 1972). Scientific names for all species mentioned in the text are given in Appendix 1.

Although the range of acoustic frequencies audible to the tested killer whale was apparently narrower than the ranges for other odontocetes studied, the killer whale's hearing sensitivity at its "best" frequency was very good. With little background noise, the killer whale could detect a signal of about 30 dB re 1 μPa near 15 kHz (Hall and Johnson 1972), compared with minimum thresholds of about 39-51 dB for the five other species tested (Fig. 7.1). The frequencies at which the six species had best sensitivity ranged from about[4] 15 kHz in the killer whale to about 75-90 kHz in the boutu (Amazon river dolphin).

For each species there is a range of frequencies where hearing thresholds are low. Within this range of best frequencies, variations of a few decibels may be artifacts of the testing procedure. Some uncertainty and variability is inevitable because of factors such as (1) the discrete intensity steps used during testing, and (2) unavoidable changes in motivation within the time period while data for different frequencies are collected.

Below the frequency range of optimum hearing sensitivity, thresholds increase gradually with decreasing frequency. It is possible that estimated auditory thresholds for many species are inaccurate, and possibly too high, for frequencies below 1-10 kHz. The relatively small tanks used for most audition tests may have had many unnatural echoes, standing waves, elevated noise levels, and pressure release boundaries (Cummings et al. 1975). Such problems were suspected in the studies by Hall and Johnson (1972), Jacobs and Hall (1972), Ljungblad et al. (1982b), and Awbrey et al. (1988). These problems may account for some of the differences between the results for two bottlenose dolphins (Fig. 7.1B; Ljungblad et al. 1982b vs. Johnson 1977). The limited and questionable data on hearing sensitivity of marine mammals at low frequencies (<1000 Hz) are a particular concern in the context of this review, since most industrial noise is primarily at low frequencies.

Above the range of optimum sensitivity, thresholds increase with increasing frequency. The increase in thresholds is often abrupt at high frequencies, at least when frequencies are shown on a logarithmic scale, as is standard (Fig. 7.1). The **upper frequency cutoff** was found to be at about 31 kHz for the one killer whale tested, 70 kHz for the false killer whale, 120 kHz for white whales, and near 140 kHz for the harbor porpoise and bottlenose dolphin.

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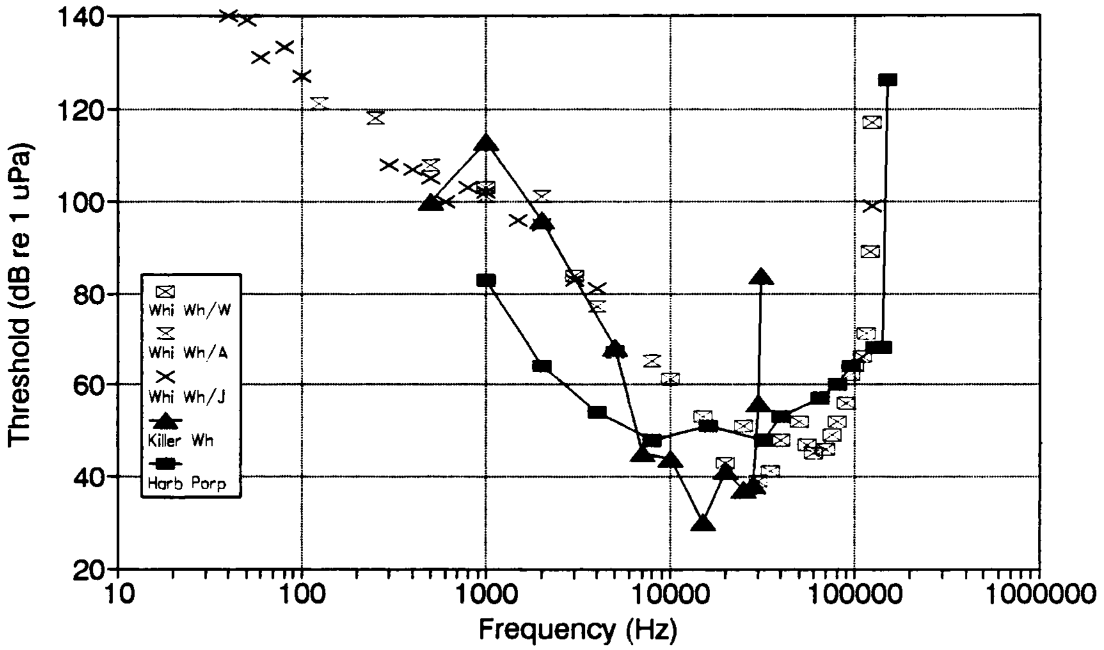
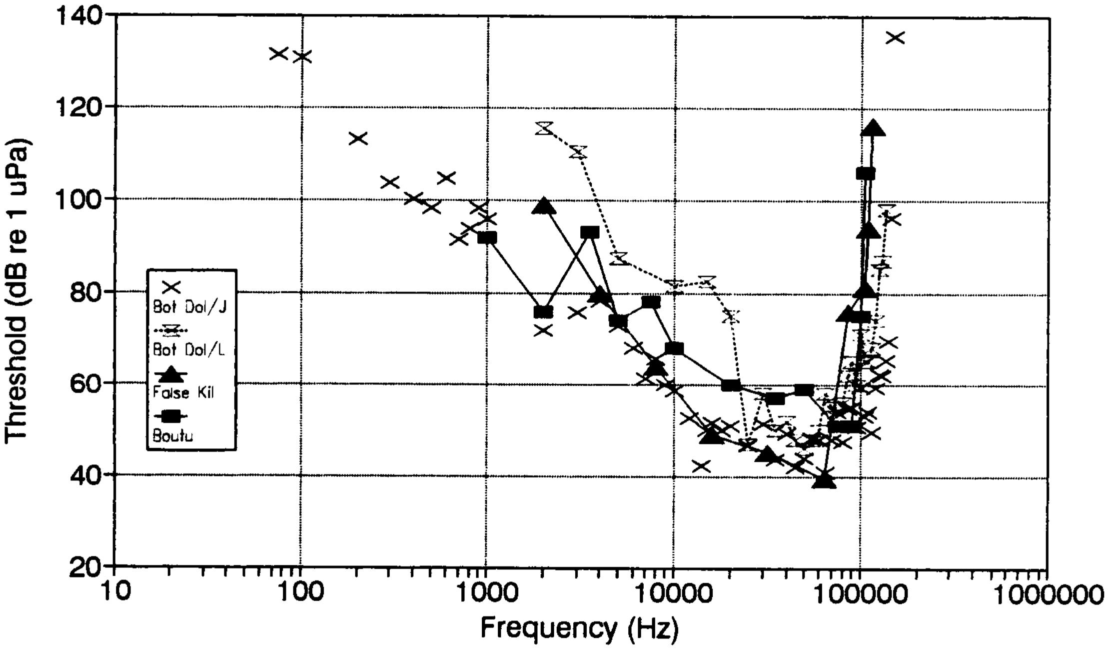
[4] We use the word "about" because sensitivity is only measured at certain discrete frequencies (Fig. 7.1). Highest sensitivity may occur at an intermediate frequency where no measurements were made, and is subject to variation.



Underwater Audiograms of Odontocetes--A



Underwater Audiograms of Odontocetes--B

FIGURE 7.1. Underwater audiograms of odontocetes: *(A)* white whale (White et al. 1978, n=2; Awbrey et al. 1988*, n=3; Johnson et al. 1989); killer whale (Hall and Johnson 1972); harbor porpoise (Andersen 1970a); *(B)* bottlenose dolphin (Johnson 1968a; Ljungblad et al. 1982c); false killer whale (Thomas et al. 1988); Amazon river dolphin or boutu (Jacobs and Hall 1972). n=1 except where noted.

* Awbrey et al. (1986) reported higher-frequency data for these white whales, but these data did not represent sensitivity in the direction of best hearing.

Johnson (1979, 1980) has suggested that, above 50 kHz, the hearing of odontocetes may be limited by water molecule motion known as thermal noise (Urick 1983).

Bullock et al. (1968) and several subsequent investigations have obtained electrophysiological audiograms from various species of dolphins and porpoises. These results are based on neural responses (evoked potentials) received by electrodes implanted in the animal's brain or, in some more recent studies, applied outside the skull. The shapes of electrophysiological audiograms are generally comparable to those obtained behaviorally. In the harbor porpoise, however, the lowest threshold determined by the evoked potential method was at a much higher frequency than that determined behaviorally (about 125 kHz vs. 8-32 kHz, Voronov and Stosman 1983; Popov et al. 1986 vs. Andersen 1970a). Electrophysiological methods provide data on the relative sensitivity of some part of the nervous system to different sounds, but do not provide data directly comparable to behavioral audiograms (Popper 1980a). However, evoked potential methods based on external electrodes hold promise for examining the hearing abilities of marine mammals such as baleen whales that are very difficult to hold in captivity (Ridgway et al. 1981; Ridgway and Carder 1983; Popov et al. 1986).

7.2.2 Pinnipeds

Underwater Hearing.--Underwater audiograms have been obtained with behavioral methods for three species of ***hair (phocid) seals***--harbor, ringed and harp seals (Fig. 7.2A). Also, the gray seal has been studied using evoked potentials. Some phocid seals apparently can detect very high frequencies of underwater sound if it is sufficiently intense--up to 180 kHz in the case of the harbor seal. However, above 60 kHz sensitivity is poor (Fig. 7.2A) and different frequencies cannot be discriminated (Møhl 1968a,b). The functional high frequency cutoff is thus around 60 kHz for the species tested (Schusterman 1981a). Below about 30-50 kHz, the hearing threshold of phocids is essentially flat down at least to 1 kHz, and ranges between 60 and 85 dB re 1 µPa (Møhl 1968a; Terhune and Ronald 1972, 1975a; Terhune 1981, 1989a; Fig. 7.2A). The lower limit of phocid hearing has not been delineated since frequencies below 760 Hz have not been tested, in part due to the acoustical limitations of small tanks. The three species for which more than one individual has been tested (ringed, harbor, and gray seals) exhibit some audiogram variability within species (Terhune and Ronald 1974, 1975a; Ridgway and Joyce 1975; Terhune 1988, 1989a). However, variation among audiograms of different phocid species may be similar to that among audiograms of individual humans (Fletcher 1940; Terhune 1981).

The high-frequency cutoff of ***eared (otariid) seals*** for underwater sound is lower than that of phocids (Schusterman 1981a); however sensitivity in the range of best hearing does not differ substantially between the two groups (Fig. 7.2). The high-frequency cutoff of both species of otariids that have been tested (California sea lion and northern fur seal) is 36-40 kHz based on behavioral techniques (Schusterman 1981a). Fur seal hearing is most sensitive, ~60 dB re 1 µPa, between 4 and 28 kHz (Moore and Schusterman 1987), whereas the sea lion apparently is most sensitive, ~80 dB, at 2 and 16 kHz (Schusterman et al. 1972).

The hearing threshold of the California sea lion rises from ~85 dB re 1 µPa at 1 kHz to ~114 dB at 250 Hz. Low frequency hearing thresholds are difficult to measure, but Schusterman et al. (1972) carefully measured echoes and ambient noise in the test tank, and rigidly positioned the subject sea lion in a position where the signal level was measured at its

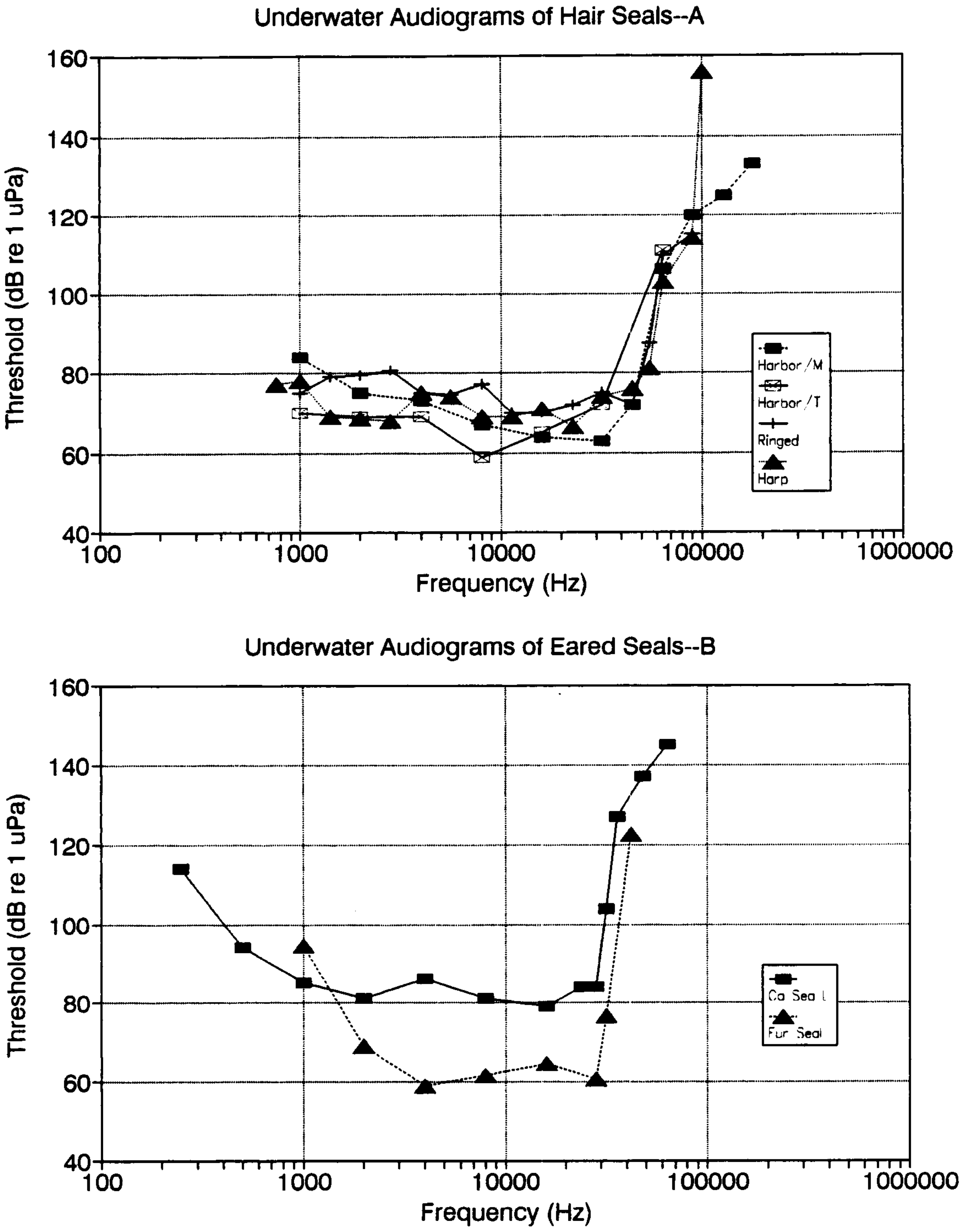


FIGURE 7.2. Underwater audiograms of pinnipeds: ***(A) hair seals*** (phocids)--harbor seal (Møhl 1968a; Terhune 1989a); ringed seal (Terhune and Ronald 1975a, n=2); harp seal (Terhune and Ronald 1972); ***(B) eared seals*** (otariids)--California sea lion (Schusterman et al. 1972); fur seal (Moore and Schusterman 1987, n=2). n=1 except where noted.

maximum. Rigid positioning is important in ensuring an accurate measurement of the sound level received by the animal, especially in a small enclosure.

In-air Hearing.--As amphibious animals, pinnipeds need to respond to airborne sound in addition to underwater sound. Aerial audiograms have been determined behaviorally for two fur seals and a California sea lion (Moore and Schusterman 1987), two harbor seals (Møhl 1968a; Terhune 1989a), and a harp seal (Terhune and Ronald 1971) (Fig. 7.3A). An earlier determination for another sea lion (Schusterman 1974) is now considered to be artefactual, and the reliability of the harp seal data for 1-8 kHz has also been questioned by Watkins and Wartzok (1985) and Moore and Schusterman (1987). Besides these behaviorally-determined results, relative thresholds of in-air hearing at different frequencies have been determined by the evoked potential method for California sea lions and a harbor seal (Bullock et al. 1971) and for a gray seal (Ridgway and Joyce 1975).

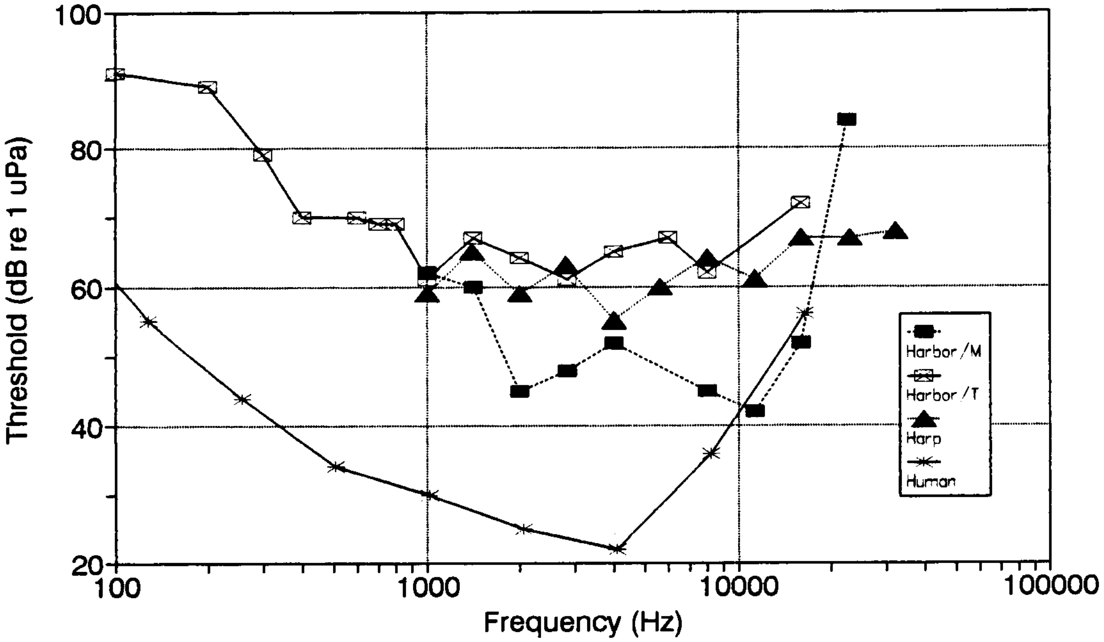
In air, otariids apparently have slightly greater sensitivity and a more elevated high frequency cutoff than do phocids (Bullock et al. 1971; Schusterman 1981a; Moore and Schusterman 1987; Fig. 7.3B vs. A). The cutoff frequency of otariid hearing in air is about 32-36 kHz, not much lower than the underwater cutoff of 36-40 kHz (Schusterman 1981). In contrast, the in-air cutoff of the harbor seal (and probably the gray seal) is ~20 kHz, considerably lower than their underwater cutoff around 60 kHz. Based on behavioral experiments, both otariid species and one of two harbor seals were most sensitive near 2 kHz and 8-16 kHz and notably less sensitive at the intermediate 4 kHz frequency (Fig. 7.3B). Otariids and phocids all appear to be considerably less sensitive to airborne sounds below 10 kHz than are humans (Fig. 7.3), probably because pinniped auditory systems are adapted to hear underwater as well as airborne sound.

The relative sensitivities of in-air and underwater hearing are difficult to compare. In this section, we have expressed hearing thresholds in dB relative to 1 μPa for in-air hearing as well as underwater hearing. In-air hearing thresholds are usually expressed in dB relative to 0.0002 dynes/cm^2 or its equivalent, dB re 0.0002 μbar (see Table 2.1 in sect. 2.2). To convert from the latter units to dB re 1 μPa, one adds 26 dB. However, even when underwater and in-air thresholds are expressed in the same units, e.g. dB re 1 μPa, they are not directly comparable because acoustic impedance differs between air and water. To allow direct comparisons, it is necessary to convert the threshold values from pressure units (which are affected by the impedance) into energy units, dB re 1 μW/cm^2 (Wainwright 1958; Wodinsky and Tavolga 1964). When this is done, it is apparent that otariids and the harbor seal all are more sensitive to sounds in water than in air (Møhl 1968a; Moore and Schusterman 1987; Terhune 1989a). For example, Figure 7.4 shows such a comparison for the two fur seals tested by Moore and Schusterman.

7.2.3 Manatees

The hearing sensitivity of manatees has not been studied with behavioral techniques. However, there has been considerable anatomical work (see references cited in Fischer 1988). Also, electrophysiological methods have been applied in a brief study of hearing by an immature Amazonian manatee (Bullock et al. 1980), and in a more detailed study of hearing by four West Indian manatees (Bullock et al. 1982). The latter is the species occurring in the southeastern U.S.A. These studies were not designed to determine audiograms, but they did provide some

In-Air Audiograms of Hair Seals--A



In-Air Audiograms of Eared Seals--B

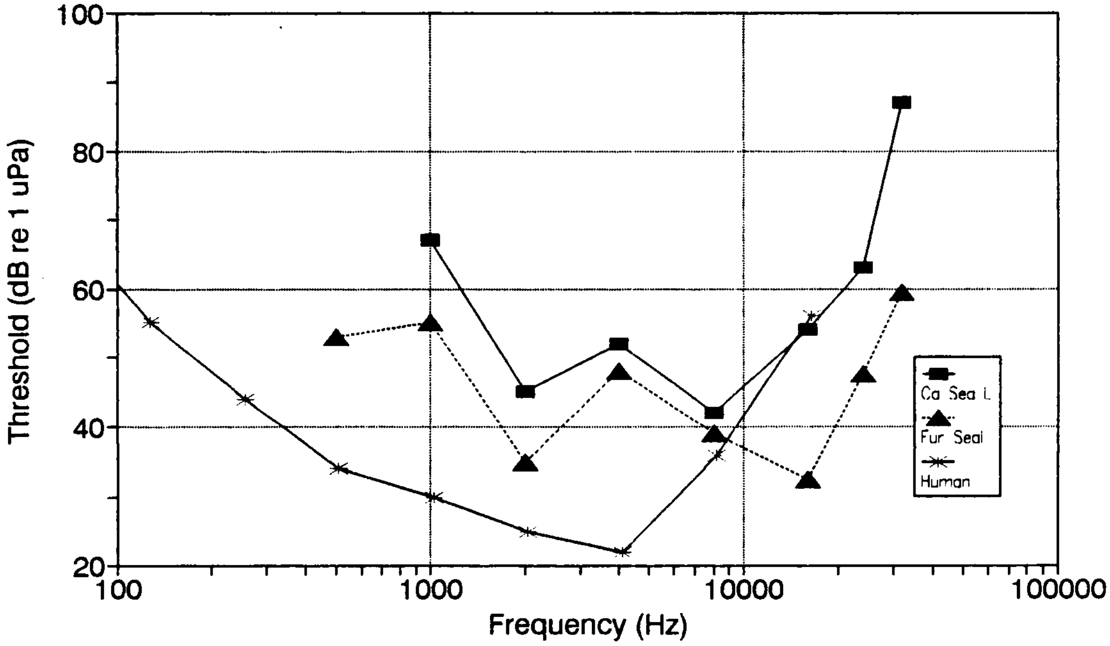


FIGURE 7.3. In-air audiograms of pinnipeds and humans: ***(A) hair seals***--harbor seal (Møhl 1968a; Terhune 1989a); harp seal (Terhune and Ronald 1971); ***(B) eared seals***--California sea lion (Moore and Schusterman 1987); fur seal (Moore and Schusterman 1987, n=2). Human data (n=9) from Sivian and White (1933) via Fay (1988). n=1 except where noted. dB re 1 μPa = dB re 0.0002 μBar + 26.

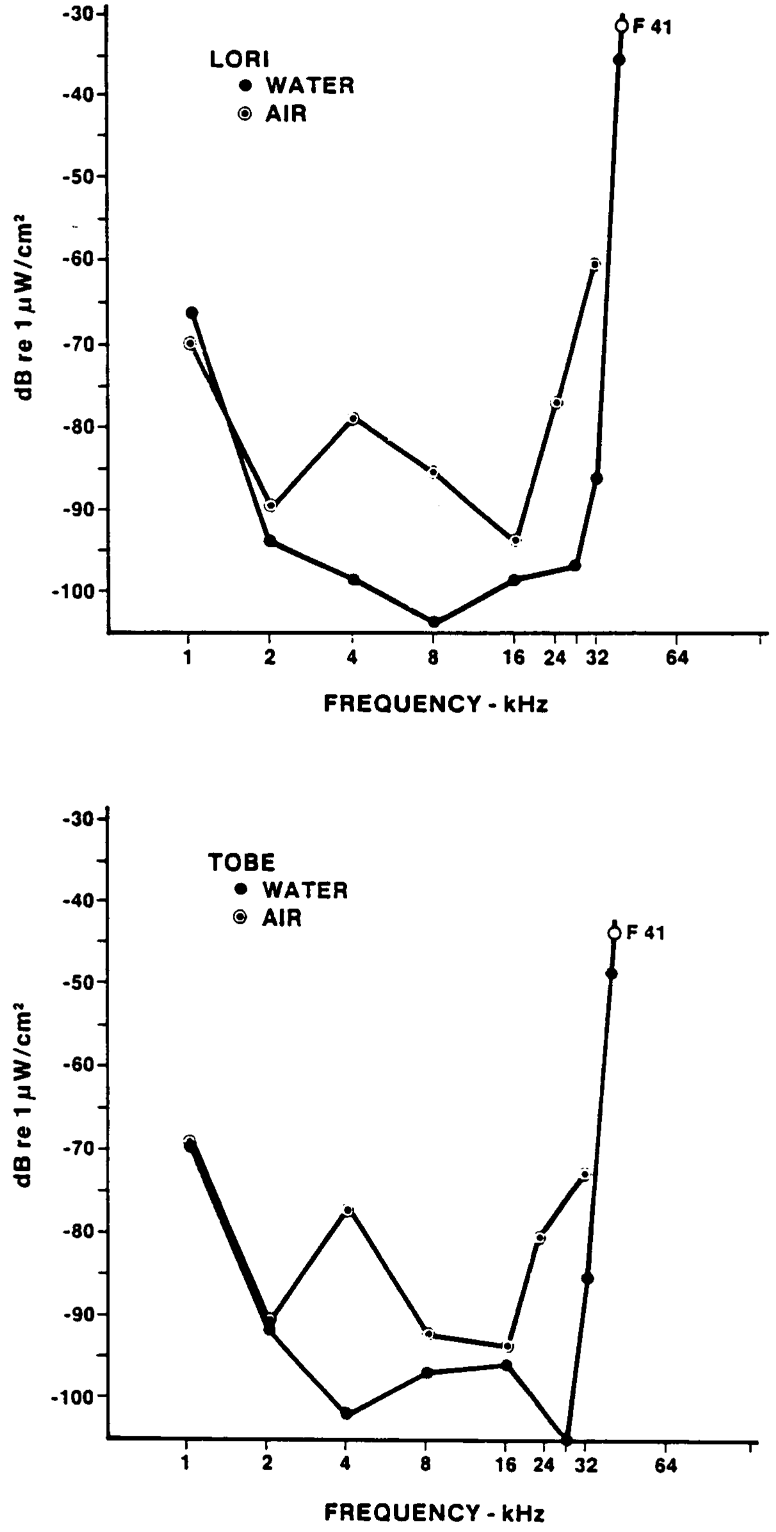


FIGURE 7.4. Comparison of in-air and in-water audiograms for two northern fur seals, with results expressed in db re 1 $\mu W/cm^2$ to allow for differences in the acoustic impedance of the two media (from Moore and Schusterman 1987).

data on relative sensitivity as a function of frequency. The West Indian manatee seemed most sensitive to frequencies around 1-1.5 kHz. Sensitivity seemed notably less at 4 kHz, and less still at 8 kHz. However, there was some sensitivity to frequencies as high as about 35 kHz. These electrophysiological results must be considered preliminary in the absence of confirmation by behavioral testing procedures.

7.2.4 Effects of Sound Duration

In terrestrial mammals, signal duration influences the hearing threshold when the signal is shorter than some specific value, typically around 0.1-1 s (Clack 1966; Fay 1988). With shorter signals, threshold increases with decreasing duration. With longer signals, threshold is not affected by duration. Since many marine mammals produce brief click sounds, most notably the echolocation clicks of odontocetes, it is important to know whether their sensitivity to such sounds is affected by click duration.

Most behavioral studies on hearing sensitivity of marine mammals have employed pure tones played to the test animals for at least ½ s, and in some cases the animals were allowed to control signal duration. These studies used signals long enough to avoid the complicating effects of signal duration on threshold. However, Johnson (1968a) investigated the effect of signal duration on detection of tones by a bottlenose dolphin, *Tursiops*. Johnson used tones of variable duration, including some that were much shorter than those employed in most studies. Frequencies ranged from 250 Hz to 100 kHz. He found that sensitivity to tones shorter than 0.1 to 0.2 s decreased as the tone duration decreased. Tones longer than 0.1 to 0.2 s elicited similar thresholds regardless of duration. Figure 7.5 shows some of the *Tursiops* data, and compares them with similar data from dogs. In *Tursiops* the threshold for high-frequency (20-100 kHz) single clicks of 0.2 ms duration was about 10-20 dB poorer (i.e. higher) than for sounds longer than 0.1 to 0.2 s (Johnson 1968a).

Likewise, Bullock and Ridgway (1972) found that evoked potentials recorded in the cerebrum of *Tursiops* increased in amplitude as tone duration increased. Also, evoked potentials recorded at most but not all locations in the auditory cortex of the harbor porpoise increased in amplitude and decreased in threshold as tone duration increased (Popov et al. 1986).

Terhune (1988, 1989a) recently did signal duration experiments on a harbor seal. At most frequencies tested, thresholds to tone pulses of various durations were similar as long as the duration was at least 50 ms, but thresholds increased as duration decreased from 50 ms. For pulses shorter than 400 cycles in duration (i.e. 100 ms at 4 kHz, 13 ms at 32 kHz), thresholds changed linearly with the logarithm of duration. The threshold for brief tone pulses or broadband clicks was 30-40 dB higher than that for a prolonged pure tone at the most sensitive frequency (Terhune 1988, 1989a).

These results suggest that single short-duration signals, such as echolocation clicks or other brief sounds, have higher thresholds than indicated on standard audiograms. However, Bullock and Ridgway (1972) found locations in the midbrain of *Tursiops* that seemed specialized for processing very brief (<2 ms), rapid-onset, rapidly-repeated, high-frequency (>30 kHz) clicks. These are all characteristics of *Tursiops* echolocation signals. Given the importance of echolocation to toothed whales, their neural processing is undoubtedly highly

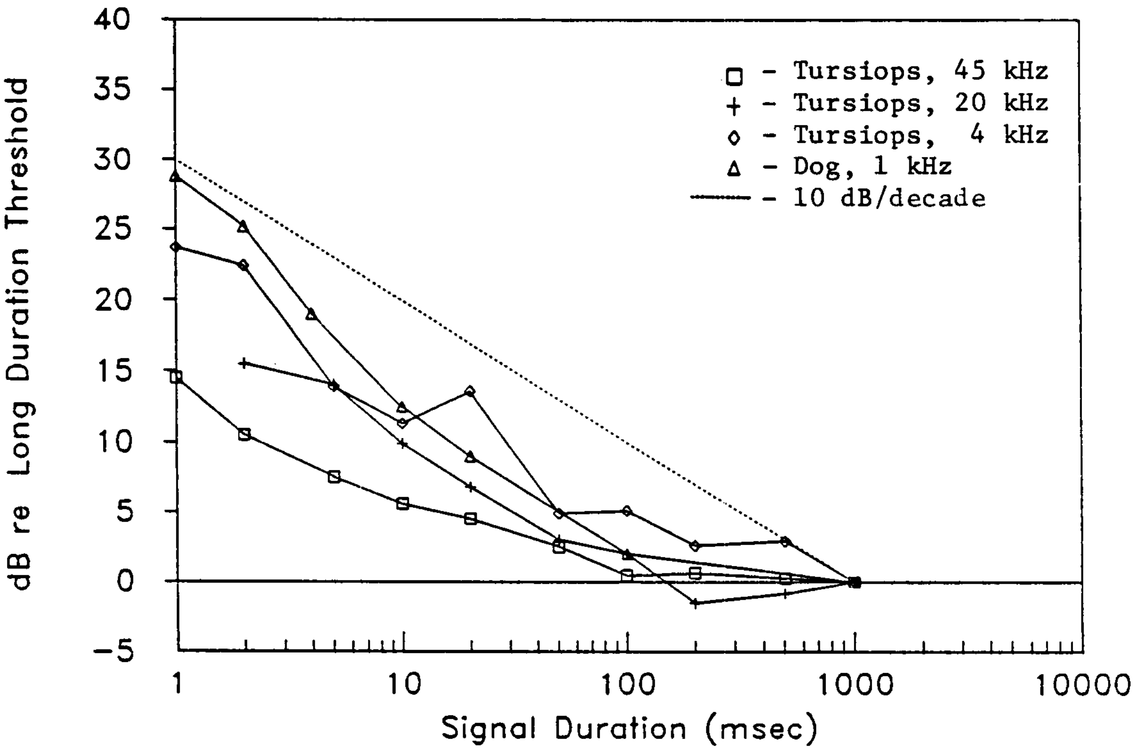


FIGURE 7.5. Hearing threshold in relation to signal duration for the bottlenose dolphin in water (from Johnson 1968a) and dog in air. The baseline (0 dB) is the threshold for long-duration signals. Diagram is from Fay (1988:479).

adapted for detecting and integrating successive echoes. Pinnipeds seem much less responsive to click stimuli than are odontocetes (Bullock et al. 1971)

7.3 Discrimination of Frequencies and Intensities

The abilities to discriminate frequencies and intensities are believed to be related to the ability to detect sound signals in the presence of background noise. Good frequency and intensity discrimination capabilities seem to be associated with good abilities to detect sounds that are partially masked by noise (sect. 7.5). Besides their role in reducing the effects of masking, these discrimination abilities are doubtless important in distinguishing and interpreting various types of calls, and in recognizing individual animals from their calls.

7.3.1 Frequency Discrimination

Frequency-modulated (FM) tones evoke greater neural responses than pure tones in odontocetes (Bullock et al. 1968; Ridgway 1980) and to a lesser degree in pinnipeds (Bullock et al. 1971). FM tonal whistles are important social signals for many odontocetes and some pinnipeds (sect. 6.2.1). The greater response of odontocetes than of pinnipeds to FM signals may be related in part to the finer frequency discrimination abilities of odontocetes (see below). These results were obtained electrophysiologically; studies examining behavioral sensitivity to

FM vs. constant frequency sounds would be valuable given the social significance of FM signals.

The ability to distinguish different frequencies is presumed to be important in communication and echolocation as well as in interpreting environmental sounds. Frequency discrimination abilities may also be related to the bandwidths of masking noise, which are important in detecting a sound signal in the presence of industrial or other background noise (sect. 7.5).

The frequency difference required to perceive two tones as being at separate frequencies, or a single tone as being constant in frequency vs. frequency modulated, is the **difference limen** or **DL** (Herman and Arbeit 1972; Jacobs 1972). The difference limen is computed by subtracting the frequency (in Hz) of the reference tone (F) from that of the tone that is perceived as being different. The absolute value of the difference in Hz is the difference limen. In mammals generally, difference limens increase with frequency, which complicates comparisons of data collected at different frequencies. For comparative purposes, difference limens (DL) are divided by the base frequency (F); the ratio DL/F is the **Weber ratio**. It is sometimes multiplied by 100 to give the **relative difference limen** (100 DL/F), which gives the difference limen as a percentage of the base frequency.

Toothed Whales.--Odontocetes that have been investigated have good frequency discrimination capabilities. Anatomical evidence is consistent with the hypothesis that the inner ears of dolphins are specialized to detect high-frequency sounds and for frequency discrimination. The **basilar membrane** is the part of the inner ear containing the cells that sense sounds. As in other mammals, the basilar membrane of dolphins is very narrow and stiff at one end. However, the change in width along the length of the basilar membrane is greater in dolphins than in humans (Wever et al. 1971b, 1972). There is a very high density of ganglion cells (Wever et al. 1971c, 1972). These features are believed to facilitate frequency discrimination, especially at high frequencies.

Psychophysical tests show that the bottlenose dolphin has excellent frequency discrimination throughout its hearing range with relative DLs of 0.21-0.81% from 2 kHz to 130 kHz (Thompson and Herman 1975; Fig. 7.6). The precise results depend on the experience of the animal and the methodology used to collect the data. However, the overall results obtained for two bottlenose dolphins during three studies were generally consistent (data of Herman and Arbeit 1972; Jacobs 1972; Thompson and Herman 1975 in Fig. 7.6; for reviews see Popper 1980a; Johnson 1986; Nachtigall 1986). In both air and water, adult humans perform about as well as the bottlenose dolphin within the limited range of frequencies where both have been tested (Fig. 7.6; Thompson and Herman 1975; Wier et al. 1977; Sinnott and Aslin 1985).

Soviet workers have reported that harbor porpoises have even better frequency discrimination abilities than bottlenose dolphins, with very low relative DLs even above 150 kHz. These results have been questioned because of the methods used and, in other publications, the lack of information about methods (*cf.* Bullock and Gurevich 1979; Popper 1980a,b). More recently, Popov et al. (1986) have reported that frequency shifts as small as 0.1% cause changes in the evoked potential from the auditory cortex of the harbor porpoise, with the smallest frequency shift thresholds being at 120-125 kHz. These electrophysiological

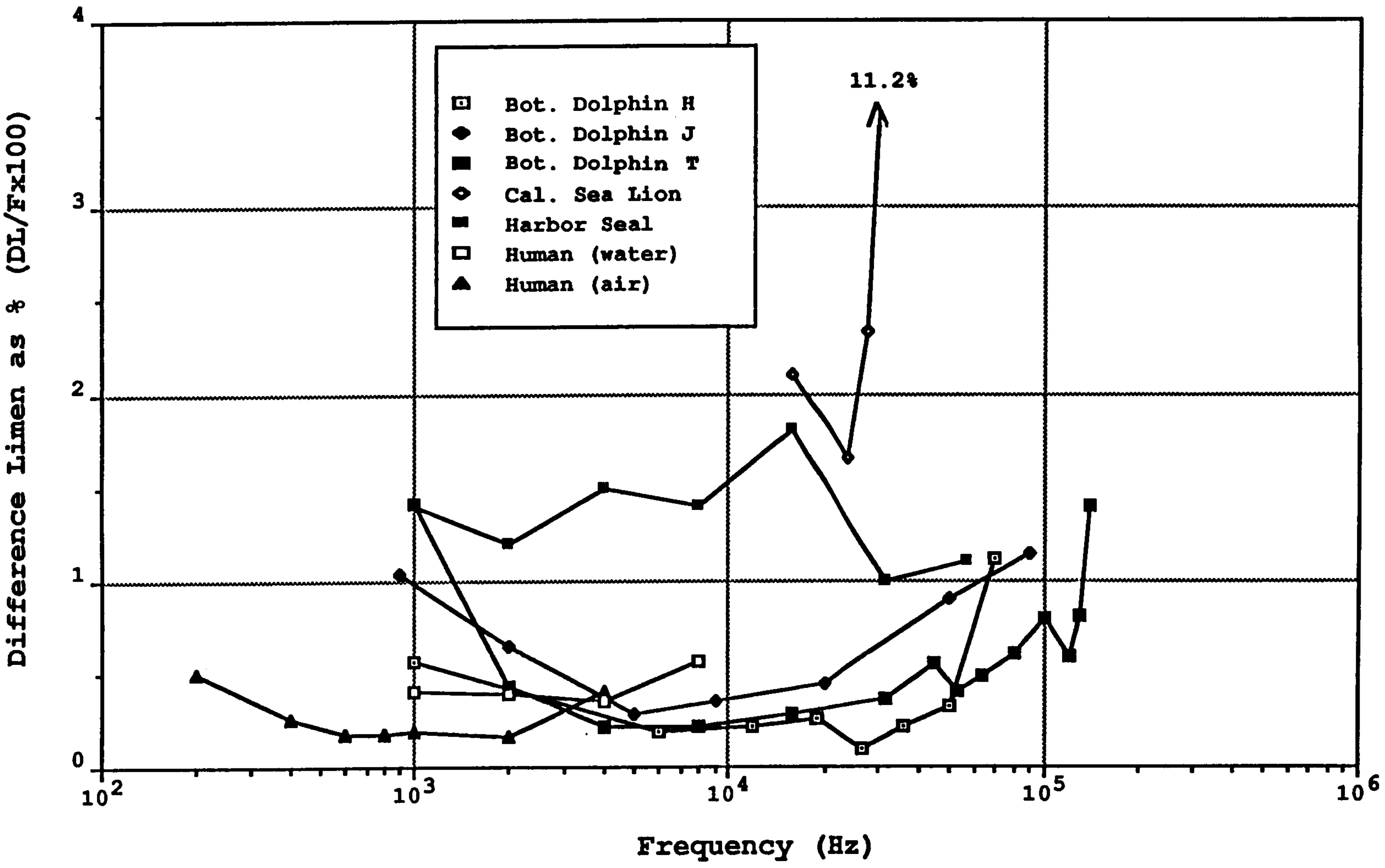


FIGURE 7.6. Underwater frequency discrimination capabilities of marine mammals and man: bottlenose dolphin (Herman and Arbeit 1972; Jacobs 1972; Thompson and Herman 1975); California sea lion (Schusterman and Moore 1978); harbor seal (Møhl 1967); human in water (Thompson and Herman 1975); human in air (Wier et al. 1977). For the sea lion, the relative difference limen was off-scale: 4.65% at 34 kHz and 11.2% at 38 kHz.

results are surprising in terms of both the small relative DL (0.1%) and the very high frequency at which it was found. Replication using a behavioral testing method is desirable.

Pinnipeds.--Pinnipeds apparently have less precise frequency discrimination abilities than do toothed whales. The harbor seal does not perform nearly as well as the bottlenose dolphin. The seal's DLs in water are 1.0 to 1.8% from 1 to 57 kHz (Møhl 1967, 1968b). The seal tested by Møhl (1967) could not discriminate any two frequencies above 60 kHz even though it could detect tones at frequencies up to 180 kHz. A California sea lion had a relative DL of 1.6% at 24 kHz, but did not perform as well at higher or lower frequencies (Schusterman and Moore 1978). Terhune and Ronald (1976b) examined frequency discrimination in two ringed seals, but stated that the true discrimination abilities may not have been measured due to experimental difficulties. However, ringed seals, like harbor seals, appear incapable of distinguishing frequencies above ~60 kHz.

7.3.2 Intensity Discrimination

Little information exists on intensity discrimination abilities in marine mammals. This is unfortunate given that intensity discrimination may be important in detecting sound signals in the presence of noise. In man, tones differing in intensity by as little as about 1 dB can be distinguished within the 200-8000 Hz range; other terrestrial species that have been tested have somewhat less precise intensity discrimination abilities (Fay 1988).

Very few data are available on intensity discrimination by pinnipeds. The California sea lion can discriminate tones differing in intensity by as little as 3 dB at 16 kHz (Moore and Schusterman 1976).

Somewhat more information is available for toothed whales. Johnson (1971, 1986) suggested, on the basis of limited data, that a bottlenose dolphin discriminated intensity differences of 0.35 to 2.0 dB. Bullock et al. (1968) reported that, in some dolphins, differences in evoked potential can occur with intensity differences as small as 1 dB. Similarly, Popov et al. (1986) found that, at 125 kHz, evoked potentials in the auditory cortex of the harbor porpoise differed when intensity changed by 3 dB at a low received level (40 dB re 1 μPa), and by as little as 0.5 dB when the received level was higher (60-80 dB). It is not known whether similarly high performance would be achieved using behavioral response methodology. Burdin et al. (1973a,b) have tested intensity discrimination in dolphins exposed to constant vs. varying-intensity white noise, but their results are difficult to understand. The just noticeable intensity difference was given as 4-7% (Burdin et al. 1973b), without a clear description of the units. Another Soviet study of *Tursiops*, based on a different method, indicated a differential intensity threshold for short pulses of 1-2 dB over a wide range of intensities (Vel'min et al. 1975 cited by Bullock and Gurevich 1979).

The limited data available suggest that odontocetes have good intensity discrimination abilities, comparable to those of humans. However, more experimental work at a variety of intensities and frequencies, preferably using behavioral testing methods, would be useful to confirm these data.

7.4 Directional Hearing and Source Localization

The ability to localize sound sources is very likely valuable in social interactions and is undoubtedly important in prey detection by echolocation or by passive listening. It is also important for detecting a signal of interest in the presence of industrial or other noise (sect. 7.5.3; Kryter 1985:49,76).

Humans and other terrestrial mammals listening in air can determine, with a variable degree of precision, the direction from which a given sound is arriving. The precision of localization depends on species, frequency, and other characteristics of the sound (Gourevitch 1980). In air, man and other mammals use differences in the arrival times, intensities and phases of sounds reaching the two ears to determine the direction of a sound source. The directional hearing ability of humans is much poorer underwater than in air (Feinstein 1966; Smith 1985), in part due to (1) the higher sound speed underwater and (2) a change in the path along which sound travels to the inner ear. Because sound speed is about 5x higher in water than in air, inter-aural differences in the time of arrival are greatly reduced in water. Also, the normal path of airborne sound to the middle and inner ear, via the external auditory canal, does not function underwater. Instead, underwater sound reaches the ear via bone conduction because of the similarity of acoustic impedances between tissue and water. The bone conduction mechanism likely detracts from the ability of a terrestrial animal (like man) to localize underwater sounds.

In whales, unlike humans, the auditory organs are largely isolated from the skull. This is believed to enhance their directional hearing abilities underwater (Dudok van Heel 1962; Fleischer 1980; Oelschläger 1986a,b). In pinnipeds the auditory organs are fused to the skull, suggesting a reduced underwater localization ability relative to that of cetaceans. However, pinnipeds have other adaptations for hearing in water as well as air (Repenning 1972; Møhl and Ronald 1975; Ramprashad 1975; Terhune 1989a).

The **Minimum Audible Angle (MAA)** is normally defined based on the angle subtended at the animal by one line through the animal's midline and another through a sound source displaced to the side. The MAA is the smallest angle at which the sound source is recognizable as being off the midline. Some experiments on sound localization by marine mammals have been based on discrimination between a midline sound source and one off-midline source (Table 7.1; Terhune 1974; Moore 1975; Moore and Au 1975). Another important experiment involved a buzzer on the midline and two projectors, one on either side of the midline; only one of the off-midline projectors was used at a time (Renaud and Popper 1975). Other tests have involved two projectors spaced equally on either side of the midline (Dudok van Heel 1959, 1962; Møhl 1964, 1968b; Gentry 1967). When two projectors on alternate sides of the midline are used to determine the minimum distinguishable projector spacing, the MAA normally is taken to be half of the angle subtended at the animal by lines extending to the two projectors. Especially in the tests where there is no projector on the midline, there has been some confusion in the literature as to whether the MAA is the "midline to one projector" angle (the usual definition and the one applied here) or the "projector to projector" angle.

Table 7.1. Minimum Audible Angles (MAA) for several marine mammals in water. MAA is defined as the angle subtended at the animal between its midline and the line to a sound source barely distinguishable as off-midline.

Species	Experimental Design	Transducer Arrangement	Signal Type	Freq. (kHz)	Criterion (%)	MAA	Source
Harbor Porpoise	Approach, horizontal[a]	2 symmetric[g]	2/3 s tone	3.5	66%	11°	Dudok van Heel (1959, 1962)
				6	70%	8°	
" "	"[b]	"	~½ s "	2	-75%	~3°	Andersen (1970b)
Bottlenose Dolphin	Stationary, hor, vert[c]	2 symmetric+ midline buzzer	80 x 3 ms tones over 1 s	6,90 & 100	70%	3.2-3.8°	Renaud and Popper (1975)
" "	"	"	"	10-80	"	2-3°	"
" "	"	"	166 x 35 μs clicks over ½ s	64	"	0.7-0.9°	"
Harbor Seal	Keypress, then approach; horizontal[a]	2 symmetric[g]	½ s tone	2	75%	3°	Møhl (1964, 1968b)
" "	Keypress; horizontal[a]	"	30 clicks/s,[d] each 0.2 ms	?	75%	4½°	Terhune (1974)
Calif. Sea Lion	Stat., then approach; horizontal[b]	2 symmetric[g]	0.3-0.4 s tone	3.5	70%	15°[e]	Gentry (1967)
				6	"	10°[e]	
" " "	Stationary; horizontal[c]	1 midline; 1 to left	30 clicks/s, each 1 ms, for 2½ s	1	75%	9°	Moore (1975)
					63%	6°	
" " "	"	"	30 x 20 ms tones /s for 2½ s	0.5	70%	12°	Moore and Au (1975)
				1	"	4.0°	
				2	-	-[f]	
				4	70%	42°	
				8	"	13.5°	
				16	"	≤18°	

[a,b,c] Animal's orientation was under (a) no, (b) limited, or (c) precise control.

[d] Duration was under animal's control.

[e] Schusterman (1981) has re-analyzed these data and obtained MAA = 26° and 12° at 3.5 and 6 kHz, respectively.

[f] Animal unable to localize at this frequency.

[g] For symmetric transducers, MAA = ½ (minimum transducer separation discriminated).

7.4.1 Toothed Whales

Some toothed whales have good sound localization abilities. A bottlenose dolphin was able to distinguish two pure tone sources as close as 2° to 3° on either side of a midline buzzer when the tones were at frequencies between 10 and 80 kHz (Renaud and Popper 1975). At 6 kHz and at 90-100 kHz the minimum audible angle (MAA) rose to 3-4° (Fig. 7.7; Renaud and Popper 1975). These MAAs were determined with the dolphin oriented toward the midpoint between two speakers. When azimuthal orientation was changed so that the dolphin was turned toward a point 15° away from the midpoint between two horizontally separated speakers, the MAA for tones at 40 kHz decreased to about 1.5° from the MAA of 2.5° at 0° azimuth (Renaud and Popper 1975). At an azimuth of 30°, MAA increased to 5°. The optimal spatial resolution when tones arrived from slightly (15°) off-midline was consistent with other evidence that the lower jaw, which is also angled relative to the midline, is important for sound reception in odontocetes (Norris and Harvey 1974; Popper 1980a). Localization ability of the one dolphin tested was generally comparable to that of the human in air (Fig. 7.7; *cf.* Mills 1958).

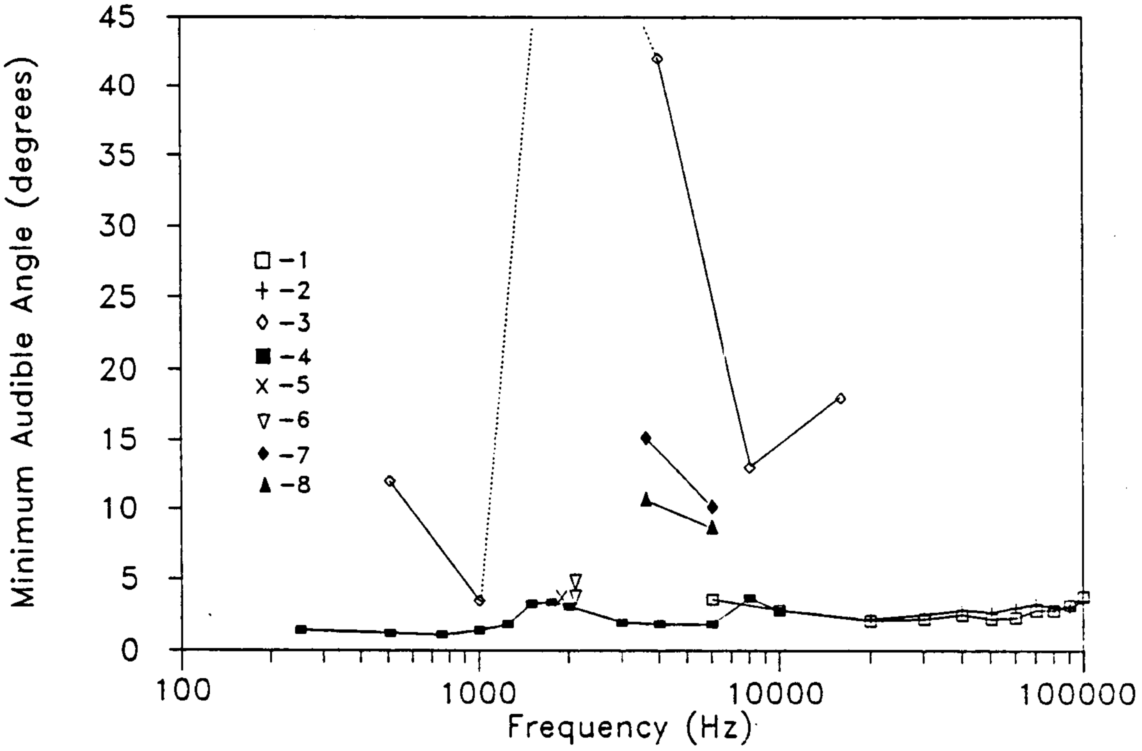
Broadband clicks resembling echolocation clicks were spatially resolved with even greater precision than tones. The bottlenose dolphin had MAAs of 0.7° and 0.9° in the vertical and horizontal planes, respectively, for clicks centered at 64 kHz (Renaud and Popper 1975). In all of their experiments, resolution was similar in the horizontal and vertical planes for all signal types. In general, clicks and other broadband sounds are expected to be more readily localized than the tones used in most experiments because clicks have greater bandwidth and contain more acoustic information.

Detailed information related to the directional hearing process in the bottlenose dolphin was obtained by Au and Moore (1984). They studied the characteristics of the cone in front of the animal in which it is most sensitive to high-frequency (30-120 kHz) sound. This is a different type of investigation than the above-described work to determine the MAA. Au and Moore exposed a stationary dolphin to sound signals (2-s tones) and background noise at differing angular separations in either the horizontal or the vertical plane. In general, the dolphin exhibited a cone of sensitivity centered about the animal's midline in the horizontal plane and directed 5-10° upward in the vertical plane. The angular width of the cone of sensitivity decreased with increasing frequency, resulting in a highly directional cone of sensitivity at the highest frequency tested:

	30 kHz	60 kHz	120 kHz
Horizontal beamwidth*	59.1°	32.0°	13.7°
Vertical beamwidth*	30.4°	22.7°	17.0°
Directivity index	10.4 dB	15.3 dB	20.6 dB

* to the -3 dB points.

The **directivity index** is a measure of the effectiveness of the acoustic receiver in limiting the effects of omnidirectional background noise. As noted in section 6.2.4, the transmitted echolocation sounds of toothed whales are also highly directional. In the bottlenose dolphin, the transmitting beam is slightly narrower than the receiving beam in both the horizontal and the vertical plane, and thus the directivity index of the emitted signals exceeds that of the auditory receiver (Au et al. 1978 vs. Au and Moore 1984).



Key for symbols:

1.	Bottlenose dolphin, azimuth	(Renaud and Popper 1975)
2.	" " , elevation	" " " "
3.	California sea lion	(Moore and Au 1975)
4.	Human in air	(Mills 1958)
5.	Harbor porpoise	(Andersen 1970b)
6.	Harbor seal in water and air	(Møhl 1964)
7.	California sea lion	(Gentry 1967)
8.	Harbor porpoise	(Dudok van Heel 1962)

FIGURE 7.7. Sound localization abilities of marine mammals in water and air and of man in air. See text for definition of Minimum Audible Angle. Figure from Fay (1988:509).

In the above experiments by Renaud and Popper (1975) and by Au and Moore (1984), the dolphin was required to keep its head stationary as the sounds were presented. In most other localization experiments on marine mammals, the animal has been able to move its head. This movement is expected to improve localization ability. Indeed, Popper (pers. comm.) noted that the MAA was reduced (improved) on an occasion when their dolphin's head was free to move. Thus, free-ranging bottlenose dolphins likely have even better localization abilities than the above results indicate. Some Soviet experiments have suggested that MAAs of dolphins can be much less than 1°, although doubts have been expressed about these reports (Bullock and Gurevich 1979:86; Popper 1980a). In any case, localization abilities of bottlenose dolphins in water are generally comparable in precision to those of humans in air (Mills 1958).

The MAA of a moving, unrestrained harbor porpoise was determined at comparatively low frequencies (2-6 kHz) in two studies. Even though these porpoises were unrestrained, their performance was not as good as that of the stationary bottlenose dolphin, whose MAA at 6 kHz was 3.6°. In one study employing a 2/3-s tone as the stimulus, the MAA of the harbor porpoise was 11° at 3.5 kHz and 8° at 6 kHz (Fig. 7.7; Dudok van Heel 1959, 1962). In another (incomplete) study using ~½-s tones as stimuli, the MAA was about 3° at 2 kHz (Andersen 1970b). These harbor porpoises were not tested with clicks, which would probably be easier to localize, or at the high frequencies used for echolocation. However, evoked potential data for this species have shown strong directional variation in hearing thresholds at 30-160 kHz; harbor porpoises were most sensitive to sounds arriving at angles within about 15-30° of straight ahead (Voronov and Stosman 1983).

7.4.2 Pinnipeds

Pinnipeds also have localization abilities, although they are less precise than those of bottlenose dolphins. The harbor seal can determine which of two underwater transducers is producing a 2-kHz tone when the sources are about 6° apart, i.e. MAA = 3° (Møhl 1964, 1968b). Another harbor seal was able to distinguish clicks from two underwater sources about 9° apart, i.e. MAA = 4½° (Terhune 1974)[5]. In air, the MAA of this harbor seal for clicks was about 1½°. This value was considerably less than the underwater MAA, although it may be important that the test procedures in air and water were different. In air, localization ability was better for broadband than for narrowband noise, and very poor for pure tones.

The sound localization ability of sea lions seems to be more variable and generally poorer than that in the odontocetes and phocids discussed above. Evoked potential tests on California sea lions revealed "only a weak directionality" of underwater hearing (Bullock et al. 1971); frequencies and methodological details were not reported. A California sea lion had an MAA of about 9° for low frequency (near 1 kHz) click sources (Moore 1975). When tones were used, the sea lion performed poorly at some frequencies and well at others. At 1 kHz, the MAA for pulsed pure tones was quite good--4° (Moore and Au 1975). The seemingly poorer

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[5] Terhune (1974) apparently defined MAA as twice the "midline-to-projector" angle. This was done even in his in-air experiment where only one projector was used, always on or to the left of the midline. For consistency with other results, we divide his 9° (in water) and 3° (in air) values by two.

localization ability for short clicks than for longer tones contrasts with results from the bottlenose dolphin and (in air) the harbor seal; those species localized clicks better than tones.

When Moore and Au tested the ability of one sea lion to localize tones at 2 kHz, localization was not evident. Given their testing procedure, either the animal could not localize tones at this frequency, or the MAA was >45°. At 4 kHz the MAA was 43°, with improvement to 13.5° at 8 kHz and ≤18° at 16 kHz (Fig. 7.7; Moore and Au 1975). Gentry (1967) performed similar experiments on a California sea lion and reported MAAs of about 10° at 6 kHz and 15° at 3.5 kHz for pure tones; at 1.5 and 2.5 kHz discrimination was not evident even with 50° separation of the two symmetric projectors (i.e. MAA >25°). The poor localization ability of the sea lion around 2 kHz may be attributable to a switch in mechanism for localization. Interaural timing difference may be used at lower frequencies and interaural intensity differences at higher frequencies (Moore and Au 1975).

7.4.3 Baleen Whales

Localization abilities of toothed whales and pinnipeds for sounds below 0.5-2 kHz are generally untested and potentially less precise than those at higher frequencies with shorter wavelengths. However, baleen whales clearly have some ability to localize sounds at frequencies of a few hundred Hertz (or below). Baleen whales have been observed to swim toward distant calling conspecifics (Watkins 1981b; Tyack and Whitehead 1983) and toward certain sounds projected into the water by playback methods (Clark and Clark 1980; Dahlheim 1987). Some baleen whales have also been observed to swim directly away from the sound source when exposed to killer whale sounds (e.g. Cummings and Thompson 1971b; Malme et al. 1983) or certain industrial noises (Chap. 8). It is not known if these whales localized sound sources by the same psychophysical processes as used by the odontocetes and pinnipeds discussed above. However, the directness and short response times of the oriented movements by baleen whales in some of the cases mentioned above suggest that they were not orienting based solely on sequential comparison of intensities at different locations.

7.5 Auditory Masking

7.5.1 Critical Ratios

Hearing threshold audiograms (Figs. 7.1-7.3) represent the lowest intensities of sound that can be detected by an animal in the absence of appreciable background noise. However, the sea is a noisy environment, even in the absence of man-made sounds, and background ambient noise often interferes with (**masks**) the ability of an animal to detect a sound signal. Thus, detectability is commonly limited by background noise rather than by the absolute hearing capabilities shown in Figures 7.1-7.3.

Background noise levels are commonly measured on a **spectrum level** basis. These measurements represent the amount of noise energy at each frequency (per hertz), and are expressed in the units dB re (1 μPa)^2 per Hz (see sect. 2.2 for details). The intensity by which a signal must exceed the spectrum level background noise in order to be audible is termed the **critical ratio**. Critical ratios for marine mammals have been determined by presenting a pure tone to a test animal while a background **white noise** is present (Johnson 1968b; Terhune 1981; Fig. 7.8). White noise is simply broadband noise in which all frequencies in the noise

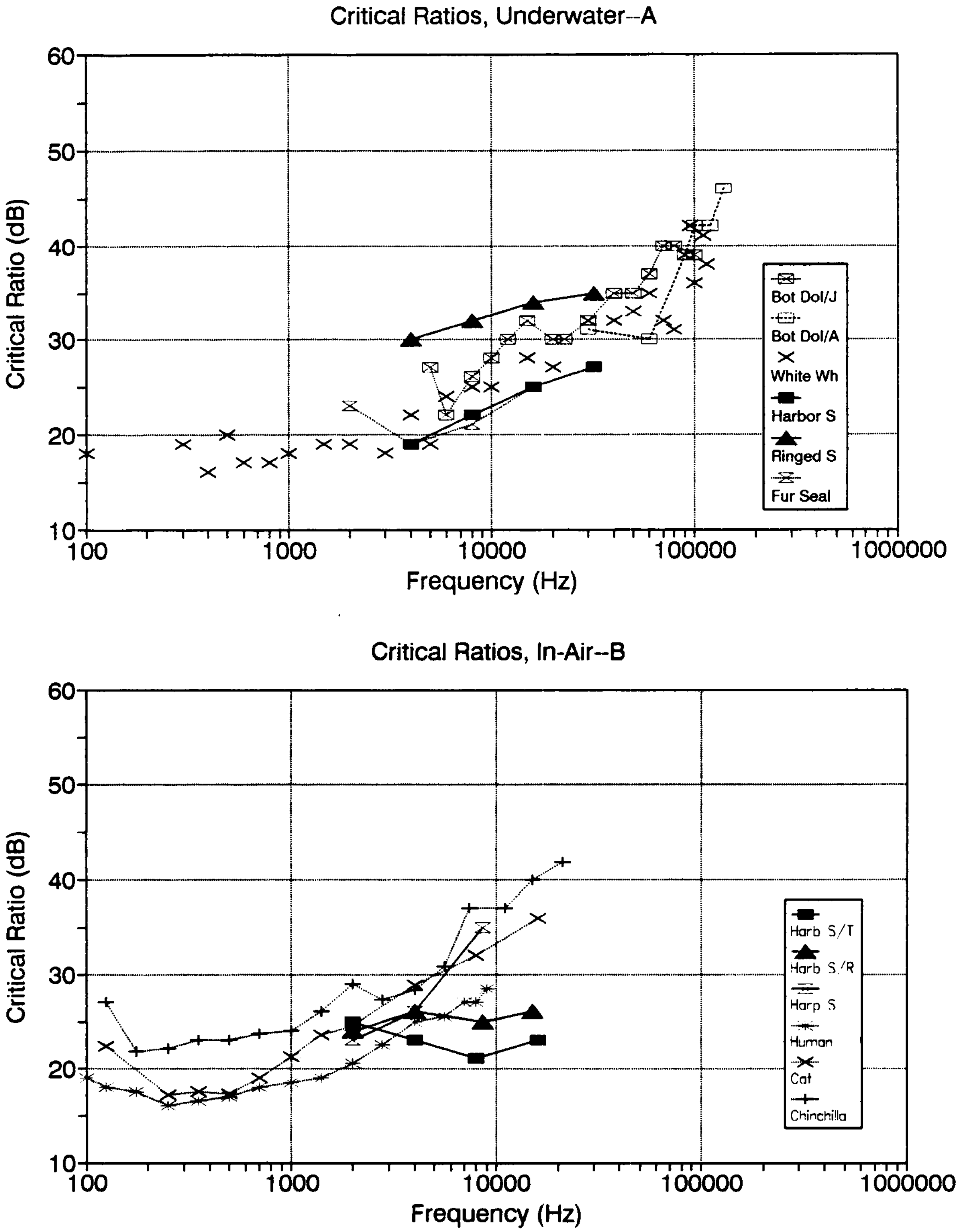

FIGURE 7.8. Critical ratios of marine mammals and several terrestrial mammals. ***(A) Underwater data:*** bottlenose dolphin (Johnson 1968b; Au and Moore 1990); white whale (Johnson et al. 1989); harbor seal (Turnbull and Terhune 1990); ringed seal (Terhune and Ronald 1975b, n=2); fur seal (Moore and Schusterman 1987, n=2). ***(B) In-air data:*** harbor seal (Renouf 1980, n=2; Turnbull and Terhune 1990); harp seal (Terhune and Ronald 1971); human (Hawkins and Stevens 1950, n=4); cat (Watson 1963, n=4); chinchilla (J.D. Miller *in* Fay 1988, n=?). n=1 except where noted.

spectrum are of equal intensity.[6] A critical ratio of 20 dB at a particular frequency means that a tone at that frequency must have a level ≥100 dB re 1 μPa to be heard over white noise with a spectrum level of 80 dB re $(1\ \mu Pa)^2$/Hz.

Except at quite low frequencies, critical ratios tend to increase with increasing frequency. In the bottlenose dolphin, a pure-tone signal at 6 kHz must exceed spectrum level noise by 22 dB to be detected, whereas a 70-kHz tone must exceed spectrum level noise by about 40 dB (Fig. 7.8A; Johnson 1968b; Au and Moore 1990). Burdin et al. (1973a) obtained some evidence that, at 1-10 kHz, critical ratios of dolphins are lower (better) than those of a human. Critical ratios for the bottlenose dolphin have not been measured directly below 5 kHz, but those of the white whale have recently been measured from 40 Hz to 115 kHz. From 100 Hz to 2 kHz, critical ratios of the white whale in water resembled those of humans in air (Fig. 7.8A vs. B). From 40 Hz to 2 kHz, the critical ratios of a white whale were relatively constant; above 2 kHz they increased with frequency. There was no evidence of deterioration in critical ratios at the lowest frequency tested (40 Hz), in contrast to results for some animals, including man (Fig. 7.8B).

Underwater, the critical ratios of the northern fur seal and harbor seal are almost identical from 4 to 32 kHz, ranging from a low of 19 dB at 4 kHz to 27 dB at 32 kHz (Moore and Schusterman 1987; Turnbull and Terhune 1990). These values are a few decibels lower than critical ratios of the bottlenose dolphin at corresponding frequencies (Fig. 7.8A). In contrast, the ringed seal apparently has critical ratios about 10 dB higher than those of the fur and harbor seals, and several dB above the dolphin and white whale through the same frequency range (Terhune and Ronald 1975b; Fig. 7.8). Moore and Schusterman (1987) suggest that the ringed seal values are suspiciously high, and may be erroneous.

Critical ratios are not greatly different for underwater and aerial hearing (Fig. 7.8; Moore and Schusterman 1987; Fay 1988). The data quoted above all represent underwater hearing. The critical ratios of one harbor seal have been measured in both water and air, and found to be very similar (Turnbull and Terhune 1990). They note that this was to be expected, since "the ability to detect a signal in noise resides in the inner ear and the central nervous system[;] impedance mismatches and other outer and middle ear influences would alter the signal and noise levels similarly. Therefore, it would be expected that the critical ratios should not vary between the two media...". In-air critical ratios have also been determined for the harp seal (Terhune and Ronald 1971) and two more harbor seals (Renouf 1980). The validity of some of the harp seal data is uncertain (Terhune and Ronald 1971; Moore and Schusterman 1987).

7.5.2 Masking Bands

A pure tone is masked almost exclusively by noise at frequencies near the frequency of the tone. Noise at frequencies outside this **masking band** has little influence on detection of the signal unless the noise intensity is very high (Spieth 1957; Kryter 1985:45*ff*). The determination of the width of the masking band has been the subject of much effort. Fletcher (1940) proposed one method, based on the **equal-power assumption**; he assumed that signal

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[6] In some masking experiments, the white noise has been filtered and limited to some range of frequencies above and below the test frequency. This should have little effect on the results as long as the bandwidth of the noise exceeds the masking bandwidth.

power must equal or exceed total noise power in the masking band in order to be audible. Since the spectrum levels of masking noise are given in dB re $(1\ \mu Pa)^2/Hz$ and the intensities of tones are in dB re 1 µPa, the spectrum level of the masking noise must be converted to a band level before evaluating equivalence. The white noise often used in masking experiments has a flat spectrum, and therefore the energy in a masking band of noise is proportional to the masking bandwidth in Hz. For white noise, **band level** BL is computed from spectrum level SL by the formula

$$BL = SL + 10 \log BW \tag{7.1}$$

where BW is the bandwidth in Hz (Urick 1983). If it is assumed that signal power must equal or exceed noise power in the masking band in order to be detectable (Fletcher 1940), then the masking bandwidth is

$$BW = \text{antilog } CR/10 \tag{7.2}$$

where CR represents critical ratio in terms of signal level relative to spectrum level noise. This gives the bandwidth in Hz of the band of masking noise that contains power equal to that of the signal tone (Scharf 1970). Johnson (1968b), Terhune (1981) and others have used equation (7.2) to calculate masking bandwidths in Hz for marine mammals based on the assumption that signal power equals masking power. Figure 7.9 shows results of such calculations, expressed as a percentage of the center frequency of the masking band.

Based on available critical ratio data and the equal-power assumption, masking bands underwater often appear to be less than 1/6th octave in width at intermediate frequencies, i.e. masking bandwidth is less than 11.6% of the center frequency (Fig. 7.9A). At intermediate frequencies, the ringed seal is the only tested species whose masking bands seem to exceed 1/3rd octave in width, i.e. >23.2% of center frequency (Fig. 7.9A). If the equal-power masking bandwidth were exactly 1/6 or 1/3 octave, the critical ratios at several frequencies would be as follows:

	100 Hz	1 kHz	10 kHz	100 kHz
1/3 octave	13.6 dB	23.6 dB	33.6 dB	43.6 dB
1/6 octave	10.6	20.6	30.6	40.6

Thus, critical ratios for most marine mammals listening underwater at most frequencies are lower than expected if the masking bandwidth is 1/3 octave or even 1/6 octave *and if the equal-power assumption is true.*

At low and very high frequencies, masking bands widen, on a percentage of center frequency basis--at least in the white whale (at low frequencies) and bottlenose dolphin (at high frequencies). This is probably a general phenomenon that would be evident in other species if they were tested at low and high frequencies. This phenomenon is evident for many terrestrial mammals listening in air (Fig. 7.9B; Fay 1988).

Masking bandwidth is important in determining the radius around a sound source at which it is barely detectable, i.e. maximum **radius of audibility**. This concept is commonly discussed in the literature concerning noise effects on marine mammals (Richardson et al. 1983, 1989; Miles et al. 1987). It is important in Chapter 9 where we discuss the potential radius of noise influence. When attempting to calculate the maximum radius of audibility of marine mammal sounds or a specific industrial noise in the presence of background noise, several workers have

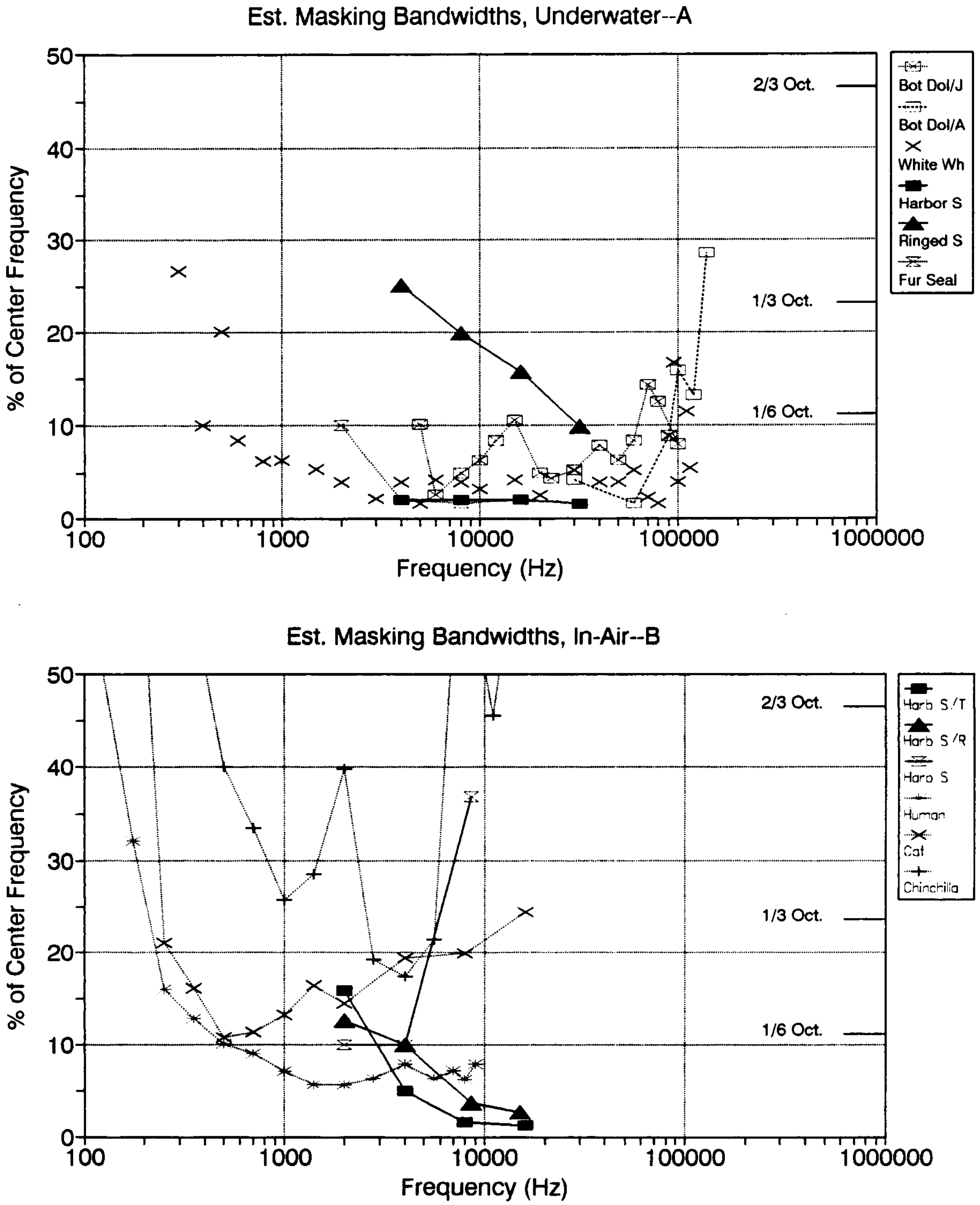

FIGURE 7.9. Estimated masking bandwidths of marine mammals and several terrestrial mammals, expressed as a percentage of center frequency. *(A)* Underwater data. *(B)* In-air data. Assumes that signal power must equal or exceed noise power in masking band in order to be detected, i.e.

Masking bandwidth = (antilog Critical Ratio)/10

Based on same sources as previous Figure.

assumed that effective masking bands are 1/3 octave wide (e.g. Payne and Webb 1971; Gales 1982; Miles et al. 1987). Figure 7.9 suggests that masking bandwidth actually is less than 1/3-octave in many cases *if the equal-power assumption is true.*

Gales (1982) also considered the possibility that, at frequencies below 450 Hz, the masking bandwidth exceeds 1/3 octave. In the human and other terrestrial mammals, critical ratios at low frequencies often exceed those expected if the masking bandwidth is 1/3 octave (Fig. 7.9B; Fay 1988). This is also true in the white whale (Fig. 7.9A), the one species of marine mammal for which critical ratios at low frequencies have been determined (Johnson et al. 1989). When masking bandwidths exceed 1/3 octave, noise power in the masking band will be higher than calculated from the 1/3 octave assumption, and the maximum radius of audibility of low frequency sound will be less than that calculated. Conversely, for intermediate frequencies where the masking bandwidth seems to be less than 1/3 octave based on critical ratio data for marine mammals, the maximum radius of audibility could be somewhat greater than calculated assuming a masking bandwidth of 1/3 octave. *All of these estimates depend on the validity of the equal-power assumption, i.e. that a narrowband sound signal is masked when total noise power in the masking band equals or exceeds the power of the signal.*

The equal-power assumption may not accurately represent the width of the masking band (Zwicker et al. 1957; Scharf 1970; Kryter 1985). Other methods measure the masking band directly by manipulating the bandwidth of noise masking a signal, or by measuring the ability of one pure tone to mask another. The term **critical band** is used for direct empirical measures of the masking band (Scharf 1970). In humans, the critical band in Hz is about 2.5 times wider than the critical ratio equal-power band at the same center frequency. This means that humans can detect a signal whose level is somewhat less than the band level of noise in the masking band, contrary to the equal-power assumption of Fletcher (1940). In this instance, the threshold signal-to-noise (S/N) ratio would be negative, i.e. <0 dB.

The only direct measurements of critical bandwidth in a marine mammal are those of Au and Moore (1990) for a bottlenose dolphin and Turnbull and Terhune (1990) for a harbor seal. For the dolphin, critical bandwidths at 30, 60 and 120 kHz were, respectively, about 11, 7 and 2 times wider than expected based on the equal-power assumption. For a harbor seal, directly-measured critical bands in both air and water became narrower on a "percent of center frequency" basis at high frequencies (Turnbull and Terhune 1990). A 16 kHz pure tone had little masking influence on signals differing by >1 kHz. Based on one standard estimation procedure, the directly-measured critical bandwidth was from below 1% to just over 2.5% of the center frequency--considerably narrower than the bands for man and some other terrestrial mammals (Turnbull and Terhune 1990).

In man, as noted above, the directly-measured critical bandwidth in Hz is about 2.5 times wider than the critical ratio equal-power band at the same center frequency. This general relationship "2.5x" relationship is not true in the bottlenose dolphin, harbor seal, or in some non-human terrestrial mammals (Au and Moore 1990; Turnbull and Terhune 1990).

7.5.3 Threshold Signal/Noise Ratio

The above-mentioned results of Moore and Au (1983) show that, at 30 and 60 kHz, the bottlenose dolphin apparently can detect sounds 10 dB and 9 dB below the total level of the noise in the corresponding critical band, i.e. at S/N = -10 and -9 dB. At 120 kHz the threshold S/N is near 0 dB.

Critical ratios of 20 dB or more are not incompatible with negative or near-zero values of threshold S/N ratios; they are merely different ways of expressing the same phenomenon. Critical ratios relate (1) total signal level in a band that may be about 1/3 octave wide to (2) the spectrum level of background noise on a "per Hz" basis. In contrast, negative or near-zero threshold S/N ratios represent signal level in a band to total noise level in that same band.

Though the conclusion that threshold S/N ratios may be negative is somewhat startling, it has been shown that human subjects can detect signals such as tones and speech at negative S/N ratios (Miller et al. 1951; Scharf 1970). Structured signals such as speech and perhaps echolocation click sequences may be especially well detected due to differences between their frequency content and that of the noise, and also due to factors such as redundancy and context that give clues about the type of sound to expect next.

The S/N ratio necessary for effective use of acoustic information may vary depending on the ability of the animal to process repetitive signals. Au and Penner (1981) estimated that S/N may need to be about 7 to 13 dB for *Tursiops* to detect an echolocation target with 75% accuracy. Here S is the overall level of the echo and N represents the spectrum level of background noise, i.e. the units are compatible with those of critical ratios. Background noise came from the direction of the target, thereby ensuring that the results were unaffected by directional hearing capabilities (see later). Turl et al. (1987) confirmed these results for *Tursiops* but found, using the same test procedure, that a white whale achieved 75% accuracy when S/N was only about 1 dB, or 9 dB better than *Tursiops*. Au and Pawloski (1989) found that a theoretical optimum receiver would outperform *Tursiops* by only ~7.4 dB. They concluded that this casts some doubt on the white whale results, since the white whale apparently had detection capabilities superior to the theoretical maximum. The white whale experiment was designed to prevent the animal from using its superior directional hearing and surface-reflected beam capabilities (*cf.* Penner et al. 1986). However, Au and Pawloski (1989) suggest that the white whale may, nonetheless, have discovered some method of spatially filtering the target echo from the masking noise.

Even for *Tursiops*, the 7-13 dB threshold for echolocation pulses is low compared to the critical ratios for single tones at corresponding high frequencies (Fig. 7.8). Furthermore, critical ratios underestimate the critical bandwidth at some frequencies (Moore and Au 1983). Thus, it is apparent that *Tursiops* detects and interprets sequences of echolocation signals whose S/N is well below 0 dB when expressed as overall echo level vs. overall noise level in the corresponding masking band.

Payne and Webb (1971) discussed human signal detection data in relation to the signals propagated by baleen whales, and suggested that baleen whales may also be capable of detecting sounds at negative S/N ratios. Hearing abilities of baleen whales are unknown, but some other groups of marine mammals (especially toothed whales) can discriminate intensities, frequencies and directions at levels comparable to those of humans. Bearing this in mind, the hypothesis of Payne and Webb (1971) on the hearing abilities of baleen whales is in line with most data on marine mammal hearing abilities presented earlier in this section. However, there are few data on hearing abilities of any marine mammal species at the low frequencies important to baleen whales. It would be especially valuable to know the relationship between critical ratios and frequency for low-frequency hearing by baleen whales.

Laboratory tests of masking may really be tests of intensity discrimination; the task is to distinguish between the critical band of noise alone and the band of noise plus a signal. If a signal is added to noise, the signal will be perceived when the sum of the intensities of signal and noise cause a perceived increase in loudness relative to the noise alone.

Even in the absence of many detailed data on intensity discrimination by marine mammals, critical ratio data give valuable information, including an indication of the frequencies that are least prone to masking. Critical ratio data also allow us to estimate the received level at which a narrow-band sound will be just detectable given a specified level of broadband background noise. However, some man-made noises have strong tonal components whose masking potential is not wholly predictable using critical ratio data. Behavioral data on masking of one pure tone by another at various similar frequencies have been reported for *Tursiops* (Johnson 1971) and the harbor seal (Turnbull and Terhune 1990). There are also limited electrophysiological data on this point (Bullock et al. 1968; Supin and Popov 1986), although their relevance to practical detection problems is uncertain. No such data are available for masking by low frequency tones, which are common components of industrial noise (Chap. 5).

7.5.4 Adaptations for Reduced Masking

Most masking studies present the signal and the masking noise from the same direction. The sound localization abilities of marine mammals suggest that, if signal and noise come from different directions, masking will not be as severe as the existing critical ratio data suggest. In fish, the critical ratio at any given frequency decreases as the angle of separation between signal and masking noise increases (Chapman 1973). When the dominant background noise comes from a small number of specific sources such as ships or industrial sites, the background noise may be highly directional. Even some natural sources of background noise such as surf (Wilson et al. 1985) or ice may be strongly directional in the horizontal plane. Wind-induced ambient noise may exhibit significant variation in the vertical plane (Hamson 1985). In these situations, directional hearing abilities could, in theory, significantly reduce the masking effects of the noise by improving the effective S/N ratio. In the cases of high-frequency hearing by the bottlenose dolphin and white whale, there is empirical evidence that masking effects do indeed depend strongly on the relative directions of arrival of the sound signal of interest vs. the masking noise (Zaitseva et al. 1975; Au and Moore 1984; Penner et al. 1986).

A study of directional masking at 80 kHz was done using an unrestrained bottlenose dolphin exposed to 0.6-s tone pulses (Zaitseva et al. 1975). The signal transducer was directly ahead of the animal, and a noise transducer playing 50 to 100 kHz white noise was moved to various positions around the dolphin in the horizontal plane. At 0° azimuthal separation the critical ratio was about 40.7 dB (Zaitseva et al. 1975), almost identical to the result obtained by Johnson (1968b). When the source of the masking noise was moved to angles 7°-180° from the signal transducer, the critical ratio decreased progressively from about 35 dB to 11 dB. Under the more restrictive condition of a stationary animal and noise coming from both sides of the signal, the reduction in masking is not as large, although still considerable (Au and Moore 1984). Also, Au and Moore showed that at lower frequencies the reduction in masking would not be as great.

Taken together, the two studies showed that the masking effect of background noise on *Tursiops* echolocation is much reduced if the noise (1) comes from a direction other than that of the target, or (2) is omnidirectional. Laboratory studies in which the noise source is in line with the target are probably not representative of the most common echolocation tasks that an animal will encounter in the wild, where the background noise will rarely come solely from the direction of the target. Thus directional hearing, coupled with the strongly directional nature of the echolocation pulses (e.g. Norris and Evans 1967; Watkins 1980b; Zbinden et al. 1981; Au et al. 1986, 1987; see sect. 6.2.4), is a very important adaptation for improving echolocation range and performance in the presence of noise.

It has been demonstrated that the white whale takes advantage of its directional sound emission and hearing capabilities while echolocating (Penner et al. 1986). When a noise source was placed in line between a white whale and the echolocation target, the whale echolocated by bouncing its beam off the water surface. This allowed the whale to concentrate its emitted echolocation beam, and presumably its "receiving beam", in a direction slightly (~7°) different than that of the noise source. In this manner the white whale could detect the target when the noise level was too high to allow detection by conventional straight-line echolocation. No such capability was demonstrated in *Tursiops* (Penner et al. 1986).

Au and Moore (1984) showed that the directionality of *Tursiops* hearing became less pronounced as frequency decreased from 120 to 60 and 30 kHz. In another experiment on *Tursiops*, Zaitseva et al. (1980) found that the angular separation between a sound source and a masking noise source has little effect on the degree of masking when the sound frequency is 18 kHz. Zaitseva et al. interpret this to mean that dolphin communication sounds are more or less equally audible regardless of their direction of arrival, which is likely to be advantageous for purposes of social interactions. However, at these moderate frequencies (and presumably at the lower frequencies where industrial noise is concentrated), masking would be almost equally severe regardless of the direction of arrival of the masking noise.

Toothed whales, and probably other marine mammals as well, have additional capabilities besides directional hearing that can facilitate detection of sounds in the presence of background noise. Au et al. (1974) obtained indirect evidence that bottlenose dolphins may shift their peak echolocation signals to 120-130 kHz from the more typical 35-60 kHz signals in an area where there was a high level of ambient noise in the latter frequency range. Acoustic source levels of echolocation signals may also be increased when necessary to circumvent noise (Au et al. 1974). Adaptation of the frequency and source levels of echolocation sounds to the prevailing noise environment was subsequently demonstrated in a more direct fashion in a white whale (Au et al. 1985).

Additional studies of masking are needed, including work on additional marine mammal species, sounds at low frequencies (<2 kHz), and directional masking. The relationships between equal-power bandwidths computed from critical ratios, directly-measured critical bandwidths, and threshold S/N ratios are especially in need of study. The demonstrated directional hearing abilities of some pinnipeds and baleen whales probably give them some improved capabilities, as demonstrated in dolphins and a white whale. Whether most marine mammals can adjust the frequencies and source levels of their various call types to increase their communication ranges in the presence of noise has not been studied. Estimated source levels of some marine mammal sounds vary widely, suggesting that the animals might be able to tailor the source level to the circumstances. However, much of this apparent variation is undoubtedly an artifact of variation in propagation conditions between the source and measurement locations. It is not known how much real variation there is in the source levels of sounds from free-ranging marine mammals.

7.6 Audition in Baleen Whales

No psychoacoustical or electrophysiological work on the auditory sensitivity of any baleen whale has been reported. However, various species have been shown to react behaviorally to calls from conspecifics and to certain man-made sounds (e.g. chapter 8). Most of the man-made sounds that elicited reactions were at frequencies below 1 kHz. The reaction thresholds were usually rather high--well above the threshold for detection by instruments. It is not known whether weaker sounds were below the whales' detection thresholds, or were detected but too weak to elicit an overt behavioral response. We suspect the latter, given that reaction thresholds are quite variable, apparently depending on the perceived degree of threat (chapter 8). Field studies of the acoustic responsiveness of marine mammals can set an upper bound on the detection threshold (e.g. Dahlheim and Ljungblad in press). However, it is possible that actual detection thresholds are significantly lower than the upper limits suggested in those studies.

On the basis of anatomical and paleontological evidence, Fleischer (1976, 1978) suggested that baleen whales are adapted for hearing low frequencies. Norris and Leatherwood (1981) examined the morphology of the hearing apparatus of the bowhead whale and several other species of cetaceans, and speculated that bowheads likely hear sounds ranging from "high infrasonic [or] low sonic to high sonic or low ultrasonic frequencies". Watkins (1986) states that baleen whales often reacted to sounds with frequencies from 15 Hz to 28 kHz, but not to pingers and sonars at 36 kHz and above. Other authors (e.g. Evans 1973; Myrberg 1978; Turl 1980) suggest that marine mammals probably hear best in the frequency range of their calls. Most baleen whale sounds are concentrated at frequencies less than 1 kHz, though sounds up to 8 kHz are not uncommon (sect. 6.1). It is reasonable to suggest, then, that baleen whales are quite sensitive to frequencies lower than 1 kHz. However, it is important to bear in mind that there are no quantitative data on any aspect of the audiogram of any baleen whale.

It is possible that some or all baleen whales can hear sounds at frequencies well below those detectable by man. The sounds produced by most of the well-studied species include components at or below 50 Hz, and some species commonly emit sounds whose dominant components are near 20 Hz (sect. 6.1). Baleen whales can be assumed to be able to hear these types of sounds. Even if the range of most sensitive hearing does not extend below 20-50 Hz, whales may hear strong infrasounds at considerably lower frequencies. In other mammals, the low frequency portion of the audiogram slopes upward gradually as frequency decreases, typically by 20-40 dB per 10-fold reduction in frequency (Fay 1988). If hearing sensitivity is good at 50 Hz, strong infrasounds at 5 Hz might be detected.

Thresholds of other marine mammals range between 30 and 80 dB re 1 µPa at the frequencies to which they are most sensitive (see Fig. 7.1, 7.2). If baleen whales have similar thresholds, but shifted to frequencies below 1 kHz, oceanic ambient noise rather than absolute detection threshold often would be the most important limiting factor. Even in quiet conditions (sea state 1) without any industrial activities nearby, average ambient noise levels in the ocean are above 75 dB re 1 μPa in all 1/3-octave bands below 1000 Hz (Fig. 4.1B). Masking bandwidths may exceed 1/3 octave at low frequencies (sect. 7.5.2), in which case ocean noise levels in masking bands would be even higher.

Though ambient noise probably limits low frequency hearing in baleen whales, the situation above 1 kHz is less clear. Ambient noise levels typically fall as frequency rises, and are less likely to limit hearing above 1 kHz.

Behavioral evidence indicates that baleen whales have directional hearing capabilities (sect. 7.4). Although audition data are totally lacking for baleen whales, sound localization ability may not be radically different than in other mammals. This may be true even though low-frequency long-wavelength sounds are probably the most important sounds for baleen whales. The baleen whale's ear is well isolated acoustically from the skull, which may be important for accurate sound localization (Fleischer 1978). The relatively great distance between the ears of large whales may enhance their ability to localize sound cues (see Gourevitch 1980 for a detailed discussion of localization). Norris (1981) suggested that baleen whales may be able to find prey concentrations by localizing the sounds produced by swimming fish (e.g. Moulton 1960). However, data on all of these points are needed.

Critical ratio functions are similar among many vertebrates (Fay 1988; Fig. 7.8), and those of the baleen whales may be comparable. Baleen whales may also have lower critical ratios when signal and noise are angularly separated. Given the large size of baleen whales' heads, this improvement in critical ratio as a result of directional phenomena may extend to lower frequencies than in other mammals.

Although even more speculation about these and other features of baleen whale hearing is possible, empirical measurements are needed. Unfortunately, it has not been practical to conduct psychoacoustical tests on baleen whales, e.g. to obtain a behavioral audiogram, or behavioral data on directional hearing or critical ratios. These tests are normally done on trained, captive animals. However, it is technically feasible to obtain an "electrophysiological audiogram" by evoked potential methods from a beached or restrained baleen whale (Ridgway et al. 1981; Ridgway and Carder 1983). Such data would have important limitations, but nonetheless would be helpful in interpreting the potential auditory capabilities of baleen whales. Empirical data are needed before confident predictions about mysticete auditory capabilities will be possible.

7.7 Summary and Comparisons

The hearing abilities of a few species of toothed whales, hair seals and eared seals have been studied in some detail. Data on the hearing abilities of manatees are very limited, and hearing abilities of baleen whales, walruses and sea otters have not been studied directly. Hearing data are important in evaluating the abilities of marine mammals to detect various natural and man-made sounds. Hearing data are also needed to assess the effects that man-made sounds will have on the detectability of natural sounds that may be important to the animals.

Toothed whales are most sensitive to sounds above about 10 kHz. Their upper limits of sensitive hearing range from about 31 kHz in a killer whale and near 70 kHz in a false killer whale to well above 100 kHz in some species. The sensitivity of many toothed whales to high frequency sounds is related to their use of very high frequency sound pulses for echolocation and moderately high frequency calls for communication. Low frequency hearing has not been studied in many species, but the bottlenose dolphin and white whale can hear sounds at frequencies as low as 40-125 Hz. However, below ~10 kHz sensitivity deteriorates with decreasing frequency. Below 1 kHz, where most industrial noise energy is concentrated, sensitivity appears to be poor.

At least in the bottlenose dolphin, sensitivity decreases as the duration of a ***single*** sound pulse decreases below about 0.1-0.2 s. However, toothed whales apparently have neural mechanisms specialized for processing ***sequences*** of short pulses, such as are used for echolocation. Toothed whales have good frequency and intensity discrimination abilities, as well as good directional localization capabilities.

Masking of sound signals by background noise has been studied under laboratory conditions in the bottlenose dolphin and white whale. Above ~2 kHz, critical ratios increase with increasing frequency, and are generally similar to those of the human at corresponding frequencies. At lower frequencies, critical ratios of the white whale (the only species studied) are unrelated to frequency. Critical bands in the bottlenose dolphin appear to be wider than would be predicted based on the equal-power assumption. This indicates that some odontocetes can detect certain sounds when the signal is less intense than the total background noise in the masking band. Most masking experiments have tested the ability of an animal to detect a sound signal in the presence of noise coming from the same direction. At very high frequencies (e.g. 80 kHz), masking is greatly reduced when the sound signal and masking noise arrive from different directions, or when the signal arrives from one direction but the noise is omnidirectional. This reduction in masking due to directional hearing is less evident at moderate frequencies (e.g. 18 kHz).

Baleen whale hearing has not been studied directly. However, there are several indirect indications that these animals are sensitive to low and moderate frequency sounds, no doubt with some variation among species. There are no specific data on sensitivity, frequency or intensity discrimination, or localization abilities. However, gray whales are able to detect killer whale sounds whose received levels are about equal to the broadband noise level, and several species seemingly can determine the direction of arrival of various underwater sounds. The lack of specific data on hearing abilities of baleen whales is a major limitation in evaluating the effects of man-made noise on this group. The data gaps are of special concern because baleen whales apparently are more dependent on low-frequency sounds than are other marine mammals; many industrial sounds are concentrated at these low frequencies.

Hair (phocid) seals apparently can detect very high frequencies of underwater sound--up to 180 kHz in the harbor seal. However, the upper limit of effective hearing is about 60 kHz, above which sensitivity is poor and different frequencies cannot be discriminated. Underwater sensitivity is about the same from 1 or 2 to 50 kHz. Within this range of best underwater hearing sensitivity, sensitivity is not as high as in toothed whales. Sensitivity at low frequencies (<760 Hz) has not been tested. In-air hearing of phocid seals is less sensitive than underwater hearing, and the upper frequency limit is lower (about 20 kHz). The underwater hearing threshold of a harbor seal increased as the duration of a sound decreased below about 50 ms, as in other animals. Pinnipeds seem less specialized for processing click sequences than are toothed whales. Their frequency discrimination abilities also seem less precise. Harbor seals have reasonably good directional localization abilities. Critical ratios increase with increasing frequency (at least in water), are similar in water and air, and probably are similar to those of other mammals.

Eared seals are similar to hair seals with regard to underwater hearing sensitivity at moderate frequencies. However, their upper frequency limit is lower--near 36-40 kHz vs. 60 kHz. At least in the California sea lion, sensitivity decreases as frequency decreases from 2000 to 250 Hz, but strong sounds at 250 Hz can be heard. In-air hearing of eared seals is less sensitive than underwater hearing, but the difference in capabilities between air and water is less pronounced than in phocids. The upper frequency cutoff in air is only slightly less than that in water (32-36 vs. 36-40 kHz). Frequency discrimination and directional localization appear to be less precise than in toothed whales. Critical ratios of the fur seal increase with increasing frequency, and are relatively low (i.e. good) in comparison with other mammals listening at corresponding frequencies.

Manatee hearing has not been studied in detail. However, electrophysiological evidence indicates that the West Indian manatee (the species occurring in the U.S.A.) may have optimum sensitivity near 1-1.5 kHz, and some sensitivity as high as 35 kHz.

8. DOCUMENTED DISTURBANCE REACTIONS[1,2]

8.1 Introduction

Many researchers have described behavioral reactions of various marine mammals to human presence, boats and aircraft. The majority of these data are anecdotal in nature. However, considered collectively, they provide useful information about situations in which some species react strongly, weakly or inconsistently, and not at all. No specific data are available on sound levels received by the animals during most of these incidents. However, some reports mention the distances at which reactions were or were not noticed.

During the past decade, several studies have been conducted specifically to determine the behavioral reactions of certain species of marine mammals to different types of human activities. In most of these studies, sound levels received by the animals were measured or estimated. Some studies involved uncontrolled observations of animals in the presence of human activities such as boats, aircraft, seismic exploration, marine construction, offshore drilling, or simple human presence. Other studies included controlled experiments designed to test the reactions of marine mammals to simulated human activities. A few studies have used both observational and experimental approaches in order to offset their differing limitations and advantages. Experimental methods have the great advantage of allowing controlled comparisons, e.g. of behavior before, during and after a simulated disturbance. Observational methods have the disadvantage of no direct control, but the advantage of greater realism when the human activity cannot be fully simulated during experiments.

Almost all available data on disturbance reactions, whether from uncontrolled observations or experiments, have concerned short-term behavioral reactions. For example, these studies often determined the distance from the disturbance source at which the animal first reacted noticeably, or occasionally the received sound level when the animal first reacted noticeably. The reactions recognized in these studies usually involved cessation of feeding, resting or social interaction, and onset of alertness or avoidance. In pinnipeds, observed avoidance reactions commonly involve movement from terrestrial or on-ice haul-out sites toward or into the water. In whales, avoidance may mean hasty diving, swimming away, or both. Various other changes in behavior have also been recognized as disturbance responses. In most studies, little or no information has been obtained about the duration of the period of altered behavior subsequent to disturbance. Thus, available data almost all pertain to short-term (minutes or at most hours) changes in behavior.

The significance of short-term behavioral responses to the long-term well-being of individuals and populations is rarely known. On the one hand, most brief interruptions of normal behavior may have little effect on the overall energy balance and reproductive performance of animals. On the other hand, physiological reactions such as elevated heart rate

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[1] By W.J. Richardson, LGL Ltd. This chapter was prepared in conjunction with the 2nd edition of a similar review for the American Petroleum Institute (Richardson et al. 1989). This version has been updated through late 1990.

[2] Constructive comments on a draft of this chapter were provided by Drs. W.C. Cummings and A.N. Popper, and by the U.S. Minerals Management Service.

and perhaps other manifestations of "stress" may occur even if no overt behavioral response is evident. This has been demonstrated in radio-telemetry studies of terrestrial mammals exposed to passing aircraft and other potential disturbances (e.g. MacArthur et al. 1979; sect. 10.8.4). Chappell (1980) reviewed the possible physiological effects of noise exposure on pinnipeds based on data from humans and laboratory mammals. These uncertainties about physiological, long-term, and population consequences are common for all types of marine mammals and all types of industrial disturbance.

This section summarizes the available information on reactions of marine mammals to noise from several categories of human activities: aircraft, ship, boat and other vehicular traffic, icebreaking, seismic exploration and underwater explosions, dredging and marine construction, offshore drilling and production facilities, and human presence in general. We emphasize results from the specific studies of these matters conducted in recent years, but we include other relevant observations. For many types of mammals, the only information available about reactions to certain human activities is anecdotal. In some cases when reactions have been demonstrated, it is not certain whether they were attributable to noise or to other stimuli. We include these doubtful cases in the review, but attempt to point out the cases in which there is doubt about whether noise was the specific stimulus. The emphasis is on underwater sounds, but for pinnipeds the majority of the available data concerns reactions of animals hauled out on land or ice to airborne sounds.

This section concludes with a review of presently available data on tolerance and habituation. The implications of the short-term behavioral reactions described in this section to the long-term welfare of marine mammals are discussed more fully in sections 10.5-10.7.

8.2 Reactions to Aircraft and Helicopters

Reactions or lack of reactions of marine mammals to aircraft have been documented in a number of situations. Airborne or waterborne noise from aircraft was probably the stimulus for many of the observed reactions, but it has rarely been possible to be sure that hearing rather than vision was involved. We review all available evidence about reactions to aircraft, but it is possible that some of the responses were not attributable to noise.

Variable responses of marine mammals to aircraft are partly a result of differences in aircraft type, altitude and flight pattern (e.g. straight vs. circling). These factors can affect the spectral and temporal properties of the noise, and the level of the noise received by the animals (see sect. 5.2.1).

8.2.1 Seals and Walrus

There has been little systematic study of the reactions of pinnipeds to aircraft overflights, but many opportunistic observations have been reported. It is difficult to generalize from these observations. Most were anecdotal and levels of the sounds received by the animals were rarely measured.

In general, pinnipeds hauled out for pupping or molting are probably the most susceptible to adverse effects resulting from disturbance by aircraft. Pinnipeds hauled out on land or ice react to airborne sound from aircraft by becoming alert and, in many cases, by rushing into the water. They tend to be more responsive to low-flying than to high-flying aircraft, to aircraft that are nearly overhead vs. those far to the side, and to abruptly changing sounds than to steady sounds. There is some evidence that reactions to helicopters may be more severe than those to fixed-wing aircraft, but the lack of data on sound exposure levels makes these reports difficult to evaluate. In at least some species, responsiveness varies according to stage of the breeding cycle. Partial habituation[3] probably occurs under some conditions. In some situations, stampedes triggered by aircraft overflights may result in increased pup mortality due to crushing or increased rates of pup abandonment. However, the frequency of this direct mortality is difficult to determine, and has rarely been documented.

The following paragraphs review the specific observations upon which the above summary is based. Many of the data come from harbor seals and walruses, but reactions of some other hair and eared seals to aircraft have been mentioned in the literature. In very few of these cases was it determined that the reaction was specifically to aircraft noise as opposed to vision.

Harbor seals often temporarily vacate pupping beaches when aircraft fly over, and do not always haul out at the same site when returning to the beach (Johnson 1977). Newborn pups are unable to follow their mothers into the water and permanent separation may result. Johnson (1977) estimated that low-flying aircraft may have been responsible for the deaths of more than 10% of ~2000 pups born on Tugidak Island, Alaska, in 1976. Aircraft of all types flying below 120 m (400 ft) altitude nearly always caused seals to vacate the beaches, sometimes for 2 h or more, with helicopters being particularly disturbing. Responses of harbor seals to overflights at altitudes between 120 and 305 m (400-1000 ft) varied with weather, frequency of disturbance, altitude and aircraft type. Aircraft were more disturbing on calm days, after recent disturbances, and at lower altitudes. Helicopters and large planes were reportedly more disturbing than small airplanes. Similarly, the many harbor seals that haul out at Cape Peirce, AK, normally leave the beach when float and amphibious aircraft land and taxi to the beach (D. Herter, LGL Alaska, pers. comm.). In Glacier Bay, AK, harbor seals usually reacted strongly to small aircraft flying by at altitudes below about 61 m. Overflights above 76 m elicited only minor reactions (Nat. Park Serv. data reviewed by Hoover 1988).

Bowles and Stewart (1980) observed the reactions of harbor seals hauled out on San Miguel Island, CA, to frequent overflights by light aircraft, military jets, and helicopters plus occasional sonic booms. They stated that "Harbor seals give the impression of constant alertness and 'nervousness'." Harbor seals reacted with alert posture and often with rapid movement, especially when the aircraft was visible. Seals rushed into the water during 7 of 12 sonic booms plus a few of the overflights by light aircraft, jets above 244 m, and helicopters below 305 m. Sometimes the seals did not return to land until the next day, although they more commonly returned the same day. Similarly, Osborn (1985), also working in California, found that aircraft flying below 150 m altitude (500 ft) over harbor seals caused alert reactions and, in 2 of 11 cases, rapid movement into the water.

Some harbor seals may habituate to aircraft when overflights are frequent. M. Bigg (*in* Johnson et al. 1989:53) noted that aircraft landing at and taking off from Vancouver

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[3] Behavioral habituation refers to the progressive waning of responses to stimuli that are learned to lack any significance to the animal (Thorpe 1963).

International Airport pass over a haul-out site; these harbor seals show little or no reaction to the aircraft.

Elephant seals and ***California sea lions*** at San Miguel Isl. seemed less responsive than harbor seals (Bowles and Stewart 1980). Light aircraft generally elicited no reaction unless below 30 m altitude. Jets above 305 m (n=25) produced no reaction; those below 305 m usually caused limited movement (5 of 7 cases) but no major reaction. Helicopters above 305 m caused no observable response (n=4); those below 305 m always caused the pinnipeds to raise their heads, often caused some movement of animals, and occasionally caused major "rushes" of a fraction of the animals into the water. Sonic booms always caused a startle reaction involving some movement into the water; in 4 of 12 cases over half of the animals present rushed to the water. The sonic booms that caused major reactions had received noise levels of 80-83 dB(A).[4] Bowles and Stewart concluded that temporary mother-pup separation resulting from disturbance may cause increased pup mortality, but they reported no direct evidence of this. There was no indication that pinnipeds were killed during disturbance-induced stampedes, at least during the daytime. Bowles and Stewart concluded that present levels of aircraft (and other) disturbance cause behavioral reactions by pinnipeds but are not significantly harmful to the populations at San Miguel Isl., given that the numbers present are stable or increasing.

Steller sea lions on haulouts exhibit variable reactions to aircraft (Calkins 1983). At least some animals usually are frightened into the water; on some occasions approaching aircraft cause all sea lions to stampede into the water. Calkins states that, during the breeding and pupping season, immatures and pregnant females are more likely to enter the water than are territorial males and females with small pups.

Northern fur seals on the Pribilof Islands sometimes stampede from rookeries and haulouts in response to low-level overflights; stampedes are especially likely after July and among non-breeding fur seals (R.L. Gentry, *in* Herter and Koski 1988). Fur seals usually seem startled by sonic booms, and sometimes stampede into the water (A. Antonelis, *in* Johnson et al. 1989). However, stampedes do not always occur after overflights or sonic booms, and mortality apparently has not been noted (Johnson et al. 1989).

Walrus responses to overflights of terrestrial haul-out sites vary with range, aircraft type, flight pattern, age-sex class of the animals, and group size. Brooks (1954 cited by Fay 1981) noted that walruses on shore were disturbed by an aircraft at 300 m. In a more extensive study of Atlantic walruses, Salter (1978, 1979) found that, at horizontal distances beyond 2.5 km, the only response elicited by aircraft was raising of the head by some of the hauled out animals. A Bell 206 helicopter 1.3 km from a haul-out site and flying at altitude <150 m prompted orientation toward the water by 31 of 47 animals. When the helicopter veered suddenly causing an abrupt change in pitch of the noise, 26 of 47 walruses rushed into the water (Salter 1979). Another flight by a Bell 206 helicopter at the same altitude but at range <1 km elicited head raising and orientation toward the water by some animals but no escape reactions--presumably because there were no sudden changes in flight pattern or noise. DeHavilland Otter aircraft (piston engine) caused escape reactions by walruses at horizontal ranges <1 km during

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[4] Based on the standard fast sound pressure measurement protocol referenced to 20 μPa (Awbrey 1980).

overflights at altitudes of 1000 and 1500 m (Salter 1979). (Note: Appendix 2 lists general characteristics of the Bell 206, DHC Otter, and other aircraft types mentioned in the text.)

Disturbances observed by Salter never caused escape reactions in all the walruses at the haul-out site; adult females, calves and immatures were more likely than adult males to enter the water during disturbance. However, severe disturbance may cause stampedes into the water by all the walruses at a haul-out site. Loughrey (1959) described calves being crushed to death by stampeding walruses. Also, Tomilin and Kibal'chich (1975 cited by Fay 1981) reported that an overflight at 150 m by an medium-sized IL-14 aircraft caused a stampede by walruses that resulted in 21 calves being crushed to death and two aborted fetuses. D. Fisher, ***in*** Johnson et al. (1989), described another case of walruses stampeding in response to a low-flying aircraft, with the result that 2 or 3 of 4000-5000 animals were killed.

Brueggeman et al. (1990, p. 3-52) stated that ~12% of 34 walrus groups observed in open waters of the Chukchi Sea and 38% of 229 groups on pack ice reacted to a Twin Otter survey aircraft, usually near 305 m altitude. Groups in the water reacted by creating a noticeable splash when diving; those on the ice "escaped" into the water.

Fay et al. (1986) observed that walruses hauled out on open pack ice in July left the ice when a helicopter approached within 400-600 m flying upwind, or 1000-1800 m flying downwind. At one location, many of the males hauled out on shore moved into the water when aircraft flew over at 60-100 m altitude. At another site, 3 passes by a fixed-wing aircraft at 60 m altitude caused little reaction by a herd of 4500 walruses; about 1000 raised their heads and 100 entered the water. Small herds may be more easily alarmed than large ones (Banfield et al. 1955). Some walruses exposed to repeated aircraft disturbance at haul out sites close to airstrips, e.g. at Cape Lisburne, AK, seem to become more tolerant of aircraft noise, i.e. partially habituated (D.G. Roseneau, ***in*** Malme et al. 1989). Johnson et al. (1989) summarize these and other similar accounts of the variable reactions of walruses to aircraft.

Ringed and ***bearded seals*** hauled out on the ice may dive when approached by a low-flying aircraft or helicopter (e.g. Burns and Harbo 1972; Burns and Frost 1983; Alliston 1981), although they do not always do so (e.g. Burns et al. 1982). Specific details on range and altitude effects for seals exposed on the ice are lacking. Kelly et al. (1986) found via radio telemetry that reactions of ringed seals concealed in their subnivean lairs (below snow on ice) to helicopter noise varied with aircraft altitude and lateral distance:

> "Seals did not leave their haul-out sites in response to helicopter flights at or above an altitude of 457 m. Departures were observed in 8 of 15 (53%) instances when helicopters were at altitudes of 305 m or less. Seals departed in 6 of 9 (67%) instances at that altitude when helicopters were within 2 km (lateral distance) of the haul-out site. At distances greater than 2 km, helicopters at or below 305 m caused 2 of 6 (33%) seals to depart...".

The noise received by a seal in a subnivean lair is probably less than that received from a corresponding overflight when the seal is exposed on the ice. Cummings and Holliday (1983) reported that snow over simulated ringed seal lairs attenuated airborne noise, especially at high frequencies (e.g. 10.5 kHz), but that attenuation was limited by "flanking propagation" through underlying ice.

Based on counts of ringed seal vocalizations in the Canadian high arctic during April, Calvert and Stirling (1985) found that seal abundance in an area subjected to low-flying aircraft and other human disturbance was similar to that at other less disturbed areas.

Burns and Frost (1983) stated that "Bearded seals usually react mildly to an airplane, even at close range. They almost always raise their heads, frequently look up at the plane and usually remain on the ice unless the plane passes directly over them". "On a warm calm spring day when they are basking they often show little concern for a low-flying aircraft." Burns and Frost noted that helicopters are disturbing to bearded seals and suggest that flight altitudes be at least 2000 feet over bearded seal habitat.

Spotted seals haul out on beaches in the summer and on the Bering Sea ice in the spring for pupping. Burns and Harbo (1977 cited in Cowles et al. 1981) reported that spotted seals on the ice react to aircraft at considerable distances by "erratically racing across floes and eventually diving off". Such disturbance might result in mother-pup separation as it apparently does in the closely-related harbor seal (*cf.* Johnson 1977).

Spotted seals that had hauled out on beaches moved into the water when a survey aircraft flew over at altitudes as high as 305-457 m (Frost and Lowry 1990). This displacement occurred despite frequent exposure to aircraft overflights at low altitude. However, the spotted seals apparently had accommodated to these overflights to the extent that they returned to the beaches quickly after the aircraft had departed.

In ***summary***, the available evidence indicates that pinnipeds hauled out on land or ice react to the airborne sound and/or sight of aircraft by becoming alert and, in many cases, by rushing into the water. They tend to react most strongly if the aircraft is flying low, passes nearly overhead, and causes abrupt changes in sounds. Helicopters may be more disturbing than fixed-wing aircraft, but the lack of data on sound exposure levels makes this difficult to evaluate. Responsiveness can vary according to stage of the breeding cycle. Partial habituation probably occurs under some conditions. However, repeated exposure of harbor seals to aircraft may result in increased rather than reduced responsiveness (Johnson 1977). In some situations, stampedes triggered by aircraft overflights may result in increased pup mortality due to crushing or increased rates of pup abandonment. However, direct mortality has rarely been documented.

The above observations almost all relate to pinnipeds hauled out on land or ice. Few specific data are available on reactions of pinnipeds in water to either airborne or waterborne sounds from aircraft. Observations during aerial surveys indicate that seals at the surface in open water often dive when overflown by an aircraft at low altitude (LGL unpubl. data). Walruses in the water occasionally dive hastily when an aircraft passes overhead at 305 m altitude (Brueggeman et al. 1990). More definitive statements cannot be made since behavior before and after disturbances, and reactions to high altitude flights, cannot be observed from the disturbing aircraft.

8.2.2 Toothed Whales

Reactions of toothed whales to aircraft have been reported less often than reactions of pinnipeds. This perhaps indicates that the airborne sounds (and visual stimuli) from an aircraft are less relevant to toothed whales and other marine mammals in the water than to pinnipeds hauled out on land or ice. Cetaceans whose behavior is disrupted by aircraft exhibit a variety of responses including diving, churning the water with flukes or flippers, and swimming away from the aircraft track. The activity of the animals at the time of the overflight sometimes seems to influence whether or not their behavior is disturbed. Insofar as we know, no data have been reported on received sound levels that do and do not elicit disturbance reactions by toothed whales.

White whales did not react to an aircraft (type not specified) flying at 500 m, according to Bel'kovich (1960) and Kleinenberg et al. (1964). When it descended to 150-200 m, they dove for longer periods, had shorter surface intervals, and sometimes swam away. Feeding white whales were reportedly less prone to disturbance, whereas lone animals dove even when the aircraft was at 500 m. Single whales and small groups often dove under large ice floes when the aircraft descended. At least some of these Soviet observations were offshore in relatively deep water.

White whales in rivers and estuaries during summer also react to aircraft. White whales concentrated in a high arctic estuary fled the area when overflown by a Twin Otter (Appendix 2) at an unstated altitude (Finley 1982). White whales in a northern Quebec river were displaced when a Beaver floatplane landed, and left the river when the plane took off and circled the area (Finley et al. 1982). Macfarlane (1981) noted an instance of white whales in the St. Lawrence estuary diving quickly as a startle reaction when jet fighters flew "low" overhead. Sergeant and Hoek (1988) stated that some of those whales dove in response to a Bell 206 helicopter passing overhead at 305 m altitude. Hunters believe that low flying aircraft often prevent white whales from entering Eschscholtz Bay, AK; the timing of aircraft traffic has been adjusted to reduce this interference (Burns and Seaman 1985).

Industry personnel reported that white whales in the Mackenzie estuary area, N.W.T., and Cook Inlet, AK, dive in response to helicopter overflights at low altitudes (Fraker 1978; Fraker and Fraker 1979; Gales 1982). Helicopters seemed to have less effect on feeding white whales than on animals that were swimming, and no white whales were reported reacting to helicopters at altitudes 150-250 m (Fraker and Fraker 1979). However, their sample size was too small to allow firm conclusions. Also, the observations reported in both Fraker and Fraker (1979) and Gales (1982) were uncontrolled observations by inexperienced observers; some disturbance may have occurred during some cases when no reaction was detected.

Aerial surveys of the Mackenzie estuary in a Cessna 185 aircraft at 300 m provoked only occasional mild responses from white whales (Fraker and Richardson 1980). However, when the aircraft circled or repeatedly flew over at the same height, the whales swam away from the area.

Data on reactions of ***other species*** of toothed whales to aircraft are very meager. Gambell (1968) mentions that sperm whales seemed unaware of a Cessna 310 observation aircraft, usually at 152 m altitude. However, Baird's and Cuvier's beaked whales reacted strongly by diving immediately and remaining submerged for long periods when a medium-sized Pembroke aircraft approached or passed over at 305 and 60 m altitude (Dohl et al. 1983). Dolphins did not react to a Bell 204 helicopter at 366-549 m altitude (Au and Perryman 1982; Hewitt 1985, pers. comm.)

8.2.3 Baleen Whales

Reactions of baleen whales to aircraft or aircraft noise have been examined systematically in two studies, on bowhead whales (Richardson et al. 1985b,c) and gray whales (Malme et al. 1983, 1984). Incidental observations of the reactions of these and some other species to aircraft have been obtained in other studies.

Bowhead whales react to a circling Islander aircraft (Appendix 2) frequently when it is at ≤305 m altitude, infrequently when it is at 457 m, and rarely when it is at ≥610 m (Richardson et al. 1985b,c). The most common reactions were a hasty dive, a turn away from the aircraft, or dispersal away from the area being circled. These reactions were most common when the whales were in shallow water, where underwater propagation of the aircraft sound is better than in deep water (Urick 1972; Greene 1985; sect. 3.7). When the Islander aircraft circled the same whales at 305 m altitude as well as 457 or 610 m, intervals between successive respirations averaged less ($P<0.001$) when the aircraft was at the lower altitude. With the possible exception of frequency of "pre-dive flexes", other behavioral variables, including call rate and types, seemed unaffected by the change in aircraft altitude. Relative roles of sound and visual stimuli in eliciting the reactions were unknown. Aircraft sound levels received by the whales during these tests were not measured, but underwater sound levels from the same aircraft were measured on other occasions (Greene 1985; sect. 5.2.1).

The responsiveness of bowheads to aircraft is quite variable. For example, the strong overall tendency for short blow intervals when an aircraft is circling low overhead is not always evident. This trend was significant in 4 of 8 tests by Richardson et al. (1985c), perhaps present but non-significant in 3 of 8 tests, and possibly reversed in one test. Wartzok et al. (1989:198) report a second case of an apparent reversal of this trend. Responsiveness appears to depend on behavioral state and habitat. Resting bowheads seem most responsive to aircraft, although this may be partly an artefact: a change in behavior is most conspicuous when the initial state is resting. Bowheads actively feeding, socializing or mating seem less responsive to aircraft (Ljungblad 1981; Ljungblad et al. 1984a; Richardson et al. 1985b,c). Bowheads in shallow water near a coast appear especially responsive, perhaps because of the more efficient lateral propagation of aircraft noise in the water or because of a "feeling of partial confinement" by the bottom and/or coast.

Most data on reactions of bowheads to aircraft have been collected during the summer and autumn. Ljungblad et al. (1980a) suggested that bowheads responded more strongly to aircraft during the spring than during autumn of 1979. However, it is not clear whether observations by Ljungblad et al. during subsequent years confirmed this seasonal difference; occasional reactions were observed in both seasons. Marquette et al. (1982) suggested that, during spring, bowheads rarely "reacted in a negative manner" to an Aerocommander Shrike aircraft. Bowheads seemed no more responsive to an observation aircraft circling at 457 m altitude in spring 1989-90 than in late summer or autumn (Richardson et al. 1990a, in prep.). The only available data from winter are that bowheads often dove in response to low altitude (150-250 m) overflights by a large P-3 patrol aircraft, although they did not always dive during the first pass (Ljungblad 1986).

Reactions to aircraft by the separate stock of bowheads summering in the eastern Canadian arctic have not been studied in detail, but seem similar to reactions in the western arctic.

Eastern arctic bowheads often, but not always, dive in response to a Twin Otter pass at 150 m altitude (W.R. Koski, LGL Ltd., pers. comm.). On one occasion, bowheads engaged in sexual interactions dove rapidly when overflown by an F-27 turboprop aircraft flying below 135 m altitude, but resumed sexual activities within 5 min after the aircraft departed (Richardson and Finley 1989). Another sexually active group was not noticeably affected by six Twin Otter passes within 2 h.

Most offshore aircraft traffic in support of the oil industry involves turbine helicopters flying along straight lines. On five occasions when a turbine helicopter near 153 m altitude made one straight pass over bowheads, there was no detectable response (Richardson et al. 1985c). Berzin and Doroshenko (1981) state that some bowheads in the Sea of Okhotsk during August paid "no attention" to a large MI-8 helicopter circling at low altitude and speed. Others dove when the helicopter first approached. Dahlheim (1981) stated that, during early spring, bowheads were rarely disturbed by two Sikorsky H-52 turbine helicopters flying at altitudes 152-228 m. Richardson et al. (1990a:211) observed that a mother/calf pair showed no apparent flight response during repeated approaches by a Bell 212.

Bowhead reactions to low-altitude photogrammetry passes are probably relevant to the question of helicopter effects. During photogrammetry studies, a Twin Otter or similar aircraft flies at about 150 m altitude directly over the bowheads (e.g. Davis et al. 1983, 1986a,b; Koski and Johnson 1987; Richardson et al. 1987b). The whales sometimes, but by no means always, dive hastily in apparent response. During the summer feeding period, many distinctively marked bowheads have been re-photographed in the same areas over periods of days or weeks. Thus, occasional low altitude overflights by a turbine-powered aircraft do not displace many (if any) bowheads from feeding areas.

Right whales and some other species of baleen whales often seem to tolerate a light single-engine aircraft circling overhead. Watkins and Schevill (1976, 1979) were able to observe feeding behavior of northern right whales by circling 50-300 m overhead in various light aircraft. Payne et al. (1983) found that southern right whales rarely reacted strongly to a small Cessna 180 aircraft circling at 65-150 m. A few (probably <2%) swam rapidly or dove as the aircraft came overhead. However, most did not show such a clear startle reaction.

Payne et al. (1983) noted that isolated southern right whales were more likely to react than were socializing groups, consistent with results from bowhead whales. Likewise, northern right whales in small groups (≤3 whales) often dove when a twin-engined survey plane flew over whereas larger groups usually did not (Fairfield 1990). However, it was not possible to determine what proportion of the dives by small groups were in response to the aircraft.

Gray whale reactions to aircraft also are variable. On the Alaskan summering grounds, cow-calf pairs seemed particularly sensitive to a small turboprop survey aircraft. The adult usually moved over the calf, or the calf swam under the adult, with the result that the calf was difficult to see from above (Ljungblad et al. 1983:47). However, a group of mating gray whales did not react to the arrival of a survey aircraft flying at 320 m altitude (Ljungblad et al. 1987:71). They dispersed after the aircraft had circled at an unstated altitude for 11 min.

Some data on reactions of migrating and wintering gray whales to helicopters are available. Malme et al. (1983, 1984) tested responses of migrating gray whales to underwater playbacks of recorded underwater sounds from a Bell 212 turbine helicopter. The noise was projected at random intervals of 10 s to 2 min (average of 3 simulated passes per min). There were significant course changes in apparent avoidance of the sounds, and in some cases the whales also slowed down. Received sound levels that caused 10, 50 and 90% of the migrating gray whales to change course to avoid the sound projector were 115, 120 and >127 dB re 1 μPa on a broadband basis. However, migration was only slightly diverted, not blocked. These tests were not designed to determine whether gray whales would respond to noise from a single helicopter overflight, a more realistic case. Also, it was not possible to reproduce the strong low frequency components of the Bell 212 noise. However, these playback results do show that gray whales respond to helicopter noise itself; vision was not involved.

SRA (1988) stated that migrating gray whales never reacted overtly to a UH-1N (Bell 212) helicopter at >425 m altitude, occasionally reacted when it was at 305-365 m, and usually reacted when it was below 250 m. Reactions were said to consist of abrupt turns, dives or both.

Walker (1949, *in* Reeves 1977) described intentional helicopter harassment of gray whales in the lagoons of Baja California. Whales were herded into shallow water by a helicopter for aerial photographs. Once in shallow water, where diving was impossible, some gray whales "churned the water with flukes and fins until their wakes became churning cauldrons of foam". When cow-calf pairs were observed, the mother occasionally "shielded" the calf with her body, as has also been observed on the summering grounds (Ljungblad et al. 1983).

Humpback whale reactions to aircraft have been mentioned by several authors, but we know of no systematic studies. Humpbacks off Hawaii reportedly do not show consistent responses to aircraft (Shallenberger 1978). Some were disturbed by flights at 305 m while others showed no apparent response to flights at 152 m. Herman et al. (1980) reported that humpback responses to a small observation aircraft depended on group size and composition, with whales in large groups showing little or no response. All-adult groups reportedly tended to engage in evasive maneuvers. Kaufman and Wood (1981) stated, without details, that "No effects of low-flying aircraft on whale behavior or usage of the area could be discerned even though numerous aircraft were observed in the area." Similarly, Friedl and Thompson (1981) reported that humpbacks in Hawaiian waters showed no obvious reaction to a P-3 patrol aircraft at 150-350 m altitude.

Concern has been expressed about helicopter disturbance to humpbacks off Hawaii (Tinney 1988; Atkins and Swartz 1989). However, specific data are apparently lacking. Malme et al. (1985) did a single helicopter noise playback test near humpbacks off southeast Alaska; results were inconclusive.

Even less information about reactions of ***other species*** of baleen whales to aircraft is available. Leatherwood et al. (1982) observed that minke whales usually responded "subtly" to an H-52 turbine helicopter at 229 m altitude. Responses included changes in course, rolling onto the side, or slowly diving. A variety of more dramatic reactions were seen occasionally. A few minke and fin whales off western Alaska reacted to the turbine survey aircraft by diving briefly (Ljungblad et al. 1982a:55). Watkins (1981b) was able to observe the behavior of fin whales from a light aircraft circling at 50-300 m, but he implies that engine noise or the aircraft shadow sometimes caused reactions. Bird (1983) and Bauer and Herman (1986) tabulated other subjective accounts of behavioral reactions of whales to aircraft.

In ***summary***, data on reactions of baleen whales to aircraft are meager and largely anecdotal. Only Malme et al. (1984) provided data on reactions of whales to aircraft sound isolated from other stimuli. Theirs was also the only study to determine whale reactions as a function of received sound level. However, sufficient data exist to allow estimates of sound exposure during some other incidents when a known aircraft type passed at known altitude directly over whales. Whales often react to aircraft overflights by hasty dives, turns, or other recognizable behaviors. Responsiveness to aircraft seems to depend on the activities and situations of the whales. Whales actively engaged in feeding or social behavior often seem relatively insensitive to aircraft. Whales in confined waters, or those with calves, sometimes seem comparatively responsive. Most of these generalizations also seem to apply to toothed whales, including the white whale. There is no indication that single or occasional aircraft overflights cause long-term displacement of whales.

8.2.4 Manatees

Rathbun (1988) stated that manatees were more disturbed by survey aircraft noise from a Bell 47G helicopter than from a Cessna 172 fixed-wing aircraft. However, the helicopter was flown at lower altitudes and speeds than the fixed-wing aircraft (20-160 m vs. 160 m; 0-20 vs. 130 km/h), so the results are difficult to interpret.

8.3 Reactions to Ships and Boats

Disturbance of marine mammals by ships and boats is of considerable interest because of the large number of vessels in use, their widespread distribution, their mobility, and their substantial noise levels. Some other offshore industrial activities involve only small numbers of operations, often at fixed locations. Even if these operations are very noisy, they may have less potential to affect marine mammals than do ships and boats.

Numerous authors have commented on reactions or lack of reactions of marine mammals (especially cetaceans) to ships and boats. Most of these reports are anecdotal, and it is often difficult to judge whether the observed behavior was appreciably different than would have occurred in the absence of the vessel. The few studies involving repeated observations or controlled experimentation are especially valuable in evaluating responses to vessels.

It is rarely certain that observed reactions of marine mammals to ships or boats are specific reactions to noise rather than to sight of the vessel or to some other sensory modality. However, the long distances to which ship noise often propagates and the documented reactions to change in engine and propeller speed (see below) make it probable that many reactions to vessels are in fact largely or entirely reactions to vessel noise. Schevill (1968b) mentioned that a partially-silenced motorboat was able to move among cetaceans without disturbing them. Thus, most reactions to vessels probably are to noise rather than to physical presence. We discuss all observed reactions to vessels in this section even though it is usually uncertain that the reactions were specifically attributable to noise.

8.3.1 Seals and Walrus

Few authors have described responses of pinnipeds to boats or ships. Most of the published information is anecdotal.

Walruses observed by Salter (1979) showed no detectable response when outboard-powered inflatable boats approached the terrestrial haul-out site to distances of 1.8-7.7 km (n=6). Similarly, Brooks (*in* Fay 1981) said that walruses appeared not to be disturbed by the sound of outboard engines on small boats at distances >400 m. On the other hand, Fay et al. (1986) stated that high-frequency noise from outboard engines appears to cause more disturbance than low-frequency noise from diesel engines. Walruses hauled out at Cape Lisburne, Alaska, seemed more tolerant of outboard-powered boats passing at a range of 100-200 m in a year when those walruses were not hunted than in other years when they were hunted from boats (D.G. Roseneau, *in* Malme et al. 1989).

Walruses hauled out on ice reacted earlier when a ship approached downwind than upwind (Fay and Kelly 1982; Fay et al. 1986). Reaction distance also depended on ship speed, and seemed to be influenced by the sight and possibly the smell of the ship as well as its sound. Walruses sometimes did not react until the ship was considerably closer than the distance at which the vessel first became audible to man. Reactions of walruses on ice-pans included waking up, head-raises, and entering the water. Groups of females with young seemed more wary than adult male walruses. Walruses in open water seemed much less responsive than those hauled out on ice pans; those in water "usually showed little concern about an approaching vessel, unless the ship was about to run over them" (Fay et al. 1986). Those authors suggested that vessel disturbance can lead to increased calf abandonment. They also observed that calves were often the last walruses to leave ice pans as a ship approached. One walrus calf was killed by a polar bear as walruses left the ice. Fay et al. speculated that ship disturbance might result in increased predation.

Northern fur seals are reportedly quite tame when first encountered by a ship, but they avoid the ship if it engages in seal hunting for a day or more in one area (H. Kajimura, *in* Johnson et al. 1989:48). Kajimura suspected that, once sensitized in this way, fur seals showed avoidance at distances as great as a mile. Steller and California ***sea lions*** both tolerate close and frequent approaches by vessels in shipping lanes, and sometimes congregate around fishing vessels (M. Bigg and J. Burns, *in* Johnson et al. 1989:50)

Harbor seals that whelp and nurse their young on tidal flats in Holland are often disturbed by boats (Reijnders 1981). The seals move off the flats into the water in response to boats. Bonner (1982) states that this can seriously reduce survival of the pups. In California, small boats that approach within about 100 m frequently cause harbor seals to leave haulout sites; less severe disturbance often causes alert reactions without departure from the haulout (Bowles and Stewart 1980; Allen et al. 1984; Osborn 1985). After leaving a haulout in response to a boat, some harbor seals return within 1 h, but others remain absent for 3 h or more. It is not known whether those that remain in the water for longer periods do so because of a continued reaction to the boat or for some other reason. Observed reactions to unpowered canoes and kayaks are at least as great as those to motorboats (Allen et al. 1984; Osborn 1985). In Glacier Bay, Alaska, harbor seals hauled out on ice floes move into the water when vessels approach within 100-300 m depending on vessel type (Calambokidis et al. 1983). Elsewhere in Alaska, harbor seals in the presence of many fishing vessels pay little attention to boats that are at least 200 m away, become alert at 150-200 m, and vacate the haulout site when boats come within about 60 m (J. Burns *in* Johnson et al. 1989:55).

In some places where there are many boats, harbor seals apparently habituate (Johnson et al. 1989). In England, some harbor seals as well as gray seals permit close approach by tour boats that repeatedly visit seal haul out locations (Bonner 1982). Bonner suggested that the seals habituate to sounds from these specific tour vessels.

Harp seal vocalizations were studied by Terhune et al. (1979) before and after a 36.5 m stern trawler approached within 2 km of a whelping area. There was little evidence of a decrease in vocalizations the first night after it arrived, but many fewer vocalizations were recorded thereafter. It was not known whether (1) some seals moved away or (2) all remained but vocalized less often. The results were confounded by temporal variation in vocalizations and varying levels of other disturbance (e.g. seal hunting). At times the vessel sounds were sufficiently intense to mask any harp seal vocalizations. However, Brodie (1981a,b) pointed out that harp and ***hooded seals*** return to traditional breeding and molting areas off Newfoundland each year despite centuries of disturbance by vessels and seal hunting.

In general, scientific evidence about reactions of seals to vessels is too meager to allow firm conclusions. However, the limited available information, together with data on reactions of seals to most other forms of disturbance, suggests that seals will normally show considerable tolerance of boats and ships. It is not known whether these animals are truly unaffected by frequent exposure to vessels, or whether they are subject to stress. This interpretational problem, which applies to many types of human activities and all marine mammals, is discussed in sections 10.6.4 and 10.8.4.

8.3.2 Toothed Whales

Odontocetes, or toothed whales, show considerable tolerance of vessel traffic in many circumstances. However, they sometimes react at considerable distances when confined by ice or shallow water, or when they have learned to associate the vessel with harassment.

There are many documented examples of tolerance of vessels by toothed whales, and of attraction of these animals to vessels. The attraction of some species to boats has been a concern when conducting ship-based surveys, since it biases the census results (e.g. Bouchet et al. 1985). Barham et al. (1980) and Shane (1980) found that bottlenose dolphins are common in ship channels used by vessels ranging in size from large tankers down to pleasure and sport-fishing boats. Watkins et al. (1981) mention that a large tanker passed within 800 m without disrupting a feeding group of porpoises. Dolphins commonly approach boats, sometimes swimming in their bow and stern waves very close to the vessel (Shane et al. 1986).

In some situations, avoidance of boats by toothed whales has been demonstrated. Sorensen et al. (1984) found evidence that densities of "squid-eating cetaceans" may be reduced within several kilometers of vessels off the U.S. east coast. In the central tropical Pacific, dolphins no longer ride the bow waves of tuna seiners. In fact, dolphins actively avoid these boats, presumably because dolphins are caught in nets set for tuna (see below).

At least some toothed whales react strongly to boats when the whales have been subjected to previous harassment (Shane et al. 1986). Irvine et al. (1981) reported that bottlenose dolphins often were observed close to a 7.3 m boat. However, individuals previously captured and released for research purposes fled as a close-knit group when the same capture boat was still 400 m or more away. Similarly, dolphins began to react to an approaching tuna seiner at a range of 5-7 km (Norris et al. 1978), and to a research ship at ranges as great as 12 km (Au and Perryman 1982). Stronger reactions usually become evident at 2-5 km (Au and Perryman 1982; Hewitt 1985). These animals probably had been "harassed" previously by seiners, since tuna fishermen purposefully set nets around dolphins to catch the associated tuna (Norris 1977; Norris et al. 1978; Pryor and Norris 1978). During seining, the fishermen use speedboats to herd the dolphins and tuna. Dolphins tend to avoid the seiner and its speedboats, and usually do not cross their wakes (Norris 1977).

Avoidance of vessel wakes has been attributed to the "sonar reflecting barrier" hypothesis (Norris 1977). Ship wakes contain air bubbles that can persist for many hours. These may reflect the echolocation signals of toothed whales. Fraker (1977b) suggested that the movements of white whales may be constrained by reluctance to cross such a "sonar reflecting barrier" caused by vessels involved in oil industry operations.

Although toothed whales sometimes flee from vessels, the reaction seems to be short term. Based on studies of individually recognizable animals, Irvine et al. (1981) noted that bottlenose dolphins captured using boats, and then released, often remained in the area.

White whale reactions to vessels have been observed in some detail in several situations. Their responsiveness to vessel disturbance varies considerably, probably depending on habitat, the activities of the whales, and the type of boat.

White whale populations that have been hunted from power boats in traditional estuarine concentration areas continue to return to those areas each summer even though hunting often causes short-term displacement (e.g. Fraker 1980; Brodie 1981a,b; Reeves and Mitchell 1981; Seaman and Burns 1981; Caron and Smith 1985). The annual return to traditional concentration points occurs even where the population has been seriously reduced by overharvesting (e.g. Finley 1982; Finley et al. 1982). Sergeant (1981) argued that the West Hudson Bay population of white whales, some of which occur in the port of Churchill in summer, has not declined despite an average of 59 ship arrivals over a 3-mo shipping season and a 20-yr commercial hunt that took about 500 whales per year. Although white whales return annually to the general areas where they are subject to hunting from motorboats, small-scale changes in distribution may occur due to disturbance and hunting (Burns and Seaman 1985).

White whales feeding on salmon in Bristol Bay, Alaska, are not easily disturbed even when purposefully harassed by motorboats (Fish and Vania 1971). White whales move back and forth amidst hundreds of salmon fishing vessels in inner Bristol Bay (L. Lowry, *in* Davis and Thomson 1984). However, Stewart et al. (1982) found that white whales in a river adjacent to Bristol Bay interrupted their feeding and swam downriver in response to noise from motorboats. Avoidance was evident even when the received noise level was low. However, thresholds of responsiveness to motorboats, in terms of noise level and distance, were not determined.

Stewart et al. (1982) found that white whales were more responsive to outboard-powered motorboats than to other vessels. Besides the fact that white whales are often hunted from outboard motorboats, the higher frequency content of the noise from outboard engines is probably a factor, given that toothed whales are much more sensitive to moderate and high frequencies than to low frequencies (sect. 7.2.1). Stewart et al. attempted to test reactions to playbacks of recorded supply ship noise, but the results were inconclusive because of small sample size and confounding by motorboat disturbance. In Cook Inlet, Alaska, white whales occur commonly in areas of considerable ship and small boat traffic (Burns and Seaman 1985). Similarly, white whales in the St. Lawrence estuary of eastern Canada are reasonably tolerant of ferry boats and other slow moving vessels traveling in consistent directions (Macfarlane 1981; Pippard 1985; Sergeant 1986). However, the whales tend to flee from fast and erratically moving small boats.

Reactions of white whales in shallow water to oil industry vessels *per se* have been studied in the Mackenzie Estuary of the eastern Beaufort Sea. White whales sometimes turn and swim rapidly away from approaching tugboats or other vessels when the vessels are as much as 2.4 km away (e.g. Fraker 1977a, 1978). Sometimes a group of white whales disperses or separates into two subgroups when a vessel approaches. On other occasions, however, white whales have been seen within 200 m of moving tugboats and/or barges (Fraker 1977b). In one case when two tugs pushing three barges approached to within 2.4 km of a group of white whales, the group split into two subgroups and the vessels passed between the subgroups. The subgroups remained separate for at least 3 h but <30 h (Fraker 1977a). Short-term avoidance reactions of these types were observed often over a several year period, but white whales continued to use traditionally-occupied shallow areas where vessel traffic was common (Norton Fraker 1983).

Observations of white whales in open water leads through ice suggest that the animals are more responsive to vessels when ice is present (Norton Fraker and Fraker 1982; Burns and Seaman 1985). Although white whales are usually quite insensitive to stationary vessels, a group of whales that came within 1 km of a stationary, inactive drillship while they were swimming along a lead changed course to avoid the ship (Norton Fraker and Fraker 1982). White whales in leads consistently swam away from supply boats in motion 1 to several kilometers away.

Reactions of white whales and narwhals to shipping in areas with much ice has been studied recently in deep channels of the Canadian high arctic (LGL and Greeneridge 1986; Barber and Hochheim [1986]; Cosens and Dueck 1988). In 1982, white whales along an ice edge moved away at high speed when an approaching ship was 35-40 km away (Finley et al. 1983a, *in* LGL and Greeneridge 1986). Ship noise was first detectable by spectral analysis when the vessel was 105 km away, and white whales began to emit "alarm" calls at about that time. Ship noise was clearly audible to humans listening to hydrophone signals before the whales moved away. Narwhal behavior also changed in response to the approaching ship, but "freeze" behavior rather than fleeing was the most evident effect on narwhals. Both species returned to the ice edge and resumed normal activities ~48 h after the ship had passed (Finley et al. 1983a; Miller and Davis 1984).

In view of these surprising 1982 results, extensive follow-up work has been conducted. Similar results were obtained in 1983-84, including alarm calls and fleeing responses by white whales when the approaching ship was still several tens of kilometers away, and "freezing" behavior by narwhals (LGL and Greeneridge 1986). White whales and narwhals were displaced by as much as 49 km and 18 km, respectively. White whales reacted to each of several onsets of ship noise over a 1-wk period, but narwhals seemed less responsive to repeated noise onsets. Parts of this 1982-84 work were replicated in 1986 by Barber and Hochheim [1986] and Cosens and Dueck (1988). They found that the whales began to react when ships were 45-60 km away. Narwhals and possibly white whales "showed large changes in orientation relative to the ship when it was nearer than 50 km".

The evidence of strong and consistent behavioral reactions at such long ranges from industrial operations is unique in the marine mammal literature. LGL and Greeneridge (1986) suggested three possible reasons for the great sensitivity of the whales and the large radii of influence around the ships: the partial confinement of the whales by heavy ice cover, the novelty of ship traffic in the high arctic in spring, and the good sound propagation conditions in deep water. The first two of these three points would also apply to white whales encountering ship traffic in leads off northern Alaska in spring. Thus, reactions of white whales in that situation might be more similar to those seen in the Canadian high arctic in spring than to the lesser reactions seen in bays and estuaries in summer.

Data on reactions of other species of toothed whales to vessels are meager. ***Harbor porpoises*** tend to avoid vessels (e.g. Flaherty 1981; Barlow 1985; Silber et al. 1988; Polacheck and Thorpe 1990). Nonetheless, harbor porpoises are often seen near boats. Barlow (1988), based on a small number of observations, suggested that avoidance reactions were limited to within 1 km of the ship. Polacheck and Thorpe (1990), based on extensive boat-based observations, found that avoidance was much stronger within than beyond 400 m from the vessel. Taylor and Dawson (1984) describe a change in surfacing behavior that occurs as a boat approaches a harbor porpoise. The closely related vaquita--the Gulf of California harbor porpoise--tends to surface for briefer periods when a boat is nearby, often "rolling" and respiring only once or twice per surfacing when near a boat (Silber et al. 1988).

Sperm whales, when chased by catcher boats, often change direction, disperse into smaller subgroups, and travel long distances underwater (Gambell 1968; Lockyer 1977). However, reactions to a passing oil industry vessel presumably would not be as strong. Sperm whales cease emitting their usual pulsed sounds when exposed to noise, including noise pulses (3-13 kHz) from pingers and vessel sonars (Watkins and Schevill 1975; Watkins et al. 1985a). Higher frequency pulses (≥36 kHz) caused no such reaction. Papastavrou et al. (1989) observed no reaction to a 50 kHz depth sounder. They also found that a small motorized vessel, when operated in a non-aggressive manner, could be used near sperm whales without disturbing them appreciably. However, startle reactions have been seen during attempts to approach close to sperm whales (Whitehead et al. 1990).

Killer whale behavior may change when a boat is within 400 m, with a change in swimming speed being the most notable effect (Kruse 1985).

Collisions between boats and toothed whales seem to be infrequent, but have been reported. Bottlenose dolphins in the Gulf of Mexico are occasionally struck and killed by boat propellers (Reynolds 1985). Sperm whales have been struck and killed by ships (Slijper 1962).

In ***summary***, toothed whales sometimes show no avoidance reaction to vessels, or even approach them. However, avoidance can occur, especially in response to vessels of types used to chase or hunt the animals. Although temporary displacement of toothed whales does occur in these instances, we know of no clear evidence that toothed whales have abandoned significant parts of their range as a result of vessel traffic. It is not known whether toothed whales exposed to ongoing vessel disturbance are stressed or otherwise affected in a negative but inconspicuous way (see Chap. 10).

8.3.3 Baleen Whales

There have been specific studies of the reactions of gray, humpback and bowhead whales to vessels, and limited information is available for some other species of baleen whales. Watkins (1986) summarized some of the reactions of whales to boats based on his general experience with several species near Cape Cod. Most low-level vessel sounds seemed to be ignored. However, whales that had been exposed repeatedly to whale-watching vessels sometimes approached those vessels. On the other hand, whales often moved away in response to strong or rapidly-changing vessel noise. Avoidance reactions were especially strong when a boat was directly approaching (Watkins 1986). These phenomena have also been mentioned by Beach and Weinrich (1989) and have been documented in more detailed studies of particular species. One indication that the reactions were to noise rather than to some other stimulus is that whales exhibited little reaction to a silenced boat (Schevill 1968b).

Gray Whale.--This species winters and reproduces along the coast of Baja California, primarily in several lagoons, and migrates north to the Bering and Chukchi seas off Alaska to summer. Reactions to vessels have been studied in winter and to some extent during migration. However, little information on reactions to vessels is available for the summering grounds near Alaska (Bird 1983; Bauer and Herman 1986:23-29).

Vessels and other forms of disturbance in lagoons of Baja California can cause short-term flight reactions, particularly when boats move at high speed or erratically (Reeves 1977; Swartz and Cummings 1978; Swartz and Jones 1978, 1981). However, there is little response to slow-moving or anchored vessels. The proportion of incidents in which the whales flee whale-watching vessels decreases as the season progresses (Swartz and Jones 1978), suggesting that habituation occurs.

During a 5-year study at a wintering lagoon where whale-watching was partially regulated, Jones and Swartz (1984, 1986) found no evidence that whales moved out of the lagoon when whale-watching vessels were present. In fact, some gray whales are attracted to quiet, idling or slow-moving boats, especially during the latter part of the winter (e.g. Norris et al. 1983; Bryant et al. 1984; Dahlheim et al. 1984; Jones and Swartz 1984). The frequency and extent of this "curious whale" behavior has increased in recent years (Swartz and Jones 1981; Jones and Swartz 1984, 1986). Some whales appear to be attracted specifically to noise from idling outboard engines (Swartz and Cummings 1978; Dahlheim et al. 1981, 1984).

No avoidance was evident in response to underwater playbacks of recorded outboard engine noise into a wintering lagoon (Dahlheim 1987). Indeed, some gray whales approached the sound projector during these playbacks. In the presence of actual boats or playbacks of outboard noise, call rate increased, call structure changed, and average received levels of calls increased. The higher received levels were interpreted to mean that source levels of the calls had also increased in the presence of boat noise, although distances to the calling whales were not known (Dahlheim 1987). Dahlheim concluded that gray whales were not seriously disturbed by noise from small boats, but that calling behavior changed so as to reduce masking of the calls by boat noise.

The long-term effects of ship and barge traffic in the lagoons where gray whales winter are questionable, but there is evidence of abandonment of certain areas. Gray whales formerly wintered in San Diego Bay in uncertain numbers, but no longer do so (Rice and Wolman 1971; Reeves 1977). Ship traffic and other direct disturbance may have been a factor, but pollution and changes in water characteristics may also have been involved (Reeves 1977). Ship traffic and other human disturbance associated with a large evaporative salt works in Guerrero Negro Lagoon are believed to have caused abandonment of that lagoon by gray whales; the lagoon subsequently was reoccupied after shipping decreased (Gard 1974; Reeves 1977; Bryant et al. 1984). However, gray whales continued to use a less confined bay nearby, even with heavy ship traffic. It is not known whether gray whales that appear to tolerate such human activities suffer any stress or other negative effects (Chap. 10).

During migration, Wyrick (1954) noted that gray whales changed course at a distance of 200-300 m in order to move around a vessel in their paths. The fastest-moving whale recorded by Sumich (1983) was one that was near a boat; fast-moving whales breathed and used energy more rapidly than slower whales. Hubbs and Hubbs (1967) suggested that migrating gray whales disturbed by vessels tend to exhale underwater and to expose their blowholes only to inhale, thereby making themselves difficult to see. Cummings and Thompson (1971b) noticed the same type of behavior in response to playbacks of killer whale sounds. Similar "snorkeling" behavior in response to boats was described by M. Bursk (*in* Atkins and Swartz 1989:11). Bursk also states that the frequency of course changes by migrating gray whales is positively correlated with the number of whale-watching boats around the whales. Despite these avoidance reactions, ships commonly come very close to migrating gray whales. Over a dozen collisions have been reported, and in at least six cases the gray whale died (Shallenberger 1978; Patten et al. 1980; Schulberg et al. 1989).

Migrating gray whales commonly remain very close to shore. Observations of considerable numbers far offshore in the southern California Bight (Rice 1965; Dohl and Guess 1979; Graham 1989; Schulberg et al. 1989) might mean that whales migrating nearshore have been disturbed by ships and other human activity and displaced offshore (Rice 1965; Wolfson 1977). However, it is also possible that the offshore route was always used but was overlooked earlier, or that a shift indeed occurred but for reasons unrelated to disturbance (Rice 1965; Dohl and Guess 1979; Graham 1989). Evans (1982) pointed out that the population of gray whales was increasing when the above observations were made, and that the evidence for an offshore shift in the migration route was very weak; increased numbers offshore may have been a function of the increased population size.

Cowles et al. (1981) point out that the eastern Pacific gray whale continues to migrate along the entire west coast of the United States and Canada each year, despite the presence of enormous numbers of ships, boats and other forms of potential disturbance. Roseneau (*in* Malme et al. 1989) described the heavy vessel traffic sometimes encountered by gray whales as they migrate through Unimak Pass, a "chokepoint" for both ships and gray whales moving between the Pacific Ocean and Bering Sea.

Little information is available about reactions to vessels by gray whales summering in Alaskan and Soviet waters. In the latter area they are still hunted from a catcher boat. Zimushko and Ivashin (1980) reported that, during summer whaling operations, frightened gray whales appear at the surface without seeming to blow; this is reminiscent of the aforementioned observations of "snorkeling" by gray whales disturbed during migration. Bogoslovskaya et al. (1981) state that "If a vessel is at a distance of 350-550 m from animals they move off, but stay in the same area; when a vessel is at a long distance from the animals they pay no attention to it at all; but when being pursued animals cease feeding and try to leave the area." A case of a "curious" gray whale has been reported from the Bering Sea (M. Dahlheim, *in* Jones and Swartz 1984:351).

Humpback Whale.--Concern has been expressed about vessel disturbance of humpback whales that winter off Hawaii and summer off southeastern Alaska; some animals move between these two areas, although not all of the ones summering off Alaska winter off Hawaii. Norris and Reeves (1978) review the situation in Hawaii, but provide few specifics. There is evidence of decreased abundance of humpbacks along the coast of Oahu since the 1940's and 50's, coincident with drastic increases in human activity including shipping. However, no direct causal link has been established. Shallenberger (1978) suggests that the main concern is the long-term cumulative effect of numerous minor disturbances by the many vessels, tourists and aircraft present in the area. Payne (1978a) states that humpbacks sometimes approach and circle boats. On rare occasions they "charge" toward the boat and scream underwater; this appears to be a threat display (Payne 1978a). Based on aerial surveys, Herman (1979) suggested, without details, that humpback density "tends to be inversely related to the density of the concentration of the human population on shore or human-related offshore marine activities." Kaufman and Wood (1981) state, also without details, that "usage of the observation area [varied] inversely with the amount of daily boat traffic", and that behavior sometimes was affected when boats came within 273 m.

A more systematic study of the short-term reactions of Hawaiian humpbacks to vessels, most of which were small boats, was completed recently (Bauer 1986; Bauer and Herman 1986). Whale activities during 148 observation sessions averaging 57 min long were examined relative to vessel traffic during those sessions. Various measures of respiration, diving, swimming speed, social exchange and aerial behaviors (breaching, head lunging) were correlated with vessel numbers, proximity, speed, and direction changes. The results often differed among categories of whales, e.g. singers, other singletons, mothers, calves. Overall, however, the results suggested that humpbacks attempt to avoid vessels and, in some cases, may direct threat behaviors toward them. Behaviors that were believed to be indicative of avoidance included increased frequencies of surfacings without blows and of dives initiated without raised flukes. The various effects often appeared to occur when vessels were ½-1 km away. Given the large number of small boats present in the study area, the authors usually did not attempt to evaluate the sequence of behaviors as a given boat approached, passed, and moved away.

Bauer and Herman (1986) discussed whether the short-term reactions to boats observed in the Hawaiian breeding grounds might lead to long-term negative consequences, e.g. on fertility. They concluded that the reactions to vessels probably are stressful to the humpbacks, but that it is impossible to judge the significance of this assumed stress. Studies of humpbacks off Hawaii have found evidence that mother-calf pairs became proportionately less frequent close to shore in an area where various types of recreational boating were increasing (Glockner-Ferrari and Ferrari 1985; Salden 1988). Whether there was a causal connection is unproven; year-to-year differences in survey procedures complicate interpretation of the data. Tinney (1988) provided a recent detailed review of possible effects of disturbance on humpbacks wintering in Hawaiian waters.

Maybaum (1990) tested the reactions of humpback whales to playbacks of 3.3-kHz sonar pulses. Humpbacks responded by moving away.

On the summering grounds off southeast Alaska, work during the 1970s suggested that humpback whales sometimes moved away or exhibited "threat" behaviors as fishing boats, cruise ships and other vessels approached within a few kilometers (Jurasz and Jurasz 1979a). The whales seemed especially responsive to rapidly moving vessels, and to abrupt changes in vessel speed. Later work showed that the sound from the noisier ships dominated the ambient sound "out to a range of up to six miles in some measurements" (Malme et al. 1981; Miles and Malme 1983). In 1978, humpbacks returned to Glacier Bay in usual numbers, but left unusually early. Whether this was attributable to increased vessel activity (Jurasz and Jurasz 1979a), to reduced food availability (Bryant et al. 1981), or some other factor was not definitely known and was the subject of considerable controversy and regulatory concern (Marine Mammal Commission 1979/80).

As a result, a systematic study of the humpback disturbance question in southeast Alaska began in 1981. The work included behavioral observations (Baker et al. 1982, 1983), measurements of underwater sound (Malme et al. 1982; Miles and Malme 1983), and examination of the food supply (Krieger and Wing 1986). The behavioral results were not always consistent or easy to interpret, but showed that humpbacks often moved away from vessels that were within several kilometers (Baker et al. 1983). Various measurements of surfacing, respiration and diving behavior were correlated with vessel activity and proximity, but the trends were not always in the same direction. Baker et al. (1983) hypothesized that humpbacks have two avoidance strategies:

1. vertical avoidance when vessels are within 2 km, i.e. increased dive durations, decreased blow intervals, and decreased swimming speeds;
2. horizontal avoidance when vessels are 2-4 km away, i.e. decreased dive durations, longer blow intervals, and greater speeds.

Baker et al. (1983) also obtained evidence that approaching vessels triggered some bouts of aerial behavior (breaching, flipper and tail slapping), as earlier suggested by Jurasz and Jurasz (1979a). Although the presence of vessels resulted in short-term changes in behavior, including avoidance, some individually identified humpbacks remained for several weeks in areas where they were frequently exposed to vessel noise.

Reactions of humpbacks to vessels vary considerably. Humpbacks sometimes show little or no obvious reaction when vessels are much closer than the several kilometer "zone of influence" alluded to above. For example, Watkins et al. (1981) reported that passage of a large oil tanker within 800 m did not disrupt a group of feeding humpbacks. Observations from vessels studying prey availability indicated that humpbacks were less likely to react overtly when actively feeding than when resting or engaged in other activities (Krieger and Wing 1984, 1986). Also, variations in sound propagation affect the radius of influence of vessel noise on humpbacks in southeast Alaska (Watkins and Goebel 1984).

Independent of but simultaneous with the systematic disturbance studies of Baker et al. (1982, 1983), Dean et al. (1985) re-analyzed data collected opportunistically during the 1970's by Jurasz and Jurasz (1979a). Although the methods of data collection resulted in unavoidable limitations during analysis, Dean et al. found evidence that avoidance and strong displays (e.g. aerial activity) occurred commonly when vessels were underway within several kilometers. The radius of influence appeared to be as much as 8 km in the case of large cruise ships. Cycles of surfacing, respiration and diving also appeared to be modified when vessels were underway nearby. Dean et al. (1985:vi) concluded that "...in the years with more vessels the whales spent less time in food-related activities and more time in avoidance. The changes in blow interval patterns [including dive durations] and activity shifts...cut across activity types in a fashion that, to us, makes it hard to accept the proposition that the principal cause was change in food supply."

Food availability studies in southeast Alaska have shown that there are dramatic local differences in prey availability, that prey availability in Glacier Bay differs among years, and that humpbacks concentrate at locations where prey is concentrated (Bryant et al. 1981; Krieger and Wing 1986; Dolphin 1987). At least some of the year-to-year changes in humpback distribution are consistent with changes in prey availability. There is no doubt that feeding humpbacks can be temporarily disturbed and displaced by approaching vessels, sometimes by vessels at considerable distances. However, the relative roles of disturbance versus changing prey availability in affecting longer-term changes in humpback distribution in southeast Alaska remain unresolved (Dean et al. 1985; Krieger and Wing 1986).

Beach and Weinrich (1989) noted that humpback whales concentrate near Cape Cod despite exposure to many ships and fishing vessels as well as whale-watching boats. Watkins (1986) suggests that humpback whales in the Cape Cod area have become noticeably less responsive to vessels in recent years, since whale-watching cruises became common (Watkins 1986). Prior to 1976, humpbacks generally moved away from passing ships, seldom remained near (or approached) quiet vessels, and usually became silent when near vessels. More recently, humpbacks have often interrupted their normal activities and approached slowly-moving whale-watching vessels (Watkins 1986). This change suggests that habituation has occurred, perhaps in response to the increase in whale-watching. Belt et al. (1989) found that it is the humpback calves and 1-3 year olds that often approach vessels; humpbacks ≥6 yr old rarely show such approaches.

In the Cape Cod area, humpbacks that are approached slowly and steadily, following established guidelines for whale-watching vessels, showed no "adverse reactions". However, those approached within <30 m, or approached with aggressive boat maneuvers, showed various changes in behavior relative to pre-approach control data (Schilling et al. 1989).

Bowhead Whale.--Reactions of bowhead whales to vessel traffic associated with offshore oil exploration have been studied in the Canadian Beaufort Sea in summer and the Alaskan Beaufort in early autumn.

In the Canadian Beaufort Sea, oil industry personnel have reported bowheads within a few hundred meters of various vessels; sometimes the whales dove, possibly in response to the vessel (Fraker 1978; Fraker and Fraker 1979, 1981). More detailed information about reactions to ships and boats operating in open water was obtained by Richardson et al. (1985b,c), who observed seven such incidents from an aircraft circling high above. When a vessel headed directly toward bowheads, obvious and statistically significant avoidance usually was evident when the vessel came within 1-4 km. However, a few whales may have begun reacting when the vessel was as much as 5-7 km away and, in contrast, a few others did not appear to react until the vessel was <1 km away. The initial reaction was usually to try to outswim the vessel. When an overtaking vessel approached within a few hundred meters, the whales often changed course and moved perpendicularly away from the boat's track. Other bowheads remained on course but dove, apparently allowing the vessel to pass more or less overhead. The whales ceased fleeing after the vessels were a few kilometers past.

The levels of underwater noise that apparently elicited these flight reactions were not very high. In one disturbance test, received noise levels 4 and 1½ km from the approaching vessel were only about 84 and 91 dB re 1 μPa in the 1/3-octave band of strongest noise. These values were only about 6 and 13 dB above the background noise in that band (Miles et al. 1987:225-231).

One radio-tagged bowhead was repeatedly approached by a small ship on several days (Wartzok et al. 1989:209). Approximate dive times were reduced on each of three days when the ship was within 500 m for 1½-2½ h. However, dive patterns were apparently normal on the three days following days of ship disturbance, and the whale remained in the general area where the ship was operating.

Similar observations were obtained in the eastern Alaskan Beaufort Sea during early autumn. In one case, bowheads 1-2 km to the side of the track of an approaching oil industry supply vessel swam rapidly away to points about 4-6 km from the vessel's track (Koski and Johnson 1987). On another occasion, a mother and calf located between two approaching ships exhibited several of the above-mentioned types of reactions even though neither ship approached closer than about 15 km--the largest radius of apparent vessel response noted for bowheads. Some individually recognizable bowheads returned to feeding locations within 1 day after being displaced by boats (Koski and Johnson 1987; Thomson and Richardson 1987). Whether they would continue to return after repeated boat disturbance was not determined.

During summer and autumn, bowheads in the Beaufort Sea typically swim significantly faster when fleeing from boats than at other times, and exhibit significantly shorter surface times, fewer respirations per surfacing, and reduced dive durations (Richardson et al. 1985b,c: Koski and Johnson 1987). The flight reaction is most conspicuous when a vessel heads directly towards bowheads at high speed.

Bowheads are more tolerant of vessels moving slowly or in directions other than toward the whales (Richardson and Finley 1989; Wartzok et al. 1989). Even so, we once noted fewer respirations per surfacing and significantly reduced surface times when a crew boat's diesel engines began idling 3-4 km away after a quiet period (Richardson et al. 1985b,c). However, Wartzok et al. (1989:207) found that bowheads >500 m to the side of or behind a small ship seemed unaffected, and that bowheads often approached within 100-500 m when the ship was not maneuvering toward the whales. They found that some of these bowheads tolerated received broadband noise levels as high as 110-115 dB re 1 µPa, in contrast to the strong avoidance noted in response to lower but increasing noise levels when a boat was approaching (*cf.* Miles et al. 1987). As in the case of aircraft disturbance, bowheads that are actively engaged in social interactions or mating may be less responsive to boats (Wartzok et al. 1989).

Only anecdotal data are available about responsiveness of bowheads to vessels during other seasons. Kibal'chich et al. (1986) observed bowheads from a vessel in the northern Bering Sea during late autumn; whales moved away if the vessel approached within 400-600 m. Because the observer was on the disturbing vessel, any whales reacting at longer ranges probably would not have been seen. During late summer and autumn, bowheads in the Beaufort Sea are more difficult to approach closely with outboards than with unmotorized boats (Hobbs and Goebel 1982; Goodyear et al. 1987). This may be related, in part, to the fact that outboard motorboats are used during the autumn hunt for bowheads off northern Alaska.

Bowheads in the eastern Canadian arctic also seem very responsive to motorboats (Degerbøl and Freuchen 1935; Finley et al. 1986; Richardson and Finley 1989). Finley found that a bowhead fleeing from an approaching outboard motorboat moved very rapidly (for a bowhead): 7.7 km/h during a dive initiated 3.7 km from the boat, and 10.3 km/h during the next dive about 2 km from the boat. During the latter dive the whale traveled 1.8 km underwater.

In general, bowheads react strongly and rather consistently to approaching vessels of a wide variety of types and sizes. Bowheads interrupt their normal behavior and swim rapidly away. Surfacing, respiration and diving cycles are affected. The flight response often subsides by the time the vessel has moved a few kilometers away. After single disturbance incidents, at least some bowheads return to their original locations. Vessels moving slowly and in directions not toward the whales usually do not elicit such strong reactions.

Insofar as we know, there have been no detailed studies of the reactions of other species of baleen whales to vessels, but a few brief reports are available.

Right Whale--Northern right whales summering in the Bay of Fundy "soon seem to become wary of close approaches by boats...[but] do not show completely consistent reactions. When engaged in mating they frequently appear oblivious to close passage of small vessels, especially if no engine is used" (Gaskin 1987; see also Goodyear 1989). Lack of responsiveness to boats has also been noted when right whales in the Cape Cod area are mating or surface feeding (Mayo and Marx 1990; RWRT 1990:10).

Watkins (1986) found that northern right whales were approachable in a slowly-moving boat both before and after the advent of whale-watching cruises. Right whales "generally moved slowly but consistently away from passing ships, and they dived quickly when disturbed...they were consistently silent when disturbed" (Watkins 1986). Right whales seen from whale-watching vessels tend to be oriented away from the vessels when first seen, but not when last seen (S. Kraus, *in* Atkins and Swartz 1989:17). Many right whales are struck and some are killed by collisions with vessels (Brownell et al. 1986; Reeves and Mitchell 1986; Kraus 1990; RWRT 1990:8).

Southern right whales on their nearshore wintering grounds off Argentina showed variable responses to small outboard-powered boats (Payne et al. 1983). Some whales allowed the boat to approach to "touching distance" and some whales approached stationary boats. However, other whales avoided boats. Close approaches were possible only when the boat moved slowly. Similar observations have been reported for right whales wintering off South Africa (Donnelly 1969; Saayman and Tayler 1973).

Rorquals.--Many workers have commented briefly on the reactions of rorquals (the balaenopterid species) to ships, but there have been no detailed behavioral studies of these reactions. Blue whales that are feeding may be relatively insensitive to passing ships (Sears et al. *in* Mansfield 1983:42). Similarly, Bryde's whales are reportedly easier to approach when they are feeding (Gallardo et al. 1983). Cummings et al. (1986) described a case of ship-seeking by a Bryde's whale. Gunther (1949) stated that fin whales "usually moved off gently" as a ship approached. However, when actively feeding they were notably less responsive to the ship.

Reactions of fin, blue and minke whales summering in the St. Lawrence estuary to vessel traffic and whale-watching have been described in three studies, in 1973-75, 1979, and 1980. In 1973-75, 232 vessel-whale encounters were observed unsystematically (Mitchell and Ghanimé 1982). In about 15% of the cases the whale(s) appeared to leave the vicinity of the vessels immediately. In about 85% of the cases the whales remained in the area, but most of these changed direction abruptly or dove to avoid close approach by the vessel. When whales remained, surfacing and respiration patterns did not appear to change in any consistent way.

Based on a second study in the same area in 1979, Edds and Macfarlane (1987) found that fin whales avoided most vessels by slight changes in heading, or by increasing the duration and speed of underwater travel. Those authors also described changes in the surfacing, respiration and dive patterns of a fin whale avoiding a ferry. The most marked reactions occurred when boats made sudden changes in speed or direction. Fin whales reacted at distances of a kilometer or more. Edds and Macfarlane also noted that low-frequency vessel noise masked fin whale social sounds, and higher frequency outboard motor noise masked minke whale sounds. They suggested that, near a heavily-used shipping lane, acoustic interference may be a more serious problem than physical harassment, since vessel noise is nearly continuous and more difficult to avoid. Fin whales did continue to call in the presence of vessel noise (Edds 1988).

Similarly, Macfarlane (1981) observed the behavior of fin and blue whales in the presence of whale-watching and other vessels during a third study in the St. Lawrence estuary, during 1980. The manner of approach rather than boat size or distance seemed critical. A slow approach, even in a large boat, usually caused little reaction. However, fast erratic approaches to blue whales reportedly caused flight reactions, separation of a pair, shorter series of respirations, and temporary movement out of the area.

Ray et al. (1978) recorded the breathing behavior of fin whales before, during and after a chase and tagging operation. During and after the chase, the whales showed reductions in surface times, number of breaths per surfacing, and dive durations. Off New England, fin whales avoiding boats also showed reduced durations of surfacings and fewer blows per surfacing. They spent a higher percentage of the time below the surface (Young 1989).

Watkins (1981a) and Watkins et al. (1981) mentioned that fin, humpback and Bryde's whales ignored observation boats if they remained >100 m away, and showed little response to slowly approaching boats if they maintained a steady speed, but avoided boats whose speed or course changed rapidly. The propellers of vessels engaged in the latter maneuvers produced strong cavitation sounds (Watkins 1981a). After a chase, whether the whale was tagged or not, behavior was usually abnormal for 2-30 min, and it was difficult to approach the whale. Off Cape Cod, fin whales observed up to about 1976 usually exhibited definite avoidance reactions in response to vessels; more recently, since whale-watching cruises became common, fin whales off Cape Cod seem more tolerant of boats (Watkins 1986).

Macfarlane (1981) reports that minke whales in the St. Lawrence estuary are difficult to approach closely. However, Winn and Perkins (1976) and Leatherwood et al. (1982) summarize numerous reports that minke whales sometimes tend to approach and/or swim under vessels. Watkins (1986) suggests that the frequency of ship-seeking by minke whales has diminished in recent years off Cape Cod. The question of ship-seeking vs. ship-avoidance by minke whales has been discussed by several authors in relation to its effects on sightability during ship-based surveys (e.g. Horwood 1981; Butterworth and Best 1982; Butterworth et al. 1982; Leatherwood et al. 1982; Joyce et al. 1989; Borchers and Haw 1990). Although results vary, the consensus is that there is no evidence of ship-seeking and some evidence of avoidance when vessels are underway at cruising speeds; ship-seeking by minke whales sometimes occurs when vessels are stationary or traveling slowly (IWC 1982:734; Tillman and Donovan 1986).

Sei whales, according to Gunther (1949), tended to be more difficult to approach with a ship than were fin whales. "They took more erratic courses...; when they reappeared after sounding they were usually far away and moving in any direction but the direction in which the ship was heading."

Summary--When baleen whales receive low-level sounds from distant vessels, the sounds often seem to be ignored. In some situations, whales may approach the sources of these sounds. When vessels approach whales slowly and non-aggressively, as during whale-watching cruises, whales often exhibit slow and inconspicuous avoidance maneuvers. However, in response to strong or rapidly-changing vessel noise, whales often interrupt their normal behavior and swim rapidly away. Avoidance is especially strong when a boat heads directly toward the whale. Some whales travel as much as several kilometers from their original location in response to a straight-line pass by a vessel through that site.

8.3.4 Manatees and Sea Otters

In Florida, more manatees are killed by collisions with boats than by any other known cause (O'Shea et al. 1985; Ackerman et al. 1989). Although propeller lacerations are common, nearly half of all boat-killed manatees die from impact trauma without propeller cuts (Beck et al. 1982). Manatees apparently can hear the sound frequencies emitted by outboard engines (sect. 7.2.3 vs. 5.2.2). Manatees attempt to avoid oncoming boats at distances as great as 100 m by diving or swimming away if they can do so (Hartman 1979). When overtaken, they are slow to change course, but may finally veer away sharply or somersault to reverse direction. Winter aggregations in favored warm-water habitats can be dispersed by human activity, and prolonged displacement into colder water may have serious effects, possibly including some mortality (Hartman 1979; Kochman et al. 1985).

Sea otters commonly allow close approaches by boats, but may sometimes tend to avoid heavily disturbed areas. For example, Roseneau (*in* Malme et al. 1989) described situations where sea otters occur in areas heavily utilized by boats. However, Garshelis and Garshelis (1984) report that sea otters tend to avoid southern Alaskan waters with frequent boat traffic, but reoccupy those areas in seasons when boats are less frequent. Riedman (1983) noted that some rafting sea otters exhibited mild interest in a boat passing a few hundred meters away, but were not alarmed. Insofar as we know, no specific studies of the behavioral reactions of sea otters to boats have been reported.

8.4 Reactions to Icebreaking

There is little information about the acoustic or other effects of icebreaking ships on most species of marine mammals. Concern about these potential effects first arose because of proposals by the Canadian oil industry to ship hydrocarbons from the Canadian arctic to southern markets using very large icebreaking ships. Those plans have not been implemented, but smaller industry-owned icebreakers now are used in the Beaufort and Chukchi Seas to extend the length of the offshore drilling season. The icebreaking cargo ship MV *Arctic*, often supported by a Canadian Coast Guard icebreaker, has also been used extensively in the Canadian arctic in recent years. Thus, the potential effects of icebreaking on mammals that inhabit ice-covered waters remain an important question.

Besides causing underwater noise from the ship and (to a lesser degree) from ice deformation, icebreakers might have several non-acoustic effects: crushing, entrapment of animals that follow the icebreaker track, and disruption of habitat in the cases of species that depend on particular types of ice. Available data on these non-acoustic effects of icebreaking are reviewed by Richardson et al. (1989).

Two types of ice-related habitat are used by northern marine mammals in winter and spring: fast ice and pack ice. The species of mammals present as well as the activities and noise levels of icebreakers are likely to differ between these two ice types.

8.4.1 Pack Ice

In pack ice areas, the density of the ice pans determines which species are likely to be present. Some species prefer close pack ice whereas others are found in the looser ice at the edges of pack ice fields. In loose pack ice, ship speed and noise may be similar to those in open water. In heavier pack ice where icebreaking is necessary much of the time, ship speed will be reduced, power levels will be higher, and propeller cavitation greater.

Except for recent work on walruses, no systematic studies of the effects of ship noise on mammals in pack ice have been conducted. There are numerous anecdotes, most unpublished, about observations or lack of observations of marine mammals from icebreakers operating in pack ice. In some cases mammals apparently reacted to the ship; in others no reactions were noted. Some seals 1-2 km from an icebreaker remain on the ice; seals closer to the icebreaker often dive into the water (Kanik et al. 1980). No general conclusions can be drawn from these anecdotes because of severe biases that occur when observations are made by personnel (often not biologists) aboard the potential source of disturbance. Animals that react at a distance may avoid the ship without being observed. Animals that are observed may be undisturbed, or may be disturbed but have no avenue of escape in the ice, or may have their communication or other signals masked. Hence, observations from ships probably underestimate effects on marine mammals.

Observations by Fay et al. (1986) of walrus responses to icebreaking are of interest because the observers were experienced and because the reactions to icebreaking vs. open-water shipping were compared. Reactions to icebreaking tended to occur at longer distances than those to open-water shipping. Walruses on the ice became alert when the ship was at least 2 km away. Females and young entered the water and swam away when the ship was ½-1 km away; males entered the water when the ship was 0.1-0.3 km away. However, Fay et al. (1986) also note that walruses, ringed seals and bearded seals often scramble *onto* ice when a ship breaking ice heads toward them. Fay et al. suggest that this behavior may have survival value in pack ice where ice deformation is a natural hazard.

The source level of noise from an icebreaker passing through close pack ice is expected to be stronger than that from the same ship in open water because of the increased power required and the likely increase in propeller cavitation (see sect. 5.2.3). Thus, reactions to noise are expected to be greater when a ship is icebreaking than when the same ship is underway in open water. The observations of Fay et al. (1986) are consistent with this.

Brueggeman et al. (1990) conducted aerial surveys of the Chukchi Sea to study the distribution of walruses around a drillship supported by an icebreaker. They also observed the reactions of walruses visible from the icebreaker *Robert Lemeur* itself. Of 60 walrus groups seen from the ship during icebreaking, 58% reacted by diving from ice floes into the water, and an additional 7% became alert while on the ice. The probability of reaction was greater for walruses <460 m from the icebreaker than for those farther away (81% vs. 45%). Aerial survey data provided circumstantial evidence that walruses hauling out on ice floes may have tended to avoid the area within ~20-25 km of the drillsite. However, the results were difficult to interpret because of day-to-day variation in ice and walrus locations, and the small number of days when the ice edge and walruses were near the drillsite. Also, relative to the drillship, the icebreaker apparently worked as much as 10 km closer to the walruses part of the time (Brueggeman et al. 1990, p. 3-61). Hence, walruses may have tended to avoid the icebreaker by 10-15 km rather than the drillsite by 20-25 km. Some of the underwater sounds from the icebreaker were potentially detectable at mid-water depth well beyond 25 km away (C. Malme *in* Brueggeman et al. 1990). However, the detection range for walruses near the water's surface or hauled out on the ice was not determined. Studies of walruses near icebreaker-supported drilling operations in the Chukchi Sea are continuing.

8.4.2 Landfast Ice

In areas of stable fast ice, operating icebreaking vessels will ensonify the water and cause local changes to the habitat. Ambient sound levels below extensive fast ice are sometimes very low (sect. 4.2), so icebreaking vessels could increase the noise level dramatically. The ringed seal is the only species that regularly occupies arctic fast ice. It maintains breathing holes in the ice throughout the winter. In late March and early April, pregnant ringed seals establish lairs under snow drifts on top of the ice. The single pup is born in the birth lair and remains there during the nursing period, which lasts several weeks. Pups and perhaps adults are vulnerable to physical disturbance and crushing by icebreakers during this period, and adults are vulnerable to disturbance and noise effects throughout the winter.

It is difficult to study ringed seals in winter when they live under the ice or under snow. Two studies have indirectly examined the effects of winter icebreaking on ringed seals, but did not distinguish between the potential effects of noise and of physical disturbance. Alliston (1980) assessed the effects of icebreaking by the MV *Canmar Kigoriak* in January and March in landfast ice in the Beaufort Sea. He compared the numbers and distribution of breathing holes in June in areas that had been disturbed by the icebreaker and in an undisturbed control area. There were no such differences, and he concluded that the limited icebreaking in January and March had not affected ringed seals detectably. From a similar study of ringed seals in Labrador, Alliston (1981) concluded that a single passage by an icebreaking ship in March had not adversely affected the numbers of ringed seals present in late spring. In both of these studies there was some evidence that ringed seals preferentially established breathing holes in the ship tracks.

As noted earlier (sect. 8.3.2), there are indications that white whales may be more responsive to vessels or aircraft when ice is present (Norton Fraker and Fraker 1982; Burns and Seaman 1985). Whales do not occur in areas of fast ice, but icebreaking in fast ice during spring disturbs white whales and narwhals along or beyond ice edges many kilometers away (LGL and Greeneridge 1986; Cosens and Dueck 1988). This has been observed during four different years by two different research teams (see sect. 8.3.2, p. 223).

The few available data on reactions of marine mammals to icebreaking have involved animals that encounter icebreakers very infrequently. High levels of icebreaker traffic, including traffic throughout the winter, do not occur yet in arctic regions of North America. Studies of the effects (acoustic and otherwise) of intensive icebreaker traffic have not been conducted.

8.5 Reactions to Other Vehicles

Passing ***snowmobiles*** elicited variable reactions from ringed seals hauled out in subnivean ("under snow") lairs on the ice (Burns et al. 1982; Kelly et al. 1986, 1988). One seal remained in its lair on two occasions when snowmobiles passed about ½ km away. However, other ringed seals left their lairs in response to snowmobiles as much as 2.8 km away. Most if not all of these seals later returned to their lairs. Reactions of ringed seals to Vibroseis and associated vehicle sounds were examined in the same study; those results are discussed under "Seismic Exploration" (sect. 8.6).

In another study of ringed seals, the potential effects of ***on-ice vehicle traffic*** and related winter construction activities were investigated (Green and Johnson 1983). They found no clear evidence that intensive on-ice work in winter displaced ringed seals. Numbers of seals within several kilometers of the ice road and construction site were similar to those elsewhere in the area. They used an intensive fine-scale aerial survey technique with replication. Even so, it is doubtful whether they could have detected any effects that might have occurred within 2-3 km of the ice-road or construction site.

Except for these observations, reactions of marine mammals to airborne and waterborne noise generated by snowmobiles and other on-ice vehicles has not been documented. In the ringed seal study of Kelly et al. (1986, 1988), the seals were under the snow and presumably responded to airborne sound alone. However, in other situations, pinnipeds on the ice may react to the visual appearance of the sound source as well as its noise. Reactions of marine mammals in the water to noise from vehicles on ice have not been studied. However, sound is transmitted through sea ice into the water, especially when new-growth ice platelets project into the water (Langleben 1970).

Hovercraft can be used for on-ice as well as marine transport. Little information is available about reactions of marine mammals to hovercraft. Fraker (1977a) quotes an anecdotal account stating that white whales left an area through which a hovercraft had passed. The whales did not return for at least 8 h. Kelly et al. (1988) noted that a ringed seal remained on the ice in its lair when a hovercraft passed about 2.5 km away. However, M. Bigg (*in* Johnson et al. 1989:53) observed that harbor seals hauled out near Vancouver International Airport were much more responsive to hovercraft than to aircraft overflights, which were more frequent.

SRA (1988) and Schulberg et al. (1989) studied reactions of migrating gray whales to military hovercraft ("LCAC"). When hovercraft approached within a few hundred meters, the spacing between animals sometimes decreased and the whales occasionally turned or stopped traveling for a few minutes. Schulberg et al. concluded that avoidance reactions usually did not occur until the LCAC was within 100 m, but in one case a cow/calf pair seemed to react at 500 m. Schulberg et al. (1989) stated that a group of pilot whales showed no reaction to a hovercraft passing <100 m in front of them, but that dolphins tended to remain farther from the LCACs than did gray whales.

8.6 Reactions to Seismic Exploration and Explosions

Marine geophysical exploration by acoustic means (hereafter called seismic exploration) produces underwater sounds with source levels that greatly exceed those of other activities associated with offshore oil and gas exploration or development (sect. 5.3). High explosives, which produce the most intense and sharp-onset sounds, are now rarely used in North American waters (Jakosky and Jakosky 1956; Brooks 1981; Campbell 1985; Wright 1985). However, airgun arrays, gas exploders and vibrators (Vibroseis) are widely used. These produce waterborne sounds with overall source levels of 220-250 dB re 1 µPa-m (e.g. Kramer et al. 1968; Lugg 1979; Duncan 1985; sect. 5.3). Although a high proportion of this energy is directed downward, underwater sound pulses from airgun arrays and similar sources are commonly audible many tens of kilometers away (Malme et al. 1983; Greene and Richardson 1988).

In this section we consider mainly the behavioral reactions of marine mammals to noise from seismic exploration and distant explosions. At close distances, explosives also produce shock waves, which propagate in a different manner than acoustical energy. Shock waves produced by high explosives can cause severe physical damage and death in certain circumstances. The few available data on effects of shock waves on marine mammals are mentioned below. For a broader review of shock wave effects, see Richardson et al. (1989); see also Yelverton et al. (1973); Hill (1978); Wright (1982) and Myrick et al. (1990a,b).

8.6.1 Seals

Open-water Seismic Exploration.--No detailed studies of reactions by seals to noise from seismic exploration in open water have been published. The following is a summary of the limited information that is available about reactions of pinnipeds to impulsive sounds. Only a minority of these observations involved actual seismic exploration.

During seismic exploration at Sable Island, Nova Scotia, gray seals exposed to noise from airguns and Aquaflex linear explosives reportedly did not react strongly (J. Parsons *in* G.D. Greene et al. 1985:283). However, no details were given. It is not clear whether the seals exposed to airgun noise were in the water or hauled out.

"Seal bombs" and shellcrackers are often used in attempts to prevent harbor seals, sea lions and other mammals from feeding on fish (e.g. Mate and Harvey 1987). These pyrotechnic devices expose the animals to sharp noise pulses of varying intensities, in some but not all ways analogous to the noise pulses used for seismic exploration. Seal bombs explode a few meters below the surface. Shellcrackers fired from shotguns and several types of smaller pyrotechnics fired from pistols can explode above, at or below the surface. The general consensus from experience with these devices on the U.S. west coast is that, when first used, they startle the animals and often induce them to move away from feeding areas temporarily. However, the avoidance response wanes when the animals learn that the noise pulses are not harmful. Thereafter, some seals tolerate quite intense underwater sound in order to gain access to food (Mate and Harvey 1987).

Similarly, cape fur seals in South Africa often disrupt fishing operations, and fishermen sometimes throw firecrackers into the water to try to drive the seals away (Shaughnessy et al. 1981). Fur seals generally dove when firecrackers exploded nearby, but usually returned within a few minutes. Underwater noise levels from the firecrackers were not measured, but similar reactions were sometimes obtained to an arc discharge transducer that produced pulses at 10-s intervals with a peak source level of 132 dB re 1 μPa-m (Shaughnessy et al. 1981). However, some fur seals did not leave when exposed to the arc discharge. Levels received by the seals were not estimated.

Marine seismic exploration with modern non-explosive techniques does not produce significant pulses of airborne noise. Nonetheless, reactions of pinnipeds to airborne noise pulses from other sources may be relevant in interpreting possible reactions to seismic pulses in water. Breeding elephant seals and California sea lions exposed to intense pulses of airborne noise from a carbide pest control cannon at a haulout site apparently were not greatly affected (Stewart 1981): "Habitat use, population growth, and pup survival of both species appeared unaffected by periodic exposure to carbide cannon impulse noise".

The above information is inadequate for any general conclusions. However, the evidence indicates that seals sometimes tolerate intense impulsive sounds when they are strongly attracted an the area for feeding or reproduction. Thus, we can hypothesize that seals will tolerate considerable noise from distant seismic exploration, e.g. when seismic vessels are >5 km away, at least when the animals are strongly tied to an area. Whether these seals would suffer any deleterious effects, e.g. stress, is unknown. Reactions of pinnipeds to seismic vessels at closer ranges are unknown and not predictable from the "seal bomb" observations. Close to a seismic vessel there is the further factor of considerable noise from the seismic ship itself.

Regarding the physical effects of explosives on pinnipeds, Fitch and Young (1948) reported that, on at least three occasions, California sea lions were killed by explosions used (at that time) for seismic exploration. However, no specific information about the explosives or the distances of the sea lions were given. Fur seals were reportedly killed by an 11.4 kg dynamite charge exploded 23 m away (H.F. Hanson, *in* Trasky 1976 and Wright 1982). Reiter (1981) reports without further details that "there was evidence of [fur] seals...killed from concussion in the immediate area of demolition" when a grounded ship was broken up by about 454 kg of explosives. Bohne et al. (1985, 1986) found that the inner ears of 5 of 11 Weddell seals showed evidence of damage consistent with exposure to high noise levels. Numerous explosive charges had been detonated in the area the previous summer, but there was no proof that the auditory damage was caused by those explosions.

On-ice Seismic Exploration--More specific information is available about reactions of ringed seals to on-ice seismic exploration by the Vibroseis method. In recent years this has been a common method of seismic exploration in nearshore areas around northern Alaska (Holliday et al. 1984; sect. 5.3.2).

Holliday et al. estimated that measurable underwater or airborne noise is detectable in ringed seal lairs at distances up to about 2-6 km from the Vibroseis source, depending on propagation and ambient noise conditions. However, most of the energy is at low frequencies. Hearing sensitivity of ringed seals has not been determined below 1 kHz (sect. 7.2.2).

Burns et al. (1981) estimated densities of ringed seals hauled out on the ice in various parts of the Alaskan Beaufort Sea in spring. In 1975-77, the average density in areas where there had been seismic exploration was 51% of that in "control" areas. Results from 1981 were confounded by early break-up, but seal densities along seismic lines were significantly lower than those along the "control" lines that Burns et al. considered most relevant (2.82 vs. 4.84 seals/km; $P<0.01$). Whether the apparent displacement was solely the result of seismic noise is uncertain. Vehicle traffic and human activity along the seismic lines might also be involved.

More recent studies (Burns et al. 1982; Cummings et al. 1984; Kelly et al. 1986, 1988) were designed specifically to determine reactions of ringed seals to Vibroseis and related noises. Contrary to the earlier results, aerial surveys in the spring of 1982 did not show reduced densities in areas where there had been seismic exploration during the preceding winter (Kelly et al. 1988). Burns et al. (1982) found that over half of the seal holes within 150 m of the seismic lines were still in use, but there was evidence that holes within 150 m of seismic lines were more likely to be abandoned than were holes farther away. Burns et al. concluded that "some localized displacement of ringed seals occurs in immediate proximity to seismic lines but, overall, displacement...is insignificant in the nearshore Beaufort Sea".

One radio-tagged ringed seal left its subnivean lair when an approaching experimental Vibroseis crew was 644 m away (Kelly et al. 1986, 1988). The experimental crew used a single Vibroseis source rather than the four sources normally used. Thus, short-term reactions of ringed seals to full-scale Vibroseis crews might occur at longer ranges. However, three other radio-tagged seals used breathing holes and lairs within 19-700 m of actual Vibroseis lines after seismic surveys were completed (Kelly et al. 1986, 1988).

Cummings et al. (1984) tested the reactions of ringed seals to underwater playbacks of recorded sounds from a Vibroseis operation. The J-9 playback system could not reproduce the lowest frequency components of the signals, nor did its source level (135-140 dB re 1 µPa-m) approach the source level of an actual Vibroseis operation. However, received levels of Vibroseis noise close to the projector simulated the levels that would be received by seals at considerably greater ranges from an actual Vibroseis operation. Cummings et al. found no clear evidence that vocalization rates or types were different after playbacks than before playbacks. Some seal vocalizations occurred during Vibroseis playbacks.

Overall, the data show that Vibroseis operations in winter and spring can cause localized movements of ringed seals away from seismic lines. However, this effect is evident only within a short distance, possibly about 150 m, and some seals remain even within that distance from seismic lines. Effects of Vibroseis on the general distribution and numbers of seals inhabiting landfast ice appear to be minimal.

8.6.2 Toothed Whales

We are not aware of any published information about reactions of toothed whales to seismic noise, and there is little information about their reactions to any similar types of noise. Small explosive charges were dropped into an Alaskan salmon river in attempts to scare white whales away (Fish and Vania 1971), apparently without success. Sperm whales ceased calling when exposed to noise pulses from acoustic pingers and military sonars (Watkins and Schevill 1975; Watkins et al. 1985a). The frequencies involved (3-13 kHz) were much higher than those emitted by airguns and other high-energy seismic sources. However, some lower-energy sources used for shallow seismic work operate in the kilohertz range, and might cause sperm whales to cease calling.

"Seal bombs" are widely used to influence the movements of the dolphins around which purse-seine nets are set during fishing operations for yellowfin tuna (Cassano et al. 1990; Myrick et al. 1990a,b). Cassano et al. estimated that "seal bombs are probably being used in 40-percent or more of all sets made on dolphins in the U.S. tuna purse-seine fishery monitored by NMFS observers". U.S. regulations prohibit the use of seal bombs containing >2.59 g of explosive during net-sets around dolphins. However, "Class-C" bombs with <2.59 g of explosive are often used in clusters, and other types of seal bombs with up to 5.76 g of explosive are also widely used. It is common for 10-50 seal bombs to be used during one net set, and as many as 200-600 seal bombs are occasionally used per set (Cassano et al. 1990).

The effects of seal bombs on dolphin hearing have not been reported. A similar device killed a human diver when it exploded ~0.3 m from his head (Hirsch and Ommaya 1972). Myrick et al. (1990a) concluded that one Class-C device will cause injury when detonated within 0.5-0.6 m of a dolphin. They estimated a safe standoff distance of 4 m or slightly more, depending on explosive type and depth. These conclusions were based on tests with dolphin carcasses, fish and inanimate targets, as well as previous studies of explosive effects on other mammals.

Most seismic exploration in open waters is conducted with airguns, not explosives. Energy emitted by airguns is at low frequencies (<100 Hz), below the frequency ranges of the calls and of the optimum hearing of toothed whales (sect. 6.2, 7.2.1). However, noise pulses recorded underwater many kilometers away from airgun arrays sometimes include considerable energy at frequencies of several hundred Hertz (Greene and Richardson 1988). At least in these cases, airgun pulses probably would be audible to toothed whales (sect. 9.7.2, 9.9.2).

8.6.3 Baleen Whales

The behavior of some species of baleen whales has been observed opportunistically in the presence of noise from distant seismic exploration. In addition, controlled experiments to determine the reactions of bowhead, gray and humpback whales to airgun noise have been conducted recently. Almost nothing has been published about effects of explosions on baleen whales.

Gray Whale.--Gray whales exposed to noise from seismic exploration via explosives "were seemingly unaffected and in fact were not even frightened from the area" (Fitch and Young 1948); no other information was given. Charges in use at that time usually consisted of 9-36 kg of high explosives. Ljungblad et al. (1982a) reported observing normal behavior of gray (and fin) whales in the Chukchi Sea during exposure to sounds from a ship firing air guns 36-68 km away. Behaviors included a gray whale nursing a calf while exposed to seismic pulses 42 km from the ship.[5]

Recent systematic experiments have shown that gray whales migrating along the California coast react to strong pulses of seismic noise from one or more airguns (Malme et al. 1983, 1984; Malme and Miles 1985). By some measures, clear behavioral effects were evident when received levels were ≥160 dB re 1 µPa, corresponding to ranges <5 km from a 65.5 L (4000 in^3) array of 20 airguns and <1 km from a single 1.64 L (100 in^3) airgun. Gray whales that reacted to seismic noise generally slowed, turned away from the noise source, and increased their respiration rates. They sometimes moved, apparently intentionally, into a "sound shadow" created by topography. There were indications that northbound mothers and calves may be more responsive to seismic noise than were other migrating gray whales. Reactions of southbound whales to an airgun array were most pronounced when it was oriented broadside, the direction in which most energy was radiated. In the test area, the effective ranges for 10%, 50% and 90% probability of avoidance were estimated to be 3.6, 2.5 and 1.2 km broadside from the airgun array (received noise levels 164, 170 and 180 dB; Malme et al. 1984). Less consistent or dramatic reactions were suspected at received levels of 140-160 dB, which would occur farther away.

The tests on migrating gray whales showed that a seismic vessel passing nearby can affect migration temporarily. The threshold for distinct reactions by gray whales to seismic pulses, about 164 dB average pulse level, was about 45-50 dB higher than their reaction threshold for

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[5] We question the statement by Ljungblad et al. (1982a:58) that the received sound level near these whales was 154 dB re 1 µPa--an unusually high level 42 km from a seismic vessel (*cf.* Greene and Richardson 1988). Standard sonobuoys do not provide reliable data at such high levels (Ljungblad et al. 1985), and theoretical calculations based on assumed source levels and propagation loss rates are also unreliable.

continuous industrial noise such as that from drillships and drilling or production platforms (Malme et al. 1984:9-6). In this respect their behavior was consistent with that of humans. Humans are more sensitive to continuous noise than to pulsed noise with an equivalent peak level (Fidell et al. 1970).

Reactions of gray whales summering in the Bering Sea to a single 1.64 L airgun (100 in^3, source level 226 dB re 1 μPa-m) were tested by Malme et al. (1986b, 1988). These authors estimated that there was a 50% probability of avoidance when the average pulse level of the received noise was about 173 dB, and a 10% probability of avoidance for 163 dB. These results were less precise than those for migrating whales because of lower sample size and other complications. However, the summer results were generally consistent with those for migrating whales. Because of better sound propagation conditions at the Bering Sea test site than off California, expected radii of responsiveness were higher in the Bering Sea. When exposed to seismic pulses, summering gray whales also had significantly shorter surfacings and dives, with fewer breaths per surfacing and longer intervals between successive breaths. These subtle effects may have persisted for >1 h after the airgun ceased firing.

Bowhead Whale.--Behavior of bowheads exposed to pulses of seismic noise has been observed opportunistically during summer and autumn (e.g. Reeves et al. 1984; Richardson et al. 1986). In addition, there have been controlled studies of bowhead reactions to single airguns and to full scale arrays of airguns (Richardson et al. 1986; Ljungblad et al. 1988b). Collectively, these studies show that, when an operating seismic vessel approaches within a few kilometers, most bowheads exhibit strong avoidance and specific changes in surfacing, respiration and dive patterns. Bowheads exposed to pulses from vessels more than ~7½ km away rarely show avoidance, but their surfacing, respiration and dive cycles tend to be altered in the same manner as those of whales closer to the vessels.

Ljungblad et al. (1988b) conducted four tests of bowhead reactions to seismic vessels in the Alaskan Beaufort Sea during early autumn. Initial behavioral changes were detected up to 8.2 km away (received noise levels 142-157 dB re 1 μPa). "Total avoidance", i.e. all whales moving away, occurred 3, 3½ and 7.2 km from three vessels using arrays of airguns, and 1¼ km from a vessel with a single airgun (152-178 dB). In one case, strong avoidance was evident when the airgun array began firing 7.2 km away (165 dB). This may have been a startle response to the sudden onset of the noise. A similar reaction might have occurred at a greater distance and lower received sound level if this had been tested. However, in another test a vessel began firing at 10.4 km (155 dB); no reaction was noticed until it had approached to 8.2 km (157 dB). Besides the active avoidance, there were strong and highly significant tendencies for reduced surfacing and dive durations, fewer blows per surfacing, and longer intervals between successive blows as at least 3 of the 4 ships approached. These effects were strongest at ranges <5 km, but also were evident at 5-10 km (Fig. 8.1). Bowheads swam rapidly and directly away from the approaching ships once active avoidance began. Some whales were displaced by several kilometers, and behavior was altered for up to an hour.

On one occasion, reactions of summering bowheads were tested using a full scale seismic vessel with a 47 L airgun array (2800 in^3; nominal source level 248 dB re 1 μPa-m). Bowheads began to orient away from the approaching ship when its airguns began to fire 7½ km away. However, some near-bottom feeding continued until the vessel was 3 km away, whereupon the last whales in the area moved away. Whales were displaced by about 2 km, and behavior was affected for at least 2.4 h (Richardson et al. 1986). There was no evidence of changes in surfacing, respiration and dive cycles, although sample sizes were small.

Based on all five full-scale seismic tests combined, the tendencies for reduced surfacing and dive durations and for fewer blows per surfacing were all highly significant ($P < 0.001$, F-tests). However, the overall tendency for increased blow intervals was marginal at best ($0.1 > P > 0.05$); that tendency was strong in the four tests by Ljungblad et al. (1988b) (Fig. 8.1) but lacking in the test by Richardson et al. (1986).

Five controlled tests with a single 0.66 L (40 in^3) airgun showed that summering bowheads usually continued normal activities when the airgun began firing 3-5 km away (received levels ≥118-133 dB re 1 µPa; Richardson et al. 1986). However, bowheads oriented away during 2 of 5 tests, at 2-4½ km and 0.1-1.2 km; in the latter case swimming speeds apparently increased. These avoidance responses were to airgun pulses *per se*; there was no boat or compressor noise to confound interpretation. Surfacing and respiration variables did not change dramatically during airgun tests, but trends were consistent with those during the tests by Ljungblad et al. (1988b) (Fig. 8.1).

Bowheads more than 6-7½ km from seismic vessels rarely show overt avoidance reactions, but may be affected subtly. Richardson et al. (1986) summarized opportunistic behavioral observations on 21 occasions when summering bowheads received noise pulses of 107 to at least 158 dB re 1 µPa from seismic ships 6-99 km away. General activities were indistinguishable from those without seismic noise, and there was no detectable avoidance. These bowheads produced calls of the usual types while exposed to seismic pulses, and calling rate was only slightly (if at all) reduced. However, on average, these bowheads had significantly shorter surfacings and dives, significantly fewer blows per surfacing, and longer intervals between successive blows than did bowheads not exposed to man-made noise (Fig. 8.1). These trends were based on largely uncontrolled observations, and could not be attributed definitely to the seismic noise. However, the trends probably represented an actual subtle effect of seismic noise, given their statistical significance and consistency with experimental data from bowheads at closer distances (see above) and from summering gray whales (Malme et al. 1988). The data suggested that subtle effects sometimes occur at distances as much as 54-73 km from seismic boats, but this needs confirmation by controlled experiments.[6]

Reactions of bowheads to seismic vessels have also been studied opportunistically in the Alaskan Beaufort Sea during autumn. As in summer, bowheads usually continued normal activities when exposed to noise pulses from ships several kilometers or more away (Reeves et al. 1984; Ljungblad et al. 1984b; Fraker et al. 1985; Koski and Johnson 1987; Richardson et al. 1987b). No overall analysis of these data has been done, but subtle reactions to seismic vessels were occasionally suspected. However, in most cases it was impossible to be sure that the whale behavior was unusual or that the suspected changes were attributable to seismic

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[6] There was much variation in behavior within and among days, as is usual. Hence, it was not possible to determine a specific distance from seismic boats beyond which behavioral changes were no longer evident. However, the "standard" pattern of altered surfacing-respiration-dive behavior was evident on two days (16 and 18 Aug 1982) when bowheads were 54-73 km from a seismic vessel (Richardson et al. 1985b:214). Received levels of seismic pulses varied from <125 dB to ≥133 dB re 1 µPa on those occasions.

exploration. In one case, bowheads swam rapidly away from an approaching seismic vessel 24 km away (Koski and Johnson 1987). Their surfacings and dives were short, with few blows per surfacing and slightly longer than average blow intervals--the same pattern noted above. This apparent response is the longest-distance avoidance of a seismic vessel noticed thus far, despite the fact that received sound levels are expected to be lower ahead of the vessel than at the same range to the side (sect. 5.3.3).

Thus, most bowheads usually show strong avoidance when an operating seismic vessel is within 6-7½ km, and there probably are some effects at greater distances. In three studies of bowheads (and one of gray whales), surfacing-dive cycles have been unusually quick in the presence of seismic noise, with fewer breaths per surfacing and longer intervals between breaths (Richardson et al. 1986; Koski and Johnson 1987; Ljungblad et al. 1988b; Malme et al. 1988). This pattern was evident among bowheads 6-99 km from seismic vessels as well as during controlled tests at closer ranges. Besides these subtle effects, strong avoidance may occur infrequently at distances of 20 km or more (Koski and Johnson 1987), although active avoidance usually does not begin unless the seismic ship is closer than 10 km.

Although bowheads react strongly to seismic ships within several kilometers, bowheads (and gray whales) often tolerate strong seismic pulses. Received noise levels when strong avoidance becomes evident are 150-180 dB re 1 µPa. This is much higher than the "avoidance threshold" for continuous sounds, e.g. from vessels, dredging, drilling or oil production. Bowheads often show no overt reactions to strong noise pulses from ships 6-25 km away. Even at 25 km, these pulses often seem, in human terms, analogous to regular and obtrusive pulses from a pile driver hammering nearby. The frequent tolerance of strong seismic pulses may be related to the fact that human annoyance thresholds are much higher for pulsed than for continuous noise (Fidell et al. 1970).

FIGURE 8.1. Surfacing, respiration, and dive behavior of bowhead whales observed in the presence and absence of seismic pulses (bowhead calves excluded). Black boxes highlight situations with seismic noise. For each variable, the **left** section shows pooled data from four experiments when bowheads were approached by seismic vessels during autumn; results are shown, in sequence, for the pre-experiment phase (no seismic source within 10 km), two experimental phases--approaching ship 5-10 km and <5 km away, and two post-experiment phases, <30 and 30-60 min after the experiment (recalculated from Ljungblad et al. 1988b: Table 2). The **center** section shows pooled data from three experiments when summering bowheads were exposed to noise from a single 0.66 L airgun 3-5 km away; behavior was observed before, during and after the airgun fired (Richardson et al. 1986). The **right** section compares data from undisturbed summering bowheads vs. those receiving pulses from seismic ships 6-99 km away (Richardson et al. 1986). Mean, ±1 SD (vertical line), ±95% confidence limits (wide bar), and sample size are shown. NS means $P > 0.1$; *, ** and *** mean $P \leqslant 0.05$, 0.01 and 0.001, respectively. NS/* means NS or * depending on how the test was done. Tests based on 1-way ANOVA for Ljungblad and airgun data, and the methods described by Richardson et al. (1986) for opportunistic data.

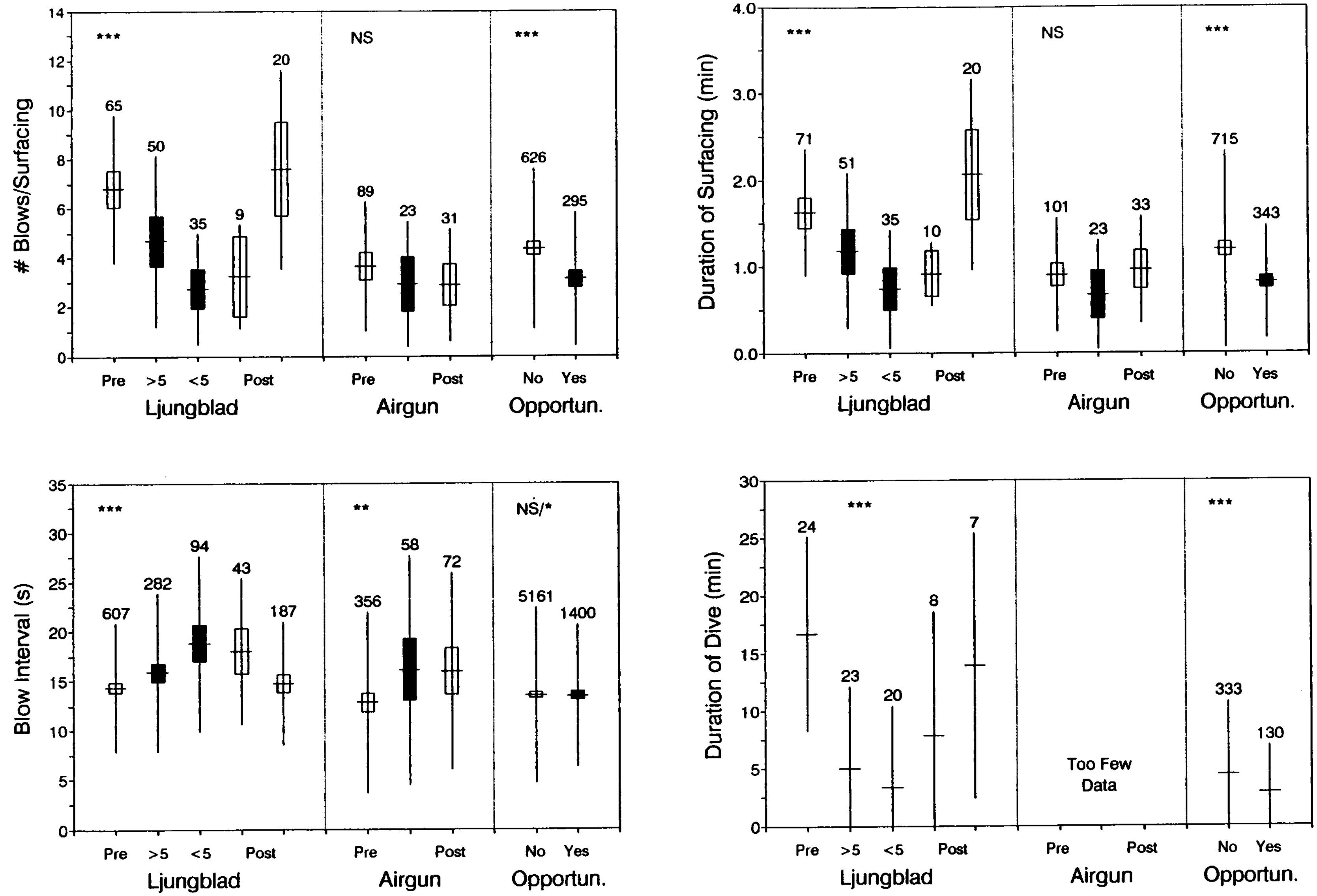

FIGURE 8.1. Surfacing, respiration, and dive behavior of bowhead whales observed in the presence and absence of seismic pulses (bowhead calves excluded). Black boxes highlight situations with seismic noise. See extended caption on facing page for more details.

On the longer term, there is also some tolerance of ongoing exposure to seismic noise. During 1984, bowheads were seen regularly for several weeks in an area where a seismic ship was working (Richardson et al. 1986, 1987a). They also saw many bowheads in areas where there had been much seismic work the previous summer. However, it is not known whether the same individual bowheads *(1)* remained for several weeks in the area with ongoing seismic noise or *(2)* returned to such areas in subsequent years.

Inupiat whalers suggest that, since seismic work began off northern Alaska, autumn bowhead migration has tended to be farther offshore (ESL et al. 1986:143). Aerial surveys conducted since 1982 provide no evidence of such a trend (Ljungblad et al. 1988a), but the question remains open. Annual sample sizes within specific hunting zones have been small, and the displacement (if it occurred) may have begun before surveys began in 1982.

Humpback Whale.--Humpback reactions to seismic noise have been studied in less detail than those of gray and bowhead whales. Payne and McVay (1971) state that "loud sounds in the ocean, for example dynamite blasts, do not seem to affect the whale's songs". Payne (1970) presented a recording of a humpback that continued to sing through the noise from two distant explosions. Payne (1978b) also mentioned this point.

Malme et al. (1985) studied movements of humpback whales summering in southeast Alaska when exposed to noise pulses from a single 1.64 L (100 in^3) airgun. They examined only whale positions and movements; other behavioral attributes usually could not be measured. No persistent avoidance response was demonstrated, but the results were confounded by gradual movement of whales away from the test site independent of any airgun effect. During 3 of 7 tests, some humpbacks seemed startled when the airgun was first turned on at ranges up to 3.2 km, but these responses did not persist. Sound levels received by the "startled" whales were 150-169 dB re 1 µPa. Malme et al. concluded that subtle effects may have occurred, but that "No clear evidence of whale avoidance of the area near the active sound source was obtained. Whales were observed at ranges corresponding to sound exposure levels of up to 172 dB effective pulse pressure level (re 1 µPa). ... In the test areas, [this] level was obtained at ranges of 140 to 260 m from the air gun."

Humpbacks responded to underwater playbacks of 3.3-kHz pulses from a sonar by moving away from the sound source (Maybaum 1990).

Summary.--Almost nothing is known about effects of explosions on baleen whales, but there has been considerable research on reactions to marine seismic exploration by non-explosive methods. Baleen whales seem quite tolerant of low- and moderate-level noise pulses from marine seismic exploration. They usually continue their normal activities when exposed to pulses with received levels as high as 150 dB re 1 µPa, and sometimes even higher. Such levels are 50 dB or more above typical ambient noise levels. However, subtle behavioral effects are suspected to occur at least some of the time at lower received levels, at least in bowheads and possibly gray whales. In those species, strong avoidance is common when received levels reach 160-170 dB, as typically occurs several kilometers from a vessel operating a full-scale airgun array. When bowheads are disturbed sufficiently to exhibit strong avoidance, they sometimes swim a few kilometers, and normal activities can be disrupted for an hour or more.

These observations of short-term reactions (or lack of reactions) of cetaceans to impulsive noises provide no information about long-term effects. It is not known whether impulsive noises affect reproduction rate or distribution and habitat use in subsequent days or years. Gray whales continue to migrate annually along the west coast of North America despite intermittent seismic exploration in that area for decades (Appendix A *in* Malme et al. 1984). Bowhead whales continue to travel to the eastern Beaufort Sea each summer despite seismic exploration in their summer and autumn range for many years. Bowheads are often seen in summering areas where seismic exploration occurred in preceding summers (Richardson et al. 1987a). Bowheads also have been observed over periods of days or even a few weeks in areas repeatedly ensonified by seismic pulses. However, it is not known whether the same individual bowheads were involved in these repeated observations (within and between years) in strongly ensonified areas. It is also not known whether whales that tolerate exposure to seismic pulses are stressed (see sect. 10.5-10.8 for discussion).

8.6.4 Sea Otters

Behavior of sea otters along the California coast was monitored by Riedman (1983) while they were exposed to noise pulses from a full-scale array of airguns (67 L) and from a single airgun. Riedman (1984) obtained additional data on reactions to a single airgun. No disturbance reactions by otters were evident when the full-scale seismic ship passed as close as 1.85 and 0.9 km. Feeding otters continued to dive and feed successfully at these times. Also, no apparent reactions were evident among otters that were rafting, grooming, swimming, mating, or interacting with pups (Riedman 1983).

Similar results were obtained in response to the single 1.6 L airgun (Riedman 1983, 1984). However, some rafting otters exhibited interest in the boat towing the one airgun. They rolled onto their sides or bellies and looked intently at the boat as it approached or passed at distances of "several hundred meters to approximately 1.5 km offshore". Because the airgun was not operating during two passes, Riedman (1983) suspected that the otters responded to the boat and compressor noise, or to [sight of] the vessel itself, rather than to the underwater seismic sounds.

Although these results suggest that sea otters are less responsive to noise pulses from marine seismic exploration than are certain baleen whales, Riedman (1983) cautioned that all otters studied by her were ≤400 m from shore. There are no data on reactions of otters farther offshore.

Sea otter studies done in association with underground nuclear tests have provided the most detailed available data on susceptibility of any marine mammal to shock waves. Based on necropsies of sea otters found dead after one test, R.L. Rausch (*in* Trasky 1976 and Fuller and Kirkwood 1977) concluded that peak pressures of 100-300 psi or 70-210 N/cm^2 (237-246 dB re 1 μPa) were lethal;[7] the thoracic organs, central nervous system and middle ear were most severely affected (Westworth 1977). Laboratory tests showed that several sea otters exposed to shock waves with peak pressure 103-251 N/cm^2 suffered unspecified damage but lived, whereas others exposed to 207-296 N/cm^2 died (Wright and Allton 1971). One pregnant sea otter exposed to 169 N/cm^2 also died.

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[7] Since x N/m^2 = x Pa, L_r (in dB re 1 μPa) = 20 log ($10^{10} \cdot x$ N/cm^2).

8.7 Reactions to Dredging and Construction

Dredges constitute some of the major sources of underwater noise in certain nearshore areas (Greene 1987b). Marine dredges are used to construct artificial islands, to deepen ship channels, and for other offshore construction projects. Acoustic effects of dredging and other construction operations on marine mammals are not well studied. We know of only a few anecdotal observations about reactions of seals and toothed whales, and one study on baleen whales.

8.7.1 Dredging

Harbor seals that haul out in Kachemak Bay, Alaska, continued to haul out during construction of hydroelectric facilities ~1.6 km away (D. Roseneau and D. Trugden, ***in*** Johnson et al. 1989:54 and ***in*** Malme et al. 1989).

White whales in the Mackenzie estuary showed less reaction to stationary dredges than to moving barges despite similarities in acoustic source levels and frequencies (Ford 1977; Fraker 1977a,b). White whales approached as close as 400 m from dredges. However, in one case, whales moved away when a tug and barge left a dredge (Fraker 1977a). He concluded that passage of white whales along a shoreline was temporarily blocked by a dredging operation involving frequent barge traffic, but not by dredging with little barge traffic. ***Spinner dolphins*** reduced their use of a Hawaiian bay after the start of a noisy construction project for a water pipeline (Shallenberger 1978).

Bowhead whales were seen near the construction site of an artificial island in the Beaufort Sea over a 2-week period in August 1980. Aerial surveys detected bowhead whales within 800 m of the site, and industry personnel reported some closer approaches (Richardson et al. 1985a,b,c, 1990b). A suction dredge and other vessels were active at that construction site when bowheads were seen nearby. Dredge sounds were well above ambient levels up to several kilometers away. The measured broadband level 1.2 km from the dredge was 120 dB re 1 µPa, or 22 dB above the average ambient level (Greene 1985, 1987b; sect. 5.4.1). Smaller numbers of bowheads were seen near other construction sites at distances where they were exposed to considerable underwater noise from suction and hopper dredges (112-117 dB: Richardson et al. 1985c, 1990b).

Insofar as we are aware, there has been only one experimental study of reactions of any marine mammal to underwater playbacks of construction noise. On 3 days, recorded underwater noise from a suction dredge was projected into the water near bowhead whales (Richardson et al. 1985c, 1990b). Estimated broadband received levels of the noise near the whales ranged from <113 to 131 dB re 1 µPa, or from <11 to 30 dB above the ambient noise level during the experiments. Although sample sizes were small, the more distant whales--those exposed to the least noise--exhibited only weak and inconspicuous avoidance reactions. Those exposed to stronger sounds exhibited more conspicuous avoidance. Whales exposed to broadband received levels of 122-131 dB (21-30 dB above ambient; 0.1-0.8 km from sound projector) stopped feeding and moved to locations >2 km from the projector.

During these dredge noise playback tests, the projected noise level was increased gradually over 10 min, so the reactions were not startle reactions in the usual sense. However, the gradual onset of dredge noise over 10 min was not fully representative of the time course of noise exposure for either a migrating whale approaching a construction site or especially for a stationary whale near such a site. Bowheads seemed to behave normally in some areas ensonified by actual dredging even though other bowheads showed avoidance at similar levels of dredge noise during playbacks.

This may mean that the whales habituate to noise from an ongoing construction operation even if they are disturbed when they first encounter it (Richardson et al. 1985c, 1990b). On the other hand, bowhead numbers in the general area of construction and drilling were apparently reduced after the first few years of intensive offshore exploration (Richardson et al. 1987a). It is not known whether this change in distribution was a long-term effect of the industrial activities or was caused by some other factor, e.g. year-to-year variability in food concentrations (Bradstreet et al. 1987; Ward and Pessah 1988).

Gray whales provide the best documented case of a long-term change in baleen whale distribution as a result of industrial activities. Gray whales were virtually absent from Laguna Guerrero Negro, Baja California, for several years when there was much shipping (Bryant et al. 1984; sect. 8.3.3). Bryant et al. suggested that "the constant dredging operation necessary to keep the channel open...may have been the main source of disturbance". Gray whales re-occupied the lagoon after shipping activities subsided.

8.7.2 Other Construction Operations

The effects on marine mammals of construction equipment operated on artificial or natural islands has not been studied in much detail. It seems to have little effect on ***white whales***, which were often seen "within a few feet" of an artificial island during quiet periods; they moved farther away but did not vacate the area when construction equipment was in use (Fraker 1977a). Sound levels were not measured, but sounds produced on an island are attenuated greatly at the air-water and bottom-water interfaces.

Three studies of ***ringed seals*** hauled out on the ice in the Beaufort Sea during spring have provided information about possible effects of artificial islands and related activities on this species:

1. Kingsley (1986) found no evidence that densities of ringed seals were lower adjacent to artificial islands than at other locations in the eastern Beaufort Sea. However, no details were given, and the minimum reduction in density that could have been detected was not stated.
2. Green and Johnson (1983) studied ringed seals around a site in the Alaskan Beaufort Sea where an artificial island had been constructed by over-ice truck transport of fill during the preceding winter. The average density of seal holes around the island in spring was no lower than that in a nearby control area. However, on a finer scale, densities in the area around the island were positively and significantly correlated with distance from the island and the associated over-ice haul road. Green and Johnson concluded that island construction during winter did not have a major effect on ringed seals, but that there probably was a limited degree of local displacement.
3. Frost and Lowry (1988) and Frost et al. (1988) found that densities of ringed seals within 3.7 km of artificial islands were lower than densities 3.7-7.4 km away. The effect was stronger near active islands (50-70% reduction within 3.7 km) than near

> inactive islands (12-30% reduction). However, on a broader scale, seal densities were higher, not lower, within the sector of the Beaufort Sea with artificial islands.

Overall, the effects of the island construction and operation on ringed seals appear to be insignificant.

Northern fur seals hauled out on St. George Isl., Bering Sea, showed very little reaction to onshore quarrying operations (Gentry et al. 1990). The strongest overt response was assumption of an alert posture (raised head) when heavy equipment was operating as close as ~100 m away or when blasting occurred ~300 m away. There was no evidence of movement away from the construction activities.

8.8 Reactions to Offshore Drilling and Production

Several anecdotal accounts have been published about the occurrence of marine mammals, mostly cetaceans, near drilling and production sites. Also, controlled studies have been conducted recently to determine the behavioral reactions of white, gray, humpback and bowhead whales and of sea otters to underwater playbacks of drilling and (in some studies) production sounds.

Production facilities have been in place in the Santa Barbara Channel off California for many years. Gray whales regularly migrate through the area (Brownell 1971), but there have been no published studies on distances of closest approach or possible disturbance caused by noise propagated from these offshore platforms. Gales (1982) interviewed platform personnel to determine whether marine mammals avoided the sites. Most persons reported seeing pinnipeds and whales, but most species identifications and behavioral observations were unreliable due to observer inexperience. A frequent observation was that animals approached more closely during low noise periods (Gales 1982; McCarty 1982). Interviews with personnel from platforms in Cook Inlet, Alaska, produced more specific results. White whales were reported within 9 m of some rigs, and noise, as long as it was consistent, was reported as being non-disturbing (Gales 1982; McCarty 1982). Flare booms were considered attractive to white whales, possibly because flares attract salmon. Pilot whales, killer whales, a minke whale and unidentified dolphins were also reported from Alaskan offshore platforms.

Kapel (1979) reported fin, minke and humpback whales as well as one bowhead near drillships in Davis Strait off West Greenland. Distances from the ships and other details were not described. Sorensen et al. (1984) saw a fin whale and various toothed whales within 10 n.mi. (18 km) of drillrigs off the New Jersey coast, but did not give more specific information about distances. For toothed whales, sightings per unit effort were similar during periods when drillrigs were present and absent.

Pinniped reactions to drilling and related activities are not well documented. As noted above, Kingsley (1986) reported no evidence of reduced numbers of ringed seals near artificial islands. However, Frost and Lowry (1988) did find reduced numbers within 3.7 km of artificial islands, on some of which drilling was underway. Sea lions were said to be common around production platforms off California and in Cook Inlet, Alaska (Gales 1982; McCarty 1982). Reactions of walruses to an icebreaker-supported drillship in the Chukchi Sea were summarized in sect. 8.4.1 (see Brueggeman et al. 1990).

White whales have often been observed near drillsites, and additional data on reactions to drilling sounds have been obtained by underwater playback techniques. White whales were seen regularly within 100 m of "operational" artificial islands (Fraker 1977a,b). During quiet periods, whales could be seen within "a few feet" of the island, but operating construction equipment or violently burning fires caused the animals to draw away from the island. Industry personnel reported white whales within 100-150 m of an island from which drilling was underway (Fraker and Fraker 1979), and those authors themselves saw white whales within 4.8 km of an island where drilling had been going on for about 12 h. However, white whales swimming along an ice lead in spring changed course when they came within 1 km of a stationary drillship, and exhibited more active avoidance when support vessels were moving near the drillship (Norton Fraker and Fraker 1982). These observations, along with data on reactions of white whales to ships and icebreakers in spring (sect. 8.3.2), suggest that white whales may be especially sensitive when in leads during spring.

Underwater playback techniques have recently been used to test the effects of drilling sounds on white whales migrating through leads north of Alaska in spring (Richardson et al. 1990a). The test sounds were from a drillrig on a grounded ice platform, and were mainly below 350 Hz. Although the sounds were detectable with hydrophones as much as 5 km from the projector, no overt reactions were detected until the white whales were within 200-400 m. Within that distance, some diverted or hesitated for a few minutes, but then continued within 50-200 m of the operating underwater projector. Richardson et al. (1990a) suggested that white whales may not have been able to hear the low-frequency drilling sounds until they came within ~200-400 m, given their poor hearing sensitivity at frequencies <1 kHz (sect. 7.2.1).

Reactions of white whales to underwater playbacks of sounds from a semisubmersible drillship have also been tested both in the field (Stewart et al. 1983) and in captivity (Awbrey et al. 1986; Thomas et al. 1990). Stewart et al. tested reactions of white whales to underwater sounds from *SEDCO 708* projected into an Alaskan river. In most tests, the sound level increased rapidly (within 5 s) from zero to maximum at a time when whales were within 1.5 km. These whales usually swam faster in the same direction as they had been moving before the playback. In some tests, respiration rates increased during playbacks. During two tests, *SEDCO 708* sounds were projected continuously as whales approached from about 3.5-4.6 km upstream. In one test there was no detectable reaction until the whales were within 50-75 m; in the second test whales reacted at 300-500 m. Reactions included rapid swimming and, in one case, reversal of direction. However, most whales passed close to the projector where received sound levels must have been high. Received levels in the shallow river were not measured, and were probably quite different than would occur at similar ranges in the ocean. Stewart et al. (1983) concluded that reactions to drillrig noise were less severe than those to motorboat noise (*cf.* Stewart et al. 1982).

Thomas et al. (1990) performed nine playback tests on four captive white whales using as stimuli recorded and simulated sounds of *SEDCO 708* (see also Awbrey et al. 1986). Brief avoidance responses occurred when the animals were startled by the onset of the sounds. However, this avoidance lasted only about 30 s. The whales frequently swam within 1 m of the sound projector, where received levels were at least 153 dB re 1 µPa. Group structure was unaffected by the presence of the noise. Surfacing-respiration-dive cycles were not strongly affected, although dive durations tended to be somewhat shorter. Plasma catecholamine levels were normal when measured 8-40 min after playbacks ceased, indicating that the animals were not stressed. Thomas et al. concluded that they "could not detect any short-term behavioral or physiological effects of drilling noise playbacks on these captive belugas" despite the high level of sound exposure. However, they recommended caution in extrapolating these results to the behavior of wild white whales around oil platforms.

These results may be another example of the degree to which white whales can adapt to repeated or ongoing man-made noise when it is not associated with negative consequences. As noted under "Reactions to Ships and Boats" (sect. 8.3.2), the responsiveness of white whales to noise is highly variable. Strong avoidance sometimes occurs even in response to weak sounds. However, in some non-threatening situations there can be little or no response to strong sounds.

Bottlenose dolphin distribution relative to oil production platforms in the Gulf of Mexico was summarized by Mullin et al. (1989). They mention evidence of a dis-association (possibly artifactual) in one depth stratum, and of attraction of herds to platforms in a deeper stratum. The latter may be a result of higher prey availability near platforms (Mullin et al. 1989). No information was given about typical distances between herds and platforms.

Bowhead whales whose behavior seemed normal have often been observed within 10-20 km of drillships in the eastern Beaufort Sea; on two occasions bowheads were only 8 and 4 km away during drilling (Richardson et al. 1985a,c, 1990b). Besides those observations by biologists, industry personnel reported to us 10 sightings of bowheads at distances of about 0.2 to 5 km from drillships, and industry personnel saw many others at unstated distances (Ward and Pessah 1988). Broadband sound levels 4 and 10 km from one of the drillships approached by bowheads were, respectively, 118 and 109 dB re 1 µPa, or 20 and 11 dB above the average background level (Greene 1985, 1987b).

Although bowheads were observed well within the ensonified zones around active drillships, playback experiments demonstrated that some bowheads show weak avoidance when exposed to drillship sounds (Richardson et al. 1985a,c, 1990b; Wartzok et al. 1989). Based on four successful playbacks of drillship noise, Richardson et al. found that some bowheads reacted to broadband received noise levels near 94-118 dB re 1 µPa--no higher than the levels tolerated by the bowheads seen several kilometers from actual drillships. As noted in section 8.7, Richardson et al. found the same phenomenon for dredges. The results of Wartzok et al. appear to be consistent, but they did not report the received noise levels at the specific locations of most whales observed during their three playback tests. The only strong reaction to drilling noise that they observed occurred at a broadband received level near 120 dB (Wartzok et al. 1989:192 vs. 183).[8]

Two explanations may account for the seemingly different reactions of summering bowheads to playbacks vs. actual drilling and dredging: habituation and variable sensitivity. Bowheads may react to the onset of industrial noise (over several minutes) during a brief playback, but habituate when that sound level continues for a long period near an actual drillship or dredge. However, playbacks also showed that responsiveness varies among

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[8] Wartzok et al. (1989) used sounds from the conical drilling barge *Kulluk*. Other drillship noise playbacks to bowhead, gray and humpback whales and to sea otters used noise from the drillship *Explorer II*. See Greene (1987b) and sect. 5.4.4 for a comparison of sounds from these sources.

individuals and days. Thus, whales seen near actual drillships may have been some of the less responsive individuals--those remaining after the more responsive animals had moved out of the area. We suspect that both habituation and variable sensitivity were involved.

Taken together, results of drillship and dredge noise playbacks indicated that a typical summering bowhead does not react overtly unless broadband received sound levels are ~115 dB re 1 µPa, or ~20 dB above the ambient level. Based on noise within the dominant 1/3-octave band, the reaction criteria are ~110 dB re 1 µPa or ~30 dB above ambient in that band. Received industrial noise levels diminish to 20 or 30 dB above the ambient noise level (radius of responsiveness) well before they diminish to the ambient level (radius of presumed audibility). Hence, the radius of responsiveness around a drillsite is apparently much smaller than the radius of audibility (Miles et al. 1987; Richardson et al. 1990b).

Recently, bowheads migrating west past an active drillship and its support vessels were monitored during autumn in the Alaskan Beaufort Sea (LGL and Greeneridge 1987). Bowheads apparently avoided the area within 10 km of the drillship; they passed either to the north (offshore) or to the south (inshore) of the drillsite. Some whales apparently began to divert around the drillsite when still 20 km or more away. At a radius of 10 km, the underwater sound field was dominated by industrial noise. Noise at that radius, where most if not all bowheads apparently reacted, averaged 114 dB on a broadband basis, and 104 dB in the two 1/3-octave bands with highest noise levels (Greene 1987a). These results suggest that migrating bowheads may be slightly more responsive than summering bowheads, since only about half of the latter reacted to 120 dB (broadband) or 110 dB (dominant 1/3-octave). However, corroboration is needed given the procedural differences between studies.

In autumn, fewer migrating bowheads were seen within 15 km of drillsites when drillships were present than when they were absent (Ljungblad et al. 1987:45). This analysis included the data of LGL and Greeneridge (1987), so it did not provide independent corroboration. The lower number of sightings near drillships despite much increased survey effort near some drillships suggested avoidance. However, a "sightings per unit effort" analysis based on unbiased data would be needed for a quantitative estimate of the degree of avoidance.

Effects of drilling platform sounds on bowheads migrating through leads north of Alaska in spring were tested by Richardson et al. (1990a, in prep.). The sounds were from a rig on a grounded ice pad, and were projected into leads amidst the pack ice through which bowheads were migrating. The projected low-frequency sounds (mainly 50-300 Hz) were detectable with hydrophones, and presumably by bowheads, up to ~5 km away. Nonetheless, many bowheads approached within a few hundred meters of the sound projector. Their migration was not blocked, but some whales showed changes in behavior and attempted avoidance when within a few hundred meters (Richardson et al. in prep.).

The calling rate of bowheads seemed lower during drillship noise playbacks than before or after playbacks during the summer-autumn studies of both Richardson et al. (1985c, 1990b) and Wartzok et al. (1989). However, the elevated background noise level during playbacks inevitably masks the fainter calls. Hence, these data do not prove that bowhead call rate declines in the presence of drilling noise.

Gray whales migrating along the California coast have been studied when they were exposed to underwater playbacks of noise from a drillship, semi-submersible, drilling platform and production platform (Table 8.1; Malme et al. 1983, 1984). The recorded drillship sounds were the same as those used during some of the playback tests near bowheads (Richardson et al. 1985b,c, 1990b). Migrating gray whales showed statistically significant responses to all sources. The usual reactions included reduced swimming speeds and slight seaward or shoreward deflections of the tracks so as to avoid the immediate vicinity of the sound projectors.

The received noise levels at which gray whales reacted were reasonably consistent among the four sources of continuous noise (Table 8.1). They were also generally consistent with the received levels of drillship and dredge sound to which bowhead whales reacted. However, the source levels for the four types of drilling and production facilities varied widely, as indicated by the "Level at 100 m" column of Table 8.1. Hence, the distances from the actual industrial sites at which reactions would be expected varied widely, from 4-20 m for the relatively quiet platforms and semisubmersible to 1.1 km for the noisier drillship. (By comparison, the corresponding estimate for a seismic ship using a large array of airguns was 2.5 km.) All of these predicted radii of response are lower than would be expected in the Bering and Beaufort seas, where sound attenuates less rapidly with increasing distance (Miles et al. 1987).

Table 8.1. Received broadband sound levels (dB re 1 µPa) at which various percentages of migrating gray whales reacted to simulated sources of industrial noise, level 100 m from the actual source, and range from the actual source at which 50% avoidance is expected (from Malme et al. 1984:9-6).

	Levels for Various Percent Avoidance			Actual Level at 100 m	Actual Range for 50% Avoidance
	10%	50%	90%		
Drillship (*Explorer II*)[a]	110 dB	117 dB	122 dB	136 dB	1100 m
Semisubmersible (*Ocean Victory*)[a]	115	120	>128	101	11
Drilling Platform (*Holly*)[a]	114	117	>128	89	4
Prod'n Platform (*Spark*)[a]	120	123	>129	109	20
Helicopter (Bell 212)[b]	115	120	>127	103	—
Airgun (100 in^3) pulses	164	170	>180	180	400

[a] Underwater playback of recorded continuous noise.

[b] Underwater playback simulating an average of 3 helicopter passes/minute.

The predicted response distances for migrating gray whales, especially for the quieter sources, are only first approximations. The sound playback experiments could not fully duplicate the near-field sound fields close to large industrial sources. Also, whales probably would react to visual cues as well as to sound when close to an actual industrial site. Although gray whales have been observed near actual platforms in the Santa Barbara Channel, no details have been published concerning distances of closest approach or behavior near the platforms.

Malme et al. (1986b, 1988) attempted similar playback tests with gray whales summering near St. Lawrence Island in the Bering Sea. The stimulus was the same recording of drillship sounds as had been used with migrating gray whales and summering bowheads. There was no clear evidence of disturbance when broadband received noise levels were 103-110 dB re 1 µPa, but there was possible avoidance at 108-119 dB in another trial. Also, surfacing-respiration-dive cycles apparently changed during exposure to drillship noise and within 30 min thereafter. Based on these limited results from summer, Malme et al. concluded that the more extensive data from migrating gray whales were probably reasonably applicable to summering animals as well.

Drillship sounds have also been projected into a wintering area of gray whales at Laguna San Ignacio (Dahlheim 1987). During prolonged (6-8 h) playbacks, the gray whales tended to move away from the sound projector and to reduce their apparent rates of calling. These results were contrary to the reactions of gray whales to outboard engine noise (*cf.* sect. 8.3.3). Wintering gray whales clearly tended to avoid the source of drilling noise, which was a novel sound in the area, but did not avoid the source of motorboat noise, a normal sound there. With drilling sound, the whales also altered some of the characteristics of their calls, and received levels tended to be higher. In these two respects, the results were similar to those with outboard engine noise, and were interpreted as adaptations to reduce masking (Dahlheim 1987).

Humpback whales were studied by Malme et al. (1985) when they were exposed to playbacks of drillship noise (n=2 trials) and of semisubmersible, drilling platform, and production platform noise (n=1 trial of each). The results were difficult to interpret, but no clear avoidance responses were evident at broadband received levels up to 116 dB re 1 µPa.

In ***summary***, cetaceans apparently avoid stationary industrial activities such as dredging, drilling and production when the received sounds are intense, but not when the sounds are barely detectable. Besides avoidance, other behavioral effects, e.g. changes in surfacing-respiration-dive cycles, are sometimes seen as well. Whales seem most responsive when the sound level is increasing or when a noise source first starts up, e.g. during a brief playback experiment or when migrating whales are swimming toward a noise source. Although limited, the data suggest that stationary industrial activities producing continuous noise result in less dramatic reactions by cetaceans than do moving sound sources, particularly ships. There are indications that some cetaceans may partially habituate to continuous noise. In the case of white whales, habituation apparently can result in a very great reduction in responsiveness.

Some cetaceans do enter areas that are strongly ensonified by stationary industrial operations. The radius of avoidance around industrial sites seems considerably smaller than the radius of audibility, assuming that mammals can usually hear sounds whose levels exceed the background level in the corresponding band. Whether there is any reduction in utilization of areas that are ensonified but beyond the radius of demonstrated avoidance cannot be determined from the available evidence. The sizes of zones of influence are discussed in more detail in Chapter 9.

Sea otters were observed by Riedman (1983, 1984) during the underwater playbacks of drillship, semi-submersible, and production platform sounds conducted by Malme et al. (1983, 1984). She reported no evidence of any changes in behavior or use of the ensonified area during the playbacks. It should be noted that sea otters observable at the surface were probably receiving little or no underwater noise at the time of the observations. Received underwater noise levels diminish at depths within about ¼-wavelength of the surface (sect. 3.5.2), and underwater sound would be inaudible to an otter with its ears above the surface. However, some sea otters continued to dive and feed below the surface in a normal manner during the playbacks, and these animals would have been exposed to the noise playbacks. Most of the foraging otters observed by Riedman (1983) were at least 400 m away from the projector site. All of those observed by Riedman (1984) were at least 1.2 km away. At 1.2 km, the received sound levels in the 1/3-octave band with the strongest sounds were usually at least 10 dB above the ambient noise level, and sometimes somewhat stronger (Malme et al. 1983:5-37; 1984:5-24).

8.9 Reactions to Human Presence

The disturbance effects of human presence are difficult to separate from reactions to vehicles, boats, aircraft and presence of various types of machinery. Furthermore, it is generally impossible to determine from uncontrolled observations whether animals are reacting to sounds from humans or to the sight, movement or smell of humans or their appurtenances. We are not aware of any controlled experiments designed to determine whether marine mammals react to sounds, as opposed to other stimuli, associated with human presence.

In this subsection we summarize data on the reactions of certain marine mammals to humans, excluding many cases where the reaction is probably to aircraft, boats, or other equipment. Most observations are anecdotal, and most pertain to pinnipeds hauled out on land or ice. It is rarely known whether the observed reactions are attributable to noise or to another sensory modality.

Harbor seals hauled out on shore can be disturbed by passing hikers, recreational vehicles and small pleasure boats. This has been noted in areas as far apart as California, Alaska, eastern Canada, and Holland (e.g. Johnson 1977; Reijnders 1981; Renouf et al. 1981; Allen et al. 1984; Osborn 1985). Similar observations have been reported for ***gray seals*** (Bonner 1978; Renouf et al. 1981). Response thresholds may be lower in areas where seals are actively hunted than in other areas (Terhune 1985). In the absence of hunting or active harassment, habituation probably occurs (Awbrey 1980; Bonner 1982). Indeed, harbor seals often haul out on man-made structures.

Monk seals that whelp on remote Hawaiian beaches are often driven into the water by passing humans (Kenyon 1972). Kenyon concluded that the Hawaiian monk seal avoids beaches where it has been disturbed often by man. Henderson and Johanos (1988) found that monk seal pups disturbed by tagging subsequently hauled out farther away from the first haul out site as compared with untagged seals.

Ringed seal numbers apparently declined adjacent to a snowmobile track on landfast ice, according to Bradley (1970). Whether this effect was attributable to disturbance, hunting, or a combination of the two is not clear. However, Calvert and Stirling (1985) found no clear evidence of reduced numbers of ringed seals in areas subject to traffic and hunting. There is some evidence that intensive industrial activity may cause local displacement of ringed seals (sect. 8.5), but the effect is difficult to detect and does not extend beyond a few hundred meters or, at most, 1-2 km. On a short term basis, passing snowmobiles sometimes displaced ringed seals from their lairs under the snow at distances as great as 2.8 km, but on other occasions did not do so at a distance of ½ km (Burns et al. 1982; Kelly et al. 1986, 1988).

Harp seals hauled out on the ice for whelping were affected temporarily by the presence of tourists (Kovacs and Innes 1990). Females spent less time with their pups when tourists were present. When with the pups, females spent more time alert and aggressive, defending their pups against human approach, and less time nursing. Pup behavior was also affected by the presence of tourists on the ice. Normal behavior was usually resumed within 1 h after tourists left (Kovacs and Innes 1990).

Sea lions and ***fur seals*** may have abandoned some haulout sites at least in part because of human harassment (Calkins 1983; C. Fowler *in* Johnson et al. 1989:48). People walking near or through fur seal rookeries and haulouts can cause major short-term disturbance (A. York *in* Johnson et al. 1989). Again, however, habituation must occur under some conditions, since sea lions are often seen hauled out on man-made structures, often close to humans. Lewis (1987) found that 22 of 23 stampedes of adult Steller sea lions from a whelping beach into the water occurred in response to deliberate human disturbance during pup censuses. The number of pups killed during these stampedes was apparently negligible. However, the subsequent behavior of at least some animals seemed to be altered, including reduced mother-pup contact.

Walruses that have hauled out are sensitive to close approaches on foot, especially if approached from upwind when scent may prompt the flight response (Loughrey 1959). Salter (1979) reviewed evidence that walruses may have abandoned some traditional terrestrial haul-out sites following establishment of nearby permanent settlements. However, hunting rather than simple human disturbance was probably a factor in those cases. Frost et al. (1983:525) also mention, without details, evidence that "regular human disturbance has prevented the long-term use" of three haul-out sites in Alaska.

Cetaceans are presumably less susceptible to disturbance by increased human presence than are pinnipeds that haul out on land. However, gray whales summering close to shore at St. Lawrence Island, Alaska, have been reported to move away when persons appear or move on the shoreline (Sauer 1963). The highly variable responses of various dolphins to boats, depending largely on the past experiences of those animals with similar boats, were summarized in section 8.3.2. In several areas, small numbers of dolphins have become habituated to man, and regularly approach humans (Lockyer 1978; Connor and Smolker 1985; Shane et al. 1986). White whales show short-term localized displacement when harassed by humans, but they persist in the use of traditional estuarine summering grounds even when hunted intensively (e.g. Finley et al. 1982).

Sea otters appear to be quite tolerant of the presence of humans nearby (e.g. Calkins 1983). However, there is at least one report that numbers of otters may be reduced in areas heavily utilized by boats (Garshelis and Garshelis 1984). Riedman (1984) commented that some sea otters dove in alarm and swam away in response to a sudden intense noise combined with sight of her at a distance of 150 m.

8.10 Tolerance and Habituation

8.10.1 Tolerance

Preceding subsections have summarized the many observations of short-term disturbance reactions by marine mammals to various human activities. Although the duration and geographic extent of the short-term reactions are often not well documented, some disturbance reactions are known to be limited to brief periods and to the local area around the source of disturbance. In addition, marine mammals are often seen in regions where there is much human activity. This indicates that certain individuals or populations must exhibit tolerance of noise and other stimuli associated with human activity. Tolerance of human activities by marine mammals has rarely been studied in a specific way, but many relevant anecdotal or "common knowledge" observations can be found in the literature.

Brodie (1981a,b) points out that many baleen whales feed in the rich fishing grounds off eastern Canada where large numbers of trawlers operate. The whales do not avoid the areas where the trawlers operate. Similarly, whales continue to use the shipping lanes in the St. Lawrence estuary and off Cape Cod each year despite frequent exposure to vessel traffic (e.g. Mitchell and Ghanimé 1982; Beach and Weinrich 1989). Gray whales continue to migrate through heavily-traveled shipping lanes along the west coast of North America twice each year. Gray whales are also exposed to seismic exploration and whale-watching boats during this migration (Miles 1984; Atkins and Swartz 1989). Similarly, the western arctic population of bowhead whales continue to return to parts of the Canadian Beaufort Sea where there has been seismic exploration in previous years (Richardson et al. 1985a, 1987a). During summer, white whales occupy several estuaries that are heavily traveled by ships or boats. Indeed, because of the ubiquitous nature of ship noise in the ocean (Wenz 1962; Ross 1976), almost any deep water area where whales occur is ensonified by ship noise to some extent.

Pinnipeds also exhibit much tolerance of some human activities. Some species often haul out on man-made structures in coastal areas where there is considerable human activity, including boat traffic, aircraft traffic, and human presence (e.g. Mate and Harvey 1987; Johnson et al. 1989). Awbrey (1980:244) mentioned that marine mammals in captivity at Sea World, presumably including both toothed whales and pinnipeds, are very tolerant of the explosions and flashes associated with fireworks displays.

In at least some areas, sea otters are also tolerant of much vessel traffic (e.g. Calkins 1983). Although manatees can be disturbed in the short-term by boat traffic and human divers, they continue to use areas where they are exposed to boats and humans.

These observations indicate that many (if not all) marine mammals can tolerate some degree of chronic exposure to noise from human activities. This is so even though the mammals may show short-term behavioral reactions and localized displacement at times when they are exposed to particularly strong disturbance. However, it is not justifiable to conclude that marine mammals are unaffected by the tolerated activities. Brodie (1981b) pointed out that at least some of these animals may, because of ecological or physiological requirements, need to occupy the specific locations where they are exposed to chronic noise. Many marine mammals may have no alternative but to continue occupying areas where they are chronically exposed to noise. Payne and Webb (1971), Miles et al. (1987) and others have discussed the potential implications of masking of communication sounds by this noise. However, there is no documentation concerning the actual occurrence or implications of such masking. Likewise, it is not known whether marine mammals that are chronically exposed to human activity are subject to negative physiological effects ("stress"). These matters are discussed further in Chapter 10, "Significance of Responses and Noise Impacts".

8.10.2 Habituation

Behavioral habituation refers to the gradual waning of responses when a stimulus is not associated with any negative consequences (Thorpe 1963). Habituation has not often been demonstrated in a rigorous way during field studies of marine mammals, since this requires repeated observations on known individual animals. However, as identified in preceding subsections, a number of apparent cases of habituation have been reported, based on comparisons of the behavior of (1) one group of animals at different times, or (2) two or more groups of animals exposed to different amounts of human activity. One example is the apparent accommodation of harbor and gray seals to repeated approaches by tour-boats as opposed to their lesser tolerance of some other vessels (Bonner 1982). Similarly, harbor seals living near a major airport tolerate repeated aircraft overflights, even though harbor seals in other situations react strongly to aircraft (Johnson 1977; M. Bigg *in* Johnson et al. 1989). Spotted seals continue to be displaced from their haulout beaches by each low-altitude aircraft overflight, but they have apparently accommodated to the extent that they haul out again quickly (Frost and Lowry 1990).

In toothed whales, one apparent example of habituation is the tolerance by white whales of the many boats that occur in certain estuaries versus the extreme sensitivity of this species to the first icebreaker approach of the year in a remote area of the high arctic (see sect. 8.3.2). In certain areas, wild dolphins have become unusually tolerant of humans, and may even actively approach humans (Lockyer 1978; Connor and Smolker 1985; Shane et al. 1986).

Several cases of apparent habituation have also been reported in baleen whales. When wintering gray whales first enter the calving lagoons, they are comparatively wary of small boats. However, later in the winter they are less wary, and some individuals actively seek out motorboats (sect. 8.3.3). Watkins (1986) suggested that, near Cape Cod, reactions of various species of baleen whales changed over the years as whale-watching cruises became popular. Some species, particularly humpback and fin whales, have become less wary of boats in recent years. Dolphin (1987) reported that humpbacks off southeast Alaska initially reacted to an outboard motorboat used in his research, but soon accepted it. Malme et al. (1985) suggested that reactions of humpbacks to noise pulses from an airgun may have waned after the first exposure. Richardson et al. (1985c, 1990b) found that some bowheads occurred near actual dredges and drillships producing continuous noise even though bowheads exhibited at least weak avoidance reactions at the onset of about the same levels of drillship or dredge noise.

These observations suggest that marine mammals, like other animals, tend over time to become less sensitive to those types of noise and disturbance to which they are repeatedly exposed. However, this reduction in responsiveness is not likely to occur if the animals are harmed or harassed severely when exposed to the noise or disturbance.

8.11 Summary and Comparisons

Aircraft overflights at low altitude can cause pinnipeds hauled out on land or ice to escape into the water, occasionally leading to some mortality of young through abandonment or trampling. Toothed and baleen whales sometimes dive or turn away during overflights, but responsiveness seems to vary depending on the activity of the animals; the effects on cetaceans seem transient, and occasional overflights probably have no long term consequences on cetaceans. The relative roles of sound and vision in eliciting these reactions are unknown.

Ship and boat noise does not seem to have strong effects on pinnipeds that are in the water, but the data are very limited. Pinnipeds hauled out on land or ice often are more responsive to nearby vessels. Many toothed whales show some tolerance of vessels, but may react at distances of several kilometers or more when confined by ice or shallow water, or when they have learned to associate the vessel with harassment. White whales near ice in spring sometimes react to noise from approaching ships at distances of 50 km or more. At some other times, white whales tolerate very high levels of human activity.

Baleen whales sometimes flee from approaching ships and boats, especially from vessels that are moving rapidly, directly toward the whales, or erratically. However, there is little evidence that baleen whales travel far or remain disturbed for long after a single vessel passes. There is evidence that gray and possibly humpback and bowhead whales have reduced their utilization of certain heavily disturbed areas. However, the continued presence of various whale species in some areas heavily traveled by ships indicates a considerable degree of tolerance to ship noise.

Icebreaker noise effects on marine mammals have not been studied extensively. There is limited evidence that icebreaker traffic in winter does not reduce numbers of ringed seals present along the icebreaker tracks later in the spring.

Seismic exploration noise is more intense than noise from any other non-explosive source. There is evidence that some ringed seals abandon areas where on-ice seismic techniques (Vibroseis) are used in winter. However, the effect is very localized. Other species of seals often tolerate intense noises.

Gray and bowhead whales often have been observed behaving normally, insofar as could be determined, in the presence of strong noise pulses from seismic vessels several kilometers or more away. However, most gray and bowhead whales interrupt their prior activities and swim away when a full-scale seismic vessel approaches within a few kilometers. Also, bowheads exposed to noise pulses from distant seismic vessels often exhibit subtle behavioral changes consistent with those seen when the whales are actively avoiding a closer seismic vessel. Thus, whales exposed to noise from distant seismic ships may not be totally unaffected even if they remain in the area and continue their normal activities.

Sea otters seem less responsive than baleen whales to marine seismic exploration. Reactions of toothed whales to seismic exploration have received little study.

High explosives, when detonated underwater, produce not only a very sharp noise pulse, but also shock waves that can do physical damage to nearby animals. Mortality of pinnipeds and sea otters exposed to explosions has been documented.

Stationary offshore activities (drilling, dredging, production) often seem to have less effect on cetacean behavior than do moving sound sources such as aircraft and ships. However, avoidance responses have been demonstrated when certain whales are exposed to high levels of these sounds either near actual oil industry operations or via underwater playbacks of recorded industrial noise. Responsiveness varies considerably. However, reactions have only been found when received noise levels were well above ambient levels. Thus, the few species of cetaceans studied apparently did not react overtly if they could barely hear the industrial noise; they only reacted when it was well above the ambient noise.

Fewer data are available concerning effects of noise from drilling, dredging and production on pinnipeds, toothed whales and sea otters. Sea otters and white whales do, at least sometimes, tolerate considerable noise from such sources.

Overall, noise from certain offshore operations of the oil industry, e.g. ship and aircraft traffic, as well as noise from other human activities, sometimes causes pronounced short-term behavioral reactions and temporary local displacement of certain marine mammals (whales and hauled-out pinnipeds). Sometimes the effects are more subtle, and at other times no effects are detectable even in the presence of strong industrial noise. Some noisy activities, notably overflights of pinnipeds at haul-out sites, can cause limited mortality through stampedes or abandonment. The continued presence of various marine mammals in certain areas despite intense ship traffic and other human activities, sometimes for many decades, suggests that many marine mammals are tolerant of much human activity. However, some marine mammals may have no suitable alternative locations. It is not known whether marine mammals that tolerate chronic noise exposure are stressed or otherwise deleteriously affected.

9. ZONES OF NOISE INFLUENCE[1],[2]

9.1 Introduction

In assessing potential effects of man-made noise on marine mammals, it is important to estimate the radius around a noise source within which acoustic effects are expected. Several different criteria for defining the radius of influence have been proposed. The most extensive of these zones is the area within which the mammal might hear the noise--the *zone of audibility*. Another concept is the *zone of masking*, the area within which the noise level is high enough to interfere with detection of other sounds of interest to a marine mammal, e.g. communication calls from conspecifics, echolocation calls, prey sounds, or other natural environmental sounds. The radius of the zone of masking is strongly dependent on the intensity of the sound that the animal is trying to hear. A third concept is the *zone of responsiveness*, the area within which the animal would react behaviorally or physiologically to the noise. This zone is likely to be considerably smaller than the zone of audibility, since marine mammals often do not react to noises that are faint but presumably audible (see Chapter 8). A fourth concept, at least at a theoretical level, is the *zone of discomfort or hearing loss*. This refers to the area close to the noise source where, in the cases of strong sources, the received level of sound might be high enough to cause physical discomfort or damage to the auditory system.

This chapter begins by discussing what is known about each of these four conceptual zones of noise influence on marine mammals. This discussion depends strongly on the material presented in the preceding chapters. The source level and spectral characteristics of a man-made noise (Chap. 5), together with its rate of attenuation with increasing distance (Chap. 3), determine its level and characteristics at various distances from the source. The level and spectral characteristics of the natural ambient noise (Chap. 4) determine the range at which the received level of man-made noise diminishes below the natural background noise and becomes inaudible. The levels and spectral characteristics of marine mammal sounds (Chap. 6) affect the distance to which they can be heard by conspecifics or, in the case of echolocation sounds, the distance to which echoes from a given target can be detected. Information about the functions of the mammal sounds is important in evaluating the consequences of acoustic masking. The hearing abilities of marine mammals (Chap. 7) are obviously important in estimating zones of acoustic influence, as are the available data on their observed reactions to man-made noise (Chap. 8).

Following a general discussion of the four "zone of noise influence" concepts, this chapter includes examples of estimated zones of audibility and responsiveness. Examples are provided for the Beaufort and Bering Seas off Alaska, the California coast, the North Atlantic, and the Gulf of Mexico. For each of these areas, we estimate the effects of distance from various sources of industrial noise on expected levels and spectral characteristics of received noise. Region-specific data on sound propagation are taken into account in these case studies. We use these physical acoustic models, along with available evidence about the hearing sensitivity and

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[1] By W. John Richardson, LGL Ltd., and Charles I. Malme, BBN Systems & Technologies Corp.

[2] Constructive comments on a draft of this chapter were provided by Drs. W.C. Cummings, A.N. Popper and D. Ross.

responsiveness of certain marine mammal species indigenous to the areas in question, to estimate how far from the noise sources the zones of audibility and responsiveness may extend. Many assumptions must be made in making these predictions. This process is instructive in revealing some of the major data gaps that exist.

9.2 Zone of Audibility

9.2.1 Limitation by Ambient Noise

The ambient noise level often determines whether or not a listening animal can detect a specific sound (man-made or otherwise). This is usually so for sounds within the frequency range where the animal has good hearing abilities. Outside that optimum frequency range, detectability may be affected more by the absolute hearing threshold (sect. 9.2.2) than by ambient noise.

Masked Hearing Threshold.--If the sound from an industrial source is substantially less intense than the background noise level, the man-made noise cannot be detected, and thus cannot affect the animal. For a man-made sound to be undetectable, its received level must be substantially below the ambient level at all frequencies to which the animal is sensitive. We use the term "substantially below" rather than just "below" because some animals can detect sounds with intensities slightly less than those of the ambient noise in the corresponding frequency band (sect. 7.5.3). This may be related to the fact that some mammals seem capable of detecting intensity differences as small as 1 dB (sect. 7.3.2). When the background noise level is x dB and there is a sound signal with level $\geq x$-6 dB, the total noise level is $\geq x$+1 dB. This is a consequence of the logarithmic nature of sound measurements (eq'n 2.8).

Weak and barely-detectable sound signals may provide little or no usable information to an animal in most situations. If so, it is unlikely that industrial sounds with received levels slightly less than the background noise level in the corresponding band (i.e. signal-to-noise ratio <0 dB) would cause disturbance or other deleterious effects even if they could be heard faintly. There is little information on this point, but Malme et al. (1983) observed that gray whales swimming toward a source of killer whale sounds first reacted when S/N was about 0 dB. Given the importance of killer whale sounds to gray whales (Ljungblad and Moore 1983), this observation suggests that man-made sounds with S/N <0 dB are unlikely to affect gray whales.

On the other hand, the two species of toothed whales whose hearing has been studied in most detail (bottlenose dolphins and white whales) possess extremely good hearing abilities for high frequency echolocation sounds in the presence of noise. They can detect certain sounds with received levels several decibels less than the level of background noise in the corresponding critical band (sect. 7.5.3; Turl et al. 1987). However, their overall hearing sensitivity is much poorer at the low frequencies where industrial noises are concentrated (sect. 7.2.1).

Under special circumstances, critical ratio data can provide specific information about the level of man-made noise that would be barely detectable. Critical ratios have been measured under laboratory conditions for a few species of pinnipeds and toothed whales, but not for any baleen whales, sea otters, or sirenians (sect. 7.5.1). The critical ratio is the difference, in decibels, between the level of a tone that is barely detectable and the spectrum level of background white noise. White noise is noise with a flat spectrum, i.e. the level is the same at each frequency.

Unfortunately, critical ratio data usually provide only rough guidance about the situations in which industrial noises would be detectable in the field. The spectrum of background ambient noise is rarely flat, although it is sometimes reasonably so within certain frequency bands. More seriously, industrial noises are rarely dominated by a single pure tone. A further complication is that most measurements of critical ratios in marine mammals concern frequencies of 2 kHz and above (Fig. 7.8). The white whale is the only marine mammal for which critical ratios have been determined at the low frequencies where most industrial noises are concentrated (Johnson et al. 1989).

As a first approximation, mammals generally can barely detect a sound signal whose received level equals the level of background noise in the same 1/3-octave band. This "rule of thumb" applies, roughly, to a wide range of species, including man, in the frequency range where they have good hearing capabilities (sect. 7.5.2). However, some marine mammals probably can hear sounds with levels a few decibels less than the background noise level in the corresponding 1/3-octave band. This is most likely within the intermediate range of frequencies where (1) hearing is most acute, and (2) critical bandwidths for some species may be less than 1/3-octave (Fig. 7.9). For pinnipeds and toothed whales, hearing probably is not very acute at the low frequencies where industrial noise is concentrated. For baleen whales, specific data on hearing sensitivity are lacking, but their hearing is probably acute at low frequencies (sect. 7.6).

Masking at Low Frequencies.--In certain terrestrial mammals, there is evidence that critical bandwidths become wider (as a percent of center frequency) at frequencies below 1 kHz, and greatly exceed 1/3-octave at and below 100 Hz (Fig. 7.9B). If this is true in marine mammals, their ability to detect low-frequency man-made sounds would be poorer than implied by preceding paragraphs. Gales (1982) took account of this possibility when he estimated potential radii of audibility of industrial sounds at low frequencies. He assumed that, below 450 Hz, the critical ratio might be a constant 20 dB, and thus critical bandwidth might be a constant 100 Hz (eq'n 7.2) rather than 1/3-octave.

The only relevant data are for one white whale whose critical ratios were measured at frequencies as low as 40 Hz (Johnson et al. 1989). Below 1 kHz, critical ratios were roughly constant at about 17 dB (Fig. 7.8A), corresponding to a masking bandwidth of about 50 Hz (eq'n 7.2). Hence, the estimated masking bandwidth as a percent of center frequency did increase with decreasing frequency, and exceeded 1/3-octave at frequencies below about 200-300 Hz (Fig. 7.9A).

There are no corresponding data for other species of marine mammals. However, the white whale is apparently specialized for high frequency hearing and yet maintains narrow critical bands at frequencies as low as a few hundred hertz (Fig. 7.9A). One might speculate that baleen whales, which are believed to be well adapted for low frequency hearing, probably have narrow critical bands at low frequencies. For the case studies later in this chapter (sect. 9.7-9.11), we assume that baleen whales can barely detect a low frequency sound signal whose received level equals the level of background noise in the same 1/3-octave band. The accuracy of this assumption cannot be established with presently-available data. This uncertainty has an important bearing on the accuracy of predicted radii of audibility when ambient noise is the factor limiting hearing.

Directional Hearing.--Animals often can localize the directions of arrival of certain sound signals. They may also be able to localize some directional components of the ambient noise. When either is possible, a sound signal may be detectable farther from its source than would be the case without a directional localization ability (sect. 7.5.4). In this review, directional hearing abilities at low frequencies are especially important. Most industrial noises are concentrated at low frequencies (<1 kHz; Chap. 5), where directional hearing is difficult because of the long wavelengths.

Localization abilities of some ***toothed whales*** are good at high frequencies (≥10 kHz), and also present at frequencies of a few kHz (sect. 7.4). However, in the bottlenose dolphin, localization abilities may be effective in improving detectability only for sounds at frequencies above 18 kHz (Zaitseva et al. 1980). ***Harbor seals*** can localize sounds at 2 kHz, but the effects of this ability on detectability of weak directional sounds are unknown. There is no information on localization abilities of toothed whales or phocid seals below 2 kHz. ***Sea lions*** have limited localization abilities at frequencies as low as 500 Hz, but their directional capabilities seem more variable and generally poorer than those of toothed whales and phocid seals. Localization abilities of ***baleen whales*** have not been tested formally, but there is evidence that they can localize some sounds at frequencies as low as a few hundred Hertz (sect. 7.4).

For pinnipeds and especially toothed whales, directional hearing probably results in increased detection distances for many directional sounds at frequencies in the kilohertz range. However, it is doubtful whether directional hearing provides them with much of an advantage in hearing continuous low frequency sounds.[3] It is possible that the apparent directional hearing abilities of baleen whales assist them in detecting directional low frequency sound. However, it is impossible to make quantitative estimates, for any marine mammal, of the improvement in S/N ratio achievable through directional hearing at the low frequencies where most industrial noises are concentrated.

9.2.2 Limitation by Hearing Sensitivity

Hearing is sometimes limited by absolute hearing thresholds rather than ambient noise levels. This occurs at frequencies where the absolute hearing threshold is higher than the background noise level around that frequency. Again, it is the background noise level within the critical bandwidth that is important. As a first approximation, we assume that critical bandwidths are about 1/3-octave in width.

Figure 9.1 suggests that marine mammal hearing is sometimes limited by absolute hearing thresholds rather than ambient noise levels. This diagram shows the underwater audiograms of three species of marine mammals (from sect. 7.2) in relation to typical levels of natural background noise (from Chap. 4). The three species--white whale, fur seal, and harbor seal--represent the three major groups of marine mammals for which behavioral audiograms have been determined: toothed whales, eared seals, and hair seals. The three parallel lines show

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[3] It is possible, but unproven, that impulsive or variable low-frequency sounds with rapid onsets or decays might be localizable to some extent.

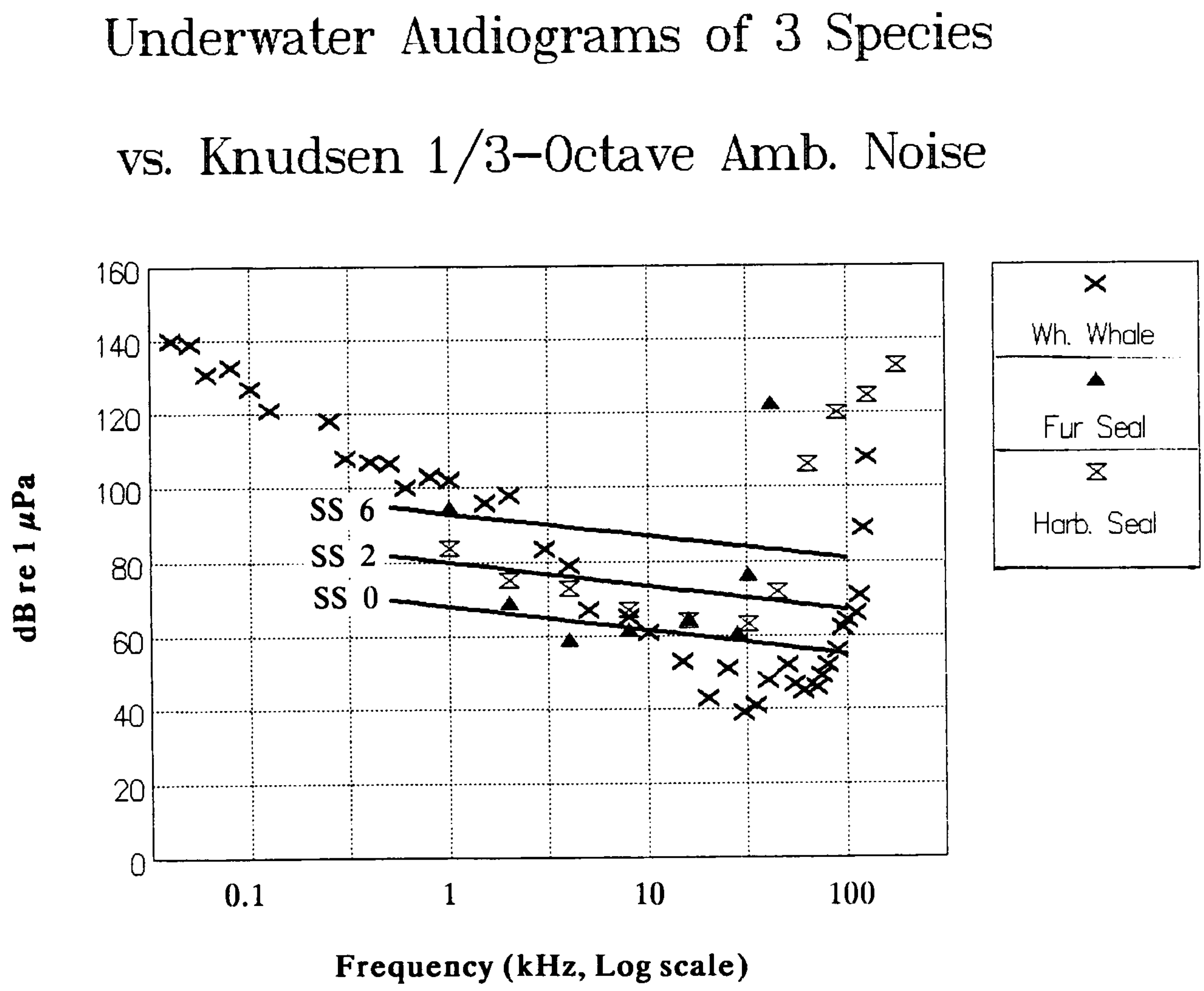

FIGURE 9.1. Underwater audiograms of a representative toothed whale, eared seal, and hair seal in relation to typical 1/3-octave ambient noise levels at three sea states. Sources are as follows: *white whale*--White et al. (1978), Awbrey et al. (1988) and Johnson et al. (1989); *fur seal*--Moore and Schusterman (1987); *harbor seal*--Møhl (1968a); *ambient noise*--Knudsen et al. (1948), converted to 1/3-octave basis.

approximate 1/3-octave band levels of ambient noise with low, moderate and high sea states, based on Knudsen et al. (1948).

The white whale has very sensitive hearing at high frequencies (10-100 kHz), but its hearing thresholds increase steadily as frequency decreases below 10 kHz. At low frequencies, the white whale's hearing is apparently limited by its high absolute hearing thresholds rather than by ambient noise (Fig. 9.1). Under high sea state conditions (SS 6), the absolute threshold of the white whale is above the typical natural ambient noise level at frequencies below ~2 kHz. Under calm conditions (SS 0), the absolute threshold is above the typical ambient noise level below ~10 kHz. Under typical (SS 2) conditions, the white whale is threshold-limited below about 4 kHz. In contrast, the white whale's hearing is limited by ambient noise at frequencies from a few kilohertz up to about 100 kHz, since absolute hearing thresholds are lower than typical ambient noise levels within this frequency range (Fig. 9.1).

Although the fur seal and harbor seal have poorer hearing sensitivity than the white whale at high frequencies, these pinnipeds apparently have better underwater hearing sensitivity than white whales between 1 and 4 kHz (Fig. 9.1). Hence, these pinnipeds are apparently noise-limited rather than threshold-limited down to slightly lower frequencies than are white whales. However, under typical (SS 2) conditions, these pinnipeds appear to be threshold-limited below ~1500 Hz. Even under windy conditions (e.g. SS 6), these pinnipeds may be noise-limited at frequencies below ~1 kHz.

The specific frequency ranges within which a given animal's hearing is threshold- vs. noise-limited depend strongly on the prevailing ambient noise conditions. As summarized in Chapter 4, ambient noise levels vary widely. However, Figure 9.1 suggests that, for many ambient noise conditions, the white whale is threshold-limited rather than noise-limited at the low frequencies where most industrial sounds are concentrated. The situation is less clear-cut for some pinnipeds, which may be noise-limited even at frequencies below 1 kHz, at least under windy conditions.

The above analysis assumes that the critical bandwidth is about 1/3-octave. In the case of the white whale, critical ratios have recently been measured at frequencies as low as 40 Hz (Johnson et al. 1989). These data allow more precise predictions about the situations when hearing is threshold- rather than noise-limited. The critical ratio represents the amount by which a received tonal signal must exceed the spectrum level of the background noise if the signal is to be heard. In the white whale, the critical ratio is about 17 dB at frequencies from 40 to 1000 Hz (Fig. 7.8). The absolute thresholds of the white whale decrease from ~140 dB at 40 Hz to 100 dB at 1000 Hz (Fig. 9.1). Thus, the white whale would be expected to be threshold-limited if the spectrum level of the ambient noise were less than 123 dB at 40 Hz or 83 dB at 1000 Hz. At these frequencies, ambient noise is almost always below these levels (Chap. 4; Urick 1983). In contrast, at 10 kHz, the absolute hearing threshold of the white whale is ~60 dB and the critical ratio is ~25 dB. Thus, at 10 kHz, this species would be threshold-limited only if the spectrum level of ambient noise were below ~35 dB, which is uncommon.

In summary, critical ratio data for the white whale are consistent with the more generalized analysis of Figure 9.1. Both approaches show that hearing by this species is typically threshold-limited at frequencies below a few kilohertz, and noise-limited at higher frequencies.

When hearing is threshold-limited, the maximum range of audibility of an industrial noise source will be limited by auditory sensitivity rather than by ambient noise conditions. The industrial noise level will fall below the hearing threshold before it reaches the ambient level (e.g. Fig. 9.2A). If the industrial noise is too faint to be heard, the animal will not be disturbed by it. This would be true even if the industrial noise level were still above the background noise level and thus detectable by instruments or by other species whose hearing at the relevant frequencies is more sensitive. In this case, the maximum possible zone of potential noise influence would be smaller than that suggested by considering ambient noise alone

In other situations, hearing will be noise-limited. This will occur when ambient levels are high or when the species has sensitive hearing at the frequencies where the industrial noise is concentrated. In these cases, the absolute hearing threshold will be lower than the typical level of ambient noise. The maximum radius of potential noise influence will be determined by the ambient noise level rather than absolute hearing threshold (Fig. 9.2B).

No data on hearing sensitivity are available for baleen whales. We assume that their auditory systems are very sensitive to low frequency sounds (sect. 7.6), since most baleen whale calls are at frequencies below 1000 Hz (sect. 6.1). If this assumption is correct, then baleen whales will be noise-limited rather than threshold-limited at the low frequencies where many industrial noises are concentrated. Thus, the maximum radius of influence of low frequency industrial noise on baleen whales is likely to be that where the industrial noise level diminishes below the ambient noise level (Fig. 9.2B). However, this is an assumption rather than an established fact.

There is no information about the significance of the very low frequency components of industrial noise to marine mammals. Infrasounds are defined here as sounds at frequencies <20 Hz. The species most likely to be able to hear infrasounds are the baleen whales. Some baleen whales emit sounds at frequencies ≤20 Hz (sect. 6.1). It can be assumed that they can hear sounds at those frequencies, and probably at somewhat lower frequencies as well. Besides the lack of data on hearing sensitivity at low frequencies, the open literature contains few data on source levels of industrial infrasounds, on their propagation losses, or on the levels of infrasonic ambient noise. Although source levels of infrasounds may be high (e.g. Cybulski 1977; Gales 1982; Hall and Francine 1990), they probably attenuate rapidly in most continental shelf waters.

In ***summary***, the maximum possible radius of influence of an industrial noise on a marine mammal is the distance from the noise source at which the noise can barely be heard. This distance can be determined by either the hearing sensitivity of the animal or the background noise level, depending upon the circumstances. Industrial sounds often are dominated by low frequency components. ***Toothed whales*** and some ***pinnipeds*** are not highly sensitive to these low frequencies. Hence, for these animals, the maximum radius of audibility of industrial sounds may often be determined by the hearing sensitivity of the animals rather than the background noise level. The radius of audibility of higher-frequency man-made sounds, e.g. at 5-30 kHz, will normally be limited by the background noise level, since toothed whales and many pinnipeds are more sensitive to high than to low frequency sounds. ***Baleen whales*** are assumed to be quite sensitive to low frequency sounds. Thus the maximum radius of audibility

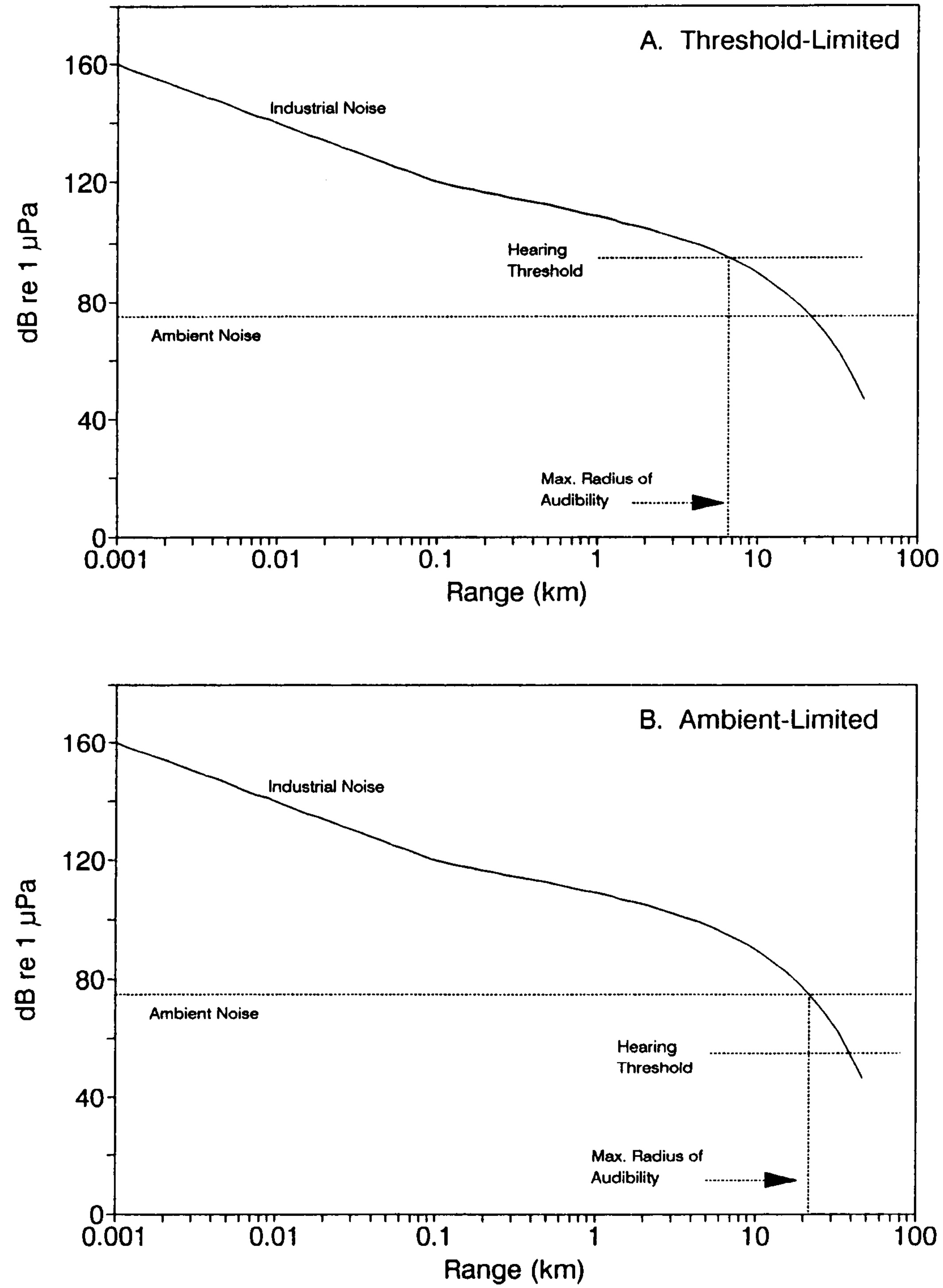

FIGURE 9.2. Schematic representation of the maximum radius of audibility of an industrial noise when the hearing threshold is *(A)* higher and *(B)* lower than the ambient noise level in the critical band. In (A), the industrial noise level diminishes below the hearing threshold before it diminishes below the ambient noise level; maximum radius of audibility is threshold-limited. In *(B)*, the industrial noise level diminishes below the ambient noise level first; maximum radius of audibility is ambient-limited.

of low frequency industrial noise to these animals is expected to be determined by background noise levels. The sensitivity of baleen whales to infrasounds is unknown.

Because the maximum radius of audibility can depend on the hearing ability of the receiving animal, this radius may vary widely depending on the type of animal under consideration. If an industrial noise is at low frequencies, the maximum radius of audibility will be greater for a species with good low frequency hearing (e.g. a baleen whale) than for another species whose low frequency hearing is less sensitive (e.g. a white whale).

Although the maximum radius of audibility of the industrial noise is the maximum potential distance at which the noise could affect marine mammals, it should not be assumed that industrial noise has deleterious effects at such large distances. As discussed in Chapter 8, many species of marine mammals seem to tolerate levels of industrial noise well above their known or presumed auditory thresholds.

9.3 Zone of Masking

Man-made noise can interfere with the detection of acoustic signals such as communication calls, echolocation sounds, and other environmental sounds that may be important to marine mammals. If the noise level is high enough relative to the received level of the acoustic signal, the latter will be "masked" and undetectable. At least in theory, a source of industrial noise will be surrounded by a region within which masking may occur--the "zone of masking". The size of this zone is highly variable, even for a single marine mammal and a single type of industrial noise. The maximum radius of masking depends on several factors. Among the most important of these is the received level of the industrial noise relative to that of the sound signal.

9.3.1 Relative Distances and Levels of Signal and Masker

Any man-made noise strong enough to be audible, i.e. to be detectable above natural background noise, will increase the total background noise (natural plus man-made). This will interfere with an animal's ability to detect a sound signal if the signal is weak relative to the total noise level. Thus, the maximum radius of audibility of a man-made noise is also the maximum theoretical radius where the noise might impair the ability to detect other sounds of interest. However, only the weakest and most marginally-detectable signals would be masked by the slight increase in background noise occurring at the maximum radius of masking. Stronger sound signals would be masked only if the listening animal were closer to the source of man-made noise.

For a receiving animal close to an industrial site, the industrial noise level will be high and the animal will be able to hear only nearby animals whose calls have high received levels. For a receiving animal farther from an industrial site, the industrial noise level will be lower and the animal will be able to hear weaker calls from more distant animals. The same arguments apply to detection of other environmental sounds that may be of interest to the animals. The only noise that is relevant is that within the masking bandwidth, perhaps 1/3-octave wide, centered at the frequency of the signal (sect. 7.5).

The main factors affecting detection of a sound signal in the presence of background noise (natural or man-made) are related as follows:

$$L_r/N_r = L_s - TL - N_r + G \qquad (9.1)$$

where L_r/N_r = Signal-to-noise ratio at the receiving whale, considering frequencies in the masking bandwidth, possibly 1/3rd octave wide;

L_r = received level of sound signal in the masking band;

N_r = noise level (natural + man-made) at the receiver within the masking band,

$$N_r = 10 \log (\text{alog}\,[N_{nat}/10] + \text{alog}\,[N_{mm}/10]\,); \qquad (9.2)$$

L_s = source level of sound signal in the masking band;

TL = transmission loss from source to receiver;

G = gain factor--an adjustment for receiver properties, such as directional discrimination.

Some specific L_r/N_r value, e.g. 0 dB, is required to detect a sound signal. An *x* dB increase in the noise level (natural or man-made), or an *x* db decrease in the source level of the signal, will reduce L_r/N_r by *x* dB. This will reduce the radius within which mammal calls or other sounds will be detectable. The degree of reduction will depend strongly on the transmission loss rate if other factors (e.g. the source level of the signal) are unchanged. For example, the expected reduction in detection distance when total noise level increases by 3-20 dB is as follows:

	3 db	6 dB	10 dB	20 dB
Spherical spreading	29 %	50 %	68 %	90 %
Cylindrical spreading*	50	75	90	99

* As discussed in Chapter 3, propagation loss often is intermediate between the spherical and cylindrical rates; cylindrical spreading does not occur close to the source.

Thus, dramatic reductions in maximum potential radius of communication will result if noise levels are increased by 10 or 20 dB while other factors remain unchanged. This is especially true when cylindrical spreading is occurring. Species that may communicate acoustically over long distances, such as some baleen whales, would be most seriously affected. There is little information about the functions of most marine mammal calls. Hence, it is impossible to predict the effects of a reduction in the range to which these calls are detectable. It has been suggested (Payne and Webb 1971) that some baleen whales may use powerful low frequency calls to communicate over very long distances. However, we know of no evidence that whales respond to one another over ranges greater than about 20-25 km (Watkins 1981b).

Miles et al. (1987) examined the potential masking of bowhead whale calls based on measured sound propagation conditions at a site in the Alaskan Beaufort Sea. Their examples illustrate how the source level of the whale call (or other sound signal) greatly affects the severity of masking by industrial noise. Estimated source levels of bowhead calls vary widely (Cummings and Holliday 1985, 1987; Clark et al. 1986), although some of this variability is probably artifactual (sect. 6.1.1). A faint call (e.g. 140 dB re 1 µPa-m) can be masked even by a distant source of industrial noise (e.g. a 170 dB source 30 km away) unless the calling and listening whales are close together (<0.7 km in this case). However, as a rough approximation, strong bowhead calls can be heard if the listening whale is closer to the calling whale than to the source of industrial noise. This is true for calls comparable in level to typical industrial noise sources, i.e. about 170-180 dB. Thus a whale 20 km from such an industrial source might hear intense calls from other whales within ~20 km, a whale 5 km from the source might hear intense calls from whales within ~5 km, etc. (Miles et al. 1987). This approximation would require modification in the cases of species whose calls are weaker or stronger than typical industrial noise levels.

Distant sources of industrial noise are unlikely to mask short-distance acoustic communication. The noise level received from a distant industrial site, even if it is audible, is likely to be well below the received level of calls from a nearby mammal. However, acoustic communication is more likely to be prevented when marine mammals are close to industrial sites, or when they are listening to distant conspecifics. In both of these cases, the received level of the industrial sounds might be similar to or greater than that of the mammal calls. The radius of masking by industrial noise is greater when the sound signal is little above the natural background level than when it is much above that level. In the extreme case when the signal is barely detectable in the absence of the industrial noise, the radius of masking might equal the radius of audibility of the industrial noise. This would occur because, in this case, even a small increase in the background noise level would raise the total background noise level (natural plus man-made) above the level of the signal.

9.3.2 Adaptations for Reduced Masking

Besides the dependence on signal source level and on relative distances of the receiving animal from the signal and noise sources, there are other reasons why no single radius of masking can be defined. These reasons include

- possible adjustments in call intensity as a function of background noise conditions,
- possible adjustments in call frequency,
- directional hearing capabilities, and
- variations over time in received levels of interfering noise.

Little is known about the roles of these processes in marine mammal hearing, but they have the potential to greatly reduce masking effects (sect. 7.5.4).

Source levels: Source levels of the calls of most marine mammals have not been studied in much detail. However, in at least a few species, source levels of calls vary widely (Chap. 6). Echolocating bottlenose dolphins sometimes adjust the source levels of their echolocation pulses as a function of the background noise level (Au et al. 1974). They apparently emit more intense pulses when the background noise is strong. Most industrial sounds will not mask echolocation sounds because most industrial noise is at much lower frequencies. However, communication calls and industrial noise often overlap in frequency. Masking of communication calls by industrial noise would be less common if marine mammals vary the intensity of their calls as a function of (1) background noise conditions, (2) "intended" communication distance, or both.

Miles et al. (1987) provided an example of this in their theoretical analysis of masking of bowhead whale calls by industrial sources in the Beaufort Sea. They considered a receiving whale 12 km from a 170 dB industrial source. It would be able to hear a calling whale only up to ~3.3 km away if the source level of the calls was 160 dB, but ~30 km away if the source level was 180 dB. However, adaptation of call intensity to background noise level has been demonstrated only in toothed whales, and only for echolocation calls--not for communication calls.

Frequency adaptation: Some toothed whales seem able to adjust the frequencies of their echolocation calls, within limits, in order to avoid frequencies where background noise levels are high (Au et al. 1974, 1985). It is not known how much flexibility various marine mammals may have in adjusting the frequencies of their communication calls. However, most species either produce broadband calls containing energy at a variety of frequencies or, at different times, produce narrowband calls at varying frequencies. When communication at one frequency is masked by strong man-made noise, the calls or call components at other frequencies may still be audible. It is not known whether marine mammals take advantage of this phenomenon by emitting communication calls dominated by frequencies subject to little noise interference.

Directional hearing: The directional hearing abilities of many marine mammals (sect. 7.4) imply that the gain factor G in eq'n (9.1) may be non-zero. If so, the maximum masking potential of industrial noise would only occur when an animal attempts to listen to a signal arriving from the same direction as the industrial noise. There is some evidence that, in toothed whales, directional hearing abilities are helpful in reducing masking at the high frequencies used for echolocation but not at the low-moderate frequencies used for communication (Zaitseva et al. 1975, 1980; Au and Moore 1984). In this respect, the ratio of sound wavelength to the spacing between the auditory organs is probably important.

The long wavelengths of low frequency sounds limit directional hearing at low frequencies. Because of their large sizes, baleen whales are the animals in which directional hearing is most likely to be important in reducing masking by low frequency industrial sounds. There is no direct evidence that the known directional hearing abilities of some marine mammals reduce masking at low frequencies. However, it is suspected that this occurs, at least in large whales.

Temporal variations: Industrial noise levels often vary over time because of varying source levels and varying propagation conditions. Thus, masking by industrial noise may be intermittent, just as masking by natural ambient noise must depend strongly on daily variations in sea state and other factors affecting natural ambient noise. Animals for which faint sound signals are important must be adapted to periodic natural masking, and presumably can tolerate occasional masking by man-made sounds.

In general, communication calls and other natural sounds important to marine mammals are undoubtedly masked by man-made and natural noise under some conditions. Some of the controlling factors are known from physical principles and auditory studies on captive toothed whales and pinnipeds. However, there is virtually no specific information about the nature and effects of masking under field conditions, nor about the adaptations that marine mammals may use to reduce masking. The few relevant data on masking have come largely from studies of high frequency echolocation by toothed whales. Echolocation calls are subject to masking by high frequency noises. However, echolocation is unlikely to be masked by most industrial noises, which tend to be concentrated at low frequencies. Industrial masking is more likely to affect detection of communication calls and natural sounds that may be important to some species (surf noise, ice noise, prey noise, etc.).

9.4 Zone of Responsiveness

We define the "zone of responsiveness" to be the area around an industrial activity within which a significant fraction of the marine mammals exhibit observable behavioral responses to that activity. In this report, we consider only the reactions to noise. Noise is often the stimulus detectable farthest away from a human activity. However, in a field situation, reactions may be to another stimulus, such as the visual appearance or perhaps the odor of the industrial site, or to a combination of stimuli.

The studies summarized in Chapter 8 indicate that many marine mammals react overtly to various man-made noises. Typically, there is no reaction when the industrial activity is beyond a given distance, and a reaction when the industrial activity is closer. However, the distance at which reactions become evident varies widely, even for a given species and a given human activity. Also, in many cases the reactions become stronger as the human activity becomes closer. Thus, the "zone of responsiveness" is a real phenomenon for many species and human activities, but its size varies. It can be considered a statistical phenomenon, in that a small percentage of the animals may react at a relatively long distance, a larger percentage may not react unless the human activity is somewhat closer, and a small percentage may not react unless it is closer still. Malme et al. (1984) formalized this concept by estimating the distances and received noise levels at which 10%, 50% and 90% of the migrating gray whales reacted to various industrial noises.

Many marine mammals have been observed to behave normally, insofar as could be determined, well within the areas where man-made noise was detectable, at least by hydrophones or microphones (Chap. 8). In many of these cases, the animals apparently behaved normally at locations well within the "zone of audibility" around an industrial site. In other cases, the animals were well within the area where the noise was detectable by man's instruments, but it is possible that the noise may not have been detectable by the marine mammals in question. This might sometimes occur when toothed whales are near sources of low frequency man-made noise, to which their hearing is not very sensitive (Chap. 7). In these cases, further analysis is desirable to assess whether or not the sounds were detectable by the animals, given what is known about the frequency-dependence of their hearing sensitivity.

9.4.1 Behavioral Indications of Disturbance

Avoidance reactions are the most obvious manifestations of disturbance. Avoidance responses can be strong or weak. For example, animals may swim rapidly and directly away from a noise source, or they may swim at a more normal speed with only a slight tendency to move away (Chap. 8). Migrating whales may avoid stationary industrial sites on their original course by deflecting their course slightly (e.g. by ~30°) to one side as they approach the industrial site (Malme et al. 1983, 1984; LGL and Greeneridge 1987). This allows them to pass well to the side of the industrial site without making a very large change in course, and without a significant increase in the length of their migration. Nonetheless, this change in course constitutes a form of avoidance. Pinnipeds hauled out on beaches or ice may stampede abruptly into the water, or they may move less quickly, perhaps leaving a fraction of the individuals on the haul-out site (Chap. 8). All of these behaviors represent avoidance, but there is a gradation in the apparent severity of disturbance.

Other changes in behavior besides avoidance have been recognized as indicative of disturbance. Pinnipeds hauled out on land or ice often become alert in the presence of noise from an approaching aircraft or vessel (Chap. 8). This alert response may be the only manifestation of disturbance, or it may be followed by avoidance (movement into the water). Similarly, cetaceans may change their general activities in the presence of man-made noise. At the onset of man-made noise, cetaceans that have been resting or socializing at the surface often begin to dive or to travel slowly. This travel is not necessarily oriented away from the noise source, so it may not be classifiable as avoidance.

In cetaceans, mean durations of surfacings and dives, number of blows per surfacing, and intervals between successive blows often are affected by the presence of man-made noise. When bowheads and gray whales are exposed to man-made noise, it is common to see shorter surfacings and dives than normal, and fewer blows per surfacing (Richardson et al. 1985b,c, 1986, 1990b; Malme et al. 1988). In some cases, generally with distant noise sources, these changes in surfacing, respiration and diving behavior have been seen in the absence of directed avoidance behavior. These changes in surfacing, respiration and diving behavior are amenable to quantification. They may be useful as indicators of stress in some situations when overt avoidance reactions do not occur.

9.4.2 Possible Response Criteria

Some attention has been given to the question, "How should one attempt to measure or define the circumstances within which a marine mammal will respond to man-made noise?". The most appropriate procedure is likely to involve an estimate of the minimum level of man-made noise that causes marine mammals to react. Acoustic thresholds of this type have rarely been determined in the field. More commonly, field researchers have estimated the distance from the noise source at which responses first occur (Chap. 8).

One possibility is that, under defined conditions, a given species of marine mammal is likely to react if the received sound level exceeds some specific level, e.g. 120 dB re 1 µPa in some specified bandwidth. If sufficient data are available, it may also be possible to specify what percentage of the animals react at various received noise levels. The one situation in which this has been done is for migrating gray whales reacting to several types of oil industry sounds. For example, in the presence of drillship sound, 10% of the gray whales exhibited avoidance behavior when the received broadband sound level was 110 dB, 50% at 117 dB, and 90% at 122 dB (see Table 8.1 in sect. 8.8; from Malme et al. 1984:9-6).

It is not certain what frequency band should be considered when deriving response criteria. In deriving the values in Table 8.1, Malme et al. (1984) considered broad bands that included all frequencies where there was significant energy. However, mammalian hearing processes tend to be affected primarily by those sounds within the same 1/3-octave band (Chap. 7). Hence, it is possible that a more appropriate response criterion would be the sound level in the 1/3-octave band containing the most intense noise. A further important restriction would be that one should consider only those 1/3-octave bands that are within the frequency range where hearing abilities are good.

Response criteria based on 1/3-octave bands would be expected to be somewhat less than those based on broad bands. The sound level in a given 1/3-octave band cannot be greater than that in any broader band containing that 1/3-octave; the 1/3-octave level is usually less than the broadband level. Richardson et al. (1990b) estimated the received levels of drilling and dredging sounds at which roughly half of the summering bowhead whales reacted. The response "threshold" was ~115 dB re 1 µPa on a broadband (20-1000 Hz) basis, and ~110 dB in the 1/3-octave band where the industrial sound was most prominent.

Another possibility is that the signal-to-noise ratio (i.e. industrial noise to ambient noise ratio) may be more important than the absolute level of industrial noise. Intuitively, one expects that a 100 dB industrial noise level will be more disturbing when the ambient noise level in the corresponding band is 80 dB than when it is 90 db or especially 100 dB, i.e. when the signal-to-noise ratio is 20 dB than when it is 10 or 0 dB. At S/N = 0 dB, the industrial noise is probably virtually undetectable. Richardson et al. (1990b) estimated that roughly half of the summering bowhead whales reacted to drilling and dredging sounds when their broadband received levels were ~20 dB above the ambient noise level, or when the level in the most prominent 1/3-octave band was ~30 dB above the ambient level in that band.

Richardson et al. (1990b) made rough estimates of the response thresholds that would apply to summering bowheads based on each of the above four procedures, *viz* broadband absolute levels and S/N ratios, and 1/3-octave absolute levels and S/N ratios. However, Richardson et al. were not able to determine which of these criteria was most appropriate. Their sample sizes were too small, the responses of different whales were too variable, and the various sound levels and S/N ratios were too highly intercorrelated. To date, no other study of marine mammal disturbance has attempted to evaluate which criterion is most appropriate.

In general, acoustic annoyance reactions in humans correlate better with the absolute level of the intruding noise than with its S/N ratio (Robinson et al. 1963). However, when the background noise level is not much less than the received level of the intruding noise, the threshold of annoyance is shifted upward (Spieth 1956; Pearsons 1966) and the S/N ratio is the more relevant parameter. As a result, the usual practice in determining human annoyance criteria for specific types of noise involves using psychoacoustic testing procedures to measure the sound levels that produce a quantifiable level of annoyance. Correction factors based on prevailing background noise levels in specific locations may then be applied (Kryter 1985).

At this time, it is not possible to determine with any confidence whether marine mammal disturbance criteria should be based on broadband sound measurements, 1/3-octave data, or some other bandwidth. It is also not known whether absolute or relative (S/N) criteria should be used.

From a management or mitigation perspective, guidelines based on distance rather than received sound level or S/N ratio may be the only practical ones. In some regions whale-watching vessels are subject to guidelines indicating that they should not approach closer than some fixed distance (Atkins and Swartz 1989). Permits issued to operators of seismic vessels sometimes indicate that they should shut down their airguns or other noise sources if whales are seen within some specified distance, or if monitoring to confirm the absence of whales within such a distance is temporarily impractical (Reeves et al. 1984). Leases for offshore hydrocarbon exploration sometimes state that helicopters or other support aircraft should maintain a specified minimum altitude either at all times or when overflying concentrations of marine mammals.

These types of distance criteria are comparatively simple to specify, implement, and monitor for compliance. However, distance criteria suffer from the drawback that received sound level and distance are imperfectly correlated. The received level of industrial noise is strongly and inversely related to distance, but it is also affected by such factors as water depth, bottom and surface conditions, and the vertical profile of temperature and salinity (Chap. 3). Thus, the received sound level *x* km from a specific human activity may vary considerably from time to time or place to place even if the source level remains constant. Furthermore, the source level of the noise emitted by a given human activity may vary from time to time, and there is additional variation in the emitted levels from different sources of a specific class (e.g. different seismic boats or different aircraft). If we assume that acoustic disturbance is related in some way to the received sound level, then it is apparent that criteria based on distance rather than sound level are less than ideal. However, guidelines or regulations based on sound levels would be much more difficult apply, since sound level is more difficult to measure than is distance.

A partial solution may be to consider data that are as site-, activity- and species-specific as possible when formulating distance criteria. In the case of aircraft disturbance, rather than apply a single altitude criterion to all situations, two or three different criteria might be developed for various combinations of habitat (e.g. coastal haul-out sites vs. at sea), aircraft type, and species. In the case of whale-watching, different criteria might apply for different regions, for small vs. larger vessels, or for mother/calf pairs vs. other animals. By refining the criteria in this way, some allowance could be made for regional variations in sound propagation conditions, and for species, regional, or other consistent variations in the responsiveness of marine mammals.

9.4.3 Variations in Responsiveness

Marine mammals show wide within-species variations in responsiveness to man-made noise. They sometimes continue their normal activities in the presence of high levels of noise from boats, seismic exploration or stationary industrial sites. At other times, members of the same species exhibit strong avoidance at much lower levels of man-made noise (Chap. 8). There are doubtless several reasons for this variation, some physical and some biological.

Physical Factors.--***Variability and rate of change of the sound*** is an important factor. There are many reports that marine mammals are more responsive to sounds with varying or increasing levels than to steady sounds (Chap. 8).

Sound propagation conditions undoubtedly account for some of the observed variation in radius of noise influence on marine mammals. Even if responsiveness remains constant, in terms of threshold noise level or signal-to-noise ratio, variations in propagation conditions can cause dramatic differences in the expected reaction distances. For example, Miles et al. (1987) showed that, within the Alaskan Beaufort Sea, there are significant geographic variations in sound attenuation rates (e.g. Fig. 9.3). They also showed that there can be significant seasonal differences in attenuation at a given site, depending on variable water mass characteristics and sound frequency (Fig. 9.4; see also Chap. 3). As a result of these geographic and temporal variations in propagation conditions, received sound levels will drop below any specified threshold at widely varying distances from the noise source (Fig. 9.3, 9.4).

Although sound propagation conditions are expected to have strong effects on the radius of responsiveness, there are few specific data on this point. Watkins and Goebel (1984) described a situation in which variations in sound propagation conditions appeared to affect the radius of influence of vessel noise on humpback whales. Also, walruses hauled out on ice tend to react at greater distances when a ship approaches downwind than upwind (Fay and Kelly 1982; Fay et al. 1986). This may be related, in part, to the effects of wind direction on airborne propagation of sound (sect. 3.6).

Background noise levels may also affect the apparent responsiveness of marine mammals to man-made noise if the response threshold is a given signal-to-noise ratio rather than a given absolute sound level (sect. 9.4.2). Background noise levels can vary by ±10 or even ±20 dB from day to day. This variation in background noise levels causes drastic changes in the distances within which man-made sounds can be heard and within which they are 10, 20 or 30 dB above the ambient noise level (e.g. Fig. 9.5). If the response threshold is a specific S/N ratio, a 20 dB increase in background noise level is expected to reduce the response distance severalfold (e.g. Fig. 9.5B vs. 9.5A). Conversely, a 10-20 dB reduction in background noise level is expected to increase the response distance significantly.

It is uncertain whether absolute levels or S/N ratios are more important to marine mammals, but noise annoyance studies in humans indicate that S/N is sometimes important (sect. 9.4.2). Variations in ambient noise level will affect the maximum radius of responsiveness only if the probability of reaction is related to the S/N ratio of the man-made sound. If the probability of reaction is related to absolute received level of the man-made sound rather than to its S:N ratio, the radius of responsiveness is not expected to change when ambient noise level changes.

Thus, reaction distances are likely to vary because of changes in propagation conditions and perhaps in background noise levels. Improved propagation conditions or reduced background noise levels can reasonably be expected to double or triple the average reaction distance in some situations. Conversely, with poorer than average propagation conditions or higher than average ambient noise levels, the reaction distance is expected to be no more than half of the average value. Superficially, these changes in reaction distances seem to represent changes in the responsiveness of the animals. In fact, variations of this magnitude are expected to occur even if the actual responsiveness of the animals, in terms of threshold noise level or S/N ratio, remains constant.

Biological Factors.--***Activity*** of the animals often seems to be important. In baleen whales, single whales that are resting quietly seem more likely to be disturbed by a given human activity than are groups of whales engaged in active feeding, social interactions, or mating (Payne et al. 1983; Krieger and Wing 1984, 1986; Richardson et al. 1985b,c; Gaskin 1987).

Age and sex classes sometimes seem to vary in responsiveness (e.g. Salter 1979; Calkins 1983; Ljungblad et al. 1983:47).

Habitat or physical situation of the animals can also be important. For example, walruses hauled out on ice seem much more responsive to approaching boats than are walruses in the water (Fay et al. 1986). Bowhead whales whose movements are partially restricted by shallow water or a nearby shoreline may sometimes be more responsive to noise (Richardson et al. 1985b,c). Vessel traffic may have stronger influences on white whales when their movements are partially confined by ice (sect. 8.3.2).

Habituation, the gradual waning of responsiveness when a stimulus is not associated with negative consequences, is doubtless responsible for some of the variation in responsiveness of marine mammals to man-made noise. Some apparent examples of habituation by marine mammals are listed in section 8.10.2. Conversely, ***sensitization*** may occur: animals that associate a specific sound with severe harassment may be especially responsive to that sound (Norris et al. 1978; Irvine et al. 1981).

Individual variation in the responsiveness of different animals is to be expected even after allowing for all of the physical and biological factors mentioned above. This inherent individual variability cannot be demonstrated in field conditions, where there is little or no control over either the external factors or the animals. However, the hearing sensitivity of captive animals under controlled conditions has been found to vary from time to time, presumably reflecting some motivational factor. Some audiograms shown in section 7.2 are averages; others are from single animals. Actual sensitivity can vary above or below these values. There probably are similar motivation-related variations in hearing sensitivity and behavioral responsiveness under field conditions.

Variation in responsiveness among different individuals, or for one individual at different times, may greatly affect the radius of responsiveness. Figure 9.6 shows the theoretical effect of a ±10 dB change in responsiveness (threshold equals S/N 10-30 dB). In the situation illustrated, the theoretical maximum radius of responsiveness ranges from about 2 km to <60 m.

In general, several physical and biological factors are known or suspected to affect the responsiveness, actual or apparent, of a given species of marine mammal to man-made noise. As a result, the maximum radius of responsiveness can vary widely between individuals, between locations, and over time. Thus, the radius of responsiveness, even for a specific type of man-made sound and a particular species, is a variable rather than a constant. Field studies of behavioral responsiveness can provide at least a limited ability to predict the radius of responsiveness under specific conditions. However, even after intensive work of this type, there will undoubtedly be unexplained individual variation in the acoustic threshold of responsiveness and in the corresponding radius of responsiveness. Thus, whenever a criterion of responsiveness is stated, there should be a statement about the situation to which it applies, and the fraction of the animals expected to react at this radius.

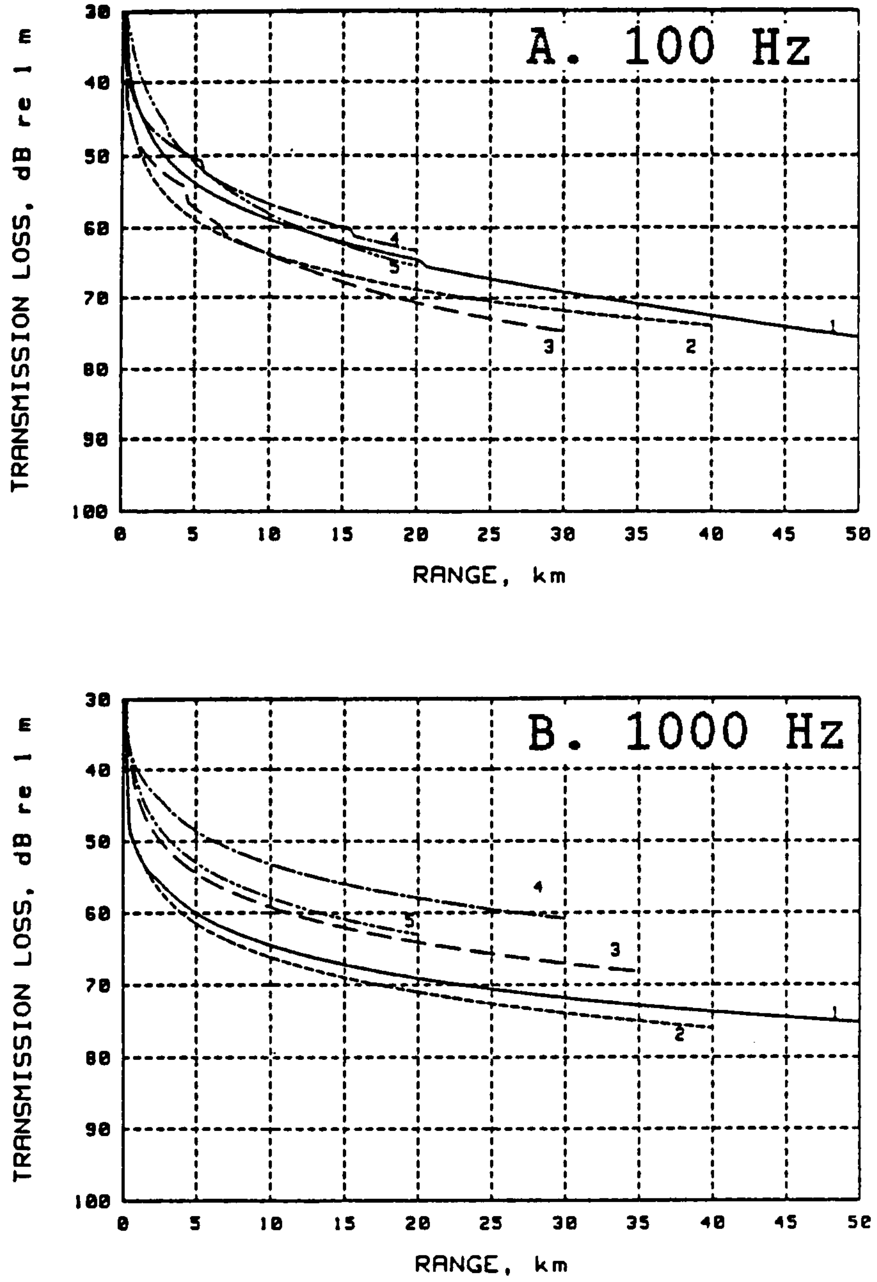

FIGURE 9.3. An example of geographic variation in sound attenuation at *(A)* 100 Hz and *(B)* 1000 Hz. Curves show predicted propagation loss at five sites in the Alaskan Beaufort Sea. All curves refer to conditions with neutral sound speed profiles. All curves are based on propagation models fitted to direct field measurements. From Miles et al. (1987:146).

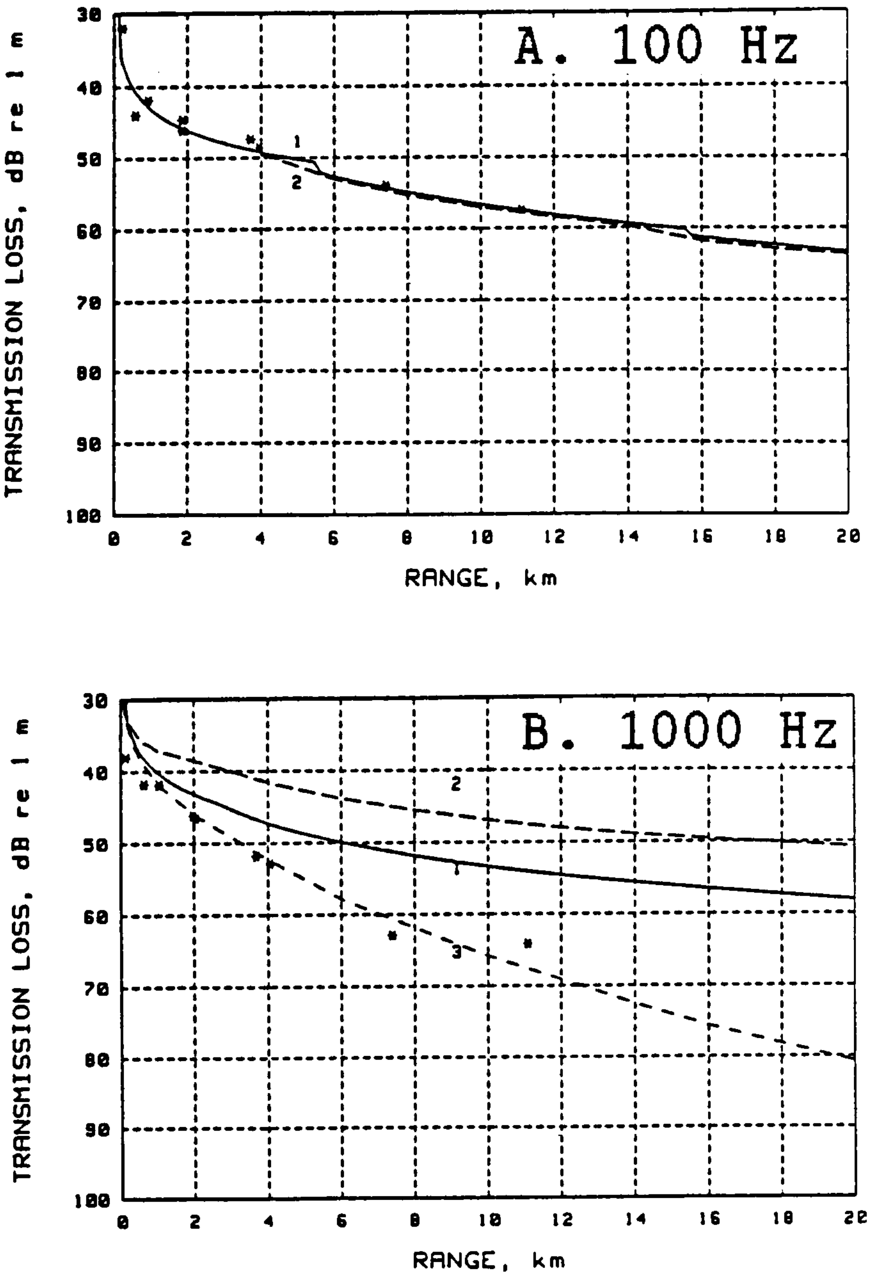

FIGURE 9.4. An example of seasonal variation in sound attenuation for *(A)* 100 Hz and *(B)* 1000 Hz. Curves show predicted propagation loss in the Alaskan Beaufort Sea with (1) neutral sound speed profile, (2) surface duct, and (3) downward refraction. Asterisks represent field measurements under downward refraction conditions. From Miles et al. (1987:137).

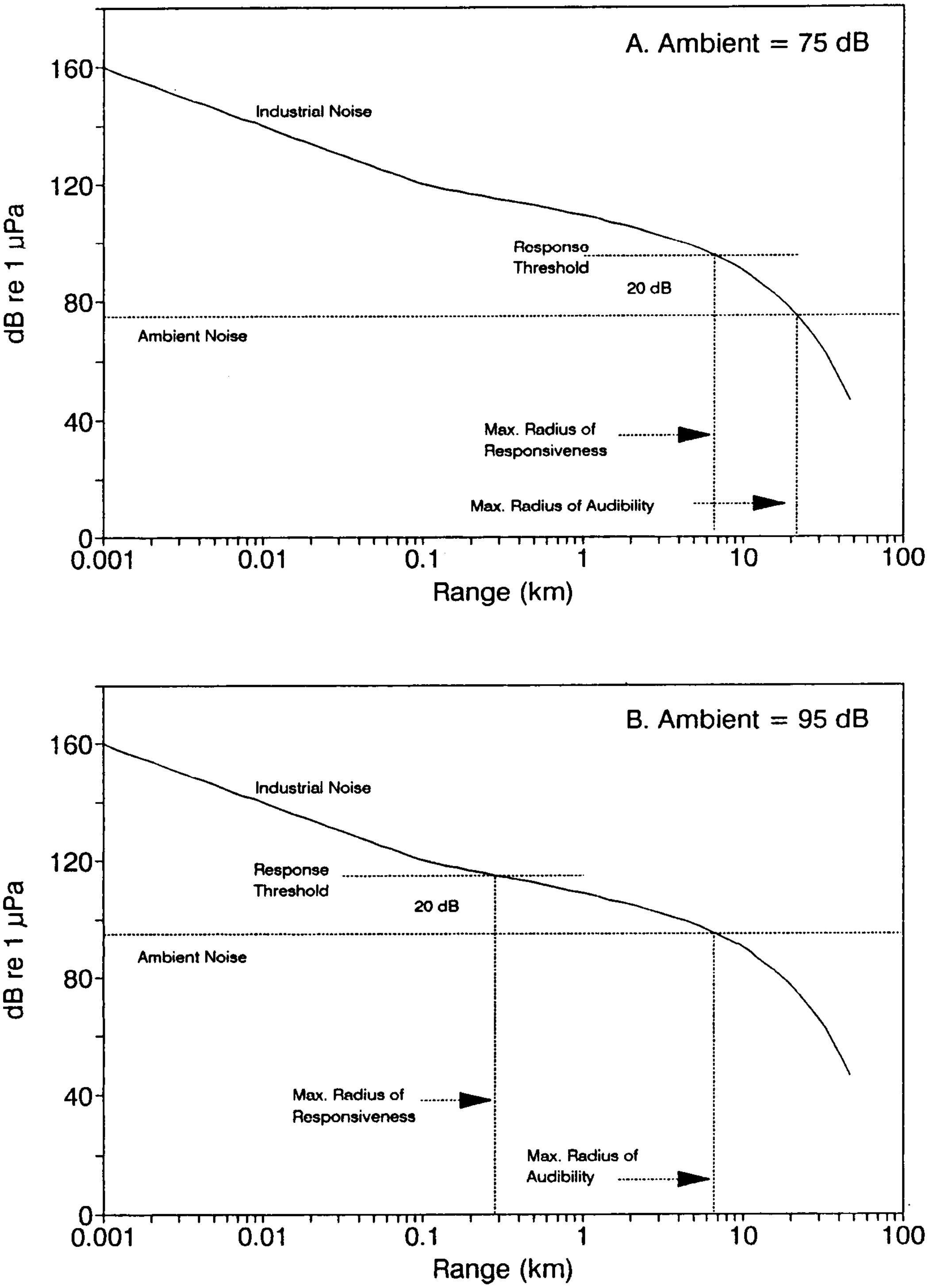

FIGURE 9.5. Schematic representation of the effect of a 20-dB change in ambient noise level on maximum radii of responsiveness and audibility, assuming that animals respond when the industrial noise level is at least 20 dB above the ambient noise level in the critical band.

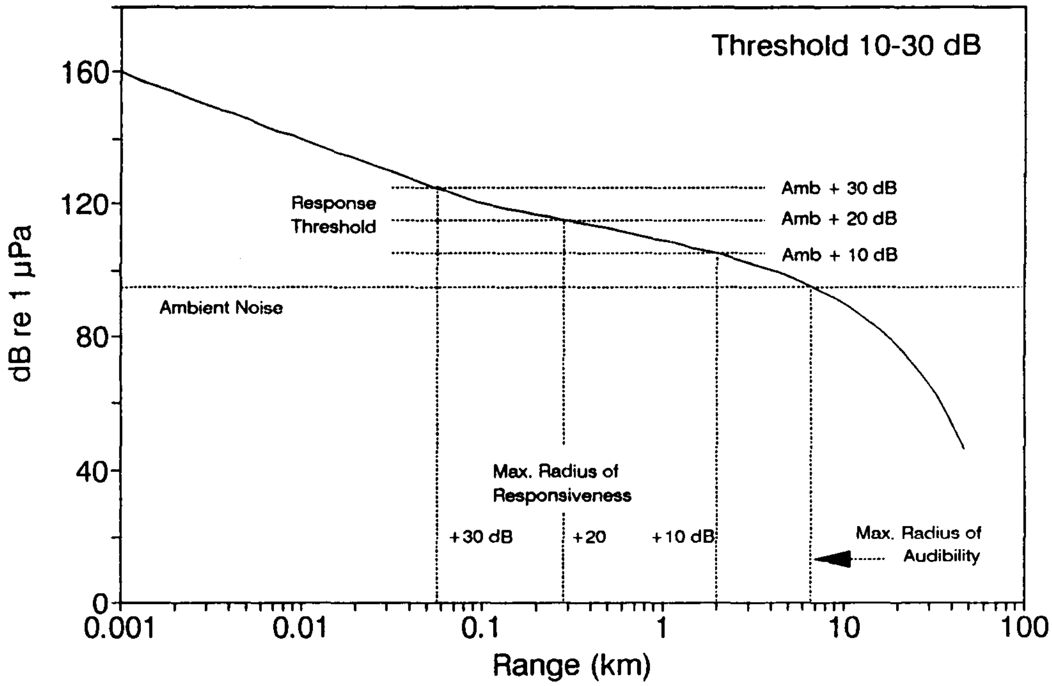

FIGURE 9.6. Schematic representation of the effects of 10-dB and 20-dB changes in response threshold on the maximum radius of responsiveness.

9.5 Zone of Hearing Loss or Discomfort[4]

In humans, prolonged or repeated exposure to high sound levels can accelerate the normal process of gradual hearing deterioration with increasing age (Kryter 1985). This deterioration is a ***permanent threshold shift (PTS)***. In addition, temporary increases in threshold occur during and shortly after exposure to high noise levels. This ***temporary threshold shift (TTS)*** can last from a few minutes to hours or days. Brief exposure to extremely high sound levels, such as those from nearby explosions, can cause discomfort, non-auditory sensory effects, and immediate onset of permanent hearing impairment.

There is no specific information about whether marine mammals are subject to analogous permanent hearing impairment after prolonged or brief exposure to intense sounds either underwater or in the air. It is also not known whether high sound levels cause "discomfort" or non-auditory effects in marine mammals. Thus, the following discussion of the radii around industrial sites at which these effects might occur is speculative. It is based almost entirely on analogies with man and other terrestrial mammals, for the most part listening in air rather than underwater. Given the special adaptations of the hearing apparatus of marine mammals, it is uncertain whether information derived from terrestrial mammals is applicable to marine mammals.

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[4] This subsection is adapted, with revisions, from a recent review by Richardson et al. (1989) for the American Petroleum Institute.

9.5.1 Permanent Hearing Impairment

Continuous Man-made Noise.--There is no information on noise levels that would induce either temporary or permanent hearing impairment in marine mammals. Gales (1982) noted that, in humans, the normal process of hearing loss with increasing age can be exacerbated by exposure to industrial noise ~80 dB above the absolute hearing threshold for 8 h per day over 10 yr. Kryter (1985) provides a detailed review of the many data from humans.

In the absence of specific data for marine mammals, we consider the implications if the 80 dB value derived for humans exposed to industrial noise also applies to marine mammals. If so, then very prolonged exposure to noise levels of about 120 dB re 1 µPa (80 dB above threshold at best frequency) would be required to induce permanent threshold shift (PTS) in white whales. The equivalent figure for fur seals would be 140 dB, given their higher absolute threshold. Hearing damage thresholds from very prolonged exposure would be >120 dB for some other toothed whales, and >140 dB for some other pinnipeds, given their higher absolute thresholds (sect. 7.2). However, we emphasize that the accuracy of these ≥120 and ≥140 dB criteria is unknown; human criteria may not describe the situation in marine mammals realistically.

Some marine mammals have been found to tolerate, at least over periods of a few hours, continuous sound whose received level is more than 120 dB. However, mammals often exhibit avoidance reactions when the industrial noise level reaches 120 dB, and avoidance reactions become more common at levels above 120 dB (Chap. 8; sect. 9.4). It is doubtful that many marine mammals would remain in areas where received levels of continuous noise remain at or above 140 dB.

In order to be exposed to a received level of ***140 dB***, mammals would have to be very close to any source of continuous industrial noise. For example, Miles et al. (1987) estimated the received levels of industrial noise that would occur at each range from each of a variety of oil industry activities in the Alaskan Beaufort Sea. An animal would have to be within 1-2 km of each of these activities (and much less than 1 km from most of them) in order to be exposed to a received level of 140 dB. Noise levels might exceed ***120 dB*** out to a radius of 10-20 km from the strongest industrial source considered by Miles et al.--an icebreaker breaking ice. However, for most sources operating at most sites, noise would diminish below 120 dB within 1-5 km, and sometimes well within 1 km (Miles et al. 1987).

Given the normal mobility of most marine mammals, we would not expect them to remain close to any one industrial site long enough to be exposed to 140 dB for very long, even if the animal exhibited no avoidance reaction to this high noise level. Some species might remain within the larger "≥120 dB zone" for periods of days or weeks, but few species of marine mammals would be expected to remain in such an area throughout a season or year. A ringed seal using breathing holes near an icebound industrial site would be the most obvious potential exception. In contrast, the "80 dB above threshold" criterion for human PTS refers to exposure for ~8 h/d over ~10 years.

Another important consideration in interpreting the analogies with humans is that the toothed whales and pinnipeds whose hearing sensitivity has been measured are most sensitive at frequencies of several kilohertz or higher. Most of the energy in the noise from most of the industrial sources of concern here is at much lower frequencies (Chap. 5). Hearing sensitivity of toothed whales and pinnipeds is known or suspected to be poorer at these frequencies. This probably reduces the potential susceptibility of their auditory systems to damage from prolonged exposure to low-frequency industrial noise (Chappell 1980). This argument may not apply to baleen whales, whose hearing sensitivity is largely unknown but presumed to be good at low frequencies.

We emphasize that this speculation assumes that the auditory systems of marine mammals are affected by prolonged intense sound in roughly the same way as the human auditory system. If so, the natural mobility of most species is likely to cause them to leave the strongly ensonified area well before they would be expected to suffer permanent hearing impairment. Furthermore, avoidance reactions are likely to cause many mammals to move out of the strongly ensonified zone earlier than they would have during their natural movements, thus providing further protection from any possibility of auditory damage. Therefore, we hypothesize that permanent hearing impairment as a result of prolonged exposure to *continuous* industrial noise is not likely to be a problem for most marine mammals. Direct evidence bearing on this hypothesis is obviously desirable. However, it is doubtful that direct evidence can be obtained given the long period of time that must pass before realistic sound levels are likely to have any detectable effects, and given the impracticality of conducting even short-term experiments that might injure the marine mammal subjects.

Impulsive Noise.--Several methods of ***seismic exploration*** produce noise pulses that are intermittent but considerably more intense than the continuous noise emitted by most oil industry sources (sect. 5.3). Received levels of pulses from arrays of airguns or other non-explosive devices often exceed 160 dB re 1 μPa out to distances of 5-10 km, and can exceed 140 dB to distances of 15-30 km (Greene and Richardson 1988). There is no direct information about the potential for underwater noise pulses to damage the auditory systems of marine mammals. Chappell (1980) discussed the available evidence concerning effects of sharp airborne pulses of sound on terrestrial mammals, and he speculated about the relevance of these data to marine mammals.

In humans, a sound that is about 155 dB above the normal threshold level is high enough to cause some immediate damage and permanent threshold shift (Kryter 1985:272). The thresholds of most marine mammals to the low frequencies where seismic pulses are concentrated are not known. If they are as low as 40-60 dB (sect. 7.2), then a received level of 195-215 dB re 1 μPa might cause immediate hearing damage if the human criterion applies. Animals directly below an airgun array could be exposed to such levels even at depths down to several hundred meters; the source levels of airgun arrays for downward propagation can be 250 dB or more (sect. 5.3.3), and spherical spreading can be assumed to occur. However, the effective source level for horizontal propagation is lower by roughly 10-30 dB, depending on aspect (sect. 5.3.3). Animals would probably have to be within 100 m to the side of an airgun array in order to be exposed to ≥195 dB.

This speculation suggests that marine mammals within 100 m horizontally from a seismic vessel might be subject to immediate hearing damage. However, this speculation is based on the 155 dB criterion from humans and an assumed 40 dB absolute hearing sensitivity. A 40 dB absolute threshold has been found in certain marine mammals, but only at frequencies much higher than those of the dominant energy in seismic pulses (sect. 7.2). Absolute thresholds at low frequencies are not known for most marine mammals, but they are likely to be well above 40 dB. Ambient noise levels at low frequencies tend to be considerably higher than those in the kilohertz range, even when ship traffic noise is ignored (sect. 4.2).[5] It is unlikely that marine mammals would have evolved low-frequency hearing so sensitive that it is always strongly masked by natural background noise levels. Thus, we suspect that the "155 dB above normal threshold" criterion, if it is meaningful for marine mammals, should be added to a normal threshold well above 40 dB. If so, marine mammals would probably have to be well within 100 m of an airgun array in order to be susceptible to immediate hearing loss.

We also suspect that extended exposure to seismic pulses is unlikely to cause permanent damage to the hearing systems of marine mammals, given

- the available data on auditory damage to terrestrial mammals exposed to airborne noise pulses,
- the transitory nature of seismic exploration,
- the presumed ability of marine mammals to tolerate exposure to intense calls from themselves or other nearby mammals, and
- the known avoidance responses that occur (at least in bowhead and gray whales) when received levels of seismic pulses exceed ~170 dB re 1 µPa.

Again, however, this "evidence" is very indirect, and the conclusion is highly speculative.

Sharp noise pulses from underwater ***explosions***, on the other hand, definitely have the potential to damage the hearing system. Explosives are no longer used for seismic exploration in U.S. waters, but may be used during marine construction or demolition, or for ice management. High explosives produce strong noise pulses with sharper onsets (more rapid pressure increases) than are produced by non-explosive sources of seismic pulses (see sect. 5.3.1, "Explosions"; Staal 1985). When kilogram quantities of high explosives are detonated, source levels of the resulting pulses exceed those from any non-explosive seismic source.

The limited evidence about effects of explosions on the hearing apparatus of marine mammals was reviewed in section 8.6. Bohne et al. (1985, 1986) speculated that cochlear lesions observed in five Antarctic Weddell seals might have been caused by explosions that had occurred in their area. However, exposure distances were unknown, and proof of a causal link between the explosions and the injuries was lacking. Sea otters killed by shock waves from an underground nuclear explosion had suffered auditory damage (sect. 8.6.4). However, the relevance of this observation to conventional underwater explosions is uncertain.

Available evidence suggests that marine mammals can suffer permanent hearing damage, as well as other physical damage, when exposed to shock waves from nearby underwater explosions. Unfortunately, there is almost no direct evidence about the threshold levels or distances for auditory damage. However, several workers have discussed procedures for estimating distances within which underwater explosions will cause death or injuries to other organs (Yelverton et al. 1973; Hill 1978; Wright 1982; Goertner 1982; Myrick et al. 1990a). Richardson et al. (1989:308-315) reviewed these non-acoustic effects of underwater explosions.

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[5] Marine mammal hearing systems evolved before ship noise was a factor. Hence, it should not be considered when discussing the ambient noise levels to which their hearing systems are adapted.

It would be useful to examine the hearing apparatus of any marine mammal killed by an explosion, especially if distance from the explosion is known and the received sound level can be estimated.

9.5.2 Temporary Threshold Shift

In humans, exposure to strong noise, even for a brief period, causes a temporary elevation of the hearing threshold, i.e. a temporary threshold shift or TTS (Kryter 1985). The magnitude of TTS depends on the level and duration of noise exposure, among other factors. In humans, exposure to continuous airborne noise with sound pressure level 90-100 dBA (re 20 μPa), roughly the level received by the operator of a lawn mower or inside a small aircraft (Table 4.2), will cause a TTS of a few decibels. Exposure to 110-120 dBA, as in a discotheque, will cause a TTS of 20 dB or more (Kryter 1985). Recovery of the normal auditory threshold following the end of exposure to the strong noise is a gradual process. It can require minutes, hours or days, depending on the degree of TTS.

There is no information about the occurrence of TTS in marine mammals, let alone about the quantitative relationships between noise exposure and severity of TTS. Assuming that TTS occurs in marine mammals, one can speculate that it could have negative effects on their ability to hear and use natural sounds. To evaluate the importance of this temporary impairment, it would be necessary to consider the ways in which various marine mammals use sound, and the consequences if access to this information were impaired or temporarily blocked. The scarcity of data on the functions of most marine mammal sounds and on the importance of other natural sounds to marine mammals makes it difficult to evaluate the significance of TTS. However, TTS could, in theory, impair the abilities of marine mammals to communicate with one another by calling; to locate food or to navigate by echolocation; and to hear sounds from prey, predators or other natural sources. In these respects, the presumed negative effects of TTS are similar to those of masking (sect. 9.3). Indeed, TTS and masking would both be expected to occur when animals are exposed to strong man-made noise.

In humans, there is a strong correlation between noises that cause TTS and those that, following prolonged exposure, cause permanent hearing damage (Kryter 1985). It would be desirable to take advantage of any opportunities (field or laboratory) that may arise to test the hearing abilities of any marine mammal after exposure to strong noise. If marine mammals exposed to strong noise exhibit TTS, this can be taken as an indication of potential susceptibility to long term hearing impairment if exposed repeatedly or continuously to such sounds (Chappell 1980; Kryter 1985).

9.5.3 Discomfort Threshold and Non-auditory Effects

Sounds with very high sound pressure levels can produce discomfort and other non-auditory effects in man. Human divers exposed to intense underwater noise (e.g. 190 db re 1 μPa) sometimes report discomfort, apparent rotation of the visual field, or dizziness (Smith 1985). Little is known about these non-auditory effects in terrestrial mammals, let alone marine mammals. Gales (1982) suggested that marine mammals are already adapted to high pressures associated with diving and, therefore, are naturally exposed to much higher pressure levels than are produced by most offshore oil and gas activities. However, there may be a considerable difference between adaptation to progressive pressure changes during diving or ascent versus the very rapid oscillations in pressure associated with a sound waveform. In any case, Gales (1982) concluded that, beyond a few tens of meters, non-auditory effects on marine mammals are unlikely to occur.

Gales (1982) noted that sounds become "uncomfortably loud" for humans at levels of about 100 to 120 dB above the most sensitive hearing threshold in humans. Applying these discomfort criteria to marine mammals, white whales might suffer discomfort at received levels of about 140-160 dB, whereas fur seals might begin to suffer discomfort at 160-180 dB. As noted above, received levels of 140 dB are restricted to well within 1 km from most oil industry sources, and levels of 160-180 dB would occur only within several meters if at all.[6] Most marine mammals can be expected to be excluded from such areas by behavioral disturbance effects, and thus not susceptible to these hypothesized physiological effects.

The applicability of human criteria, especially those for in-air hearing, to marine mammals listening in water is highly questionable. It is not known whether marine mammals are subject to phenomena analogous to the discomfort reported by humans. Odontocete echolocation calls produce much more intense sound pressure levels than these postulated discomfort levels (Chap. 6). Nonetheless, the use of human data may provide useful conservative criteria for defining zones of potential "discomfort" around industrial noise sources.

Seismic exploration creates the most intense sounds of any oil industry activity. The received level can be 160 dB out to 5-10 km, and 180 dB out to perhaps 1 km. Whales have been seen within these distances of operating seismic vessels (sect. 8.6). Whether seismic sound pulses cause any discomfort to such animals is not known. It is probably important that the seismic sounds are intermittent rather than continuous. Intermittent pulses with peak levels 160 dB are much less likely to cause discomfort than would continuous 160 dB noise. Human divers operating stud guns underwater are typically exposed to impulsive noise levels of 210 dB re 1 μPa, but do not report discomfort or "noticeable effects on ears" (J. Mittleman *in* Smith 1985).

Disturbance effects are likely to cause most if not all marine mammals to vacate the theoretical "zone of hearing loss or discomfort" well before the latter effects take place. Ringed seals confined by fast ice are one possible exception, although recent radiotelemetry evidence suggests that even they have some ability to move (Kelly et al. 1986).

9.6 Procedures for Case Studies

The remainder of this chapter provides examples of predicted radii of noise influence around selected human activities in offshore waters. We consider both radii of audibility and radii of responsiveness. We include examples for five general areas: Beaufort Sea (sect. 9.7), Bering Sea (sect. 9.8), California coast (sect. 9.9), Atlantic coast (sect. 9.10), and Gulf of Mexico (sect. 9.11). The species considered for each of these areas are among the more abundant species of marine mammals occurring there. The types of human activities consid-

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[6] Source levels of many oil industry sources exceed 160 dB re 1 μPa-m, and source levels of a few (e.g. icebreakers) may exceed 180 dB. However, most of these sources are not point sources. Hence, actual received levels 1 m from any part of the source would be less than the nominal source level.

ered for each area are among those that occur, or might in the foreseeable future occur. We do not consider all possible combinations of species and possible human activities in each area. However, considering all five areas, we provide scenarios involving four major groups of marine mammals (toothed whales, baleen whales, hair seals, eared seals) and most of the major human activities associated with offshore hydrocarbon exploration and development (aircraft, shipping, icebreaking, seismic exploration, drilling, production platform). No examples are given for sea otters or manatees, given the lack of data on their absolute hearing sensitivity.

Besides providing specific examples of estimated radii of influence, sections 9.7-9.11 also show how radii of influence can be estimated. If the necessary data are available, readers can apply the same approach to other species, locations, and industrial activities of interest to them. These case studies also highlight the many important data gaps that exist, and illustrate the types of data that need to be acquired in order to predict radii of influence with reasonable accuracy.

To predict radii of noise influence around human activities, it is necessary to consider

- the source levels and characteristics of the noise from each activity,
- the attenuation of that noise as it is transmitted through water or air,
- the ambient noise level, and
- the hearing and response thresholds of the marine mammal in question.

9.6.1 Source Levels

Source level spectra for the human activities considered in the case studies are shown in Fig. 9.7-9.9. These spectra are given on a 1/3-octave basis, since that bandwidth seems most consistent with the properties of mammalian hearing systems (sect. 7.5.2 and 9.2.1). Most of these source level spectra were derived by Malme et al. (1989) from field measurements by various authors. Chapter 5 provides more information about the characteristics of the sounds from these types of human activities.

For most human activities, no source level data are available at frequencies above 5-20 kHz. Many marine mammals can hear sounds extending up to much higher frequencies (sect. 7.2). Hence, it has been necessary to extrapolate the 1/3-octave source level data. This was done based on the slope of the spectrum at the highest frequencies for which data are available. In Figures 9.7-9.9, the portions of the spectra where no datapoints are shown represent extrapolations. The slopes for cavitating and impulsive sources follow the generally accepted power laws for these phenomena. However, it was sometimes necessary to extrapolate over several octaves. Hence, the extreme extrapolations for the highest frequencies should be considered very speculative. Fortunately, for all of the activities considered, 1/3-octave source levels diminish with increasing frequency. Hence, the questionable estimates at high frequencies are not a serious problem, since the higher and better defined source levels at lower frequencies are the key ones in estimating zones of influence.

For most of the sources considered, the source level can be estimated at frequencies as low as 15-25 Hz. Source levels at lower frequencies are generally unknown but are probably high for certain sources. The lack of data at very low frequencies is not believed to be a significant problem when assessing noise effects on pinnipeds or toothed whales. However, it may be an important data gap in the cases of baleen whales.

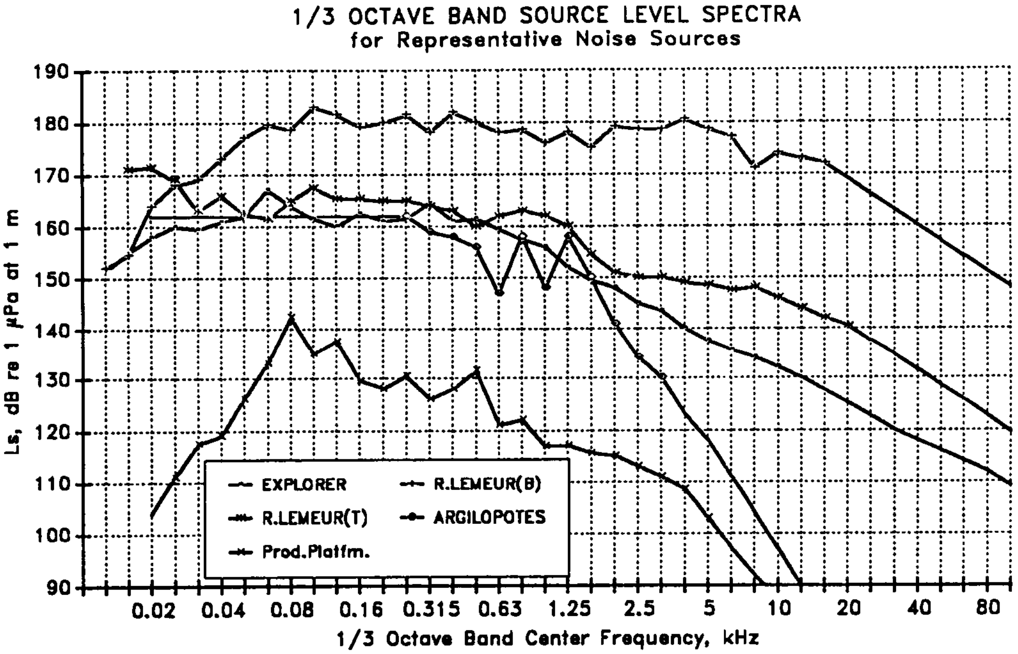


FIGURE 9.7. Estimated 1/3-octave source levels for underwater sounds from representative drillship (*Explorer II*), icebreaking supply vessel in transit through open water (T) and icebreaking (B) (*Robert Lemeur*), clamshell dredge (*Argilopotes*), and production platform off California. Descending lines to the right of the highest-frequency datapoint are extrapolations.

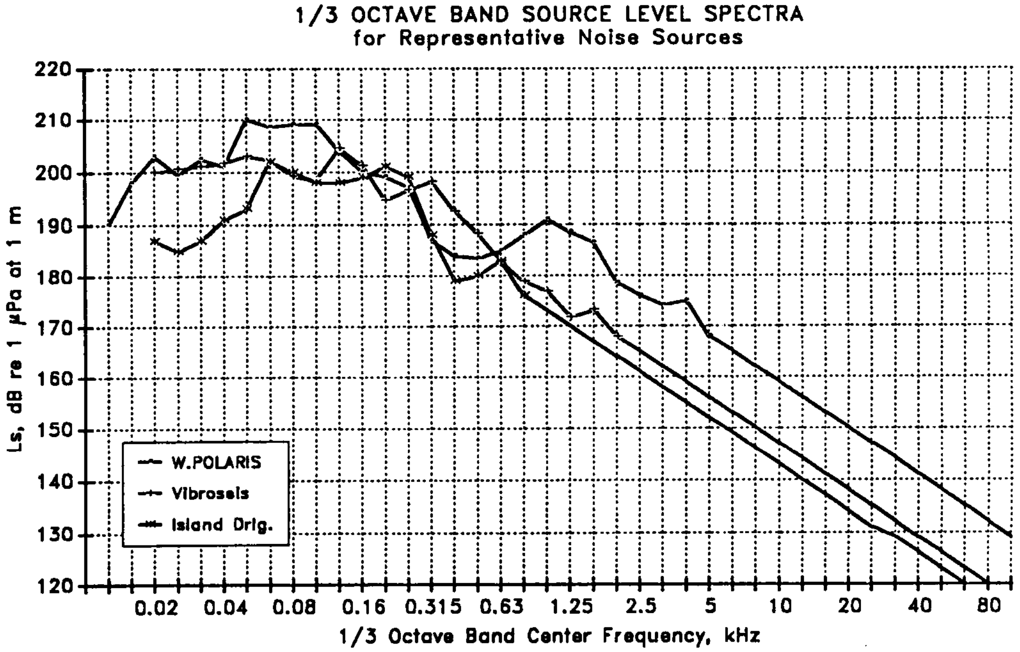


FIGURE 9.8. Estimated 1/3-octave source levels for underwater sounds from seismic exploration with an airgun array (*Western Polaris*) and with Vibroseis, and for drilling on an ice platform. Descending lines to the right of the highest-frequency datapoint are extrapolations.

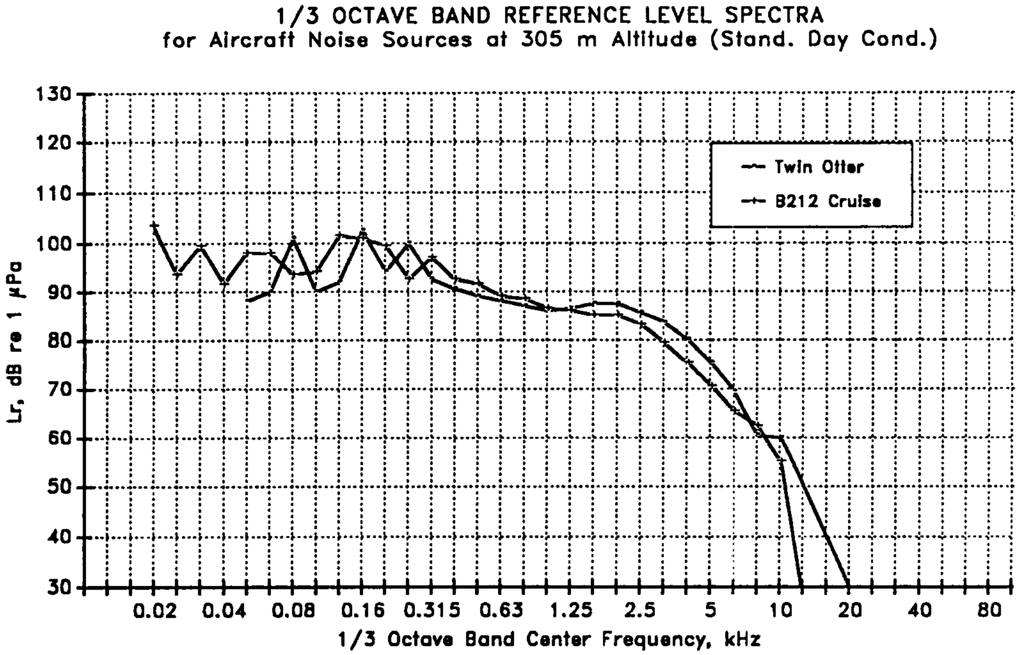


FIGURE 9.9. Estimated 1/3-octave sound levels for airborne sounds from a Twin Otter aircraft and Bell 212 helicopter at 305 m altitude, as measured at the surface under standard day conditions.

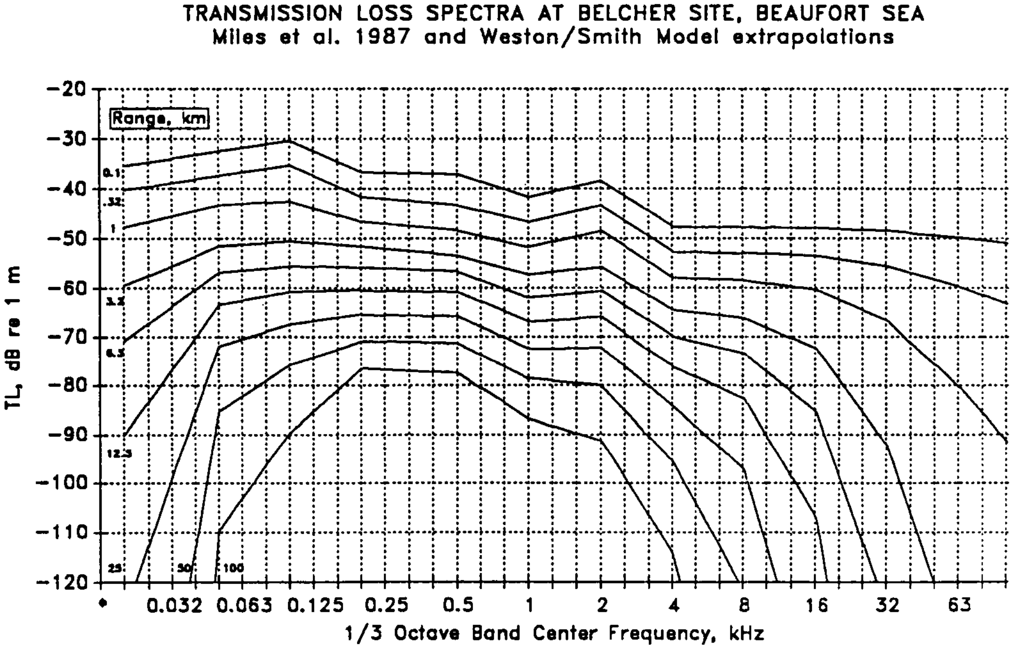


FIGURE 9.10. Example of estimated transmission loss spectra, showing expected TL between the sound source and ranges 0.1-100 km as a function of frequency. Based on Miles et al. (1987), as described in section 9.7.1. See Appendix 3 for similar spectra from other sites.

9.6.2 Transmission Loss

For each region of interest, acoustic transmission loss (TL) had to be measured or estimated in order to estimate received levels as a function of range. (Received level equals source level minus TL.) TL data were organized by one-third octaves, matching the 1/3-octave source level spectra. A standardized procedure was developed to combine source level spectra and transmission loss data. This procedure used a computer spreadsheet to obtain 1/3-octave TL and received level spectra at selected range intervals (Malme et al. 1989). These range intervals corresponded to ~10 dB decrements in received level. The spreadsheet procedure interpolates and extrapolates, as necessary, to allow for 1/3-octaves where source level or TL data are missing.

The hearing bandwidth of many marine mammals extends above or below the frequency range for which transmission loss data or model estimates are available. The Weston/Smith propagation model (sect. 3.4) was used to provide transmission loss estimates for regions and frequencies lacking TL data. When bottom loss data were available for adjacent frequency bands but not for the frequency in question, the data for adjacent bands were used as a guide. When no such data were available, bottom composition information was used to estimate the acoustic properties. The model incorporates the Thorp volumetric absorption equation (Thorp 1967) to predict absorption losses at high frequencies.

Figure 9.10 shows, as an example, transmission loss near the Belcher drillsite in the Alaskan Beaufort Sea. Each curve represents the transmission loss between range 1 m and the range specified at the left end of the curve. TL is shown for selected ranges from 0.1 km through 100 km. The curves are based field measurements of TL at several frequencies and ranges (Miles et al. 1987), smoothed, interpolated and extrapolated using the Weston/Smith propagation modeling procedure. Similar TL graphs for other locations considered in the case studies are given in Appendix 3. By adding TL spectra from these diagrams to source level spectra from Fig. 9.7-9.9, received level spectra can be estimated.

Range-independent models, such as the Weston/Smith model, require that the bottom parameters remain nearly constant along the entire propagation path considered in the model. A limited set of measurements made in the coastal region of the Alaskan Beaufort Sea shows good agreement with model results out to a range of at least 24 km (Miles et al. 1987). However, off California, the bottom properties vary considerably, depending on whether it is smooth or is traversed by underwater canyons. In that region, model results are reasonable as long as they involve only a single bottom type.

The specific procedures used to estimate transmission loss for each of the areas considered are described in the corresponding sections, below. The transmission loss estimates have been extended well beyond the frequencies and distances for which field data are available, and well beyond the frequencies and ranges to which the models are normally applied. As a result, our TL and received level estimates for frequencies below 100 Hz and above 5 kHz, and for ranges beyond 40 km, should be considered approximate. In all cases, transmission loss and received level predictions are valid only for the specific bottom types for which they were derived.

9.6.3 Ambient Noise

Estimates of ambient noise are necessary to determine the radius of audibility, i.e. the distance at which the received level diminishes below the ambient level in the corresponding band (Fig. 9.2). Also, some mammals may respond overtly to noise if its level exceeds the ambient level by a specified amount, e.g. 20 dB (sect. 9.4.2). If so, ambient noise data are needed to determine the radius of behavioral responsiveness (Fig. 9.5). For these purposes, ambient noise data need to be expressed on a one-third octave basis. Procedures used to estimate typical ambient noise levels in each area are described in the corresponding section, below.

9.6.4 Hearing and Response Thresholds

Hearing thresholds of all marine mammals for which thresholds have been measured by psychoacoustic methods are given in section 7.2. These data are used in the following sections to judge whether radii of audibility for a given species and sound type are threshold-limited or noise-limited, as discussed in sect. 9.2.2. When the radius of audibility is limited by ambient noise, the auditory threshold is not relevant. However, when the radius of audibility is threshold-limited, the specific threshold is important and the ambient noise level is not (Fig. 9.2).

For species in which hearing thresholds are unknown, including all baleen whales, an assumption is necessary about whether the animals are threshold- or noise-limited. As discussed in sections 7.6 and 9.2.2, we assume that baleen whales have sensitive hearing at the low-moderate frequencies where most industrial noises are concentrated. Thus, we assume that these species are noise-limited. Hence, hearing threshold data are not essential to estimate radii of audibility of low frequency sounds. The lack of data on the sensitivity of baleen whales to infrasonic sounds (<20 Hz) is a significant data gap, given that large vessels and some industrial activities can be strong sources of infrasound.

Assumptions about response thresholds are based on the data reviewed in Chapter 8, along with the concepts summarized in section 9.4. For most species and human activities, the available data are meager or lacking, and assumptions must be made.

9.7 Beaufort Sea Case Study

The Beaufort Sea is the portion of the Arctic Ocean north of Alaska and northwestern Canada. For that area, a considerable amount of information is available about sound propagation, ambient noise, and reactions of certain marine mammals to industrial noise. Conditions in this area change drastically from summer to winter because of the presence of ice in winter. Hence, we present a wider range of examples from this area than for most other areas. We consider both a relatively deep-water site near the outer edge of the continental shelf (Belcher site, depth 55 m), and a shallow site closer to shore (Sandpiper, depth 15 m). In addition, for Sandpiper we consider both late summer (open water) and late winter (ice covered) conditions. These two sites are actual exploratory drillsites, and physical acoustic measurements have been obtained at each of them (Johnson et al. 1986; Miles et al. 1986, 1987). A drilling barge (*Kulluk*) has been used recently at Belcher; a man-made sand and gravel island was used to drill at Sandpiper.

Two species of whales are common in the Beaufort Sea, one baleen whale (the bowhead) and one toothed whale (the white whale). The ringed seal is the most common seal in the Beaufort Sea, and it is present during winter as well as summer. The scenarios discussed here consider these three species.

9.7.1 Physical Acoustics

Belcher, Late Summer Conditions.--The Weston/Smith model was used to predict sound transmission loss at this site (Fig. 9.10). Bottom loss parameters used in the model were obtained from measurements for 100 Hz to 4 kHz (Miles et al. 1987). Bottom loss parameters for lower and higher frequencies were estimated by extrapolation from the measured data. A uniform water depth of 55 m was used in the model, corresponding to sound transmission parallel to the coast. Sound transmission offshore into deeper water was not specifically modeled. Sound transmission toward shore was also not modeled, but is predicted to have higher losses than those obtained for constant depth transmission (Miles et al. 1987).

Expected ambient noise levels at the Belcher site were estimated by Miles et al. (1987). Their estimates were based on measurements made nearby during late summer and early autumn of 1985-86, supplemented by data from similar sites in the Beaufort Sea studied by Greene (1982) and Moore et al. (1984).

Sandpiper, Late Summer Conditions.--Transmission loss predictions for this site (Appendix 3B) were obtained using the Weston/Smith model with bottom loss parameters measured at the site by Miles et al. (1987). This site is located near shore in water 15 m deep. The TL predictions assume a propagation path oriented directly offshore with an average bottom slope of 0.0008 (i.e. increasing water depth with increasing range from noise source). The rate of attenuation of sound was relatively low at this site, apparently because of two factors: (1) low bottom loss, probably caused by the presence of sub-bottom permafrost, and (2) the downward-sloping bottom. The transmission loss predictions beyond 20 km from this site should be considered as general indications only because of the expected changes in transmission properties offshore.

When a source is located at or near the air-water interface, sound propagated underwater incurs an additional 10 log R spreading loss (sect. 3.5.2). Thus for the island drilling considered at this site, an additional 10 log R factor was included in the transmission loss model (Appendix 3C). The source in this case was assumed to be a rotary table drillrig that coupled noise and vibration directly to the ground surface on the island and then into the water near the surface. The receiver was assumed to be a whale at mid-depth. If the receiver was also near the surface, an additional 10 log R spreading loss would be incurred, resulting in a total spreading loss of 35 to 40 dB per decade of range. This type of shallow source to shallow receiver transmission loss has been observed near drillsites on islands and on a grounded ice pad in shallow waters near Prudhoe Bay (Malme and Mlawski 1979; Greene *in* Richardson et al. 1990a).

Expected ambient noise levels at the Sandpiper site were estimated by Miles et al. (1987). Their estimates were based on measurements made nearby during late summer in 1985-86 supplemented by data from similar sites in the Beaufort Sea studied by Greene (1982) and Moore et al. (1984).

Sandpiper, Late Winter Conditions.--The site was assumed to have 100% ice cover with average ice thickness 2 m and average underice roughness of 1 m. The Parabolic Equation (PE) model (U.S. Naval Oceanographic Office 1988) was used to estimate the additional attenuation caused by absorption and scattering by the ice layer. This additional attenuation was added to the values predicted previously for this site using the Weston/Smith model. Since the Weston/Smith model was partly based on site-specific measurements, this procedure was expected to produce more accurate predictions than a procedure using the PE model alone.

For island drilling and Vibroseis at this site during winter, an additional 10 log R factor was included in the transmission loss model to provide for the source location at the air-water interface (Appendix 3D).

The airborne transmission loss model used for predictions of noise transmission from a helicopter source incorporated 20 log R spreading loss. Atmospheric absorption was predicted based on an assumed temperature of 0°C and 20% relative humidity (sect. 3.6.1; Appendix 3E).

Expected underwater ambient noise levels were predicted using information from Urick (1983) together with measured data obtained near Barrow, Alaska, by Clark et al. (1986).

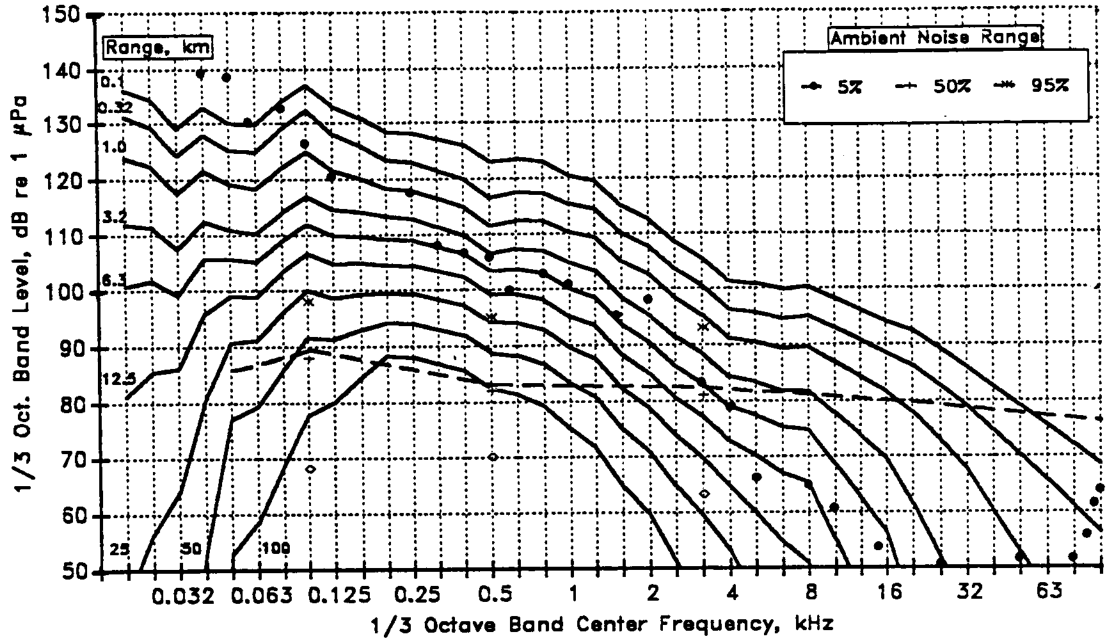
We know of no available data on airborne ambient noise levels over arctic ice. Levels are presumably related to nearby ice roughness features and to mean wind speed. Ice cracking activity would also be important. In the absence of both wind and ice activity, ambient noise levels would be very low if no man-made noise sources were nearby. As an approximation to arctic over-ice conditions, we used ambient noise levels obtained in the California desert for low and moderate wind speed conditions (Fidell and Bishop 1974).

9.7.2 Predicted Radii of Influence

Ship Noise.--Figure 9.11 shows the predicted received levels of supply ship noise, on a 1/3-octave basis, at various distances from a supply ship underway at Belcher (Fig. 9.11A) and Sandpiper (Fig. 9.11B). These spectra were obtained by subtracting the transmission loss estimates shown in Fig. 9.10 and Appendix 3A,B from the source level spectrum of the supply ship *Robert Lemeur* in transit through open water (Fig. 9.7). Received sounds in several 1/3-octave bands are expected to be above the median ambient level out to a distance just over 100 km from each site. Even on days with considerably higher background levels (90th percentile), supply ship sounds in certain bands are expected to be above the ambient level out to 25+ km from Belcher and 32+ km from Sandpiper (Fig. 9.11B).

The supply ship sounds audible at these long ranges would be at frequencies up to a few hundred hertz. High frequency sounds, e.g. above 4 kHz, drop below the median ambient level at considerably closer distances. Very low frequency sounds (<50 Hz) are rapidly attenuated in shallow waters. Sounds at these frequencies would be audible many kilometers from the supply ship if it were operating at Belcher, but much less far away if it were operating in the shallower waters near Sandpiper (Fig. 9.11A vs. B).

ESTIMATED RECEIVED LEVEL AT BELCHER SITE, BEAUFORT SEA
Source – Supply Vessel Transit (R. Lemeur)



ESTIMATED RECEIVED LEVEL AT SANDPIPER SITE, BEAUFORT SEA
Source – Supply vessel in transit (R. LEMEUR)

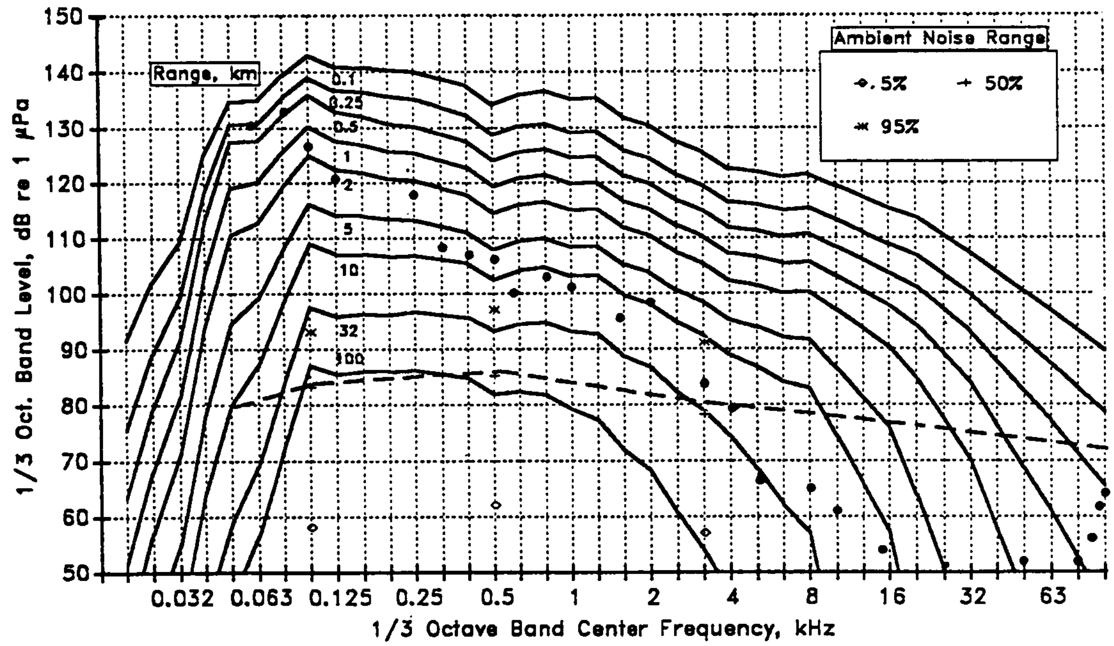


FIGURE 9.11. Predicted 1/3-octave received level spectra at various ranges from a supply ship in transit near the *(A)* Belcher and *(B)* Sandpiper sites in the Alaskan Beaufort Sea. The dashed line shows the expected median ambient noise spectrum, also on a 1/3-octave basis; open circles and asterisks show expected 5th and 95th percentile ambient noise levels. The filled dots show the absolute underwater hearing thresholds of white whales (sources as in Fig. 9.1).

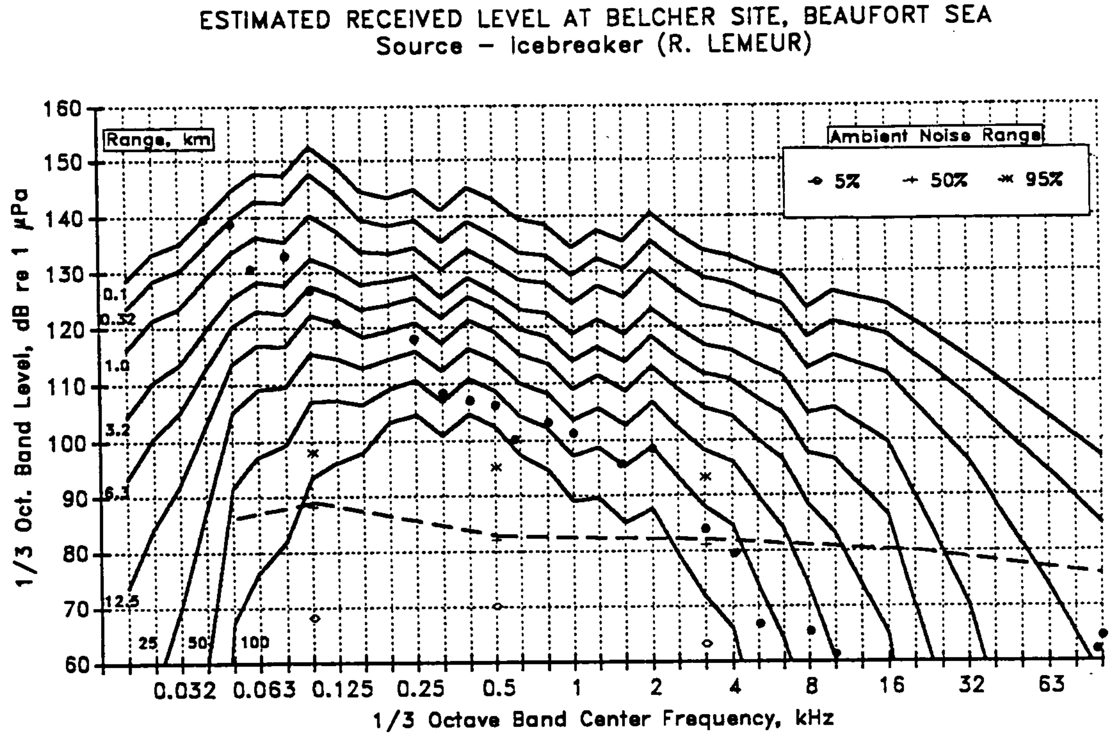


FIGURE 9.12. Predicted 1/3-octave received level spectra at various ranges from an icebreaking supply ship breaking ice near the Belcher site in the Alaskan Beaufort Sea. Presentation as in Fig. 9.11.

A given ship produces considerably higher levels of noise when it is breaking ice than when it is in transit through open water (Fig. 9.7), largely because of the effects of propeller cavitation. Consequently, the received level at any given distance is stronger when the ship is breaking ice (Fig. 9.12 vs. 9.11A).

Radii of audibility can be predicted by considering the ambient noise level and the absolute hearing threshold of the species of concern (sect. 9.2). The low frequency hearing of the bowhead whale is assumed to be limited by ambient noise conditions rather than by the absolute hearing threshold (sect. 9.2.2). The components of the supply ship and icebreaking noise that are audible farthest away are within the low frequency range where bowhead hearing is expected to be acute. Thus, even ignoring the possibility that detection is enhanced by directional hearing, we expect that bowheads would be able to hear the ship or icebreaker at the long distances quoted above (>100 km; see also Table 9.1).

In contrast, white whale hearing is apparently threshold-limited at low frequencies (sect. 9.2.2; Fig. 9.1). At Belcher and Sandpiper, expected 1/3-octave median ambient noise levels are less than the white whale hearing threshold at frequencies below about 3-4 kHz (Fig. 9.11). Thus, under average ambient noise conditions, the maximum radius of audibility of the supply ship to a white whale is limited by the hearing threshold at frequencies below 3-4 kHz, and by

Table 9.1. Summary of predicted radii of audibility and responsiveness around selected industrial operations in the Beaufort Sea.

AL = Ambient-limited. TL = Threshold-limited. Radii of audibility marked as "AL" assume typical ambient noise conditions, and would be strongly affected by variations in ambient noise. All estimates are subject to many other sources of variability and uncertainty (see text). Bracketed values are especially speculative.

Location	Season	Species	Industrial Act.	Medium	Radius of Audibility	Radius of Response
Beaufort--Outer shelf (Belcher)	Autumn	Bowhead	Supply ship (Lemeur)	Water	100+ km (AL)	5-25 km
			Icebreaking	"	100+ km (AL)	[>(5-25 km)]
			Seismic--airguns	"	100+ km (AL)	1-25 km (avoidance) 10-100 km (subtle)
			Drillship (Explorer II)	"	100 km (AL)	2½-6 km
"	"	White Whale	Supply ship (Lemeur)	Water	6 km (TL)	[≤6 km]
			Icebreaking	"	50-75 km (TL)	[≤50-75 km]
			Seismic--airguns	"	100 km (TL)	?
			Drillship (Explorer II)	"	5-10 km (TL)	[≤5-10 km]
Beaufort--Inner shelf (Sandpiper)	"	Bowhead	Supply ship (Lemeur)	Water	100+ km (AL)	5-25 km
			Seismic--airguns	"	100+ km (AL)	1-25 km (avoidance) 10-100 km (subtle)
			Dredge (Argilopotes)	"	50 km (AL)	4-5 km
			Island drilling	"	>16 km (AL)	5-6 km
"	"	White Whale	Supply ship (Lemeur)	Water	20 km (TL)	[≤20 km]
			Seismic--airguns	"	100 km (TL)	?
			Dredge (Argilopotes)	"	5 km (TL)	[<5 km]
			Island drilling	"	3 km (TL)	<3 km
"	Winter	Ringed Seal	Island drilling	Water	[7 km @ ≥1 kHz (TL)] *	<1 km?
			Vibroseis	"	[9 km @ ≥1 kHz (TL)] *	<1 km?
			Helicopter (B-212)	Air	[1¼ km @ ≥1 kHz (TL)] *	2 km?

* Radius of audibility may be greater at lower frequencies where hearing sensitivity is unknown.

the ambient noise above 3-4 kHz. Near Belcher, the received level of supply ship noise is predicted to drop below this composite threshold within about 6 km. Ship noise within some of the 1/3-octave bands between 300 and 4000 Hz is expected to be audible out to about this distance. At Sandpiper, the received level in the 600-6000 Hz frequency range is expected to remain above the composite threshold out to about 20 km. The stronger noise from icebreaking is expected to remain above the hearing threshold out to distances on the order of 50-75 km from Belcher at some frequencies between 300 and 3000 Hz.

Radii of responsiveness are more difficult to predict. They cannot be greater than radii of audibility, and are expected to be less. Both bowhead and white whales have been observed to be highly responsive to approaching vessels under some conditions, but to be quite tolerant of vessels in other situations (sect. 8.3).

In one test, bowheads exhibited strong avoidance reactions to an approaching 13-m diesel-powered boat when its noise was only about 10 dB above the ambient noise level (sect. 8.3.3; Miles et al. 1987:225*ff*). It is unknown whether this 10 dB S/N criterion would also apply to the stronger and predominantly lower-frequency sounds from a larger ship. If so, bowheads might react as much as 25 km from a supply ship operating at Belcher or Sandpiper under median ambient noise conditions (Fig. 9.11). This distance is somewhat greater than the maximum distance at which bowheads have been observed to show avoidance reactions to actual supply ships (~15 km; Koski and Johnson 1987). It should be emphasized that bowheads have often been seen considerably closer to supply ships and similar vessels. The above predictions concern the special case of a ship heading directly toward bowheads that are especially responsive to ship noise. If a 20 dB S/N ratio is required to elicit avoidance under more typical circumstances, reactions would be expected within about 5-20 km of the ship (Fig. 9.11). All of these predictions are highly sensitive to the ambient noise level. Predicted reaction distances would be increased severalfold on a near-calm day with low ambient noise, and reduced severalfold on a stormy day with high ambient noise.

Based on the 10 dB S/N criterion, bowhead reactions might be predicted >100 km from the icebreaker operating at Belcher on a day with average ambient noise conditions (Fig. 9.12). In fact, reactions of bowheads to operating icebreakers have not been studied. We suspect that such reactions would have been noticed through opportunistic observations if they occurred at distances approaching 100 km. We doubt that the 10 dB S/N criterion applies in the case of vessels at such great ranges. The rate of increase of sound from an approaching vessel is much slower if the ship is 100 km away than if it is only a few kilometers away. Also, typical icebreaking noise is irregular, particularly when heard at large distances. It would not increase steadily as the icebreaker approached. In any case, occasional reactions to icebreaking are likely to occur at distances greater than the 5-25 km predicted for a supply ship in open water.

Predicted radii of responsiveness for white whales are even more uncertain because of this species' extreme variability in responsiveness to vessel noise (sect. 8.3.2). Based on spring results from the Canadian high arctic (LGL and Greeneridge 1986; Cosens and Dueck 1988), it appears that white whales may sometimes react to very faint ship sounds, i.e. to those that they can barely hear. If so, they might react to the supply ship at distances as far as 6 km from Belcher and 20 km from Sandpiper, and to the icebreaker at distances as great as 50-75 km (see "Radii of audibility", above). However, white whales are apparently not nearly as responsive to ship noise during the summer open water season as they are during spring, and maximum reaction distances in summer and early autumn are probably much less than the radii of audibility.

Seismic Pulses.--Figure 9.13 shows the predicted received levels of noise pulses from a large array of airguns, on a 1/3-octave basis, at various distances from a seismic vessel operating at Belcher (Fig. 9.13A) and Sandpiper (Fig. 9.13B). These spectra were obtained by subtracting the transmission loss estimates shown in Fig. 9.10 and Appendix 3A,B from the source level spectrum of the seismic ship *Western Polaris* (Fig. 9.8). Received sounds in many 1/3-octave bands are expected to be above the median ambient level out to distances well beyond 100 km from each site. Even on days with high background noise levels (e.g. 90th percentile), some components of the seismic pulses are expected to be above the ambient level, and thus detectable, at distances exceeding 100 km.

The dominant components of the seismic sounds audible at long ranges would be at about 80 to 300 Hz. Because of the shallower water at Sandpiper than at Belcher, the lowest frequency components of the seismic pulses (<50 Hz) are expected to attenuate more rapidly at Sandpiper (Fig. 9.13B vs. A).

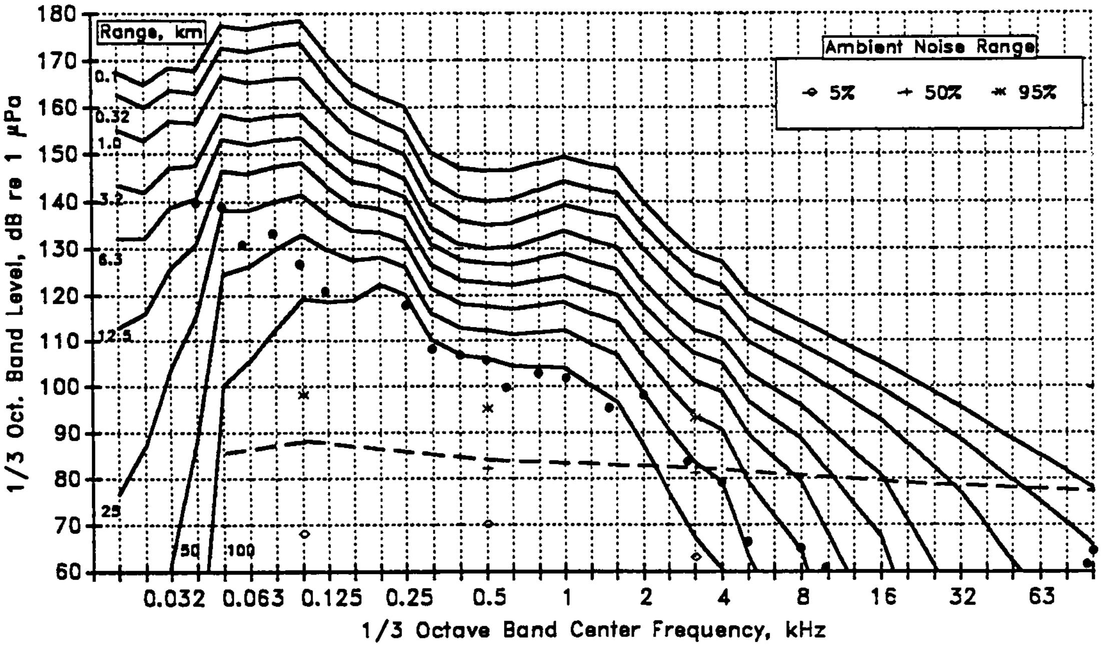
Radii of audibility around the seismic ship are very large. Assuming that bowheads have sensitive hearing at low frequencies, they are expected to hear seismic pulses at distances well exceeding 100 km from Belcher or Sandpiper.

The pulses are sufficiently strong that even white whales, despite their relatively insensitive low frequency hearing, are expected to detect the pulses as much as 100 km from the source. At frequencies from 100 or 200 Hz to 1600 Hz, expected 1/3-octave received levels of the seismic pulses at range 100 km equal or exceed the absolute hearing thresholds of white whales (Fig. 9.13).

Radii of responsiveness for bowheads near seismic ships are difficult to estimate because of the seemingly great variability in responsiveness. Active avoidance has been seen at received noise levels of 152-178 dB (Ljungblad et al. 1988b). However, subtle effects on surfacing, respiration and diving behavior are evident in some bowheads receiving lower levels, on the order of 130-160 dB (Richardson et al. 1986; Ljungblad et al. 1988b). These levels are peak broadband levels. The corresponding levels in the 1/3-octave bands with the strongest noise would be roughly 10 dB lower, *viz* 142-168 dB for active avoidance; 120-150 dB for subtle behavioral effects. At both Belcher and Sandpiper, received levels in a few 1/3-octave bands are expected to equal or exceed 120-150 dB at ranges as great as 10-100 km (predicted radii of subtle behavioral effects), and to equal or exceed 142-168 dB at ranges as great as 1-25 (predicted radii of active avoidance). These two ranges of distances are in rough agreement with field observations of bowheads exposed to seismic pulses in the Beaufort Sea. Apparent active avoidance has been reported at distances as great as 24 km (Koski and Johnson 1987), but other bowheads showing no active avoidance have been seen within a few kilometers of seismic ships.

The responsiveness of white whales and other toothed whales to seismic pulses has not been determined in even a general way (sect. 8.6.2). Hence it is not possible to estimate radii of responsiveness for white whales near seismic vessels.

ESTIMATED RECEIVED LEVEL AT BELCHER SITE, BEAUFORT SEA
Source – Seismic Array (WESTERN POLARIS)



ESTIMATED RECEIVED LEVEL AT SANDPIPER SITE, BEAUFORT SEA
Source – Seismic Array (WESTERN POLARIS)

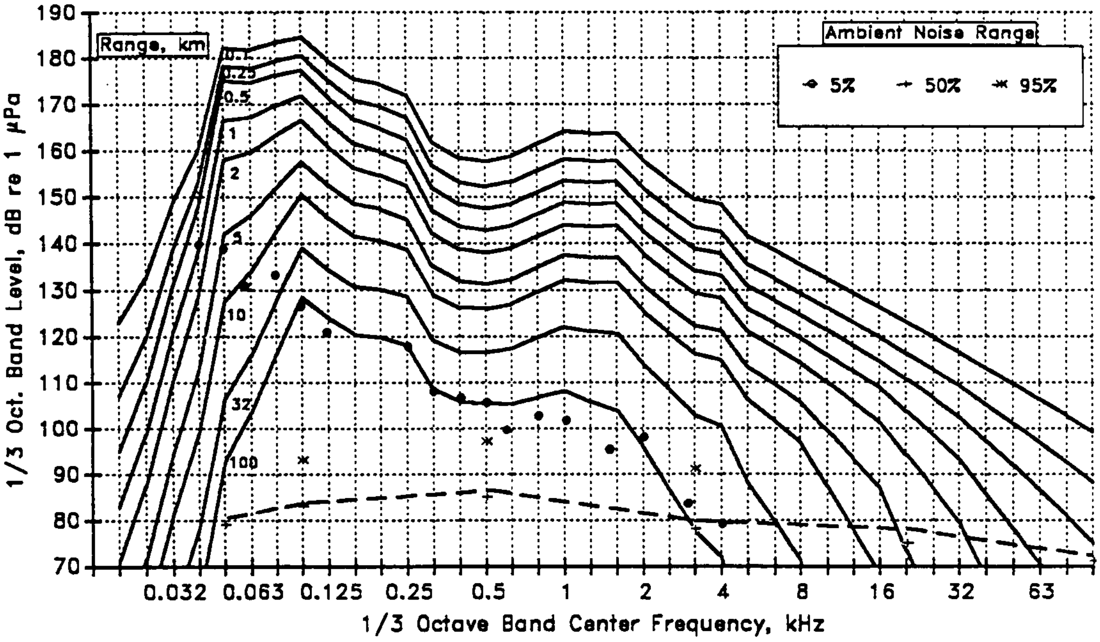


FIGURE 9.13. Predicted 1/3-octave received level spectra at various ranges from an array of airguns operating near the *(A)* Belcher and *(B)* Sandpiper sites in the Alaskan Beaufort Sea. Presentation as in Fig. 9.11.

Drillship and Dredge Noise.--In the Beaufort Sea, exploratory drilling on the outer shelf at sites like Belcher is done using drillships. In contrast, drilling in shallow waters at sites like Sandpiper is done from caissons or islands whose construction often involves dredging. Figure 9.14 shows predicted received levels of noise, on a 1/3-octave basis, at various distances from Belcher if a drillship were operating there (Fig. 9.14A), and from Sandpiper if a clamshell dredge were operating there (Fig. 9.14B). These spectra were obtained by subtracting the transmission loss estimates shown in Fig. 9.10 and Appendix 3A,B from the source level spectra of the *Explorer II* drillship[7] and *Argilopotes* dredge (Fig. 9.7). Received sounds in a few 1/3-octave bands are predicted to equal or exceed median ambient levels out to ~100 km from the drillship at Belcher and ~50 km from the dredge at Sandpiper (Fig. 9.13A,B). On days with higher background levels (90th percentile), these radii are predicted to be reduced to ≤25 km. The drillship sounds audible at long ranges from Belcher would be mainly at frequencies 50-500 Hz. Clamshell dredge sounds audible at long ranges from Sandpiper would be mainly at 80-1600 Hz.

Radii of audibility of drillship and dredge noise to bowhead whales are expected to be limited by the ambient noise level, given the presumed sensitivity of bowheads to the low frequencies that dominate the drillship and dredge spectra. Thus, bowheads might be able to hear these sources 50-100 km away under median ambient conditions, and up to 25 km away under 90th percentile ambient conditions.

In contrast, the white whale hearing threshold at frequencies ≤3-4 kHz is higher than expected 1/3-octave median ambient noise levels (Fig. 9.14). Thus, under average ambient noise conditions, the maximum radius of audibility of the drillship or dredge to a white whale would be limited by the hearing threshold at frequencies below 3-4 kHz, and by ambient noise above 3-4 kHz. The received levels of drillship and dredge noise are predicted to drop below this composite threshold within about 5-10 km. The noise components that would be barely audible at these distances would be the 1/3-octave bands from 300 to 600 Hz in the case of the drillship at Belcher, and some bands from 300 to 1600 Hz for the dredge at Sandpiper.

Radii of responsiveness of typical bowhead whales to drillships and dredges have been estimated as roughly 110 dB in the strongest 1/3-octave band, or alternatively 30 dB above the ambient noise level in that band (sect. 8.7, 8.8; Richardson et al. 1990b). The received sound level in the strongest 1/3-octave band would diminish to 110 dB about 6 km from the drillship at Belcher and ~5 km from the clamshell dredge at Sandpiper (Fig. 9.14). The received level would diminish to 30 dB above the median ambient level ~2½ km from the drillship and 4 km from the dredge. It is not known whether the 110 dB absolute level criterion or the 30 dB S/N criterion is more realistic. In either case, the responsiveness of different individual bowheads varies widely (Richardson et al. 1990b). Hence, some individual bowheads are expected to react at distances greater than the 2½-6 km predicted above, whereas others are likely to approach within closer distances.

It is emphasized that the above predictions pertain to a particular drillship and clamshell dredge. Some other drillships and dredges produce sounds that differ considerably in level and

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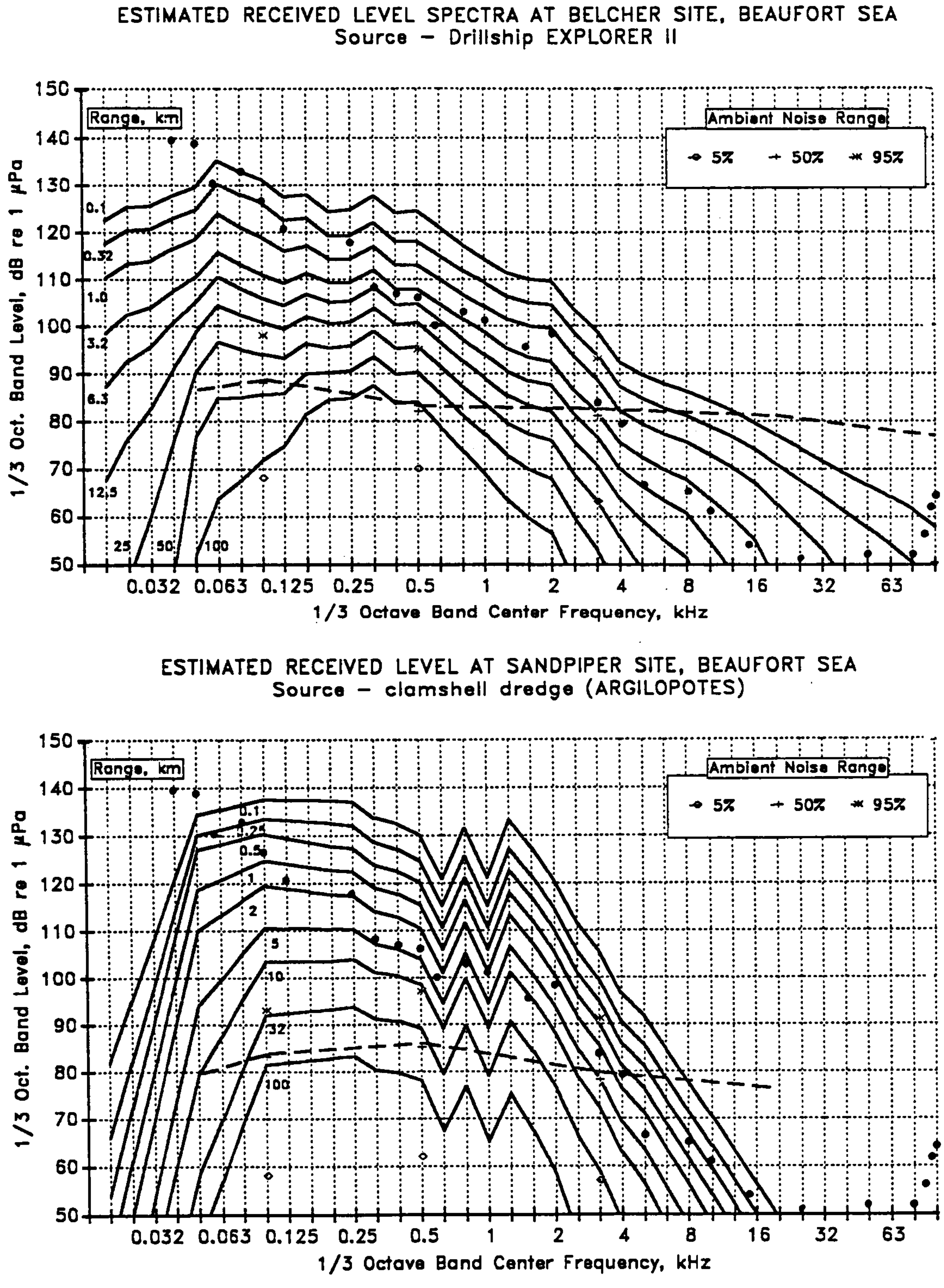
[7] In actuality, drilling at Belcher was done by the drilling barge *Kulluk*, whose acoustic source level is higher than that of the drillship *Explorer II* considered in this theoretical analysis (Fig. 5.39; Greene 1987b).



ESTIMATED RECEIVED LEVEL SPECTRA AT BELCHER SITE, BEAUFORT SEA
Source – Drillship EXPLORER II

ESTIMATED RECEIVED LEVEL AT SANDPIPER SITE, BEAUFORT SEA
Source – clamshell dredge (ARGILOPOTES)

FIGURE 9.14. Predicted 1/3-octave received level spectra at various ranges from *(A)* a drillship at the Belcher site and *(B)* a clamshell dredge at the Sandpiper site in the Alaskan Beaufort Sea. Presentation as in Fig. 9.11.

spectral characteristics (sect. 5.4, Greene 1987b). These differences must be taken into account when predicting radii of audibility or responsiveness around specific drillships or dredges. Also, at least some drilling platforms emit strong infrasonic sounds (Hall and Francine 1990); it is not known whether bowheads can hear these sounds.

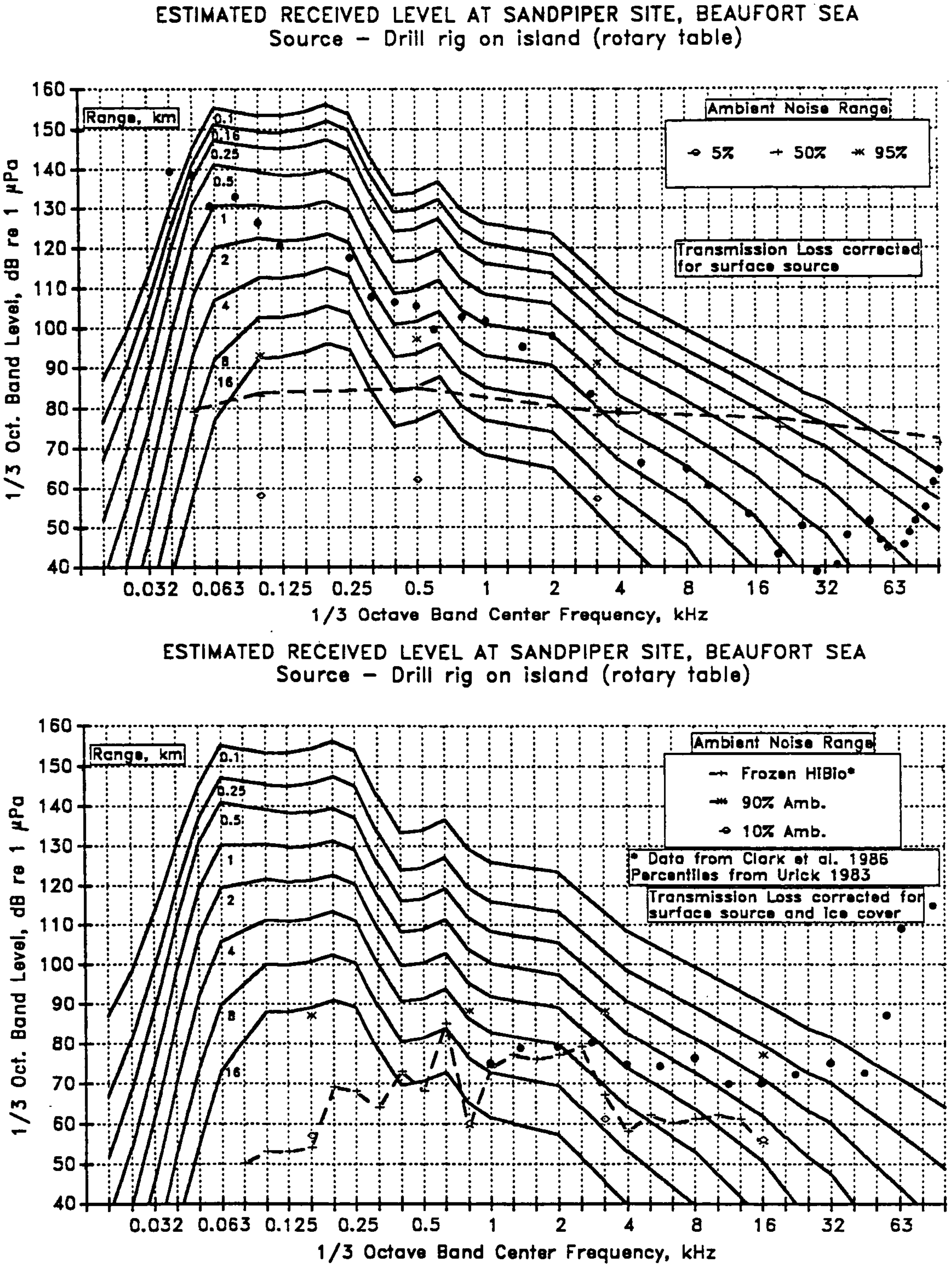
No specific criteria of responsiveness have been reported for white whales near drillships or dredges. However, opportunistic observations and playbacks of semisubmersible drillship noise indicate that (1) white whale responsiveness to drilling and dredge noises varies widely, and (2) white whales often tolerate considerable drilling and dredge noise (sect. 8.7, 8.8). Even in situations when white whales are highly responsive to these noises, they would not be expected to react at distances greater than the maximum radius of audibility (5-10 km, see above). In most situations the radius of responsiveness is expected to be considerably smaller, given that white whales have often been observed well within the ensonified zones around some industrial sites (sect. 8.7, 8.8).

Drilling on Man-made Island.--Exploratory drilling in shallow nearshore waters of the Beaufort Sea is often done from artificial islands constructed of sand and gravel. The following predictions are based on measurements and modeling of acoustic transmission loss at the Sandpiper site, where water depth was 15 m (Miles et al. 1987; Appendix 3C,D). During the open water season, received industrial sound levels in several 1/3-octave bands may exceed the typical ambient noise levels in those bands out to distances exceeding 16 km (Fig. 9.15A). In winter, propagation losses are expected to be somewhat greater than those in summer because of scattering by the ice undersurface. However, ambient noise levels at many frequencies tend to be lower under the landfast ice during winter than in the open water during summer. Consequently, drilling sounds are expected remain above the ambient level out to greater ranges in winter than in summer (Fig. 9.15B vs. A).

Radii of audibility of drilling noise from an artificial island to bowheads are expected to be limited by the ambient noise level, given that the strongest noise is at low frequencies where bowheads are assumed to have sensitive hearing. In open water conditions, bowheads might hear some components of these sounds at distances exceeding 16 km (Fig. 9.15A).

In contrast, the white whale hearing threshold at frequencies <4 kHz is higher than the typical ambient noise levels (Fig. 9.15B). Under average open-water conditions, the maximum radius of audibility of this industrial noise to a white whale would be limited by the hearing threshold at frequencies below about 4 kHz, and by ambient noise at higher frequencies. Received levels of the drilling noise are expected to drop below this composite threshold at a range of about 3 km.

In winter, the ringed seal is the one species of marine mammal occurring on and under the landfast ice that surrounds artificial islands in nearshore waters. Its auditory threshold in water equals or exceeds typical ambient noise levels at all frequencies above 1 kHz (Fig. 9.15B). At these frequencies, drilling noise is predicted to diminish below the hearing threshold, and thus become inaudible, within about 7 km. However, the strongest underwater sounds are at frequencies below 300 Hz. There are no data on the hearing sensitivity of any hair seal at such frequencies. Hence, the radius of audibility of underwater sounds from drilling on an icebound artificial island to ringed seals cannot be predicted with any confidence.


ESTIMATED RECEIVED LEVEL AT SANDPIPER SITE, BEAUFORT SEA
Source – Drill rig on island (rotary table)

ESTIMATED RECEIVED LEVEL AT SANDPIPER SITE, BEAUFORT SEA
Source – Drill rig on island (rotary table)

FIGURE 9.15. Predicted 1/3-octave received level spectra at various ranges from a rotary-table drillrig on an artificial island at the Sandpiper site in the Alaskan Beaufort Sea during *(A)* the open water season, and *(B)* the winter. Presentation of (A) is as in Fig. 9.11; filled dots show underwater hearing thresholds of the white whale. (B) differs in that the filled dots show underwater hearing thresholds of the ringed seal (Terhune and Ronald 1975a; no data are available below 1 kHz).

Radii of responsiveness of bowhead whales in open water near an artificial island are predicted to be about 5-6 km if the response threshold is a sound level of 110 dB re 1 µPa in one or more 1/3-octave bands or 30 dB above the typical ambient level. These estimates assume that the response threshold for this type of industrial noise is about the same as that for drillship or dredge noise. That assumption has not been verified.

For white whales, no data exist on the acoustic threshold for avoidance of drilling on an artificial island. The maximum reaction distance can be assumed to be no greater than the predicted radius of audibility, which is 3 km. White whales have been observed considerably closer than 3 km from actual drilling operations on artificial islands (sect. 8.8), but sound levels were not monitored during those observations.

No data on the acoustic response thresholds of ringed seals to drilling or related sounds have been published. Ringed seals have often been seen near actual artificial islands, on some of which there was drilling (sect. 8.7). There is some evidence of reduced densities of ringed seals close to artificial islands (Green and Johnson 1983; Frost and Lowry 1988). Although the probability of avoidance as a function of distance and received sound level has not been determined, the typical avoidance distance is probably less than 1 km. It is not known whether the apparent avoidance effect is attributable to (1) underwater noise from drilling, (2) some other underwater or airborne noise component, or (3) some other stimulus.

Vibroseis Seismic Exploration in Winter.--The Vibroseis method of seismic exploration is used on the landfast ice in late winter and spring (sect. 5.3.2). The dominant low frequency (<500 Hz) components of the underwater sounds from a Vibroseis operation are expected to remain above the typical ambient noise level to distances beyond 16 km (Fig. 9.16A). At 1 kHz, the lowest frequency for which the ringed seal's hearing sensitivity is known, the ringed seal may be able to hear faint sounds from a Vibroseis operation as much as ~9 km away under typical ambient noise conditions (Fig. 9.16A). The radius of audibility for some of the lower frequency components of Vibroseis sound may exceed 9 km. However, this is uncertain because the ringed seal's hearing sensitivity at frequencies <1 kHz is unknown.

Acoustic response thresholds of ringed seals to underwater noise from Vibroseis have not been determined. There is evidence that some ringed seals within a few hundred meters of Vibroseis operations show avoidance reactions. However, it is uncertain whether their reactions are to its underwater or to its airborne noise (sect. 8.6.1). Also, ringed seals often remain at breathing holes within a few hundred meters of Vibroseis operations (sect. 8.6.1), well within the expected radius of audibility. Thus, some ringed seals apparently tolerate significant Vibroseis noise.

Helicopter Overflight.--Airborne sound from an aircraft is normally detectable farther away than its underwater sound. Ringed seals hauled out on the ice in spring would be exposed to the airborne noise from helicopters and other aircraft. If ambient noise levels in the air above arctic ice are comparable to those over desert areas (Fidell and Bishop 1974), airborne noise levels from a Bell 212 helicopter would exceed ambient noise at distances out to at least 5-10 km for third-octaves up to 400 Hz (Fig. 9.16B). These distances are consistent with our own subjective experience concerning the radius of audibility of the low frequency airborne noise from a Bell 212 in the arctic.

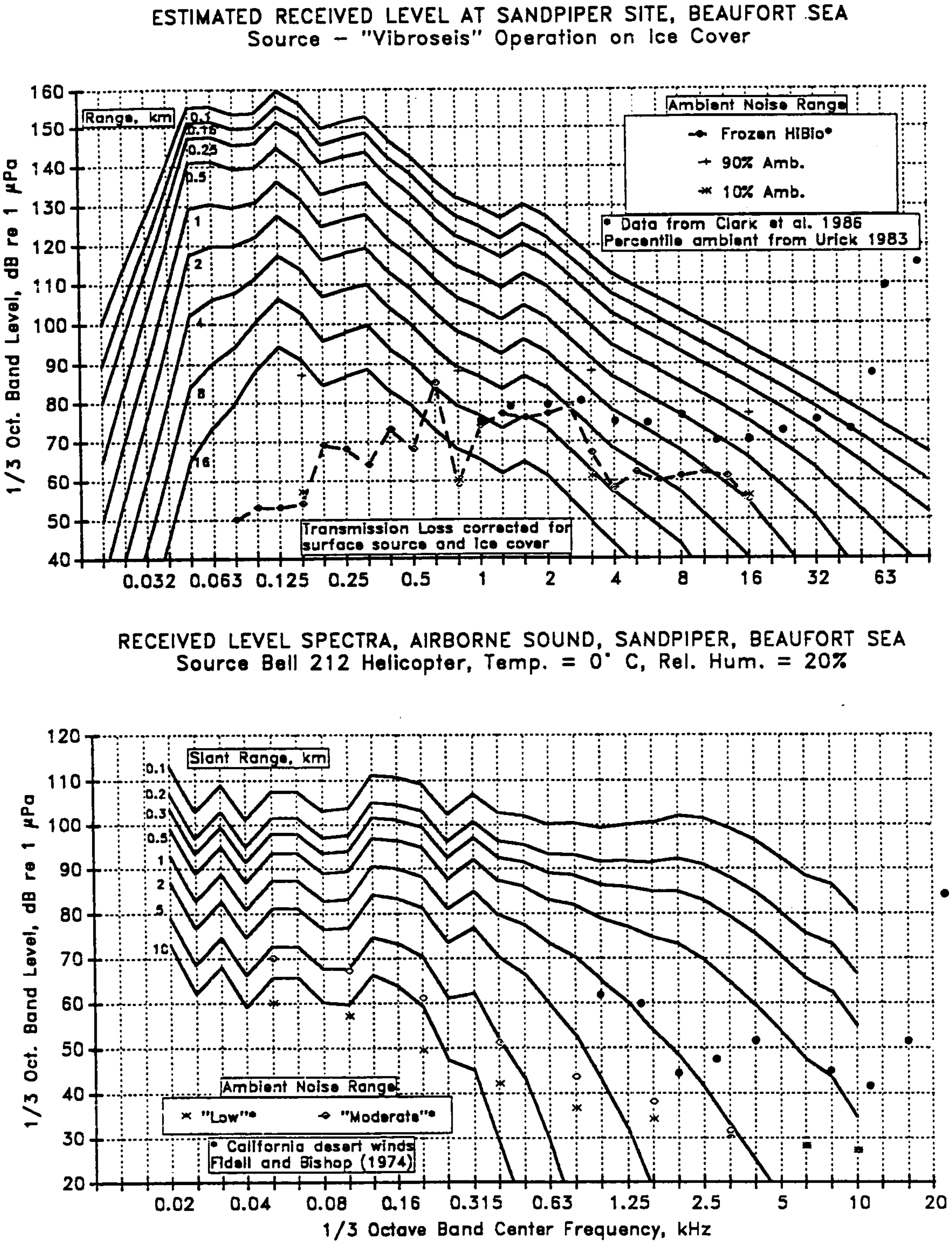


FIGURE 9.16. Predicted 1/3-octave received level spectra at various ranges from *(A)* a Vibroseis seismic operation, and *(B)* a Bell 212 helicopter operating at the icebound Sandpiper site in the Alaskan Beaufort Sea during winter. Presentation of (A) is as in Fig. 9.15A; filled dots show absolute underwater hearing thresholds of the ringed seal. (B) shows received noise levels *in the air* just above the surface as a Bell 212 flies by at an altitude of 300 m at various slant ranges; filled dots show absolute in-air hearing thresholds of a harbor seal, from Møhl (1968a). (No in-air data are available for ringed seals.)

The in-air hearing sensitivity of the ringed seal has not been reported. The in-air sensitivity of the closely-related harbor seal, from Møhl (1968a), is shown in Fig. 9.16B (see also sect. 7.2.2). Above 1 kHz, in-air auditory thresholds of the harbor seal exceed the typical ambient noise levels reported by Fidell and Bishop (1974). This suggests that, above 1 kHz, the radius of audibility of aircraft noise to a seal may be limited by its auditory sensitivity rather than by ambient noise. This assumes that airborne ambient noise above arctic ice is similar to that over a desert, and that ringed seal hearing in air is similar to that of the harbor seal. Given these assumptions, a seal would be expected to detect some of the high frequency (≥1 kHz) components of Bell 212 sound at slant distances as great as about 1¼ km (Fig. 9.16B). There are no data on the in-air sensitivity of seals to the lower frequency components of helicopter sound, which are stronger than high frequency components. Depending on their low frequency sensitivity, seals may be able to hear airborne low frequency sound from a Bell 212 helicopter at distances exceeding 1¼ km. Airborne sound propagation is affected by many variables that could increase or decrease the predicted detection distance (sect. 3.6). Also, it is possible that seals would react to the sight of the helicopter as well as to its sound.

Response thresholds of ringed seals to airborne noise from aircraft have not been reported. Ringed seals often dive into the water when an aircraft approaches, but in most cases it is unknown whether avoidance is in response to noise or to sight of the aircraft (sect. 8.2.1). Seals in lairs beneath snow, and thus unable to see the aircraft, usually dived when a helicopter came within 2 km, and occasionally dived when it was >2 km away (Kelly et al. 1986).

Summary.--Predicted radii of audibility and responsiveness around industrial operations in the Beaufort Sea vary widely (Table 9.1). Radii depend on the sounds emitted from each source, site-specific and season-specific variations in propagation and ambient noise, and species-specific variations in sensitivity. Considerable caution should be exercised in interpreting the predictions. They depend on many assumptions, and day to day variability in physical and biological factors are expected to cause wide variations in apparent sensitivity.

For ***bowheads***, all estimated radii of audibility depend on the assumption that the bowhead hearing apparatus is highly sensitive to low frequency sounds (i.e. those from about 20 to 1000 Hz). All radius of audibility estimates assume that bowheads can detect any low frequency sound whose level, in at least one 1/3-octave band, exceeds the ambient level in the corresponding band. Predicted radii of responsiveness of bowheads are somewhat better supported by empirical data, but nonetheless there are many uncertainties. One data gap is the lack of information about the possible sensitivity of bowheads to infrasounds (at <20 Hz). Some industrial sources emit strong infrasounds. It is not known whether bowheads hear or react to these sounds.

For ***white whales***, the existing data on hearing sensitivity, including recent measurements at frequencies as low as 40 Hz, are very helpful in determining radii of audibility. In white whales, radii of audibility are determined by the rather high auditory thresholds at low frequencies rather than by ambient noise levels. However, the scarcity of quantitative data on behavioral response thresholds hinders estimation of radii of responsiveness.

For ***ringed seals***, the lack of data on hearing sensitivity at frequencies below 1 kHz is a significant data gap. This data gap prevents us from making meaningful estimates of radii of audibility. Usable data on response thresholds are also scarce.

9.8 Bering Sea Case Study

9.8.1 Physical Acoustics

Only a limited amount of empirical information about underwater sound transmission in the Bering Sea area is available in the unclassified literature (MacKenzie 1973; Malme et al. 1986b). Hence it was necessary to use a transmission loss model developed for the northernmost part of the Bering Sea--the Chirikof Basin--by Malme et al. (1986b, 1989). They used the semi-empirical Weston/Smith model to obtain predictions covering an extended frequency range. The bottom loss parameters used in the Weston/Smith model were appropriate for the sand/silt bottom material reported for this region. A flat bottom with a water depth of 30 m was assumed. The predictions (Appendix 3F) agreed with the limited data reported by MacKenzie (1973). However, propagation loss predictions for frequencies above 10 kHz and ranges beyond 40 km are approximate.

The airborne transmission loss model used to predict noise transmission from helicopter and turboprop aircraft assumed (1) 20 log R spreading loss and (2) atmospheric absorption as expected at 10°C and 50% relative humidity (sect. 3.6.1; Appendix 3G).

Underwater ambient noise levels expected in this area during open water conditions were predicted based on the data for shallow water regions summarized by Wenz (1962). Airborne ambient noise levels near the shoreline are expected to be dominated by surf noise. Some representative surf noise data reported by Abrahamson (1974) and BBN (1960) (see sect. 4.6) have been used to estimate the expected levels at a typical Bering Sea beach during the ice-free season.

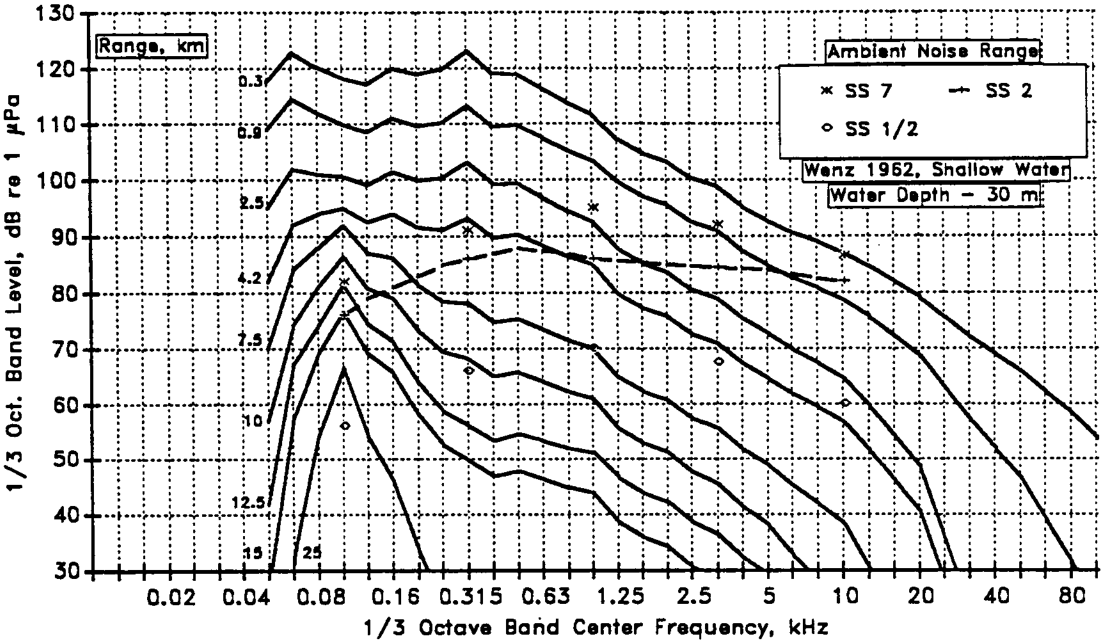
9.8.2 Predicted Radii of Influence

Drillship Noise.--Received third-octave spectra of drillship sound as a function of distance were predicted by combining the source level spectrum of *Explorer II* (Fig. 9.7) with the transmission loss estimates for the Chirikof Basin from Appendix 3F. Attenuation in this area is expected to be considerably more rapid than that at the Belcher site in the Beaufort Sea. The maximum detection distance under typical (SS 2) ambient noise conditions is predicted to be about 15 km in the Chirikof Basin (Fig. 9.17A) vs. as much as 100 km in the Beaufort Sea (Fig. 9.14A).

The maximum radius of audibility for gray whales can be estimated based on the same assumptions applied previously for bowheads. The hearing apparatus of gray whales is assumed to be quite sensitive to low frequency (20-1000 Hz) underwater sounds. Their ability to detect such sounds is assumed to be limited by ambient noise rather than their (unknown) absolute hearing thresholds. They are assumed to be able to hear a sound whose level, in at least one 1/3-octave, equals or exceeds the ambient noise level in the same band. Based on these assumptions, gray whales are expected to be able to hear the drillship at distances out to ~15 km (Fig. 9.17A; Table 9.2A).

About 50% of the gray whales exhibit avoidance when the broadband received level of drillship sounds is 117 dB re 1 μPa (Malme et al. 1984, 1986b, 1988; sect. 8.8; Table 8.1).

ESTIMATED RECEIVED LEVEL SPECTRA, CHIRIKOF BASIN, BERING SEA
Source – Drillship EXPLORER II



ESTIMATED RECEIVED LEVEL SPECTRA, CHIRIKOF BASIN, BERING SEA
Source – Seismic Survey (WESTERN POLARIS)

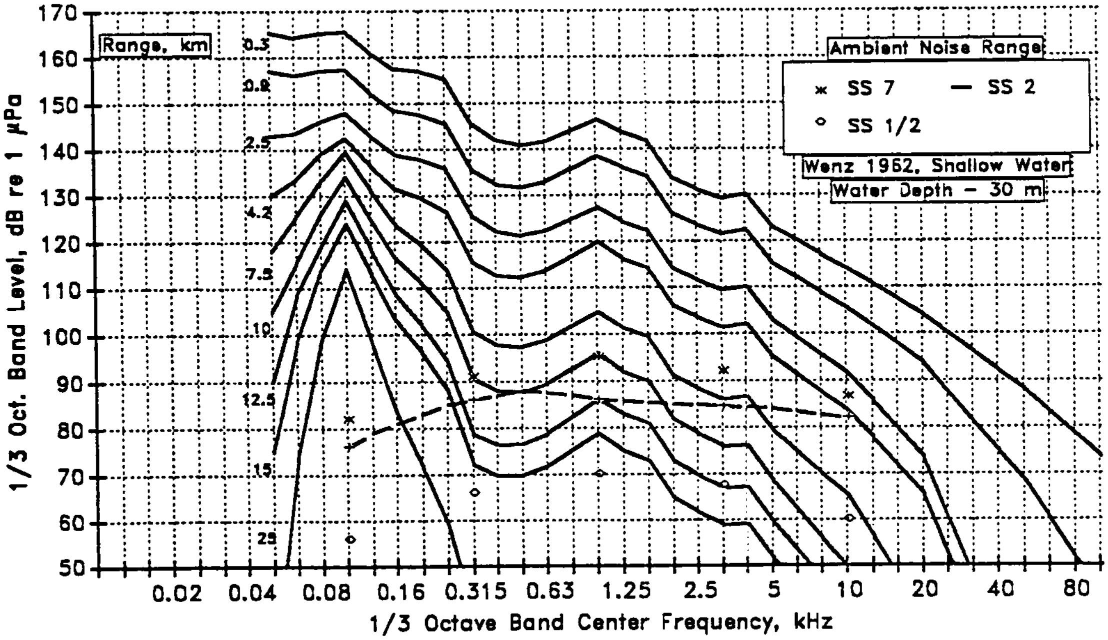


FIGURE 9.17. Predicted 1/3-octave received level spectra at various ranges from *(A)* a drillship and *(B)* an array of airguns operating in the Chirikof Basin, northern Bering Sea. Presentation as in Figure 9.11.

Table 9.2. Summary of predicted radii of audibility and responsiveness around selected industrial operations in the Bering Sea, Scotian Shelf, and Gulf of Mexico.

AL = Ambient-limited. TL = Threshold-limited. Radii of audibility marked as "AL" assume typical ambient noise conditions, and would be strongly affected by variations in ambient noise. All estimates are subject to many other sources of variability and uncertainty (see text). Bracketed values are especially speculative.

Location	Season	Species	Industrial Act.	Medium	Radius of Audibility	Radius of Response	
A. Bering Sea	Summer	Gray Whale	Drillship (Explorer II)	Water	15 km (AL)	2 km	
			Seismic--airguns	"	>25 km (AL)	≤1 km	
"	"	Harbor Seal	Aircraft (B-212 or Twin Otter)	Air	[2-3 km @ ≥1 kHz (AL)] *	<1 km	<---- Offshore
				"	[1 km @ ≥1 kHz (AL)] *	<1 km	<---- Beach/Surf
B. Scotian Shelf	Summer	Baleen Whale	Supply ship (Lemeur)	Water	50 km (AL)	?	
			Drillship (Explorer II)	"	50 km (AL)	[3 km?]	
			Production Platform	"	5 km (AL)	[<0.3 km?]	
"	"	Harb. Porp.	Supply ship (Lemeur)	Water	50 km (AL or TL)	~1 km	
			Drillship (Explorer II)	"	35 km (AL or TL)	?	
			Production Platform	"	<0.3 km (AL)	[<0.3 km?]	
C. Gulf of Mexico	Summer	Bottlenose Dolphin	Supply ship (Lemeur)	Water	10-25 km (AL or TL)	[~1 km?]	
			Production Platform	"	<0.1 km (AL or TL)	[<0.1 km]	

* Radius of audibility may be greater at lower frequencies where hearing sensitivity is unknown.

This broadband response criterion is equivalent to ~106 dB in a 1/3-octave band.[8] The received levels of drillship sounds in the Chirikof Basin are predicted to diminish below 106 dB in the strongest 1/3-octave band about 2 km from the drillship (Fig. 9.17A). This is somewhat less than the predicted radius of responsiveness of bowhead whales in the Beaufort Sea to the same drillship (2½-6 km).

Seismic Pulses.--Received 1/3-octave spectra of seismic pulses as a function of distance were predicted by combining the source level spectrum of *Western Polaris* (Fig. 9.8) with the transmission loss estimates for the Chirikof Basin (Appendix 3F). Although the attenuation rate is greater than in the Beaufort Sea, seismic pulses are again expected to be strong at distances exceeding 25 km (Fig. 9.17B). Assuming that gray whales have sensitive hearing at low frequencies, they can presumably hear seismic pulses at correspondingly long distances.

Most gray whales exhibit pronounced avoidance when the broadband received level of seismic pulses is 164-180 dB re 1 µPa (Malme et al. 1984, 1986b, 1988; sect. 8.8; Table 8.1). This is equivalent to ~156-172 dB in a 1/3-octave band.[9] The received levels of seismic pulses in the Chirikof Basin are predicted to diminish below 156-172 dB (1/3-octave basis) at distances ≤1 km from the seismic ship (Fig. 9.17B; Table 9.2A). Weaker reactions are likely at somewhat greater distances (Malme et al. 1983, 1984). The predicted avoidance distances are considerably less than the predicted radius of responsiveness of bowhead whales in the Beaufort Sea to the same seismic ship (5-25 km). The difference is attributable to two factors: (1) the greater rate of sound attenuation in the Chirikof Basin, and (2) a higher apparent response threshold for gray whales (156-172 dB) than for bowheads (142-168 dB).

Helicopter and Fixed-wing Overflights.--Predicted in-air near-surface noise levels from two twin-turbine aircraft flying at 300 m altitude are shown Figure 9.18A (Bell 212 helicopter) and 9.18B (Twin Otter fixed-wing aircraft). In-air ambient noise levels are estimated for beaches subjected to surf (*, o, from Abrahamson 1974) and for the quieter conditions prevailing offshore (+, from BBN 1960). These in-air ambient noise levels are considerably higher than those assumed over landfast ice of the Beaufort Sea (*cf.* Fig. 9.16B). At frequencies 50 Hz and above, a receiver on a beach with surf is unlikely to hear either aircraft at distances beyond ~2 km. Under offshore conditions, either aircraft would be detectable somewhat farther away.

Radii of audibility of aircraft noise to seals cannot be estimated reliably because of the lack of data on in-air auditory thresholds of seals at frequencies below 1 kHz. At and above 1 kHz, the thresholds of the harbor seal (Møhl 1968a) are similar to the assumed ambient noise level offshore, and less than ambient noise levels on a beach with surf. Thus, above 1 kHz, the radius of audibility of aircraft noise to a seal in the Bering Sea may usually limited by ambient noise rather than by the absolute hearing threshold. In contrast, on the landfast ice of the Beaufort Sea, where the ambient noise level is assumed to be weaker, the absolute hearing threshold may be the limiting factor (*cf.* Fig. 9.16B). A harbor seal offshore in the Bering Sea might detect some high frequency (≥1 kHz) components of Bell 212 or Twin Otter sound at slant distances as great as about 2-3 km (Fig. 9.18A,B). On a beach with surf, the radius of audibility of high frequency components is expected to be only about 1 km. There are no data

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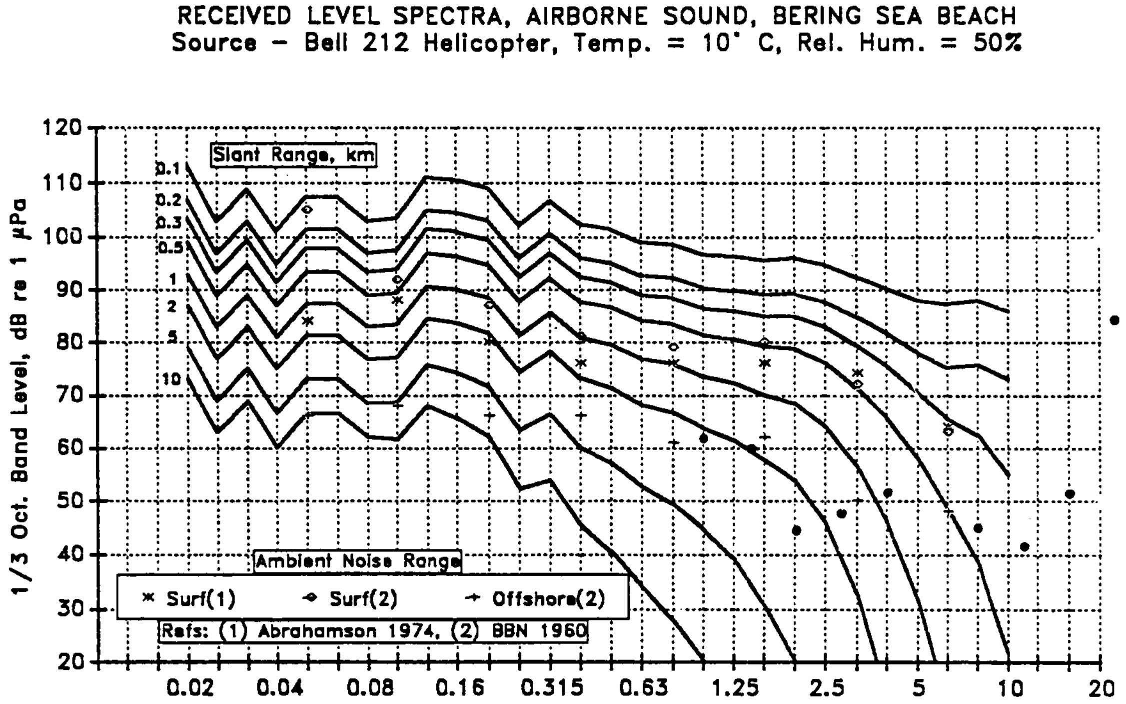
[8] Drillship sound was strong in about twelve 1/3-octave bands (Fig. 9.17A).

[9] Seismic sound was strong in about six 1/3-octave bands (Fig. 9.17B).



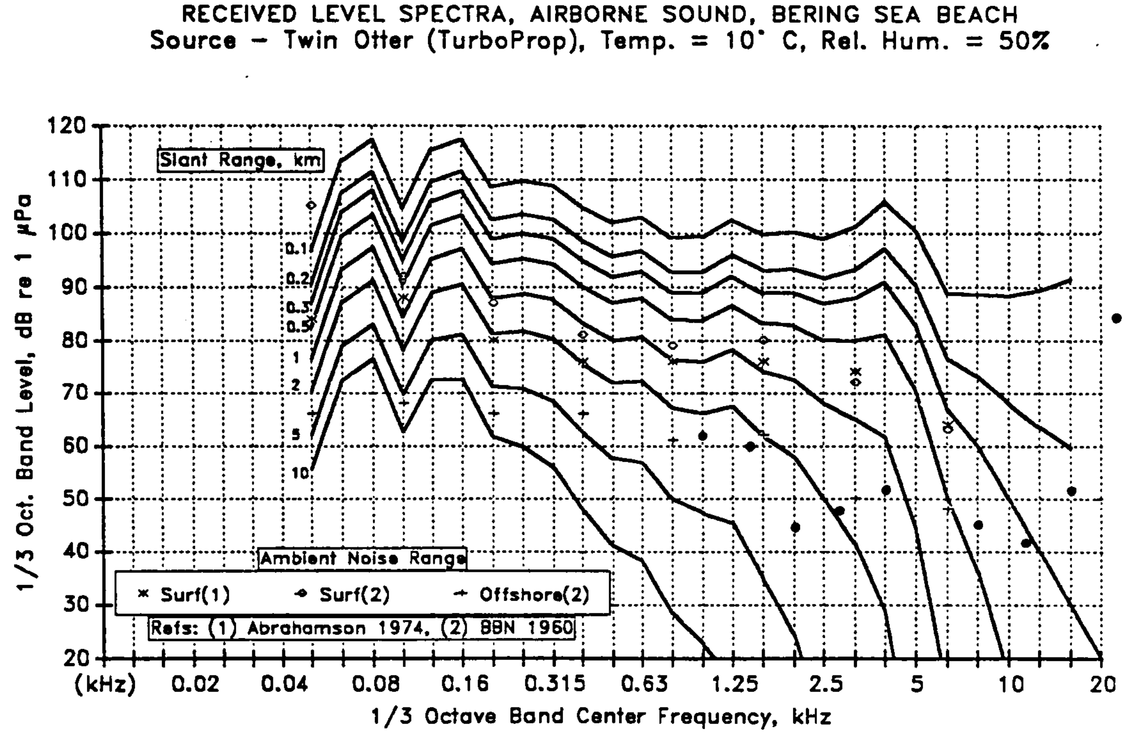


FIGURE 9.18. Predicted 1/3-octave received level spectra in the air just above a Bering Sea beach as *(A)* a Bell 212 helicopter and *(B)* a Twin Otter fixed-wing aircraft fly by at an altitude of 300 m at various slant ranges. Filled dots show absolute in-air hearing thresholds of a harbor seal, from Møhl (1968a). Ambient noise data in selected 1/3-octaves are shown by +, * and o symbols.

on the in-air sensitivity of seals to the lower frequency components of aircraft sound, which are stronger than high frequency components.

Acoustic response thresholds of harbor seals to aircraft noise have not been reported. However, there have been many observations of their reactions when aircraft pass at various altitudes and lateral distances (sect. 8.2.1). Responses are highly variable. The aircraft altitude that causes most harbor seals to rush into the sea has been reported to be as low as 61 m (Hoover 1988) and as high as 300 m (Bowles and Stewart 1980). Surf conditions are unknown for most of these observations. However, it appears that strong avoidance by harbor seals may occur only when aircraft approach well within the radius of audibility (Table 9.2A). Again, it should be noted that seals may react to the sight of the aircraft as well as to its sound. Most available data do not distinguish acoustic from visual effects.

9.9 California Case Study

9.9.1 Physical Acoustics

Nearshore Waters.--Transmission loss estimates for this area were obtained from the data of Malme et al. (1983, 1984, 1986a), supplemented by Weston/Smith models to summarize the data and extend the frequency range covered. The models assumed an average water depth of 50 m along a path parallel to the shoreline. The results (Appendix 3H) are applicable to California coastal regions with a relatively smooth bottom and no underwater canyons.

The airborne transmission loss model used to predict noise transmission from aircraft assumed 20 log R spreading loss and atmospheric absorption loss based on an assumed temperature of 25°C and 80% relative humidity (Appendix 3J).

The underwater ambient noise levels nearshore are dominated by sounds produced by shrimp. The level of shrimp noise is related to the water depth; it becomes stronger with decreasing depth until the surf zone is reached. This noise extends from 500 Hz to above 20 kHz. Below 500 Hz, noise from coastal shipping has an important influence on ambient noise levels. Spectra reported by Malme et al. (1984) were used, together with the Sea State 7 spectra of Wenz (1962) as an upper limit for the expected range of ambient levels.

Airborne ambient noise along the California coast is dominated by surf noise. Data used for the Bering Sea beach (sect. 4.6, 9.8.1) are also used here.

Near the Shelf Break.--Only a few transmission loss measurements have been reported from deeper waters near the shelf break off the California coast (Malme et. al. 1983, 1986a). The data suggest that the bottom material there is somewhat harder than the sand and rock sub-bottom found near shore. The bottom material near the shelf break contains less sand and has more rock outcrops and ledges. The Weston/Smith model was used for this region, with the bottom loss parameters adjusted for the harder conditions. An average depth of 180 m was assumed, with transmission parallel to the coastline (Appendix 3I).

Shrimp noise is not a significant contributor to ambient noise levels near the shelf break. Ship traffic and wind noise are the dominant factors. Hence, we used the Wenz (1962) spectra for Sea States ½, 2 and 7 in deep water. Moderate to heavy ship traffic was assumed to be present at long distances.

9.9.2 Predicted Radii of Influence

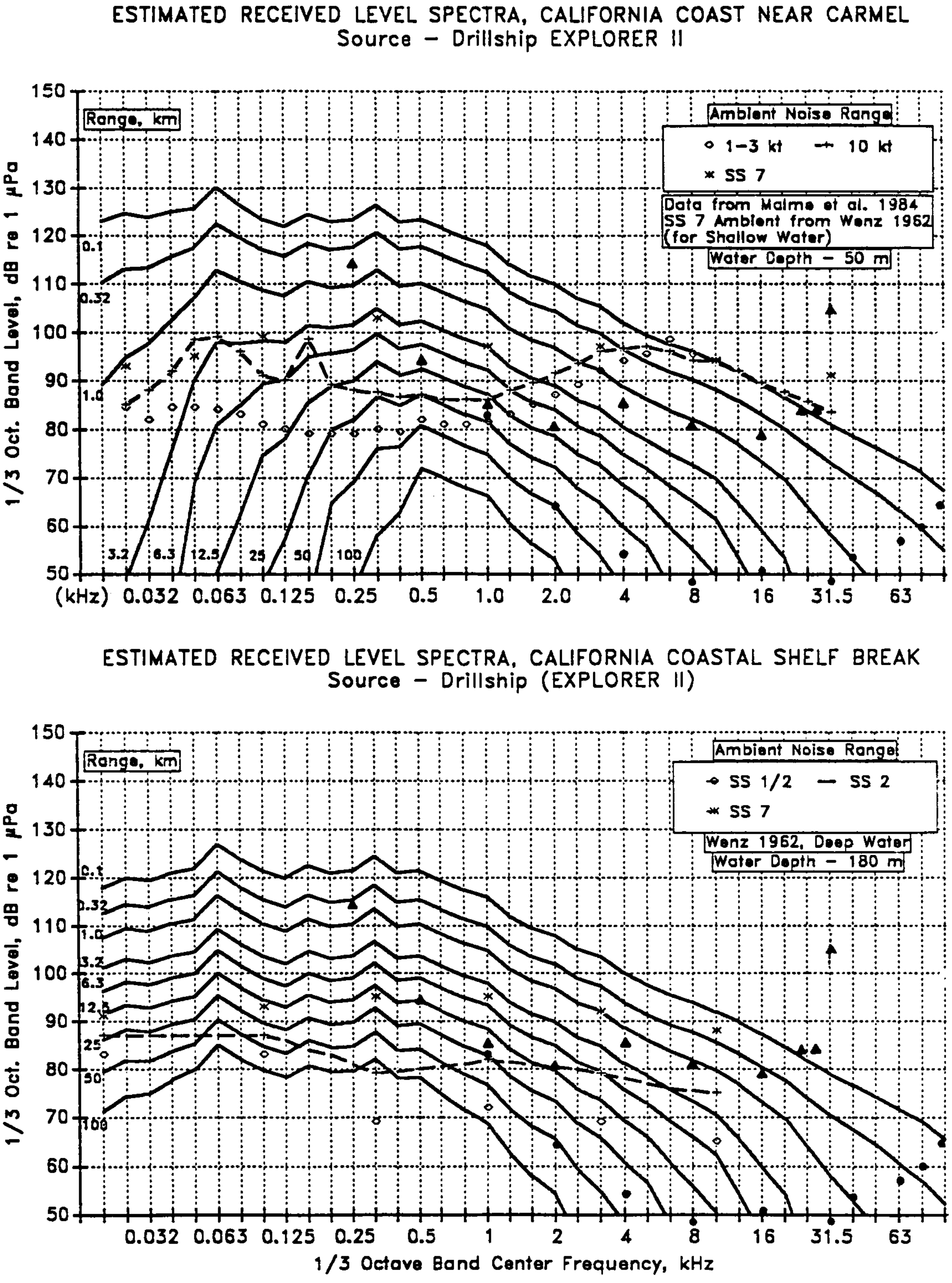
Drillship Noise.--Received third-octave spectra of drillship sound as a function of distance were predicted by combining the source level spectrum of *Explorer II* (Fig. 9.7) with the transmission loss estimates for the California coast from Appendix 3H (nearshore) and Appendix 3I (shelf break). Attenuation was considerably more rapid in the nearshore area than near the shelf break. The maximum detection distance under typical ambient noise conditions is predicted to be about 25 km in the nearshore region (Fig. 9.19A) vs. as much as 100 km near the shelf break (Fig. 9.19B). Again assuming that baleen whales have sensitive hearing at low frequencies, they are expected to be able to hear the drillship at distances as great as 25 km (nearshore, e.g. gray whale) and 100 km (shelf break, e.g. blue whale; Table 9.3).

About 50% of the gray whales exhibit avoidance when the received level of drillship sounds is 117 dB re 1 µPa on a broadband basis (Malme et al. 1984, 1986b, 1988; sect. 8.8) or ~106 dB in a 1/3-octave band (see sect. 9.8.2). The received levels of drillship sounds are predicted to diminish below 106 dB in the strongest 1/3-octave band at a range of ~3 km in nearshore waters (Fig. 9.19A) and ~6 km near the shelf break. However, it is not known whether the response thresholds of blue whales, which are more likely to occur near the shelf break, are similar to those of gray whales.

The harbor porpoise is a common coastal species off California. Like other toothed whales, it has sensitive hearing at high frequencies, but below 4 kHz its sensitivity diminishes rapidly with diminishing frequency (sect. 7.2.1). Nonetheless, its sensitivity at 2 kHz would be sufficient to detect noise from a very distant drillship (range ~50 km) if the ambient noise level were low enough to allow this (Fig. 9.19A,B). However, under typical ambient noise conditions, the radius of detectability will be limited by ambient noise rather than absolute hearing sensitivity at frequencies ≥1 kHz (Fig. 9.19A,B). With typical ambient noise, the maximum radius of detectability may be ~12 km in nearshore waters and ~25 km near the shelf break. These predictions are speculative, since hearing sensitivity of the harbor porpoise below 1 kHz is unknown. The predictions assume that hearing sensitivity of harbor porpoises continues to deteriorate with diminishing frequency below 1 kHz, as is known to occur in two other toothed whales (sect. 7.2). There are no data on acoustic response thresholds of harbor porpoises to drillship sounds, so radii of responsiveness cannot be estimated.

The California sea lion has more sensitive underwater hearing at moderate to high frequencies (≥1 kHz) than at lower frequencies. However, its absolute sensitivity at high frequencies is considerably poorer than that of the harbor porpoise and other toothed whales (sect. 7.2.2). Its underwater hearing sensitivity around 500-2000 Hz is apparently sensitive enough to detect noise from a drillship 10-15 km away in both nearshore and shelf break waters (Fig. 9.19). However, the ambient noise level will often be high enough to prevent detection of the drillship that far away. Again, there are no data on acoustic response thresholds of California sea lions near drillships, so radii of responsiveness cannot be estimated.

Production Platform Noise.--The acoustic source levels of production platforms of the types used in the Santa Barbara Channel are apparently considerably lower than those of


ESTIMATED RECEIVED LEVEL SPECTRA, CALIFORNIA COAST NEAR CARMEL
Source – Drillship EXPLORER II

ESTIMATED RECEIVED LEVEL SPECTRA, CALIFORNIA COASTAL SHELF BREAK
Source – Drillship (EXPLORER II)

FIGURE 9.19. Predicted 1/3-octave received level spectra at various ranges from a drillship operating off the California coast *(A)* in nearshore waters and *(B)* near the shelf break. Presentation as in Figure 9.11, except that filled dots and filled triangles show absolute underwater hearing thresholds of a harbor porpoise (Andersen 1970a) and the California sea lion (Schusterman et al. 1972), respectively.

Table 9.3. Summary of predicted radii of audibility and responsiveness around selected industrial operations off California.

AL = Ambient-limited. TL = Threshold-limited. Radii of audibility marked as "AL" assume typical ambient noise conditions, and would be strongly affected by variations in ambient noise. All estimates are subject to many other sources of variability and uncertainty (see text). Bracketed values are especially speculative.

Location	Season	Species	Industrial Act.	Medium	Radius of Audibility	Radius of Response
Nearshore		Gray Whale	Drillship (Explorer II)	Water	25 km (AL)	3 km
			Production Platform	"	½ km (AL)	<0.1 km
			Seismic--airguns	"	>100 km (AL)	0.1-1 km
"		Harb. Porp.	Drillship (Explorer II)	Water	12 km (AL)	?
			Production Platform	"	~0.1 km	≤0.1 km
			Seismic--airguns	"	100 km	?
"		Cal. Sea Lion	Drillship (Explorer II)	Water	10-15 km (AL or TL)	?
			Production Platform	"	~0.1 km	≤0.1 km
			Seismic--airguns	"	100 km	?
Shelf Break		Baleen Whale	Drillship (Explorer II)	Water	100 km (AL)	6 km
			Production Platform	"	2 km (AL)	<0.1 km
			Seismic--airguns	"	>>100 km (AL)	0.1-2 km
"		Harb. Porp.	Drillship (Explorer II)	Water	25 km (AL)	?
			Production Platform	"	~0.1 km (AL or TL)	≤0.1 km
			Seismic--airguns	"	>100 km (AL or TL)	?
"		Cal. Sea Lion	Drillship (Explorer II)	Water	10-15 km (AL or TL)	?
			Production Platform	"	<0.1 km (AL or TL)	<0.1 km
			Seismic--airguns	"	>100 km (AL or TL)	?
Beach		Harb. Seal &	Aircraft (B-212 or	Air	[2-3 km @ ≥1 kHz (AL)] *	?
		Cal. Sea Lion	Twin Otter)	"	[1 km @ ≥1 kHz (AL)] *	?

* Radius of audibility may be greater at lower frequencies where hearing sensitivity is unknown.

drillships (Fig 9.7), although additional quantitative data on their levels are needed (sect. 5.4.5). Consequently, the received levels of platform sounds are expected to diminish below the ambient noise level at considerably closer distances (Fig. 9.20). Under typical ambient noise conditions, noise from a production platform might be detectable no more than ½ km away in nearshore waters and 2 km away near the shelf break. Based on our usual assumptions about baleen whale hearing, these distances are the predicted radii of audibility for gray, blue or other baleen whales.

The response threshold of a typical gray whale to playbacks of production platform noise was 123 dB re 1 μPa on a broadband basis (sect. 8.8; Malme et al. 1984). This would be about 117 dB on a 1/3-octave basis, given that the energy was predominantly in ~4 third-octaves (Fig. 9.7). The received level of production platform noise in the strongest 1/3-octave is expected to diminish below 117 dB well within 100 m of the platform in both nearshore and shelf-break waters (Fig. 9.20). Hence, the predicted maximum radius of responsiveness of gray whales to production platform noise is <100 m. It is possible that at such short distances, visual stimuli might be important as well.

For harbor porpoises, the predicted radius of audibility of production platform noise is limited by its low source level, the animals' poor hearing sensitivity at low frequencies, and the high ambient noise levels at moderate to high frequencies (Fig. 9.20). Under typical ambient noise conditions, porpoises are not expected to detect the production platform noise at distances beyond 100 m, assuming that their hearing continues to deteriorate with diminishing frequency below 1 kHz. Response thresholds are unknown, but no reaction to the noise would be expected beyond the maximum radius of audibility (i.e. ≤100 m). Again, visual effects are a consideration at such close ranges.

The situation is similar for California sea lions. Predicted levels of production platform noise are below the hearing threshold, the ambient noise level, or both at all distances beyond 100 m. California sea lions have been reported to be common around production platforms off California (Gales 1982; McCarty 1982).

Seismic Pulses.--In contrast, noise pulses from airguns have very high source levels, and are expected to remain above the typical ambient noise levels out to distances exceeding 100 km--especially in the deeper waters near the shelf break (Fig. 9.21). Baleen whales off California are expected to hear seismic pulses from seismic ships more than 100 km away.

Most migrating gray whales exhibit pronounced avoidance when the broadband received level of seismic pulses is 164-180 dB re 1 μPa (Malme et al. 1984; sect. 8.8). This is equivalent to ~156-172 dB in a 1/3-octave band (see sect. 9.8.2). Received levels of seismic pulses off California are predicted to diminish below 156-172 dB (1/3-octave basis) at about 0.1-1 km from a seismic ship in nearshore waters, and 0.1-2 km from a ship near the shelf break (Fig. 9.21; Table 9.3). Weaker reactions are likely at somewhat greater distances (Malme et al. 1983, 1984). The predicted avoidance distances are considerably less than the observed and predicted response radii of bowhead whales in the Beaufort Sea. The difference is attributable to the greater rate of sound attenuation off California and a higher apparent response threshold for gray whales than bowheads.

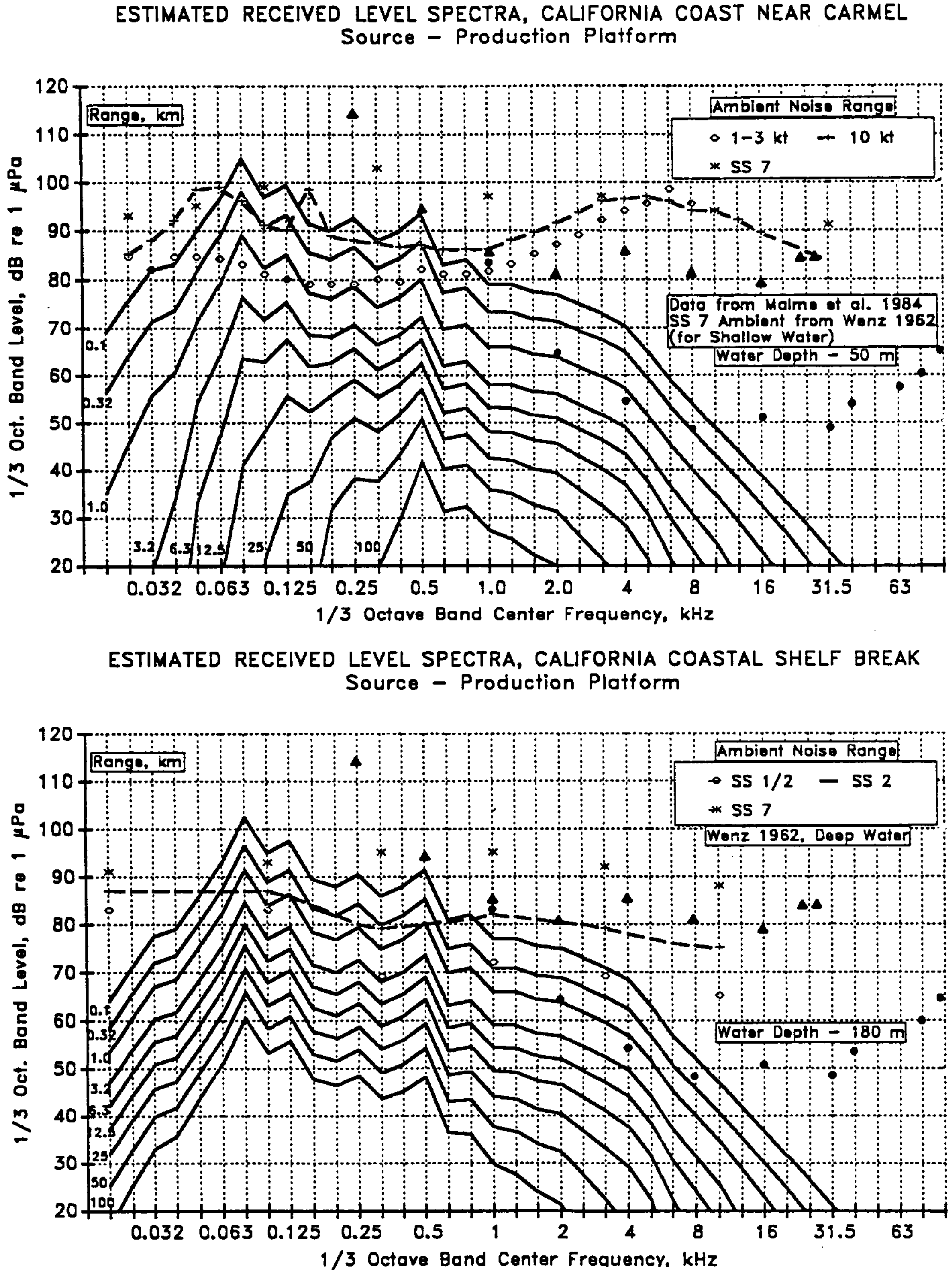
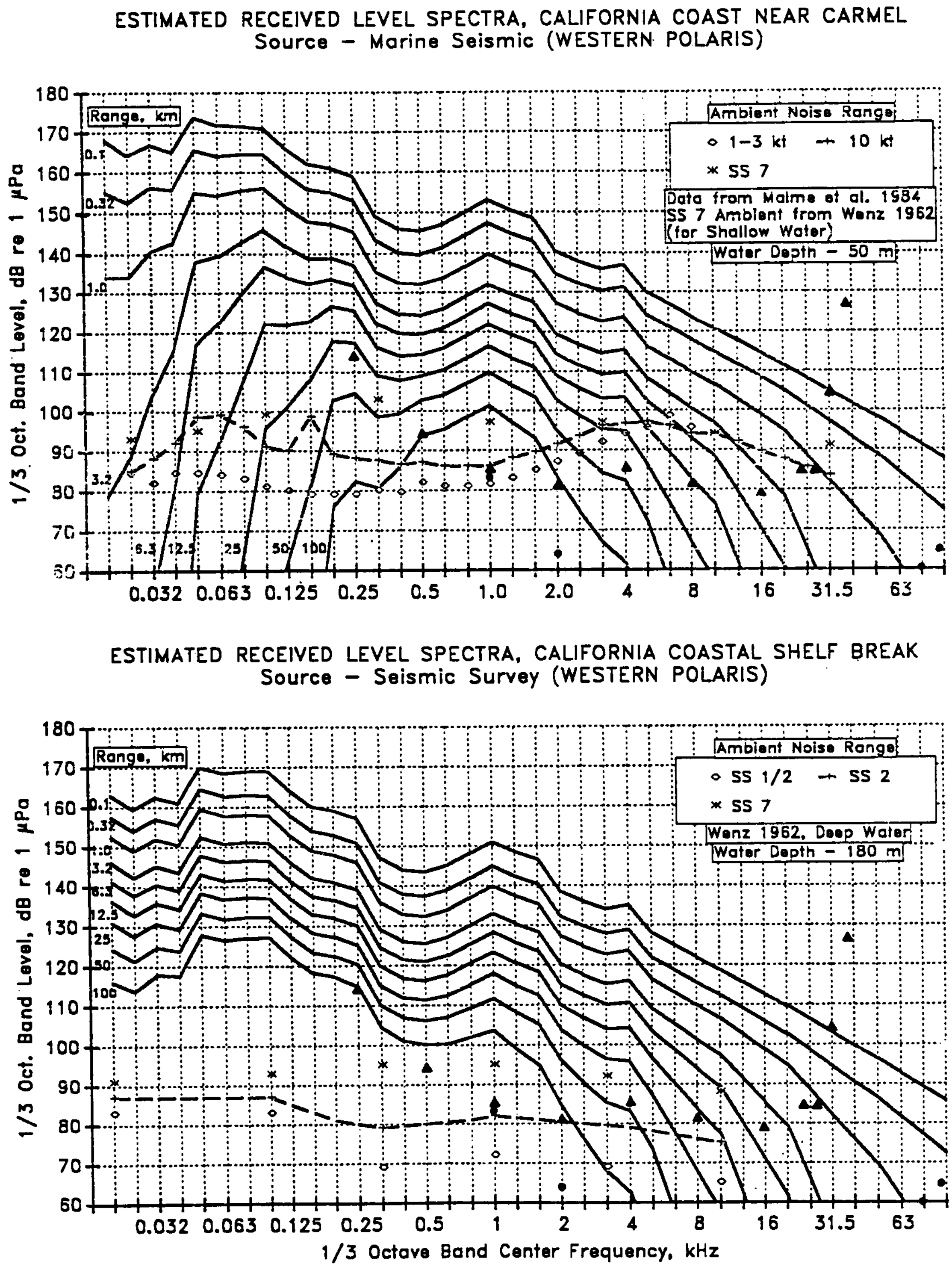


FIGURE 9.20. Predicted 1/3-octave received level spectra at various ranges from a production platform operating off the California coast *(A)* in nearshore waters and *(B)* near the shelf break. Presentation as in Figure 9.11, except that filled dots and filled triangles show absolute underwater hearing thresholds of a harbor porpoise (Andersen 1970a) and the California sea lion (Schusterman et al. 1972), respectively.


ESTIMATED RECEIVED LEVEL SPECTRA, CALIFORNIA COAST NEAR CARMEL
Source – Marine Seismic (WESTERN POLARIS)

ESTIMATED RECEIVED LEVEL SPECTRA, CALIFORNIA COASTAL SHELF BREAK
Source – Seismic Survey (WESTERN POLARIS)

FIGURE 9.21. Predicted 1/3-octave received level spectra at various ranges from an array of airguns operating off the California coast *(A)* in nearshore waters and *(B)* near the shelf break. Presentation as in Figure 9.11, except that filled dots and filled triangles show absolute underwater hearing thresholds of a harbor porpoise (Andersen 1970a) and the California sea lion (Schusterman et al. 1972), respectively.

The seismic pulses are also expected to be strong enough to be detectable by harbor porpoises and California sea lions at distances as great as 100 km from the seismic vessel (Fig. 9.21A,B). Components of the seismic sounds around 500-800 Hz are expected to exceed both the typical ambient noise levels and the absolute auditory thresholds of both species at those frequencies. (For harbor porpoises, this conclusion assumes that thresholds deteriorate steadily as frequency decreases below 1 kHz.) On days with higher-than-average ambient noise levels, the radius of audibility of seismic pulses in shallow waters could be less than 100 km for both harbor porpoises and sea lions.

Radii of responsiveness of harbor porpoises and sea lions to seismic pulses cannot be estimated. We know of no data on responses of harbor porpoises or other toothed whales to seismic pulses. There are published observations, largely anecdotal, suggesting that sea lions and some other pinnipeds may tolerate strong noise pulses (sect. 8.6.1). However, these data are inadequate for any estimation of response distances.

Helicopter and Fixed Wing Overflights.--Predicted in-air near-surface noise levels from two twin-turbine aircraft flying at 300 m altitude are shown in Figure 9.22. These graphs are very similar to those for the Bering Sea (*cf.* Fig. 9.18). Minor differences arise from different assumptions about air temperature and humidity. At 50 Hz and above, a receiver on a beach with surf is unlikely to detect either aircraft at distances beyond ~2 km. Under offshore conditions, either aircraft would be detectable somewhat farther away.

Figure 9.22 shows in-air hearing thresholds for the harbor seal (Møhl 1968a); values for the California sea lion at corresponding frequencies are very similar (Fig. 7.3). As in the Bering Sea, radii of audibility of aircraft noise to a seal or sea lion may usually limited by ambient noise rather than by the absolute hearing threshold. An animal offshore in the Bering Sea might detect some high frequency (≥1 kHz) components of Bell 212 or Twin Otter sound at slant distances as great as about 2-3 km (Fig. 9.22A,B; Table 9.3). On a beach with surf, the radius of audibility of high frequency components is expected to be only ~1 km. There are no data on the in-air sensitivity of pinnipeds to the lower frequency components of aircraft sound, which are stronger than high frequency components.

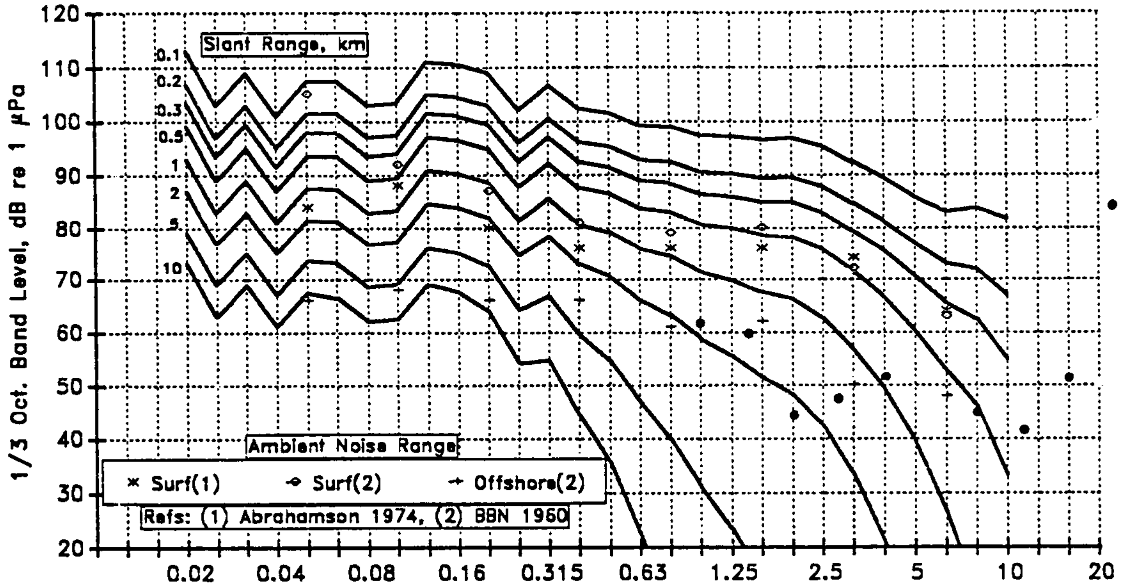
Radii of responsiveness cannot be estimated from acoustic data because response thresholds of pinnipeds to aircraft noise have not been reported. Section 8.2.1 summarizes available observations of reactions to various aircraft at different altitudes and lateral distances. Strong avoidance may occur only when aircraft approach well within the radius of audibility.

9.10 Atlantic Case Study

9.10.1 Physical Acoustics

Several studies of underwater sound transmission on the Scotian Shelf have been done by Ellis and Chapman (1980) and others. Unfortunately, the available data do not include several frequency bands of interest to this study. Hence it again was necessary to fill in the gaps with model predictions. An IFD model developed for the Aleutian Basin, an area with bottom properties similar to those of the Scotian Shelf, was used as the basis for the Scotian Shelf predictions. Transmission loss estimates for the Aleutian Basin, based on the IFD model (sect. 3.4; Malme et al. 1989), compared well with Scotian Shelf data for the same water depths and

RECEIVED LEVEL SPECTRA, AIRBORNE SOUND, CALIFORNIA BEACH
Source – Bell 212 Helicopter, Temp. = 25° C, Rel. Hum. = 80%



RECEIVED LEVEL SPECTRA, AIRBORNE SOUND, CALIFORNIA BEACH
Source – Twin Otter (TurboProp), Temp. = 25° C, Rel. Hum. = 80%

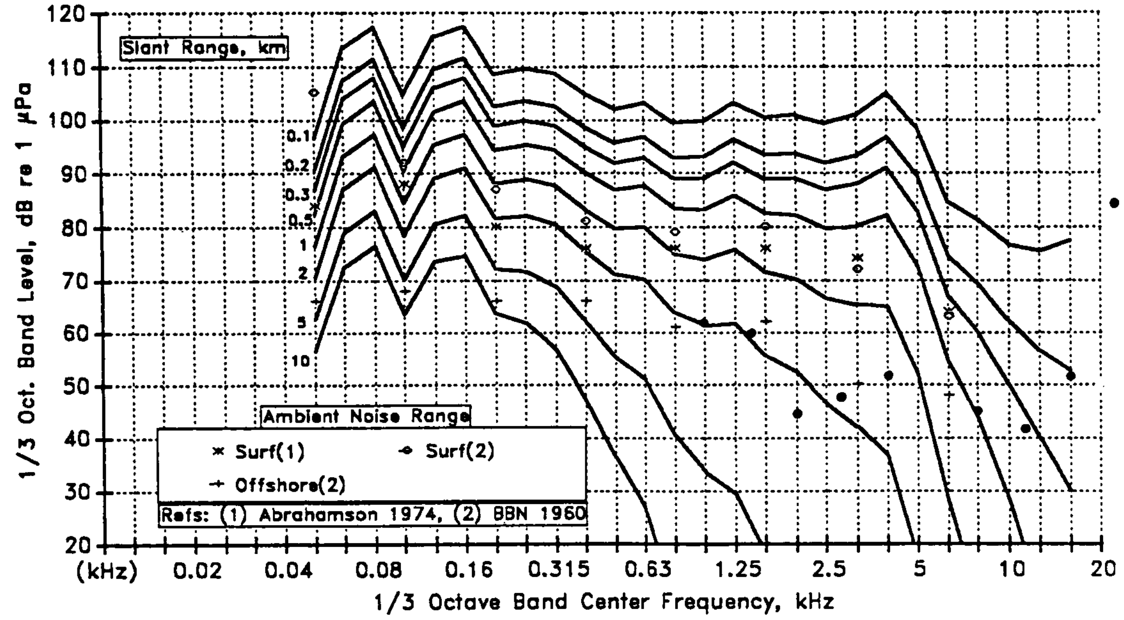


FIGURE 9.22. Predicted 1/3-octave received level spectra in the air just above a California beach as *(A)* a Bell 212 helicopter and *(B)* a Twin Otter fixed-wing aircraft fly by at an altitude of 300 m at various slant ranges. Filled dots show absolute in-air hearing thresholds of a harbor seal, from Møhl (1968a). Ambient noise data in selected 1/3-octaves are shown by +, * and o symbols.

frequencies (Ellis and Chapman 1980). Consequently the IFD model, supplemented by Weston/Smith models, was used to obtain transmission loss estimates for the wide range of frequencies of interest. A region with an average water depth of 70 m was assumed. The propagation loss estimates are summarized in Appendix 3K.

The shallow water ambient noise curves of Wenz (1962) for Sea States ½, 2 and 7 were used to estimate the range of expected ambient noise levels on the Scotian Shelf. Light to moderate shipping was assumed.

9.10.2 Predicted Radii of Influence

Some components of supply ship and drillship noise are predicted to remain above typical background noise levels at corresponding frequencies out to distances of ~50 km (Fig. 9.23). In contrast, all components of production platform sounds are expected to diminish below the typical ambient noise level within ~5 km (Fig. 9.24). The smaller radius of detectability of the production platform sounds is attributable to their lower source levels (Fig. 9.7).

Baleen whales, e.g. right and finback whales, are expected to be able to hear the supply ship and drillship at distances as great as 50 km, and the production platform at distances up to ~5 km (Table 9.2B). These predictions are based on acoustic information for frequencies as low as 20 Hz. The emitted industrial sounds at lower frequencies (infrasounds) are generally unknown. Fin whales often call at frequencies as low as 20 Hz (sect. 6.1), and presumably can hear strong sounds at somewhat lower frequencies. The scarcity of data on industrial infrasounds and on their detection by whales causes some interpretation difficulties. However, the rapid attenuation of very low frequency sounds in most shallow-water regions means that these data gaps are less severe than they might otherwise be.

Radii of responsiveness of baleen whales on the Scotian Shelf cannot be estimated in any detail because response thresholds to the types of industrial sounds discussed here are not known. For gray and bowhead whales, the response thresholds for stationary sources are often ~110 dB re 1 μPa in the strongest 1/3-octave band. If that criterion applies to species occurring on the Scotian Shelf, reactions would be expected up to ~3 km from the drillship but to much less than 300 m from the production platform (Fig. 9.23B, 9.24; Table 9.2B).

In the case of the harbor porpoise, absolute hearing thresholds at frequencies above 1 kHz are less than the typical 1/3-octave ambient noise levels expected on the Scotian Shelf (Fig. 9.23, 9.24). Hearing thresholds at lower frequencies are unknown but are expected to increase with diminishing frequency. If so, harbor porpoises can probably detect the moving supply ship as much as 50 km away and the drillship at 35 km (Fig. 9.23). The production platform is unlikely to be audible to a harbor porpoise as little as 300 m away (Fig. 9.24).

Response thresholds for harbor porpoises near moving ships, drillships and production platforms are unknown. However, the reaction distances of harbor porpoises to moving ships are probably on the order of 1 km (sect. 8.3.2). This is much less than the predicted 50 km radius of audibility of the supply ship. Thus, harbor porpoises apparently tolerate some ship noise.

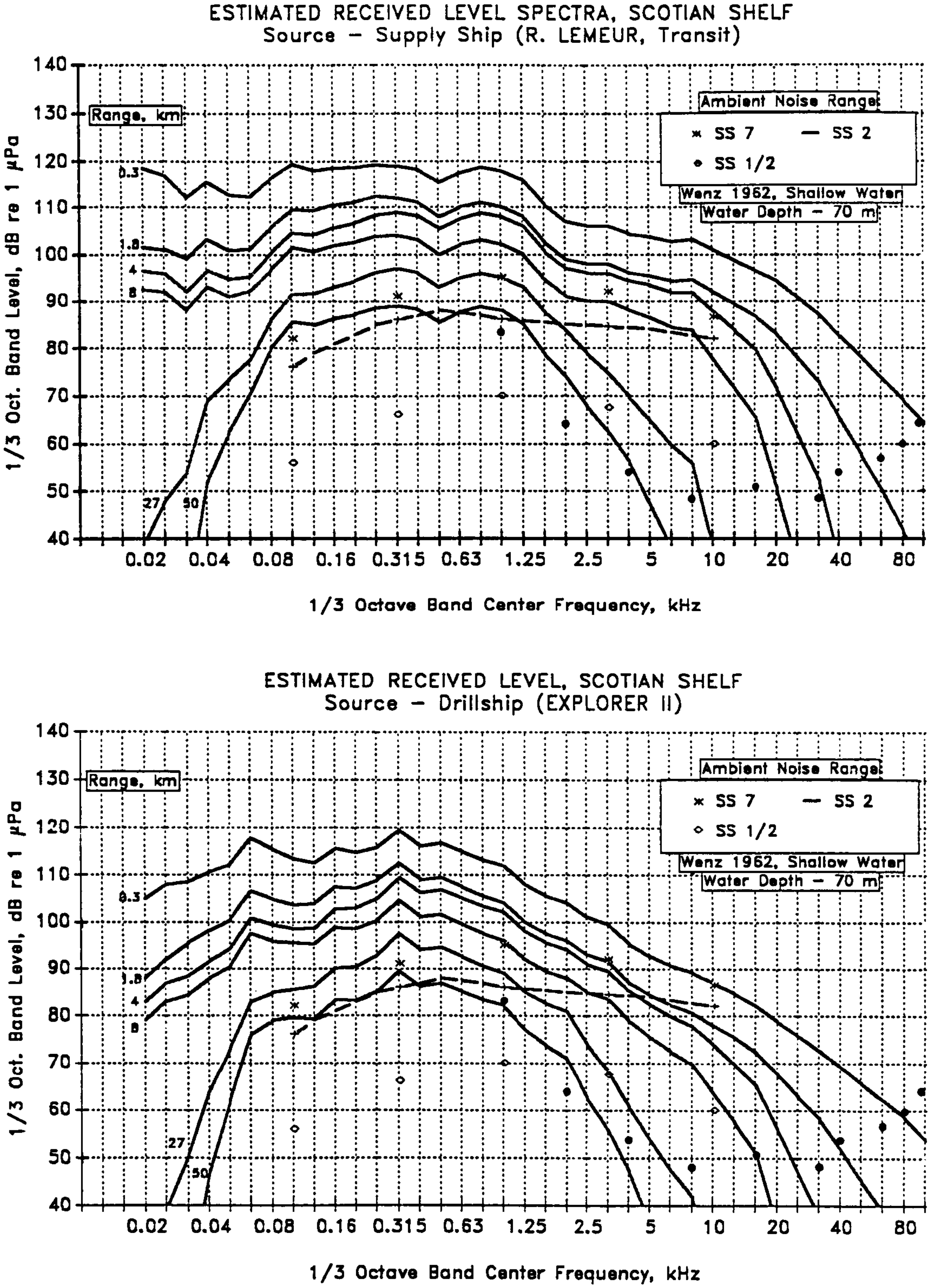


FIGURE 9.23. Predicted 1/3-octave received level spectra at various ranges from *(A)* a supply ship in transit and *(B)* a drillship in Scotian Shelf waters off New England. Filled dots show the absolute underwater hearing thresholds of a harbor porpoise (Andersen 1970a). Otherwise as in Figure 9.11.

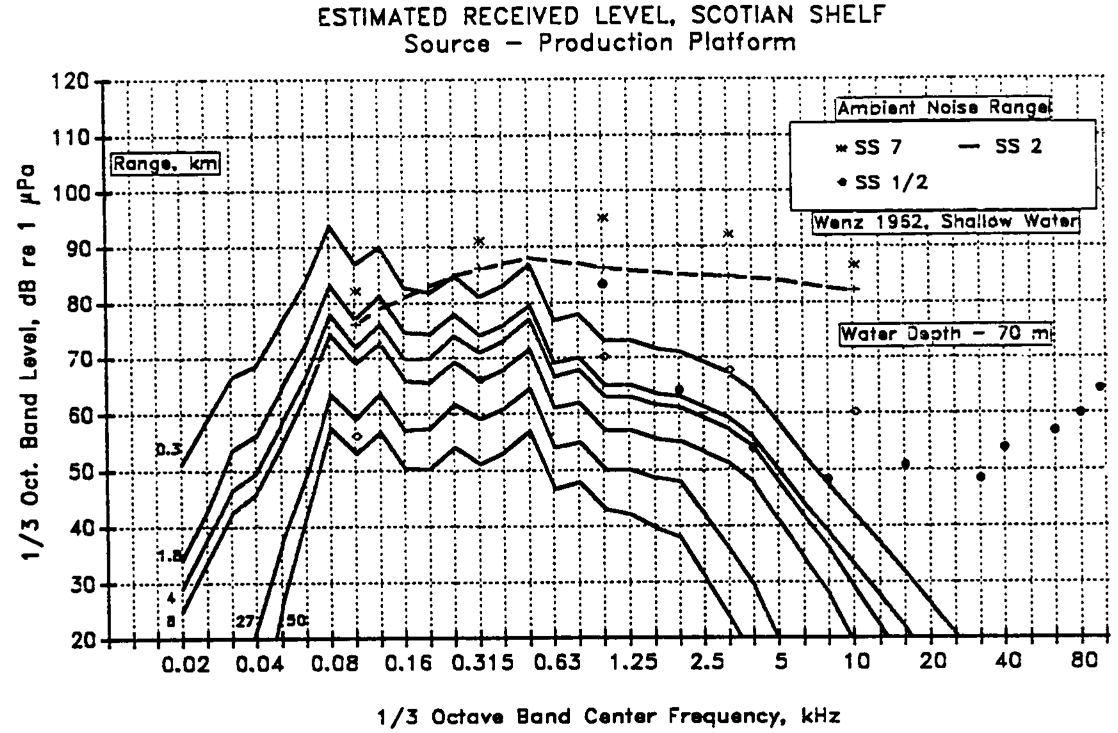


FIGURE 9.24. Predicted 1/3-octave received level spectra at various ranges from a production platform in Scotian Shelf waters off New England. Filled dots show the absolute underwater hearing thresholds of a harbor porpoise (Andersen 1970a). Otherwise as in Figure 9.11.

9.11 Gulf of Mexico Case Study

9.11.1 Physical Acoustics

Transmission loss and ambient noise were estimated for summer conditions off the west coast of Florida--specifically near Charlotte Harbor. The bottom composition there is similar to that along some parts of the California coast: a thin layer of sand over underlying sedimentary rock (Shepard 1963). However, the continental shelf near Charlotte Harbor is shallower and more extensive than is typical off California. In the absence of specific underwater transmission loss data for Florida, Weston/Smith models for the nearshore California region were revised using an average bottom depth of 30 m (Appendix 3L).

Ambient noise levels off western Florida are strongly affected by shrimp. Hence, ambient noise measurements obtained off the California Coast (Malme et al. 1984) were used to estimate the expected range of ambient noise off Florida (Fig. 9.25). However, the assumed water depth is 30 m in the Florida case, as compared with 65 m in the nearshore case off California. Because shrimp noise tends to increase with decreasing water depth, this component of the ambient noise may be underestimated by 3 to 5 dB in the 1/3 octave bands above 1 kHz.

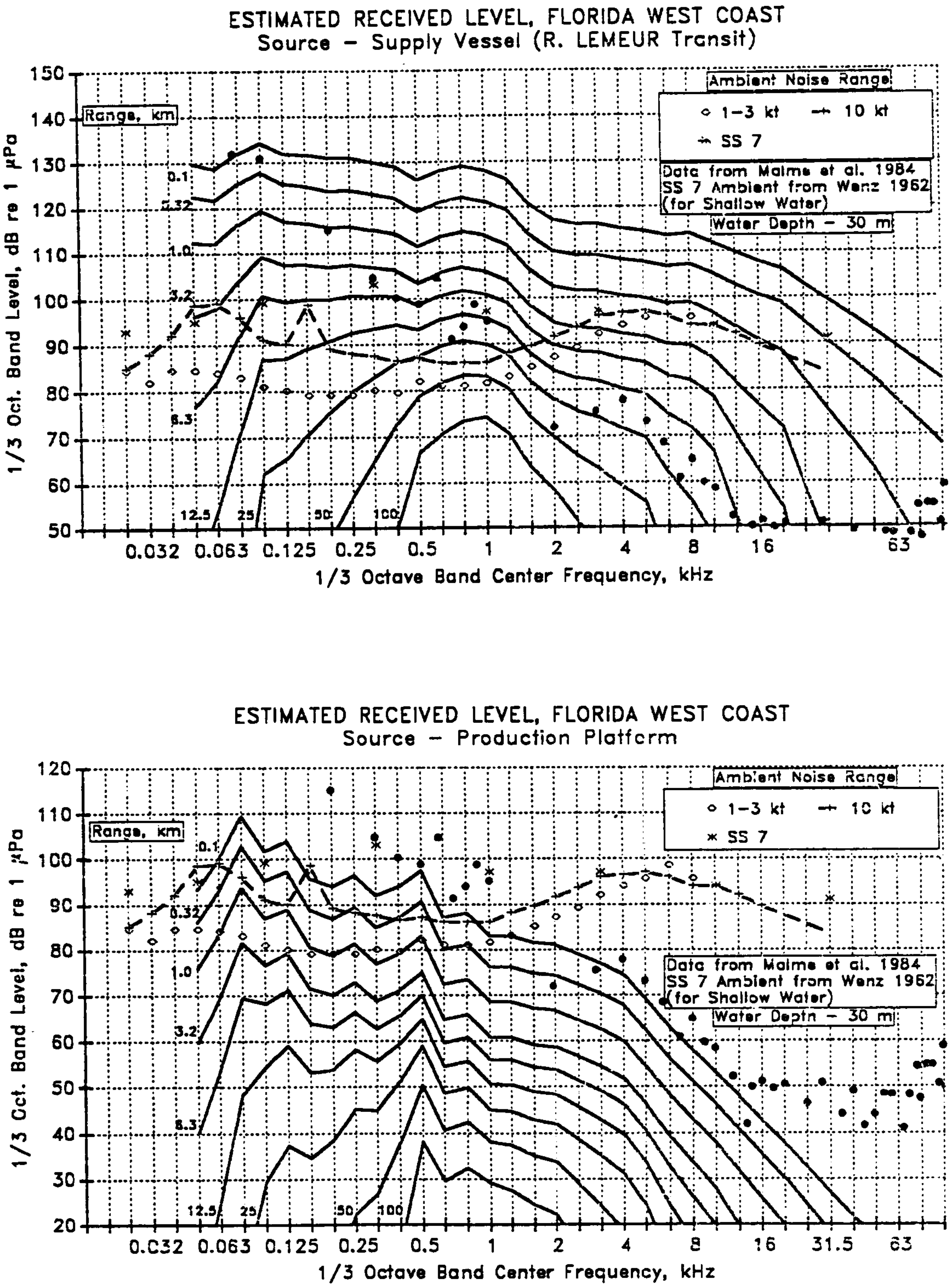


FIGURE 9.25. Predicted 1/3-octave received level spectra at various ranges from *(A)* a supply ship in transit and *(B)* a production platform in the Gulf of Mexico off Florida. Filled dots show the absolute underwater hearing thresholds of a bottlenose dolphin (Johnson 1967). Otherwise as in Figure 9.11.

9.11.2 Predicted Radii of Influence

For this region, we consider the potential radii of influence of a supply ship and a bottom-founded production platform on the bottlenose dolphin, the most characteristic marine mammal of the area. The hearing abilities of this species are comparatively well known (Chap. 7), including data on its absolute hearing thresholds at low frequencies (sect. 7.2.1). The source level of the supply ship is much higher than that of the production platform (Fig. 9.7). Hence received levels of supply ship noise are expected to remain above the ambient noise level out to considerably longer distances. The 1/3-octave levels near 500-1250 Hz are predicted to equal or exceed the typical 1/3-octave ambient noise levels at distances out to 25-40 km (Fig. 9.25A). In contrast, the weaker noise from a production platform would diminish below the typical ambient noise level within 1 km for all 1/3-octave bands (Fig. 9.25B).

The predicted radii of audibility of these industrial noises to the bottlenose dolphin are limited by the hearing thresholds of this species at 1 kHz and below. This species has much better hearing sensitivity at 2 kHz and above. However, radii of audibility of high frequency components of the industrial sounds would be limited by the anticipated high ambient noise levels at these frequencies (Fig. 9.25). Components of the supply ship noise near 600-1000 Hz might be audible as much as 10-25 km away, although not on days with higher than average ambient noise levels (Fig. 9.25A). No components of the production platform noise are expected to be audible more than 100 m from the platform, given the high hearing thresholds below 2 kHz and the high ambient noise levels at and above 2 kHz (Fig. 9.25B; Table 9.2C).

Radii of responsiveness of bottlenose dolphins to these industrial sounds are difficult to estimate because of the lack of response threshold data. In general, bottlenose dolphins often seem quite tolerant of shipping (sect. 8.3.2). However, they may become very responsive to the noises from specific vessels that have harassed those animals (Irvine et al. 1981). Given the anticipated small radius of audibility of a production platform (<100 m), the corresponding radius of acoustic responsiveness is expected to be of negligible size. Visual and other non-acoustic effects may also need to be considered at such close ranges.

9.12 Summary and Comparisons

Predicted radii of audibility and responsiveness for the various scenarios discussed above are summarized in Tables 9.1-9.3. Much caution is essential in interpreting these values. They are probably most useful when compared with one another, i.e. in a relative sense. They are undoubtedly less useful as predictors of actual radii of audibility or responsiveness in specific circumstances. The quantitative predictions depend strongly on many variables. These variables include the source level and spectral characteristics of the industrial activity in question, the rate of acoustic attenuation with distance, and the ambient noise level and its spectral characteristics. For example, radii of audibility listed in Tables 9.1-9.3 assume "typical" ambient noise levels. Normal day-to-day variations in ambient noise are expected to cause drastic changes in the radius of audibility for all situations listed in the Tables as "ambient limited" (AL). Predicted radii of influence are also uncertain because of variability and uncertainties in biological phenomena like auditory sensitivity, detection of infrasounds, and behavioral response thresholds.

9.12.1 Radii of Audibility

Despite the limitations of these predictions, it is clear that some industrial activities will be audible much farther away than others. Strong acoustic sources like seismic exploration and icebreaking are probably audible 100 km or more away in many cases. This is especially true for baleen whales, assuming that their hearing is very sensitive to low frequency sounds. However, low frequency seismic pulses may be strong enough to be heard at distances of 100 km or more even by some toothed whales and pinnipeds, whose low frequency hearing is apparently not very sensitive. At the other extreme, a bottom-founded oil production platform like that used off Santa Barbara is not expected to be audible to toothed whales and pinnipeds more than a few hundred meters away, or to baleen whales more than a few kilometers away.

Available propagation loss and ambient noise data show that average radii of audibility are expected to vary seasonally and among regions. For example, attenuation of underwater sounds is less rapid in the Beaufort Sea than in most other areas. Elevated levels of ambient noise caused by snapping shrimp or surf, for example, can cause significant reductions in typical radii of audibility. Within any one region, day-to-day variability in ambient noise can affect the radius of audibility drastically. This can be seen in Figures 9.11-9.25 by noting the effect on expected radius of audibility if the dashed ambient noise curve were drawn through the "high ambient" or "low ambient" symbols (usually * or o) instead of through the "typical ambient" levels.

Uncertainties about absolute hearing sensitivity are important data gaps in estimating radii of audibility. For baleen whales, no direct data on hearing sensitivity are available. We assumed that the auditory systems of these species are quite sensitive to low frequency sounds, since most of their calls are at low frequency. However, corroboration is needed. Also, the lack of data on the sensitivity of baleen whales to infrasounds (at <20 Hz) is an important data gap, given their assumed sensitivity to slightly higher frequencies and the evidence of strong infrasonic components in certain industrial noises. Behavioral audiograms of several species of toothed whales and pinnipeds have been determined, but in most cases there are no data for frequencies below ~1 kHz. These are the frequencies where most industrial noises are strongest. The lack of data on hearing thresholds at low frequencies prevented us from estimating meaningful radii of audibility in several of the above scenarios, and required bold extrapolations in other cases. The lack of behavioral audiograms for manatees and sea otters prevented any consideration of these animals.

All of our estimates of radius of audibility are based on the assumption that marine mammals can hear a sound whose level in one or more 1/3-octave bands exceeds the background noise level in the corresponding band. Masking bandwidths undoubtedly vary. Although experimental data on masking exist for a few species of marine mammals, these data are of only general usefulness because almost all of them concern the rather artificial case of pure tones masked by white noise. A further concern is the assumption that the minimum detectable signal-to-noise ratio is 0 dB. The effective value may be somewhat above or below 0 dB. The minimum detectable S/N may also depend on the directions of arrival of the signal vs. the dominant components of the background noise, at least at high frequencies. The above scenarios do not allow for the possibility that directional hearing extends the radius of audibility.

For all of these reasons, our estimates of radii of audibility must be taken as preliminary first approximations. Their greatest usefulness is probably in identifying phenomena and situations that deserve further study.

9.12.2 Radii of Responsiveness

Many marine mammals tolerate exposure to industrial noise that is apparently audible but not unduly intense. Many species occur well within the ensonified areas around industrial sites. However, when the industrial noise level is high enough, marine mammals often exhibit avoidance or other behavioral reactions. Thus, the radius of responsiveness is often considerably less than the radius of audibility. For example, seismic pulses are often detectable 100 km or more away, but gray and bowhead whales usually do not show overt avoidance unless the seismic vessel is within a few kilometers.

Very few studies have attempted to determine the threshold noise levels that elicit behavioral reactions. Thus, for many of the scenarios considered above, we could only quote the closest distances at which marine mammals have been seen, without allowance for the actual (but unknown) received noise levels. Even the distance data are lacking for some scenarios, identified with a "?" symbol in the "Radius of Response" columns of Tables 9.1-9.3. Thus, the scarcity of measured noise levels at which marine mammals do and do not react to various industrial activities is a significant data gap.

Even for a given species in a given area and season, there is wide variability in the responsiveness of different individuals to noise. Therefore, large sample sizes are needed to characterize response criteria. Also, response criteria are statistical rather than absolute. Most of the "radius of response" predictions summarized in Tables 9.1-9.3 are the distances where we expect an average individual to react. Some individuals may occur closer to the industrial source; others may react strongly at greater distances. Among the many factors that may affect responsiveness are the current activity of the animal and its past experience (if any) with that type of sound.

The above scenarios consider only the acoustic characteristics of industrial activities. Some marine mammals may also react to their appearance or odor. This is perhaps most likely in the cases of industrial activities that are not expected to have long-distance acoustic effects.

10. SIGNIFICANCE OF RESPONSES AND NOISE IMPACTS[1,2]

10.1 Introduction

Marine mammals undoubtedly hear man-made noises from many sources. Cetaceans and manatees are exposed primarily to underwater sounds. Pinnipeds and sea otters are often subjected to airborne as well as underwater sounds. Most man-made sounds to which marine mammals are exposed are concentrated at low frequencies, although there are exceptions (e.g. ship sonars). The hearing systems of baleen whales are assumed to be adapted for detecting natural low frequency sounds. Pinnipeds and especially toothed whales are better adapted for detecting higher frequency sounds, but they can undoubtedly hear strong low frequency sounds as well (chap. 7). Data on the hearing abilities of manatees and sea otters are meager or lacking, preventing any meaningful assessment of their abilities to detect industrial sounds.

The fact that most marine mammals can detect man-made noise does not, in itself, show that marine mammals are affected deleteriously by the noise. Chapter 8 cites many examples of marine mammals that commonly occur close enough to noise sources to be well within the ensonified zone. In many of these cases, activities of animals within the ensonified zone seem unaffected by the noise.

However, there is rarely any definitive information about the numbers of mammals within the ensonified zone relative to the numbers that would have been there if there were no man-made noise. Also, there is essentially no information about the possibility that marine mammals occurring within an ensonified zone are "stressed" or otherwise affected in a way that might impair their long-term well-being, or their reproductive success. For example, acoustic masking will reduce the ability of a marine mammal near a noise source to hear faint calls from distant conspecifics or other faint natural sounds. The consequences of masking are unclear, given the paucity of information about the importance of various natural sounds to most marine mammals.

Overt behavioral reactions are directly observable when marine mammals are exposed to man-made noise. These reactions can range from subtle to very obvious. Some of the more obvious reactions include pinnipeds stampeding into the water when disturbed by humans on foot or in aircraft, boats or cars; and whales swimming at maximum speed away from an approaching ship. However, even in the most extreme cases, the duration of observable disturbance is usually short--on the order of minutes or at most a few hours. The longer-term implications of these short-term reactions are usually unknown. However, in the case of pinnipeds at breeding rookeries, recently-born calves are sometimes killed or maimed.

Most of these matters have been mentioned in earlier chapters. This chapter discusses these issues further. In addition, it includes a brief review of some parallels between marine and terrestrial mammals with respect to their reactions to man-made noise. In many ways, terrestrial mammals are easier to study than are marine mammals. Some techniques useful in

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[1] By W. John Richardson, LGL Ltd., and Bernd Würsig, Texas A & M University at Galveston.

[2] Constructive comments on a draft of this chapter were provided by Drs. W.C. Cummings and A.N. Popper, and by the U.S. Minerals Management Service.

disturbance studies of terrestrial mammals may be relevant for future work on marine mammals, e.g. radio-telemetry of heart-rate or other physiological variables. Telemetry has shown that, in some terrestrial species, heart rate increases in response to man-made noise even when there is no outward evidence of disturbance. Such findings in terrestrial mammals may be relevant in interpreting observations of marine mammals, or at least in designing future marine mammal studies.

This chapter also includes brief comments on some ways in which negative effects of man-made noise can be reduced. This can often be done by effective facility designs and by regulations concerning methods or timing of operations. In addition, the adaptations of marine mammals to variability in the natural environment probably provide them with some capabilities useful in coping with man-made noise. These may include an ability to adjust call intensity or frequency to reduce acoustic masking, and a tendency to move away from areas where stressors of various types are present.

10.2 Sizes of Zones of Influence vs. Amount of Habitat Available

A relevant factor in considering the possible effects of a noisy human activity on marine mammals is the size of the zone of acoustic influence relative to the amount of *suitable* habitat available to the animals. Special concern would arise if a marine mammal population concentrates in one or a few areas whose dimensions are small relative to the potential radius of noise influence, and if a noisy human activity is expected to occur near a concentration point. Examples include pinnipeds that haul out in dense aggregations on favored beaches, cetaceans that concentrate in localized nearshore areas, and manatees that concentrate in warm-water discharges. The dimensions of these mammal concentrations are often smaller than the dimensions of the area ensonified by a single industrial activity, or by a single passing vessel or aircraft.

Thus, a significant proportion of a marine mammal population might be exposed to noise if the animals are highly concentrated in the area ensonified by a single noisy activity. On the other hand, there may also be more potential for effective mitigative measures if a population is highly concentrated. It may be easier to adjust the locations and timing of human activities to minimize disturbance to the mammals if they concentrate in one area, or in a few small areas, than if they are broadly distributed.

In contrast, some species of marine mammals can be widely dispersed within offshore areas totalling 10^5-10^7 km^2. In these cases, only a small percentage of the population is likely to be within the radius of acoustic influence around a given human activity. For example, if the radius of responsiveness is 20 km (a relatively large value--see chap. 9), the area of responsiveness is ~10^3 km^2 (πr^2). This is only 1% to 0.01% of 10^5-10^7 km^2. Thus, a single human activity is unlikely to cause disturbance *at any given time* to more than a very small percentage of a widely dispersed population. Of course, it may at the same time affect a concentration of another species with a more clumped distribution.

Even in the case of widely dispersed populations, there are situations in which a large percentage of the population might be exposed to man-made noise:

1. If the radius of responsiveness is 20 km, radii of audibility and masking could be on the order of 100 km. This corresponds to an area of audibility or masking of 0.3×10^5 km², or 30% to 0.3% of 10^5-10^7 km². Thus, there are situations when a significant percentage (e.g. up to 30%) of a dispersed population may be able to hear a single human activity even if only a small percentage (e.g. ≤1%) are within its radius of responsiveness. In general, however, marine mammals that are exposed to faint noise from a distant human activity usually show no overt reactions to it (chap. 8), and only the faintest natural sounds would be masked by weak man-made noise from a distant human activity (sect. 9.3).

2. Although the number of animals in an ensonified area at one time may be small, a high percentage of the population may have to pass through that area at some time within a season. This situation would apply in the case of animals that migrate through a narrow passage whose waters might be ensonified by a stationary human activity, e.g. gray whales migrating through Unimak Pass in the Aleutian Islands in spring and autumn, or bowhead whales migrating through nearshore lead systems around northwest Alaska in spring. If the passage is narrow relative to the typical radius of responsiveness, most or all individuals in the population might be affected.

3. A given population of marine mammals is likely to be exposed simultaneously to noise from various human activities within its range, e.g. a ship in one place, fishing boats somewhere else, marine construction in a nearshore area, and perhaps oil drilling or production elsewhere. Although the proportion of the population exposed to noise from any one source may be small, the proportion exposed to at least one noise source may be much higher. In this case, there may be few parts of the range where man-made noise is absent. Very little is known about the question of cumulative noise effects on marine mammals (see sect. 10.7, below).

4. Although a marine mammal population may be distributed over a large area, certain parts of that area may be more important than others because of the presence of an important food source, breeding area, etc. If the zone of influence of a noise source includes one or more key areas, a disproportionate percentage of the population might be affected.

Thus, there are circumstances in which significant numbers of marine mammals can be exposed to man-made noise even when the population is widely distributed.

10.3 Auditory Interference by Masking

The auditory masking process was described in section 7.5, and the size of the "zone of masking" around a noise source was discussed in section 9.3. Although masking has been studied in laboratory conditions in a few species of toothed whales and pinnipeds, it is difficult to extrapolate these results to practical field conditions. Experimental studies normally assess the effects of uniform "white noise" on the audibility of pure tone signals. White noise has the same level at each frequency across a broad band. In reality, background noise is not "white", and sound signals are rarely pure tones. It would be useful if additional laboratory work on masking could be done using sound signals and background noises more typical of those occurring in field conditions. Although it is difficult to work with low frequency sounds (<1 kHz) in small tanks, studies of masking need to extend down to the low frequencies where most industrial noise is concentrated. One recent study, on white whales, has done so (Johnson et al. 1989).

Some marine mammals have auditory capabilities that apparently compensate, to an unknown degree, for masking (sect. 7.5.4, 9.3.2). Most of the available data on compensatory mechanisms concern echolocation pulses and other high frequency sounds. Additional studies of these compensatory abilities are needed, emphasizing lower frequencies where industrial noise is concentrated. Previous studies of masking in toothed whales and pinnipeds have shown that work of this type is feasible in these groups. Similar work might also be possible in sea otters and manatees. Unfortunately, masking processes in baleen whales are not amenable to laboratory study. This is of considerable concern, since it is the baleen whales whose sounds tend to overlap most with the frequencies of many industrial noises.

A further complication is that there is little information about the consequences if communication, echolocation, or ambient sounds are masked for various periods of time. Too little is known about the functions and importance of these natural sounds in the lives of even the best-studied species of marine mammals. Masking affects primarily the weaker sound signals received from distant sound sources. Masking noise must be strong in order to conceal strong signals from close sources. There is little information about the importance to marine mammals of hearing the weak sounds that are most subject to masking.

Masking is a natural phenomenon with which marine mammals must cope even in the absence of man-made noise, just as humans and other terrestrial animals cope with their inability to hear natural sounds from sources beyond certain distances. The maximum radius of audibility of airborne and waterborne sounds varies widely because of natural variations in background noise. The presence of man-made noise at certain places and times will increase the variability in background noise levels, and increase the frequency of occurrence of masking.

The consequences of elevated background noise levels, especially when these increases are temporary and local, are impossible to determine with any quantitative precision based on available data. The ocean is a naturally noisy and variable environment. Masking is a natural and highly variable phenomenon to which marine mammals are well adapted. Hence, marine mammals undoubtedly can tolerate, with few or no negative effects, some increase in masking relative to natural levels. The limits of this tolerance cannot be determined until more is known about *(1)* the functional importance to marine mammals of faint sound signals from conspecifics (chap. 6), predators, prey, and other natural sources; *(2)* signal detection abilities of marine mammals in the presence of background noise (sect. 7.5), including directional hearing abilities at frequencies where masking is an issue (sect. 7.4); and *(3)* abilities of marine mammals to adjust their call intensities and perhaps frequencies to minimize masking effects (sect. 7.5.4, 9.3.2).

Although further data are needed, it is probable that localized or temporary increases in masking normally cause few problems for marine mammals, with the possible exception of populations that are highly concentrated in an ensonified area. However, a more extensive and continuous noise field could result if a number of noise sources were distributed through a major part of the range of a mammal population. In this "multiple/distributed source" case, masking might be more of a problem.

10.4 Behavioral Disruption

Most data on marine mammal disturbance, whether based on uncontrolled observations or on experiments, concern short-term behavioral reactions. Various studies have determined the distance from the disturbance source, or occasionally the received sound level, at which the animals first react. Reactions often include cessation of resting, feeding, or social interactions; increased alertness (in pinnipeds); changes in surfacing, respiration or diving cycles (in cetaceans); and onset of avoidance. Avoidance may mean evacuation of a haul-out site (pinnipeds), hasty diving, swimming away, or some combination of these actions. In most studies, little or no information has been obtained about the duration of the period of altered behavior subsequent to disturbance. Thus, available data almost all pertain to short-term (minutes or at most hours) changes in behavior. However, pinnipeds that leave terrestrial-haul out sites in response to disturbance sometimes do not return until the next day (sect. 8.2.1).

10.4.1 Variations in Sensitivity

Marine mammals show wide within-species variations in sensitivity to man-made noise. They sometimes continue their normal activities in the presence of high levels of man-made noise. At other times, members of the same species exhibit strong avoidance at much lower noise levels. This apparent variability is partly attributable to variations in physical factors, specifically the characteristics of the man-made noise, its attenuation rate, and the background noise level (sect. 9.4.3). However, the variability in responses is also partly attributable to real differences in the sensitivity of different individual animals, or of the same animal at different times. Some of these differences are associated with differences in activities (e.g. resting vs. feeding vs. socializing), age and sex differences, habitat effects, habituation, and residual individual variation (chap. 8; sect. 9.4.3). Thus, the radius of responsiveness varies widely among individuals, between locations, and over time. No single criterion of disturbance will apply to all circumstances, even for a particular type of animal and a particular human activity.

This variability in sensitivity makes it difficult to define criteria of responsiveness, and has led to seemingly conflicting evidence about sensitivity to particular types of noise. Large sample sizes are needed in order to characterize the range of variation in sensitivity. Careful attention must be given to the situation in which each observation was collected. Even when the circumstances of the observations are well defined or controlled, there will be inherent individual variation in sensitivity. No single criterion of responsiveness will apply to every individual even within a defined situation.

10.4.2 Short-term Behavioral Disruption and Displacement

Relatively little is known about the consequences of short-term disruptions in the normal activities of marine mammals. This lack of information is largely a result of the scarcity of information about the importance of most natural activities of marine mammals. In the absence of such data, it is difficult to assess the consequences of a disruption in natural activities.

The first reaction of pinnipeds hauled out on land or ice is often to raise the head and become alert (chap. 8). When the disturbance is mild, this may be the only overt reaction, in which case the consequences for the animals are presumably insignificant or nil. In cases of more severe disturbance, pinnipeds commonly move into the water, often in a stampede. There have been a few reports of young being trampled to death during stampedes (sect. 8.2.1), and a report of a walrus calf being killed by a polar bear as walruses left the ice in response to ship disturbance (sect. 8.3.1; Fay et al. 1986). However, direct mortality during disturbance-induced stampedes seems uncommon. Several workers have suggested that some pinniped young may be permanently separated from their mothers during stampedes, and subsequently die of starvation (e.g. Johnson 1977) or predation. However, direct proof of this is difficult to obtain.

Pinnipeds normally move back and forth between the water and haul-out sites on land or ice even in the absence of disturbance. When they move into the water as a result of disturbance, they typically return within a few hours or by the next day (sect. 8.2.1, 8.3.1). Thus, a single displacement probably does not have severe consequences. Repeated disturbance and displacement is more likely to have important negative effects, especially in the cases of haul-out sites used for breeding or pup-rearing.

In contrast to the many observations of reactions of pinnipeds hauled out on land or ice to airborne noise, there is little information about effects of man-made noise on pinnipeds that are in the water.

Cetaceans often change their general activity when exposed to man-made noise. Cetaceans that were at rest at the surface often become active, begin to dive and surface, and may begin to swim away from the noise source (chap. 8). Cetaceans that are actively engaged in feeding or especially socializing often seem to tolerate considerable disturbance before reacting. However, when exposed to sufficiently strong or threatening noise (perhaps supplemented by other sensory cues), feeding or socializing cetaceans often interrupt this normal activity and dive or begin to swim away. The duration of behavioral disruption following the end of disturbance has rarely been determined.

Bowhead whales that flee from approaching boats (including seismic vessels) sometimes resume their previous behavior within ½-1 h, although altered behavior sometimes persists for longer periods (sect. 8.3.3, 8.6.3; Richardson et al. 1986). On two occasions, bowheads whose feeding was interrupted by boat disturbance swam several kilometers away but returned to the feeding area by the next day (sect. 8.3.3). It is not known how often bowhead whales have access to zooplankton in densities suitable for efficient feeding (Bradstreet et al. 1987; Richardson et al. 1987b). If good feeding conditions are infrequent, temporary displacements of this nature might have significant energetic consequences if repeated several times in a season (sect. 10.6.3).

10.4.3 Social Disruption

Social disruption is another potentially important negative effect of disturbance. Animals that are aggregated may flee in different directions upon the approach of a fast-moving noisy vessel or aircraft. The duration of this social disruption is rarely determined, but it is often at least several hours (e.g. cetaceans engaged in cooperative feeding or sexual activity) and possibly a day or more in some cases (e.g. pinnipeds returning to a haul-out site). The consequences of this disruption on individuals and the population are poorly understood. It may result in disruption of social ordering, sexual behavior, care of the young, and cooperative activities. It may also increase aggression when the social order is in flux. At least in pinnipeds, social disruption may cause the dominant males in these polygynous societies to lose control of reproductively receptive females. However, there is little direct information about most of these points. We can only assume that repeated social disruption is a disadvantage because it decreases or disrupts the activities that would have occurred naturally, and it may affect adversely a social ordering that took time and energy to become established. This disruption is likely to affect the efficiency of avoiding predators, finding food, mating, and caring for the young.

Separation of dependent young from their mothers is a potentially severe consequence of disturbance-induced social disruption. The possibility of mother-calf separation when pinnipeds stampede from a haul-out site has already been mentioned. Concern has also been expressed about the possibility of mother-calf separation in cetaceans if these animals flee in different directions. This is unlikely to occur unless the whales are already separated by some distance before disturbance begins. In baleen whales, older (but still nursing) calves occasionally are separated from their mothers by a few hundred meters. However, at least for bowhead whales, present knowledge of reaction thresholds, sound propagation and masking suggests that a mother and calf separated by up to 1 km would be able to communicate acoustically as they began reacting to an approaching ship, and presumably could rejoin (Koski et al. 1988). Consistent with this, Wartzok et al. (1989:136,213) reported two sightings of bowhead cows and calves separated by a few hundred meters that re-joined as a small ship approached.

In general, little is known about the biological significance of the short-term disturbance reactions discussed in chapter 8. We suspect that isolated disturbance incidents usually have minimal or no lasting effects. Marine mammals cope with occasional disruption of their activities by predators, bad weather, unusual ice conditions (at high latitudes), and other unpredictable natural phenomena. It is reasonable to suppose that they can also tolerate occasional brief periods of man-induced disturbance, e.g. by a single passing ship or aircraft. However, prolonged disturbance, as might occur if a stationary and noisy human activity were established near a marine mammal concentration area, likely is a more important concern. The long-term implications of such an activity would depend in part on the degree to which the marine mammals habituate. If they fail to habituate and, as a consequence, are excluded from an important concentration area or are subject to ongoing stress while in that area, then there could be long-term effects on the individuals and the population. Conversely, when habituation occurs, as it does for some marine mammals exposed to ongoing human activities, then the consequences may be minimal.

10.5 Habituation vs. Continued Responsiveness

Behavioral habituation is the gradual waning of responsiveness when a stimulus is not associated with any negative consequences. Marine mammals are often seen in situations indicating that they are tolerating exposure to some man-made noise (sect. 8.10.1). In a few cases there is evidence--usually indirect or circumstantial--that the animals were sensitive to the noise when first exposed, but habituated during continued or repeated exposure (sect. 8.10.2).

Insofar as we are aware, there have been no specific studies of habituation in marine mammals. However, there are many references to this process in other types of animals (e.g. chap. III *in* Thorpe 1963; Majors and Myrick 1990). Habituation is, by definition, a process that occurs only when there is repeated or continuous exposure to a stimulus and when the stimulus is not accompanied by anything that the animal "perceives" as threatening. Many man-made sounds, both waterborne and airborne, appear to fall into this category. However, certain forms of disturbance probably are encountered too rarely or irregularly to allow habituation. Even if habituation to a given stimulus has developed in a marine mammal, it is not known how often the animal must be exposed to that type of disturbance in order to remain habituated to it. For example, if animals are exposed to disturbance repeatedly during one season of the year, and become habituated during that season, it is uncertain whether they would still be habituated the next year. The "friendly-" or "curious-whale" phenomenon in wintering gray whales appears to involve both a long-term waning in responsiveness to tourists over the years and a shorter-term component within each winter season (sect. 8.3.3).

Animals are less likely to habituate to a highly variable sound than to a steady sound. They are unlikely to habituate to a sound associated with a threat, e.g. to motorboat noise if they are hunted or harassed from motorboats. There have been a few observations suggesting that certain marine mammals discriminate between threatening stimuli (e.g. noise from a boat used to capture dolphins--Irvine et al. 1981) and comparatively benign stimuli (other boats); they may remain more sensitive to the former.

10.6 Long-term Effects

Short-term reactions of many species of marine mammals to man-made noise have been documented (chap. 8). Masking of communication calls and other natural sounds has not been specifically studied in the field, but it must inevitably occur in some situations when background noise levels are raised by man-made noise (sect. 7.5, 9.3). There has been some speculation about the biological significance of these short-term effects (sect. 10.3, 10.4). However, in most cases there is little evidence about their importance to the long-term well being of individuals or populations.

10.6.1 Mortality

There have been very few documented cases of direct mortality as a result of disturbance, and there is much evidence that most types of disturbance do not cause direct mortality. The best-documented cases of direct mortality caused by noise disturbance involve occasional trampling of young pinnipeds during stampedes from haul-out sites, usually triggered by aircraft overflights (sect. 8.2.1). Disturbance may also lead to increased mortality via abandonment of dependent pinniped pups by their mothers (Johnson 1977), and perhaps to increased predation on the young (Fay et al. 1986).

Disturbance-induced displacement of manatees from warm-water discharges in Florida during cold winters may cause some mortality due to hypothermia (Hartman 1979; Kochman et al. 1985). However, this is probably less common than manatee mortality via direct collision with motorboats.

Ships and icebreakers occasionally injure or kill other marine mammals by collision. Collision-induced mortality cannot be attributed directly to noise disturbance. Indeed, local displacement in response to the noise of an approaching vessel is a potential method for avoiding injuries or mortality caused by collisions. However, some whales react to the sound of an approaching boat by attempting to outrun it. This response to the noise is often ineffective, especially for slow-swimming species like bowhead and probably right whales. Because the animals react to noise in the way that they do, they are often closely approached by vessels and sometimes hit.

Although occasional mortality of a few individual animals as a result of disturbance is undesirable and often illegal, it is--from a biological perspective--the long-term population consequences of disturbance and mortality that are of most concern. For example, if disturbance causes long-term abandonment of part of the range where the population formerly concentrated, the carrying capacity of the environment for the population might be reduced. If many individuals continue to occur in an area subject to ongoing or intermittent disturbance, concern arises about the possibility that normal activities might be affected enough to reduce the reproductive rate via social disruption, effects on energy balance, or some other form of stress.

10.6.2 Long-term Displacement

Although certain marine mammals no longer occupy some areas that they used in earlier years, it is rarely known what role (if any) noise disturbance had in causing long-term abandonment of a part of the range. Habitat may become unsuitable for reasons other than elevated noise levels. For example, the suitability of an area for marine mammals may be affected by local increases in hunting or by-catch, or by changes (natural or man-related) in turbidity, water temperature, or food abundance. In an uncontrolled field situation where many factors change simultaneously, it is rarely possible to isolate the specific cause of any observed change in numbers of marine mammals. Indeed, it is uncommon to have a series of reliable counts long enough to quantify the numerical change, let alone determine its cause.

In baleen whales, a few cases of medium- or long-term displacement of animals from local areas have been ascribed, at least tentatively, to repeated disturbance. Underwater noise was presumably a major factor in some or all of these cases, although noise effects cannot be separated from those of "physical presence" or other stimuli.

1. The best documented case was the abandonment by gray whales of a calving lagoon in Baja California for several years, and their return after vessel traffic diminished (sect. 8.3.3; Gard 1974; Reeves 1977; Bryant et al. 1984).

Other examples are less well established:

2. Humpback mothers and calves avoid nearshore areas off Hawaii where human activities, largely recreational, are intense (sect. 8.3.3; Glockner-Ferrari and Ferrari 1985; Salden 1988).

3. Reduced use of Glacier Bay, Alaska, by humpback whales has been suspected to be a consequence of vessel disturbance (sect. 8.3.3; Jurasz and Jurasz 1979a; Dean et al. 1985). However, changes in prey abundance probably also had a major influence on

local distribution of humpbacks off southeast Alaska (Bryant et al. 1981; Krieger and Wing 1986; Dolphin 1987).

4. Numbers of bowhead whales using an area of intensive offshore oil exploration in the Canadian Beaufort Sea apparently diminished a few years after the onset of offshore drilling in 1976. Numbers of bowheads in the main industrial area were high in 1980, lower in 1981, near zero in 1982, and low in 1983-86. The few bowheads in the main industrial area in 1983-86 were mainly near its edges, contrary to 1980-81. These data, plus limited evidence from 1976-79, indicate that bowheads were numerous in the center of the main industrial area in 3 of 5 years from 1976 to 1980 vs. 0 of 6 years from 1981 to 1986. During the mid-1980s, vessels working in and near the main industrial area included 5 drillships, 2 drilling caissons, 5-6 seagoing dredges, 9-10 helicopters, 3-4 seismic exploration ships, 4 icebreakers, ~10 supply ships, and other support vessels. Industrial activities in this area declined in the late 1980s. Unfortunately, funding for surveys also was curtailed then, so it is not known whether use of the area by bowheads increased after industrial operations declined.

   Whether the decline in bowhead use of the main industrial area in the early-mid 1980s was caused by disturbance, changing food availability, or other factors is unproven (Richardson et al. 1985a, 1987a; Duval (ed.) 1986; Ford et al. 1987; Ward and Pessah 1988). Bowheads are known to concentrate in areas where zooplankton is highly concentrated, and locations of zooplankton concentrations vary within and between years (Bradstreet et al. 1987).

5. Nishiwaki and Sasao (1977) suggested that reduced catches of minke and Baird's beaked whales off parts of Japan in recent decades are attributable to greatly increased ship traffic in those areas. However, their results were severely confounded by changes in harvest methods and effort, and in other forms of potential disturbance. In our view, and that of Payne (1978b), the results do not prove that numbers of whales declined as a result of shipping. Indeed, the continued presence of beaked whales off the entrance to Tokyo Bay despite very frequent ship traffic shows considerable tolerance of shipping. There are many other published examples of marine mammals tolerating much noise from human activities (sect. 8.10.1).

A simple tabulation of the many reports of noise tolerance versus the very few convincing cases of long-term displacement by noise might be misleading. There are few areas for which numbers of marine mammals have been monitored with reliable and consistent methods over many years. Changes in marine mammal utilization of an area may be quite slow and difficult to detect, given the long lifetimes of most marine mammals and the slow rate of change in habitat quality in many areas. The effects of man-made noise on marine mammals have been an issue for less than 20 years, and most of the research directed specifically at this topic has been done in the past 10 years. If marine mammals did react to noise from human activities by reduced use of certain areas, there would--in many cases--be insufficient reliable and systematic information to document the trend. In contrast, it is easy to document cases where marine mammals remain in an ensonified area. Thus, cases of partial or even complete abandonment of disturbed areas may be more common than available evidence indicates.

If permanent displacement occurs, the consequences to the population are difficult to determine. In general, one can speculate that an area where the density of animals is low, and similar to the densities in many other areas, is unlikely to be critical either to individuals or to the population. However, this generalization would not apply if the area were important to a small but important component of the population (e.g. mothers with calves), or for an important function (e.g. mating). Areas used consistently by many animals are likely important both to individuals and to the population. However, it is rarely known whether a particular location provides unique resources not available elsewhere. It is also rarely known whether other similar habitats to which displaced animals might move are already supporting as many marine mammals as they can. It should not be assumed, in the absence of specific information, that displaced animals will be able to fare as well in some other part of the population's range. On the other hand, it is also not justifiable to assume, without specific information, that displaced animals will be seriously harmed or will cease to reproduce. One of the many complications is that, for many marine mammals, the habitat on which they depend is mobile, varying within and among years.

Very little research has been done on these questions, in part because of the near-impossibility of conducting the necessary types of work on marine mammals. Such research would require long-term study of the well-being and reproductive success of known individuals, including some that remain in preferred undisturbed locations ("controls") and others that are displaced. This type of work is most likely to be practical on pinnipeds that haul-out in areas that are consistent and amenable to study. If such animals are expected to be displaced by a planned human activity, it would be very desirable to initiate long-term research on the fate and reproductive success of displaced individuals as compared with controls.

10.6.3 Energetic Consequences

The energetic consequences of one or more disturbance-induced periods of interrupted feeding, rapid swimming, or both, have not been evaluated quantitatively. Subjectively, one would expect that a single such incident would not have significant negative consequences on the energetic status of a marine mammal. However, repeated incidents of interrupted feeding and rapid swimming as a result of disturbance can be assumed to have negative effects on the well-being of individuals if the disturbance occurs sufficiently often and for sufficiently prolonged periods.

The frequency and duration of disturbance that might initiate negative effects are unknown, and would undoubtedly depend on the species, area, feeding requirements, and reproductive status of the marine mammals involved. In a region with abundant and widely distributed food resources, the energetic consequences are expected to be less severe than they would be in an area where feeding is necessary but suitable food is less readily available. Animals subject to heavy natural energy drain, most notably females in late pregnancy or lactation, probably would be most severely affected.

Energetic models that could be helpful in evaluating the energy cost of disturbance and displacement have been developed for other purposes in recent years (e.g. Huntley et al. 1987). For some species it may be possible to make reasonable estimates of the energy cost of x displacements averaging y km at average swimming speed z km/h, and of a w-hour interruption in feeding time. However, we suspect that there are few if any marine mammals for which food availability and foraging behavior are known well enough to allow meaningful predictions of energy intake by displaced vs. undisplaced individuals. Thus, estimates of the net energetic effects of displacement probably are still well beyond our prediction abilities. Even if this could be estimated, effects of a specified energy cost on individual reproductive output would be difficult to estimate. There is evidence that energetic status is related to reproduction in some marine mammals (e.g. Boyd 1984; Stewart and Lavigne 1984; Lockyer 1986), but the available data are too sparse to allow quantitative predictions.

10.6.4 Tolerance and Stress

Many marine mammals have been seen in areas ensonified by man-made noise, often behaving in seemingly-normal ways (sect. 8.10). In some cases there is at least suggestive evidence of true habituation, i.e. diminished responsiveness after repeated or prolonged exposure to the noise (sect. 8.10.2). Animals that tolerate man-made noise are presumed to be less affected by the noise than are others whose behavior is changed overtly, sometimes with displacement.

However, the presence of marine mammals in ensonified areas does not prove that the population, or even those individuals, are unaffected by the noise. It is rarely known how many individuals would have been present in the ensonified area in the absence of noise, other factors being equal. The numbers in the ensonified area may be only a fraction of the numbers that would have been there in the absence of man-made noise. It is also not known whether masking of weak natural sounds by man-made noise causes any problems (sect. 10.3).

Brodie (1981b) suggested that marine mammals may stay in an area despite the presence of noise disturbance if there are no alternative areas that meet the requirements of the animals. These animals might be stressed. Stress is the physiological response of the body to a demand made upon it by one or more external stimuli, the "stressors" (Selye 1973). Stress involves activation of the pituitary-adrenal axis. In response to external stimuli, the anterior pituitary releases more ACTH (adrenocorticotropic hormone), which in turn stimulates the adrenal cortex to release more adrenal corticoid hormones. These cause various more or less standardized responses in different parts of the body--responses that may increase the animal's ability to cope with various problems (Turner 1965; Russell 1966; Selye 1973). However, chronic activation of these physiological mechanisms may lead to harmful physiological effects (Selye 1973).

Many studies of terrestrial mammals, including man, have looked for evidence that chronic noise exposure causes stress. Some studies have provided evidence of noise-induced stress, but the majority have been inconclusive or have shown no such evidence (for reviews, see chap. 10 *in* Kryter 1985; Majors and Myrick 1990). Marine mammals exhibit some of the same stress symptoms as found in terrestrial mammals, judging from the few species studied (e.g. Thomson and Geraci 1986; St. Aubin and Geraci 1988). However, there has been virtually no study of noise-induced stress in marine mammals. One exception was a study in which plasma catecholamines were measured in captive white whales before and after exposure to playbacks of recorded semisubmersible drillrig noise (Thomas et al. 1990). Elevated levels of catecholamines are often found in stressed mammals. Noise exposure did not lead to elevated levels of catecholamines in the blood. The general significance of this one study of white whales is unknown, especially in view of the short durations of noise exposure.

10.7 Cumulative Effects

The cumulative effects of noise from multiple human activities have not been studied. However, the presence of multiple noise sources in an area has the potential to increase the severity of any deleterious noise effects that may exist for single sources. Although the proportion of the population exposed to noise from any one source may be small, the proportion exposed to at least one noise source may be much higher. If the animals are displaced from an area around some or all of these sources, the total amount of habitat affected will be greater than for any one source. Thus, a higher proportion of the population is likely to be affected as the number of sources increases. This would be true whether or not the sources and animals are mobile.

If either the animals or the noise sources are moving, an individual animal is likely to encounter a noise source more often as the number of sources increases. Thus, interruption of behavior, and possibly displacement, will be more frequent as the number of sources increases. The consequences of this increasingly frequent disturbance are uncertain but presumably negative. If the spacing of noise sources were on the same order as the radius of avoidance, the presence of a number of noise sources in an area might displace marine mammals from that entire area.

The long-term consequences of multiple noise sources are likely to depend, in part, on the degree to which the animals habituate to repeated noise exposure. Given the meager available information about habituation in marine mammals (sect. 10.5), only qualitative predictions are possible. We expect that habituation would be more rapid and complete if the various noise sources emit similar sounds than if they emit sounds with varying characteristics. Also, habituation to an array of stationary sources, such as offshore drilling or production rigs, is likely to be more complete than that to an equal number of moving vessels provided that noise levels from the moving vessels are at least as intense as those from the rigs.

The simultaneous presence of a number of noise sources is expected to increase the masking problem. The larger the number of noise sources in an area, the larger the percentage of the area that will be subject to a given severity of masking. If either the noise sources or the animals are moving, individual animals will be subject to masking a higher percentage of the time as the number of noise sources increases. Marine mammals must be able to cope with occasional masking, since masking is a natural phenomenon. However, consider a species that can hear one another over distances of 10 km about 75% of the time in undisturbed conditions. These animals may be unable to coordinate their activities to the usual degree if there are enough noise sources to allow communication over 10 km only 10% of the time, and to allow communication with 75% success only within a radius of 2 km. Another possible concern is that, as the number of sources of man-made noise increases, the masking noise becomes less directional, and the directional hearing abilities of marine mammals will become less useful in detecting sounds of interest in the presence of the background noise.

As noted earlier, little is known about the importance of long-distance communication and the detection of other weak natural sounds by marine mammals. Without this information, no specific assessment of the consequences of masking by multiple noise sources is possible.

Although the effects of multiple noise sources on marine mammals have not been studied specifically, some relevant field observations have been mentioned earlier in this review. In some areas cetaceans (both toothed and baleen whales) remain in areas where many boats are present. Some pinnipeds often persist in hauling out in areas with repeated boat traffic, aircraft overflights, or human presence. Thus, there is evidence of considerable tolerance of repeated exposure to noisy human activities that do not pose a direct threat to the animals (sect. 8.10). Habituation is probably a major factor in these cases. However, there are also cases of seemingly reduced numbers of marine mammals in areas with many human activities (sect. 10.6.2). As noted earlier, it is difficult to obtain conclusive evidence about long-term population trends. Hence, the frequency of occurrence of long-term declines might be underestimated based on a simple tabulation of the number of studies reporting declines vs. no *apparent* decline.

The above comments have dealt with the cumulative effects of several different noise sources within the geographic range of a marine mammal population. The cumulative effects of the acoustic and non-acoustic components of human activities are a further consideration. A discussion of non-acoustic effects is beyond the scope of this review (for reviews, see Geraci and St. Aubin 1980, 1988; Richardson et al. 1989). However, some of the earlier comments on reactions (or lack of apparent reactions) of certain marine mammals to human activities include non-acoustic as well as acoustic effects. In uncontrolled field situations, it is generally impossible to isolate the specific stimuli to which marine mammals are responding.

10.8 Relevance of Evidence from Terrestrial Mammals

Much effort has been expended in recent decades to assess the effects of noise disturbance on many types of animals, including invertebrates, fish, birds and mammals, including man. In assessing effects of noise on marine mammals, the most meaningful comparisons may be with terrestrial mammals, and particularly with ungulates. Ungulates share a common ancestry with cetaceans, and a number of the behavioral traits of ungulates are similar to those of cetaceans. Many terrestrial mammals are easier to study than are most marine mammals. Hence, the available data on reactions to noise are often more comprehensive for terrestrial mammals. Although data from terrestrial mammals cannot be extrapolated directly to marine mammals, a review of noise effects on terrestrial mammals could be helpful in interpreting the less detailed information from marine mammals. One cannot assume that marine and terrestrial mammals will react in the same ways to a particular situation. However, the existence of various parallels is instructive in judging the potential significance of some marine mammal data. Work on terrestrial mammals may be especially useful in suggesting useful hypotheses, study approaches, and ways of evaluating the results.

This brief comparison cites some of the data on short- and longer-term reactions of terrestrial animals to noise, habituation, and physiological effects. More extensive reviews are given by Fletcher and Busnel (ed., 1978), Shank (1979), Sopuck et al. (1979), Dufour (1980), Kryter (1985) and Majors and Myrick (1990).

10.8.1 Short-term Reactions

Many authors describe the factors that affect "flight distances" or "reaction distances" of terrestrial mammals to various forms of disturbance. The concept of a flight or reaction distance in terrestrial mammals (Hediger 1934) is parallel to the "radius of responsiveness" concept for marine mammals (sect. 9.4). In terrestrial mammals, almost all results are presented in terms of distances rather than received sound levels. Reactions to acoustic, visual or odor cues are rarely distinguished in terrestrial mammals. Even with this ambiguity, data from terrestrial mammals may be relevant here. Behavioral responses of animals to distant sources of disturbance may, in some cases, be similar regardless of the stimulus type(s) involved.

Short-term reactions of terrestrial mammals to disturbance (acoustic or otherwise) generally begin with a cessation of normal activities such as feeding or traveling. In cases of mild disturbance, the reaction consists of an alert stance (sometimes with the head oriented toward the source of disturbance), listening, watching, and sniffing (e.g. Reynolds 1974; Luz and Smith 1976; McLaren and Green 1985). In more disruptive situations, the animal moves away slowly or bolts rapidly, fleeing the area. For example, over 80% of mountain goats (*Oreamnos americanus*) subjected to aircraft overflights responded by some form of behavioral change, and 33% displayed strong flight responses (Foster and Rahs 1983). Both auditory and visual cues were involved. Similar short-term flight reactions have been documented for other large mammals, including caribou (*Rangifer tarandus*) responding to aircraft and trucks (Calef et al. 1976; Cameron et al. 1979; Horejsi 1981), white-tailed and other deer (*Odocoileus* sp.) responding to snowmobiles (e.g. Dorrance et al. 1975; Richens and Lavigne 1978; Freddy et al. 1986), and muskoxen (*Ovibos moschatus*) responding to aircraft and snowmobiles (Miller and Gunn 1980; McLaren and Green 1985). Fleeing generally lasts only one to several minutes when the stimulus is brief, such as an aircraft passing overhead without circling. In most cases, previous behaviors are re-established quickly. These types of responses are generally parallel to those seen in various marine mammals (*cf.* chap. 8).

Responses of terrestrial animals to relatively silent-walking humans sometimes are stronger than those to intense noises audible from farther away. Again, visual or odor cues rather than sound may be involved. Startle and flight reactions often occur when people approach on foot, and may even be elicited at greater distances than in response to noisy vehicles like snowmobiles (Richens and Lavigne 1978; Eckstein et al. 1979; Freddy et al. 1986). Similar observations have been made in pinnipeds (Allen et al. 1984; Osborn 1985) and in cetaceans. Spinner dolphins, dusky dolphins and southern right whales usually react more strongly to the sudden appearance of a swimmer or kayaker than to the approach of a noisy outboard vessel audible from a relatively long distance (Würsig pers. obs.).

Behavioral responses to human disturbance vary widely in nature and severity in terrestrial as well as marine mammals. In moose (*Alces alces*) and elk (*Cervus elaphus*), variations in sensitivity are related to "...a seasonally changing threshold of sensitivity due to reproductive and nutritional status; variations due to type of habitat; and variations due to the specific experience of the individual or group" (Altmann 1958). Moose mothers with newborn calves hide in dense cover or charge toward the intruder rather than run away. However, both run from intruders after the calf is about a month old. Moose bulls usually begin to flee when an intruder is far away, but during the rutting season the flight distance decreases almost to zero. However, the reaction distance of moose is largest during the hunting season (Altmann 1958).

Deer are generally less likely to run if in heavy cover than if in light cover (Eckstein et al. 1979). Ungulates that are resting or feeding tend to be less sensitive than are solitary animals, which seem more wary (Altmann 1958; Espmark 1972). This dependence of sensitivity on activity and physical situation has many parallels in marine mammals (sect. 9.4.3).

10.8.2 Masking

Masking of communication calls and other sounds by background noise has not been a major consideration in studies of large terrestrial mammals. However, there have been studies of masking of the airborne calls of birds and bats, and of the waterborne sounds important to fish. A few authors have emphasized the potential negative consequences of masking of natural sounds (Myrberg 1978). However, Busnel (1978) noted that some birds and fish live in naturally noisy environments, and apparently can hear the sounds important to them. Busnel suggested that masking or jamming of acoustic signals is difficult to accomplish, given the adaptations that animals have developed to reduce masking (e.g. Griffin et al. 1963; Busnel and Mebes 1975; Nachtigall and Moore [ed.] 1988). Marine mammals have many of these same adaptations (sect. 7.5.4, 9.3.2).

10.8.3 Long-term Effects and Habituation

Long-term effects of noise on terrestrial mammals, like those on marine mammals, have been difficult to study. Mountain goats moved away when subjected to repeated human use of their area (Foster and Rahs 1983). They showed no habituation, and indeed appeared to become more rather than less sensitive to sounds. Mountain goats returned to one area within 2 weeks after a drilling camp was shut down. Freddy et al. (1986) found no evidence of "immediate" habituation of mule deer (*Odocoileus hemionus*) to repeated human disturbance; however, they may not have continued their tests long enough for a full evaluation. Moen et al. (1982) found no evidence that disturbance effects on heart rate diminished with repeated exposure of deer to snowmobiles.

However, most long-term studies indicate that habituation occurs rather rapidly, after only a few exposures. For example, muskoxen habituated to helicopter overflights after only four days of helicopter activity; responses that had at first been abrupt and strong waned to a brief interruption of normal activity (Miller and Gunn 1980). White-tailed deer returned within hours to areas from which they had been displaced by snowmobiles (Dorrance et al. 1975), and showed less displacement in mid- to late winter than in early winter (Richens and Lavigne 1978). The latter phenomenon is suggestive of habituation, but may also be related to increased snow depth, reduced food availability, and deteriorating physical condition (*cf.* Schultz and Bailey 1978). Deer that were exposed to ongoing lumbering activities (e.g. chainsaw noise) seemed relatively insensitive to snowmobiles, perhaps because of habituation to noise from small engines (Eckstein et al. 1979; Moen et al. 1982).

Some studies have reported that domesticated and laboratory mammals habituate, at least partially, to ongoing noise exposure. Domesticated sheep acclimate to intermittent sounds unless they are extremely intense (Ames 1978). Both farm and wild animals exhibit brief startle reactions to sonic booms, but responses to subsequent sonic booms are usually reduced (Espmark 1972; Cottereau 1978). Physiological reactions of dogs and rhesus monkeys to ongoing noise tend to habituate (reviewed in Majors and Myrick 1990).

Terrestrial mammals, like marine mammals, often occur in areas where they are exposed chronically to man-made noise. This indicates some degree of tolerance. However, as in the case of most marine mammals seen in such circumstances, it is rarely known whether the numbers of animals present are as high as they would have been in the absence of noise. It is also rarely known whether mammals in the ensonified area are deleteriously affected by stress.

10.8.4 Physiological Effects and Stress

Physiological effects of noise on terrestrial mammals have been studied in the laboratory and, in a few cases, by heart rate telemetry from free-ranging mammals. In bighorn sheep (*Ovis canadensis*) and white-tailed deer, heart rate sometimes goes up in response to vehicles or humans, even in cases with no overt change in behavior (MacArthur et al. 1982; Moen et al. 1982). Moen et al. found no evidence for habituation of the heart rate response. The observation that heart rate sometimes changes without outward change in behavior suggests that heart rate may be a sensitive indicator of disturbance. An elevated heart rate is likely associated with elevated metabolic rate and the stress response. Since heart rate can be monitored via telemetry, it may be a valuable indicator of stress reactions that are otherwise very difficult to detect. To date, no study of marine mammals has included an analysis of telemetered heart rate data relative to disturbance. In cetaceans, such a study would be valuable to determine whether observed respiration rates are related to heart rate. If so, we could be more confident that observed correlations between disturbance and respiration rate (see chap. 8) are related to stress.

In laboratory animals, prolonged exposure to strong noise often results in significant increases in adrenal cortex activity and other related measures of stress. Most of this work has been on rodents, but similar results have been found in several studies of rhesus monkeys (reviewed by Majors and Myrick 1990). Noise has also been shown to cause various physiological changes in domesticated sheep, swine and cattle (e.g. Bond 1971; Ames 1978). Some studies have suggested that strong noise can have negative effects on reproduction in laboratory animals (e.g. Busnel and Molin 1978; Majors and Myrick 1980). Most of the studies in which noise has been shown to cause adrenal activation and other physiological changes have involved intense sounds. Many authors have reported little or no apparent effect in response to weaker noise. The data from terrestrial mammals do not allow us to predict whether physiological responses would occur in marine mammals exposed to specific types, levels and durations of man-made noise. However, these studies are useful in suggesting the types of effects that might occur, and thus in designing studies of marine mammals.

10.9 Methods by Which Marine Mammals May Mitigate Noise Effects

At least some marine mammals possess capabilities and behavioral traits that tend to reduce their susceptibility to the potential negative effects of man-made noise. These traits have presumably evolved to cope with natural variability and challenges in the environment. However, they can also assist marine mammals in coping with man-made noise.

10.9.1 Characteristics of Sounds Emitted

In at least two species of toothed whales, the bottlenose dolphin and white whale, there is evidence that source levels of ***echolocation signals*** increase when the background noise level is high. In addition, these species sometimes adjust the frequencies of their echolocation signals to avoid a frequency range where the background noise level is high (Au et al. 1974; 1985). A white whale has also been observed to direct its echolocation beam such that echolocation signals were bounced off the water's surface, providing angular separation between the returning echoes and a point source of background noise (Penner et al. 1986). These observations indicate that the characteristics of the echolocation sounds of certain toothed whales are modified in response to prevailing background noise in order to maximize the effectiveness of echolocation.

It is not known whether toothed whales or other marine mammals adjust the source levels or frequencies of their ***communication sounds*** as a function of background noise conditions. However, there is great variability in the source levels of sounds emitted by some species, e.g. by bowhead whales (Clark et al. 1986; Cummings and Holliday 1987). Frequencies of sounds emitted by many species also vary widely (chap. 6). This variability suggests that characteristics of communication sounds might be tailored to prevailing background noise conditions. However, little is known about the functions of most marine mammal sounds. The observed variability in sound characteristics presumably occurs, in part, because the different characteristics may convey different information to receiving animals. Little is known about the degree to which calls having a given function can be modified without changing their meaning.

10.9.2 Hearing Abilities

The known directional hearing abilities of certain marine mammals must often assist them in detecting natural sounds in the presence of background noise (sect. 7.4, 9.3.2). Directional hearing can be of assistance when the directional characteristics of the sound signal and background noise differ, e.g. signal is directional and background noise omnidirectional; signal and background noise are both directional, but come from differing directions; signal is omnidirectional but background noise directional.

Directional hearing will be most beneficial in detecting sounds of interest in the presence of background noise if the frequency of the sounds is high and the wavelength is commensurately short. In toothed whales, directional hearing is important in detecting high-frequency echolocation signals in the presence of noise (Zaitseva et al. 1975, 1980; Au and Moore 1984). However, a few small and medium sized marine mammals have directional hearing at frequencies as low as 1-2 kHz (sect. 7.4), which is within the upper end of the frequency range where significant industrial noise often occurs. It is not known how effective these directional capabilities in the 1-2 kHz range may be in detecting sound signals against background noise at those frequencies.

There is little information about the directional hearing abilities of baleen whales (sect. 7.4, 7.6), whose low-frequency calls overlap broadly in frequency with the dominant low-frequency noise of many human activities. However, because of the large sizes of many baleen whales relative to acoustic wavelengths, baleen whales may have good localization abilities at low frequencies (<1 kHz). If so, their directional hearing capabilities may be an important preadaptation for coping with low-frequency noise from human activities.

10.9.3 Displacement

Displacement of marine mammals caused by man-made noise is normally assumed to be a negative effect. When an animal is displaced, its normal behavior and social interactions with conspecifics are interrupted at least briefly, there is an energy cost (whether or not feeding was disrupted), and the location to which the animal is displaced may provide habitat that is less suitable.

However, displacement can have the benefit of removing the animal from a location where, had the animal remained, there might be more serious consequences. By moving away from a noisy human activity, an animal will reduce the masking effect of the man-made noise. Displacement may also, after a brief period of active disturbance, reduce or avoid further behavioral disruption or physiological stress that might persist if the animal remained close to the noise source. In the case of extremely strong noise sources such as explosive discharges, displacement would remove the animal from the area where there might be a possibility of physical damage to the hearing system or other organs (sect. 9.5). Displacement from the path of an oncoming ship would reduce the possibility of collision, which might otherwise injure or kill the animal (e.g. sect. 8.3.3; Richardson et al. 1989:315-318).

The net effect of displacement from a preferred area is unlikely to be beneficial. However, it may be preferable for an animal to be displaced rather than to remain in an area where it is subjected to risk of physical injury or chronic behavioral or physiological effects. In this sense, displacement can be a mitigating measure that is initiated by the animal itself.

10.9.4 Habituation

If exposure to a particular type of man-made noise is not associated with any serious concomitant problems or risks, habituation may occur. If so, an animal that showed avoidance or other disturbance reactions during initial exposures to the noise may show weaker or no reactions during later exposures. This waning of responsiveness might allow the animal to continue to occupy its normal habitat and to continue its normal activities in the presence of some man-made noise. This could be beneficial to the animal, provided the noise has no serious residual effects via masking or some other mechanism not alleviated by habituation.

10.10 Methods by Which Man Can Mitigate Noise Effects

In many cases, the noise impacts of human activities can be reduced or avoided by careful planning. Engineering aspects of noise control are outside the scope of this review. However, this section provides some general comments on noise-control approaches that have been used, or might be used, to reduce the effects of noise from offshore oil industry activities on marine mammals. Noise reductions may be possible through appropriate choice or design of equipment and facilities. Also, it may be possible to adjust the seasonal timing of noisy activities to avoid periods when mammals are most sensitive. Aircraft and vessel traffic can sometimes be routed so as to avoid the most sensitive areas, and it may be possible to site some shore facilities so as to avoid coastal locations of special sensitivity.

10.10.1 Equipment Design

Some types of offshore equipment and facilities are quieter than other types with similar functions. In circumstances when two or more types of equipment could fulfil the desired function in a region with many marine mammals, it may be possible to select the less-noisy equipment.

For example, semisubmersible drillships appear to be less noisy than conventional-hull drillships, and bottom-founded platforms are probably quieter than either semisubmersibles or conventional drillships (sect. 5.4). There are situations when two or three of these types of drilling platforms might be considered for use. If the area is important to marine mammals, it may be appropriate to give some weight to relative noise emissions when deciding which type of platform to use. Similarly, in a noise-sensitive area with a steeply-sloping bottom, there might be situations in which directional drilling from a relatively quiet bottom-founded platform in shallow water would be preferable to use of a drillship farther offshore.

Few data have been reported concerning the relative noise emissions of various offshore oil production facilities. However, different types of platforms emit noise with varying levels and characteristics (Gales 1982). Island or caisson structures may be quieter than platforms with metal legs. If oil production facilities are to be installed in an area where noise disturbance to marine mammals is a concern, it would be desirable to investigate the noise emissions of various types of offshore production equipment.

Support vessels and aircraft operating around offshore drillsites and production sites can contribute a substantial proportion of the total man-made noise around the site. This is especially true in the arctic, where icebreaking--an especially noisy activity (sect. 5.2.3)--is often necessary around drillships. In contrast, bottom-founded caissons generally do not require icebreaker support. Furthermore, the caisson would probably emit less underwater noise than the drillship itself. There is a narrow range of water depths where either a drillship or a caisson might be considered for use. In noise-sensitive areas, the caisson perhaps should be given preference.

Aside from the general type of platform, the specific design of equipment on the rig may have an important influence on acoustic emissions. Much of the noise from various platforms originates from power generation equipment (sect. 5.4). Gales (1982) found that platforms supplied with electrical power from shore tended to be considerably quieter than those with their own generators. When generators must be used continuously, it might be possible to reduce their noise output by giving more attention to the designs of their mountings and mufflers. Top-drive drillrigs are expected to create less noise than rotary table rigs, and may be preferable for noise control as well as other reasons.

Noise control engineers, especially naval architects, give much attention to the problem of reducing the noise emissions of ships (chap. 10 *in* Ross 1976). When vessels are being designed for offshore industrial activities, it would be appropriate to take advantage of existing noise-control expertise.

10.10.2 Seasonal Timing

It may be possible to adjust the seasonal timing of noisy activities to avoid periods when mammals are most sensitive. For example, regulatory agencies have placed seasonal restrictions on several types of oil exploration operations in the Alaskan Beaufort Sea. The timing of on-ice seismic exploration has been restricted so as to avoid Vibroseis operations (sect. 5.3.2) during the spring when ringed seals are pupping. Permits for open-water seismic operations with airgun arrays have often contained provisions requiring shutdown if bowhead whales are seen close to the seismic boats or, during the bowhead migration season, if poor visibility prevents visual monitoring for whales. Offshore drilling in the Alaskan Beaufort Sea during the autumn migration period of the bowhead whale has been restricted in various ways in different years.

The above examples involve permit stipulations that restrict operations by the oil industry. In some circumstances, it may be possible to plan the timing of noisy activities such that there is little or no interference with either the human activity or the marine mammals. For example, blasting is sometimes necessary for marine demolition or construction, and it may need to be done near a coastal haul-out site or some other concentration point for marine mammals. In such a situation, it would be desirable to blast during a season when the concentration of marine mammals is absent. In this way, careful planning may avoid interference with a human activity while also protecting marine mammals.

10.10.3 Routing and Positioning

Aircraft and vessel traffic can sometimes be routed so as to avoid the most sensitive areas. This is practical when marine mammals are concentrated in well-defined and consistent areas, e.g. coastal haul-out sites for pinnipeds. In the case of aircraft traffic, negative effects on local sensitive areas can be reduced or avoided by maintaining either a certain horizontal distance or a specified minimum altitude. Restrictions on horizontal distance and altitude are often included in lease offerings and permits for offshore industrial activities. However, altitude restrictions may only be practical when clouds are absent or high. Both altitude and horizontal restrictions are impractical if there are concentrations of marine mammals near essential landing sites.

It may be possible to locate some shore facilities so as to avoid coastal sites of special sensitivity. For example, there may be two or more possibilities for a harbor development, causeway, heliport, pipeline terminus, or other logistics base. If one of these is a concentration point for marine mammals, it will be desirable, from the marine mammal perspective, to select an alternative site for development.

11. CONCLUSIONS AND DATA NEEDS[1],[2]

In this section we summarize the main conclusions from previous chapters, and we identify important data needs concerning noise effects on marine mammals. Many data needs relating to particular species or particular human activities would become important only if there was a plan to initiate that industrial activity in an area important to one or more species of marine mammals. Thus, the relative importances of many data needs depend on development plans. In most cases the type of needed research is self-evident. However, in some cases we give specific recommendations about high-priority research topics.

11.1 Sound Propagation

11.1.1 Present Knowledge

Sound levels, both underwater and in-air, produced by animals, human activities and other specific sources diminish with increasing distance from the source. However, the rate of transmission loss depends strongly on local conditions (chapter 3). Consequently, a moderate-level source transmitting over an efficient path may produce the same received level at a given range as a stronger source transmitting through an area where sound is rapidly attenuated. Likewise, the radius of acoustic influence for a given industrial source can vary as much as 10-fold depending on local propagation conditions. Thus, a site-specific model of sound propagation is needed in order to predict received sound levels in relation to distance from a noise source.

In the relatively simple case of non-ducted direct-path underwater transmission, or air-to-ground transmission for an aircraft, the rate of attenuation approximates "spherical spreading" ($20 \log_{10} R$) with an added absorption term αR:

$$L_r = L_s - 20 \log_{10} R - \alpha R - 60 \qquad (11.1)$$

Here L_r is the received level at range R km and L_s is the source level at range 1 m; both L_r and L_s must be measured in the same dB units, normally dB re 1 µPa underwater and dB re 20 µPa in air. α is the molecular absorption coefficient, which is frequency dependent. Underwater, the αR term is negligible at frequencies below a few kilohertz but it can be important at higher frequencies. In air, the αR term is significant even at lower frequencies.

Even in the deep ocean or unbounded atmosphere, equation 11.1 is only a first approximation, given the effects of various modifying influences. In shallow waters or for airborne propagation near the ground, a more complex formulation is necessary. Modifying influences underwater include water depth, source and receiver depths, bottom slope, bottom composition, sea surface conditions, and vertical profiles of temperature and salinity. For very shallow water or ducted transmission beginning at distance R_0 from the source, eq'n 11.1 can be modified to assume cylindrical spreading ($10 \log R$) beyond range R_0 plus an additional

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[1] By W. John Richardson, LGL Ltd.

[2] Constructive comments on a draft of this chapter were provided by Drs. W.C. Cummings and A.N. Popper, and by the U.S. Minerals Management Service.

linear loss factor *(A)R*. The *(A)R* term, in dB/km, represents "duct leakage" or other attenuation phenomena that are directly related to range:

$$L_r = L_s - 20 \log_{10} R_0 - 10 \log_{10} (R/R_0) - \alpha R - (A)R - 60 \qquad (11.2)$$

The transition range R_0 between spherical and cylindrical spreading depends on local conditions, but is often assumed (as a rough approximation) to equal the water depth or duct thickness.

More elaborate theoretical or semi-empirical models for underwater and airborne sound propagation exist, usually with provision for incorporating parameters representing site-specific conditions. In the case of underwater propagation, most of these models are designed for specialized applications (often classified) and are not directly useful in predicting received levels of industrial sounds. In many cases, especially in shallow water, no standard theoretical model can adequately predict received levels at long distances; empirical site-specific data are then required.

Sound traveling from a source in air (e.g. aircraft) to a receiver underwater is a special case. The received level is affected by both in-air and underwater propagation processes, further complicated by special processes occurring at the air-water interface. The received level underwater depends in a complex way on source altitude and lateral distance, receiver depth, water depth, and other variables. Considerable theoretical and limited empirical work on this problem has been published. Section 11.3.1 summarizes the characteristics of sounds from passing aircraft.

11.1.2 Data Needs and Recommended Research

Site-specific models for underwater or airborne propagation of sound are often lacking when a potentially noisy industrial activity is planned. *If it is necessary to predict received sound levels vs. range, the lack of an adequate model is a major data need.* A theoretical or semi-empirical model usually can be developed based on existing physical data or assumptions, but its accuracy will depend on the circumstances and available data.

Field measurements to support or verify the acoustic modeling are required in some situations. In the case of underwater propagation, field measurements will be needed if data on water mass and bottom properties are lacking, and if there is a requirement for high precision, for estimates of received levels at long ranges, or for estimates of propagation through shallow water. In the case of airborne propagation, field data may be needed if propagation near the ground is important, or if there is complex topography. *In these cases, the lack of required site-specific data on physical conditions would be a major data need.*

11.2 Ambient Noise

11.2.1 Present Knowledge

Ambient noise is the residual background sound exclusive of components from specific sources. It is important because it strongly affects the distances to which animal sounds, specific industrial sounds, and other sounds of interest can be detected. As a first approximation, a sound signal is detectable only if its level is higher than that of the ambient noise at similar frequencies. As ambient noise level increases, sounds from a specific source diminish below the ambient level and become undetectable at progressively shorter ranges. Even within the range of detectability, variation in ambient noise greatly affects the prominence (signal-to-noise ratio) of sound signals.

Ambient noise levels at a given frequency and location typically vary by as much as 20 dB or more from one day to the next (chapter 4). Hence, a given sound source may be detectable ten times farther away on one day than on the next, and its signal to (ambient) noise ratio at each distance may change by 10-20 dB.

Above 500 Hz, ambient noise levels underwater are often dominated by wind and wave noise (sect. 4.2). Ambient noise tends to increase with increasing wind speed and wave height; wind speed has the direct influence. From ~500 Hz to at least 20 kHz, ambient levels on a "per Hz" or "spectrum level" basis tend to decrease with increasing frequency, often at a rate of about -5 dB per doubling of frequency (i.e. per octave). On a third-octave basis, ambient levels also tend to decrease with increasing frequency, but with a lesser slope of about -2 dB per octave or 0.67 dB per 1/3 octave. The reduced slope occurs because 1/3-octave bands become progressively wider with increasing frequency. At very high frequencies, above ~50 kHz, the ambient noise level increases with increasing frequency because of thermal noise related to molecular motion.

Below 500 Hz, especially in deep water, ambient noise underwater is often dominated by noise from distant shipping. Levels of ambient noise at low frequencies vary widely depending on the strength of the distant shipping component. In coastal areas, surf noise can be an important contributor and source of variation. Intermittent noises from volcanic and tectonic activity can also cause variation in low-frequency ambient noise, mainly below 100 Hz. Even at these low frequencies, ambient noise levels are related to wind speed when the shipping component is weak.

Precipitation, sea ice, and sounds from animals can also affect underwater ambient noise levels substantially. In addition, man-made sounds that come from unknown sources, or sources different from those of primary interest, are often considered to be part of the ambient noise. The importance of these contributions to ambient noise varies from day to day and, in some cases, with season.

In shallow water, the typical range of ambient noise levels is wider than that in deep water; the highest levels are higher and the lowest levels are lower (sect. 4.4). Differences in sound transmission conditions between shallow and deep water are partly responsible.

11.2.2 Data Needs and Recommended Research

Factors contributing to variability in ambient noise are known in a general way, but site-specific data on ambient noise levels at various places and times are often lacking. Variations in ambient noise have direct and large effects on the distance at which a given sound signal--e.g. industrial noise or marine mammal call--can be heard, and on its signal to (ambient) noise ratio at a given distance. *If these variables must be estimated accurately, the lack of site-specific data on ambient noise may be a major data need. This is especially true for shallow water areas where ambient noise is especially variable.*

Ambient noise data should be collected over a period long enough to be representative of the typical range of ambient noise conditions. Data should be collected at different seasons. Environmental data, including wind, wave, precipitation and ice conditions, should be recorded concurrently to allow analysis of factors affecting ambient noise. Care must be taken to avoid system noise problems that can invalidate ambient noise measurements. Ambient noise statistics should be determined separately for all frequencies audible to all types of animals that are of concern. Both spectrum-level and third-octave band-level statistics are desirable when interpreting the implications of ambient noise to marine mammals.

11.3 Man-Made Noise

11.3.1 Present Knowledge

Sources of man-made noise that could affect marine mammals include aircraft, ships and boats, icebreakers, hovercraft, geophysical (seismic) surveys, marine dredging and construction, offshore drilling, and offshore hydrocarbon production. The composite noise associated with specific offshore industrial sites often results from a combination of human activities. The sounds emitted by a source are characterized by their source level, frequency composition, and temporal variation. As a basis for reference, overall source levels of underwater sounds from human activities typically are 140-150 dB re 1 µPa-m for some sources, 160-170 dB for moderately-strong sources, 180-200 dB for the strongest sources of continuous noise (icebreakers and large ships), and 215-250 dB for very intense but transient impulsive sounds from seismic exploration.

Underwater sounds from ***aircraft*** are transient events. Strong underwater sounds are detectable for a period roughly corresponding to the time the aircraft is within a 26° cone above the receiver (sect. 5.2.1). The zone of strong ensonification is enlarged in rough seas and in shallow water. Usually, an aircraft can be heard in air well before and after the brief period while it passes overhead and is heard underwater. Sound pressure in the water directly below an aircraft is greatest at the surface and diminishes with increasing receiver depth. However, the opposite can be true when the aircraft is not directly overhead. The peak received level diminishes with increasing aircraft altitude, but the duration of audibility often increases with increasing altitude.

The primary sources of sound from propeller-driven aircraft and helicopters are their propellers or rotors. The rotating blades produce tones with fundamental frequencies proportional to the rotation rate and number of blades; the fundamental frequency is typically below 100 Hz. Harmonics are common at integer multiples of the fundamental frequency, but most energy is below 500 Hz.

Ship noise levels are roughly related to ship size, speed, and mode of operation (sect. 5.2.2). Large ships tend to emit more sound than small ones, and ships underway with a full load (or towing/pushing a load) produce more noise than unladen vessels. Noise increases with a ship's speed, whether loaded or unloaded. The state of maintenance strongly influences radiated sound level. Ships with old auxiliary machinery (e.g. generators and compressors) tend to radiate more noise than newer or well-maintained vessels. Source levels in the strongest third-octave band may range from 150-160 dB re 1 µPa-m for outboards and other small vessels to 185-200 dB for supertankers and large container ships.

Propeller cavitation produces much of the broadband noise from ships and boats, and propeller singing can produce strong tones at the propeller blade rate and some of its harmonics. Propellers create considerably higher noise levels if they are damaged, not operating synchronously, or operating without nozzles. Propulsion and auxiliary machinery can also radiate significant noise. The dominant frequency tends to increase with decreasing vessel size. For medium to large ships, the fundamental blade-rate tone is below 15 Hz; most of the energy is below 100 Hz, with some energy to 500 Hz. Noise from smaller boats tends to be concentrated at higher frequencies. Small boats with outboard engines emit considerable noise over a wide frequency range, from about 100 Hz to several kilohertz.

Icebreaking produces some of the higher-level sounds associated with the offshore oil and gas industry (sect. 5.2.3), but this noise is restricted to high-latitude areas. Icebreakers pushing ice radiate noise about 10 to 15 dB stronger than that when not pushing ice. During icebreaking, alternating periods of ice ramming and backing cause pronounced variations in radiated noise levels and spectral characteristics. The highest noise levels are due primarily to strong propeller cavitation, especially when backing up. There are tones at harmonic frequencies of the propeller blade-rate below 200 Hz, and lesser components extending beyond 5 kHz. The duration of a single episode of strong cavitation noise is generally ~1 min, followed by several minutes of less intense noise as the icebreaker repositions. When present, nozzles around the propellers significantly reduce radiated propeller noise during all phases of a ship's operation, but especially during icebreaking. Underwater noise from icebreaking is sometimes detectable 50 km or more away.

Vehicles on ice can transmit significant noise into ice-covered waters. Levels are greatly affected by the condition of the ice (temperature, snow cover, voids) and are generally much lower than noise levels generated by vessels in water (sect. 5.2.4). Snow absorbs sound, so vehicles on ice blanketed by snow transmit less noise to water than the same vehicles on bare ice. Underwater propagation of these sounds has not been studied extensively, but it would be unusual for a vehicle operating on ice to be audible underwater at distances beyond 1-3 km.

Underwater explosions can produce extremely intense pulses of underwater noise that are often detectable tens or even hundreds of kilometers away (sect. 5.3.1). High explosives produce pulses with a very rapid onset (shock waves). Explosives are now rarely used in marine seismic surveys, especially in U.S. waters, but they are used for marine demolition.

Vibroseis, a technique for on-ice seismic exploration, is frequently used in the arctic (sect. 5.3.2). Sound energy is projected through the ice into the water and sediments from a convoy of vehicles operating on landfast ice. The fundamental frequency of the energy sweeps from 10 to 70 Hz over several seconds, with harmonics extending up to ~1.5 kHz. Widely varying source levels have been reported. One study indicated that Vibroseis sounds would diminish to the ambient noise level at distances of 3½-5 km.

Airgun arrays are used nowadays for most marine seismic exploration. They, along with other seismic sources, are by far the strongest sources of underwater noise associated with oil and gas exploration and development (sect. 5.3.3, 5.3.4). Arrays of airguns, gas guns, and related sources generate high-amplitude noise pulses lasting a fraction of a second. The interval between successive pulses is typically 10-15 s, but can be less. Most of the energy in the pulses is below 100 Hz. However, this low-frequency energy is often attenuated rapidly because of shallow-water effects. Consequently, the dominant energy at horizontal ranges beyond a few kilometers is often at 100-250 Hz. With increased distance from the source, received pulses decrease in level but increase to ¼-½ s in duration. In shallow water, the elongated pulses received at ranges beyond a few kilometers sound "chirp"-like, with higher frequencies usually arriving before lower frequencies.

Overall source levels of noise pulses from airgun arrays are very high--typically 240-250 dB re 1 μPa-m. However, most energy is directed downward, and the short duration of each pulse limits the total energy. The effective source level for horizontal propagation can be 220-230 dB abeam of the seismic ship but it can be as much as 20 dB lower along the axis of the tow line ahead of or behind the ship. Pulses from high-powered seismic arrays are often detectable in the water 50-100 km away from the survey ship, and received levels within a few kilometers typically exceed 160 dB re 1 μPa. The received signals are generally lower by 1 to 7 dB near the surface (depth 3 m) than at deeper (≥9 m) depths.

Marine dredging and some ***marine construction*** operations introduce strong sounds of varying characteristics into the water (sect. 5.4.1). Estimated source levels of two dredges were 167 and 178 dB re 1 μPa in their strongest third-octave bands. Suction dredges are among the strongest sources of low-frequency continuous noise associated with the offshore oil industry. Because dredging occurs in relatively shallow water, and because of the rapid attenuation of low frequencies in shallow water, most components of dredge noise normally are undetectable underwater at ranges beyond 20-25 km. Tones often appear in the spectra of dredge noise, usually at frequencies below 1 kHz but sometimes at higher frequencies. Dredging, in contrast to shipping and icebreaking, often continues in one area for days or weeks at a time.

Construction of artificial islands in winter, involving construction and use of an ice road, was relatively quiet underwater. Such activities are most likely in shallow water, through which low-frequency sounds do not propagate well. In open water areas, construction involves barges or dredges and boats, with the attendant noises made by such vessels.

Offshore drilling produces widely varying underwater sounds, depending on the type of drilling platform (sect. 5.4.2, 5.4.3). Drilling from natural barrier islands or man-made islands generally produces only low-intensity underwater sounds that are inaudible at ranges beyond ~1 km. Drilling noise from a self-contained concrete caisson was also relatively weak at the frequencies usually considered, but there was a strong infrasonic tone near 1.4 Hz. Drilling noise from conventional metal-legged platforms is apparently not particularly intense, and is strongest at very low frequencies (5 Hz). Drilling noise levels from semi-submersibles are not especially high--154 dB re 1 μPa-m in the 10-500 Hz band. Drilling noise from a caisson retained island (ring caisson) was somewhat stronger--estimated as almost 160 dB re 1 μPa-m in the strongest third-octave band. Drillships produce higher levels of underwater noise than do other types of drilling platforms, with estimated third-octave source levels up to 167 and 177 dB re 1 μPa-m in the cases of two drilling vessels.

Drilling noise usually includes prominent tonal components at frequencies below ~300 Hz. In the few cases where very low frequency sounds were studied, the strongest tones were at or below 5 Hz. Besides the strong dependence of noise level on type of drilling platform, noise from a particular platform varies considerably over time.

Underwater noise from ***offshore production*** activities has not been studied extensively, but production seems to radiate more noise underwater when conducted from metal-legged platforms than when conducted from islands (sect. 5.4.5). Platforms powered by gas turbines generally produce stronger sounds than those with shore power. The strongest spectrum levels and tones are below 500 Hz.

Noise levels from almost all sources associated with the oil industry are highest at relatively low frequencies--less than 500 Hz--when tones or conventional spectrum-level measurements are considered. However, measurements on a third-octave basis may be more relevant to marine mammals. On a third-octave basis, the strongest sounds from most oil industry sources are again below 500 Hz, although sometimes not as low in frequency as the peak spectrum levels or the strongest tones. Also, relative levels at low and high frequencies are less divergent when measured in third octaves. This occurs because third-octave bands become wider with increasing frequency. Sources for which higher frequency components (>500 Hz) are especially important, on a third-octave basis, include small boats and icebreaking.

11.3.2 Data Needs and Recommended Research

Sounds emitted by various specific aircraft types, ships, icebreakers, seismic arrays, dredges, drillrigs and production platforms have been measured. Extrapolations to similar unstudied sources are often possible. However, there is considerable variation among individual vessels or rigs. *When there is serious concern about the acoustic effects of a type of sound source that has not previously been studied, e.g. a different class of ship or drillrig, the lack of data on the spectral characteristics and source level of its sounds would be a major data need.*

Characteristics of underwater noise propagating horizontally from various sound sources used for shallow geotechnical surveys, e.g. sparkers, water guns, side-scan sonars, have not been reported in the open literature insofar as we know. Pressure waveform signatures for such sources differ from one another, and from those of higher energy sources such as airguns or Vibroseis (sect. 5.3.5). Thus their transmission properties are likely to be different as well. Field measurements are needed in order to determine their signal characteristics as a function of horizontal range.

Underwater noises from marine dredging and construction have been studied in the arctic but less so elsewhere. Hence, data are scarce or lacking on noise characteristics of dredging and construction techniques that are not used in the arctic. *Widely varying equipment and techniques are used in different circumstances, so noise characteristics will vary considerably. This could be a major data need if extensive construction were planned in an area important to marine mammals.*

Data on underwater sounds from most types of drilling structures have been reported, but the available data are incomplete. For most types of platforms there has been little replication of measurements. Given the seemingly wide variation in levels depending on the type of activity underway on the platform, it would be desirable to obtain longer series of measurements for most types of platforms. In the case of conventional metal-legged drilling platforms, underwater noise spectra have been determined, but the near-field measurement procedures did not allow determination of the source levels of these sounds.

Available data on sounds from oil production platforms are very limited; source levels seem relatively low but cannot be determined quantitatively from available data.

Underwater sounds from many man-made sources have not been measured at frequencies below 10 or 20 Hz. However, some sources--e.g. large ships, some drillrigs, some production platforms--are known to emit strong sounds at frequencies below 10 Hz. Some (if not all) baleen whales are expected to have good hearing sensitivity at frequencies below 20 Hz. *When effects on baleen whales are a concern, the scarcity of data on noise levels at low frequencies is a major data need.*

Airborne noise from most offshore oil industry activities has not been described. The lack of such data could be a major data need if industrial activities were planned near important haul-out sites for marine mammals.

11.4 Marine Mammal Sounds

11.4.1 Present Knowledge

Marine mammal sounds apparently have two basic functions: communication and echolocation. *(1)* All marine mammals emit sounds that are known or suspected to be used for intraspecific communication underwater, in air, or both. Call types used for communication are very diverse. For example, bottlenose dolphin sounds are mainly whistles, sperm whale sounds are generally click trains, and killer whales often emit other kinds of pulsed sounds. Baleen whales mainly utter low frequency sounds. Pinniped sounds are highly variable. *(2)* Odontocetes are the only marine mammals in which echolocation has been proven to exist. All proven cases of echolocation involve click sounds.

Evidence for associations between specific underwater sounds and specific functions is, for most species, weak or non existent. Many marine mammals are gregarious, often coordinate activities, and often have to find one another in a visually-limited environment. It is assumed but only occasionally demonstrated that these phenomena are mediated, in part, by calls. *(1)* Some sounds appear to be used for long distance communication. In whales, sounds produced while individuals are far enough apart to be out of visual contact may be associated with announcement of reproductive intentions, establishment of territory or spacing between animals, coordination of foraging and other activities, and maintenance or establishment of group structure. *(2)* Over short distances, sounds may be used in social interaction situations involving aggression between individuals and establishment of dominance, for individual identification, and for establishment and maintenance of the mother-pup bond.

Underwater sounds of ***baleen whales*** (sect. 6.1) are primarily at frequencies below 1 kHz and have durations from ~0.5 s to over 1 s (sometimes much longer). Some have fundamental frequencies as low as 20 Hz. Thus, the dominant frequencies in baleen whale sounds overlap broadly with the dominant frequencies in many industrial sounds. Many baleen whale sounds are uncomplicated tonal moans or sounds that have been described as knocks, pulses, ratchets, thumps, and trumpet-like. Humpback and bowhead whale sounds are more complex, and include extended songs. Source levels of most baleen whale sounds are in the range 150-190 dB re 1 μPa-m, apparently with much within-species variation.

Some ***odontocete (toothed) whales*** apparently communicate underwater with whistles at frequencies below 20 kHz; most of their energy is typically near 10 kHz (sect. 6.2). Source levels for whistles may be 100-180 dB re 1 μPa-m. The killer whale produces whistles but most sounds are pulsed sounds at frequencies 1-6 kHz; source levels range up to 160 dB re 1 μPa. Most calls by the sperm whale and the phocoenid porpoises are clicks, some of which may be used for communication. Most odontocete sounds are detectable to humans with hydrophones at distances within no more than 1 km. However, sperm whale clicks may propagate well to distances >1 km. Most components of odontocete social sounds are above the low frequency range where most industrial sounds are concentrated.

The echolocation capabilities of the odontocetes that have been studied are very well developed (sect. 6.2.4). Echolocation pulses are generally at high frequencies--30 to 100 kHz or higher. However, killer whale echolocation signals have most energy at 12-25 kHz. The echolocation signals are projected forward of the animal in a narrow beam extending several degrees on either side of the animal's center line. Source levels can be over 200 dB re 1 μPa-m. The effective range of odontocete sonar may be up to 350 m, depending on ambient noise levels, size and reflectivity of the target, species, and numerous other factors. Although the capabilities of echolocation systems have been studied in much detail in a few species held in captivity, the specific functions of echolocation sounds in nature have not been well demonstrated.

Pinnipeds that mate and breed on land typically use airborne vocalizations as well as visual displays to establish and defend territories, compete with other males for access to females, mate, and establish and maintain the mother-pup bond. Underwater vocalizations appear to be limited to barks and clicks with frequencies ranging from <1 kHz to 4 kHz (sect. 6.3). In contrast, pinnipeds that mate in the water are often quite vocal during the breeding season. Most underwater sounds have frequencies ranging from <1 kHz to 10 kHz. Source levels for three phocid species that mate in the water are ~95-160 dB re 1 μPa-m.

All pinnipeds, the sea otter, perhaps the manatee, and at least some cetaceans use sound to establish and maintain the mother-offspring bond. The calls appear to be especially useful when mother and pup are attempting to reunite after a separation.

11.4.2 Data Needs and Recommended Research

Sounds of many species of marine mammals have been described in varying levels of detail, but the source levels, directionality, and maximum detection distances of most sound types are unknown or poorly documented (chapter 6). Many of the source level data that do exist were obtained from captive animals. In most cases it is unknown whether these data are representative of source levels in free-ranging animals. For species in which data of these types are lacking, it is not possible to estimate the maximum detection distances of the sounds either in natural conditions or in the presence of industrial noise.

The functions of most so-called communication calls are unknown or understood in only a rudimentary way. This prevents a definitive assessment of the consequences to the animals if the sounds become inaudible because of masking by industrial noise. *Lack of information about the distances over which marine mammals may need to communicate acoustically is a major data need in evaluating the effects of masking.*

The uses of echolocation by free-ranging odontocetes are not well documented (sect. 6.2.4). This would be a major data need if a human activity involving strong noise at very high frequencies was planned to continue for a prolonged period in an area important to odontocetes. However, very few human activities emit significant noise at frequencies above 30 kHz, where most odontocetes echolocate. High-frequency sonars and echosounders are the main concern.

11.5 Marine Mammal Hearing

11.5.1 Present Knowledge

Toothed whales are most sensitive to sounds above ~10 kHz (sect. 7.2.1). The reported upper limits of sensitive hearing range from about 31 kHz in the killer whale and near 70 kHz in the false killer whale to well above 100 kHz in some species. The sensitivity of many toothed whales to high frequency sounds is related to their use of very high frequency sound pulses for echolocation and moderately high frequency sounds for other functions, including communication. Low frequency hearing has not been studied in many species, but the bottlenose dolphin and white whale can hear sounds at frequencies as low as 40-125 Hz. However, below ~10 kHz sensitivity deteriorates with decreasing frequency. Below 1 kHz, where most industrial noise energy is concentrated, sensitivity appears to be poor, but data are scarce.

At least in the bottlenose dolphin, sensitivity decreases as the duration of a *single* sound pulse decreases below about 0.1-0.2 s. However, toothed whales apparently have neural mechanisms specialized for processing *sequences* of short pulses, such as are used for echolocation (sect. 7.2.4). Toothed whales have good frequency and intensity discrimination abilities, as well as good directional localization capabilities (sect. 7.3, 7.4).

Masking of sound signals by background noise has been studied under laboratory conditions in the bottlenose dolphin and white whale (sect. 7.5). Above ~2 kHz, critical ratios increase with increasing frequency, and are generally similar to those of the human at corresponding frequencies. At lower frequencies, critical ratios of the white whale (the only species studied) are unrelated to frequency.

Critical bands in the bottlenose dolphin appear to be wider than would be predicted based on the equal-power assumption. This indicates that some odontocetes can detect certain sounds when the signal is less intense than the total background noise in the masking band. Most masking experiments have tested the ability of an animal to detect a sound signal in the presence of noise coming from the same direction. At very high frequencies (e.g. 80 kHz), masking is greatly reduced when the sound signal and masking noise arrive from different directions, or when the signal arrives from one direction but the noise is omnidirectional. This reduction in masking due to directional hearing is less evident at moderate frequencies (e.g. 18 kHz).

Baleen whales probably are sensitive to low and moderate frequency sounds, probably with some variation among species (sect. 7.6). There are no specific data on sensitivity, frequency or intensity discrimination, or localization abilities. However, gray whales are able to detect killer whale sounds whose levels are about equal to the broadband noise level, and several species seemingly can determine the direction of arrival of various underwater sounds.

Hair (phocid) seals have an effective upper frequency limit near 60 kHz, above which sensitivity is poor and different frequencies cannot be discriminated (sect. 7.2.2). Underwater sensitivity is about the same from 1 or 2 kHz to 50 kHz. Within this range of best underwater sensitivity, sensitivity is not as high as in toothed whales. Sensitivity at low frequencies (<760 Hz) has not been tested. In-air hearing of phocid seals is less sensitive than underwater hearing, and the upper frequency limit is lower (~20 kHz). The underwater hearing threshold of a harbor seal increased as the duration of a sound decreased below about 50 ms, as in other animals. Pinnipeds seem less specialized for processing click sequences than are toothed whales. Their frequency discrimination abilities also seem less precise (sect. 7.3.1). Harbor seals have reasonably good directional localization abilities (sect. 7.4.2). Critical ratios increase with increasing frequency (at least in water), are similar in water and air, and probably are similar to those of other mammals (sect. 7.5.1).

Eared seals are similar to hair seals with regard to underwater hearing sensitivity at moderate frequencies. However, their upper frequency limit is lower--near 36-40 kHz vs. 60 kHz (sect. 7.2.2). At least in the California sea lion, sensitivity decreases as frequency decreases from 2000 to 250 Hz, but high-level sounds at 250 Hz can be heard. In-air hearing of eared seals is less sensitive than underwater hearing, but the difference in capabilities between air and water is less pronounced than in phocids. The upper frequency cutoff in air is only slightly less than that in water (32-36 vs. 36-40 kHz). Frequency discrimination and directional localization appear to be less precise than in toothed whales (sect. 7.3.1, 7.4.2). Critical ratios of the fur seal increase with increasing frequency, and are relatively low (i.e. good) in comparison with other mammals listening at corresponding frequencies (sect. 7.5.1).

Manatee hearing has not been studied in detail. However, electrophysiological evidence indicates that the West Indian manatee (the species occurring in the U.S.A.) may have optimum sensitivity near 1-1.5 kHz, and some sensitivity as high as 35 kHz (sect. 7.2.3).

11.5.2 Data Needs and Recommended Research

Data on absolute hearing sensitivity as a function of frequency are needed to evaluate the abilities of marine mammals to hear specific natural or man-made sounds. Such data are lacking for all baleen whales, manatees, and sea otters (sect. 7.2). Valuable data on absolute thresholds are available for several species of toothed whales and pinnipeds, but in most species these data do not extend below 1 kHz where most industrial noises are concentrated. *The lack of absolute threshold data for a species and frequency band of concern could be a significant data need if a substantial number of animals is to be exposed to man-made noise for a prolonged period. The data need would be major if corresponding data were not available for any closely-related species.*

The scarcity of data on noise masking under field conditions, compensatory mechanisms, and consequences of interrupted acoustic communication is a major data need (sect. 7.5).

Available data on masking are limited to a few species of odontocetes and pinnipeds, and to detection of pure tones against a white noise background. (White noise has the same level at each frequency.) In practical field situations, the sound signals of interest often are not tones, and the background noise--natural or industrial--is rarely white noise. Data are lacking on the effectiveness of directional hearing and other compensatory processes in allowing detection of sound signals against a strong noise background, especially at the low frequencies where most industrial noise is concentrated.

No aspect of baleen whale hearing has been studied directly. There are no specific data on sensitivity, frequency or intensity discrimination, or localization abilities (sect. 7.6). This is a major data need when evaluating the effects of man-made noise on baleen whale hearing and behavioral responsiveness. This data need is of special concern because baleen whales apparently are more dependent on low-frequency sounds than are other marine mammals; many industrial sounds are concentrated at these low frequencies. No practical method has been developed for conducting psychoacoustic tests on any baleen whale. *The lack of data on the sensitivity of baleen whales to infrasounds (at <20 Hz) is a major data need, given their assumed sensitivity to slightly higher frequencies and the evidence of strong infrasonic components (<20 Hz) in certain industrial noises.*

11.6 Disturbance Reactions

11.6.1 Present Knowledge

Aircraft overflights at low altitude can cause pinnipeds hauled out on land or ice to escape into the water, occasionally leading to some mortality of young through abandonment or trampling (sect. 8.2.1). Toothed and baleen whales sometimes dive or turn away during overflights, but sensitivity seems to vary depending on the activity of the animals. The effects on cetaceans seem transient, and occasional overflights probably have no long term consequences on cetaceans (sect. 8.2.2, 8.2.3). The relative roles of sound and vision in eliciting reactions to aircraft are unknown.

Ship and boat noise does not seem to have strong effects on pinnipeds that are in the water, but the data are very limited. However, pinnipeds hauled out on land or ice often are quite responsive to nearby vessels (sect. 8.3.1). Many toothed whales show some tolerance of vessels, but may react at distances of several kilometers or more when confined by ice or shallow water, or when they have learned to associate the vessel with harassment. White whales near ice in spring sometimes react to noise from approaching ships at distances of 50 km or more. At some other times, white whales tolerate very high levels of human activity (sect. 8.3.2).

Baleen whales sometimes flee from approaching ships and boats, especially from vessels that are moving rapidly, directly toward the whales, or erratically. However, there is little evidence that baleen whales travel far or remain disturbed for long after a single vessel passes. There is evidence that gray and possibly humpback and bowhead whales have reduced their utilization of certain heavily disturbed areas. However, the continued presence of various whale species in some areas heavily traveled by ships indicates a considerable degree of tolerance to ship noise (sect. 8.3.3).

Icebreaker noise effects on marine mammals have not been studied extensively. There is limited evidence that icebreaker traffic in winter does not reduce numbers of ringed seals present along the icebreaker tracks later in the spring (sect. 8.4).

Seismic exploration noise is more intense than noise from any other non-explosive source. There is evidence that some ringed seals abandon areas where on-ice seismic techniques (Vibroseis) are used in winter. However, the effect is very localized. Other species of seals often tolerate strong impulsive noises to which they have become accustomed (sect. 8.6.1).

Gray and bowhead whales often have been observed behaving normally, insofar as could be determined, in the presence of strong noise pulses from seismic vessels several kilometers or more away. However, most gray and bowhead whales interrupt their prior activities and swim away when a full-scale seismic vessel emitting noise pulses approaches within a few kilometers (sect. 8.6.3). Also, bowheads exposed to noise pulses from distant seismic vessels often exhibit subtle behavioral changes consistent with those seen when the whales are actively avoiding a closer seismic vessel. Thus, whales exposed to noise from distant seismic ships may not be totally unaffected even if they remain in the area and continue their normal activities.

Sea otters seem less sensitive than baleen whales to marine seismic exploration (sect. 8.6.4). Reactions of toothed whales to seismic exploration have not been studied (sect. 8.6.2).

High explosives, when detonated underwater, produce not only a very sharp noise pulse, but also shock waves that can do physical damage to nearby animals (sect. 8.6.1). Mortality of pinnipeds and sea otters exposed to explosions has been documented.

Stationary offshore activities (drilling, dredging, production) seem to have less effect on cetacean behavior than do moving sound sources such as aircraft and ships. However, avoidance responses have been demonstrated when certain whales are exposed to high levels of these sounds either near actual oil industry operations or via underwater playbacks of recorded industrial noise (sect. 8.7-8.8). Responsiveness varies considerably. However, reactions have only been found when received noise levels were well above ambient levels. Thus, the few species of cetaceans studied apparently did not react overtly if they could barely hear the industrial noise; they only reacted when it was well above the ambient noise.

Fewer data are available concerning effects of noise from drilling, dredging and production on pinnipeds, toothed whales and sea otters. Sea otters and white whales sometimes tolerate considerable noise from such sources.

Overall, noise from certain offshore operations of the oil industry, e.g. ship and aircraft traffic, as well as noise from other human activities, sometimes causes pronounced short-term behavioral reactions and temporary local displacement of certain marine mammals (whales and hauled-out pinnipeds). Sometimes the effects are more subtle, and at other times no effects are detectable even in the presence of strong industrial noise. Overflights of pinnipeds at haul-out sites can cause limited mortality through stampedes or abandonment. The continued presence of various marine mammals in certain areas despite intense ship traffic and other human activities, sometimes for many decades, suggests that many marine mammals are tolerant of much human activity (sect. 8.10). However, there may be no suitable alternative locations for some marine mammals.

11.6.2 Data Needs and Recommended Research

In many cases it is uncertain whether behavioral reactions of marine mammals to industrial activities are attributable to noise, visual cues, or a combination of cues. This doubt applies to most data on reactions to aircraft, and some data on reactions to ships and various other human activities. This uncertainty often is unimportant for practical purposes; the important feature is the effect on the animals, not the specific cue. *However, this distinction may be a major data need when mitigative measures are being designed. The most appropriate mitigative measure(s) may depend on the specific cue(s) to which animals react.* Noise playback experiments provide a method for testing the reactions to industrial noise in isolation from other cues associated with industrial operations.

Some mortality of pinnipeds hauled out on land or ice has been reported or suspected as a result of aircraft overflights and ship approaches (sect. 8.2.1, 8.3.1). Mortality has been attributed to stampede-induced injuries and pup abandonment. Any such mortality is a direct and negative impact on individuals and populations, but the extent of the mortality is unclear. Many pinnipeds apparently habituate to such disturbances. Better data on reactions to aircraft and surface vessels are desirable for any situation in which a major pinniped haul-out site is to be subjected to repeated close approaches by aircraft or vessels.

Icebreaker effects on marine mammals have been the subject of much speculation but only limited field study (sect. 8.4). The intense and variable underwater noise from icebreakers is one reason for concern, along with demonstrated sensitivity of white whales and narwhals in the Canadian high arctic to icebreaker noise. *The lack of data on reactions of other high-latitude species to icebreakers would be a major data need if plans for icebreaking tankers were re-vitalized, or if icebreaking in support of oil industry or other operations were greatly expanded.*

Little is known about reactions of odontocetes and pinnipeds to underwater noise from airgun arrays and other noise sources used for seismic exploration in open water (sect. 8.6.1, 8.6.2). There are no data for manatees. Given the very high levels of noise pulses from seismic sources, these are major data needs.

Short-term behavioral reactions of some species of marine mammals to various marine construction, drilling, and oil production operations have been reported. In other cases, tolerance of these operations has been reported (sect. 8.7, 8.8). It is not known how extensively these data can be extrapolated to related but untested species, or to noise from similar but untested industrial operations. As yet, too few combinations of species and industrial activities have been studied to allow confident judgments about the generality of the results that have been obtained.

Any possible long-term effects of man-made noise on marine mammal individuals and populations are, for the most part, unknown. This is a major data need, since it is the long-term effects on distribution and reproductive success that are most important. It is unclear whether the presence or absence of strong short-term behavioral reactions is a good indicator of long-term consequences. If industry is regulated based on the apparent short-term sensitivity (or lack of sensitivity) of marine mammals, and if short- and long-term effects are not well correlated, then the restrictions placed on industry may be unnecessary or ineffective. Research that can provide insight into long-term effects of noise on any species of marine mammal is a high priority. Useful approaches may include studies of stress as assessed by telemetry of physiological parameters, site fidelity of known individuals to ensonified areas, and long-term displacement of populations. In order to be useful, most types of studies of long-term effects must be conducted in a consistent way over prolonged periods.

The scarcity of specific data on habituation of marine mammals to man-made noise is a major data need (sect. 8.10.2). It is not known whether marine mammals that tolerate chronic noise exposure are stressed or otherwise deleteriously affected. Behavioral habituation is a process that might allow marine mammals to adapt to the presence of ongoing or repeated exposure to more-or-less innocuous man-made noises. A better understanding of habituation in marine mammals is needed to allow more reliable predictions about the likely long-term effects of repeated noise exposure.

11.7 Zones of Noise Influence

11.7.1 Present Knowledge

The ***zone of audibility*** around a source of man-made noise is the area within which a marine mammal can hear the noise (sect. 9.2). Although the predicted radius of audibility around a noise source is subject to many variables and uncertainties, some industrial activities clearly are audible much farther away than others (sect. 9.7-9.12; Tables 9.1-9.3). Strong acoustic sources like open-water seismic exploration and icebreaking are probably audible 100 km or more away in many cases. This is especially true for baleen whales, assuming that their hearing is very sensitive to low frequency sounds. However, low-frequency seismic pulses may be strong enough to be heard at distances of 100 km or more even by some toothed whales and pinnipeds. At the other extreme, a bottom-founded oil production platform like that used off Santa Barbara is not expected to be audible to toothed whales and pinnipeds more than a few hundred meters away, or to baleen whales more than a few kilometers away.

Propagation and ambient noise data show that the average radius of audibility around a particular type of noise source will vary considerably among regions. For example, attenuation of underwater sounds is less rapid in the Beaufort Sea than in many other areas. Elevated levels of ambient noise caused by snapping shrimp or surf, for example, can cause significant reductions in typical radii of audibility. Within any one region, day-to-day variability in ambient noise can affect the radius of audibility drastically. Thus, even for a specific industrial activity in a specific area, it is not possible to find a single threshold distance within which animals will detect the noise and beyond which they will not do so. The relationship between detectability and distance will be probabilistic.

Because of the numerous variables, assumptions and limitations, the radii of audibility predicted in this report and elsewhere must be taken as preliminary first approximations. Their greatest usefulness is probably in identifying phenomena and situations requiring further study (see "Data Needs", below).

The ***zone of masking*** around a noise source is the area within which the noise level is high enough to interfere with detection of other sounds of interest to a marine mammal, e.g.

communication calls from conspecifics, echolocation signals, prey sounds, or other natural environmental sounds (sect. 9.3). Any man-made noise strong enough to be audible increases the total background noise--natural plus man-made. This interferes with an animal's ability to detect a sound signal if the signal is weak relative to the total background noise level. Thus, the maximum radius of audibility of a man-made noise is also the maximum theoretical radius where the noise might impair detection of other sounds of interest.

Only the weakest and most marginally-detectable signals would be masked by the slight increase in background noise occurring at the maximum radius of masking. Stronger sound signals would be masked only if the listening animal were closer to the source of man-made noise. Dramatic reductions in the maximum potential radius of communication will result if noise levels are increased by 10 or 20 dB while other factors remain unchanged. Species that communicate acoustically over long distances would be most seriously affected.

The ***zone of responsiveness*** around a noise source is the area within which the animal would react behaviorally or physiologically to the noise. This zone is expected to be considerably smaller than the zone of audibility, since marine mammals often do not react to noises that are faint but presumably audible (sect. 9.4). However, when the industrial noise level is high enough, marine mammals often exhibit avoidance or other behavioral reactions. For example, seismic pulses can be detectable 100 km or more away, but baleen whales usually do not show overt avoidance unless the seismic vessel is within a few kilometers.

Even for a given species, area and season, there is wide variability in the sensitivity of different individuals to noise (sect. 9.4.3). Therefore, large sample sizes are needed to characterize response criteria. Also, response criteria are probabilistic rather than absolute. Most "radius of response" predictions summarized in Tables 9.1-9.1 are the distances where we expect an average individual to react. Some individuals may occur closer to the industrial source; others may react strongly at greater distances. Among the many factors that may affect sensitivity are the current activity of the animal and its past experience (if any) with that type of sound.

The ***zone of auditory damage*** around a noise source is the small area where, with a strong source, the received level of sound (and attendant acceleration and displacement) might be high enough to cause physical discomfort or damage to the auditory system (sect. 9.5). Shock waves from explosions constitute the one type of "noise" that definitely can cause hearing damage (and other physical damage) to marine mammals. Although specific data are lacking, marine mammals are unlikely to suffer permanent hearing damage due to noise from most other human activities. The radius of responsiveness is normally expected to be much greater than the radius of hearing damage, so most marine mammals are expected to avoid the smaller area where hearing damage is a possibility. Also, most marine mammals are unlikely to remain within any one small area long enough to be harmed even if they do not show active avoidance. Seals that are confined near breathing holes through ice are a possible exception. Noise pulses from airgun arrays and similar sources may also be high enough to cause hearing damage to the few animals that remain within ~100 m of the noise source.

11.7.2 Data Needs and Recommended Research

Many assumptions must be made in predicting radii of audibility and responsiveness, partly because of data needs and partly because of the wide variability in the quantitative factors involved in the predictions. Thus, much caution is necessary in interpreting these predictions. They are probably most useful in a relative sense, and less useful as predictors of actual radii of audibility or responsiveness in specific circumstances. All radii of audibility listed in Tables 9.1-9.3 assume "typical" ambient noise levels. Normal day-to-day variations in ambient noise will cause drastic changes in the radius of audibility for all situations listed in those Tables as "ambient limited" (AL). Predicted radii of influence are also uncertain because of variability and uncertainties in biological phenomena like auditory sensitivity, detection of infrasounds, and behavioral response thresholds.

Radii of audibility often cannot be estimated with confidence because of data needs concerning absolute hearing sensitivity (sect. 11.5.2). For baleen whales, manatees and sea otters, no direct data on hearing sensitivity are available. For most species of toothed whales and pinnipeds, there are no data on sensitivity at frequencies below about 1 kHz, where most industrial noises are strongest. *The scarcity of data on hearing thresholds at low frequencies is a major data need, in that it prevents meaningful estimates of radii of audibility for many species and situations, and requires bold extrapolations in other cases.*

Our estimates of radii of audibility are based on unverified assumptions about detection of sounds in the presence of background noise (sect. 9.2.1). We assumed that marine mammals can hear a sound whose received level exceeds the background noise level in the corresponding frequency band, and that the masking bandwidth is 1/3 octave. However, masking bandwidths undoubtedly vary, and can be more or less than 1/3 octave. A related concern is the assumption that the minimum detectable signal-to-noise ratio is 0 dB. The effective value may be somewhat above or below 0 dB. Additional uncertainties about masking (sect. 11.5.2) also affect the reliability of estimated radii of audibility.

Radii of masking cannot be predicted precisely, given the data needs noted in the previous paragraph (see also sect. 9.3). Furthermore, the scarcity of data on the functions of most marine mammal sounds makes it impossible to predict the effects of a reduction in maximum acoustic range. *Verification of these assumptions would be a major data need in a situation where an important area for resident marine mammals is exposed to intense and continuous man-made noise.*

Radii of responsiveness of cetaceans and pinnipeds to human activities are often reported in terms of distance but less commonly in terms of received sound level. This limits our ability to generalize to other locations where propagation loss differs, or to other industrial activities differing in source level. *This scarcity of data on response thresholds is a major data need.* For manatees and sea otters, almost no data are available on behavioral responses to human activities. Thus, their radii of responsiveness to most types of human activities are unknown and unpredictable.

Radii of responsiveness predicted in sections 9.7-9.12 consider only the acoustic characteristics of industrial activities. Some marine mammals may also react to visual appearance or odor. This is perhaps most likely in the cases of industrial activities that do not have long-distance acoustic effects.

Radii of auditory damage are speculative because there are no data on the levels of sounds that cause permanent hearing damage or temporary threshold shifts in marine mammals (sect. 9.5). Given the basic similarities in mammalian hearing processes, data from humans and other terrestrial mammals probably are useful. However, it is not known how closely those data apply to marine mammals. We have speculated that exposure to man-made noises (aside from explosions) is rarely likely to cause hearing damage in marine mammals. However, this needs confirmation.

In humans exposed to strong sounds, hearing sensitivity is reduced temporarily even if there is no permanent damage (sect. 9.5.2). It is not known whether marine mammals experience this temporary threshold shift (TTS), but it is likely. If so, their ability to detect calls, echolocation sounds, and other ambient sounds will be degraded by TTS as well as by masking during exposure to strong man-made noise. The consequences of this reduced access to acoustical information are unknown.

11.8 Conclusions: Significance of Responses and Impacts

Marine mammals undoubtedly hear man-made noises from many sources. Cetaceans and manatees are exposed primarily to underwater sounds. Pinnipeds and sea otters are often subjected to airborne as well as underwater sounds. Most man-made sounds to which marine mammals are exposed are concentrated at low frequencies, although there are exceptions (e.g. ship sonars). The hearing systems of baleen whales are assumed to be adapted for detecting low frequency sounds. Pinnipeds and especially toothed whales are better adapted for detecting higher frequency sounds, but they can undoubtedly hear strong sounds at low frequencies.

The fact that marine mammals can detect man-made noise does not, in itself, show that they are affected deleteriously by the noise (sect. 10.6.4). Many types of marine mammals commonly occur close enough to noise sources to be well within the ensonified zone. In many cases, activities of animals within the ensonified zone seem unaffected by the noise. However, when marine mammals are found within a zone ensonified by man-made noise, there is rarely any definite information about the numbers present relative to the numbers that would have been there if there were no man-made noise. Also, there is essentially no information about the possibility that marine mammals occurring within an ensonified zone are stressed or otherwise affected in a way that might impair their long-term well-being, or their reproductive success.

Special concern arises when a significant proportion of a marine mammal population is concentrated in the area ensonified by a noisy activity (sect. 10.2). However, effective mitigative measures may be practical in these cases, since a minor change in siting of facilities or in seasonal timing of operations may greatly reduce the noise exposure. In contrast, marine mammals at sea sometimes are thinly distributed within large areas, and only a small percentage of the population is likely to be within the radius of acoustic influence around a given human activity. There are, however, circumstances in which many marine mammals can be exposed to man-made noise even when the population is widely distributed.

Masking is a natural and highly variable phenomenon to which marine mammals must be well adapted (sect. 9.3.2). Hence, marine mammals undoubtedly can tolerate some increase in masking relative to natural levels. However, the limits of this tolerance are unknown (sect. 10.3). The significance of acoustic masking in field conditions cannot be determined until more is known about *(1)* the functional importance to marine mammals of faint sound signals from conspecifics, predators, prey, and other natural sources; *(2)* signal detection abilities of marine mammals in the presence of background noise, including directional hearing abilities at frequencies where masking is an issue, and *(3)* abilities of marine mammals to adjust the intensities and perhaps frequencies of emitted sounds to minimize masking effects. More laboratory work on masking should be done with sound signals and background noises typical of those occurring in field conditions, including low frequency sounds.

Marine mammals show wide within-species variations in behavioral response thresholds when exposed to man-made noise. Thus, the radius of responsiveness varies widely among individuals and locations, and over time. No single criterion of disturbance will apply to all circumstances, even for a particular type of animal and a human activity (sect. 10.4.1).

Although there is little definite information about the long-term effects of short-term disturbance reactions, one can speculate that isolated disturbance incidents usually have minimal or no lasting effects. Marine mammals cope with disruptions by predators, bad weather, unusual ice conditions (at high latitudes), and other natural phenomena, and no doubt can also tolerate occasional brief periods of man-induced disturbance (sect. 10.4).

The energetic consequences of most single disturbance incidents probably are insignificant, but there has been no specific work on this topic. Recurrent incidents of interrupted feeding and rapid swimming, if sufficiently frequent, can be assumed to have negative effects on the well-being of individuals. Relationships between disturbance frequency and severity of energetic effect have not been studied. Energetic modeling studies emphasizing disturbance effects could be of some value (sect. 10.6.3).

Prolonged or repeated disturbance, as might occur if a stationary and noisy human activity were established near a marine mammal concentration area, is a more important concern than isolated short-term disturbance. The long-term implications of ongoing disturbance would depend in part on the degree to which the marine mammals habituate (sect. 10.5). A better understanding of habituation by marine mammals to man-made noises is needed. We need repeated observations of the reactions of known individual animals. This work should be done with free-ranging animals that are individually recognizable via natural or artificial marks. Radio telemetry may be helpful in maintaining contact with known individuals and in providing physiological data related to stress.

There are a few reports of probable or possible long-term displacement of marine mammals from ensonified areas (sect. 10.6.2). It is rarely possible to identify the specific cause of an apparent long-term displacement; even the occurrence of displacement can be difficult to detect. The consequences of long-term displacement from ensonified areas are generally unknown. Meaningful studies of this question would be very difficult. Long-term work on the well-being and reproductive success of known individuals would be needed, including data from some animals that remain in preferred undisturbed areas and others that are displaced.

Cumulative effects of multiple noise sources should be considered in impact assessments (sect. 10.7). Although the proportion of a marine mammal population exposed to noise from any one source may be small, the proportion exposed to at least one noise source may be much higher. The presence of multiple noise sources is expected to cause more frequent masking, behavioral disruption, and short-term displacement. These effects may be partly mitigated by habituation. Cumulative effects from non-acoustic as well as acoustic components of human activities are also a concern.

Reactions of marine mammals to man-made noise are in many ways similar to those of certain terrestrial mammals, especially ungulates (sect. 10.8). Noise effects on some phenomena, e.g. physiological stress, are better known in terrestrial than in marine mammals. Some procedures known to be useful in terrestrial studies, e.g. heart-rate telemetry, should be considered for use in studies of marine mammals. Studies of disturbance effects on terrestrial mammals should be taken into account by those designing and interpreting studies of marine mammal disturbance.

Marine mammals possess a number of characteristics that apparently pre-adapt them to cope with limited exposure to man-made noise (sect. 10.9). These traits include certain attributes of their calls and hearing processes, the use of short-term avoidance reactions to reduce exposure to strong noise, and habituation. Within limits, these traits assist marine mammals in coping with man-made noise.

Noise impacts of human activities often can be reduced by careful planning (sect. 10.10). Noise reductions are sometimes possible by appropriate choice or design of equipment. Seasonal timing of activities often can be adjusted to avoid periods when marine mammals are present or most sensitive. The most sensitive areas often can be avoided when selecting sites for onshore facilities, routes for shipping and aircraft, and aircraft altitudes.

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APPENDIX 1

Scientific Names of Marine Mammals Mentioned in the Text

Toothed Whales - **Odontocetes**

Narwhal - *Monodon monoceros*
White Whale - *Delphinapterus leucas*
Killer Whale - *Orcinus orca*
Pygmy Killer Whale - *Feresa attenuata*
False Killer Whale - *Pseudorca crassidens*
Northern Right-Whale Dolphin - *Lissodelphis borealis*
Dusky Dolphin - *Lagenorhynchus obsurus*
Peale's Dolphin - *Lagenorhynchus australis*
Pacific White-Sided Dolphin - *Lagenorhynchus obliquidens*
Atlantic White-sided Dolphin - *Lagenorhynchus acutus*
Atlantic Spotted Dolphin - *Stenella plagiodon*
Spinner Dolphin - *Stenella longirostris*
Striped Dolphin - *Stenella coeruleoalba* (= *S. styx*)
Bottlenose Dolphin - *Tursiops truncatus*
Common Dolphin - *Delphinus delphis*
Risso's Dolphin - *Grampus griseus*
Commerson's Dolphin - *Cephalorhynchus commersonii*
Rough-toothed Dolphin - *Steno bredanensis*
Boutu (Amazon River Dolphin) - *Inia geoffrensis*
Tucuxi - *Sotalia fluviatilis*
Franciscana - *Pontoporia blainvillei*
Indus Susu - *Platanista indi*
Short-finned Pilot Whale - *Globicephala macrorhynchus*
Long-finned Pilot Whale - *Globicephala melaena*
Dall's Porpoise - *Phocoenoides dalli*
Harbor Porpoise - *Phocoena phocoena*
Vaquita (Gulf of Calif. Harbor Porp.) - *Phocoena sinus*
Sperm Whale - *Physeter catodon*, *P. macrocephalus*
Pygmy Sperm Whale - *Kogia breviceps*
Northern Bottlenosed Whale - *Hyperoodon ampullatus*
Baird's Beaked Whale - *Berardius bairdii*
Cuvier's Beaked Whale - *Ziphius cavirostris*
Beaked Whales - *Mesoplodon* sp.
Blainville's Beaked whale - *Mesoplodon densirostris*

Baleen Whales - **Mysticetes**

Fin Whale - *Balaenoptera physalus*
Blue Whale - *Balaenoptera musculus*
Minke Whale - *Balaenoptera acutorostrata*
Bryde's Whale - *Balaenoptera edeni*

Continued...

Appendix 1. Concluded.

Sei Whale - *Balaenoptera borealis*
Humpback Whale - *Megaptera novaeangliae*
Gray Whale - *Eschrichtius robustus*
Bowhead Whale - *Balaena mysticetus*
Northern Right Whale - *Eubalaena glacialis*
Southern Right Whale - *Eubalaena australis*

Hair or Earless Seals - Phocids

Weddell Seal - *Leptonychotes weddelli*
Bearded Seal - *Erignathus barbatus*
Ringed Seal - *Phoca hispida*
Ribbon Seal - *Phoca fasciata*
Harbor Seal - *Phoca vitulina*
Spotted Seal - *Phoca largha*
Harp Seal - *Pagophilus groenlandicus*
Hawaiian Monk Seal - *Monachus schauinslandi*
Elephant Seal - *Mirounga angustirostris*
Gray Seal - *Halichoerus grypus*

Fur Seals and Sea Lions (Eared Seals) - Otariids

Northern Fur Seal - *Callorhinus ursinus*
Cape Fur Seal - *Arctocephalus pusillus*
Guadalupe Fur Seal - *Artocephalus townsendi*
California Sea Lion - *Zalophus californianus*
Steller Sea Lion - *Eumetopias jubata*

Other

Walrus - *Odobenus rosmarus*
Sea Otter - *Enhydra lutris*
Amazon Manatee - *Trichechus inunguis*
West Indian Manatee - *Trichechus manatus*

APPENDIX 2

Characteristics of Aircraft Mentioned in the Text

		Engines		Approx. Wt (kg)		No. of
Manufacturer	Model	No.	Type[a]	Empty	Max. TO	Rotors
Fixed-Wing Aircraft						
Aero Commander	Shrike	2	Pi	2050	3060	-
Britten-Norman	Islander	2	Pi	1590	2725	-
Cessna	172	1	Pi	555	1045	-
	180	1	Pi	695	1270	-
"	185	1	Pi	715	1520	-
"	310	2	Pi	1625	2500	-
DeHavil. Canada	Beaver	1	Pr	1360	2315	-
" "	Otter	1	Pr	2010	3630	-
" "	Twin Otter	2	Tp	3000	5670	-
Fokker	F-27	2	Tp	11000	19700	-
Grumman	Turbo Goose	2	Tp	?	?	-
Hunting Percival	Pembroke	2	Pr	4020	5380	-
Ilyushin	14 'Crate'	2	Pr	?	17000	-
Lockheed	P-3 Orion	4	Tp	30645	63470	-
Lockheed	C-130 Herc.	4	Tp	36000	77000	-
Helicopters						
Bell	47	1	Pi	835	1340	1 + tail
Bell	204/205	1	Ts	2200	4310	"
Bell	206	1	Ts	715	1450	"
Bell	212 (UH-1N)	2	Ts	2770	5085	"
Bell	214ST	2	Ts	4300	7945	"
Mil	MI-8 'Hip'	2	Ts	7400	12000	"
Sikorsky	S-61	2	Ts	5500	9100	"
Sikorsky	S-62 (H-52)	1	Ts	2305	3675	"

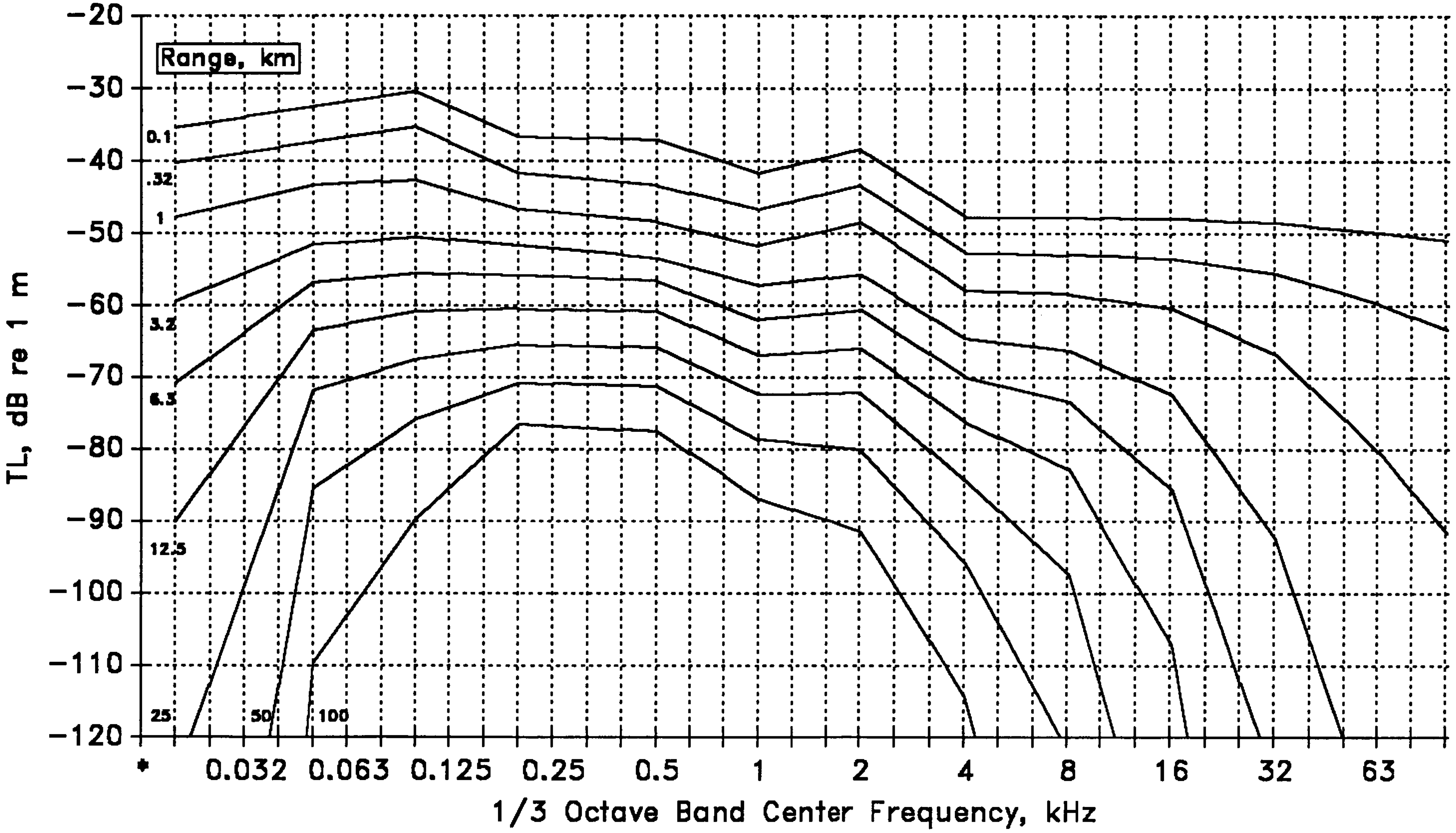
[a] Pi = Piston, inline; Pr = Piston, rotary; Tp = Turboprop; Ts = Turboshaft

APPENDIX 3

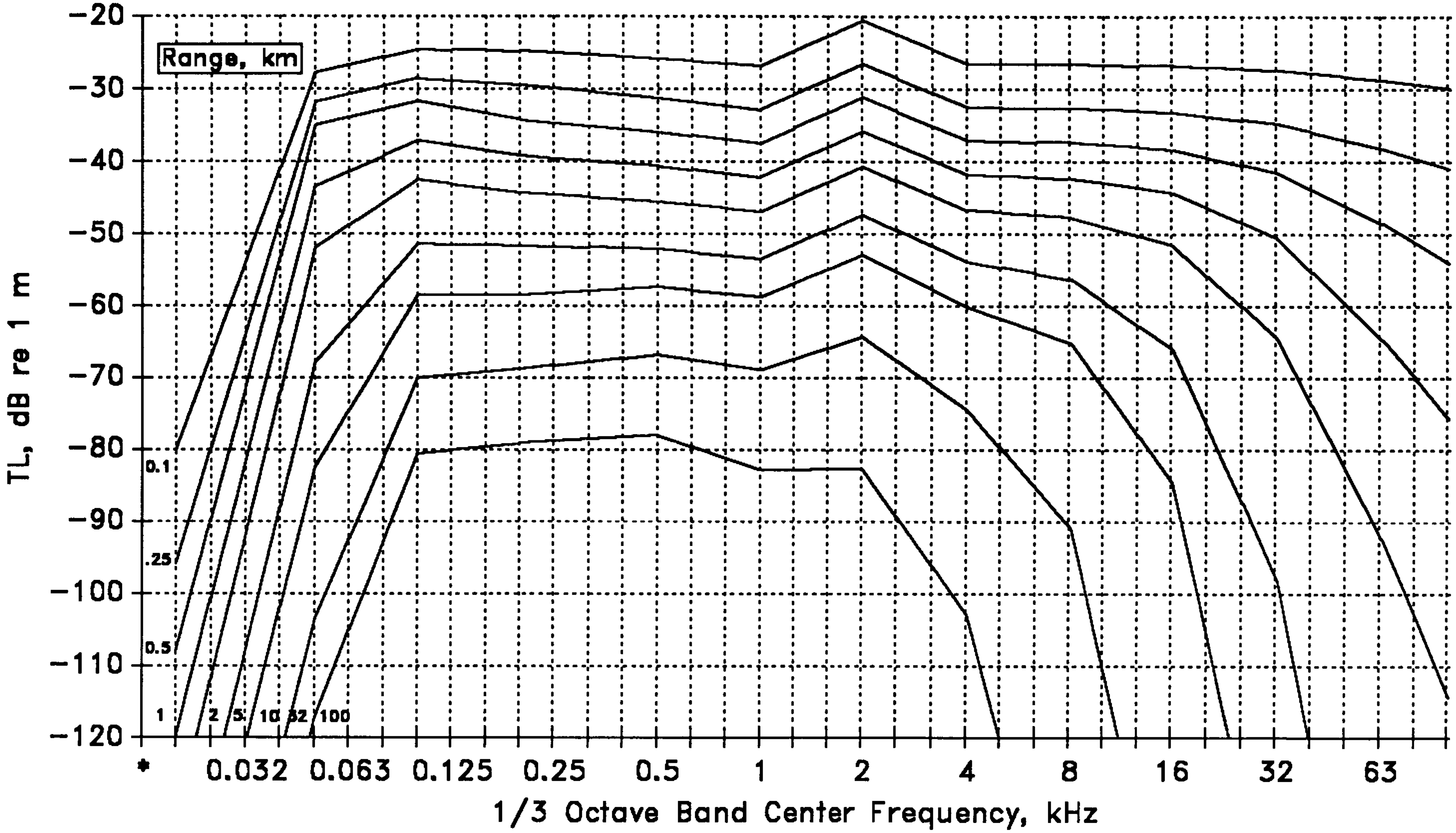
Predicted Sound Transmission Loss for Case Studies

The following graphs show the estimated transmission loss for underwater sound at the various sites considered in sections 9.6 to 9.11. Each curve represents the estimated transmission loss from 1 m to the specified range, as a function of frequency. See sections 9.6 to 9.11 for data sources, assumptions, and procedures.

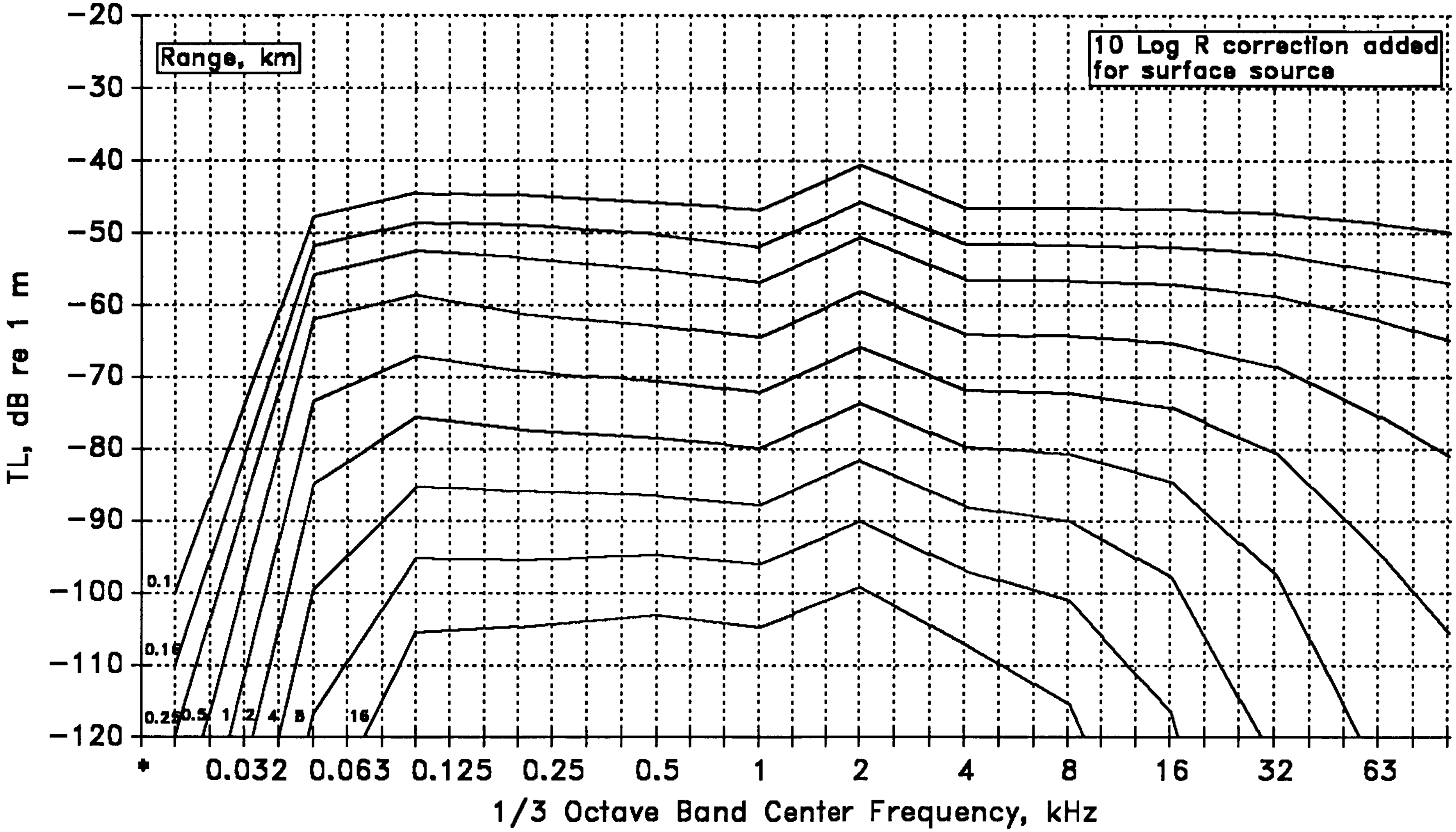
A. TRANSMISSION LOSS SPECTRA AT BELCHER SITE, BEAUFORT SEA
Miles et al. 1987 and Weston/Smith Model extrapolations



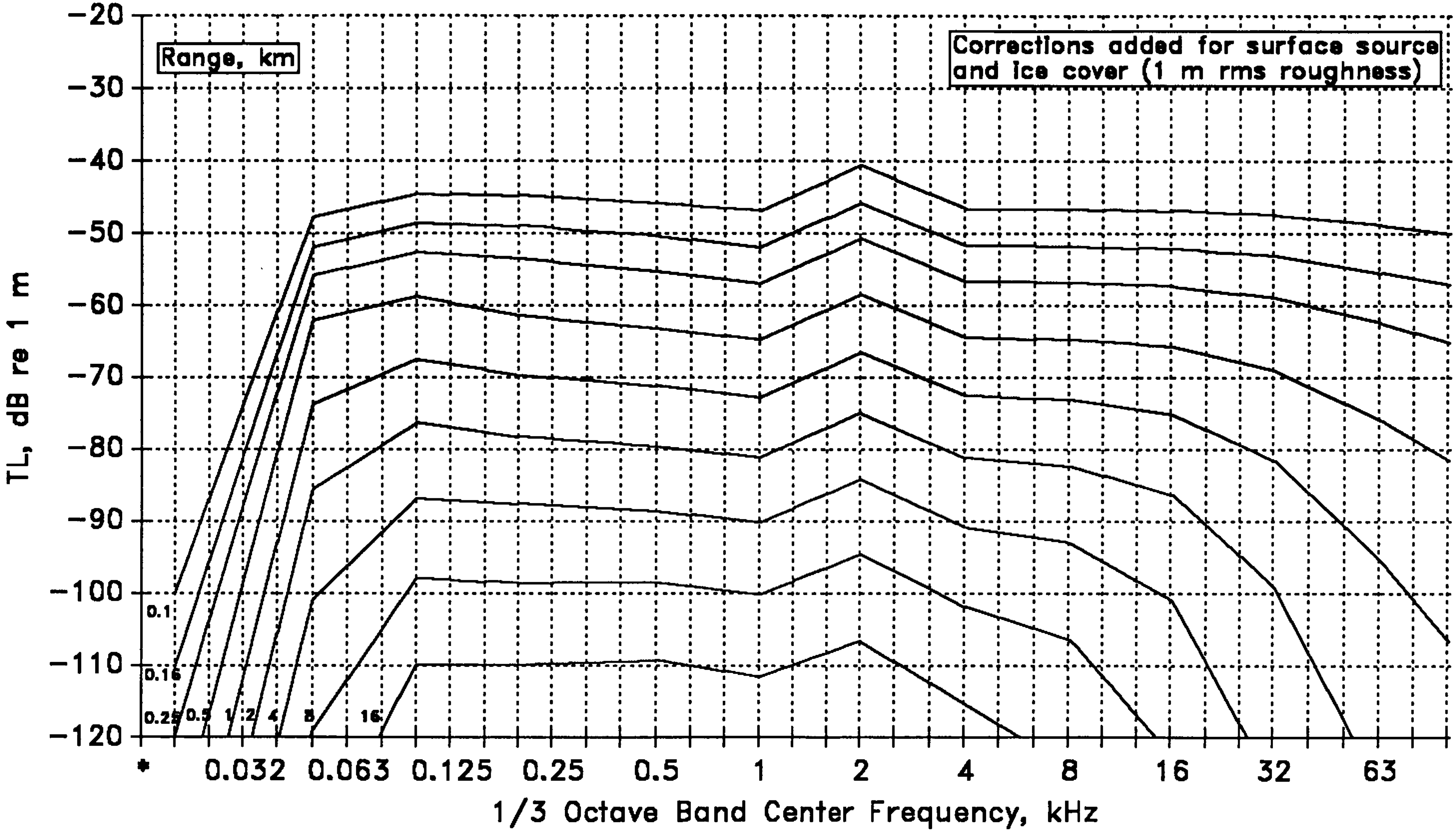
B. TRANSMISSION LOSS SPECTRA AT SANDPIPER SITE, BEAUFORT SEA
Miles et al. 1987 and Weston/Smith Model extrapolations



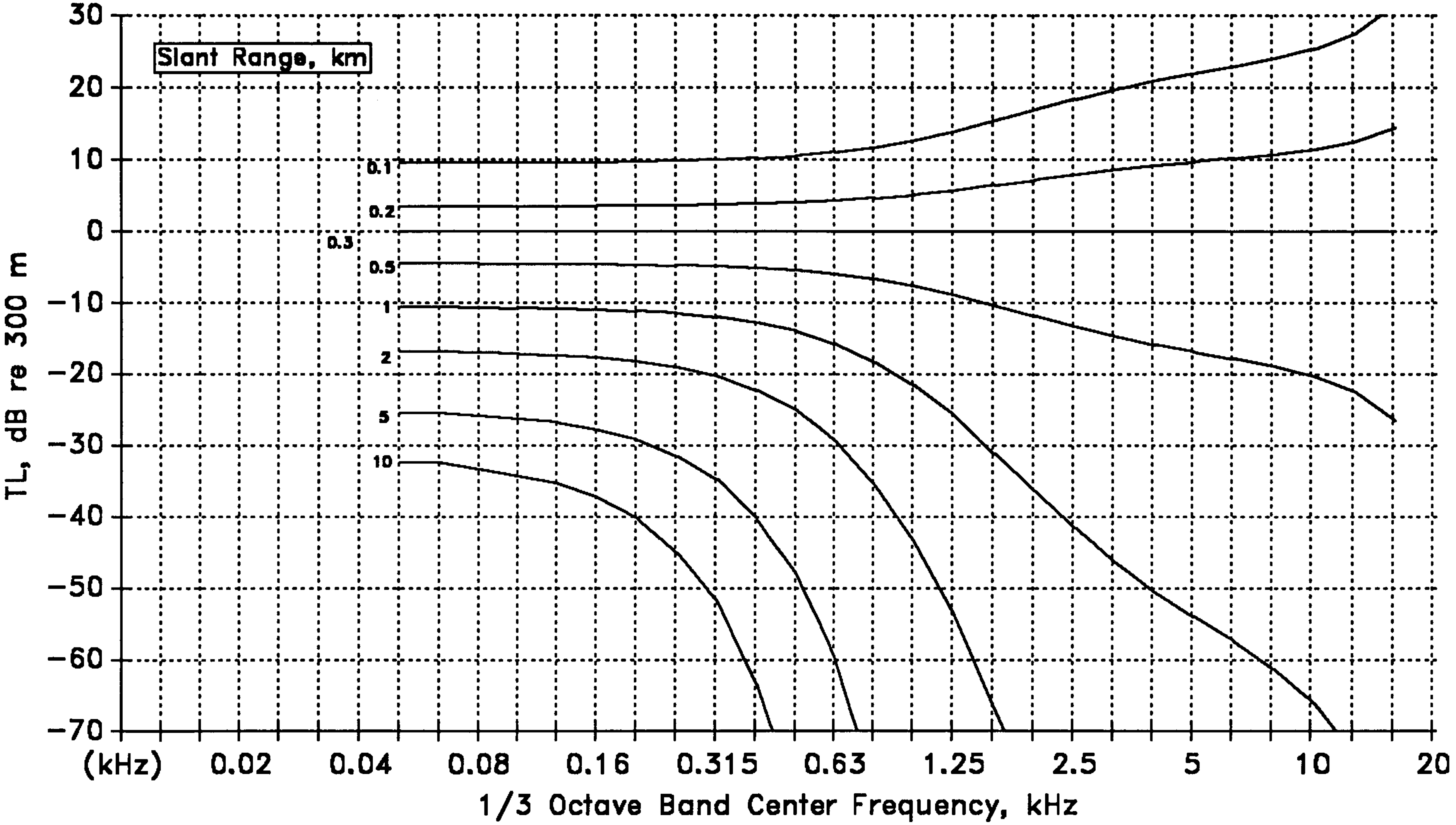
C. TRANSMISSION LOSS SPECTRA AT SANDPIPER SITE, BEAUFORT SEA
Miles et al. 1987 and Weston/Smith Model extrapolations



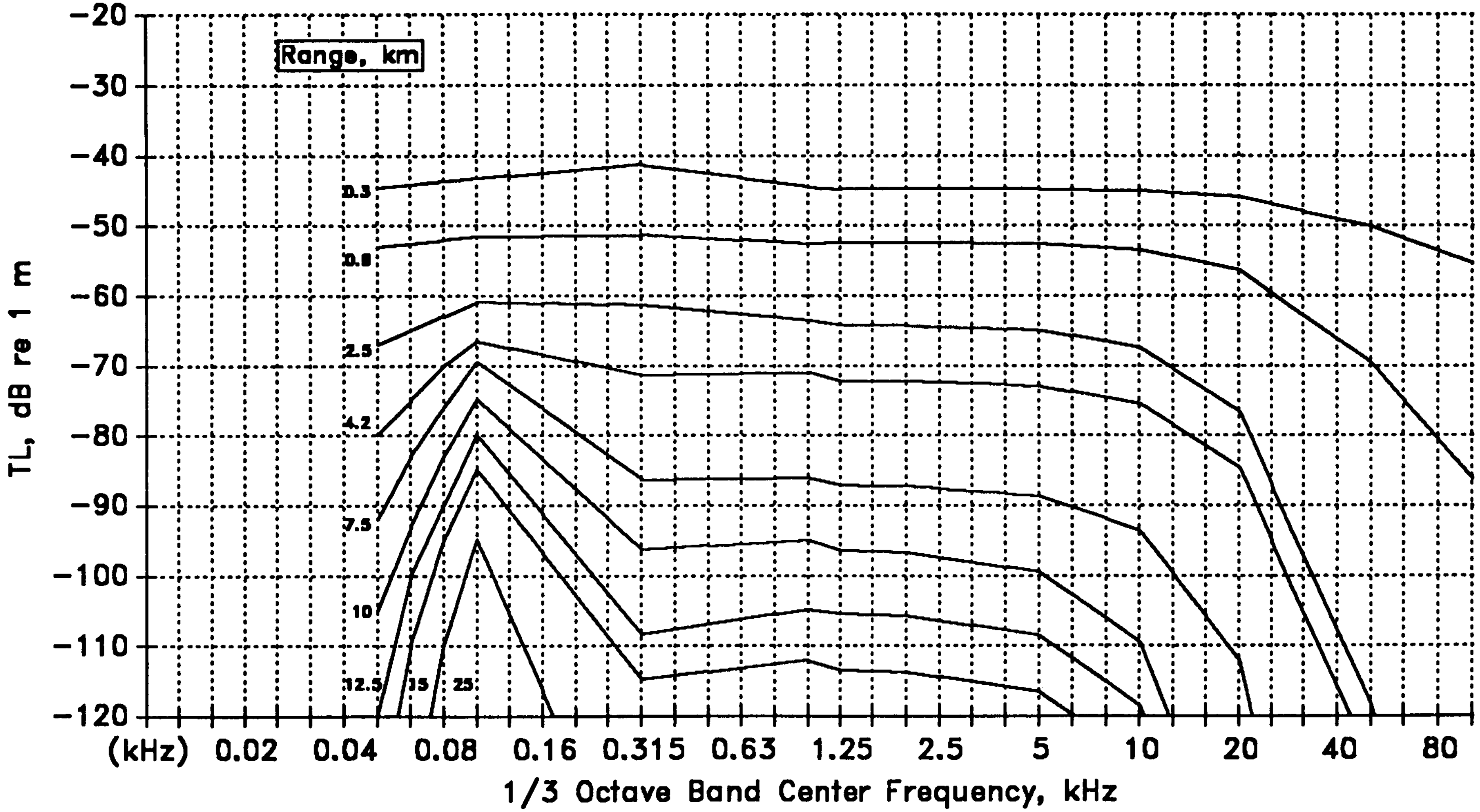
D. TRANSMISSION LOSS SPECTRA AT SANDPIPER SITE, BEAUFORT SEA
Miles et al. 1987 and Weston/Smith Model extrapolations



E. TRANSMISSION LOSS SPECTRA, AIRBORNE SOUND, SANDPIPER SITE, BEAUFORT SEA
Reference Range – 300 m, 0° C, 20% Rel. Humidity

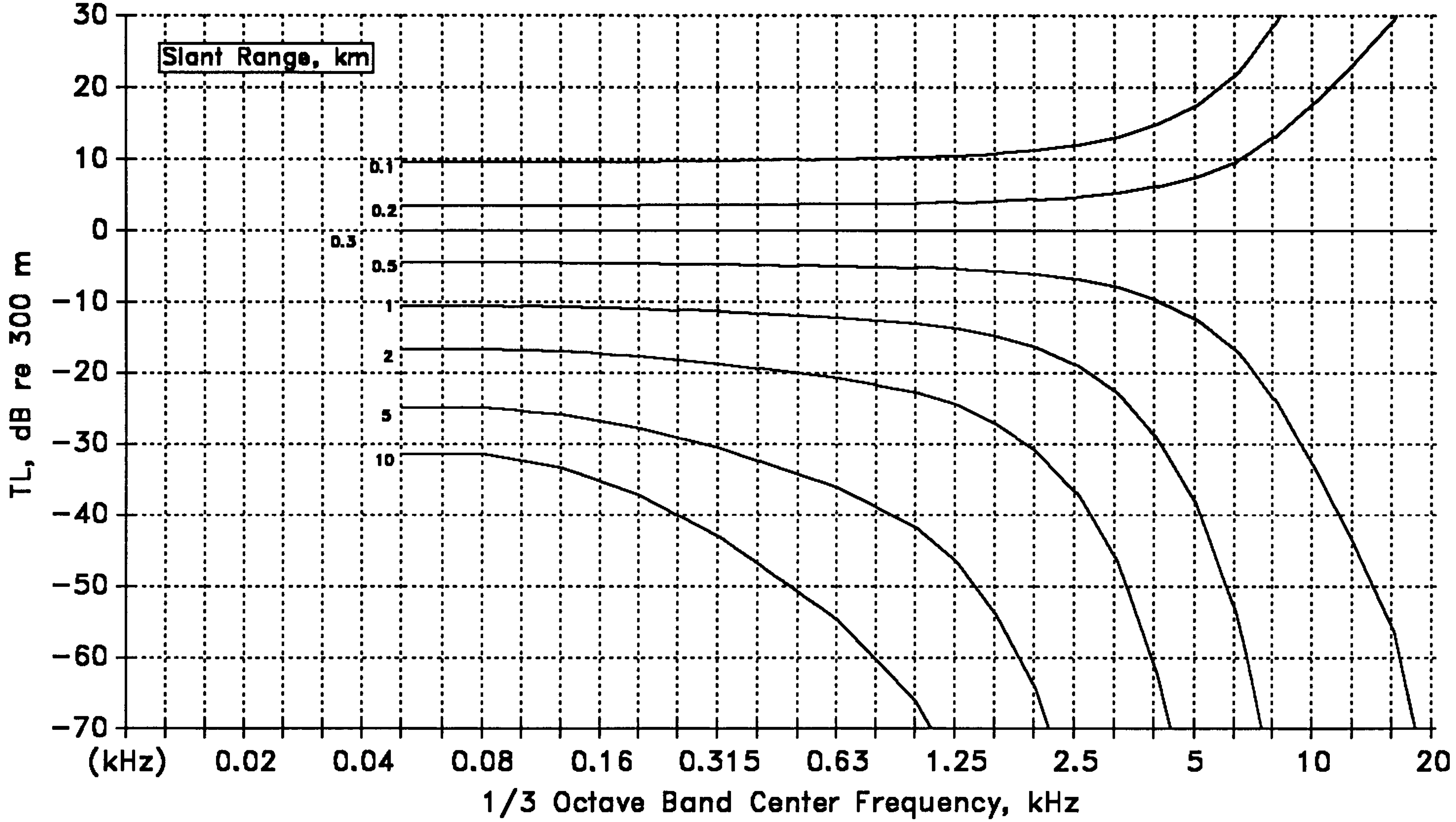


F. TRANSMISSION LOSS SPECTRA, CHIRIKOF BASIN, BERING SEA
Estimated using IFD and Weston/Smith Models, Avg. Depth – 30 m

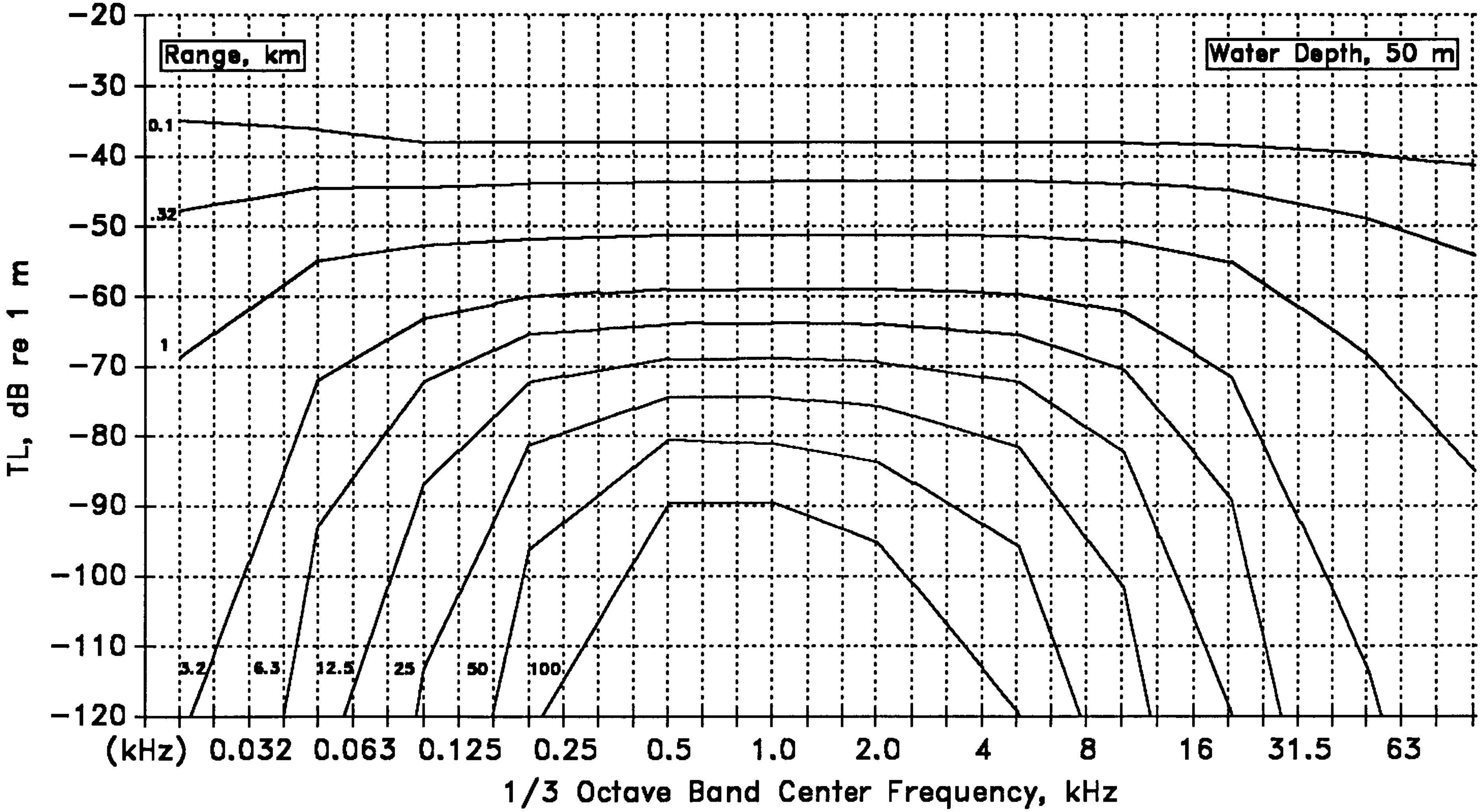


G. TRANSMISSION LOSS SPECTRA, AIRBORNE SOUND, BERING SEA BEACH

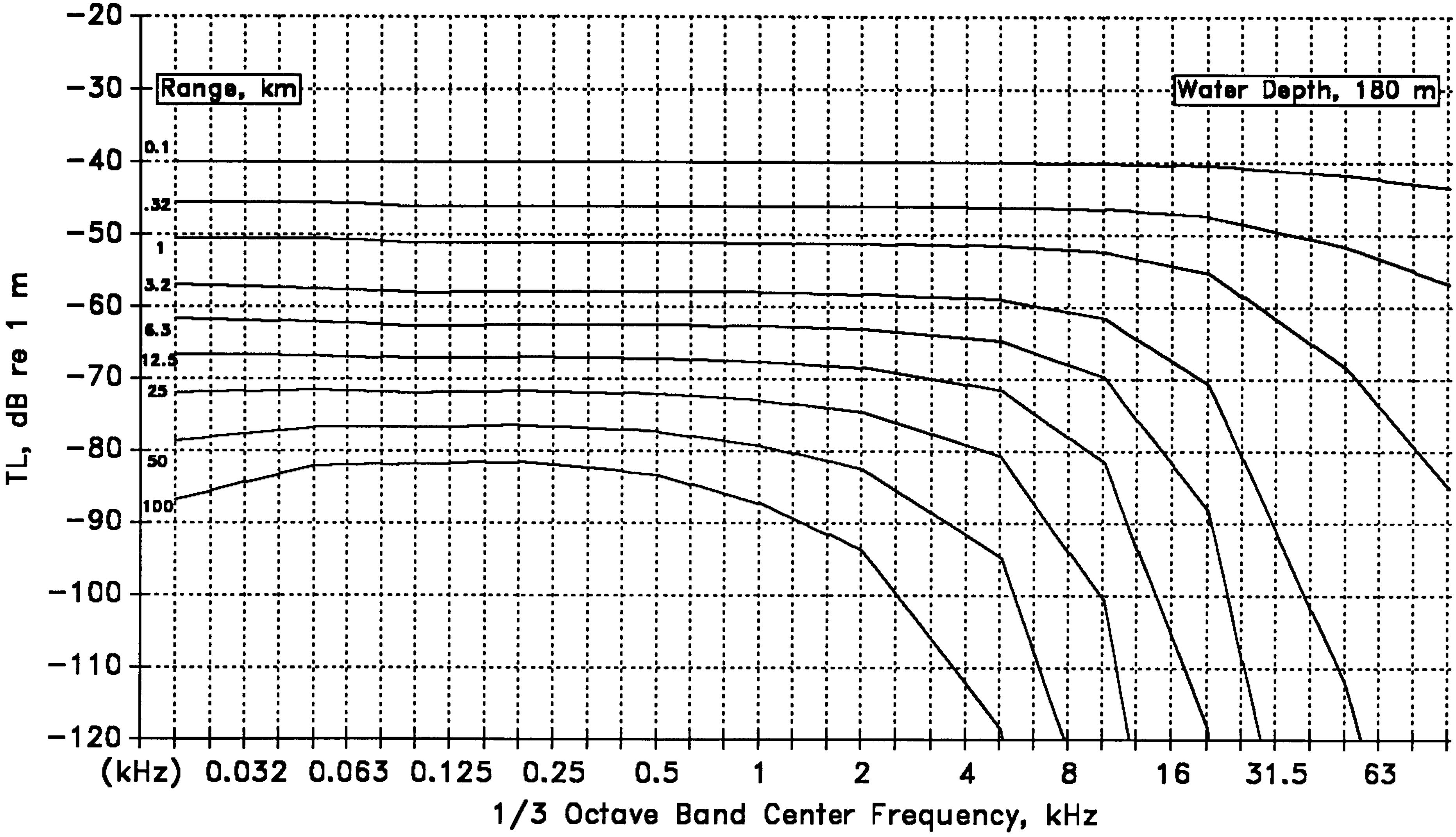
Reference Range – 300 m, 10° C, 80% Rel. Humidity



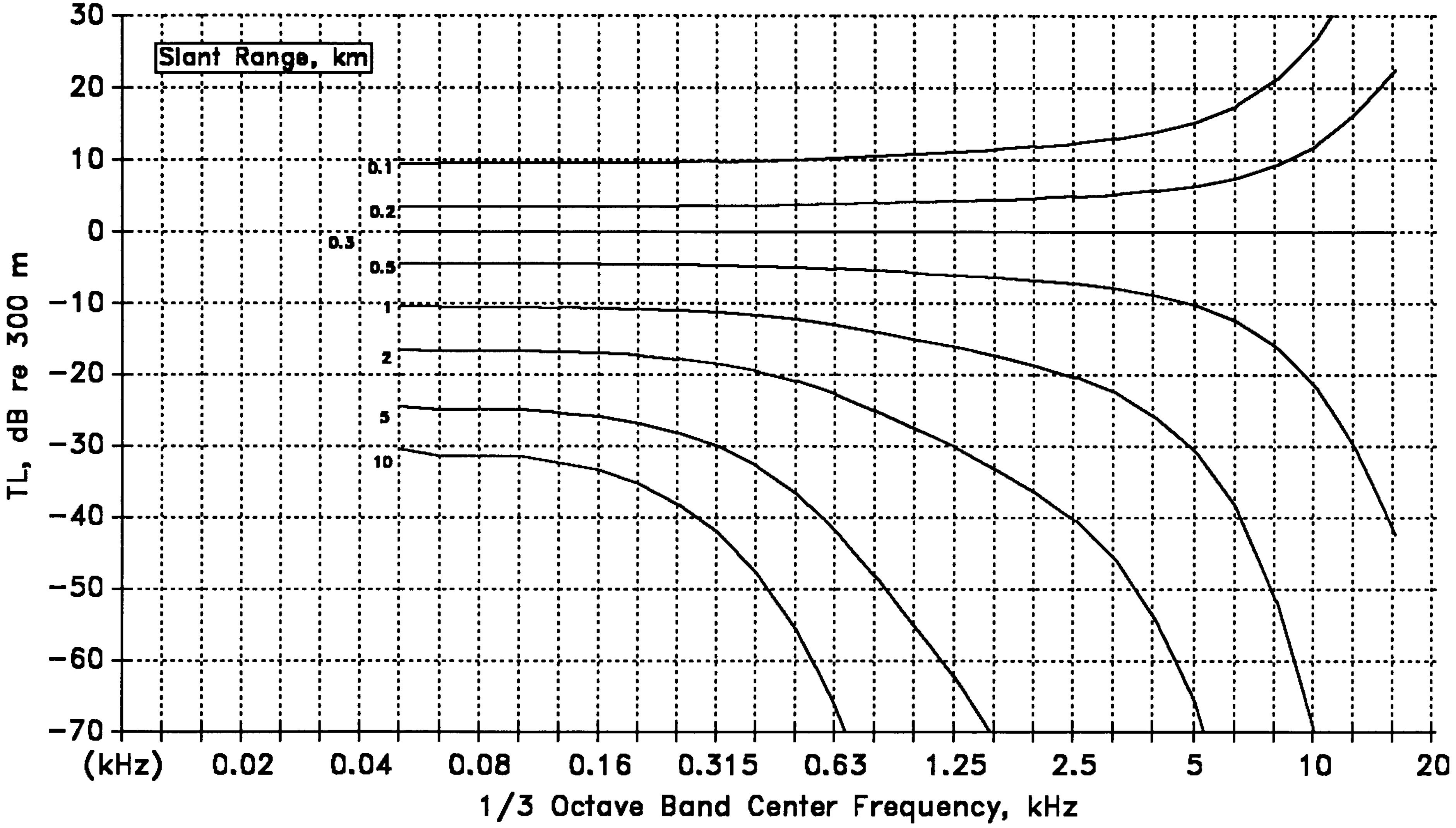
H. TRANSMISSION LOSS SPECTRA, CALIFORNIA COAST NEAR CARMEL
Malme et al 1986 and Weston/Smith Model Extrapolations



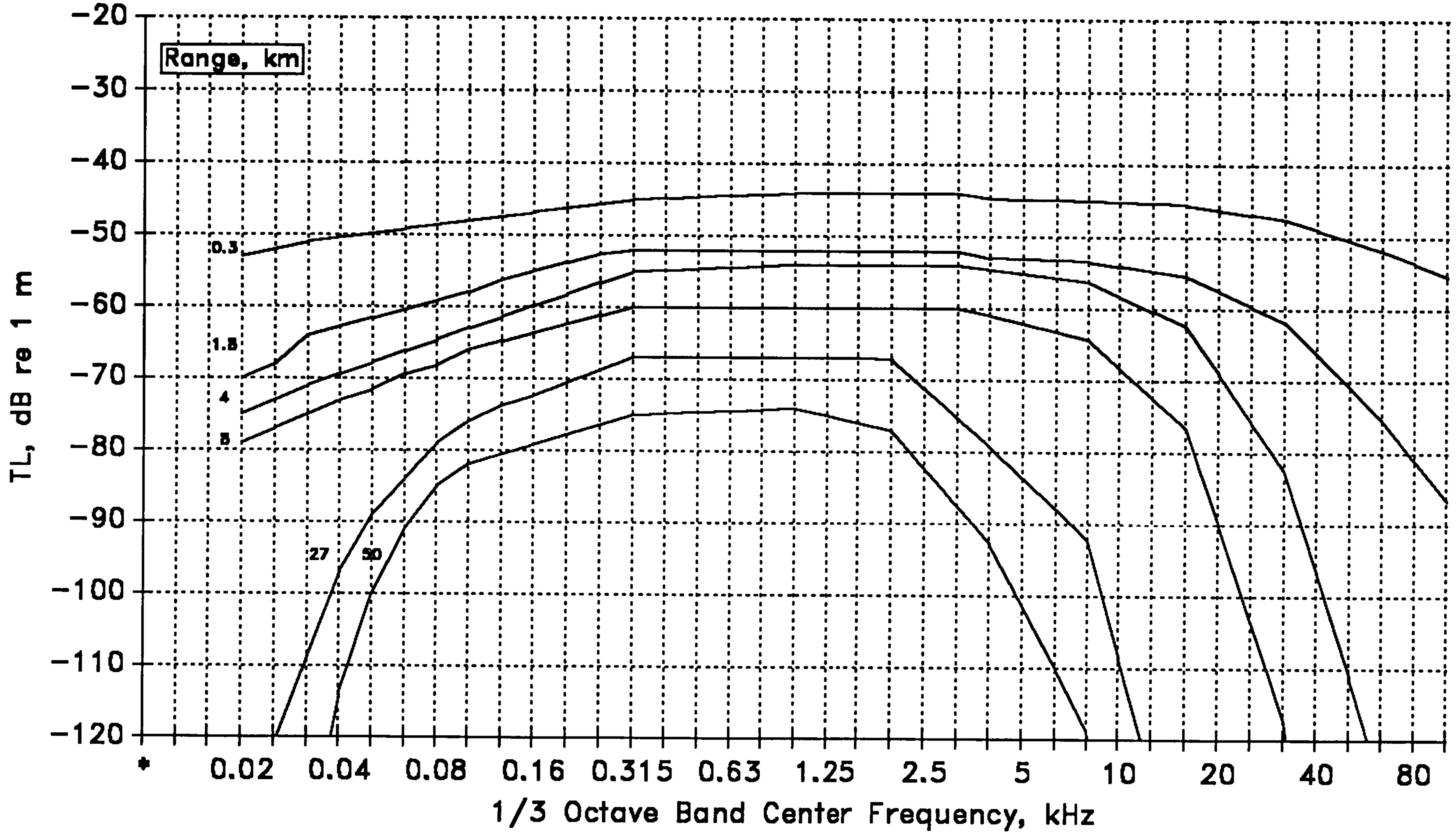
I. TRANSMISSION LOSS SPECTRA, CALIFORNIA COASTAL SHELF EDGE
Weston/Smith Model Estimates



J. TRANSMISSION LOSS SPECTRA, AIRBORNE SOUND, CALIFORNIA BEACH
Reference Range – 300 m, 25° C, 80% Rel. Humidity

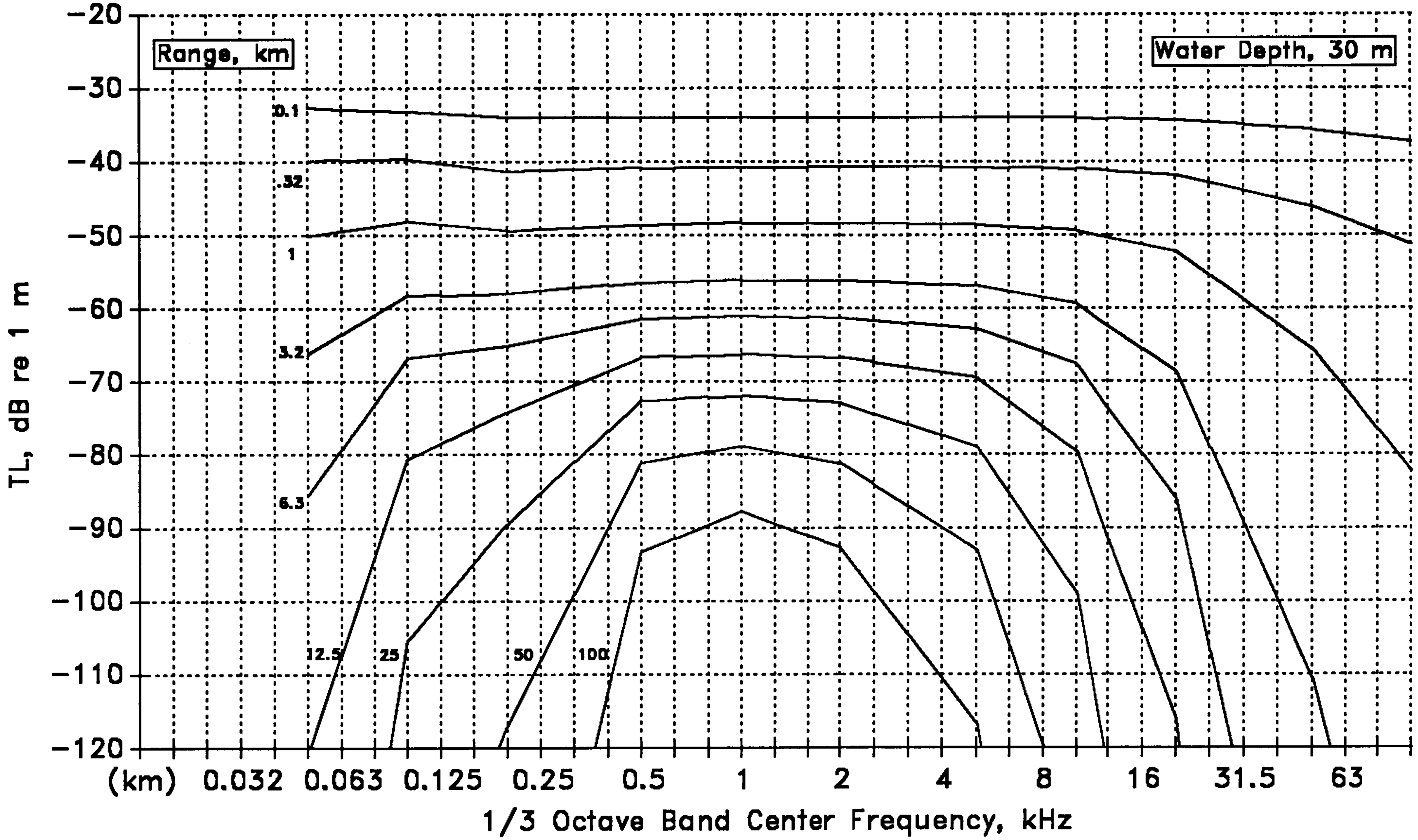


K. TRANSMISSION LOSS SPECTRA, SCOTIAN SHELF REGION
Estimated from IFD and Weston/Smith Model Results, 70 m depth



L.

TRANSMISSION LOSS SPECTRA, FLORIDA WEST COAST
Weston/Smith Model Predictions



INDEX

Page numbers containing tabulated data are shown in *italics*. Page numbers containing graphs are shown in **boldface**.
