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Report No. 6185

OCS Study
MMS 86-0046

Prediction of Drilling Site-Specific Interaction of Industrial Acoustic Stimuli and Endangered Whales: Beaufort Sea (1985)

Contract No. 14-12-0001-30295

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Prepared for:
U.S. Department of the Interior
Minerals Management Service
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PREDICTION OF DRILLING SITE-SPECIFIC INTERACTION OF INDUSTRIAL ACOUSTIC STIMULI AND ENDANGERED WHALES: BEAUFORT SEA (1985)

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October 1986

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ABSTRACT

The underwater acoustic environment and sound propagation characteristics associated with five offshore oil drilling industry sites in the Alaskan Beaufort Sea were measured during the mid-August to mid-September 1985 period, completing the first year field effort of a two-year program. Similar information on a sixth site had to be estimated since heavy sea-ice prevented research vessel access. Some of these sites were active. Analysis of the field data has resulted in a compilation of ambient noise statistics, noise signatures of sources of sound associated with oil industry activities at those sites, and a quantitative ability to predict noise levels from oil industry activities as a function of distance from the sound source. Previous research by LGL (environmental research associates) and BBN Laboratories regarding behavioral responses of bowhead whales (<u>Balaena</u> <u>mysticetus</u>) and gray whales (<u>Eschrichtius</u> <u>robustus</u>) to acoustic stimuli have been used in this study as well. The synthesis of the new acoustic data with prior information regarding whale behavioral response to underwater sound has permitted the derivation of site-specific estimates of zones of influence relating whale response to industrial noise. The results of this first year effort are provided in this report. The summer 1986 field measurement research will be used to supplement these results.

The sound propagation findings to date indicate that there is very efficient cylindrical spreading (10 log Range) of acoustic energy at least to ranges of about 5 km near the Alaskan Beaufort sites studied. A 10 log R algorithm is used to extrapolate losses beyond the 5 km measurement range but must be verified by experiment in 1986. Two acoustic criteria have been used in relating industrial noise levels to whale behavioral response; predicted signal-to-noise ratio (S:N) in the 1/3-octave band of highest S:N and absolute received sound pressure level in the effective bandwidth of the signal. Since it is not known at the present time which criterion is more important in eliciting response in bowhead and gray whales, both have been considered in developing behavioral response predictions. However, major emphasis has been on signal-to-noise ratio in the bowhead response discussions and absolute received level has received the most attention in gray whale response.

Site-specific zones of potential responsiveness of bowhead whales (for a signal-to-noise ratio at the whale of 20 dB) are estimated to extend to 6-22 km from a dredge noise source, 11-30 km for tug noise, 6-19 km for drillship noise and 0.1 to 1.7 km for man-made gravel island drilling noise. Only a fraction of the bowhead whales are expected to respond in the 20 dB signal-to-noise situation.

However, roughly half of bowheads have been observed to respond (approximate avoidance probability of 0.5) when the signal-to-noise ratio is 30 dB. At the sites investigated, 30 dB signal-to-noise ratios are expected to occur at distances of 1.5 to 7.4 km for dredge noise, 2.7 to 13 km for tug noise, 1.3 to 6.5 km for drillship noise and 0.02 to 0.7 km for island drilling noise.

Similar zones of responsiveness predictions for gray whale response to drillship noise in the Beaufort Sea are presented for signal-to-noise ratios of 20 and 30 dB.

With regard to using the absolute received level criterion associated with drillship operation at the selected sites, zones of responsiveness of gray whales vary in range from the sites from 1.9 to 16 km for a received level of 110 dB re 1 μPa and 0.1 probability of avoidance and 0.6 to 6.0 km for 120 dB received level (0.5 probability of avoidance). Bowhead whale zones of responsiveness on the other hand vary from 1.1 to 11 km and 0.2 to 2.9 km for received levels of 110 dB and 120 dB, respectively.

ACKNOWLEDGEMENTS

The research represented by this report was performed for and with support from the Alaska OCS Office of the U.S. Department of the Interior, Minerals Management Service, in Anchorage, Alaska. The support and interest in all aspects of the project provided by Dr. Jerome Montague, Contracting Officer's Technical Representative, of that office are particularly appreciated. The following groups and individuals were also very important to the completion of the first year effort under this contract.

The cooperation extended to BBN by the operators at the sites visited in the Alaskan Beaufort Sea was very important: Shell (Sandpiper and Corona), Unocal (Hammerhead), Exxon (Orion), and Amoco (Erik and Belcher) all provided helpful assistance during the field measurement portion of the project.

Dr. Charles Greene of Greeneridge Sciences, Inc., provided BBN with copies of selected portions of magnetic tape recordings which he acquired at Hammerhead and Sandpiper during the 1985 field season. The availability of those data, the release of which was approved by Unocal, Shell and LGL, was particularly important since heavy ice conditions during the BBN field measurement period prevented BBN from acquiring the needed data. Dr. Greene also contributed historical acoustic data from measurements in the Canadian Beaufort, including some unpublished data, which were reworked by LGL to provide additional 1/3 octave band information for Appendix B. Dr. Greene's interest and assistance to the project in these ways were very helpful and important to the first phase of this two-year project.

The availability of the M.V. JUDY ANN on short notice as research vessel for this project through Oceanic Research Services, Inc., of Ester, Alaska, and the operation of that vessel by Mr. Geoffrey Orth and Mr. Richard Schuerger under difficult weather and ice conditions were essential to the successful performance of the 1985 field measurement effort.

At LGL Ltd., environmental research associates, Ms. M.A. McLaren assisted Dr. Richardson in compiling data on whale response. Her help is greatly appreciated.

The following BBN staff members assisted the authors in several important ways in contributing to the success of the field portion of this project. Their enthusiasm and dedication were essential to the performance of that work:

Dr. Daniel L. Nelson, Senior Scientist

Mr. Jeffrey Doughty, Engineer

Mr. Arthur J. Margerison, Engineering Assistant

Dr. Preston W. Smith, Jr., provided important assistance in application of the Weston shallow water acoustic transmission loss model to Beaufort Sea conditions. The word processing talents and patience demonstrated by Ms. Judy Russo in the preparation of the manuscript of this report are especially appreciated.

PROJECT ORGANIZATION

While the authors of this report have been responsible for specific sections, they have worked closely together in the review of the full document to ensure continuity of technical content. The scientists and their individual report and project responsibilities are:

Mr. Paul R. Miles:	Program Manager and Project Scientist, prepared the Executive Summary, Introduction and Objectives, Methods and Description sections and worked jointly with the other authors on the Conclusions and Recommendations sections. He has been responsible for the overall management and coordination of the project and this report and has participated in field measurements.
Mr. Charles I. Malme:	Assistant Project Scientist and Field Measurement Manager, co-authored the section regarding industrial noise measurements and gray whale behavior and prepared the section on acoustic models and the discussions of gray whale response to acoustic stimuli. He organized and directed the field measurement effort as well.
Mr. George W. Shepard:	Assistant Project Scientist and Data Analysis Manager, coordinated and performed the necessary analysis of the field data, prepared the ambient noise section and co-authored the industrial noise chapter. He also was a key member of the field measurement task team.
Dr. W. John Richardson:	LGL Ltd., environmental research associates, was contracted by BBN to perform the analysis required to synthesize data on bowhead whale response to acoustic stimuli and to develop "zone of influence" projections based on the acoustic environmental data obtained by BBN.

	Dr. Richardson authored the sections on zones of influence (Sect. 2.3, 3.4, App. A) and Appendix B, a data summary of bowhead responses to industrial noise.
Mr. James E. Bird:	An independent consultant to this project, Mr. Bird has applied his specialized skills to the literature search and review aspects of the project. He prepared Appendix C, which is a review of selected literature associated with bowhead whale research in the Beaufort Sea.

In addition to these five team members, whale behavioral research scientists Dr. Peter Tyack and Dr. Christopher Clark have provided assistance in the form of review of the manuscript of this report.

Other project staff members who have contributed to the project are:

Dr. Daniel L. Nelson:	Senior Scientist, assisted in environmental acoustics measurements and provided technical support.
Mr. Jeffrey Doughty:	Engineer, assisted in field measurements.
Mr. Arthur Margerison:	Engineering Assistant, assisted in field measurements.

EXECUTIVE SUMMARY

This report presents the results of the first year of research applied in a two-year program concerning behavioral responses of endangered whales to industrial noise sources associated with offshore oil exploration in the Alaskan Beaufort Sea. The basic purpose of the research is to derive, compile and apply the data and support information needed to develop an understanding of the distances between a sound source and whale when one may expect industrial noise to be detected by whales as evidenced by elicitation of some behavioral response. The endangered whales of concern to this project are the bowhead whale (Balaena mysticetus) and gray whale (Eschrichtius robustus). Field work was required to develop a quantitative description of the acoustic environment, including definition of the sound propagation characteristics, at planned and active offshore oil drilling sites. The first increment of that work was performed from 16 August to 19 September 1985. Other essential ingredients in the research reported here are historical data regarding responses of bowhead whales and gray whales to industrial underwater noise, derived in recent years by LGL Ltd. and BBN Laboratories, respectively, and statistically based analytical techniques.

Five offshore drilling sites in the Alaskan Beaufort Sea were selected by Minerals Management Service to be studied:

- Orion, where the Concrete Island Drilling System (CIDS) was operated by Exxon in Harrison Bay; the CIDS was at the Orion site during our field period but not in full operation,
- Sandpiper Island, a man-made gravel island used as a base for standard drilling equipment, operated by Shell near Prudhoe Bay
- Hammerhead Prospect, drillship CANMAR EXPLORER II, north of Flaxman Island; Union Oil of California (Unocal)
- Erik and Belcher Prospects, drilling expected to be performed by drilling vessel KULLUK, north and east of Barter Island, respectively; Amoco.

In addition, Shell's Corona prospect was visited; CANMAR EXPLORER II was also scheduled to operate at Corona. Similarly, some acoustic data were acquired at Northstar and Seal Islands, two man-made gravel islands near Sandpiper, to supplement the description of the acoustic environment of the region.

The environmental conditions existing during the field measurement work were dominated by drifting sea ice and, at times, heavy winds, which combined to permit acoustic measurements during only 15 days of the contracted 35 day field period. The unusually heavy ice conditions in 1985 prevented the acquisition of any data at Hammerhead and hampered data acquisition at other sites. The acoustic data acquired by us have been supplemented with copies of 1985 data tapes obtained by Greeneridge Sciences, Inc., providing acoustic signatures from drilling at Sandpiper Island and drillship CANMAR EXPLORER II at Hammerhead.

Ambient or natural background underwater noise data were acquired at the above sites (except Hammerhead) during 5-15 minute periods at random intervals during the day. The resulting recordings were analyzed to provide both narrowband and one-third octave band spectra. Cumulative distribution functions were derived to estimate the 5th, 50th and 95th percentile statistical levels of ambient noise experienced at each site. The resulting data presented in this report are critical to the development of signal-to-noise ratio statistics which are used in predicting the behavioral responses of whales. The acoustic environmental characteristics of Hammerhead have been estimated based on measurements at similar sites, pending actual measurements in 1986.

The radiated noise or underwater sound signatures of two tugs working together at Sandpiper Island, one tug working with a dredge barge at Erik, a clam-shell dredge at Erik, EXPLORER II drillship operations at Hammerhead and gravel island drilling at Sandpiper were all acquired and analyzed. Both narrowband and one-third octave band analyses were performed.

Measurement of the sound propagation or transmission loss (TL) characteristics from each site toward the expected location of whales was performed, usually using a controlled sound source and measuring received sound level as a function of distance from that source. A second method used was to measure noise levels versus distance from some continuous industrial noise source associated with a particular site. These methods are range limited to a maximum distance of about 5 km. To estimate propagation loss rates over longer ranges, published data on received levels of seismic survey pulses in a typical Alaskan Beaufort Sea area were considered. Acoustic transmission loss is very site-specific and hence there is a need to measure the TL characteristics of each site. These data are the most critical element in the description of the acoustic environment of migrating or feeding whales since only a quantitative description of the site-specific TL will permit valid predictions of industrial noise levels at expected whale locations. The measurements have demonstrated that a cylindrical spreading law applies, at least over short ranges, at each of the sites visited. This law describes a loss of acoustic energy according to 10 log (range) from the source. Variations in ocean bottom and surface conditions at each site, e.g. bottom composition, ice cover, wave conditions, cause site-specific differences in the TL algorithms.

Sub-bottom conditions also influence sound propagation. There is strong evidence that the presence of sub-sea permafrost and overconsolidated clay sediments contribute in an important way to unusually efficient sound transmission over the continental shelf of the Beaufort Sea. In fact, comparison of the TL characteristics in the Beaufort with those measured in similar water depths in more temperate ocean areas demonstrates that the Beaufort TL characteristics are unusually efficient; TL in other areas frequently is found to vary as 15 log R and sometimes as high as 25 log R.

It must be emphasized that the 1985 TL data are based on short range (5 km) experiments. Extrapolation of the 10 log R algorithm to distances of 20-30 km can only be considered a preliminary estimate and must be substantiated through long-range experiments at each site in 1986.

The ambient noise statistics, industrial noise data and acoustic transmission loss data were combined in analyses performed by LGL Ltd. to estimate those distances from the sound sources when bowhead whales could be expected to detect and/or respond to the presence of industrial sounds. Zone of influence tables and figures are presented which relate predicted industrial sound levels at particular sites to historical data regarding whale response to acoustic stimuli. Similarly, BBN has summarized from prior yet similar research conducted in California and the Bering Sea investigating the behavioral responses migrating and feeding gray whales to industrial underwater acoustic stimuli, and has discussed those data as they may apply to gray whale response in the Beaufort Sea.

Two acoustic criteria have been used in relating industrial noise levels to whale behavioral response; predicted signal-to-noise ratio (S:N) in the 1/3-octave band of highest S:N, and absolute received sound pressure level in the effective bandwidth of the signal. Since it is not known at the present time which criterion is more important in eliciting response in bowhead and gray whales, both have been considered in developing behavioral response predictions. The analysis applied in this research has assumed that either one or both of these two criteria represent the basic causal acoustic measure(s) regarding behavioral response. Less emphasis has been given to other factors such as visual cues. For instance, both the previous bowhead and gray whale sound playback research discussed in this report considered visual cues as a possible influencing factor in the experimental protocol through observing whale behavior during vessel presence but without sound playback or seismic sound radiation. However, major emphasis has been on signal-to-noise ratio in the bowhead response discussions and absolute received level has received the most attention in gray whale response studies.

With regard to the bowhead whale, which commonly inhabits the coastal regions of the Beaufort Sea in the summer (the gray whale is rarely seen), LGL has estimated that depending on the specific site of interest, the zones of potential responsiveness (distance between sound source and whale) typically have a radius of:

Dredge:	1.5 to 7.5 km
Tug:	2.5 to 13 km
Drillship:	1.3 to 6.5 km
Artificial Island Drilling:	0.02 to 0.7 km.

These radii are based on the observation that about half of the bowhead whales show avoidance responses (probability of avoidance of about 0.5) to the onset of industrial sounds which have a 30 dB S:N. A small proportion of the bowheads react when the S:N ratio is about 20 dB, which would occur at greater ranges than those summarized above. On the other hand, some bowheads apparently tolerate S:N ratios as high as 40 dB; for those individuals the zone of responsiveness is smaller.

Predictions of gray whale zones of responsiveness based on S:N ratio are quite similar to those noted above for bowheads. The following zones of responsiveness to drillship noise are estimated for gray whales in the Beaufort Sea. The estimates have been calculated for 0.1 and 0.5 probability of avoidance corresponding to received levels of 110 dB and 120 dB re 1 μPa, respectively. The radius of the zone of responsiveness is site-specific, as is the case for use of the S:N ratio criterion for zone estimates.

Drillship Noise:	110 dB re 1 μPa	120 dB re 1 μPa
Probability of Avoidance:	0.1	0.5
	Est. Range (Zone of Responsiveness)	
Belcher	4.1 km	0.9
Erik	7.7	2.0
Hammerhead	8.0	1.8
Sandpiper	15.6	6.0
Orion	10.2	3.7

Bowhead whale zones of responsiveness estimated on the basis of these same absolute received levels of drillship noise are 1.1 to 11 km for 110 dB and 0.2 to 2.9 km for 120 dB, respectively, depending on the specific drillsite.

All of the details of the findings of this first year research effort covering the 1985 measurement season are contained in the body of this report.

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1. INTRODUCTION AND OBJECTIVES

The continuing exploration and development activities regarding oil and gas resources in the Alaskan Beaufort Sea, Outer Continental Shelf (OCS) region, carries with it the need for investigations relating to potential environmental impact. Included in that issue is a need to quantify the extent to which industrial acoustic stimuli may influence the behavior of endangered whales. The bowhead whale (Balaena mysticetus), in particular, frequents the Beaufort Sea from March into October (e.g. Braham et al, 1980, Ljungblad et al, 1985a), including areas of oil and gas exploration and development. The gray whale (Eschrichtius robustus) also feeds in the Arctic during summer months, although they are not sighted frequently in the Beaufort (Braham, 1984; Marquette and Braham, 1982). Concern regarding potential environmental impact has centered on these two endangered species. In the process of developing a quantitative understanding of whale behavioral response to acoustic stimuli, it is necessary to quantify the underwater ambient noise characteristics, the acoustic signatures of various industrial activities, and the underwater sound propagation characteristics of the region (which, more often than not, are site-specific) in order to predict sound levels at potential whale locations. The resulting data must be combined with the results of research into the behavioral response of whales to acoustic stimuli obtained through extensive observation of undisturbed behavior under natural conditions, during disturbed conditions from uncontrolled "intrusions" by industrial activity, and during controlled experiments. Statistical analysis of the resulting data provides the needed understanding of the behavioral response of whales to acoustic stimuli as a function of such variables as ambient background noise and the frequency content and level of the sounds (which vary with distance between the sound source and whale).

Accordingly, Minerals Management Service (MMS) contracted BBN Laboratories Incorporated and their subcontractor, LGL Ltd., (environmental research associates), to perform a two-year research project which will develop the needed quantitative understanding of whale behavioral response to acoustic stimuli at site-specific sites in the Alaskan Beaufort Sea. Required tasks under the project includes measurement and modeling of the acoustic environment at selected sites on the Alaskan Beaufort Sea OCS during the 1985 and 1986 summer/fall seasons by BBN and the use of the resulting data by LGL to develop an understanding of whale behavioral response. Field data and analytical experience gained by BBN and LGL in previous research projects regarding environmental acoustics and the responses of bowhead, gray and humpback whales to controlled acoustic stimuli (Malme et al., 1983, 1984, 1985, 1986; Richardson, 1985; Richardson, et al., 1985a,b,c) are key elements in the design and performance of this project. The following purpose and objectives of this project are quoted from the contract.

Purpose

The purpose of this project is "to provide information necessary to predict the range at which bowhead and gray whale behavior is likely to be influenced by sounds produced at specific offshore drilling sites."

Objectives

The objectives are "to develop and implement a research plan in the Beaufort Sea lease sale area to:

A. Acquire measurements of the acoustic environment prior to the onset of industrial operation.

B. Measure transmission loss characteristics of sounds associated with activities of each offshore drilling site concurrent with the major period of exploration (in 1985 and 1986) resulting from Diapir Field Lease Sales 71 and 87.

C. Monitor the characteristics of sounds associated with offshore drilling sites throughout the study period. As appropriate for the specific site, marine geophysical sounds will also be monitored as a secondary focus.

D. Synthesize, through mathematical/statistical techniques, the results of objectives A-C with data and/or simple models of bowhead and gray whale response to sounds associated with offshore drilling activities in order to develop site-specific "zone of detection/potential influence" projections.

E. Coordinate with ongoing endangered species studies in the Beaufort Sea area and maintain appropriate liaison with local residents and government agencies.

F. Prepare appropriate tabular or graphic results, synthesize with other recent literature and report findings."

This report summarizes the measurements made during the 1985 field season (16 August-19 September) and presents the results of the analyses performed on the field data, the synthesis of whale response in the context of the 1985 acoustic environment, and the derivation of zones of potential influence on whales. MMS requested that data be acquired at five sites within the specified lease sale area:

- Hammerhead (Unocal),
- Sandpiper (Shell),
- Orion (Exxon),
- Erik (Amoco),
- Belcher (Amoco).

One additional site was visited, Corona (Shell). Since a limited amount of industrial noise data were obtained at these sites within the contracted field period (BBN could not reach Hammerhead during drilling operations due to intervening pack ice, for instance), some noise data were obtained for Hammerhead and Sandpiper from Greeneridge Sciences Inc. through MMS, LGL, Unocal and Shell. Greeneridge (Dr. Charles Greene) acquired acoustic data for other purposes at Hammerhead and at Sandpiper (which conducted drilling operations before or after BBN was in the field) and provided those data to this project. Detailed results from the Greeneridge studies are given by McLaren, et al. (1986) and Johnson et al. (1986). More detail on site locations and site activity will be given in Sec. 2. The 1985 summer season in the Alaskan Beaufort Sea was dominated by unusually heavy drifting sea-ice conditions. Since our vessel, the M.V. JUDY ANN operated by Oceanic Research Services, could only work in up to 2/10 ice cover conditions, the fluctuating insurgence of ice and heavy wind at the sites resulted in acquisition of approximately half of the desired data.

As noted in the stated purpose of this research project, the potential impact of industrial acoustic stimuli on gray whales in the Alaskan Beaufort Sea must be evaluated. While the dominant endangered whale species in that area is the bowhead, gray whales are observed occasionally in the western regions of the Beaufort Sea and in the eastern Chukchi Sea (Braham 1984, Ljungblad et al. 1985a, Marquette and Braham, 1982). Some have also been seen at times near Prudhoe Bay, and near Tuktoyaktuk in the Northwest

Territories (Rugh and Fraker, 1981; Richardson, 1985). The primary gray whale summer feeding grounds are in the Northern Bering Sea and Southern Chukchi Sea regions (Braham, 1984). All of these areas are candidates for oil exploration and development.

BBN has performed research studies (Malme, et al. 1984, 1985, 1986) regarding behavioral responses of migrating and feeding gray whales to controlled acoustic stimuli (playback of underwater sounds associated with oil and gas exploration and development). This report will discuss the responses of migrating gray whales to acoustic stimuli in the Beaufort Sea environment by applying the results of BBN studies of migrating gray whales in California and feeding gray whales in the Northern Bering Sea.

Section 2 of this report provides details of the study area and methods used to acquire the data needed to describe the acoustic environment of the selected sites and to perform the behavioral response analysis. The results of the 1985 portion of this project are presented in Sec. 3 including:

- a statistical description of the short-term ambient noise environment,
- a presentation of the underwater industrial sounds measured at various sites,
- sound propagation characteristics of each site (acoustic models), and
- synthesis of whale response to sounds including derivation of zones of potential influence.

Conclusions and recommendations from this initial 1985 phase of the research effort are given in Secs. 4 and 5, followed by a listing of cited literature. Appendix A provides a summary of sound propagation (range) for various combinations of industrial noise types, signal-to-noise ratio, absolute received level, and bottom slope. Appendix B summarizes previous data on observed and measured endangered whale responses to industrial noise, and Appendix C presents a review of selected literature, regarding bowhead whale research in the Beaufort Sea.

2. DESCRIPTION OF THE STUDY AREA AND METHODS

2.1 The Study Area and Selected Sites

The study area for this project, as noted previously, is the continental shelf of the Alaskan Beaufort Sea. The specific sites to be studied were selected by Minerals Management Service. Figure 1 gives the layout of the coast from Point Barrow in the west to Demarcation Bay at the U.S./Canadian border to the east with the six sites located from Harrison Bay to the Barter Island region and Table 1 provides details of the site locations, water depths, operators and general comments. The field measurement period was 16 August-19 September 1985. Expected industrial operations on several of the sites were not begun during the field period, in part because of seasonal drilling restrictions designed to prevent drilling during the bowhead migration season. The Concrete Island Drilling System (CIDS), the GLOMAR BEAUFORT SEA I, did not reach the Orion site (coordinates shown in the table) until late in August and drilling operations there did not commence until after the BBN field period. Drilling at Sandpiper Island was curtailed during part of the bowhead migration period. The drillship CANMAR EXPLORER II was forced off the drillsite at Hammerhead by ice before the BBN vessel (JUDY ANN) could reach the site and did not resume operations until 19 September, when BBN had to stop measurement work. The circular drillship KULLUK did not occupy either Erik or Belcher sites as scheduled. A dredge (ARGILOPOTES) and tug (ARCTIC FOX) were working at Erik at the time of acoustic measurements by BBN, however.

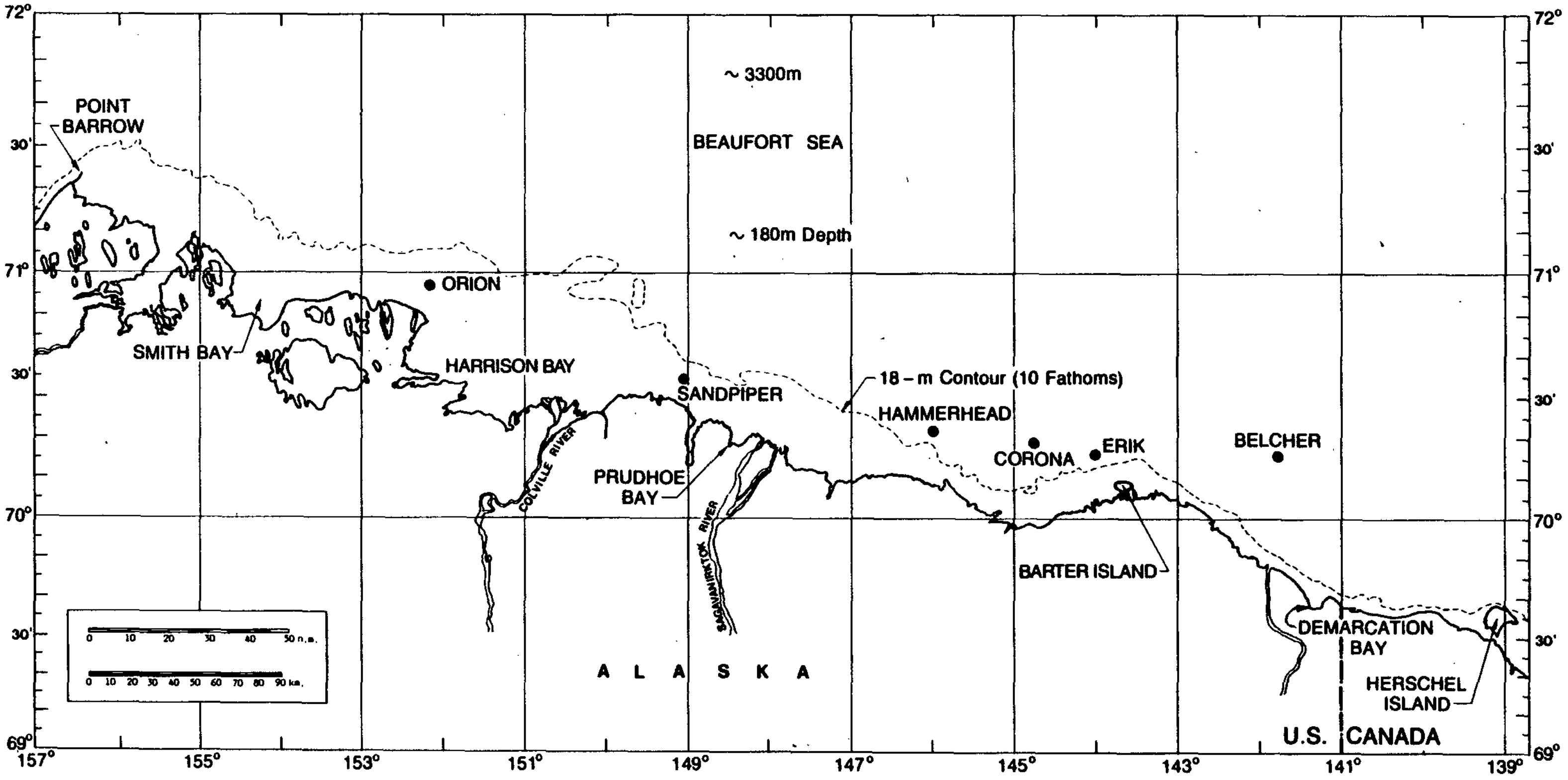

FIGURE 1. SELECTED MEASUREMENT SITES IN THE ALASKAN BEAUFORT SEA.

TABLE 1. GENERAL DETAILS OF SELECTED MEASUREMENT SITES IN THE ALASKAN BEAUFORT SEA.

Site	Area	Approx. Coordinates	Approx. Water Depth meters	Operator	Comments
Orion	Harrison Bay	70°57.41'N 152°03.78'W	14	Exxon	Glomar Beaufort Sea I Concrete Island Drilling System (CIDS)
Sandpiper	North of Pole Is.	70°35.08'N 149°05.81'W	15	Shell	Artificial gravel island
Hammerhead	North of Flaxman Is.	70°21.88'N 146°01.47'W	28	Unocal	CANMAR EXPLORER II (drillship not on site during BBN measurements)
Erik	N. of Barter Is.	70°16.6'N 143°58.67'W	40	Amoco	Dredge and Tug (site moved 4 n.m. So. from orig. MMS location)
Belcher	East of Barter Is.	70°16.4'N 141°47.0'W	55	Amoco	No operations on site
Corona	N. of Camden Bay	70°18.88'N 144°45.53'W	35	Shell	CANMAR EXPLORER II (drillship not on site during BBN measurements; site not on original MMS list)

2.1.1 Migration habits

It is important to summarize briefly the migration habits of the bowhead in relation to the study area and the selected operational sites. Figure 2 includes a general indication of the routes and/or corridors for spring and fall migration. The spring migration route in the March-May period heads eastward from near Point Barrow to 50-90 n.m. offshore following open leads in the ice cover, often categorized as 8/10-10/10 conditions. Most of the migration route is in deep water north of the continental shelf edge. Ljungblad (1985a) and Braham et al. (1980) provide ample evidence of the regularity of the spring migration route. Swimming speeds are generally between 3-8 km/h (Carroll and Smithhisler, 1980) and behavior consists primarily of traveling with some social activity once the whales leave the Barrow area. Ljungblad distinguishes between the specific migration corridor and the broad migration route since his year-to-year observations generally show that the "corridor" width may change from year-to-year but that the general route is relatively invariant. The general impression from the results of Ljungblad, Braham and others is that the offshore spring route is probably dictated by ice conditions. Bottom fast ice and floating fast ice extend at least north to the offshore shoal regions on the North Slope. In early spring the 10/10 solid ice cover extends far offshore.

The fall west-bound migration pattern is equally repeatable in all reported observations, with the Ljungblad data-base being the largest (Ljungblad, et al. 1985a). A few bowheads start to leave their traditional summering grounds in the Canadian Beaufort Sea in late August, but many whales do not enter Alaskan waters until late September, depending on the ice conditions. In their westerly movement, the bowheads travel parallel to the coastline, generally offshore of the 10-fathom (18-m) bathymetric

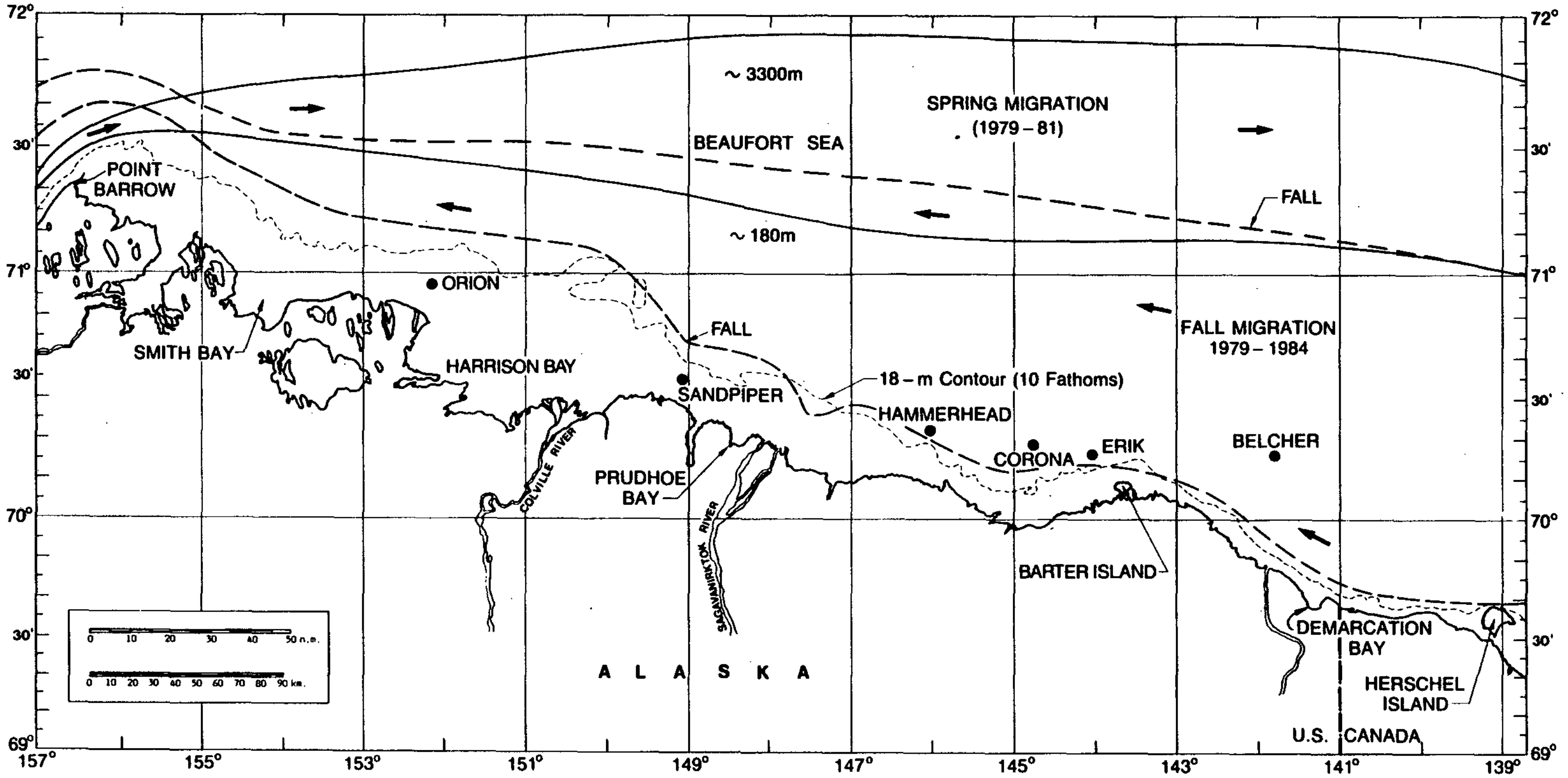

FIGURE 2. APPROXIMATE BOWHEAD WHALE MIGRATION CORRIDORS AND SELECTED DRILLSITES.

contour. The 10-fathom contour also defines the location of shoal regions in-shore of that contour where grounded ice occurs in winter (these regions are called stamukhi zones by Arctic marine geologists). The inshore fall migration route may be related to the need to continue summer feeding wherever possible during the return to the Chukchi and Northern Bering Sea regions for the winter. Ljungblad et al. (1985a, 1985c) report that feeding bowheads tend to migrate within a corridor which is approximately 40-50 km wide with the southern boundary at about the 18-meter contour. Particularly during 1983 he reports that non-feeding fall migrants were observed as much as 120 km offshore, traveling in the southern region of the spring corridor. Their southern boundary was again the 18-m contour. During light ice conditions, the westward migration is slow (~1 km/hr). It is accompanied or interrupted by feeding, and whale calls are frequently heard. In heavy ice years, the fall swimming rate is fast (3 to 5.5 km/hr) and there are few calls.

Drill-site noise is probably undetectable to bowheads in the spring migration corridor which is 60-90 miles away. However the potential exposure to detectable site noise during the fall migration is high. Note that Hammerhead, Corona, Erik and Belcher are all located within the migration corridor. Sandpiper and Orion are 10-15 n.m. (18-28 km) south of the south edge of the fall migration corridor as described by Ljungblad et al. (1985a). Some bowheads have been seen during fall migration in the general areas where oil exploration is underway (Hickie and Davis 1983; Davis et al. 1985; Ljungblad et al. 1985a, 1985c).

2.1.2 Ocean bottom conditions

There are several important variables which influence the propagation characteristics of underwater sound, including water depth, the speed of sound (which in turn varies primarily with water temperature and salinity) and the physical characteristics of the ocean surface (roughness and ice cover) and ocean bottom. There is ample evidence (for instance, see Urick, 1983) that the types and thicknesses of materials in the ocean bottom can cause significant differences in propagation characteristics as the acoustic energy interacts with the sand, silt or clay sediments. Exposed or sub-bottom regions of hard layers of bedrock, semi-consolidated and consolidated sediments often result in more efficient sound transmission than would occur with thick absorptive soft materials such as silt and clay. More will be said about site-specific sound propagation loss and the influence of the ocean bottom in Sec. 3. It is useful here, however, to discuss briefly the ocean bottom characteristics in the Beaufort Sea study area. The region of interest lies on the continental shelf and south of the shelf edge (which is commonly defined as the 100-fathom (180-m) contour*). The 180 meter contour in the study area is about 40-50 n.m. (>75 km) from shore. The average slope of the ocean bottom to at least 20 miles seaward from the selected sites is 0.02 degrees at Sandpiper, 0.04 degrees at Hammerhead, 0.06 degrees at Orion and Corona, 0.06 to 0.16 degrees at Erik and to about 0.04 to 0.6 degrees at Belcher. While these slopes are small, they do have an important influence on long range sound propagation.

Bottom materials at the water/bottom interface on the shelf are quite site-specific and poorly sorted but generally grade from sand and gravel near shore (except inside the barrier islands where silt and clay (or "mud") is common) to medium and fine sand, silt, and clay offshore, near the 100-fathom contour (Barnes and Reimnitz, 1974; Morack and Rogers, 1984; Naidu et

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*Some Arctic marine geologists place the Beaufort Sea continental "shelf break" at a depth of 50-70 meters (27-38 fm) which occurs about 35 n.m. from shore.

al., 1984). Sediment thicknesses below the water/bottom interface and above the bedrock interface in the vicinity of the sites apparently can be 750 meters or greater (Neave and Sellman, 1984).

Two forms of acoustically reflective intermediate layers occur within the oceanic sedimentary column of the Beaufort Sea continental shelf; sub-sea permafrost or ice-bonded sediments and "overconsolidated" clay. These layers are important to discuss since they almost certainly influence underwater sound propagation.

Ice-bonded sub-sea permafrost zones are commonly encountered in drilling operations offshore and have been attributed to relict permafrost which formed offshore approximately 18,000 years ago when sea level fell to a minimum (Morack and Rogers, 1984). These zones appear to be quite variable in thickness and horizontal extent. Seismic refraction survey data and physical sampling have located sub-sea permafrost at less than 10 meters below the near shore water/bottom interface to 20-40 meters as far as 20-60 km (11-32 n.m.) offshore from Prudhoe Bay and Harrison Bay (Morack and Rogers, 1984; Neave and Sellman, 1984). The depths to this ice-bonded sediment zone are quite variable both locally and from area to area. Thicknesses in some areas may be several hundred meters and seismic refraction data indicate a probable permafrost zone as deep as 200 to 450 meters. Neave and Sellmann (1984) present data which strongly indicate that both Orion in Harrison Bay and Sandpiper near Prudhoe will in all likelihood have sub-sea permafrost zones extending seaward from those sites. It is probable that ice-bonded sediments exist at Hammerhead, Corona, Erik, and Belcher as well. These layers exhibit high seismic compressional wave speeds providing a strong acoustically reflective zone. Figure 3, adapted from Morack and Rogers (1984) and expanded to include typical "hard-rock" data, demonstrates the compressional wave speed contrasts between unbonded and ice-bonded sediments. It is common to measure wave speeds of 2500 m/sec to over 4000 m/sec, providing the needed compressional wave speed contrast for an acoustically reflective interface.

It has also been suggested* that "overconsolidated" sub-bottom sedimentary layers, primarily in the form of dense clay, could also contribute to acoustic reflectivity. Laboratory tests and field observation of environmental parameters such as water and sediment temperatures and pressures indicate that exposure to many freeze-thaw cycles is a probable major contributor to the overconsolidation of the clay and silty-clay sediments*. The result is a material which is nearly impervious to diver-operated sampling devices and which is widespread and geometrically homogeneous to depths of 20-m or more on the North Slope. It is entirely possible that this dense clay zone works in concert with sub-sea permafrost regions to provide efficient acoustically reflective regions which strongly influence acoustic propagation. More will be said on this subject in Section 3 regarding the site-specific acoustic propagation measurements and models. Ideally, it would be very useful to this project to obtain substantiation of these two types of sub-bottom layers at each of the sites. Attempts will be made to do so through further literature search and discussions with off-shore operators (through MMS) and CRREL.

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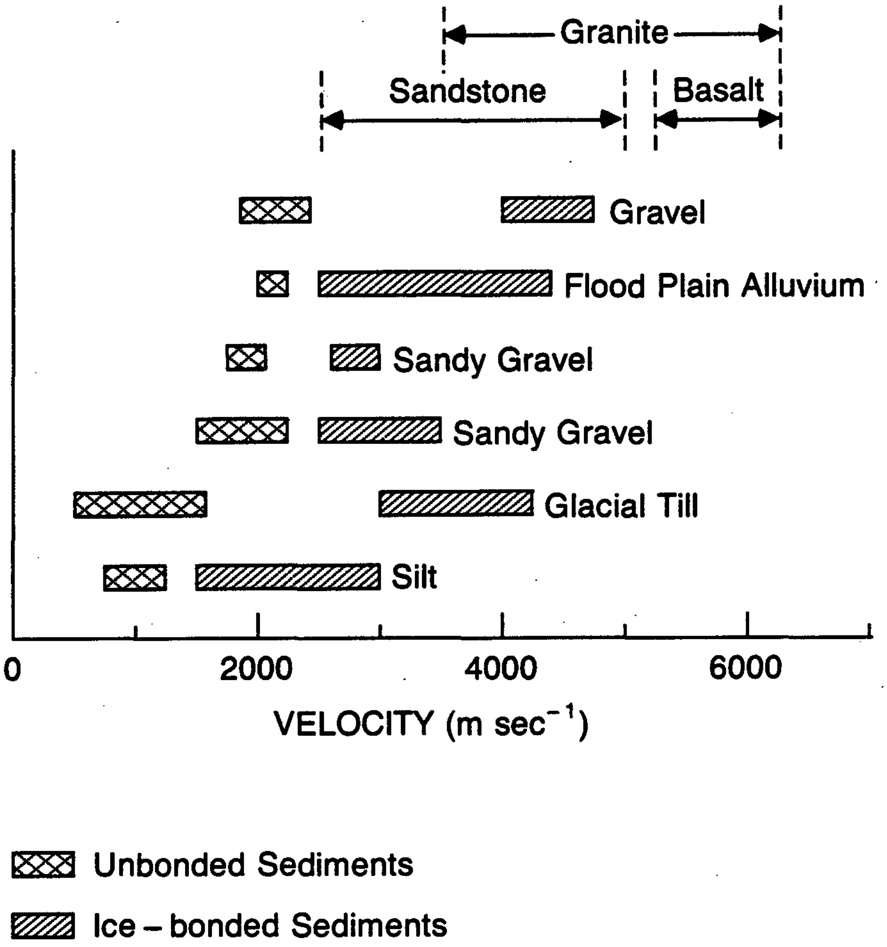
*Personal communication: Paul V. Sellmann, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH, 3/12/86.



Adapted from Morack and Rogers (1984)

FIGURE 3. COMPRESSIONAL WAVE SPEEDS IN ALASKAN BEAUFORT SEA SEDIMENTS COMPARED TO THOSE FOR TYPICAL BEDROCK.

2.2 Acoustic Environment Measurement and Analysis Methods

The basic objective of this research project is to use existing data on the behavioral responses of bowhead and gray whales to assess the potential zones of influence of underwater sounds associated with industrial activities at six pre-selected sites associated with Diapir Field Lease Sales 71 and 87 in the Alaskan Beaufort Sea. Therefore, the acoustic environment of that region must be defined before any site-specific analysis of potential whale behavioral response can be accomplished. Because of the variability of industrial activity at the sites, fluctuating weather and sea-ice conditions, and limited duration of the measurement season, the acoustic environmental measurements have been scheduled to span two summer periods. As noted, this report discusses details of the 1985 measurements and the results of the data analysis and interpretation in the context of whale behavioral response. Defining the underwater acoustic environment entails the measurement of ambient or background noise conditions (ideally without industrial activity contributions) and their variability, the radiated noise signatures of the various industrial operations proceeding at the selected sites, and the sound propagation characteristics as a function of distance from each site (transmission loss or TL). The analysis of the resulting data provides a basis for predicting industrial noise as a function of range from each site, and for evaluating the detectability of those sounds in the presence of typical variations in ambient noise.

Table 2 summarizes the data acquired during the planned 35 days of acoustic measurements during August and September 1985. As noted, some of the needed data were acquired during the 15 days when work was possible. Heavy sea-ice conditions and poor weather frequently caused lengthy delays in reaching the selected sites if not actual cancellation of departure of the

TABLE 2. BEAUFORT SEA MEASUREMENTS (Test Period: 16 August - 19 September 1985 = 35 Field Days).

Site		Ambient Noise	Sound Transmission Loss (TL)	Sound Speed Profile	Signatures and Comments
MMS SPECIFIED SITES	Hammerhead	None	-	-	Ice conditions prevented access
	Sandpiper Island	8/25 (3) 8/27 (1) 8/30 (1) 9/01 (1) 9/05 (4)	8/27 (2) 8/30 (5)	8/25 (2) 8/27 (1) 8/30 (2) 9/01 (1) 9/05 (1)	8/25 Two workboats (distant) 8/30 Two tugs opposite side of island Whale calls during TL 9/05 Drilling scheduled but not detected
	Orion, Harrison Bay	8/28 (2) 8/29 (2)	8/28 (1) 8/29 (1)	8/28 (2) 8/29 (1)	8/28 Downhole pulsing GLOMAR BEAUFORT SEA I
	Erik Prospect	9/09 (9) 9/13 (6)	9/13 (1)	9/09 (1) 9/13 (1)	9/09 Clam-shell dredge and tug 9/13 Clam-shell dredge and tug; air gun in background
	Belcher Prospect	9/10 (3) 9/11 (1)	9/10 (1) 9/11 (1)	9/10 (1) 9/11 (1)	No activities on site
OTHER SITES	Corona Prospect	9/08 (2)	-	9/08 (1)	No activities on site
	Northstar Island	9/01 (1) 9/03 (1) 9/04 (1)	9/01 (1)	9/01 (1) 9/03 (1) 9/04 (1)	9/01 Island construction activity
	Seal Island	-	-	8/18 (1)	No activities on site
No. Site days per parameter		14	8	15	7

Notes: 1) Parenthetical numbers denote number of measurements or tests.
2) Ambient noise segments are 5 to 15 minutes long.
3) Acoustic signature tape data from Greeneridge Sciences:
(1) Hammerhead; CANMAR EXPLORER II Drillship 8/27-28/85
(2) Sandpiper Island; drill rig 10/17/85
(3) Corona Site; Icebreaker 10/21/85

research vessel, M.V. JUDY ANN, from port. The measurements achieved at the five sites specified by MMS are shown in the top five rows of the table. Other industrial sites visited because they were accessible when required sites could not be reached, include Corona (a site where drillship CANMAR EXPLORER II was expected to drill after our field season), Northstar Island, and Seal Island, which are both artificial islands near Sandpiper Island. The parenthetical numbers in the table indicate the number of measurements or tests of each type at each site. The ambient noise segments were selected at random times during occupation of a site, and lasted from 5 to 15 minutes each. Since Greeneridge Sciences was also performing acoustic measurements at Hammerhead and Sandpiper Island for other purposes and at a time when industrial activities were proceeding (Johnson et al. 1986; McLaren et al. 1986), it was arranged through MMS, LGL, Unocal, and Shell to obtain copies of the Greeneridge taped signatures. Those taped signatures are listed in the notes section of the table.

The results of the analysis of the data summarized in Table 2 are provided in Section 3. Presented below are brief discussions of the measurement and analysis methods applied under this project.

2.2.1 Measurement systems

Ambient noise data should be acquired at the selected sites either prior to the onset of industrial activity or, at least, during periods when such activities are intermittent or at a minimum. Such data on natural background noise are needed as a basis for comparison of industrial noise measured at each site, and to determine the potential zone of influence on whales. Ideally, an ambient noise model should be developed which could predict noise spectrum levels at each site as a function of easily measurable environmental parameters (e.g., sea-state and percent ice cover). Unfortunately, past experience in the arctic and in more temperate regions has shown that the relationship between noise level and the environment is a complex function and is dependent on a large number of environmental parameters. Accurate models require extensive amounts of data recorded over long periods of time. Clearly, this is beyond the scope of this project; but the work discussed in this report constitutes a useful step toward that goal. Our approach is to develop a simple empirical model which provides a statistical characterization of the ambient noise field. Five- to 15-minute recordings of ambient noise are recorded at random intervals during the more lengthy period of site occupation. Analysis of the resulting data provides a reasonable statistical sample of the ambient noise conditions at that site under the conditions prevailing at the times or recording. In addition to recording ambient noise at each site, it is necessary to document physical factors which influence background noise, such as sound speed profile, water depth, ice cover, sea state, wind speed, wind and wave directions and measurement hydrophone depth.

Similarly, the measurement of industrial noise data requires close coordination or communication with the industrial operator to relate any changes in received sound to specific industrial functions. In addition to logging the above noted physical variables, which influence industrial noise as well as ambient noise characteristics, it is necessary to measure and log the distance between the measurement system and the industrial noise source.

Measurements of the sound propagation or transmission loss (TL) characteristics associated with each site are a critical element in developing the ability to predict potential industrial noise levels at expected positions of whales. These site-specific measurements were accomplished through controlled projection of bands of noise from an underwater sound projector at the research vessel and measurement of sound received from that projector as a function of distance using a second vessel (an inflatable AVON). Measurements were made out to distances (4 to 5 km) which were limited by either the need for a measurable signal-to-noise ratio or environmental (wind, sea-state, and ice) conditions.

2.2.1.1 Physical Measurements

Distances and relative positions of M.V. JUDY ANN, industrial noise sources, and the Avon (during TL measurements) were obtained using the JUDY ANN's radar system. When the AVON radar return was difficult to measure at large distances due to clutter from drifting sea-ice, it was necessary to resort to measurement of the acoustic travel times of underwater impulses transmitted from the JUDY ANN received at the AVON. Radio transmission of the received impulse time was recorded on the JUDY ANN and compared with the recorded impulse initiation time.

A standard fathometer provided depth information at the JUDY ANN. Navigation charts were used to estimate depth profiles along the TL paths.

Sound speed profile data were obtained through use of a Beckman Model RS5-3 Induction Salinometer which provides temperature, salinity, and conductivity of the ocean water as the sensor is lowered in depth. Sound speed is calculated at discrete depth intervals using a hand calculator pre-programmed with Wilson's equation:

$$c = 1449.2 + 4.623T - 0.0546T^2 + 1.391\ (S-35)\ ,$$

where c is the sound speed in meters/second, T is the temperature (°C) and S is the salinity in parts per thousand (Urick 1983).

Wind conditions were obtained from the shipboard anemometer, and sea wave and swell heights were estimated visually. Ice cover estimates were also estimated visually.

2.2.1.2 Acoustic Measurement Systems

Three acoustic measurement systems were applied in this project; a primary dual channel system used for both ambient noise and industrial noise measurements, a single channel system used on the AVON during transmission loss experiments and for ambient noise and industrial noise data collection, and a sonobuoy system that permitted remote measurement of ambient noise, industrial noise, and is also useful for transmission loss data measurements.

Ambient and Industrial Noise Measurement System

A standard hydrophone system that combined an ITC Type 6050C hydrophone with a low-noise preamplifier and tape-recorder was used to obtain ambient noise data. The hydrophone sensitivity and electrical noise-floor characteristics are shown in Fig. 4. The acoustic noise measurement system block diagram is shown in Fig. 5a. Overall frequency response of the measurement system was generally flat from 20 Hz to 15 kHz. All components of the system were battery operated during ambient and industrial noise measurements. Cable fairings and a support float system were used to minimize strumming and surge noise effects on the ambient measurement hydrophone. At times, particularly when recording transient sounds and industrial noise requiring wide dynamic range, it was useful to record data from a single hydrophone at two different gain settings, using both record channels. At

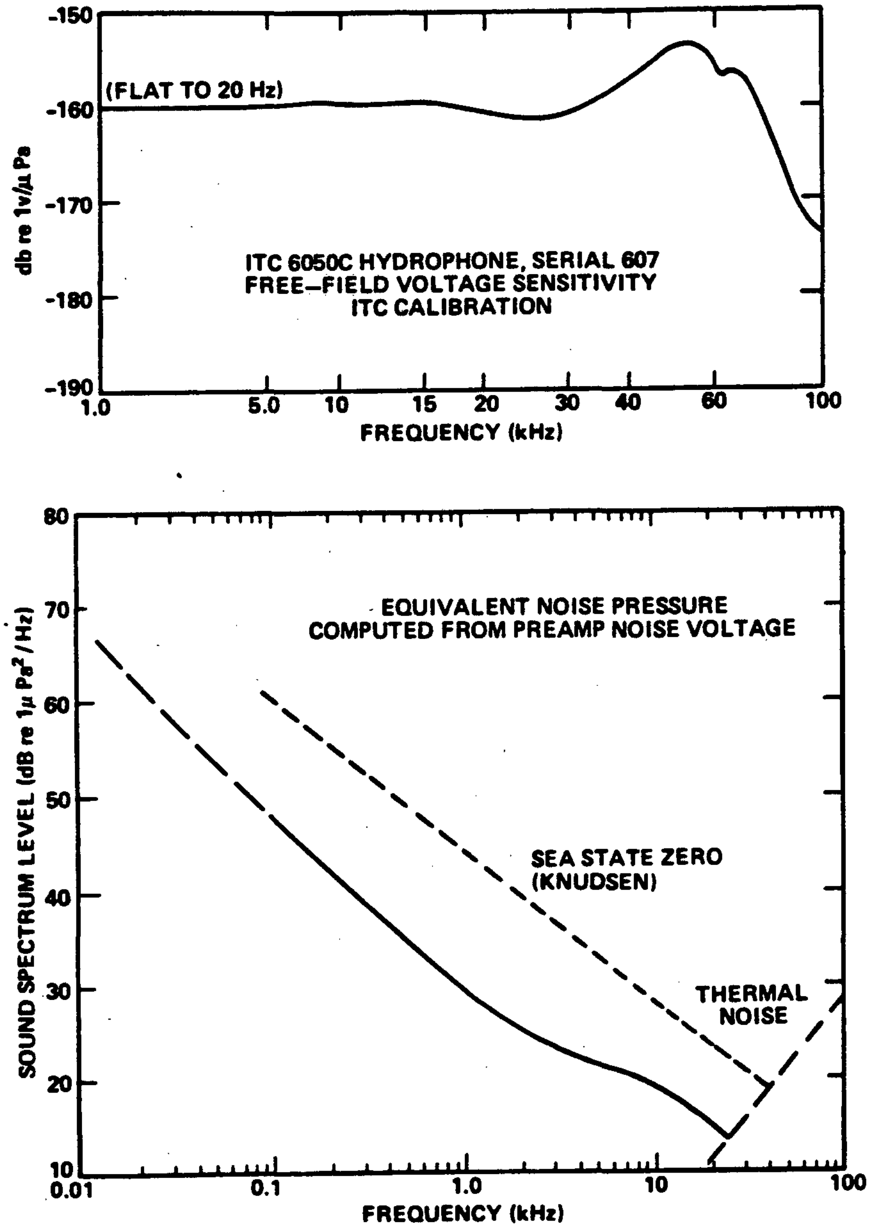


FIG. 4. MEASUREMENT HYDROPHONE CHARACTERISTICS.

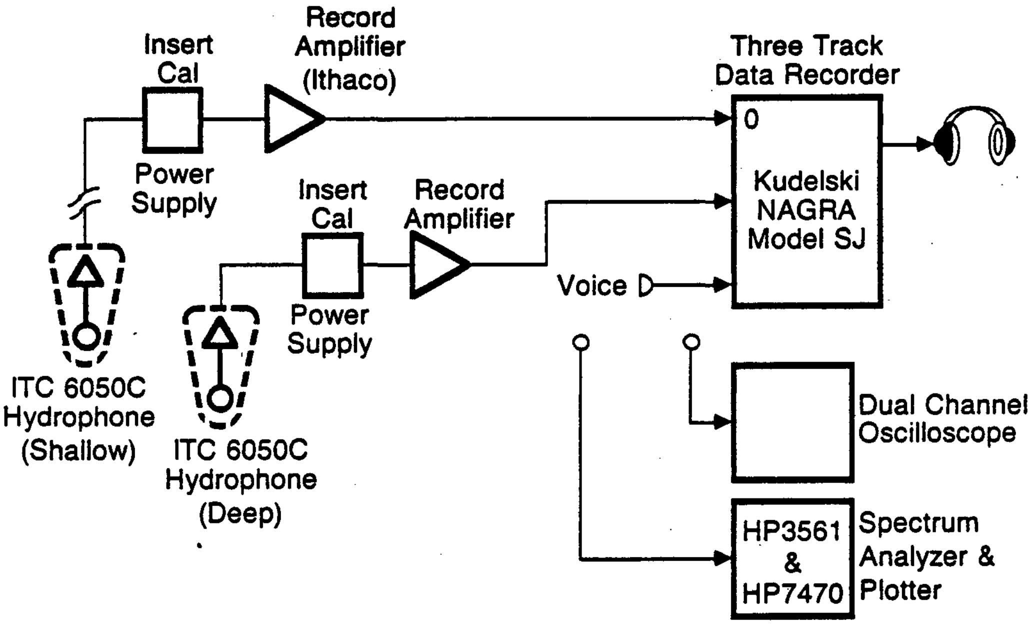


FIG. 5a: GENERAL PURPOSE ACOUSTIC MEASUREMENT SYSTEM.

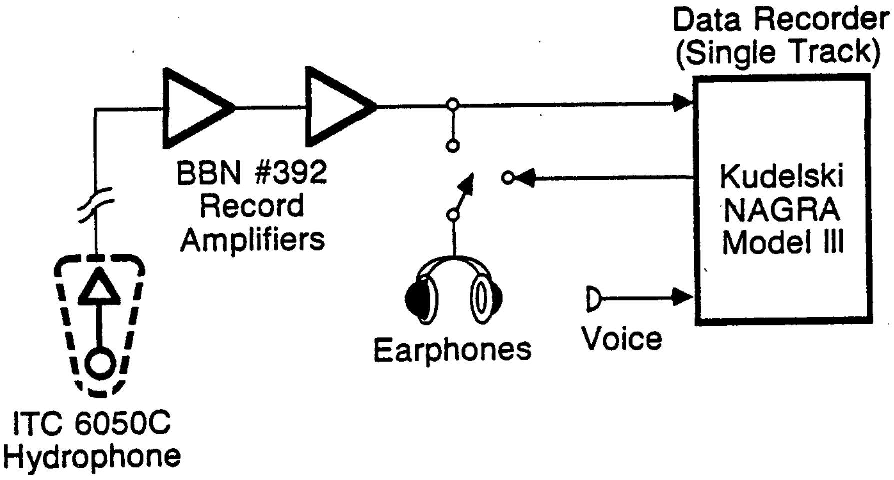


FIG. 5b. BATTERY POWERED ACOUSTIC MEASUREMENT SYSTEM FOR AVON TL MEASUREMENTS.

7.5 in. per second, the recorder has a nominal flat frequency response from 25 Hz to 20 kHz and a 60 dB dynamic range.

Single Hydrophone Receiver System (Avon)

Figure 5b provides a diagram of the single channel hydrophone system used by the second vessel (AVON). As noted, it also uses an ITC 6050C hydrophone and is compact, battery-operated, and provides the needed frequency response (30 Hz to 10 kHz at 7.5 in./sec) and dynamic range (60 dB).

Sonobuoy Measurement System

The sonobuoy measurement system permits remote measurement (3 to 4 km) of industrial noise, ambient noise, or transmission loss data, and is particularly useful when shipboard sound sources would cause contamination of the underwater acoustic data due to their proximity to a ship-mounted hydrophone. The sonobuoy electronics (a Navy SSQ57A transmitter coupled with an Edo hydrophone and Ithaco amplifier) are mounted in a 4 1/2-ft spar buoy which can either be free-drifting or moored. The frequency response of the system is flat from below 100 Hz to 10 kHz. When moored, it is often placed near an industrial site and sampled periodically during the day while the research vehicle is performing other experiments or it can be used to receive acoustic transmissions during transmission loss experiments. Figure 6 is a block diagram of the sonobuoy/spar-buoy measurement system used for this project. The buoy incorporates a high sensitivity, calibrated hydrophone, a low-noise signal preamplifier, and a sonobuoy radio transmitter. Battery life permits continuous operation for about three days. A range of about 5 km has been obtained depending on the available antenna height on the receiving vessel.

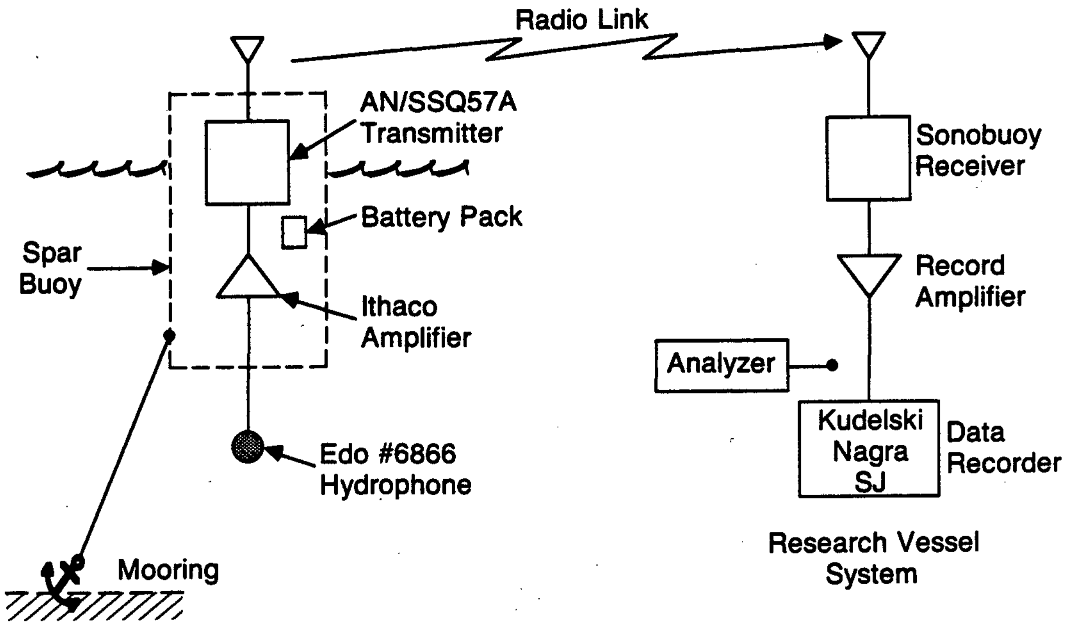


FIG. 6. SONOBUOY MEASUREMENT SYSTEM.

2.2.1.3 Sound Projector System for Transmission Loss Experiments

As described previously, it is necessary to determine the site-specific characteristics of sound propagation from the selected industrial sites. To accomplish this, a sound source with known frequency and sound level characteristics must be located near a site and the level of the controlled radiated signal measured as a function of distance from the source. If an industrial source radiates sounds in a continuous or invariant manner, that industrial source can be used as the "transducer". Recording that continuous sound as a function of distance provides the needed TL data. However, industrial sources rarely produce invariant sounds. Hence, a calibrated source of known characteristics is a more useful alternative. The industrial noise spectrum of interest to this project is primarily low frequency in character, mostly concentrated below 1 kHz (e.g., Greene 1985). Since some energy is encountered occasionally in the 1 to 4 kHz region, it was decided that a standard U.S. Navy J-13 sound projector would suffice for the expected 1985 field measurement conditions.* Figure 7 provides a plot of the transmit frequency response characteristics of the J-13 transducer together with a block diagram of the sound projector system used during this project. The J-13 projector is calibrated by the U.S. Navy Underwater Sound Reference Division of the Navy Research Laboratory. In order to maintain continuity from one experiment to the next, a series of 1/3 octave band tones and pulses from 100 Hz to 4 kHz were recorded on a cassette tape. The output of that tape is amplified and adjusted for consistent and repeatable drive signals to the J-13 projector. As noted, the acoustic output of the J-13 is monitored

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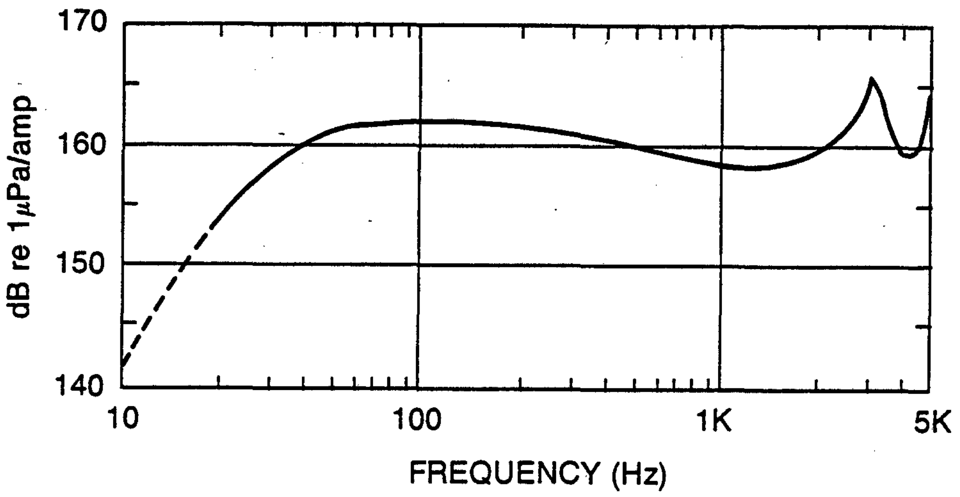
*It appears from analysis of the resulting data that two J-13 transducers operated in parallel from a single location probably should be used in 1986 to obtain transmission loss data to greater distances.



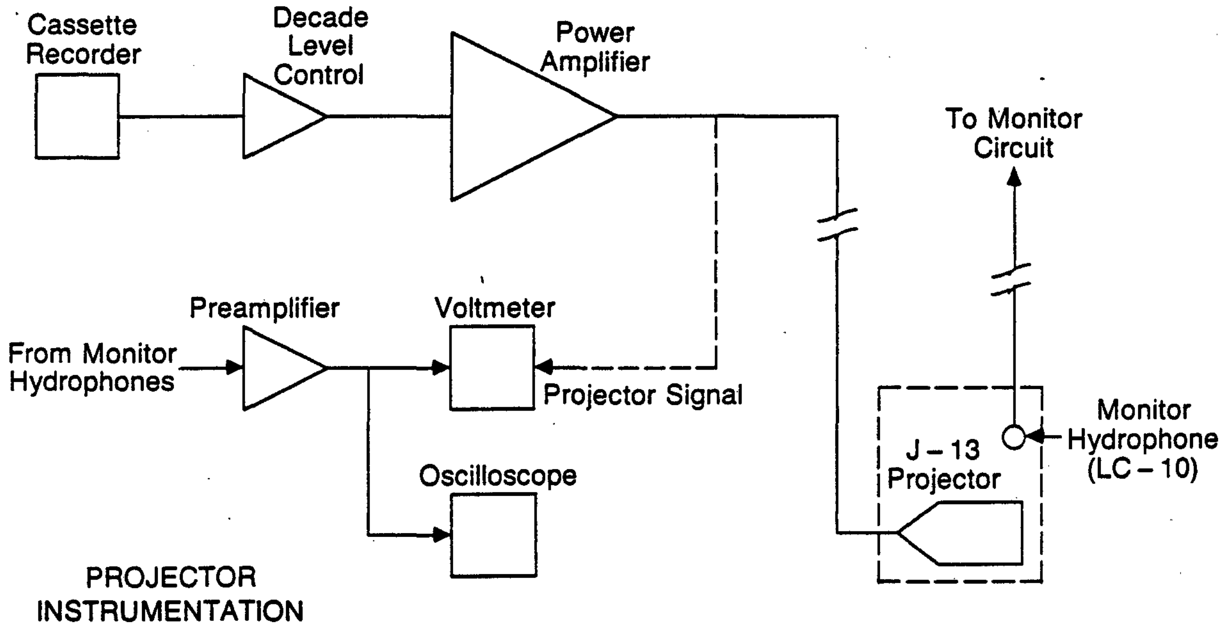


FIG. 7. J-13 FREQUENCY RESPONSE AND PROJECTOR SYSTEM.

continuously with an LC-10 hydrophone. The J-13 was suspended over the side of the JUDY ANN and operated with the vessel free drifting (engines off) next to a selected site. Ideally, the vessel should be moored but this was not possible in the Beaufort because of the potential for damage by drifting ice and because the water depths at some sites (Hammerhead, Erik, Belcher, and Corona) were beyond the anchoring capability of JUDY ANN.

Since the variation of sound speed with depth is important to the interpretation of the measured transmission loss (TL) data, the sound speed profile is determined at regular intervals with the Beckman salinometer at each site, not only before and after the TL experiments but at the time of measuring ambient noise segments and industrial noise signatures.

2.2.2 Analysis of acoustic data

Recorded data on ambient noise, industrial noise, and underwater sound propagation were analyzed to provide a quantitative definition of the underwater acoustic environment in the Diapir Field region of the Beaufort Sea. The analysis format was selected to be compatible with the requirements of the 'zone of influence' assessment to be performed by LGL Ltd. For example, the emphasis on third octave data in this report is a result of data requirements for the 'zone of influence' assessment. The analysis procedures and results used by LGL are described in Section 2.3, Section 3, and Appendix B. The methods used in analysis of the acoustic data are described below, the results of which are provided in Section 3.

2.2.2.1 Ambient Noise Analysis

The objective of the ambient noise measurement and analysis effort is to develop a statistical description of the variation of the underwater background noise conditions at each of the selected sites. Ideally this should include long-term measurement of noise conditions as a function of time of day, month, and season to permit a complete statistical description. For practical reasons, this project was only able to collect short-term samples of the ambient noise field during a 35-day period. This results in an incomplete description of the ambient noise condition for the sites of interest. In order to estimate the noise statistics over a wider range of conditions and times, additional analysis was done using published wind and ice data for the North Slope area to supplement the summertime measurements, resulting in noise statistics over a wide range of conditions and times.

Estimation of the 5th, 50th, and 95th percentile levels of the site-specific ambient noise statistics was accomplished for both a 1-Hz band basis and for one-third octave bands spanning the frequency range of interest. Typically, estimates were derived for 1/3 octave bands centered at 100, 500, and 2000 Hz. However, at the Orion location there were interfering tonal sounds at 2 and 4 kHz, so we analyzed noise statistics at that site for bands centered at 100, 500, 1000, and 3000 Hz.

The data analysis procedure employed was as follows. The analog tape recordings were passed through a signal conditioner and then through a one-third octave band filter set at the desired frequency. The band limited signal was then amplified using a logarithmic amplifier, filtered with a 10 Hz low pass filter that acts as an envelope detector and fed into a spectrum analyzer (Hewlett Packard Model 3562) for histogram generation and calculation of the cumulative distribution function (CDF). Figure 8 is a block diagram of the data analysis system. Average narrowband power spectra were also developed to provide a general overview of the noise characteristics.

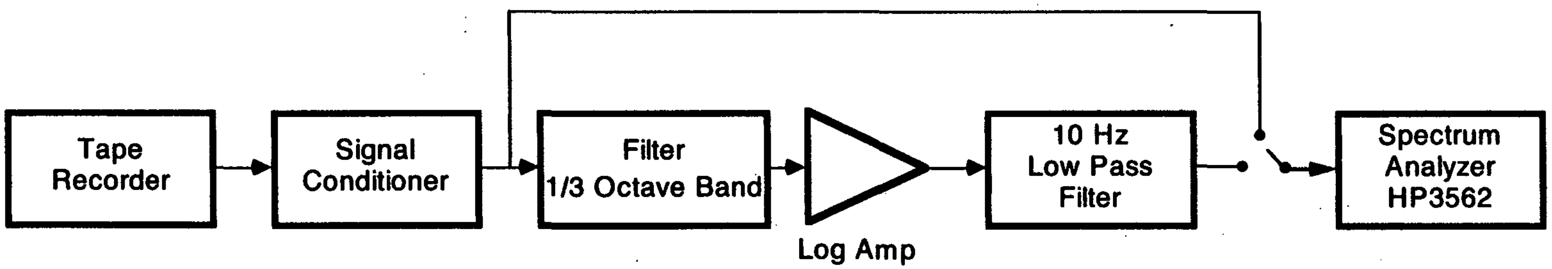


FIGURE 8. AMBIENT NOISE DATA PROCESSING SYSTEM.

From the CDFs, three ambient noise levels were collected: the level below which the third octave band noise remained 95% of the time, the median (50th percentile) noise level and the level below which the noise occurs 5% of the time. The data samples were relatively short (3 to 5 minutes) since we are not trying to characterize the long term (seasonal or yearly) ambient noise statistics. This is beyond the scope of the current effort. Our goal is to characterize the site-specific noise statistics at the times we occupied the site. It is expected that the 1986 measurement effort will result in a strengthening of the 1985 ambient statistics described here and in Section 3.

Ice cover and wind statistics for the Beaufort Sea regions of interest to this study were obtained from a recent NOAA publication (Brower, et al., 1977). Those data, together with established algorithms used for estimating the dependence of ambient noise levels upon ice cover and wind speeds, permitted the derivation of long-term ambient noise statistics for ice and wind extremes not encountered in the 1985 field season. The resulting 95th, 50th, and 5th percentile ambient spectral estimates were provided to LGL for their consideration in the synthesis of whale behavioral response.

2.2.2.2 Industrial Noise Analysis

A quantitative description of the underwater noise associated with industrial operations at selected sites on the North Slope is a necessary part of this research effort, as described previously. The objective of the industrial noise measurement and analysis effort is to determine the source levels of dominant frequency components of underwater noise related to industrial operations. The 1985 field season produced a relatively small sample of industrial noise due to limited site accessibility caused by unusually heavy sea-ice conditions. The 1986 field season should produce a larger sampling of industrial noise signatures. The analysis procedures used on the available data are described below.

The analog recordings of ambient noise and industrial noise obtained in the field were played back into a spectrum analyzer and average power spectra were measured. The durations of these averages varied depending on the noise source but typically were on the order of 1 to 2 minutes. The spectra were corrected for system gains and hydrophone sensitivities to produce data on absolute received levels versus frequency. These calibrated levels were then compared to ambient noise measurements taken at the specific sites to establish data validity in terms of acceptable signal-to-noise ratio. Narrowband tonals and broadband components that exceeded the ambient noise spectra were assumed to be due to the industrial activity.

In some cases, where measurements were made at various ranges, the noise components were examined as a function of range. Those which disappeared at short ranges are typically ignored in this analysis. (For example, the 90 and 100 Hz tonals observed during drilling at the Sandpiper site, discussed in Section 3.)

The final step in the analysis was to correct the received levels for the site-specific transmission loss (TL) characteristics to provide spectra in terms of radiated noise source level referred to a standard reference distance of 1 meter. Independent measurements of TL at the Erik site were used to derive source level estimates, corrected to a 1 m reference range for the two industrial activities at that site. For the Hammerhead data, no TL measurements with a calibrated invariant source were available, requiring the use of the industrial noise itself (McLaren et al. 1986) to estimate the local site-specific TL characteristics. The drilling activity at Sandpiper Island posed another problem. Although we had measured the TL characteristics, the environmental conditions had included 1/10-2/10 ice cover at the time. The Greeneridge Sciences drilling noise data (Johnson et al. 1986) were acquired later, with 8/10-10/10 ice cover. Since ice cover directly influences the sound transmission loss characteristics, rather than use potentially inappropriate TL estimates, the actual radiated noise measurements were used to estimate the site-specific local TL characteristics and thus to adjust the Sandpiper noise spectra to 1-meter source levels.

2.2.2.3 Transmission Loss Data Analysis

Sound propagation data were acquired and analyzed to determine the dependence of received level on the range from a calibrated source. Warble tones with a 1/3 octave bandwidth were projected in a sequence with center frequencies of 100, 200, 500, 1000, 2000, and 4000 Hz. Received sound levels of these controlled tones were measured at discrete distances from the sound projector. Measurements were made to determine the sound speed profile at each of the test sites. This information was used to select the sound source and receiving hydrophone depths for the TL measurements. Generally depths of 10 to 12 m were used which were below most observed surface layer effects and representative of mid-depth conditions.

The transmission characteristics were expected to follow either a 10 Log R or a 15 Log R spreading law depending on the prevailing sound velocity gradients and ocean bottom conditions. A 10 Log R relationship has been found to be widely applicable in the Canadian Beaufort Sea (Greene 1985), but few corresponding data for the Alaskan Beaufort were available previous to this project. Accordingly, a procedure was used to determine which of these characteristics provided the best fit to each data set using a 2-parameter, least-squares regression technique. Generally the 10 Log R characteristic was found to provide the lowest mean square error values between the measured data and model predictions.

The semi-empirical transmission loss (TL) models provided for a selected spreading loss and two empirically determined parameters to incorporate the effects of local conditions. A cylindrical spreading loss model is appropriate for conditions where the water depth is comparable to the dominant acoustic wavelengths, depth variation is small, and modal acoustic theory is applicable. It is also appropriate for conditions where acoustic ducting and upward refraction are dominant. The model used for these conditions can be stated as:

$$TL = 10\,\mathrm{Log}(H_{av}) + 10\,\mathrm{Log}(R) + A(R) + Av(R) - An + 30 \text{ (dB re 1 m)} \tag{1}$$

where $H_{av} = (H_s + H_r)/2$, the average of the water depths at the source (H_s) and receiver (H_r) (m),

R = the range (km),

A = the attenuation (dB/km) caused by losses at the bottom and surface,

Av = the attenuation (dB/km) caused by volumetric absorption in the water (this term can be neglected for frequencies less than 500 Hz and ranges less than 20 km), and

An = the local anomaly in the source level caused by bottom- and surface-reflected energy (dB).

A spreading loss intermediate between cylindrical and spherical spreading is applicable to shallow water propagation conditions where ray theory is appropriate and a significant amount of downward refraction and bottom contacting ray paths are present. The propagation model used for these conditions is given as:

$$TL = 5\,\mathrm{Log}(H_{av}) + 15\,\mathrm{Log}(R) + A(R)/H_{av} + Av - An + 41 \ (\mathrm{dB\ re\ 1\ m}) \qquad (2)$$

A is again the attenuation (dB/bounce) caused by bottom and surface reflections, but is different from that of Eq. (1) since the number of reflections is assumed to be proportional to R/H_{av}.

In applying these equations to the analysis procedure, a computer algorithm is used to solve automatically for the values of A and An which give the lowest mean-square error for a given data set. A data set consists of all of the data for a given frequency at a specific test site since no significant directional dependence was observed at any of the sites.

A computer-implemented analytic transmission loss model was also used to predict long-range sound transmission characteristics near the test sites. This model is based on a shallow water sound transmission analysis by Weston (1976) and was used to supplement the transmission loss data obtained during the 1985 field season. Long range transmission loss measurements are planned for the 1986 field work to check the predictions of this model and refine the zone of influence calculations. Further discussion of the use of this model is included in Sec. 3.3.

2.3 Whale Behavioral Response Analysis Methods*

To estimate the radius from a specific industrial site within which whales will react to its underwater sound, two main types of information are needed: (1) measurements or predictions of the levels of industrial noise at various distances from the site, and (2) information about the responsiveness of whales to varying sound levels. Previous studies have obtained considerable information about the characteristics of industrial sounds from oil industry activities in the Beaufort Sea (e.g., Ford 1977; Malme and Mlawski 1979; Cummings et al. 1981a,b; Greene 1983, 1985; Moore et al. n.d. [1984]; Davis et al. 1985; Ljungblad et al. 1985b). However, most of these data did not come from the specific sites where the Alaskan oil industry is planning to drill. Similarly, most of the available data on reactions of bowhead whales to oil-industry activities, and all of those for gray whales, came from locations different from those where drilling is now underway or planned in the Alaskan Beaufort Sea. A central objective of this project is to obtain the site-specific data that are necessary, along with existing non-site-specific data, to estimate zones of potential noise influence for various industrial activities at several specific sites in the Alaskan Beaufort Sea.

Because different industrial activities result in sounds with differing source levels and frequency composition, the type of industrial activity at a given site will affect the size of the predicted zone of influence. Furthermore, because propagation conditions differ between sites, the size of the zone of influence for a given industrial activity will depend on the location of that activity. Thus, separate zone of influence

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analyses are needed for each combination of industrial activity and site. At locations where water depth or bottom composition are different on different bearings, the zone of influence is likely to extend farther in some directions than in others.

It is impractical to conduct propagation experiments to measure received sound levels for each potentially relevant combination of site, bearing, and type of industrial sound. It would be even more impractical to test the reactions of whales to all of these combinations. The approach used in this study has been to determine the levels and frequency characteristics of the sounds emitted by the key types of industrial activity, to measure sound propagation characteristics at each site of interest, and to develop site-specific models that predict received sound levels as a function of source level, frequency, distance and bottom slope (i.e., bearing). These models can then be used to make site-specific estimates of received levels of sounds from any industrial activity that might occur at that site, provided that its source level and frequency characteristics are known. Zones of potential influence can then be estimated, to a first approximation, by relating these acoustic results to behavioral data from previous studies of the responsiveness of whales to various types and levels of industrial sounds.

2.3.1. Definition of zone of influence

Noise can affect animals in several different ways, at least in theory. The sizes of the zones of audibility, responsiveness, masking, and hearing damage will differ greatly (Richardson et al. 1983). The time element (sustained vs. impulsive high level noise) is also a potential factor to consider. When the noise level is extremely high, discomfort or permanent damage to the auditory system is possible (Kryter 1985). Industrial noise levels high enough to cause auditory damage would be expected to be restricted to relatively strong noise sources and to relatively close distances. Auditory damage would not occur at any distance unless the source level of the noise was quite high. Thus the 'zone of auditory damage' is expected to be small or absent. At the other extreme, the behavior of an animal might be affected, at least subtly, at any distance where the industrial noise was audible. The 'zone of audibility' would be much larger than that where auditory damage is possible. The zone of influence of a noise source might also be defined as the area where animals respond overtly by avoidance or some other alteration in behavior. This 'zone of responsiveness' might, in theory, be as large as the zone of audibility if animals responded to any industrial sound that they could hear. However, it might also be considerably smaller than the zone of audibility if animals responded only to industrial sounds that exceeded a specific absolute level, or to sounds that exceeded the detection threshold by some minimum amount. Still another possibility is a 'zone of masking' which would be the area within which the ability of an animal to hear important environmental sounds (calls from other members of its own species, etc.), would be impaired by the masking effect of industrial noise.

The size of the estimated zone of influence around an industrial site will vary greatly depending on the definition of zone of influence that is used. The following subsections review the major factors known or suspected to affect the sizes of the zones of audibility, masking and responsiveness. These subsections provide the justification for some of the procedures that we have applied in this study.

Zone of Audibility. -- This is the largest of the zones of possible influence. The radius of audibility will depend partly on the source level of the industrial noise and on its rate of attenuation with increasing range. However, the size of this zone will also depend on the ambient noise level and the minimum ratio of industrial noise to ambient noise that can be detected. This ratio is often taken to be 0 dB, i.e., assuming that a sound can be detected provided that it is no less intense than the background noise at corresponding frequencies. However, in some circumstances sounds can be detected even when they are somewhat less intense than the background noise, i.e., at a signal-to-noise ratio slightly less than 0 dB (see Richardson et al. 1983a for review). Another consideration is the hearing absolute sensitivity of the animal. If the absolute detection threshold is above the ambient noise level, then the zone of audibility will be limited by detection threshold, not ambient noise.

Any attempt to estimate the zone of audibility of a sound to bowhead or gray whales is hampered by the fact that there have been no measurements of the hearing thresholds of any baleen whales. Baleen whales apparently communicate with one another by calls at low to moderate frequencies (Thompson et al. 1979; Clark 1983). Most bowhead calls are at frequencies 50-500 Hz, but some calls contain energy up to 4000 Hz (Ljungblad et al. 1982; Clark and Johnson 1984). It seems safe to assume that whales are sensitive to the frequencies contained in their calls; there is behavioral evidence that some baleen whales detect and respond to calls from conspecifics many kilometers away (Watkins 1981; Tyack and Whitehead 1983). The structure of the hearing apparatus of baleen whales is appropriate for detection of low and moderate frequencies (Fleischer 1976). Malme et al. (1983) demonstrated that migrating gray whales could detect the presence of Orca sounds in a tape playback experiment when the signal-to-noise ratio was about 0 dB.

Payne and Webb (1971) pointed out that, at 20 Hz, detection range would be limited by background noise rather than auditory sensitivity even if auditory sensitivity were as much as 30 dB poorer than human auditory sensitivity at humans' most sensitive frequency. Thus, following Payne and Webb (1971) and Gales (1982a,b), we assume that ambient noise, not limited auditory sensitivity, sets the upper limit on the zone of audibility.

In estimating the zone of potential audibility, another factor that must be considered is the 'critical bandwidth' at each frequency. The critical bandwidth is the range of frequencies at which background noise affects the ability of the animal to detect a signal. Critical ratio, in dB, is equal to 10 log (critical bandwidth). Here we are concerned with the detection of an industrial sound signal in the presence of natural background noise from wind, waves, ice, etc. In those mammal species that have been studied, the only background noise that has a significant effect on detection of a sound signal is the noise within a band roughly 1/3 octave wide, centered at the frequency of the sound signal (Fig. 2-9; Popper 1980; Gales 1982a,b). A 1/3-octave band around any frequency x extends from

$$x(2^{-1/6}) \text{ to } x(2^{1/6}) ,$$

i.e., from 0.891x to 1.122x. The width of a 1/3-octave band is 23% of the center frequency. For example, the 1/3-octave bands around 50, 500 and 5000 Hz are approximately 45-56, 450-560, and 4500-5600 Hz, respectively.

Critical bandwidths have not been determined for any baleen whale, but the 1/3-octave 'rule of thumb' seems to be a good first approximation for in-air and in-water hearing by a variety of mammals and even fish (Fig. 9). Again following Payne and Webb (1971) and Gales (1982a,b), we have assumed that the critical bandwidth is 1/3 octave. (Gales also considered a wider bandwidth when the frequency was <450 Hz.) It should be noted

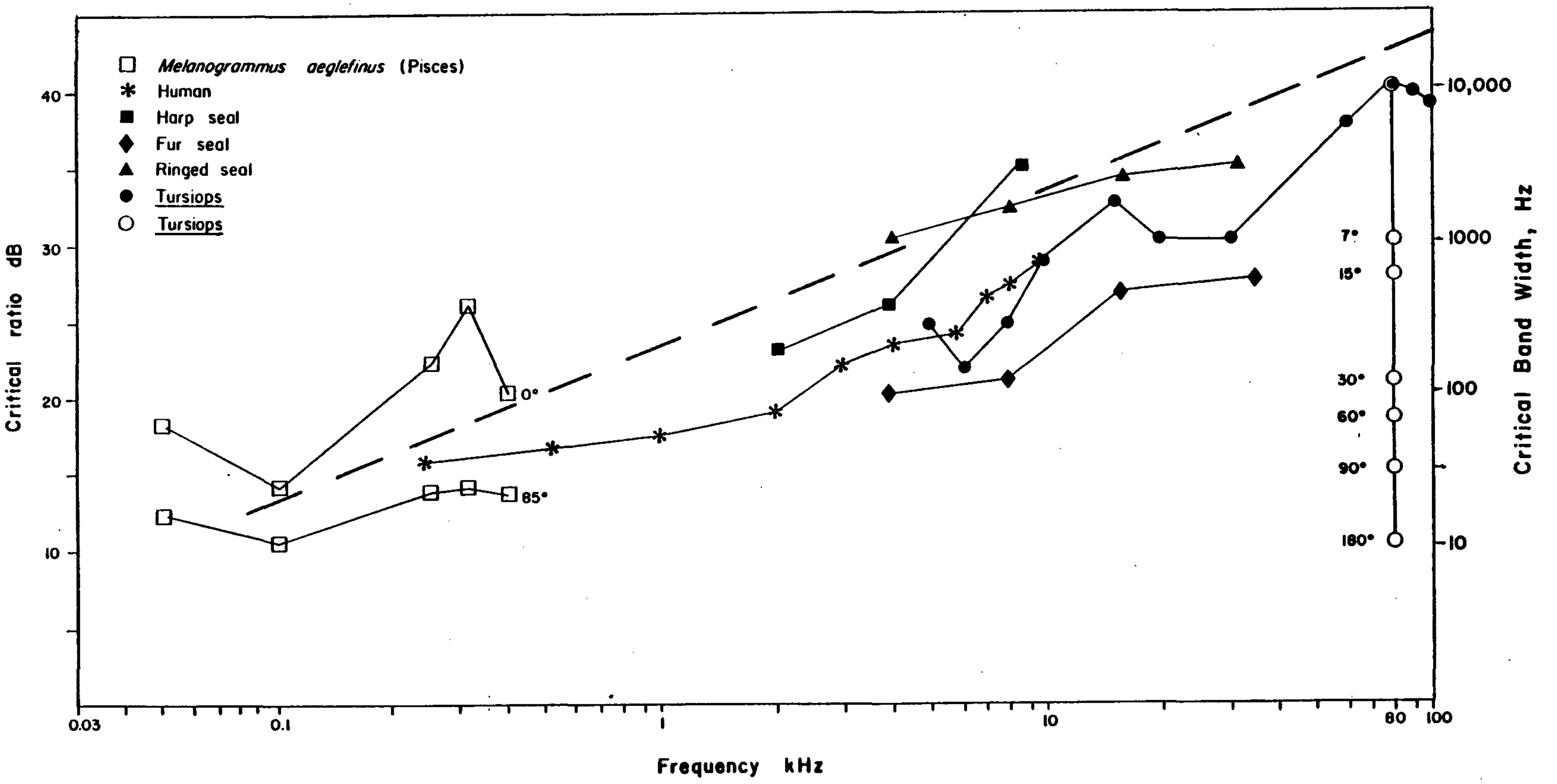

FIGURE 9. CRITICAL RATIOS AND ASSOCIATED CRITICAL BANDWIDTHS OF SEVERAL MARINE MAMMALS, MAN, AND HADDOCK. DASHED LINE REPRESENTS 1/3 OCTAVE. CRITICAL RATIOS FOR THE BOTTLENOSE DOLPHIN (Tursiops) AND HADDOCK ARE KNOWN TO DEPEND ON THE ANGULAR SEPARATION BETWEEN SIGNAL AND NOISE SOURCES (SEE OPEN SYMBOLS). SOURCES ARE CHAPMAN (1973) FOR HADDOCK, HAWKINS AND STEVENS (1950) FOR HUMAN, TERHUNE AND RONALD (1971) FOR HARP SEAL, P. MOORE (NOSC, pers. comm.) FOR FUR SEAL, TERHUNE AND RONALD (1975) FOR RINGED SEAL, AND JOHNSON (1968) AND ZAYTSEVA ET AL. (1975) FOR Tursiops. MODIFIED FROM RICHARDSON ET AL. (1983).

that signal-to-noise ratios for many industrial sounds relative to ambient noise do not depend strongly on the bandwidth chosen for analysis. Industrial noise and ambient noise typically include broadband peaks in their spectra which are greater than 1/3 octave band in width. In this situation, if a bandwidth wider or narrower than 1/3 octave is chosen, the industrial and ambient noise levels will increase or decrease more or less proportionately, and the signal-to-noise ratio may not change much.

The directional hearing abilities of baleen whales are unknown. In theory, if they can determine the direction from which a sound signal (e.g., industrial noise) is arriving, they might be able to detect it even at a signal-to-noise ratio well below 0 dB. An ability to detect a sound in the presence of much noise is in some respects equivalent to having a very narrow critical bandwidth. The sound detection ability of dolphins has been shown to depend strongly on the relative directions of the signal and noise sources, at least at high frequencies (Fig. 9). The directional effect is not expected to be as great at low frequencies because of the longer wavelengths and, in shallow water, the complex interactions of the sound with the bottom and surface. On the other hand, the large separation of hearing organs in baleen whales may partly compensate for the long wavelengths of the dominant industrial sounds. Following Payne and Webb (1971) and Gales (1982a,b), we have not assumed that baleen whales gain any increased auditory sensitivity through directional hearing.

Payne and Webb (1971) provided the first comprehensive attempt to estimate the zone within which a baleen whale could detect a particular sound. Their analysis concerned the range to which fin whales might detect the intense 20-Hz calls made by other fin whales. However, the principles described in their paper are equally relevant to the detection of industrial sounds, many of which are predominantly at low frequencies. Payne and Webb showed that, in certain deep-water situations, the intense calls of fin whales might be detectable hundreds or even thousands of kilometers away. The source levels of fin whale calls, about 180 dB re 1 μPa at 1 m, are not dissimilar to source levels of some industrial sounds. Thus, the zone of audibility might be very large in some situations.

The first detailed attempt to estimate the zone of audibility of underwater sounds from an oil industry activity involved noise from proposed icebreaking Liquefied Natural Gas 'tankers' (Peterson [ed.] 1981). To estimate the expected source levels and frequencies, theoretical models and measurements from existing large ships were considered (e.g., Leggat et al. 1981). Existing data on propagation losses within the proposed operating area were used, along with existing ambient noise statistics (Leggat et al. 1981; Verrall 1981). It was tacitly assumed that marine mammals would be able to hear ship noise if its received level was above the ambient noise level at corresponding frequencies. It is noteworthy that many of the data and analyses used in this assessment came from naval investigations, only a minority of which have been reported in the open literature. Data on sound propagation and background noise in some other areas of interest to the oil industry are undoubtedly available in restricted sources.

Gales (1982a,b) estimated zones of audibility around a semi-submersible drilling rig and two fixed drilling platforms. His estimates were based on measurements of sound levels and spectral characteristics near the industrial sites, along with a series of alternative assumptions about propagation losses (spherical vs. cylindrical) and ambient noise (low, moderate and high). Gales made the same types of assumptions about baleen whale hearing as were made by Payne and Webb, with one elaboration: Gales considered the possibility that the critical bandwidth for low frequencies is wider than 1/3 octave. Gales concluded that noisy platforms radiate low frequency underwater sounds that could be audible at ranges 'on the order of hundreds of miles' under favorable conditions of propagation and ambient noise. However, under unfavorable conditions, i.e., poor propagation and high ambient noise, even the noisiest platforms might be detectable only within ranges 'of the order of 100 yards'. Estimated ranges of audibility differed by factors of 10-1000 depending on the assumed propagation conditions and ambient noise levels.

Gales (1982b) concluded that accurate site-specific predictions of detection range will require data on (1) the acoustic source spectrum for the particular industrial source of interest, (2) propagation conditions for the particular location and season, and (3) ambient noise under the specific conditions of interest. Gales also suggested that it would be important to consider the particular species of animal involved as listener. However, in the case of baleen whales, species-specific predictions of the zone of audibility will not be possible until something is learned about the relative auditory capabilities of different baleen whales.

In shallow waters where most oil industry activities take place, the zone of audibility is expected to be restricted by the greater rate of attenuation of underwater sound in shallow water. There have been no previous specific estimates of the zone of audibility around oil industry sites in the Beaufort Sea, although several studies have provided measurements of received sound levels at various distances from such sites.

Zone of Masking. -- When there is an increase in the background noise level against which an animal is attempting to detect a sound signal, the signal-to-noise (S:N) ratio is reduced. If, for example, the signal of interest is a whale call, the background noise consists of natural ambient sounds plus any industrial noise that may be present. If the receiving whale is close to an industrial source, the received industrial noise level will probably exceed the natural ambient level, and thus will reduce the S:N ratio for the whale call. If the received whale call is intense, it will still be audible despite the reduced S:N ratio. However, if the whale call would be barely detectable in the absence of industrial noise, it may not be detectable in the presence of the noise. Such a call is said to be masked by the industrial noise (Terhune 1981).

The received level of a whale call is likely to be at least roughly related to the distance between the calling and the receiving whales. If the S:N ratio of a whale call received in the absence of industrial noise is low, the call was probably made by a distant whale. Thus, it is primarily the calls from distant whales that will be inaudible if the background noise level increases. Masking by elevated industrial noise levels has the potential to reduce the distance to which a whale can hear calls from other whales, or from other sources of interest.

It is emphasized that the actual importance of masking to whales, particularly baleen whales, is largely unknown. There is little information about the importance of long-distance communication to whales, or about the significance of a temporary interruption in this ability. Long-distance communication must often be interrupted by the natural masking effect of the elevated noise levels associated with storms and moving ice. It is not known whether baleen whales can adapt to increased background noise levels by increasing the intensities or altering the frequencies of their calls; certain toothed whales apparently do this (Au 1980; Au et al. 1985). If the calls or the auditory system of baleen whales have any directional properties, this may provide some resistance to masking. These complications are discussed in more detail by Richardson et al. (1983, 1985c).

Even a slight increase in background noise level has the potential to mask a sound signal that is barely audible. Hence, masking of faint sounds could occur anywhere within the zone where the received level of industrial noise exceeds the natural ambient noise. By this extreme criterion, the zone of masking would be the same as the zone of audibility of the industrial sound. However, many sounds that are relevant to a whale, e.g., sounds from other whales nearby, will have received levels well above natural ambient levels. These sounds would still be detectable, albeit with reduced S:N ratios, even if the background noise level were considerably elevated by industrial noise.

For example, for a bowhead call with source level 180 dB re 1 μPa at 1 m and a bandwidth <1/3 octave (Clark and Johnson 1984; Cummings and Holliday 1985), the received level would be about 140 dB at range 100 m and at least 120 dB at 1 km. Near most drillsites and island construction operations in the Canadian Beaufort Sea, received 1/3-octave noise levels exceed 140 dB only within about 100 m of the industrial site. Received noise levels exceed 120 dB only within about 0.5 to 5 km (Appendix B). At distances greater than 0.5 to 5 km from the industrial site, a bowhead could probably hear other bowheads up to at least 1 km away, assuming a detection threshold of about 0 dB S:N. Thus, short-distance communication would be prevented only for whales closer to industrial sites than to potentially responding whales, and the zone where masking is likely to be important will be substantially smaller than the zone of audibility.

To calculate the degree to which masking might reduce communication range for a receiving whale at a given distance from an industrial site, several factors must be estimated. The ambient noise level and the received level of industrial noise at the whale's location must be determined. In addition, the source levels and propagation characteristics of whale calls (or other sounds of possible interest to whales) must also be estimated. Since propagation from two different sources must be considered, uncertainties about propagation losses will result in large uncertainties in the 'range reduction factors' attributable to masking. Hence, we have deferred any detailed quantitative analysis of masking until the end of this project, when more refined site-specific data on sound propagation are expected to be available.

Zone of Responsiveness. -- Gales (1982a,b) emphasized that the zone of influence should be estimated based on the noise levels that cause whales to react overtly. However, when his analyses were done, there was little specific information about the noise levels that would and would not elicit responses from baleen whales. Consequently, Gales could only estimate zones of potential audibility, not zones of responsiveness.

Reactions of several species of baleen whales to underwater sounds from industry have been studied intensively in recent years. Appendix B summarizes the data concerning reactions of bowhead and gray whales to drilling and island construction sounds. To assist in interpreting the bowhead data, Appendix B also includes previously unreported noise data on a 1/3-octave band level basis (unpubl. noise data from C.R. Greene, compiled by LGL). With the data that are now available, we can make at least rough estimates of noise levels that do and do not elicit responses from bowhead and gray whales. For gray whales, the data are from Malme et al. (1983, 1984). For bowheads, the behavioral data are from Richardson et al. (1985b,c), and the noise data are from Greene (1985 and unpubl.).

The studies mentioned above provided some direct indications about the ranges from industrial sites at which reactions were observed. However, the studies were not done at the specific sites in the Alaskan Beaufort Sea where drilling is occurring or planned. Hence, the zones of responsiveness determined in the previous studies provide only an indication of the likely zones of responsiveness at any particular site. Sound propagation phenomena at the site of interest must be taken into account before the presently available data can be translated into site-specific estimates of zones of responsiveness.

Whales might, in theory, react to underwater industrial noise at any range where it is audible. If so, the zone of responsiveness would be the same as the zone of audibility. However, the recent studies of bowhead and gray whales, and less detailed observations of some other species of baleen whales, indicate that whales often are seen within areas ensonified by industrial activities. In the Canadian Beaufort Sea during summer, bowheads have often been seen to engage in seemingly-normal activities within several kilometers of drillships or dredges, where the broadband industrial noise level was up to 16 dB above the average ambient level. In these cases, noise levels in the 1/3-octave band of maximum signal-to-noise ratio were up to 29 dB above average ambient (see Table B3 in Appendix B). A few individual bowheads have been seen at locations with even higher noise levels (Appendix B; Richardson et al. 1985b,c).

Noise playback experiments have also indicated that some bowheads show no detectable reaction to broadband noise up to about 20 dB above ambient levels (Table B4). On the other hand, some other bowheads show avoidance reactions (orient and move away) when drillship or dredge noise is received at broadband levels as low as about 10 dB above ambient (Appendix B). Again, corresponding figures for the 1/3-octave band of maximum noise were higher -- some bowheads avoided the source for S:N ratios as low as 16 dB whereas others showed no detectable reaction to S:N ratios as high as 38 dB. In the case of summering gray whales, avoidance reactions were observed when the broadband drillship noise is about 20 dB above ambient (i.e., when the one-third octave band of drillship noise having the highest signal-to-noise ratio exceeds the 50%ile ambient by 20 dB).

These results show that there is indeed a 'zone of responsiveness' for baleen whales near drillsites and island construction operations. However, if our assumption that whales can hear sounds with signal-to-noise ratios as low as 0 dB is even approximately correct, then the zone of responsiveness is considerably smaller than the zone of audibility. Not surprisingly, given the natural variability of whale behavior, the outer boundary of the zone of responsiveness is indistinct. Some individual whales react to industrial noise at lower received noise levels and signal-to-noise ratios than do others.

To translate the above information into estimated radii of responsiveness around specific industrial sites, data on source levels of the industrial sounds and on propagation losses at the specific sites of interest are necessary. The present project was designed to provide the necessary data, and to use those data to derive estimates of the zones of responsiveness.

2.3.2 Methods used for estimating zones of influence on whales

A primary objective of this study was to estimate the zone of potential influence of various drilling and dredging sounds that might occur at several specific sites in the Alaskan

Beaufort Sea. To do this, it was necessary to determine the source levels and spectral characteristics of those sounds. Propagation losses had to be estimated in order to calculate received levels at various distances from each site. We assumed that whales can detect sounds whose received levels equal or exceed the ambient noise level. By knowing the range of expected ambient levels at each site, we attempted to estimate the radii at which industrial sounds would attenuate to levels below ambient, and therefore become inaudible (Fig. 10). Given that most whales apparently react to industrial sounds only if they are at least 20 dB above the natural ambient level (Appendix B), we also aimed to estimate the radii at which industrial sounds would attenuate to 20 dB above ambient, 30 dB above ambient, etc. (Fig. 11).

2.3.2.1 Industrial Noise Level Measures*

The industrial noise level at which a specific whale behavioral response, such as avoidance, is expected can be specified as a level above the natural ambient (S:N ratio) or as a specific received level (Lr). The literature on animal response to man-made noise is very sparse and does not provide guidance on the best acoustic measure for quantizing observed reactions. Fortunately, the literature on human response to industrial noise is much more extensive. The studies of annoyance caused by specific sources such as traffic noise and aircraft flyover noise, as discussed by Kryter (1985), were reviewed since the annoyance reaction in humans can be considered to be analogous to the avoidance reaction in whales.

In general, annoyance reactions in humans have been found to correlate better with the absolute level of the intruding noise

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*By C. Malme, BBN Laboratories Incorporated.

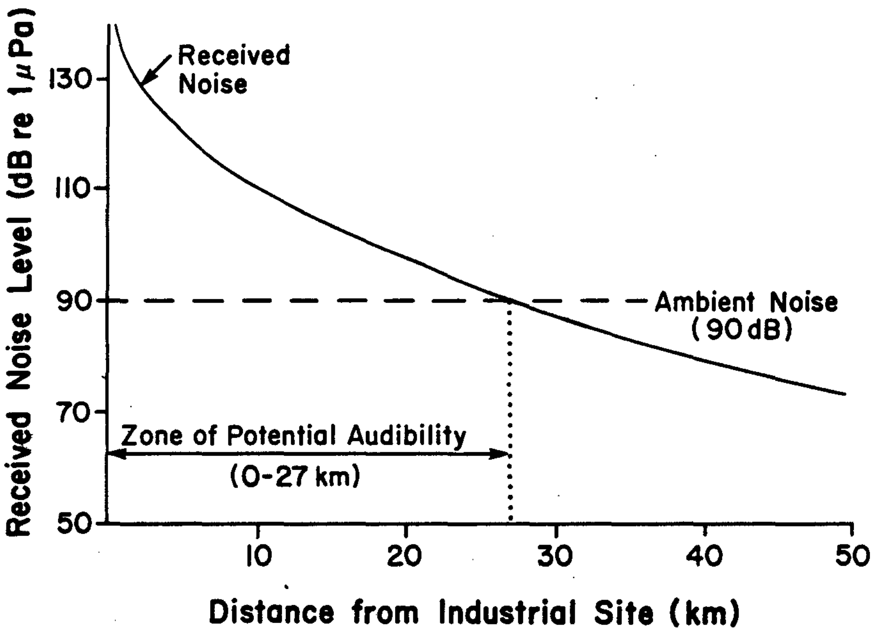

FIG. 10. PROCEDURE FOR ESTIMATING ZONE OF AUDIBILITY FROM INTERSECTION OF RECEIVED LEVEL VS RANGE CURVE WITH AMBIENT NOISE LEVEL. DATA ARE ARTIFICIAL.

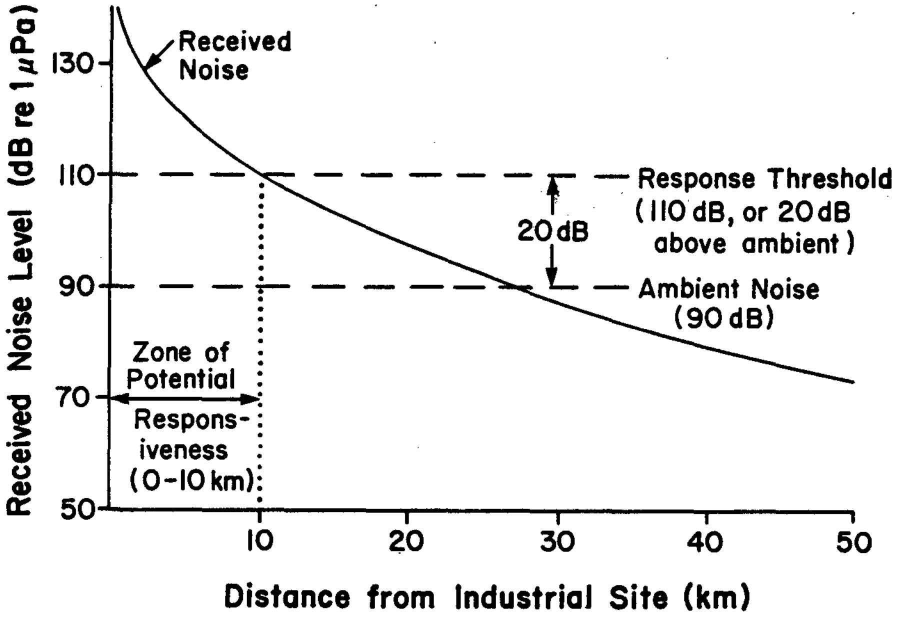

FIG. 11. PROCEDURE FOR ESTIMATING ZONE OF RESPONSIVENESS FROM INTERSECTION OF RECEIVED LEVEL VS RANGE CURVE WITH RESPONSE THRESHOLD. THE RESPONSE THRESHOLD COULD BE EITHER AN ABSOLUTE NOISE LEVEL (110 dB IN THIS CASE), OR A "SIGNAL : AMBIENT" RATIO (20 dB IN THIS CASE). DATA ARE ARTIFICIAL.

than with the maximum S:N ratio (Robinson et al. 1963). However, when the background noise is high, the threshold of annoyance with intruding noises has been found to be shifted upward (Pearsons 1966), (Spieth 1956). As a result, the usual practice in determining annoyance criteria for specific types of noise involves measurement of the sound levels which produce a quantifiable level of annoyance using psychoacoustic testing procedures. Correction factors based on the prevailing background noise levels in specific locations may then be applied to the criteria values (Kryter 1985).

The bowhead whale response data considered in this report have been analyzed by LGL considering a S:N ratio measure of response, whereas the gray whale response data were analyzed by BBN using, primarily, absolute received pressure levels. The data bases have not been reanalyzed to determine if a greater correlation with response is obtained for one or the other of the two possible measures of acoustic exposure. Until this is done, it is not appropriate to select a single acoustic parameter as the "correct" measure based on results for human noise exposure tests, since both the environment and the subject species are greatly different. As a result, the present report will provide both S:N ratio and absolute level measures of response for bowhead and gray whales.

2.3.2.2 Sources of Industrial Noise Considered

Zone of influence analyses were done for those drilling and island construction operations whose source spectra could be estimated reliably. After review of the industrial sources whose sounds were recorded during this study, five sources were selected for zone of influence analyses:

1. Dredge bucket being hauled up, as recorded at Erik site. This operation produced stronger sounds than other phases of the dredging cycle at Erik.
2. Tug ARCTIC FOX beginning to tow loaded barge away from Erik site. The strongest tug sounds emitted during any phase of the Erik tugboat/barge operation were recorded at this time.
3. Pair of tugs forcing a barge against Sandpiper artificial island.
4. Drilling by EXPLORER II drillship at Hammerhead drillsite (recorded by Greeneridge Sciences Inc. -- McLaren et al. 1986).
5. Drilling at Sandpiper artificial island (recorded by Greeneridge Sciences Inc. -- Johnson et al. 1986).

The circumstances when these recordings were made are described in Section 3.2. For each of these five types of industrial activity, BBN estimated source levels (i.e., theoretical levels at 1 m range) for various 1/3-octave bands, including the bands where levels were highest (see Section 3.2).

For each of these five industrial sources, detailed analyses were done on data from various 1/3-octave bands within the 40-4000 Hz range. The selected bands were those for which the source level was high relative to either (a) typical ambient levels in the corresponding band, or (b) source levels in adjacent bands. In most cases, the selected bands met both criteria. The rationale was that sound components whose source levels were high would be the ones that would be detectable at longest ranges. For most sources we considered two to four 1/3-octave bands, not just the one band with maximum signal-to-noise ratio. We did this because propagation losses depended on frequency. It was possible that the band with highest signal-to-noise ratio at the source might be one where propagation losses were high. If so, another band with slightly lower source level (or source S:N) might result in higher received levels because of a lower rate of propagation loss.

2.3.2.3 Zones of Audibility

Five of the six sites studied in 1985 were considered in the zone of audibility analyses; they are Orion (CIDS), Sandpiper, Hammerhead, Erik, and Belcher. Their locations and descriptions were provided in Table 1.

For each of these five sites, received levels at various distances were estimated assuming that, in turn, each of the five industry sources listed in the previous subsection were present. This was done by applying the site-specific propagation models (Section 3.3) to the source level estimates for the five industrial sources (Section 3.2). The site-specific propagation models are of the general form developed by Weston (1976), and take account of frequency, water depth, bottom slope, bottom reflection losses, and absorption. For each industrial source, LGL used BBN's propagation models and source level estimates to calculate received level as a function of distance, considering each of the 1/3-octave bands that had relatively high source levels.

The assumption that each of the five types of industrial operation listed in Section 2.3.2.1 might occur at each of the five sites is not completely realistic. An artificial island of the type at Sandpiper would not be built in water as deep as that at most of the other sites. Conversely, drillships like EXPLORER II do not drill in water as shallow as that at Sandpiper Island. Thus, some of the combinations of industrial sources and sites considered in this analysis are of only theoretical relevance.

For each analysis band, the range of potential audibility was considered to be the range where the received level equaled the expected ambient noise level (Fig. 10). Three different estimates of ambient noise were considered: the 5th, 50th and 95th percentiles. These represent situations when ambient noise is low, average, and high. Section 3.1 describes how BBN estimated these three percentiles for two groups of sites: (1) the shallow westernmost sites, Orion and Sandpiper; and (2) the deeper more easterly sites, Hammerhead, Erik and Belcher. Insufficient data on ambient noise were available to develop separate ambient noise statistics for each individual site, e.g., for Orion as distinct from Sandpiper.

For a given site, industrial source, and ambient noise condition, we obtained estimates of the radius of audibility of sounds in each of the 1/3-octave bands with relatively high source levels (Appendix A). The zone of audibility was considered to be the maximum of these values. The radius at which the received level equaled the assumed ambient level can be determined from graphs of received level vs. range (Fig. 12). However, the values tabulated in the Results section and Appendix A were actually determined mathematically and printed out by the computer program used to perform the model calculations (see sample printout in Fig. 12).

Because the sites of interest are on a continental shelf where the water depth increases gradually from south to north, radii of audibility were expected to depend on bearing from the site. Orion and Sandpiper Island are south of the main autumn migration corridor of bowhead whales (Fig. 2; Davis et al. 1985; Ljungblad et al. 1985a). Consequently, for these sites, we made

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WESTON SHALLOW-WAT. SOUND PROP'N MODEL                              Run date=860412
LGL version for Apple II, including absorption term; Vers. 1.3,  5 Apr 86

Site = ORION/CIDS                             Source type = EXPL.II.HAMHD

SOURCE LEV (DB)          161                  LOCAL ANOMALY (DB)      14
FREQUENCY (HZ)           240                  WAT.DEP @ SOURCE (M)    27
BOTTOM SLOPE (-1 TO 1) 0                      SINE (CRIT.ANG.), 0-1   .8
BOTTOM REFL. 'B', 0-5  .7                     SOUND SPEED (M/S)       1435


Max R for sph.spr. = .01 km                   Max R for cyl.spr. = .09          km
Max R for multimode= 6 km                     Max believable R   = 32 km

Ranges where RL = various standard levels:
RL= 75    R= 46.4     RL= 80    R= 40.1     RL= 85    R= 34       RL= 90    R= 28.1
RL= 95    R= 22.4     RL= 100   R= 16.9     RL= 105   R= 12       RL= 110   R= 7.6
RL= 115   R= 4.7      RL= 120   R= 2.5      RL= 125   R= 1.3      RL= 130   R= .619
RL= 135   R= .298     RL= 140   R= .15      RL= 145   R= .06      RL= 150   R= .024

Ranges where RL = 5%, 50%, 95%ile of ambient:
5% (60 dB):  R= -9       50% (84 dB):  R= 35.2     95% (95 dB):  R= 22.4

Ranges where RL = median ambient +5 dB, +10 dB, etc.:
Med+5 :   R= 29.3     Med+10:   R= 23.5     Med+15:   R= 18       Med+20:   R= 12.9
Med+25:   R= 8.4      Med+30:   R= 5.3      Med+35:   R= 2.9      Med+40:   R= 1.4
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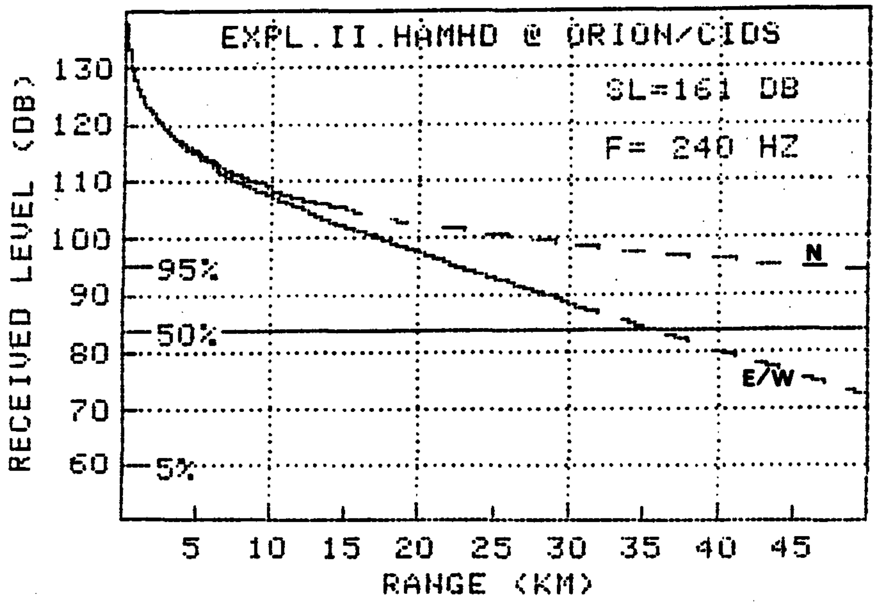


FIG. 12. **SAMPLE RESULTS FROM WESTON SHALLOW-WATER SOUND PROPAGATION MODEL APPLIED FOR PURPOSES OF ESTIMATING ZONES OF NOISE INFLUENCE AROUND A SPECIFIC INDUSTRIAL SITE. THE PRINTOUT IS FOR THE 'BOTTOM SLOPE 0' (EAST/WEST OF SITE) CASE. THE GRAPH ALSO SHOWS RESULTS FOR THE 'BOTTOM SLOPE 0.001' (NORTH OF SITE) CASE. R = Range in kilometers; RL = Received level in dB re 1 μPa; SL = Source Level in dB re 1 μPa at 1m range; F = Frequency in Hz.**

two estimates of the zone of audibility. One analysis assumed a constant water depth with increasing range (representing propagation parallel to the depth contours, i.e., east-southeast and west-northwest). The other analysis simulated propagation to the north-northeast, and assumed that water depth increased with increasing range at a rate appropriate to the site in question. The Erik and Belcher sites are within the autumn migration corridor of bowheads (Fig. 2), and whales could travel westward either south or north of these sites. Hence, three estimates of the zone of audibility were made for Erik and Belcher, assuming decreasing, constant, and increasing water depth with increasing range. Since the propagation model for Hammerhead was less well established than that for the other four sites, only the 'constant water depth' approach was applied there.

In the absence of information about the relative auditory sensitivities of bowhead and gray whales, both species were assumed to be able to detect industrial noise only when its received level equaled or exceeded the ambient level in the corresponding 1/3-octave band. Thus, the estimated zones of audibility were the same for both species.

2.3.2.4 Zones of Responsiveness

Data from recent studies of the behavioral reactions of bowhead and gray whales to industrial noise are summarized in Appendix B. These data were used to estimate the industrial noise levels and industrial noise-to-ambient noise ratios at which the two species do and do not react. There is no one threshold value above which all whales react and below which none react. Instead, above some minimum industrial noise level the probability of reaction appears to increase with increasing noise.

In the case of bowheads, few if any individuals appear to react overtly to industrial noise levels less than 15 dB above the natural ambient level. Some individuals apparently tolerate much higher levels (see Tables B.3, B.4 in Appendix B). However, a minority of the bowheads move away at the onset of drillship or dredge noise whose level is 20 dB or more above ambient. Roughly half of the bowheads move away at the onset of sounds with a signal-to-noise ratio of 30 dB, or an absolute received level of 110 dB. A few bowheads apparently tolerate noise levels up to 40 dB above ambient. These levels and industrial-to-ambient ratios are based on levels in the 1/3-octave band with the maximum level of industrial noise relative to average ambient noise in the corresponding band (Appendix B). As a first approximation, the median zone of responsiveness of bowhead whales could be defined as the area where the received noise level is 30 dB or more above ambient. However, it should be noted that some individual bowheads probably respond at lower S:N ratios (i.e., greater ranges), and others apparently do not respond unless S:N is more than 30 dB.

In the case of migrating and summering gray whales, more precise data are available concerning the probability of avoidance as a function of received noise level (Malme et al. 1983, 1984, 1986; Appendix B). Calculations for summering gray whales in the Bering Sea applied to the Beaufort Sea environment, indicate that a 0.1 probability of avoidance would occur for received broadband industrial noise levels of 110 dB re 1μPa and a 0.5 probability of avoidance would occur when the absolute received level is 120 dB. This corresponds to industrial : ambient noise ratios of about 20 to 30 dB, respectively.

As a first approximation, the zone of responsiveness of gray whales, like that of bowheads, is considered to be the area where the received noise level is 20 dB or more above ambient.

The radii within which the industrial noise level would exceed the median ambient level by 20 dB, 30 dB, and 40 dB (possible criteria for zone of responsiveness) were determined in the same way as the radii where industrial noise equaled ambient noise (zone of audibility, Section 2.3.2.2). We also estimated the radii within which the absolute level would exceed 110 dB which is another possible criterion of responsiveness. Separate calculations were done for each combination of five industrial sources, five sites, and 1 to 3 bottom slopes per site, considering the 1/3-octave bands that had high source levels.

It should be recognized that there is considerable variability in responsiveness of different whales, and there may be differences of opinion about the most appropriate criterion for defining the zone of responsiveness. In addition, future studies may refine present information about response thresholds. Hence, we have also calculated the ranges where the received levels would diminish to a variety of other S:N ratios besides 20, 30, 40 dB (Fig. 12). Furthermore, we determined the ranges where the received level would equal various absolute levels, e.g., 100, 110, 120 and 130 dB re 1 μPa (Fig. 12). All of these figures are tabulated in Appendix A but some are not considered in the Results.

3. RESULTS

This section presents the results concerning ambient noise statistics, industrial noise spectra and acoustic transmission loss models, and concludes with detailed discussions of potential zones of influence on bowhead and gray whales.

3.1 Ambient Noise Statistics

Presented in this section are ambient noise statistics calculated from data measured at three sites: Orion (the location of the CIDS in Harrison Bay), Sandpiper Island, and the Corona site. Measurements of the noise field at the Erik site and the Belcher site were contaminated by high level seismic signals and are not presented here. We hope to be able to make these measurements during the 1986 field effort. In addition to the short-term results calculated for specific sites during the 1985 season, ambient noise level statistics are presented for two regions of the Beaufort Sea during the September-October migration period. These estimates are based on information from the NOAA Climatic Atlas for the Beaufort Sea area (Brower et al. 1977) together with our data and other reported arctic ambient noise data (Urick, 1983; Moore, et al. n.d[1984]). Two ambient noise level statistical estimates are presented, one representative of the shallow water sites (Orion and Sandpiper) and the other for the deeper water locations (Hammerhead, Erik and Belcher). These results are used in Sec. 3.4 to predict whale behavioral responses.

For this report, the measurements made at the Corona site are used as being representative of the Hammerhead, Erik and Belcher sites because the water depths at these sites are similar.

3.1.1 Ambient Noise at the Corona Site

Ambient noise measurements were made at the Corona site on 8 September 1985, when no industrial activity was present. Data were collected at two sensor depths, 10 and 20 m, in a water depth of 35 m. Sea state 3 conditions existed with some breaking waves, winds 10-15 kts and there was no ice. Figures 13 and 14 show the measured noise statistics at the shallow and deep depths, respectively. Between 50 and 500 Hz, the spectrum level of the noise decreases with increasing frequency at a rate of 6-8 dB per octave. Between 500 and 2 kHz, the spectrum level falls off at 5-6 dB per octave. The shapes of both plots are typical of data from open ocean deep water. Under calmer conditions we would expect the difference in noise level between the 5% and 95% levels to decrease with increasing frequency, as seen at other sites in the Beaufort (see below).

Our Corona data are combined with historical information (as noted above) to produce a more representative estimate of the expected variability in ambient noise levels for areas in the Beaufort Sea with similar water depths (Hammerhead, Erik and Belcher) and environmental conditions (wind and ice cover). We considered only the data environmental from the September-October migration period. The results are displayed, on a third octave basis, in Fig. 15. Since we lack measured ambient noise data at the Erik and Belcher sites, the noise level estimates presented in Fig. 15 are assumed to be representative of the noise field at these two sites and are used in Sec. 3.4 for the behavioral analyses.

3.1.2 Ambient Noise Near Orion in Harrison Bay

On 28 and 29 August, 1985, BBN measured the ambient noise field near Orion, the Concrete Island Drilling System (CIDS)

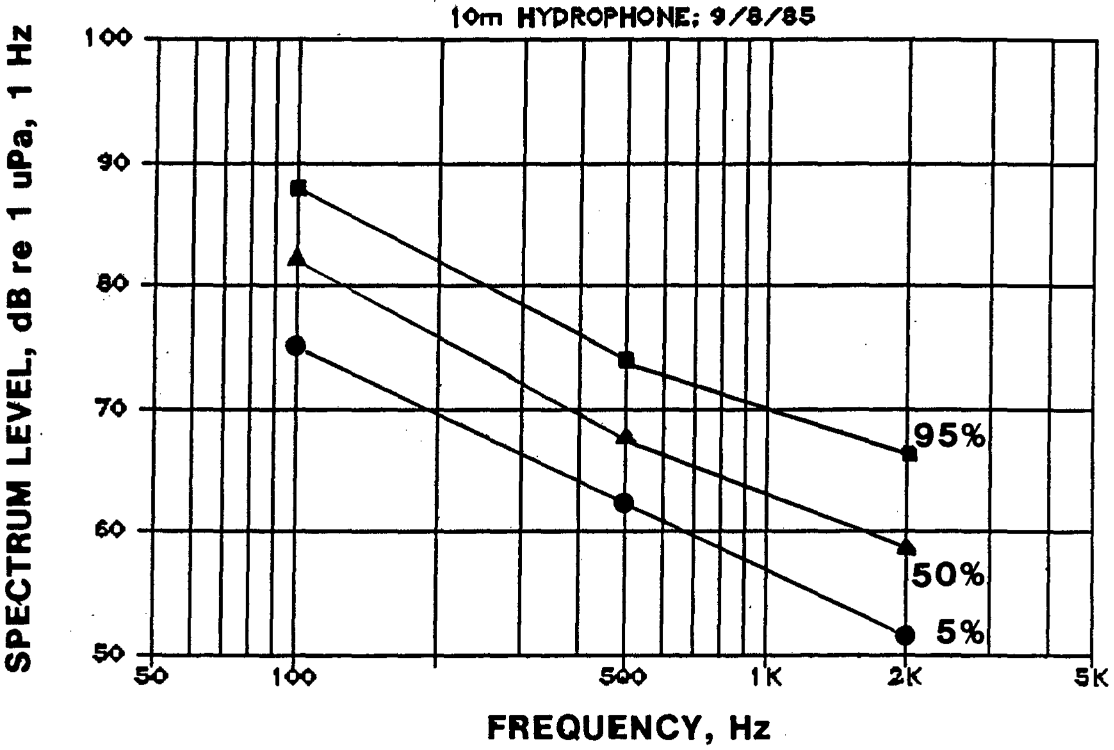


FIGURE 13. MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES AT THE CORONA SITE, 9/8/85. HYDROPHONE AT 10 m DEPTH. VALUES ARE EXPRESSED AS SPECTRUM LEVELS.

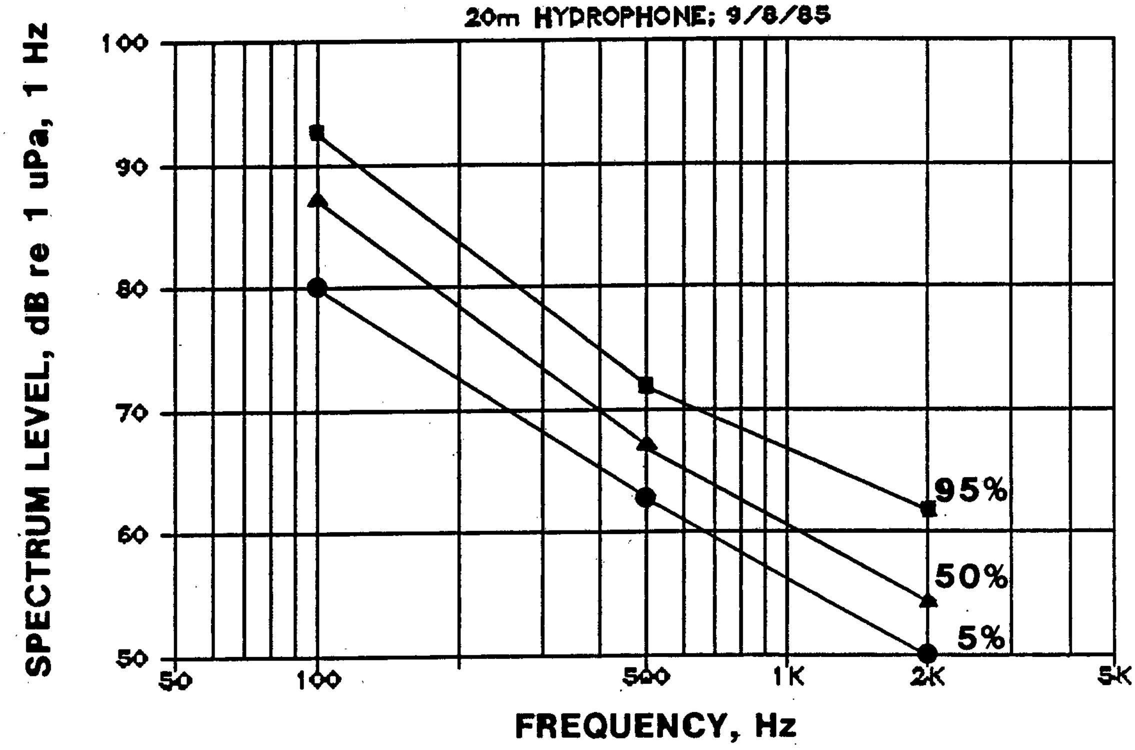


FIGURE 14. MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES AT THE CORONA SITE, 9/8/85. HYDROPHONE AT 20 m DEPTH. VALUES ARE EXPRESSED AS SPECTRUM LEVELS.

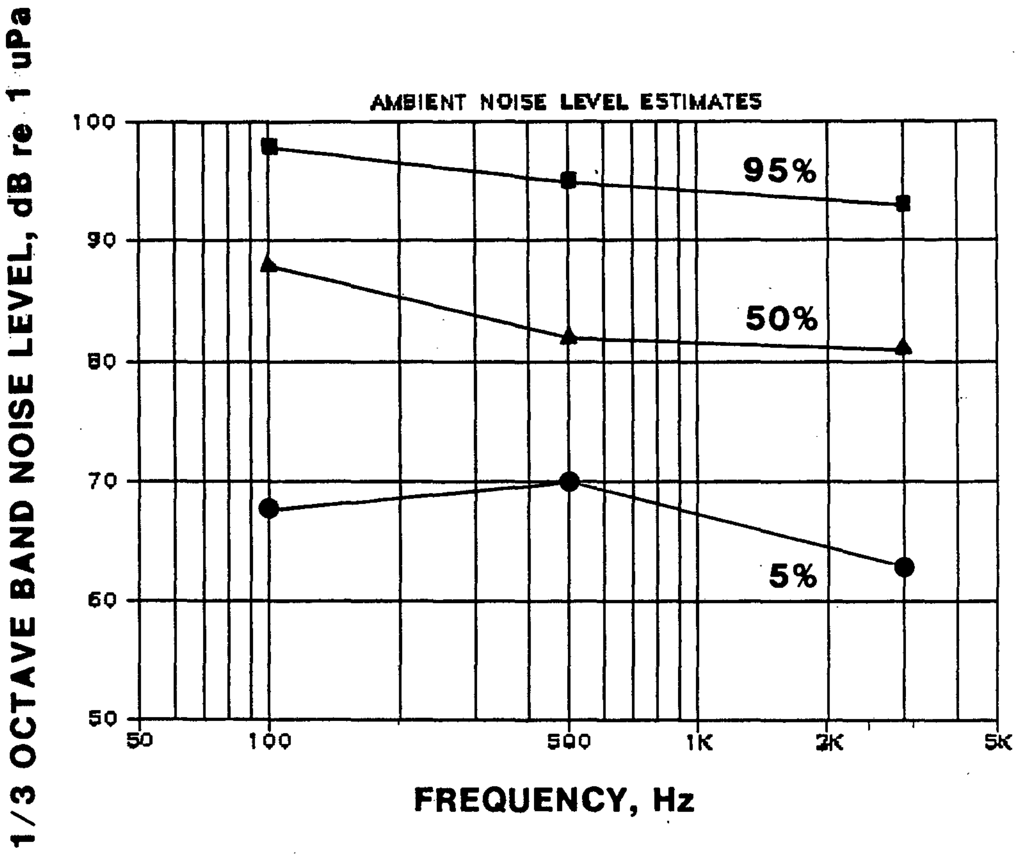


FIGURE 15. AMBIENT NOISE LEVEL PERCENTILE ESTIMATES FOR THE SEPTEMBER-OCTOBER MIGRATION PERIOD AT THE HAMMERHEAD, CORONA, BELCHER, AND ERIK SITES. VALUES ARE EXPRESSED ON A 1/3 OCTAVE BAND (OB) BASIS.

site. CIDS was not drilling but had recently drilled test holes and was transmitting downhole pings at 7 second intervals during most of our site visit. These pings were frequency modulated sounds (FM sweeps with a 0.5 second in duration) that started at about 900 Hz and ended at about 200 Hz. Upon examination, this sound proved highly directional and our data base is insufficient to make a reliable estimate of its source strength this year. The CIDS platform at Orion also occasionally transmitted two continuous narrowband tonals at 2 and 4 kHz. These tonals interfered with our ambient noise measurements as noted below.

In order to avoid man-made sounds, the ambient noise field was sampled at a range of 3 km from the CIDS platform on 29 August after downhole pinging had stopped. Data were recorded from a hydrophone suspended at 8 m in a water depth of 16 m. The sea state was 0-1 with light winds, overcast skies and a 1/10-2/10 ice cover. Because the 2 and 4 kHz tones were present, third octave band analyses were performed at 100, 500, 1000 and 3000 Hz. The results are shown on a spectrum level basis in Fig. 16. The dual gradient structure is typical of noise spectra in shallow water environments as described in the literature (e.g. Urick, 1983). Note that the variability in noise level decreases with increasing frequency.

3.1.3 Ambient Noise Near Sandpiper Island

The ambient noise field near Sandpiper Island was measured on three separate occasions during September 1985 (9/1, 9/4 and 9/5). Earlier measurements (8/25, 8/27, 8/30) were contaminated by either small boat activity or tug noise. The results from both 9/1 and 9/4 are presented here because they were gathered under different environmental conditions. (The 9/5 data are similar to the 9/4 data.)

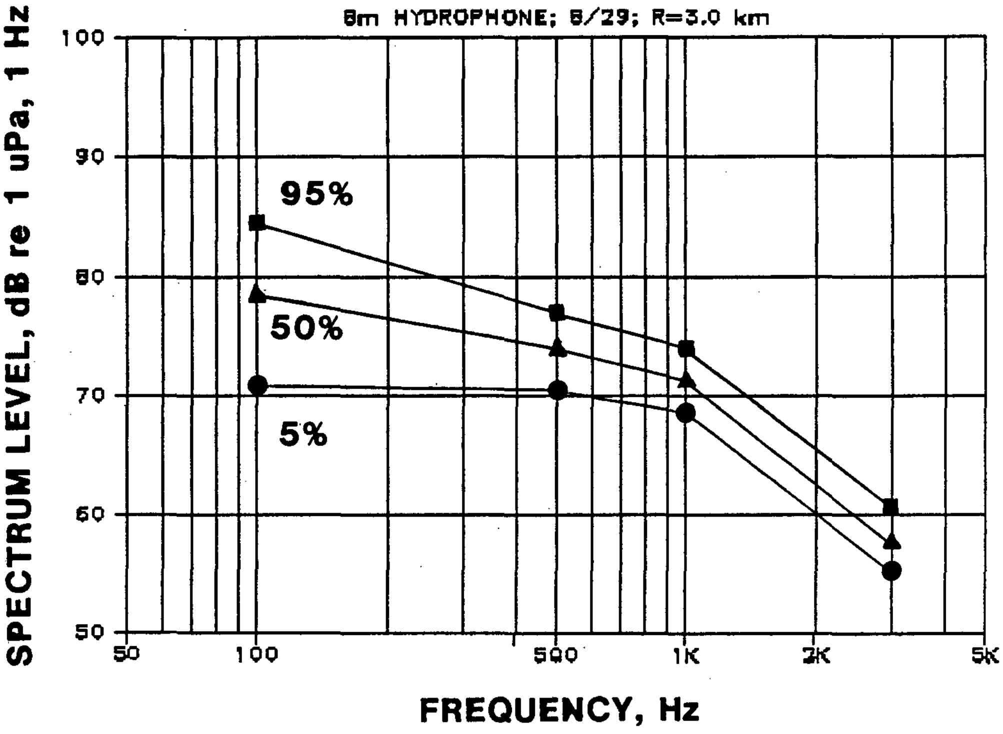


FIGURE 16. MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES AT THE ORION SITE, 8/29/85. HYDROPHONE AT 8 m DEPTH. VALUES ARE IN TERMS OF SPECTRUM LEVEL.

Figures 17 and 18 show the spectrum level results for two sensor depths (3 and 10 m, respectively) on 1 September. No drilling activity was observed but the island was occupied and site preparations were underway. The weather conditions were as follows: 10-15 kt winds, sea state 1-2, overcast skies and 6/10-8/10 ice cover. Because of the ice, we were unable to make our measurements as far north as the island. These data were acquired 2.4 km to the southeast of Sandpiper in water depths of about 11 m. There was no indication of industrial noise in the acquired data.

Figures 19 and 20 show the results at the same two sensor depths measured on 4 September, 1985. Our measurement platform was located roughly 7 km from Sandpiper and 4.1 km from Northstar Island on a line connecting the two. (Northstar is another artificial island similar to Sandpiper Island.) These results represented our quietest observations near Sandpiper. The sea state was 0-1 with light winds and 1/10-2/10 ice cover. The water depth was 14 m. No drilling activity was observed on either island and no evidence of industrial noise is apparent in the ambient data.

By combining the measured data for both the Orion site and Sandpiper Island locations with historical information (Brower et al. 1977), we can estimate the seasonal (September/October) ambient noise levels on a percentile basis as shown in Fig. 21. These curves are representative of geographic locations with water depths and environmental conditions that resemble those at the CIDS and Sandpiper sites, i.e. 15 m water depth, and similar wind and ice cover characteristics. Only data for the September-October migration period were used to generate this figure. Figure 21 forms the basis for some of the behavioral analyses in Sec. 3.4.

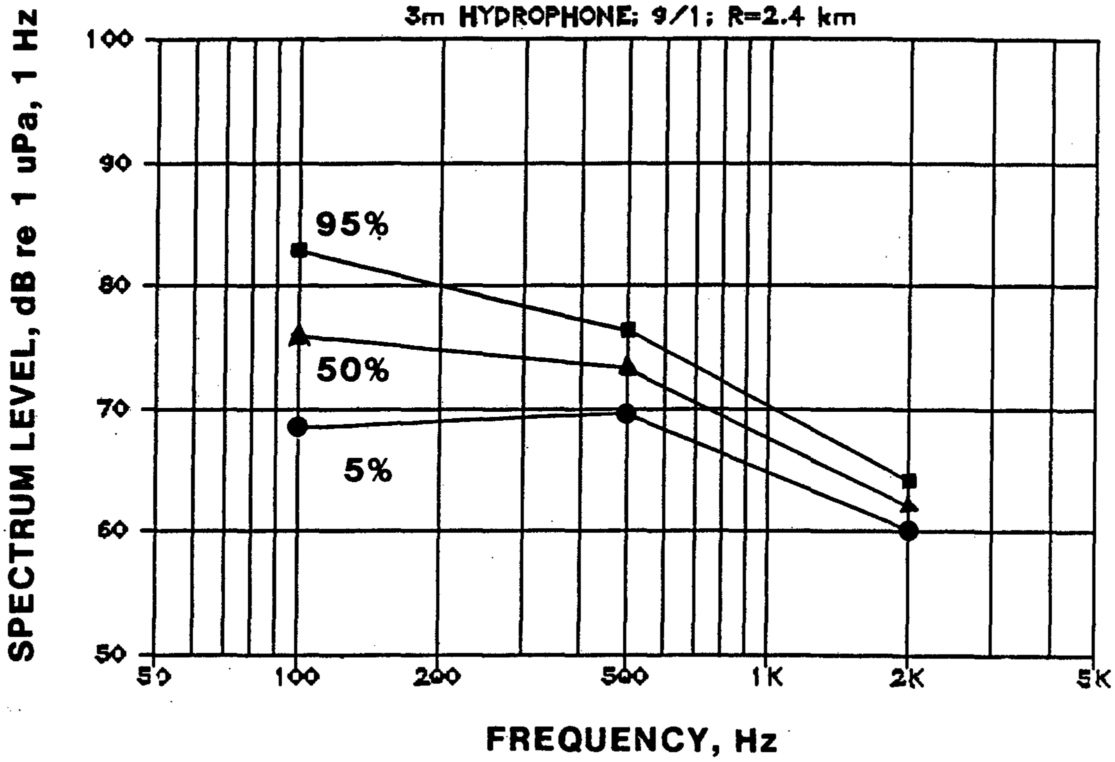


FIGURE 17. MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES NEAR SANDPIPER ISLAND, 9/1/85. HYDROPHONE AT 3 m DEPTH. VALUES ARE IN TERMS OF SPECTRUM LEVEL.

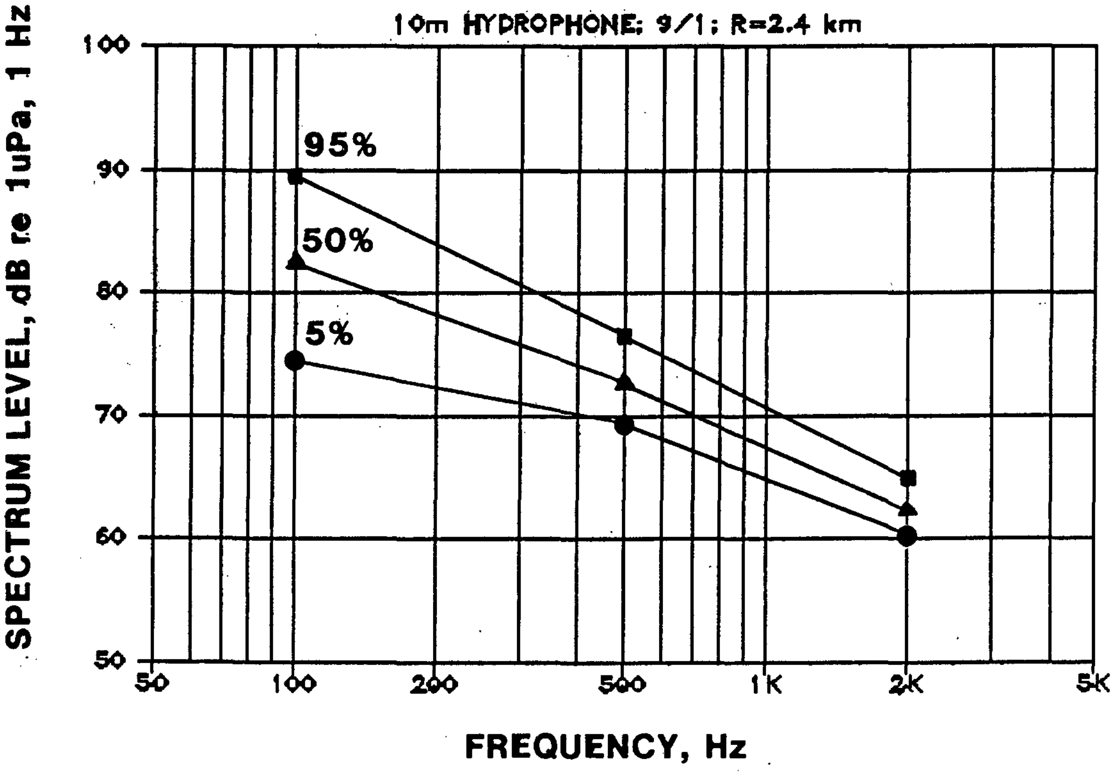


FIGURE 18. MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES NEAR SANDPIPER ISLAND, 9/1/85. HYDROPHONE AT 10 m DEPTH. VALUES ARE IN TERMS OF SPECTRUM LEVEL.

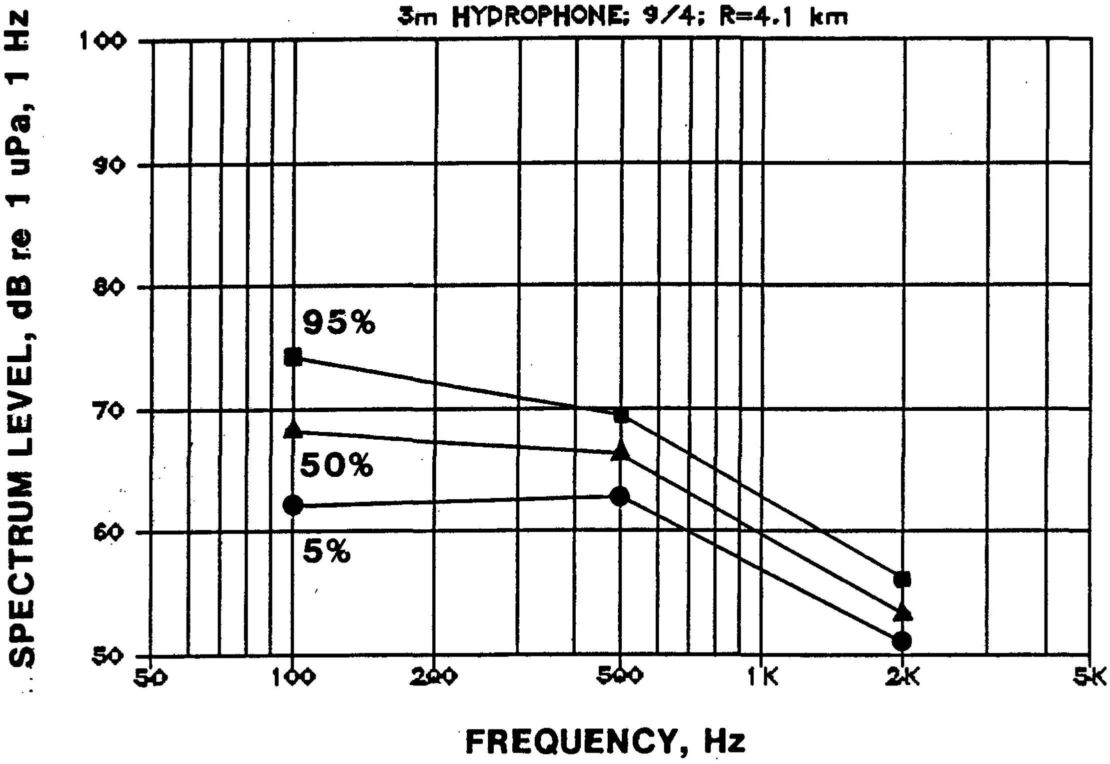


FIGURE 19. MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES NEAR SANDPIPER ISLAND, 9/4/85. HYDROPHONE AT 3 m DEPTH. VALUES ARE IN TERMS OF SPECTRUM LEVEL.

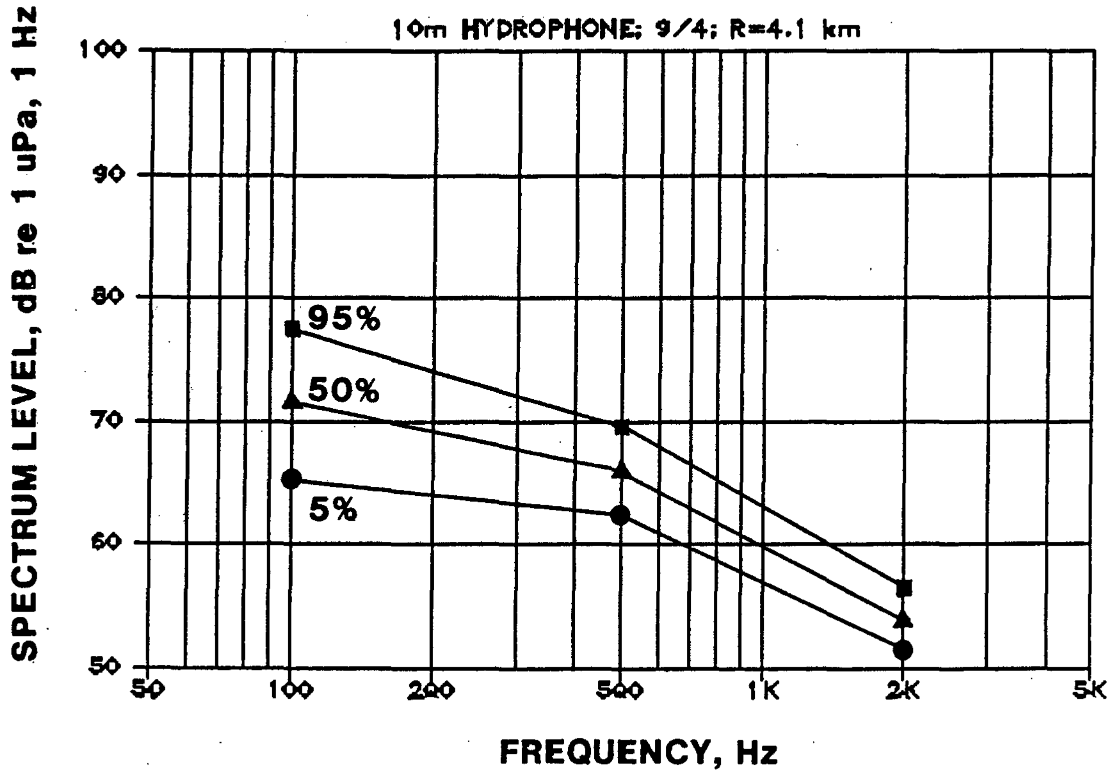


FIGURE 20. MEASURED SHORT-TERM AMBIENT NOISE LEVEL PERCENTILES NEAR SANDPIPER ISLAND, 9/4/85. HYDROPHONE AT 10 m DEPTH. VALUES ARE IN TERMS OF SPECTRUM LEVEL.

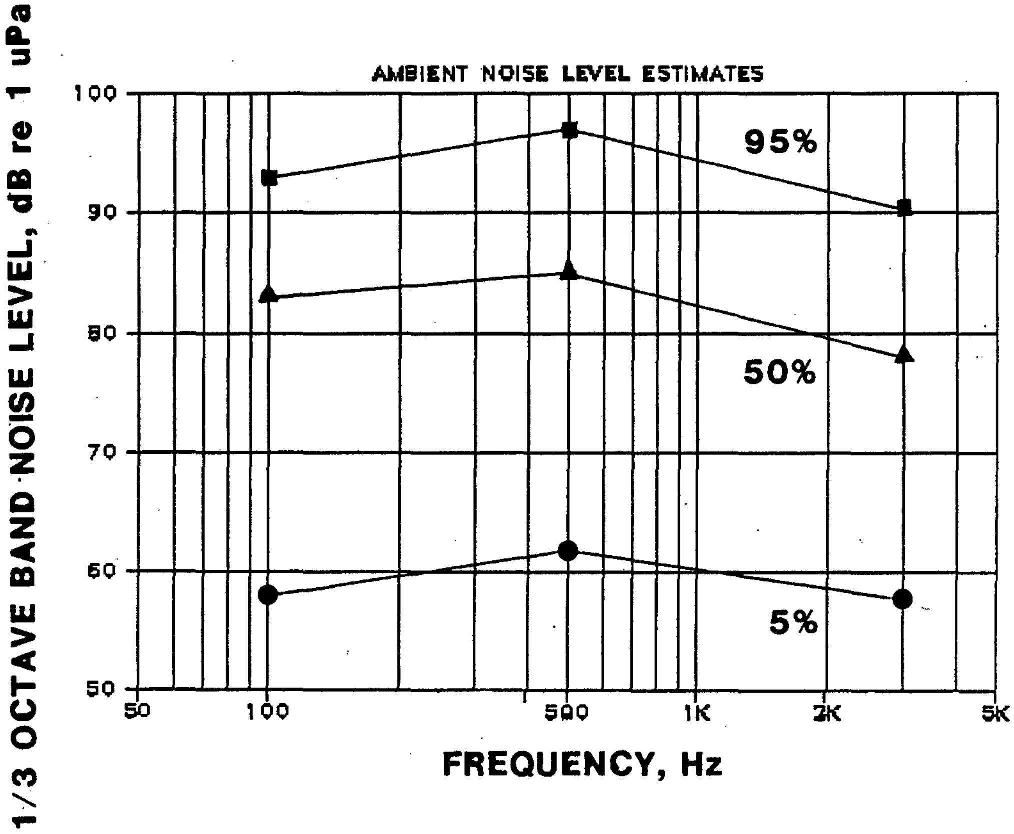


FIGURE 21. ESTIMATED AMBIENT NOISE LEVEL PERCENTILES FOR THE SEPTEMBER-OCTOBER MIGRATION PERIOD AT THE SANDPIPER AND ORION SITES. VALUES ARE EXPRESSED ON A 1/3 OCTAVE BAND BASIS.

3.2 Industrial Noise Sources

Based on measurements made in 1985, we have analyzed the radiated noise from five acoustically significant industrial activities. These are dredge operation and tug maneuvers at the Erik site, a pair of tugs forcing a barge against Sandpiper Island, EXPLORER II during drilling operations at the Hammerhead site, and drilling activity on Sandpiper Island. Each will be examined individually below. The first three were measured by BBN last fall, the latter two were measured by Greeneridge Sciences also last fall and graciously given to us by Charles Greene. Unfortunately, we were not able to gather any drilling noise data from CIDS at the Orion site in Harrison Bay, which was waiting for the finish of the fall bowhead migration. Regarding the other sites under investigation, Corona and Belcher were unoccupied until after our field measurement period.

In the following sections, we discuss the five source level estimates. Each consists of a source level versus frequency plot and a sample narrowband power spectrum of the received signature at a specified range.

3.2.1 Dredge Operation at the Erik Site

BBN visited the Erik site twice in 1985 on September 9 and 13. The data presented here are from the 13th. On the 9th, the fog was too thick to observe the dredge operation and coordinate the acoustic measurements with specific activities. The weather on 13 September was clear, sea state 0-1, light winds with only an occasional piece of sea ice.

During the 13th, we observed the dredge ARGILOPOTES drop its clam-shell into the water, winch it back up, move the clam-shell along an overhead rail and empty its contents into an attendant barge. Measurements were made at two depths, 7 and 12 m. The water depth was about 38 m. No acoustic noises attributable to the dredge itself were observed except during the clam-shell retrieval phase. Two sounds were apparent during retrieval. First, a "clank" was heard as the clam-shell jaws closed underwater. This sound was very short, and although audible, had little acoustic energy and therefore is not addressed here. Second, the dominant sound occurred while the winch hauled the loaded clam-shell back to the surface and was produced by the motor which drove the winch. The radiated noise was rich in harmonics and a sample narrowband spectrum is shown in Fig. 22. Note that a strong fundamental frequency, 125 Hz, was not observed. Examination of this and other data samples indicates that significant acoustic radiation occurred at frequencies below 3.5 kHz.

Throughout these measurements, seismic exploration activity in the vicinity was very prevalent. Examination of the time series from one of the hydrophones on a strip chart recorder indicates that two seismic vessels were in operation. One vessel generated impulses roughly every 9 sec and the other at 14 sec intervals. Due to this interference, third octave band analysis is not appropriate because the measurement intervals between impulses were not of sufficient duration to generate an uncorrupted third octave band spectrum, much less permit any spectral averaging to get a statistically stable sample. If we averaged over an 8 sec period, the seismic noise masked the dredge noise at frequencies below about 400 Hz and significantly affected higher frequencies.

Narrowband analysis on the HP3562 dynamic signal analyzer can produce spectra from shorter data sampling intervals for the same spectral bandwidth. Judicious manual operation allowed us to calculate uncontaminated results. Fortunately, the dredge

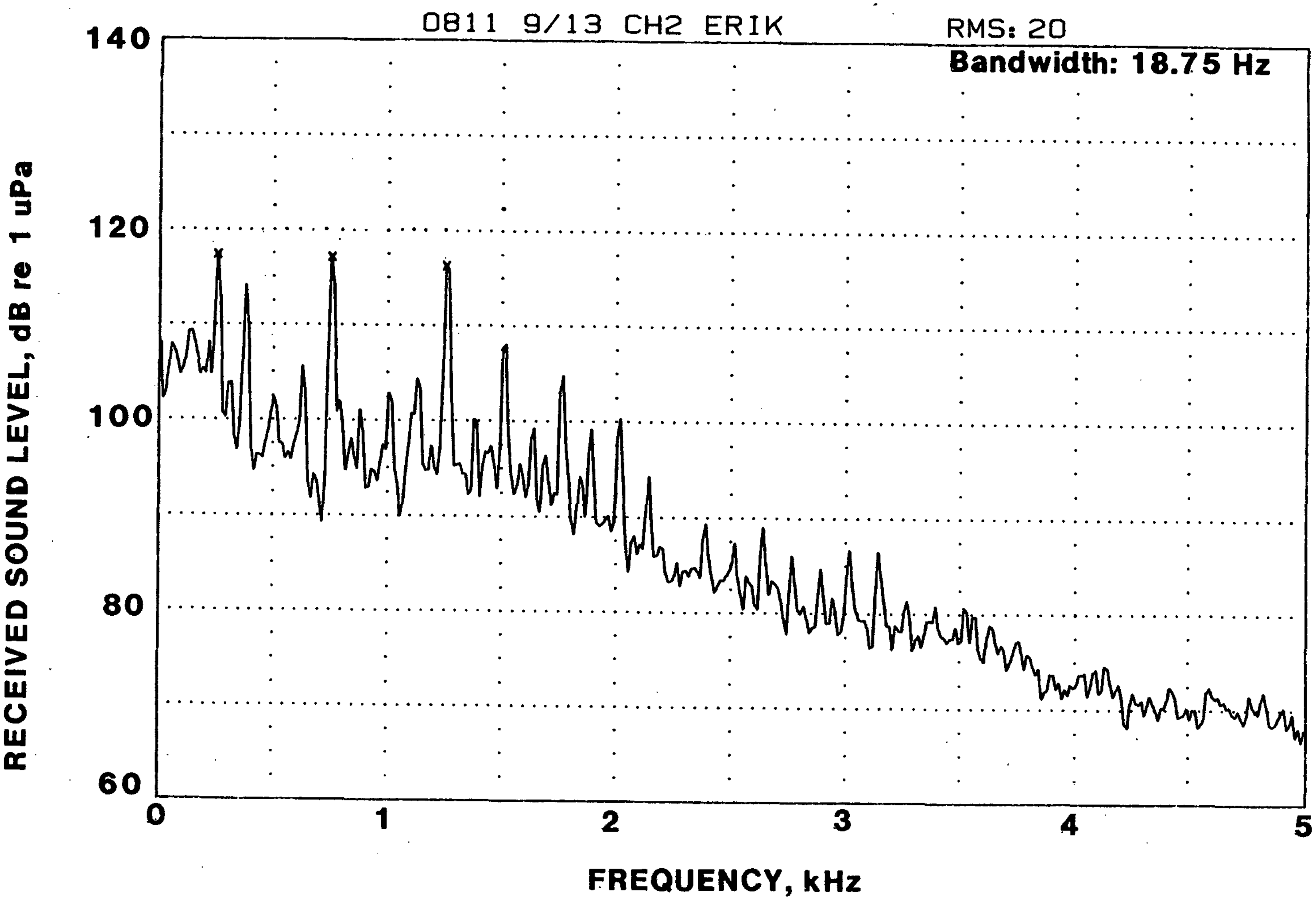


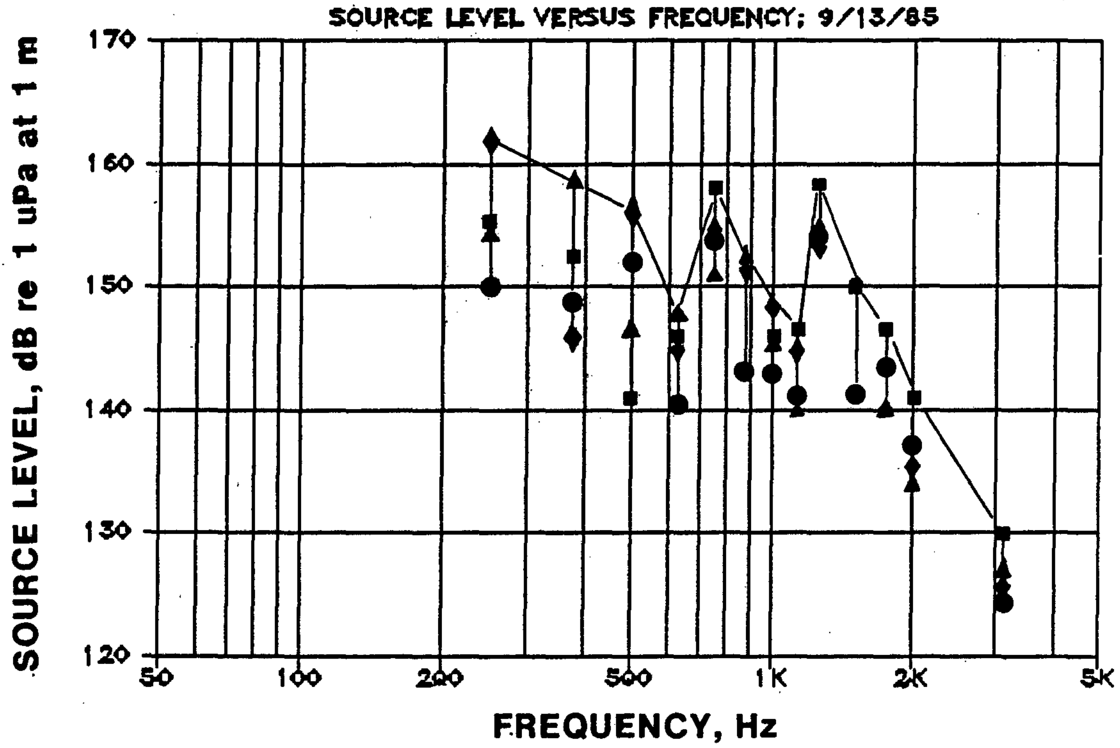
FIGURE 22. SAMPLE NARROWBAND RECEIVED SPECTRUM OF DREDGE NOISE FROM THE ARGILOPOTES AT THE ERIK SITE, 9/13/85.

acoustic signature is dominated by reasonably narrowband tonals. If a third octave band encompasses a single strong tonal whose level is $\geq$ 9 dB above the levels of the rest of the frequencies in that band, the third octave band level is equal to the tonal level, to within 1 dB. Examination of Fig. 22 shows that for the most energetic tonals (250, 750 and 1250 Hz), these narrowband components dominate their respective third octave bands by more than 9 dB and therefore their third octave band levels equal the tonal levels.

Four independent measurements of clam-shell retrieval sounds (taken at four ranges) were corrected for the site specific TL characteristics (Sec. 3.3). The tonal levels were then extracted and are shown in Fig. 23. Below 1.25 kHz, source level estimates for each harmonic are displayed. At higher frequencies, a few tonals are presented to show the signature envelope. We hypothesize that the variability is due to differences in the weight of clam-shell loads and changes in the acoustic propagation characteristics during the measurements as the water masses changed and the receiver platform drifted.

3.2.2 Tug Operations at the Erik Site

The tug ARCTIC FOX assisted the dredge ARGILOPOTES at the Erik site on the 13th of September. Its function was to transport a barge roughly 0.5 n.m. from the dredge, dump the material and return the barge to the dredge. The procedure consisted of backing the tug away from the dredge, maneuvering to the opposite side of the dredge, attaching to the barge, and hauling the barge off. The first and last steps produce the highest level radiated noise because the tug propeller is cavitating. No sounds were heard as the barge was emptied. (The environmental conditions are described in Sec. 3.2.1)



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

NOTE: The symbols indicate levels observed during four different times and modes of dredge operation to indicate fluctuations in levels being observed.

FIGURE 23. ESTIMATED SOURCE LEVELS OF TONES FROM THE DREDGE ARGILOPOTES AT THE ERIK SITE DURING HOPPER RETRIEVAL, 9/13/85.

Figure 24 shows a sample narrowband received signature taken while the tug backed away from the barge. The low frequency components below about 400 Hz are due to local seismic activity. In general, the radiated tug noise is broadband with no significant tonals. The propeller blade rate harmonics were masked by the seismic signals.

Figure 25 displays source level estimates for the ARCTIC FOX during four modes of operation. As noted in the previous section, seismic activity prevented third octave band analysis directly. So again, narrowband analysis was employed. Because the tug noise varies relatively smoothly with frequency, the peak envelope of the measured narrowband spectra was sampled at 500 Hz intervals and these values corrected to third octave band levels by adding 10 log (BW) where BW is the appropriate third octave bandwidth for each center frequency. Finally, these levels were corrected for the site specific TL to produce the source level estimates displayed in Fig. 25.

3.2.3 Twin Tugs at Sandpiper Island

The transport of heavy materials and equipment to and from artificial islands is carried out mainly by barges, which are either self-propelled or pushed by tugs. On 30 August, 1985, BBN measured the radiated noise from a pair of tugs which were keeping a barge pressed against the loading ramp at Sandpiper Island. Both vessels applied high thrust to the barge and therefore propeller cavitation noise levels were high. On that day, the wind speed was 0-5 kt, the sea state was zero and the ice cover about 1/10.

A sample narrowband received level spectrum is shown in Fig. 26. In general, the radiated noise is broadband in character. The few narrowband components were unstable in both

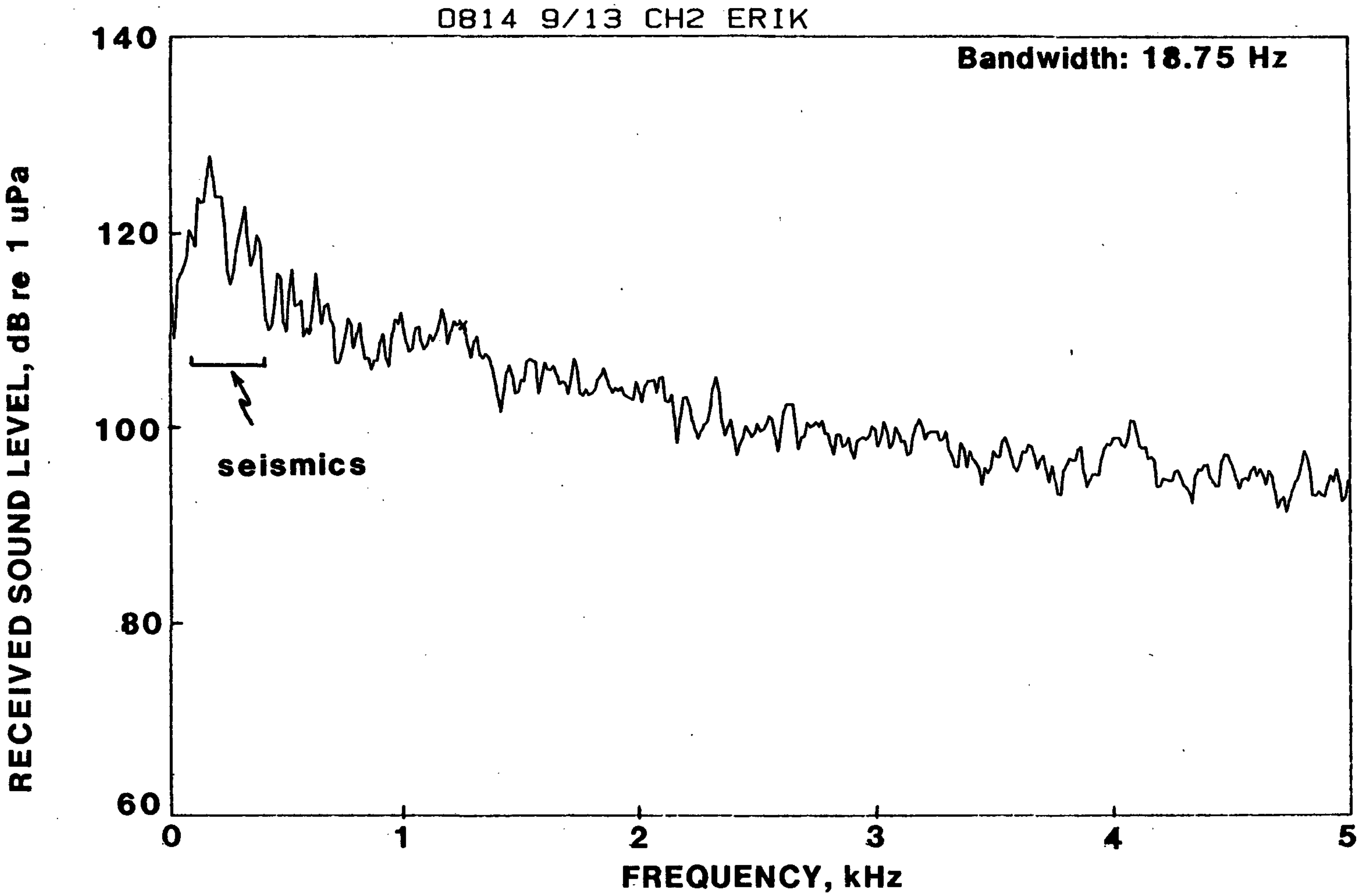
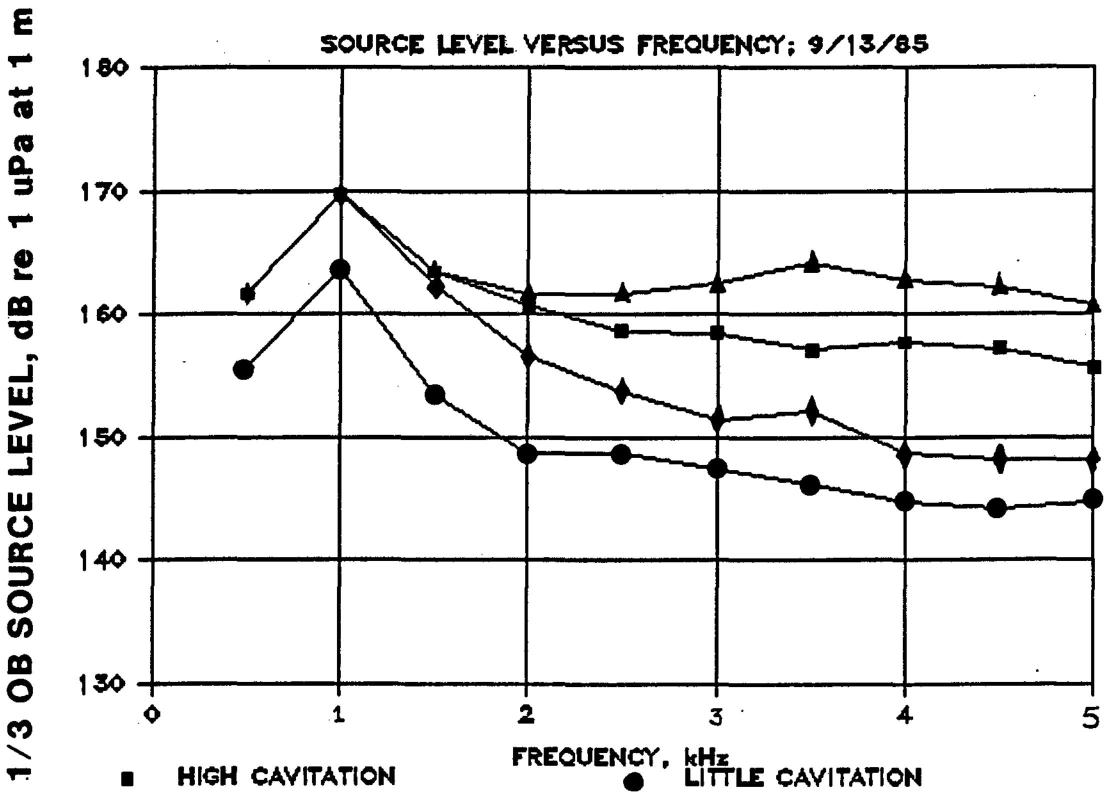


FIGURE 24. SAMPLE NARROWBAND RECEIVED SPECTRUM OF RADIATED NOISE FROM THE TUG ARCTIC FOX AT THE ERIK SITE, 9/13/85.



Key: ▲ = source level estimates during tug with fully loaded barge

■ = tug backing from barge (high thrust, low speed, high caviation)

♦ = tug maneuvers before attaching to barge

● = tug transit without barge

FIGURE 25. ESTIMATED 1/3 OB SOURCE LEVEL OF THE TUG ARCTIC FOX AT THE ERIK SITE, 9/13/85. TRIANGLES CORRESPONDS TO NOISE GENERATED AS THE TUG BEGINS TO MOVE A FULLY LOADED BARGE.

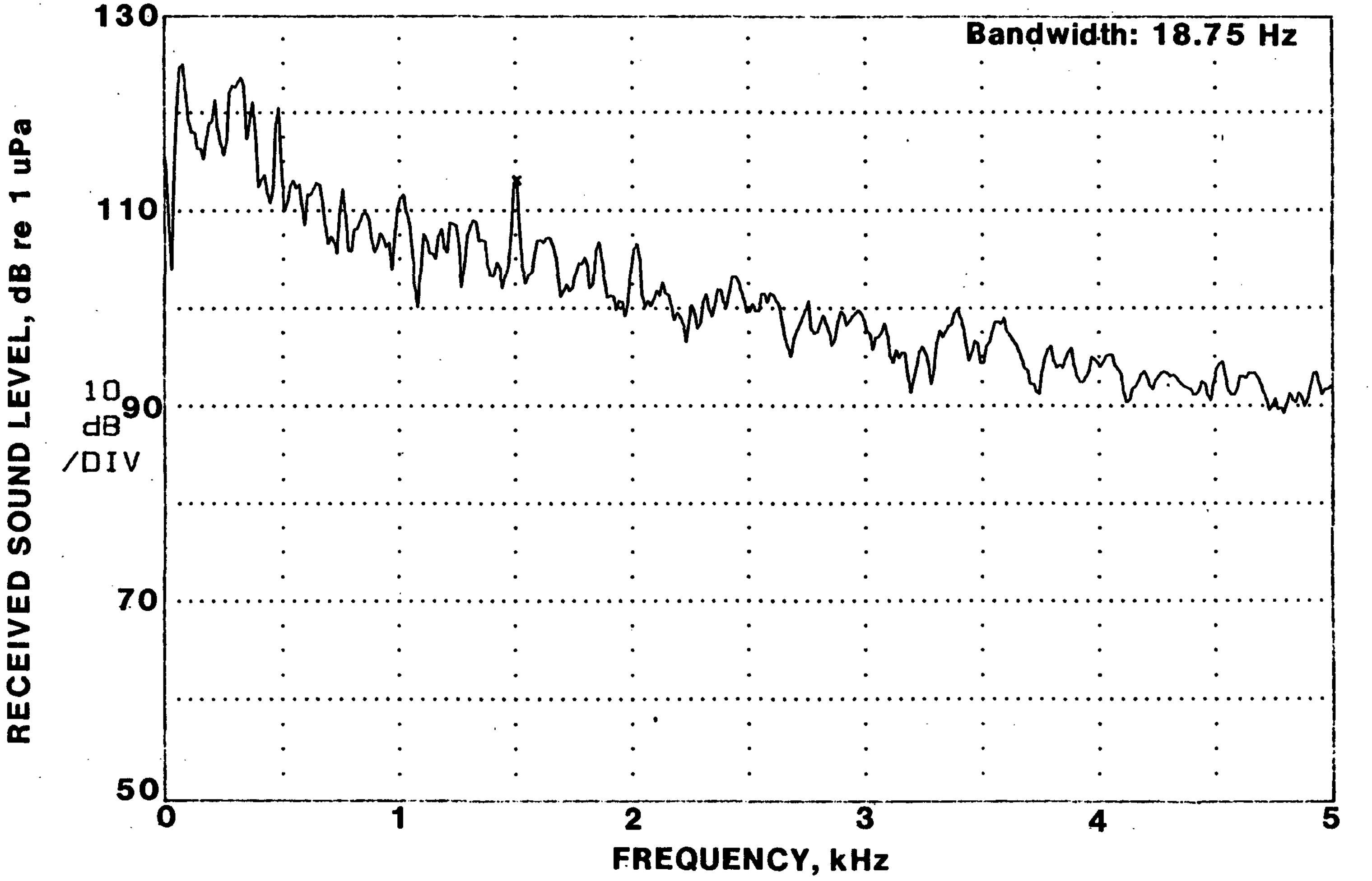


FIGURE 26. SAMPLE NARROWBAND RECEIVED SPECTRUM OF RADIATED NOISE FROM TWIN TUGS PUSHING A GROUNDED BARGE AT SANDPIPER ISLAND, 8/30/85.

frequency and level. The analysis procedure is much the same as with the tug at the Erik site. A smoothed envelope of the peak spectrum levels versus frequency is sampled at discrete frequencies. The values are then adjusted for the site-specific TL and corrected to third octave band levels. The result is shown in Fig. 27. Two additional curves are presented in Fig. 27. These show the effect of partial island shadowing as a receiver moves circumferentially around the island. Although no further use is made of these curves, it is important to realize that this industrial noise source has significant spatial variability.

3.2.4 EXPLORER II at the Hammerhead Site

On the 27th of August, Greeneridge Sciences made a series of measurements of the radiated noise from the drillship EXPLORER II during drilling operations (McLaren et al. 1986). Data were acquired at ranges from 0.1 n.m. (0.2 km) to 5.0 n.m. (9.3 km) to the north of the drillship. The environmental conditions were as follows: 32 m water depth, 5 kt wind speed, clear skies and about 1/10 ice cover. The measurements presented here were recorded at a 9 m depth.

A sample received level spectrum is presented in Fig. 28, taken at a 0.5 n.m. range. The dominant radiated noise components are; 1) a reasonably narrowband tonal near 72 Hz (the bandwidth at 3 dB down from the peak equals about 10 Hz), 2) a narrowband tonal at 239 Hz, 3) a broadband energy peak centered at about 920 Hz, and 4) another broadband peak centered at about 1640 Hz. Figure 29 displays a third octave band received spectrum with the bands corresponding to the frequencies noted. In order to estimate the source strength of these components (in the absence of site specific TL measurements), TL estimates were calculated using the radiated noise measurements and the least-squares error procedure outlined in Sec. 3.3. The TL model

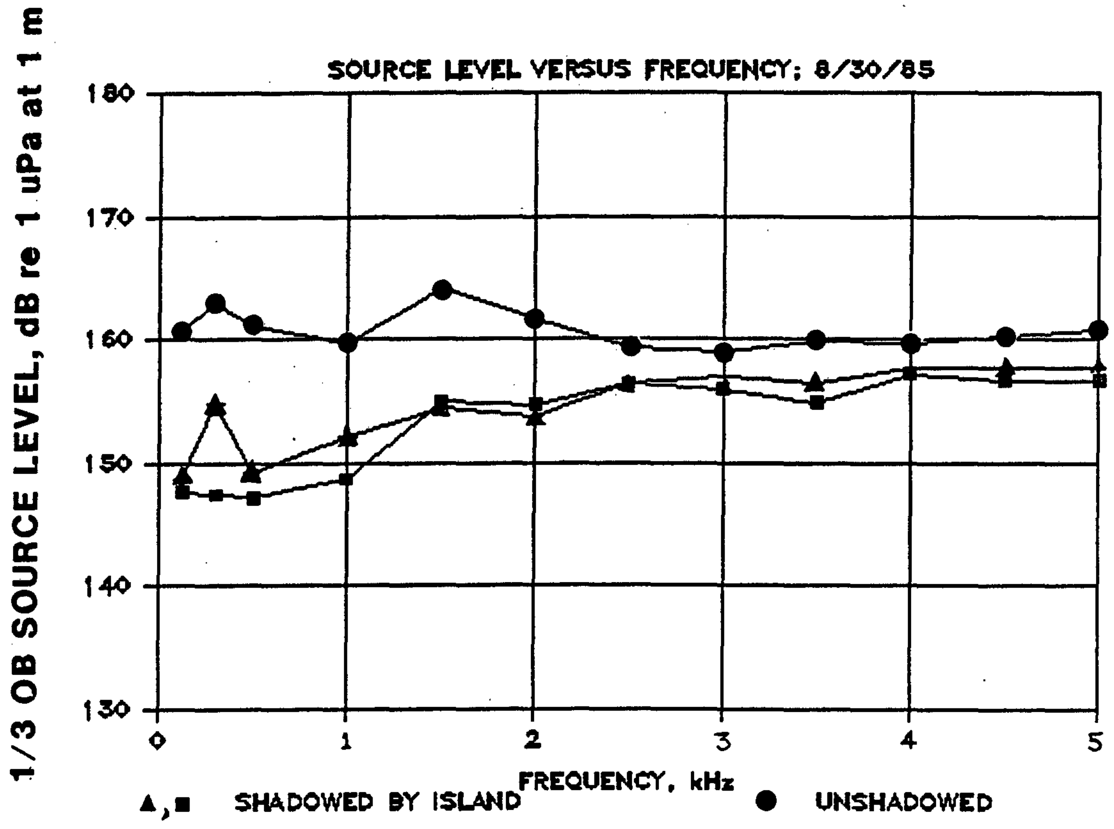


FIGURE 27. ESTIMATED 1/3 OB SOURCE LEVEL OF TWIN TUGS PUSHING A GROUNDED BARGE AT SANDPIPER ISLAND, 8/30/85. DIAMONDS CORRESPOND TO UNSHADOWED ESTIMATES. OTHERS ARE FOR DIRECTIONS PARTIALLY IN THE SHADOW OF THE ISLAND.

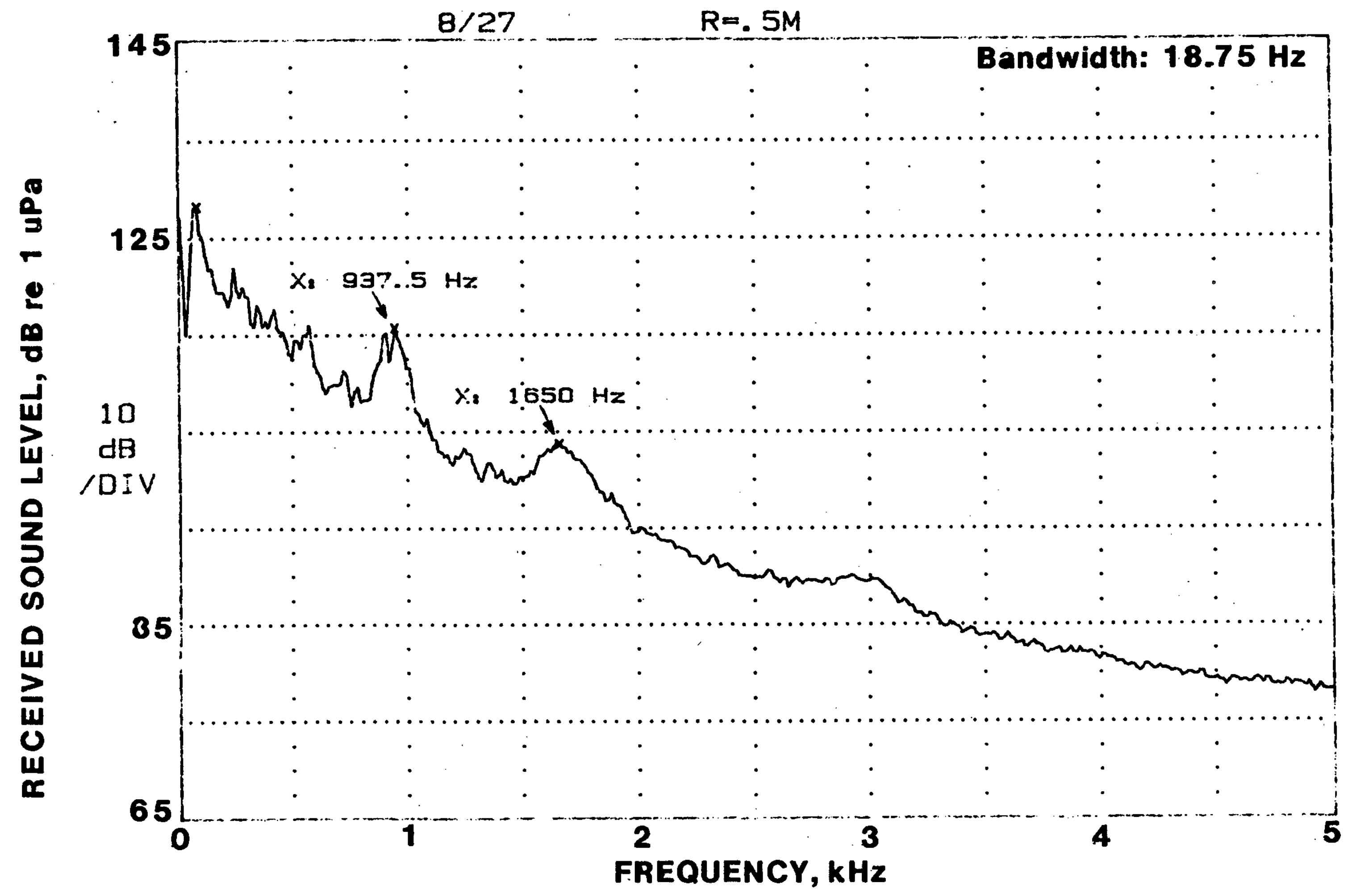


FIGURE 28. SAMPLE NARROWBAND RECEIVED SPECTRUM OF RADIATED NOISE FROM EXPLORER II DURING DRILLING OPERATIONS AT THE HAMMERHEAD SITE, 8/27/85. (DATE PROVIDED BY GREENERIDGE SCIENCES.)

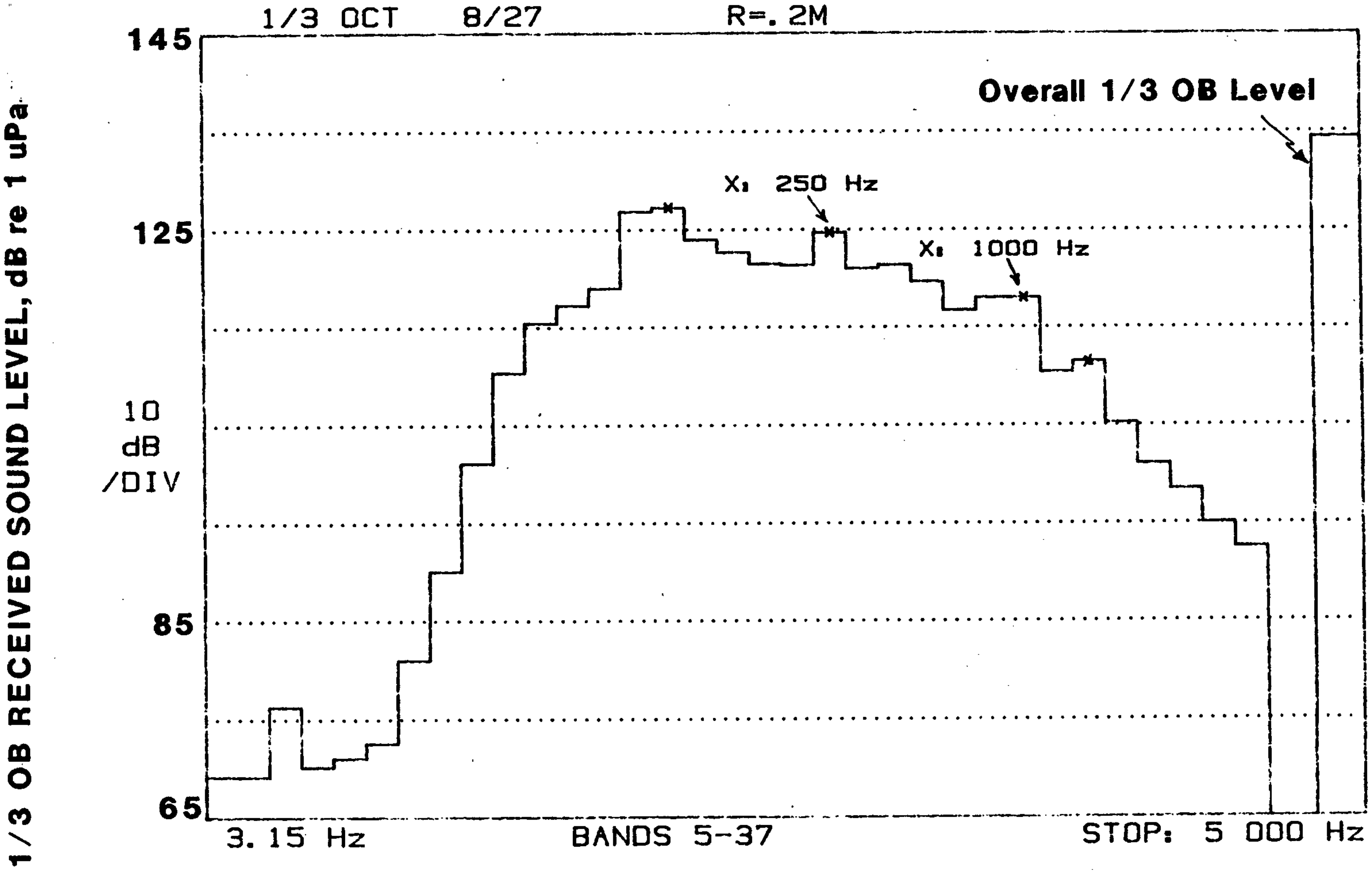


FIGURE 29. SAMPLE THIRD OCTAVE BAND RECEIVED SPECTRUM OF RADIATED NOISE FROM EXPLORER II DURING DRILLING OPERATIONS AT THE HAMMERHEAD SITE, 8/27/85. (DATA FROM GREENERIDGE SCIENCES.) FOR COMPARISON, FIGURE B-5 IN APPENDIX B SHOWS THIRD OCTAVE SPECTRA FROM THE SAME DRILLSHIP RECORDED IN 1981.

analysis uses a least-squares error estimation of the source level and applies a loss factor which is water depth dependent. Based on these estimates, the third octave band received spectrum was adjusted for the site-specific TL and the source level estimate was generated. Figure 30 displays the results.

Two observations are in order. First, previous measurements of the EXPLORER II radiated signature (see Greene 1985 and Fig. B4 in Appendix B) showed a dominant tonal at about 278 Hz. This is no longer evident. Second, it appears that this 278 Hz tonal has been replaced by the 239 Hz tonal. The new tonal shows an estimated source level of about 162 dB re 1 µPa at 1 m compared to roughly 166 dB for the old tonal (cf. Malme, et al. 1983).

3.2.5 Drilling Sounds from Sandpiper Island

Greeneridge Sciences measured the radiated noise during drilling operations from Sandpiper Island on 17 October 1985 (Johnson et al. 1986). Data were collected from a bottom mounted hydrophone estimated to be at a range of 0.45 km and from two sonobuoys deployed through the ice at ranges of 2 and 5 n.m. (3.7 and 9.3 km, respectively). The former rested on the bottom at a depth of about 16 m while the latter two were suspended at a depth of 9 m. The weather was overcast, visibility clear, with wind speeds roughly 10 kts and an ice cover of 8/10-10/10.

Figure 31 is a sample narrowband received level spectrum measured by the bottom sensor. No significant industry-related acoustic components were observed above about 200 Hz on any of the 3 receivers. Indeed, no man-made noise at all was observed on the 5 n.m. sensor and therefore it is not discussed further. As is obvious from Fig. 31, the dominant tonals are at 20 Hz and 40 Hz. The lower level tonals at 90, 100 and 120 Hz do not

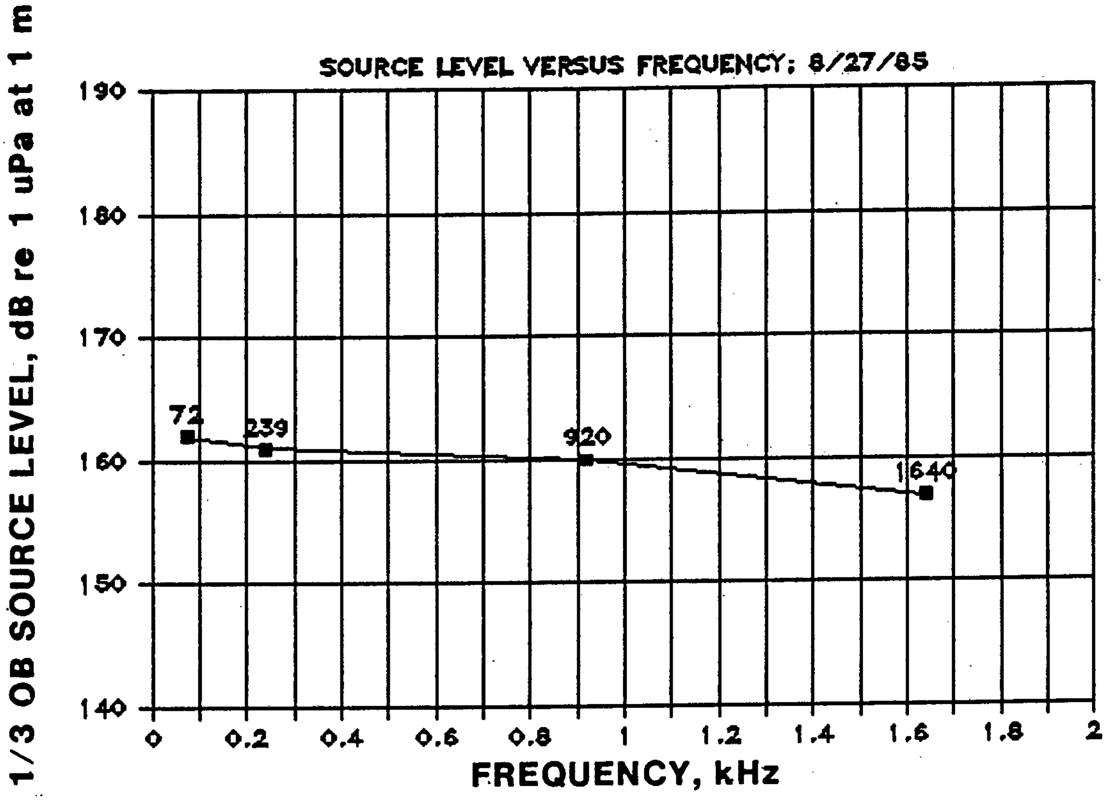


FIGURE 30. ESTIMATED 1/3 OB SOURCE LEVEL OF THE DOMINANT ACOUSTIC COMPONENTS FROM EXPLORER II WHILE DRILLING AT THE HAMMERHEAD SITE, 8/27/85. (DATA FROM GREENERIDGE SCIENCES.)

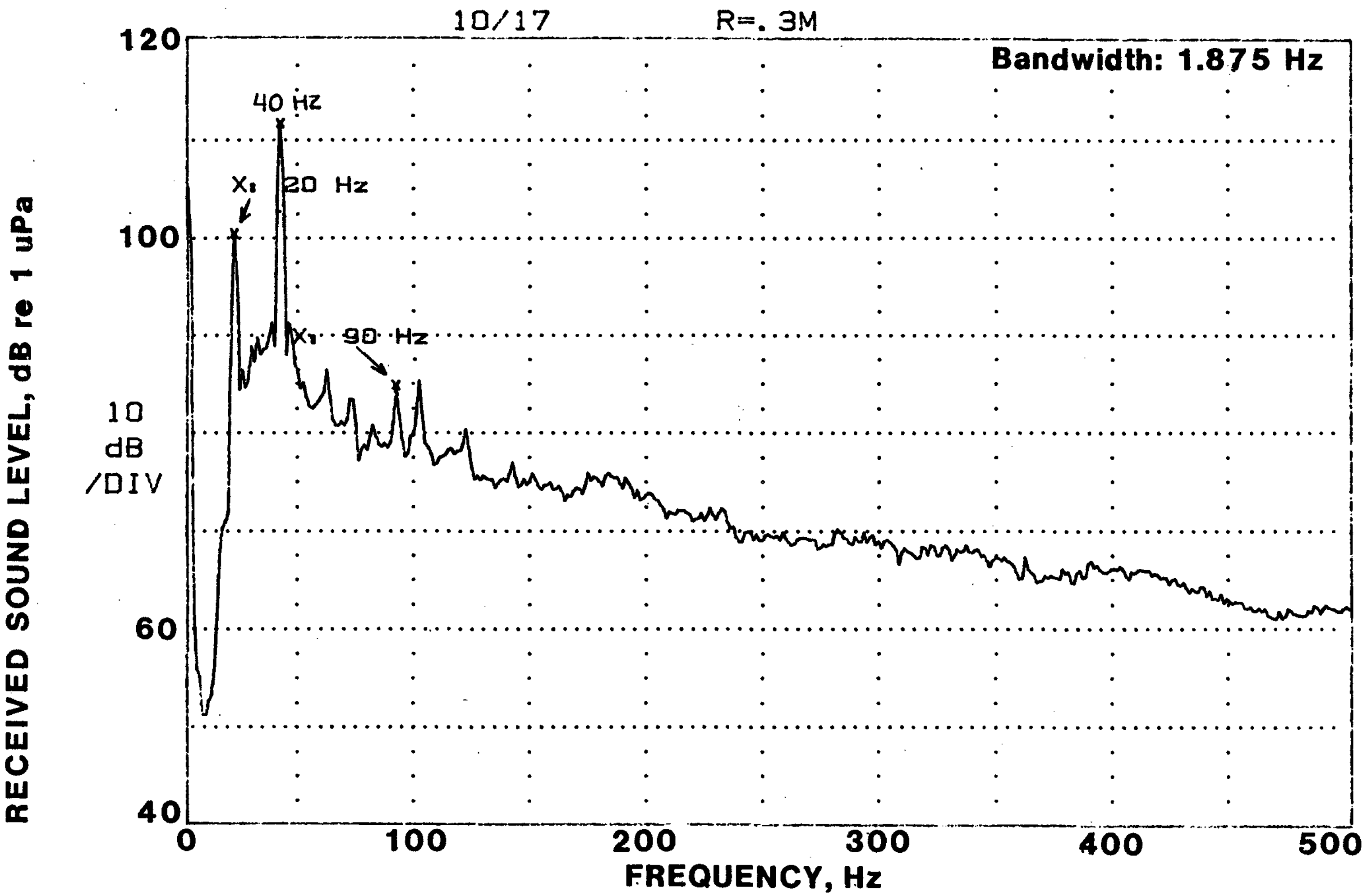


FIGURE 31. SAMPLE NARROWBAND RECEIVED SPECTRUM OF RADIATED NOISE FROM SANDPIPER ISLAND DURING DRILLING OPERATIONS, 10/17/85. BANDWIDTH 0-500 HZ. DATA PROVIDED BY GREENERIDGE SCIENCES.

appear at the 2 n.m. sonobuoy and therefore cannot be examined further due to lack of TL data under the high ice cover conditions during these measurements.

For the 40 Hz tonal, we used three data samples at two ranges (6 data points) and applied the least-squares error TL model. We therefore estimated that the source level of the 40 Hz tonal was 145 dB re 1 μPa at 1m. Because this tonal dominates the third octave band centered at 40 Hz, the source level estimate for the third octave band near 40 Hz is also 145 dB re 1 μPa at 1 m. This appears to be the only significant radiated signal from Sandpiper Island during drilling operations (see also Johnson et al. 1986).

3.3 Acoustic Models and Sound Propagation Characteristics

Sound transmission in shallow water is highly variable, since it is strongly influenced by surface conditions, by acoustic properties of the bottom material, and by sound speed variations in the water column. Variations in the temperature and salinity of the water column cause sound energy paths to be bent (refracted) downward or upward resulting in varying energy loss depending on the extent of interaction with the bottom and surface boundaries in addition to the attenuation due to geometric spreading.

When the sound wavelengths (λ) are comparable to the water depth (H) ($0.25 < H/\lambda < 2$), the sound energy is considered to be spreading cylindrically in a two-dimensional horizontal waveguide. This is the condition where acoustic mode theory is appropriate. Mode theory predicts that if the water depth is less than $\lambda/4$, no acoustic energy can propagate. In many cases, however, the bottom consists of water-saturated sediment and is not a discrete reflecting boundary for all of the sound energy.

Here the propagation of low frequency sound energy involves the bottom as an extension of the water column. Thus, hard sub-bottom layers under the upper sediment bottom often provide the dominant reflecting surface for low frequency sound energy.

At high frequencies or in deeper water where the water depth is large compared with the sound wavelengths ($H/\lambda > 5$), acoustic ray theory is applicable and acoustic energy can be considered to propagate along paths that are usually multiply reflected from the surface and bottom. A range (R)-dependent spreading loss of 15 Log R, which is midway between the cylindrical spreading loss of mode theory (10 Log R) and the spherical spreading loss (20 Log R) of unbounded deep water, has been found to be generally appropriate in shallow water when sound speed gradients are either neutral or downward refracting. When gradients are upward-refracting so the bottom reflection losses are minimized, a 10 Log R cylindrical type of sound propagation is appropriate, even though ray theory (not mode theory) is relevant.

Transmission Loss Models

No analytic or computer-based transmission loss model exists that is capable of handling all of the significant environmental parameters that influence shallow water sound propagation. The major modeling difficulties occur at low frequencies for sites with a sloping bottom and strong sound velocity gradients. As a result, we have developed semi-empirical models which use sound transmission data obtained from in-situ measurements to provide a general sound propagation characteristic for a specific area. These semi-empirical models have been developed assuming both the 10 Log R and 15 Log R spreading loss characteristics. In addition, a computer-based analytic model has also been found to be useful within the restriction that it is appropriate only for conditions of neutral or small sound speed gradients. All of these models have been applied in analyzing the transmission loss data to obtain the most general interpretation of the results. The following discussion covers the development and application of both the analytic and empirical models.

3.3.1 Analytic sound propagation model

The shallow-water environment is very complex from the acoustical viewpoint. A complete specification would involve descriptions of

- the sound speed profile in the water,
- bottom topography,
- bottom stratigraphy as function of location,
- surface conditions (roughness, ice).

Elaborate computer programs are required to use this information in a prediction of transmission.

Fortunately, since such detailed information is rarely available, it has been found possible to make reasonable predictions from simple formulas in the typical case where the sound speed is nearly independent of depth and the bottom slopes uniformly and gradually. These formulas have been developed and tested by Dr. D.E. Weston of the British Admiralty Research Establishment (Weston, 1976).

In the simplified formulas, there are five parameters:

1. dominant frequency
2. water depth at the source
3. bottom slope along track

4,5. two parameters to describe the reflection loss of the bottom.

In these formulas, the term for the reflection loss (RL) in decibels for reflection of a plane sound wave incident at a grazing angle ϕ is taken to be:

$$\begin{aligned} &\text{RL (dB)} = 4.34\ b \sin\phi, \text{ if } \phi < \phi_{cr}, \text{ or} \\ &\text{RL} = \text{large}, \text{ if } \phi > \phi_{cr}. \end{aligned} \tag{1}$$

The two parameters to be estimated are b and the critical angle ϕ_{cr}.

Because of bottom stratigraphy, the bottom reflection loss parameters are found to vary with frequency (Smith, 1986). The explanation is simple. A typical bottom in shallow water consists of a layer of sand or silt overlying rock. If the layer is thin, the sound is effectively reflected off the rock; if the layer is thick, the sound is effectively isolated from the rock. Calculations indicate that the transition occurs when the surface layer thickness equals about one-half wavelength of sound.

Typical values of the bottom loss parameters are

sand/silt: $b = 2$, $\sin\phi_{cr} = 0.4$
hard rock: $b = 0.4$, $\sin\phi_{cr} = 0.7$.

Soft rock, such as limestone or chalk, can be very absorptive because of transmission of energy in the shear wave. The values of the parameters b and ϕ_{cr} are very sensitive to the value of the shear wave speed (Smith, 1986).

Weston's formulas for transmission loss divide the transmission path into four regions, each of which has a characteristic range dependence. The regions are, in order of increasing range,

a. spherical spreading, where bottom-reflected rays are steeper than the critical angle;

b. a transitional, cylindrical spreading region;

c. a "mode stripping" region, wherein energy striking the bottom at steeper angles is attenuated more rapidly than that at shallower angles;

d. the "lowest-mode" region, wherein only the fundamental mode carries significant energy.

Only in the last region is transmission dependent on frequency, so long as the sand layer is either thin ($d < \lambda/2$) or thick ($d > \lambda/2$) at all frequencies of interest. (See discussion of bottom reflection loss, above.)

In addition to water depth and bottom composition, the slope of the bottom is also important in determining transmission loss in shallow water. For sound transmission from a shallow region to deeper water, the increasing depth permits the sound energy to spread out over a larger volume than would have been available if the depth had remained constant. This results in a reduction in sound level. On the other hand, the increase in depth 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 so the net effect of a positive bottom slope (increasing depth with increasing range) is lower transmission loss. This effect is most pronounced when neutral or upward refracting sound speed gradients exist. For these conditions sound transmission becomes ducted and is no longer influenced by bottom reflection loss.

For sound transmission into a decreasing depth region (negative bottom slope), the decrease in available volume for the sound energy would normally cause the sound level to be higher than it would be at the same range in a constant depth region. However the number of surface and bottom reflections increases as the depth decreases. This causes the sound level to drop. This effect again usually predominates and the transmission loss becomes higher as sound propagates upslope. As the depth decreases, a depth is reached where there is a transition from multimode to single mode propagation. This usually results in a shift from a 15 Log R to a 10 Log R spreading loss characteristic. The attenuation per kilometer is determined primarily by the bottom material and may be quite high for soft bottom sediments. As water depth continues to diminish, there will be a point when effective propagation to long distances for frequencies of interest is not efficient (transmission loss becomes very high).

The Weston formulas noted previously apply to both positive and negative uniform bottom slopes as well as to the constant depth case.

A BASIC computer program was designed by P.W. Smith, Jr. at BBN which incorporates these formulas, yielding a value of transmission loss (dB re 1 m) when given a value of range. This model, which we have called the Weston/Smith model, does not incorporate refraction effects produced by sound speed gradients and is appropriate for conditions where gradients are small or neutral. Nevertheless, it has been found to provide good predictions in shallow water conditions and thus was used as a comparison to the measured data at several sites.

3.3.2 Empirical sound propagation models

Multi-Mode Model (15 Log R)

This empirical model is based on the shallow water acoustic ray theory for an isospeed sound channel. The transmission characteristic for this case where many propagating modes are present has been given as:

$$T = (2\pi/bHR^3)^{1/2}\, e^{-a_v R} , \tag{2}$$

where b is a bottom loss factor defined previously in Eq. (1), H is the bottom depth, R is the range from the source, and a_v is the volumetric absorption (Smith, 1971). This is the characteristic that applies in the region c (mode stripping) portion of the computer model discussed previously. To develop the empirical model, we allow for an approximately uniformly sloping bottom by substituting

$$H_{av} = (H_s + H_r)/2 = H \quad (m) \tag{3}$$

where H_{av} is the average depth between the water depth at the source (H_s) and at the receiver (H_r). An additional range-dependent loss factor is added to account for surface and bottom scattering and for losses produced by refraction not accounted for in the original analytic expression. The resulting modified transmission characteristic is

$$T = (2\pi/bH_{av}R^3)^{1/2}\, e^{-a_a R/H_{av}}\, e^{-a_v R}, \tag{4}$$

where a_a is an anomalous attenuation factor which can be considered as a "loss-per-bounce," with the number of ray bounces being determined by the ratio of the range to the average depth.

For convenience, Eq. (4) is converted to the logarithmic form of transmission loss (TL), where TL = -10 Log T or

$$TL = 5 \log (bH_{av}) + 15 \log R + A_a R/H_{av} + A_v R - 4 \text{ (dB)} \qquad (5)$$

Equation (5) is similar in form to a semi-empirical formula developed earlier by Marsh and Schulkin (1962) for intermediate range shallow water transmission loss prediction. In applying this relationship, the attenuation factor A_a is determined by analyzing a set of measured received level data which have been obtained in the area of interest. A calibrated sound source is used to obtain these data. To implement this analysis, Eq. (5) is used in the received level (L_r) equation

$$L_r = L_s - TL$$

where L_s is the source level (dB re 1μPa at 1 m) or,

$$L_r = L_s' - 5 \log H_{av} - 15 \log R - A_a R/H_{av} - A_v R + 4 \text{ dB re } 1\mu\text{Pa} \qquad (6)$$

where

$L_s' = L_s + A_n - 45$, dB re 1μPa at 1 km = effective source level

L_s = Source Level, dB re 1μPa at 1 m

A_n = Local anomaly

The constant (-45) represents a correction for units

R = range, km

A_v = volumetric absorption, dB/km (may be neglected for ranges less than 10 km and frequencies less than 1 kHz)

A_a = bottom and surface absorption and scattering losses, dB m/km.

This equation is used in a computer-implemented, two-parameter, least-squares analysis using the measured values of L_r versus range. The results of this analysis produce estimated values of both the effective source level L_s' and A_a. Since the actual source level is known, this permits estimation of the effective increase in source level resulting from surface- and bottom-reflected energy. This increase will be called the local anomaly, A_n. For low sea states where surface losses are negligible, $A_n \approx -5 \log b$. Since the usual values of the local anomaly, A_n are small, the mean error of the regression curve fit must also be small to obtain a good estimate of the loss factor, b. Conversely, if a good calibration of the local anomaly for a given area is available, this permits estimation of the source level of an uncalibrated source.

Cylindrical Spreading Model (10 Log R)

The analysis procedure using Eq. (5) and Eq. (6) is not appropriate at low frequencies in water depths where only a few modes are propagating and ray acoustic theory does not apply. It also is not appropriate at higher frequencies when ducted or upward refracted (RSR) sound propagation paths dominate.

For these conditions, Eqs. (5) and (6) have been modified to incorporate a cylindrical spreading loss and a continuous boundary attenuation loss

$$TL = 10 \log H_{av} + 10 \log R + A_s R + A_v R \text{ (dB)} \tag{7}$$

or

$$L_r = L_s' - 10 \log H_{av} - 10 \log R - A_s R - A_v R \text{ (dB re } 1\mu\text{Pa)} \quad (8)$$

where

$L_s' = L_s + A_n - 30$ dB re 1μPa at 1 km

A_s = boundary attenuation loss, dB/km.

Equation (7) is also similar to the cylindrical spreading TL equation developed earlier by Marsh and Schulkin (1962).

The two-parameter least-squares analysis was carried out using Eq. (8) if propagation conditions were appropriate and/or if the analysis using Eq. (6) produced negative values of A_a. For some conditions analysis was performed using both equations and the equation producing the smallest mean-squared error value was selected as the best fit to the experimental data. Equations (7) and (8) are not suitable for areas where there is a large variation in bottom depth along the propagation path (> 20%).

3.3.3 Transmission Loss Characteristics at the Test Sites

Introduction

Acoustic transmission loss data were obtained during the 1985 field period in the vicinity of four of the five test sites designated by MMS. The amount of data obtained was reduced as a result of limited site access due to the summer ice conditions in 1985. The primary goals of the transmission loss measurements during this first field season were to quantify the influence of the local bottom and water column properties on sound transmission at each site and to measure the noise radiation characteristics of any industrial activities operating at each site. These goals were met for each of the sites that were accessible (Orion, Sandpiper Island, Erik, and Belcher). The fifth designated site, Hammerhead, was not accessible because of ice conditions. Weather and ice conditions also prevented TL measurements at the alternate Corona site.

Discussion of Data from Specific Sites

Orion Site

This is a very shallow site (14 m). The sound velocity gradient (Fig. 32) observed at the site during the TL measurement period showed a shallow surface duct present between 3 and 10 m. This may have influenced the measured TL, which was lower than would normally be expected for such shallow water. The 10 Log R empirical model was found to provide the best fit to the measured data for all frequencies tested. The results of the least-squares curve-fitting process are shown in Figs. 33 through 35. The high local anomaly (A_n) values noted in each figure of 9 to 12 dB at low frequencies are the result of very reflective bottom conditions. The sound levels are thus 9 to 12 dB higher than they would be at comparable ranges in deep water. The data point at 4.9 km for 100 Hz in Fig. 33 has been assumed to be anomalous in the curve fitting process until additional experimental data can be obtained.

It is possible that, in this area, a hard sub-bottom layer such as permafrost acts as the effective boundary for low frequency sound propagation - the upper sediment would be basically an extension of the water column. To test this possibility, the TL data at low frequencies were reanalyzed using the 10 Log R empirical model with various assumed values of effective water depth. At 100 and 200 Hz, an effective bottom depth of 30 m gave the lowest value of a mean square error between calculated and measured sound levels. For higher frequencies, the error was lowest for the actual depth of 14 m. This provides evidence of a sub-bottom reflecting layer (either

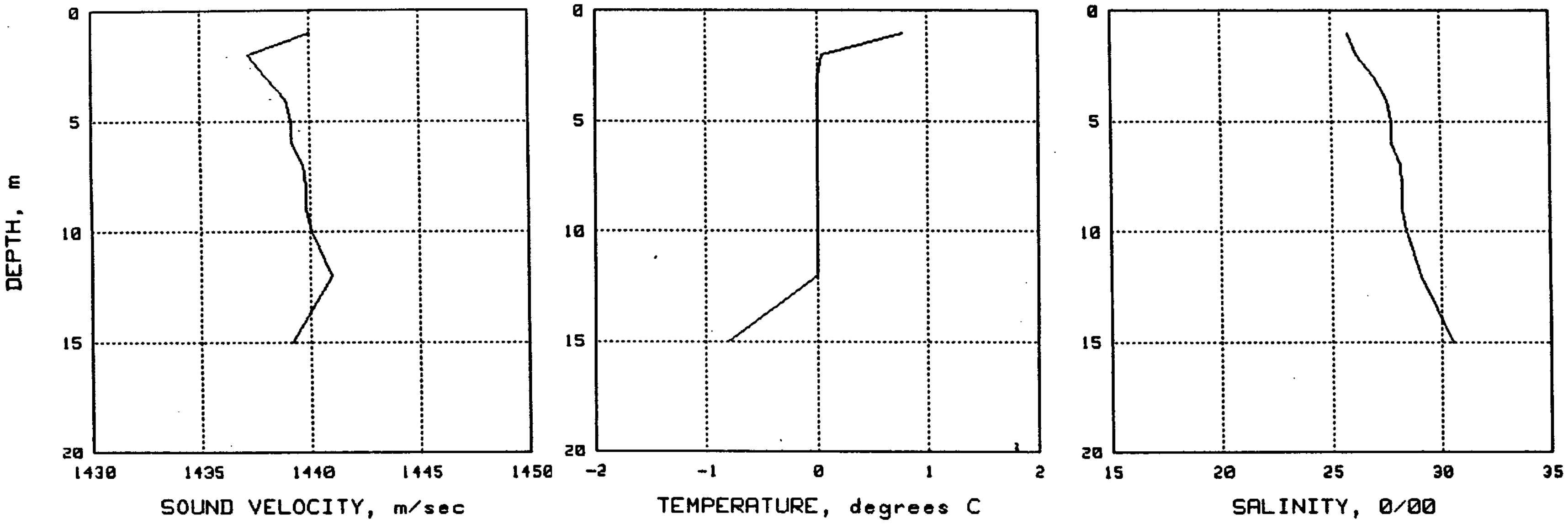
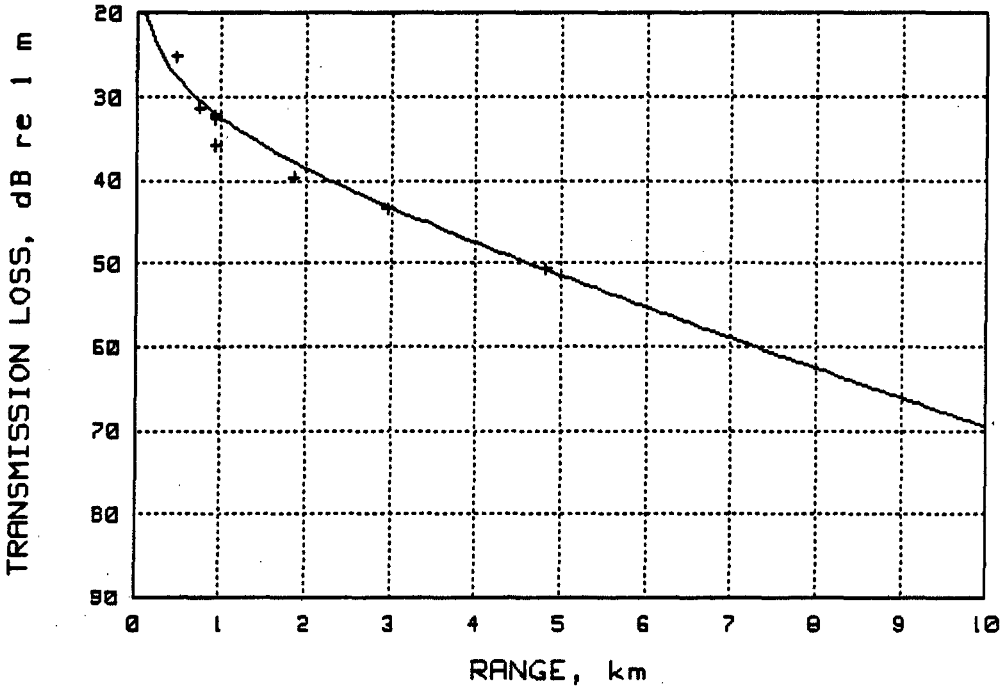
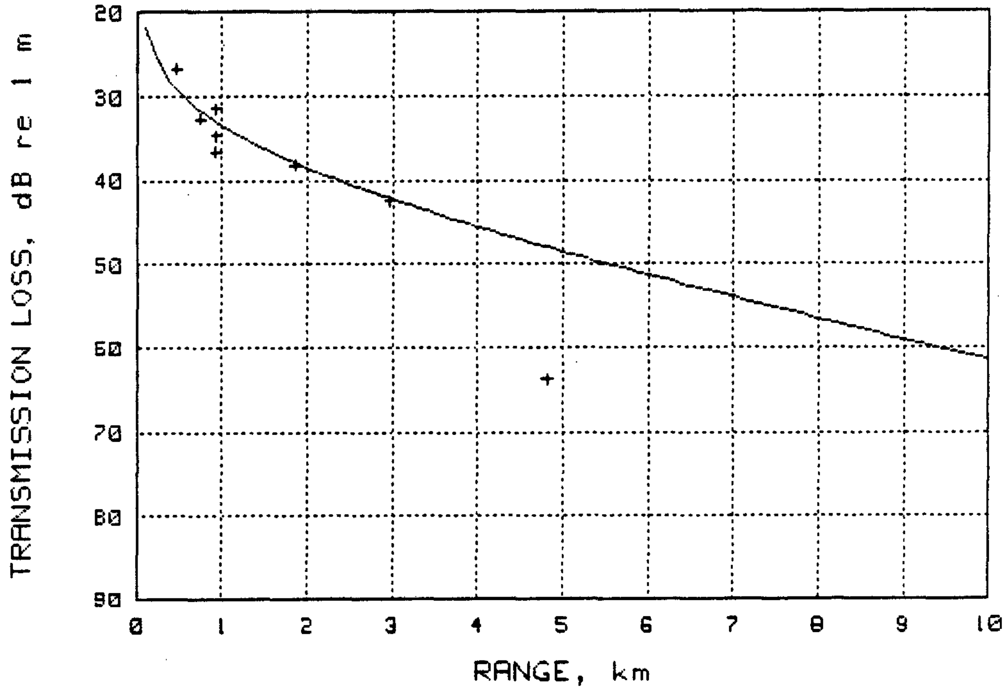


FIGURE 32. ENVIRONMENTAL DATA FOR ORION SITE, 8/28/85.

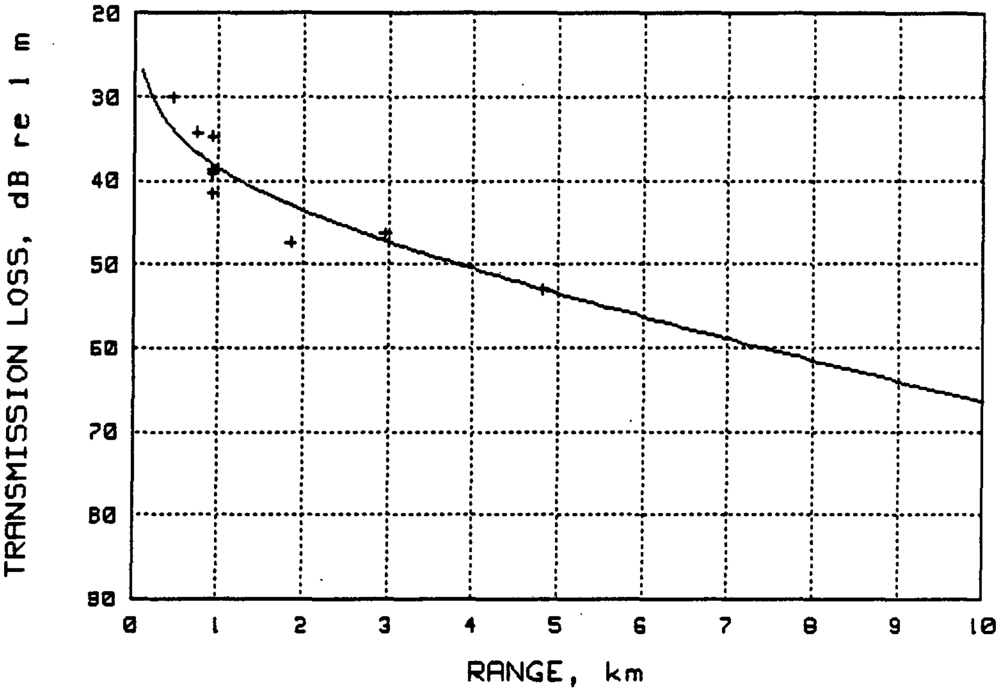


CIDS 200 Hz Data, Curve - 10 LOG R TL Model with A=3, An=12

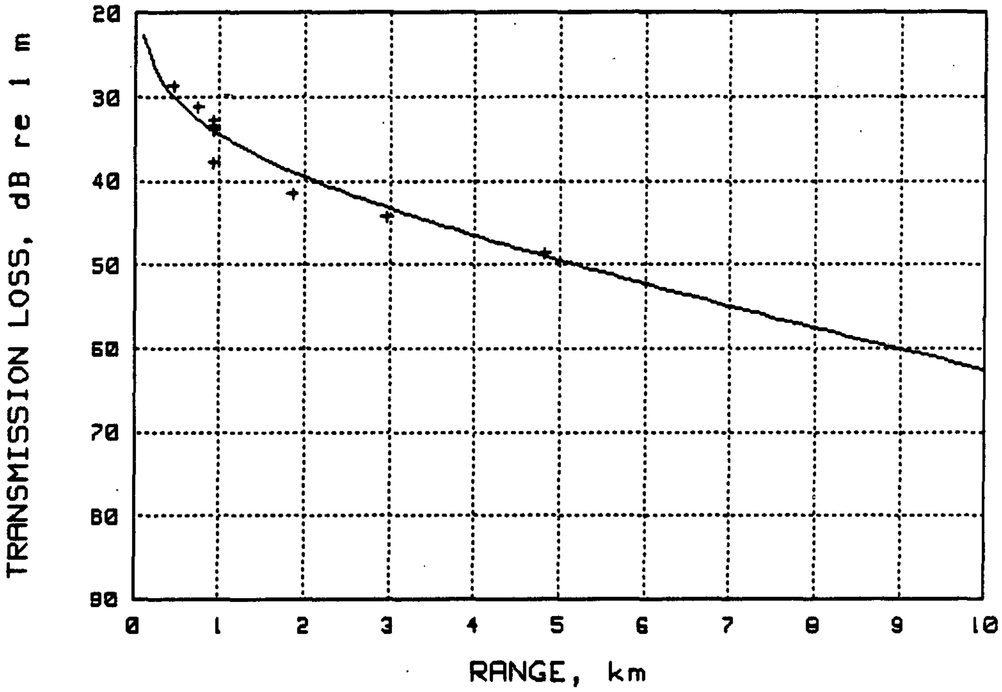


CIDS 100 Hz Data, Curve - 10 LOG R TL Model, A=2, An=10

FIGURE 33. TRANSMISSION LOSS AT ORION SITE USING AN ACOUSTIC PROJECTOR AT 100 HZ AND 200 HZ.

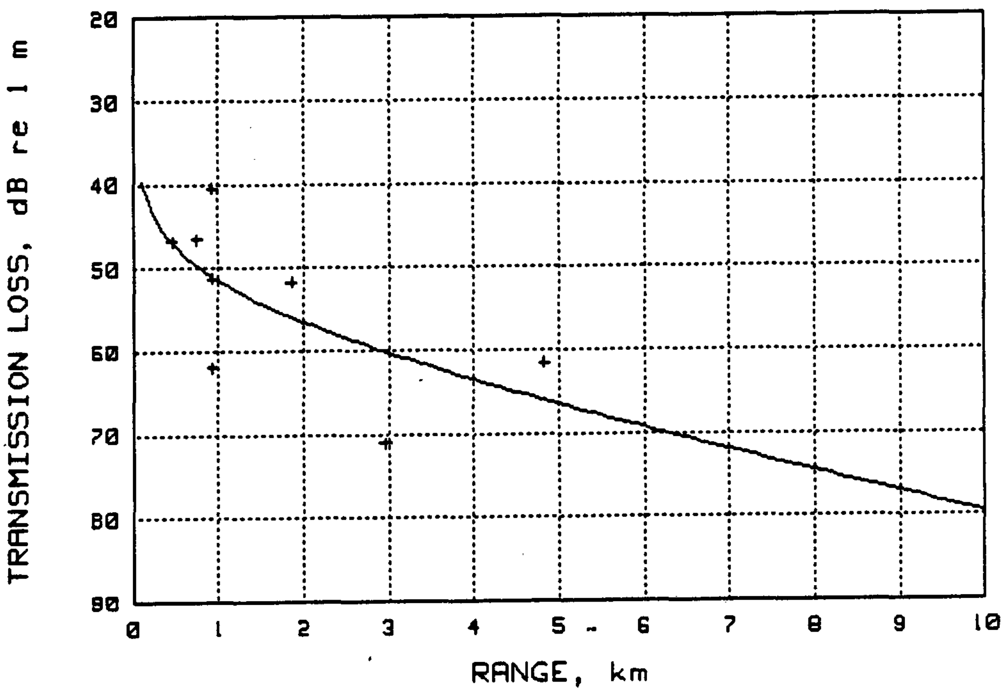


CIDS 1 kHz Data, Curve - 10 LOG R TL Model with A-2, An-5

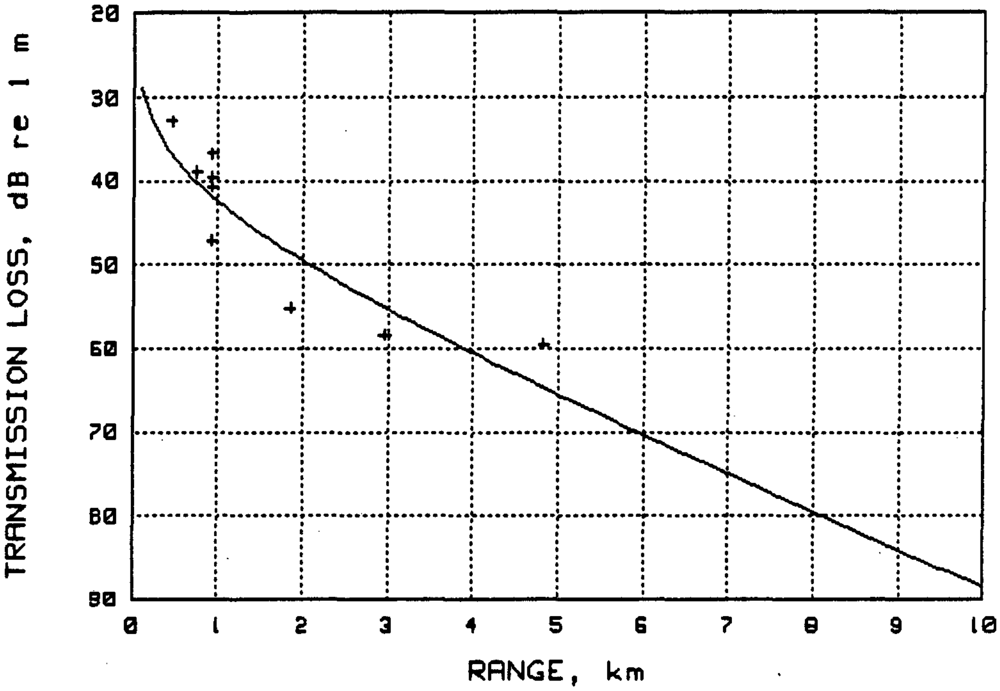


CIDS 500 Hz Data, Curve - 10 LOG R TL Model with A-2, An-9

FIGURE 34. TRANSMISSION LOSS MEASUREMENTS AT ORION SITE USING AN ACOUSTIC PROJECTOR AT 500 HZ AND 1 KHZ.



4 kHz Data, Curve - 10 LOG R TL Model with A=2, An=-8



2 kHz Data, Curve - 10 LOG R TL Model with A=4, An=3

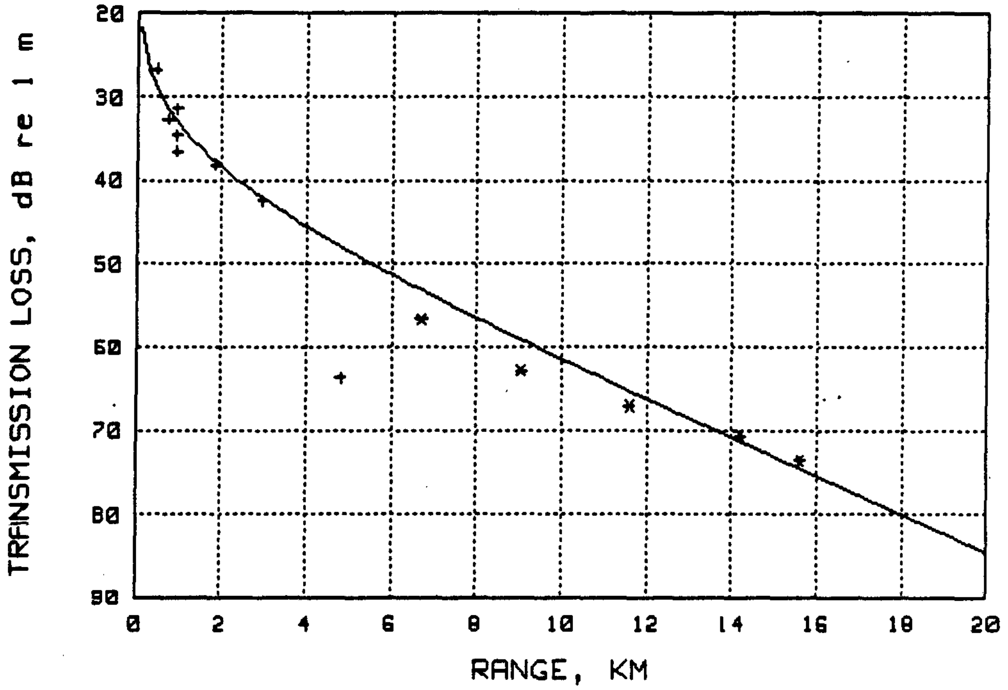
FIGURE 35. TRANSMISSION LOSS MEASUREMENTS AT ORION SITE USING AN ACOUSTIC PROJECTOR AT 2 KHZ AND 4 KHZ.

permafrost or overconsolidated clay as discussed previously in Sec. 2.1.2) that is effective for frequencies below 200 Hz.

Our data have been augmented by including an analysis of air gun array sound level data reported by Ljungblad et al. (1985b) for a nearby site having a similar water depth (18 m). The air gun data were obtained later in the season (23 September 1984) when whale migration was in progress. The dominant frequencies in airgun array data are at about 100 Hz. A TL estimate was obtained from the array data and was adjusted using the measured local anomaly (A_n) at 100 Hz for the Orion site. The results are shown with the measured TL data at 100 Hz for the Orion Site in Fig. 36.

Two types of propagation models were compared with the combined 100 Hz data. The 10 Log R empirical model, using the constants determined by a least-squares analysis of the on-site projector data, provided a reasonably good fit to the seismic array data which extend out to a range of about 16 km (Fig. 36A). (The projector data point at 4.8 km is believed to be anomalous.) The Weston/ Smith model was also used to provide estimated TL values for this site. This model is more appropriate for use in long range TL predictions since it provides for the transition from multi-mode propagation to single-mode propagation which often occurs for low frequency propagation in shallow water. Thus, if we can obtain a good match between the Weston/Smith model and the measured data at short range, we can expect it to provide better long-range predictions than those provided by simply extending the empirical model predictions. However, it is very important to point out that without site-specific long range TL data, there is potential for error in estimating TL if any TL model is used to extrapolate beyond the ranges for which experimental data are available.

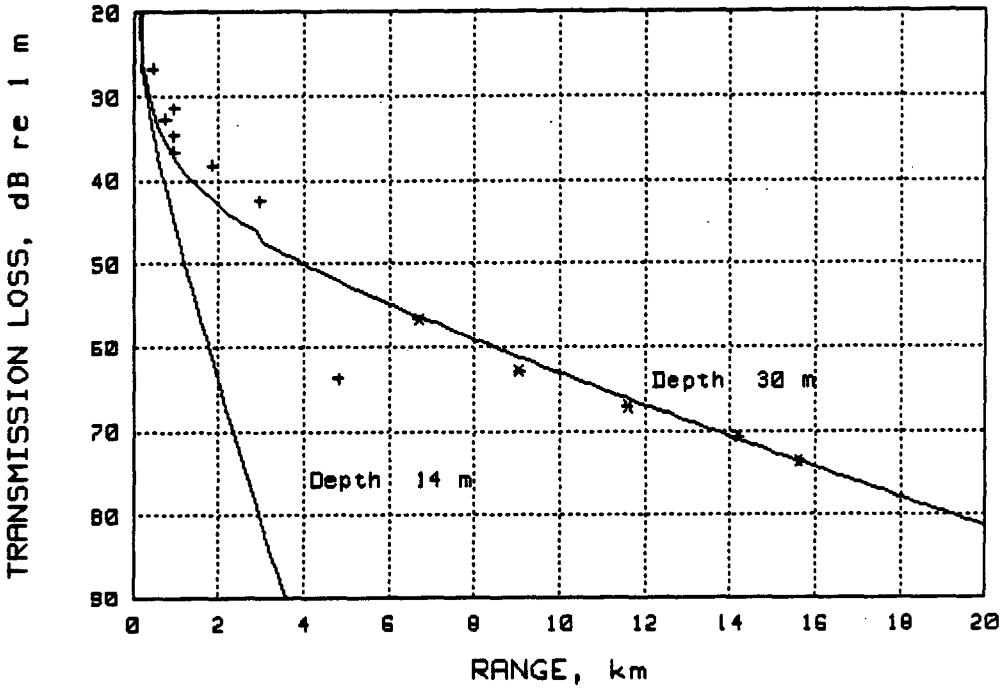
A.



CIDS 100 Hz Data (+) and ARCTIC STAR Seismic Array Data (*)

Curve - 10 LOG R TL Model with A=2, An=10

B.



CIDS 100 Hz Data (+) and ARCTIC STAR Seismic Array Data (*)

Curves - "Weston/Smith" Model, B=.35, Sin0c=.8, An=10

FIGURE 36. TRANSMISSION LOSS AT ORION SITE; LONG RANGE ESTIMATE AT 100 HZ USING DATA OF LJUNGBLAD ET AL. (1985b), *, AS WELL AS DATA FROM THIS PROJECT (+). (CURVE FITTING EXCLUDES THE 4.8 KM DATA POINT.)

The Weston/Smith model results are compared with the projector and seismic array data in Fig. 36B for both the actual water depth (14m) and the estimated sub-bottom layer depth (30 m). The model for the actual 14 m depth predicted much higher TL values than were observed but the predicted values based on the assumed sub-bottom depth can be seen to be in good agreement. The bottom parameter values used to obtain this fit are consistent with values for soft rock. They are assumed to be appropriate for permafrost based on information described in Sec. 2.1.2.

Sandpiper Island

This is another shallow water site (15 m) which had variable ice conditions during the 1985 field season. The sound velocity profiles during the measurement period were influenced by the nearby ice and generally showed upward refracting conditions, as shown in Fig. 37. The measured TL data followed a 10 Log R spreading loss with a low attenuation factor (1 dB/km or less for all frequencies measured). The results of the analysis are shown in Figs. 38 through 40. There is no obvious reason for the wide scatter of the 4 kHz data in Fig. 40 although anomalous sub-bottom reflectors could be one cause.

The very low TL values showed that a bottom or sub-bottom layer of high acoustic reflectivity was present at this site also. Subsequent analyses indicated that a sub-bottom layer at a depth of about 35 m may be the dominant reflecting surface for frequencies below 200 Hz. Predicted values of TL using the Weston/Smith Model and a layer depth of 35 m are shown in Fig. 41. The measured data show less TL than the model, possibly as a result of the local sound speed gradient (the model assumes that no significant gradients are present). For conditions of no nearby ice and normal summer heating, the TL characteristic at

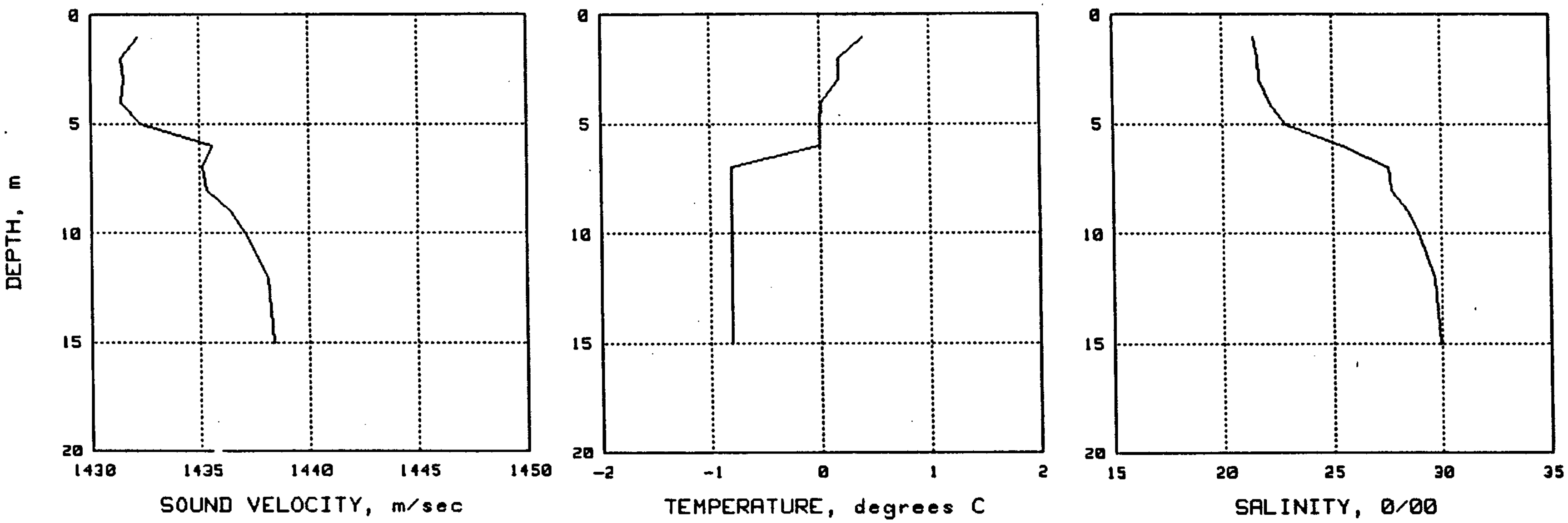
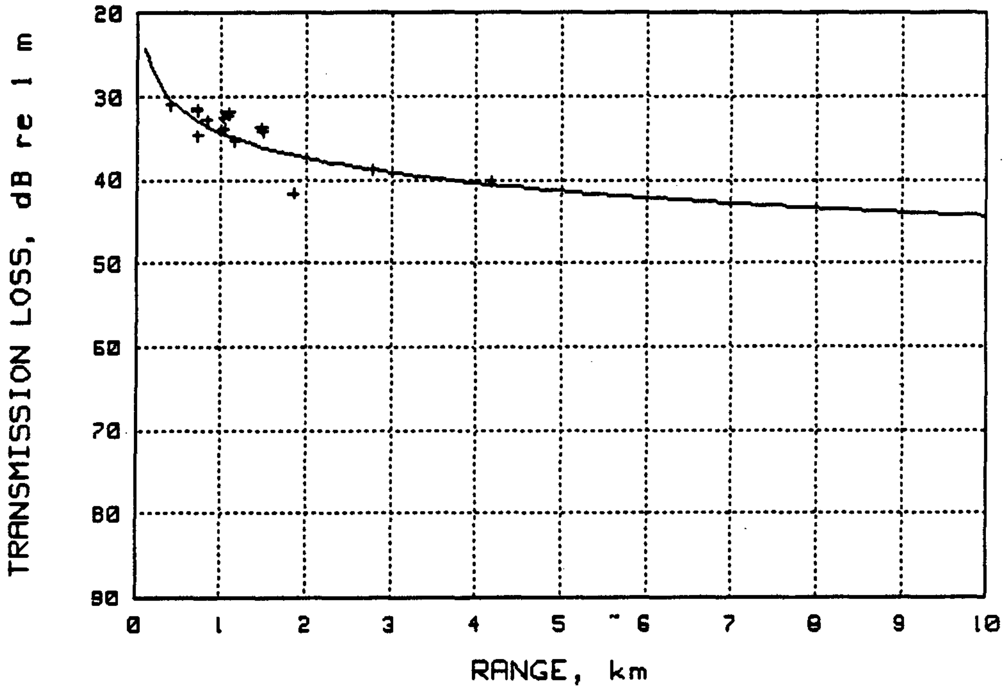
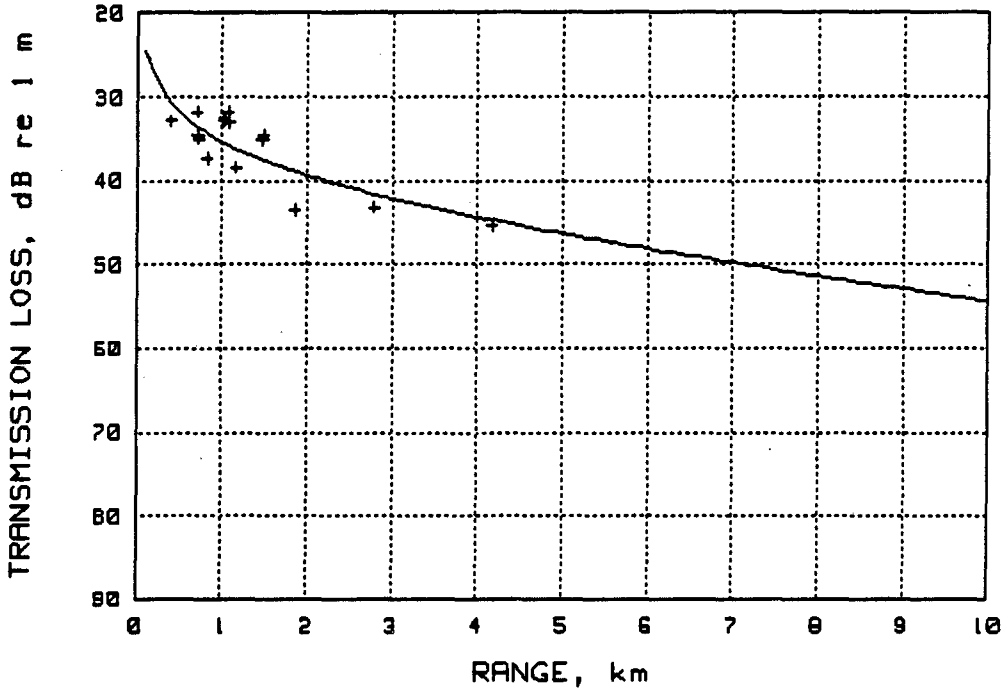


FIGURE 37. ENVIRONMENTAL DATA FOR SANDPIPER SITE, 8/27/85.

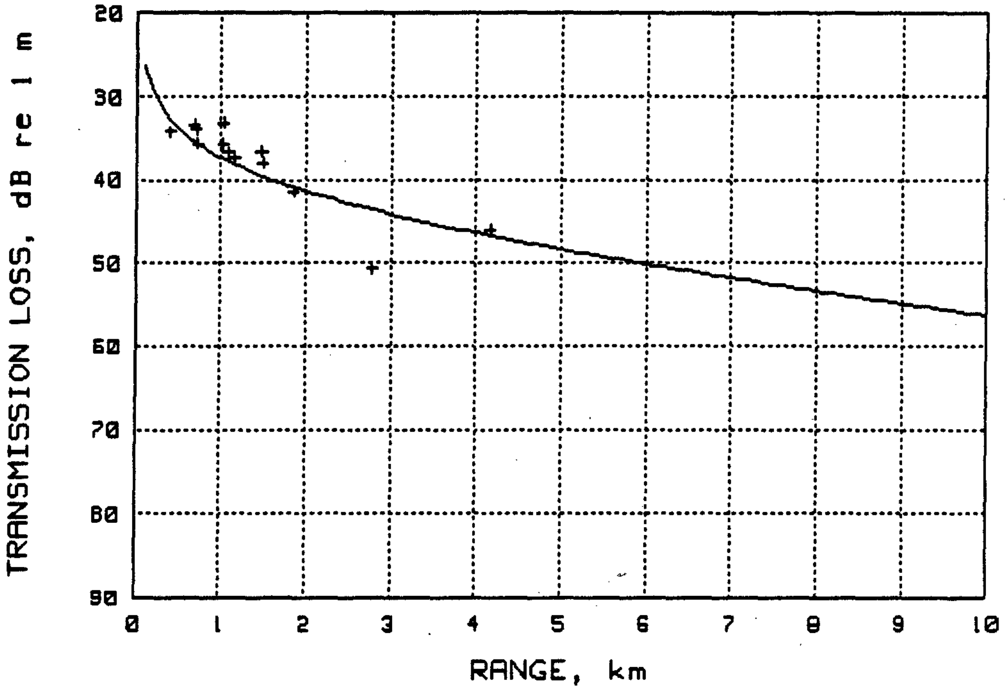


SANDPIPER 200 Hz Data, Curve - 10 LOG R TL Model, A=0, An=8

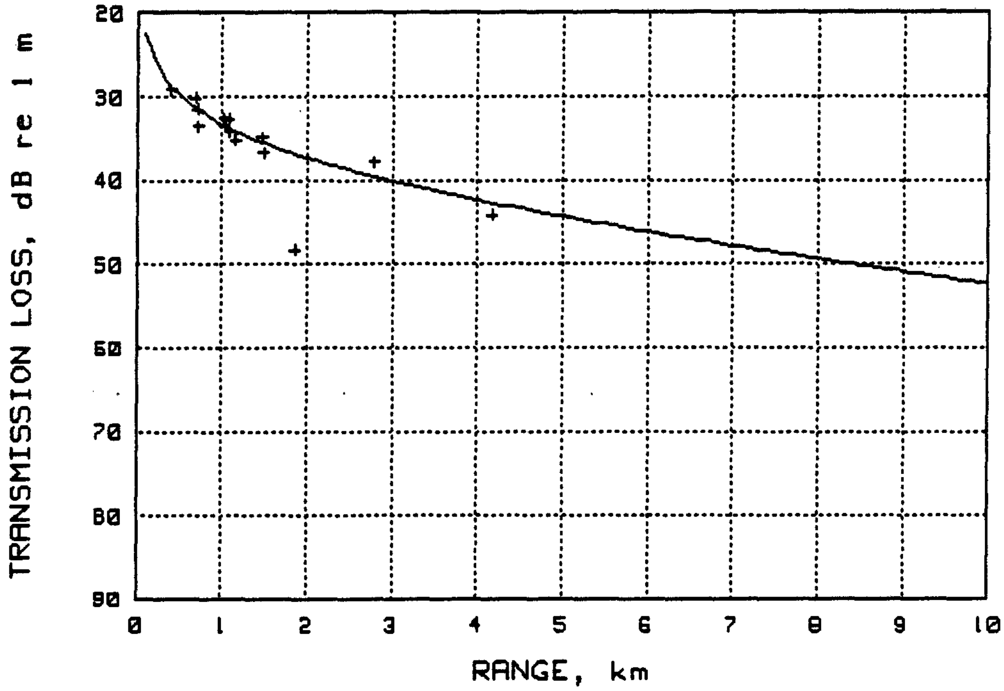


SANDPIPER 100 Hz Data, Curve - 10 LOG R TL Model with A=1, An=8

FIGURE 38. TRANSMISSION LOSS MEASUREMENTS AT SANDPIPER SITE USING AN ACOUSTIC PROJECTOR AT 100 HZ AND 200 HZ.

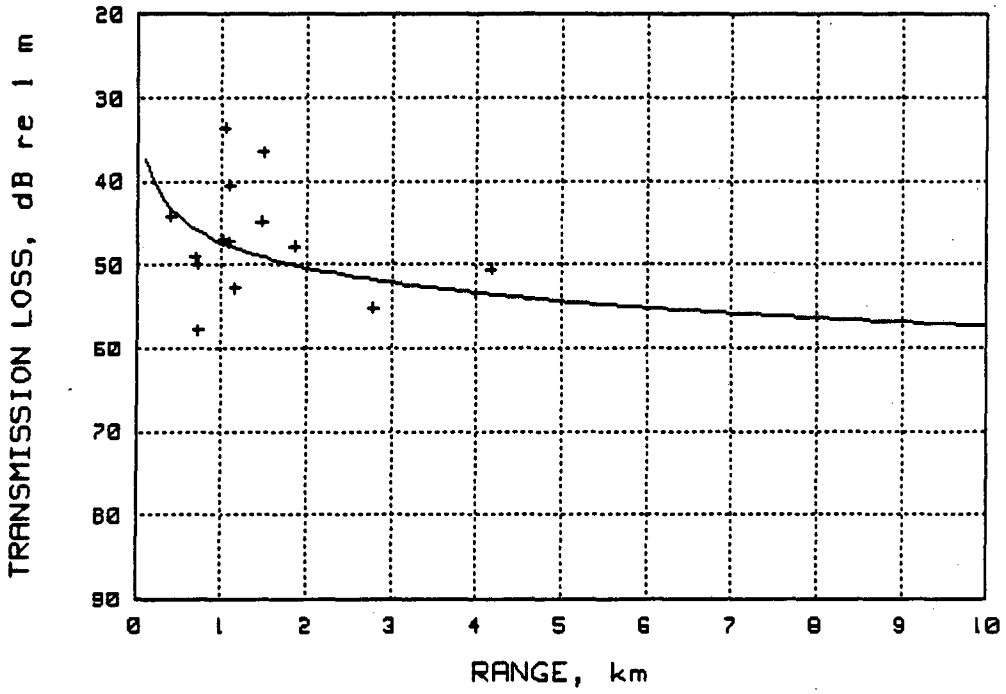


SANDPIPER 1 kHz Data, Curve, 10 LOG R TL Model, A-1, An-6

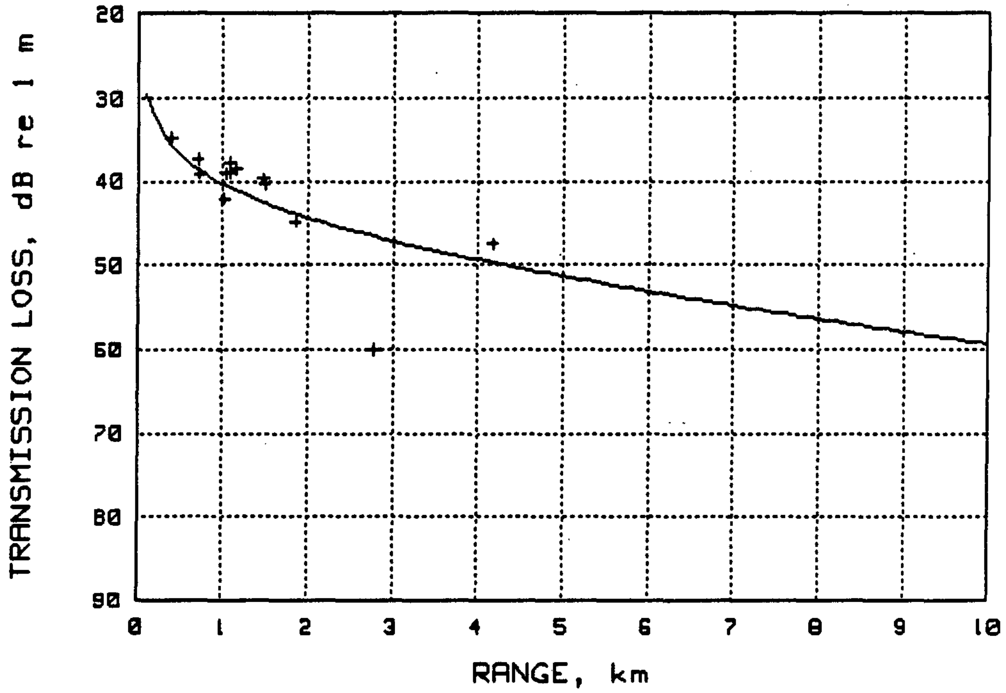


SANDPIPER 500 Hz Data, Curve - 10 LOG R TL Model with A-1, An-10

FIGURE 39. TRANSMISSION LOSS MEASUREMENTS AT SANDPIPER SITE USING AN ACOUSTIC PROJECTOR AT 500 HZ AND 1 KHZ.



SANDPIPER 4kHz Data, Curve - 10 LOG R Model, A=0, An=-5



SANDPIPER 2 kHz Data, Curve - 10 LOG R TL Model, A=1, An=3

FIGURE 40. TRANSMISSION LOSS MEASUREMENTS AT SANDPIPER SITE USING AN ACOUSTIC PROJECTOR AT 2 KHZ AND 4 KHZ.

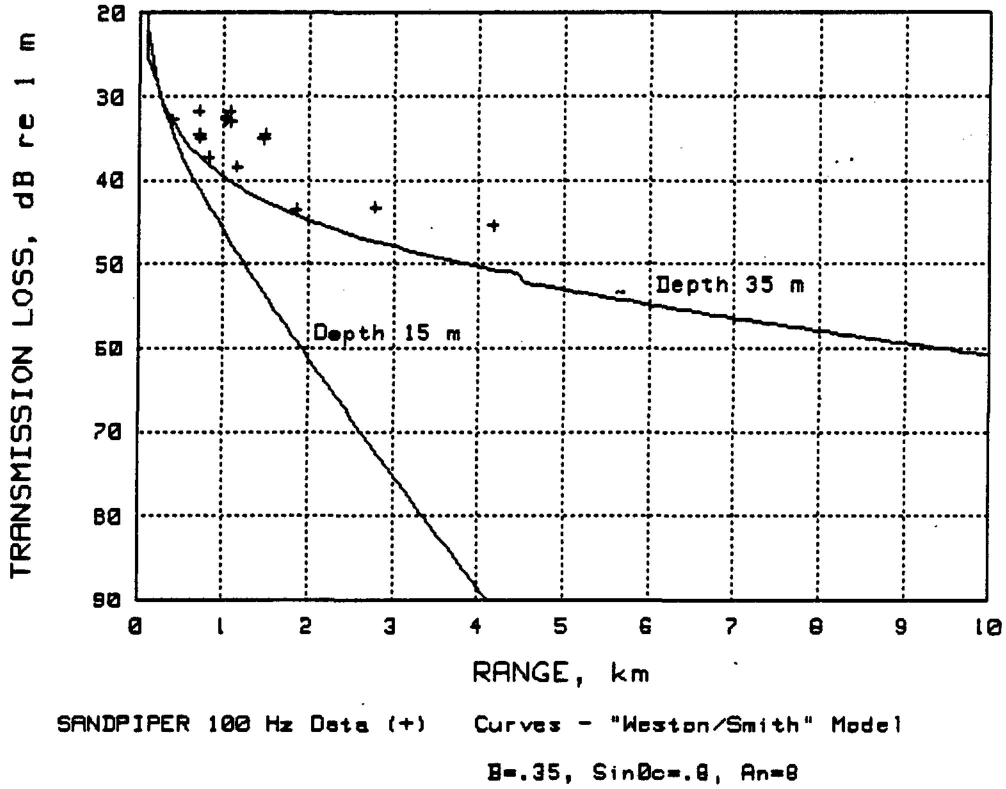


FIGURE 41. TRANSMISSION LOSS AT SANDPIPER SITE, COMPARISON WITH MODEL FOR 100 HZ AND TWO WATER DEPTHS (SOURCE: J-13 SOUND PROJECTOR).

this site would be expected to show a higher attenuation rate than was observed during the 1985 season. This needs verification by further measurements. No additional long range data were available from other measurements in this general area so TL information at ranges greater than 4 km will have a high measurement priority during the coming field season.

Erik Site

The Erik site is located in deeper water (40 m) than Orion and Sandpiper. The site was ice free during the measurement period and the sound velocity profiles may have been influenced by solar heating near the surface. It is also possible that the sound speed profiles were influenced by the southern edge of a 'plume' of lower salinity and warmer surface water that often occurs over the outer shelf and shelf break of the eastern Alaskan Beaufort Sea under predominating easterly winds. A plume was observed by Fissel et al. (1986) in the MacKenzie River bay area and was described in detail for the September 1985 period. As a result, an upward refracting layer was observed above 5 m with a possible slight sound channel from 10 to 25 m as shown in Fig. 42. Transmission loss data were obtained to a range of about 2 km. Analysis of these data showed a 10 Log R characteristic for all frequencies. The data are presented in Figs. 43 through 45.

The TL values are low for this site suggesting that a strong bottom or sub-bottom reflecting layer is present here also. Even though this site is about 20 km from shore, it is possible that the reflecting layer is permafrost and/or overconsolidated clay, based on information presented previously in Sec. 2.1.2.

Radiated noise data from an air gun operation near the Erik site were reported by Ljungblad et al. (1985b). Analysis of

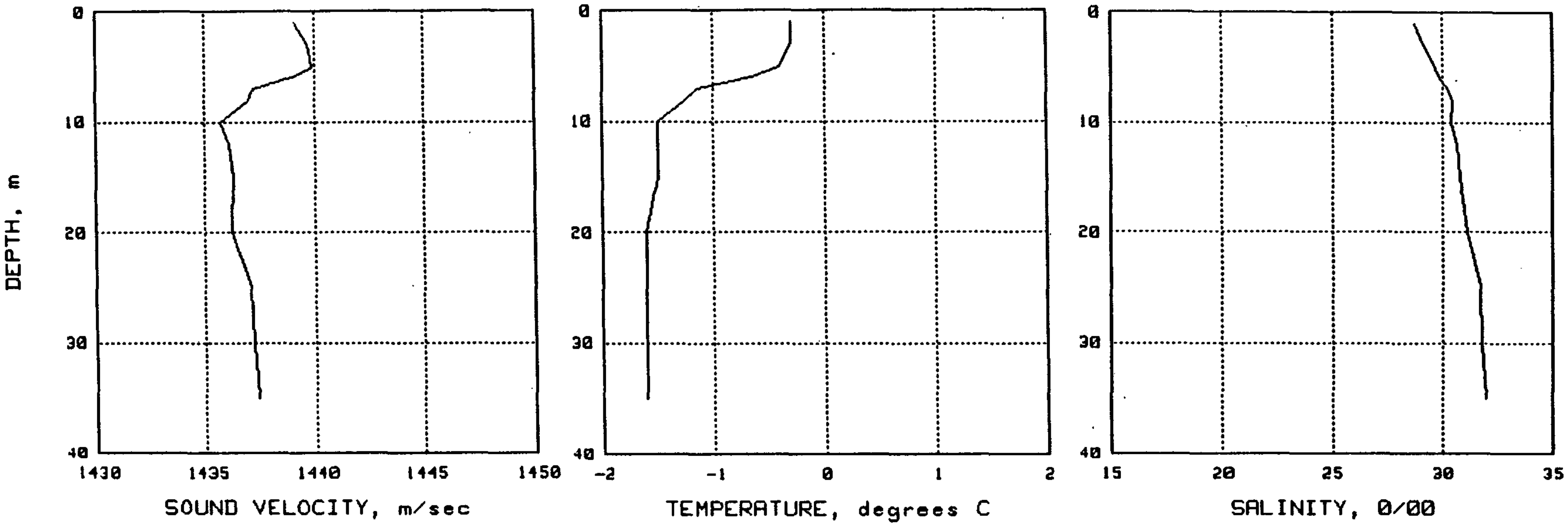
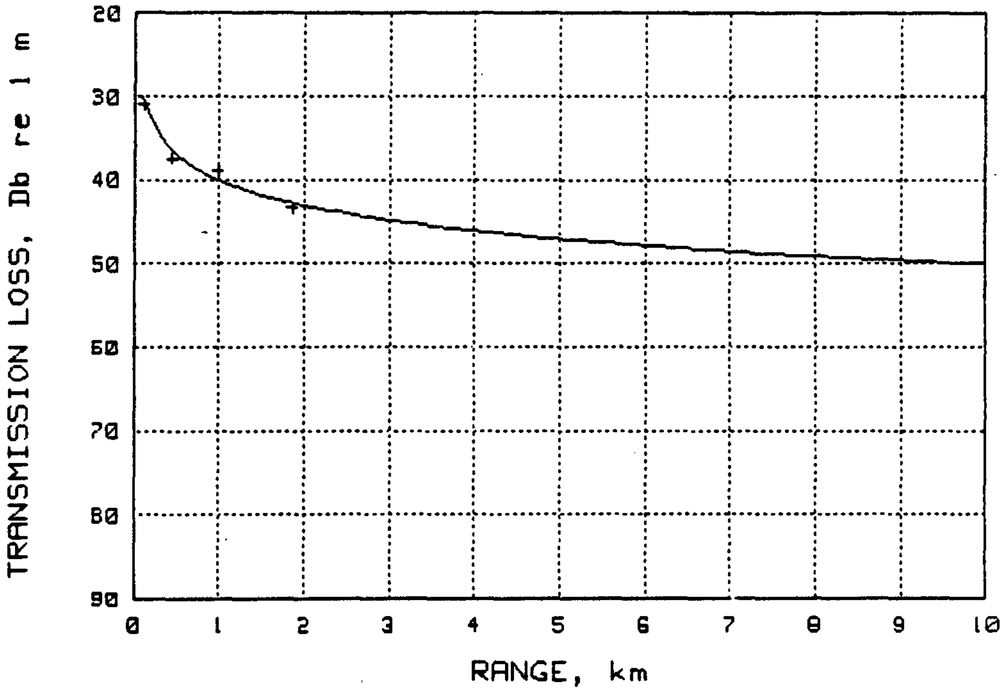
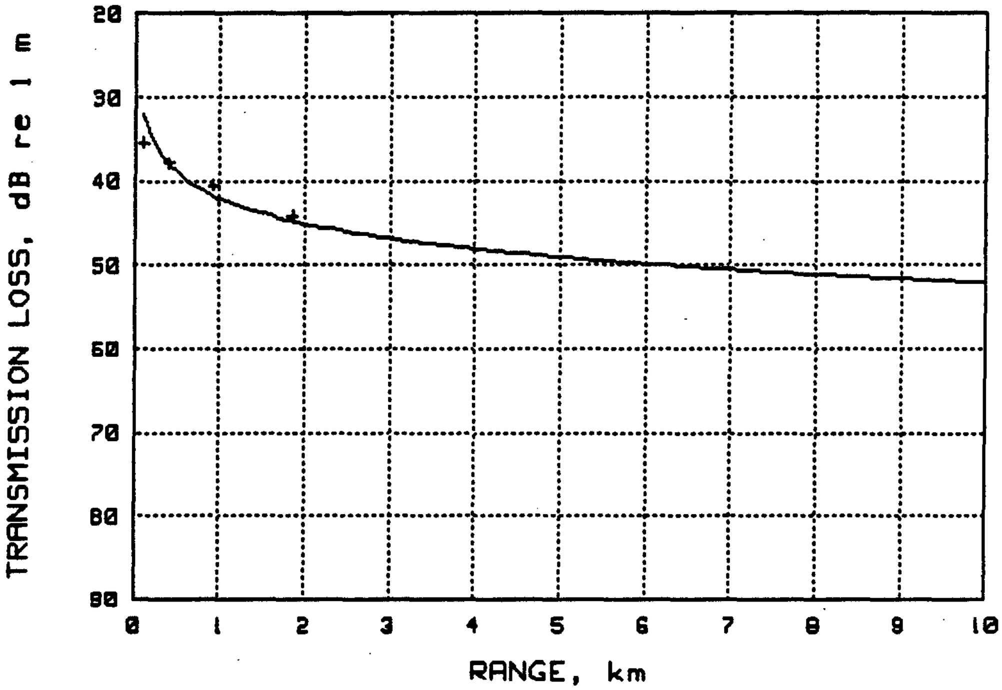


FIGURE 42. ENVIRONMENTAL DATA AT ERIK SITE, 9/13/85.

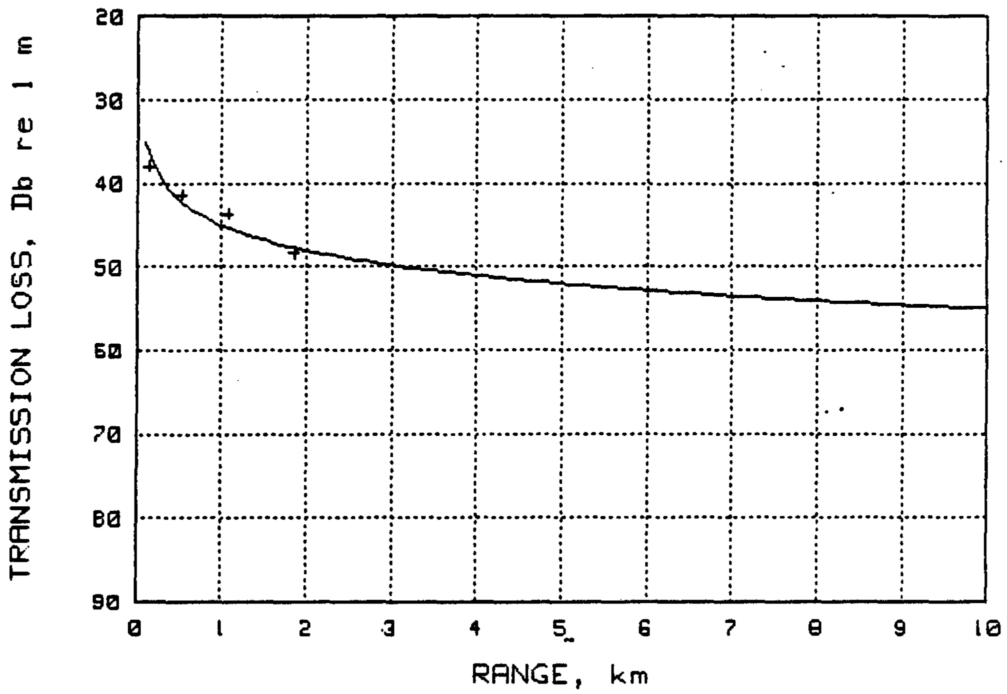


Erik 200 Hz Data, Curve -10 log R TL Model, A = 0.2, A_n = 6

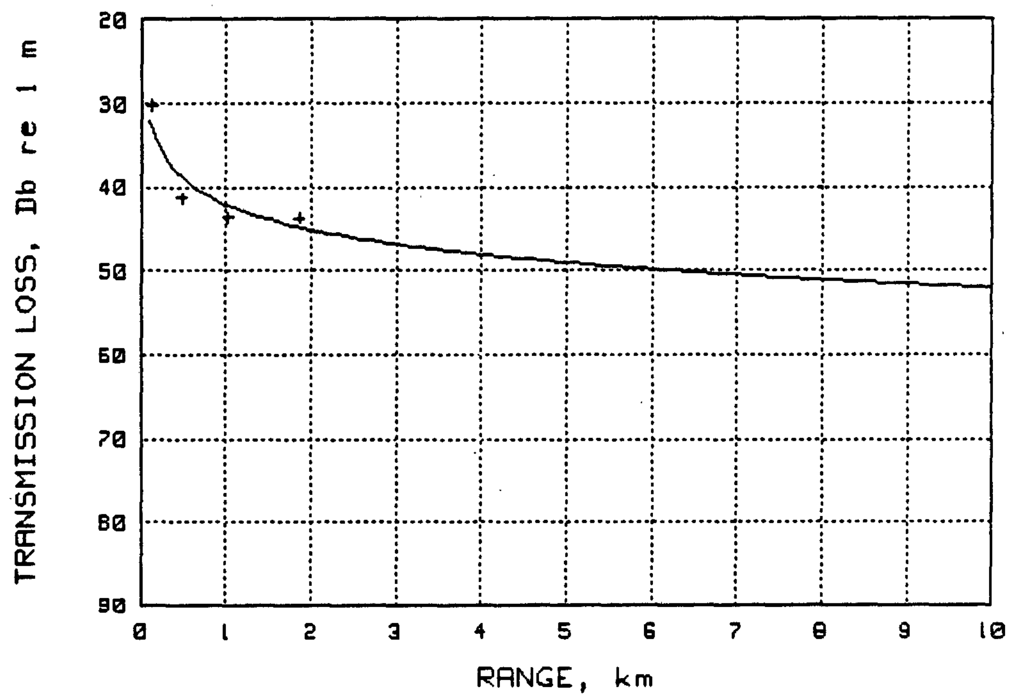


Erik 100 Hz Data, Curve -10 log R TL Model, A = 0, A_n = 4

FIGURE 43. TRANSMISSION LOSS MEASUREMENTS AT ERIK SITE USING AN ACOUSTIC PROJECTOR AT 100 HZ AND 200 HZ.

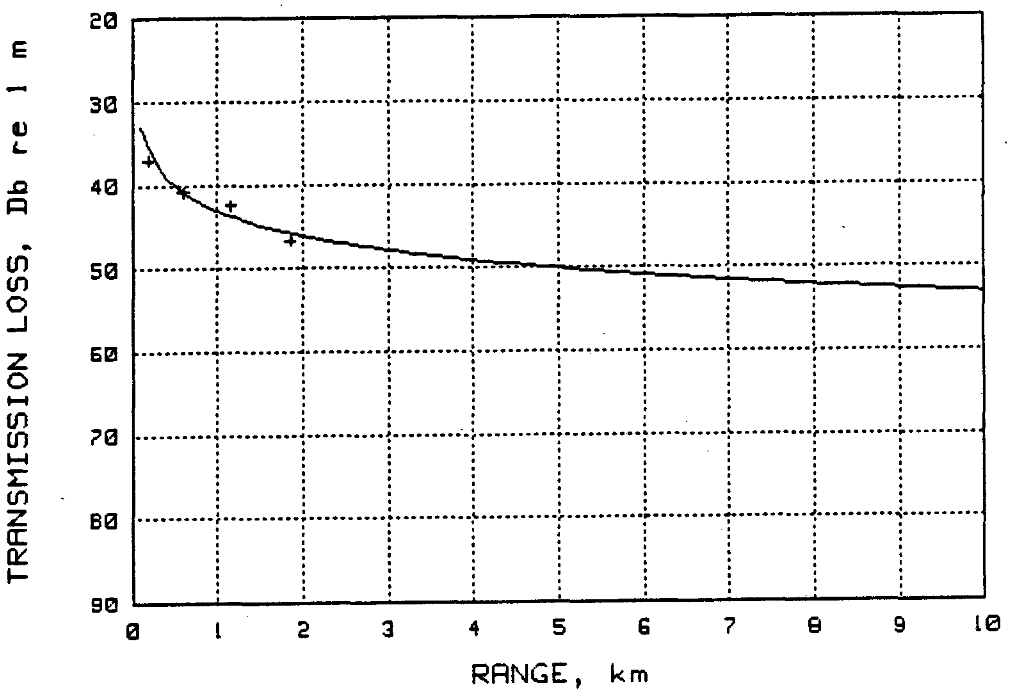


ERIC 1 kHz Data, Curve - 10 LOG R TL Model, A=0, An=1

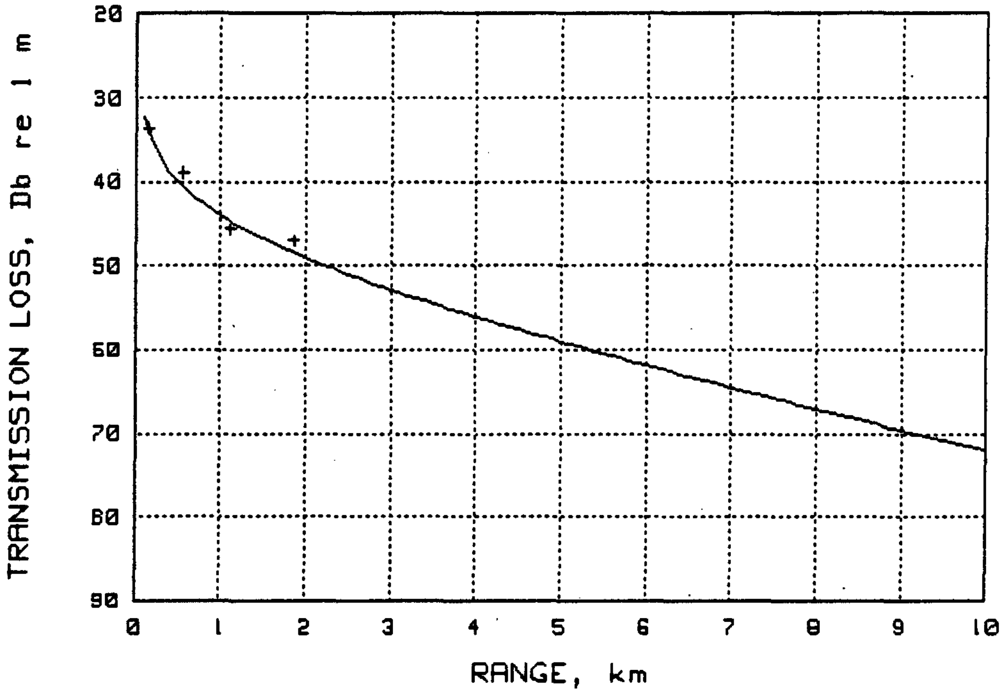


ERIC 500 Hz Data, Curve - 10 Log R Model, A=0, An=4

FIGURE 44. TRANSMISSION LOSS MEASUREMENTS AT ERIK SITE USING AN ACOUSTIC PROJECTOR AT 500 HZ AND 1 KHZ.



ERIC 4 kHz Data, Curve - 10 LOG R TL Model, A=0, An=3



ERIC 2 kHz Data, Curve - 10 LOG R TL Model, A=2, An=4

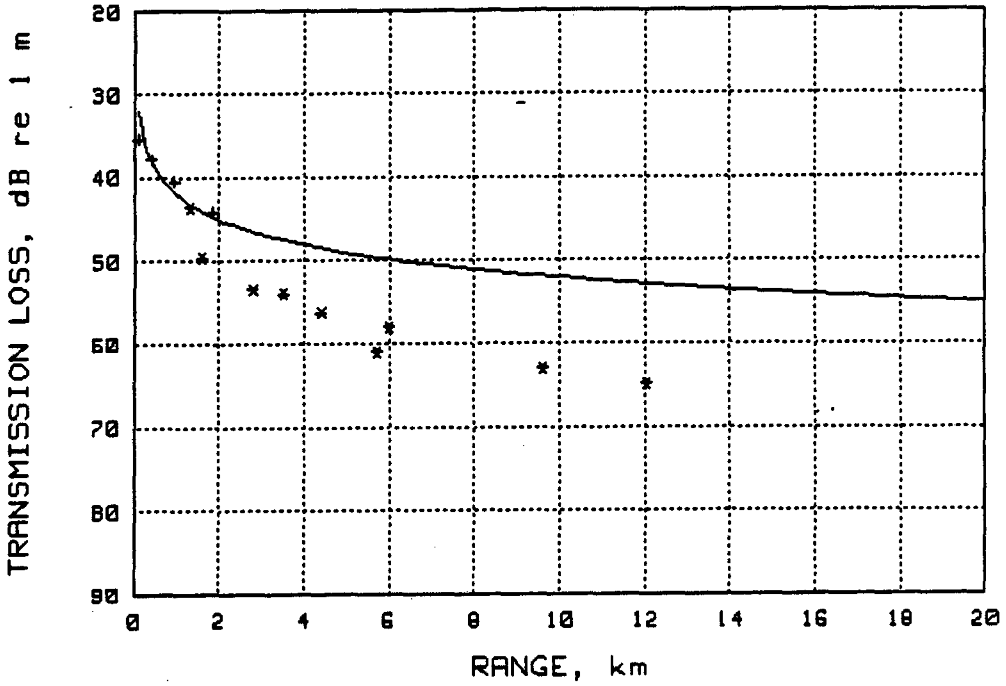
FIGURE 45. TRANSMISSION LOSS MEASUREMENTS AT ERIK SITE USING AN ACOUSTIC PROJECTOR AT 2 KHZ AND 4 KHZ.

these data provided supplementary TL information out to a range of 12 km. These supplementary data were compared with both the 10 Log R model and the Weston/Smith model at 100 Hz (Fig. 46). The 10 Log R model can be seen to underestimate the TL at ranges beyond 2 km, whereas the Weston/Smith model provides a better fit. The parameters used in the model were appropriate for a hard rock bottom at a depth of 40 m. The air gun data were measured on 9/18/84, only 1 week later in the season than the projector data obtained during the 1985 field season. Therefore, the sound velocity gradients would normally be expected to be comparable except for the seasonal variation influence of the MacKenzie River plume.

Belcher Site

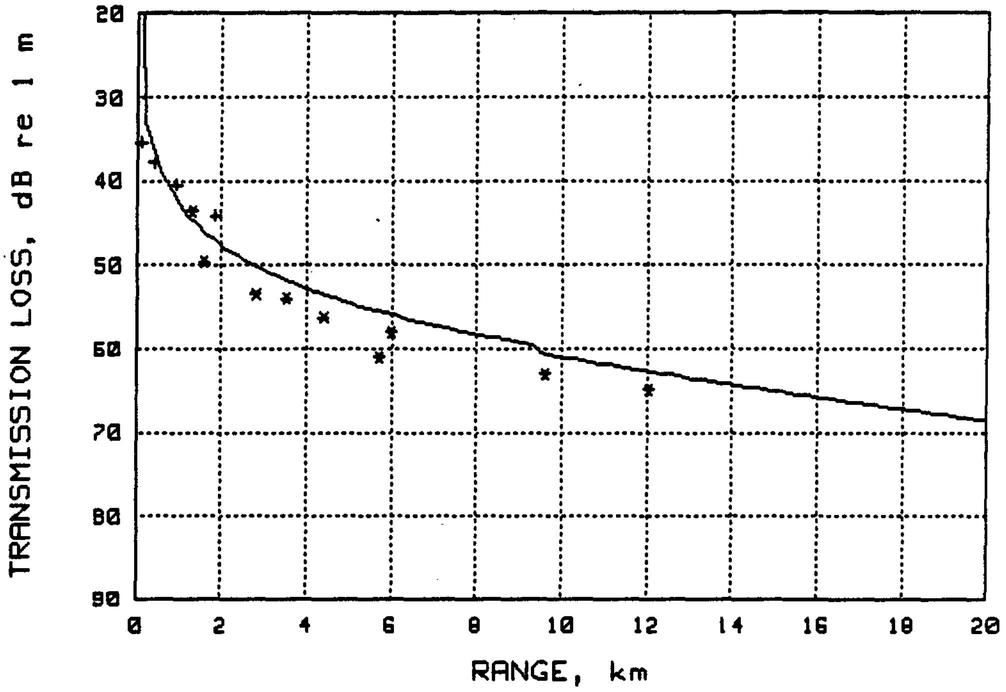
Belcher was the deepest and most easterly test area (55 m), and thus was the site most likely to be influenced by the plume of warmer fresher surface water mentioned above (Fissel et al. 1986). It also was ice free during the acoustic measurement period. The sound velocity gradients (Fig. 47) showed a weak surface channel that would cause upward refraction above a depth of 8 m. A moderate sound channel was present between 10 and 20 m.

Measurements made out to a range of about 2 km showed that a 10 Log R TL characteristic was appropriate for short range sound transmission at this site. The TL data are presented in Figs. 48 through 50. The TL characteristics at this site also show very low attenuation values, again indicating hard bottom conditions. A set of data were also available from seismic array measurements made nearby in 1984 by Ljungblad et al. (1985b). These data were processed to obtain supplementary TL information out to a range of about 12 km (Fig. 51). The Weston/Smith model provided a good match to the array data. The bottom parameters used correspond to soft rock. The two data points from the



ERIC 100 Hz Data (+) with WESTERN BEAUFORT Air Gun TL Data (*)

Upper Curve 10 LOG R TL Model, A=0, An=4



ERIK 100 Hz Data (+) with WESTERN BEAUFORT Air Gun TL Data (*)

Curve - 'Weston/Smith' TL Model, B=.25, Sin0c=.8, An=4

FIGURE 46. TRANSMISSION LOSS AT ERIK SITE, LONG RANGE ESTIMATE FOR 100 HZ USING DATA OF LJUNGBLAD ET AL. (1985b) AS WELL AS DATA FROM THIS PROJECT.

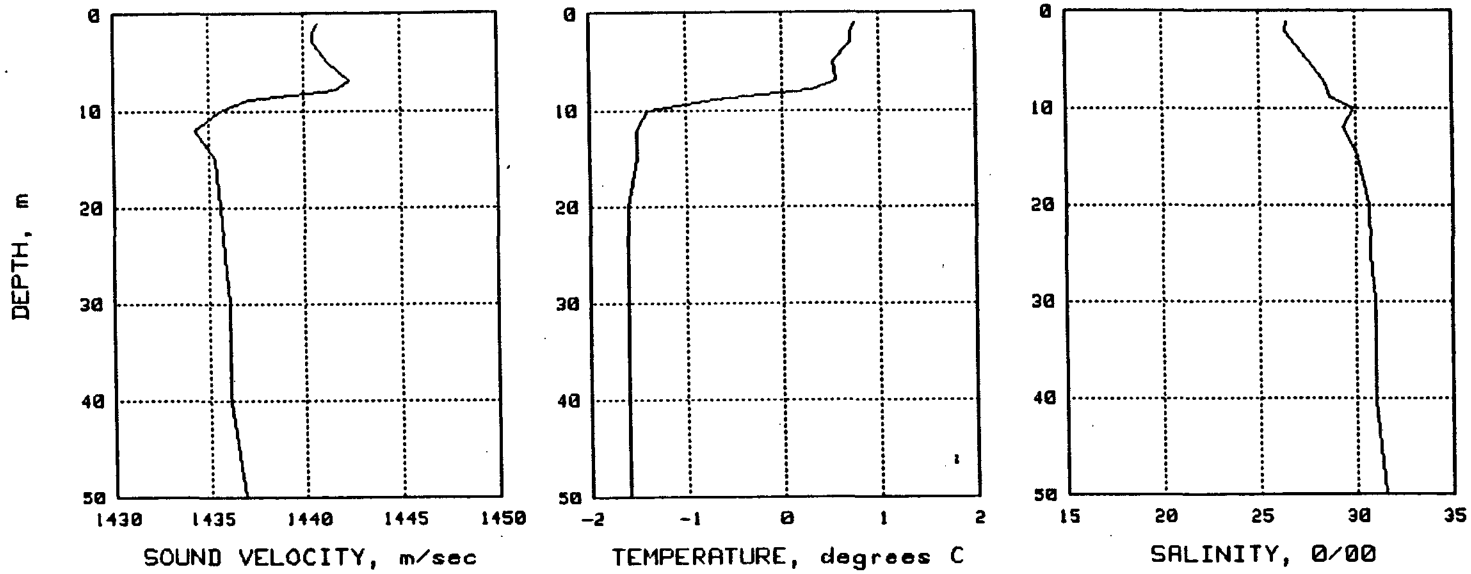
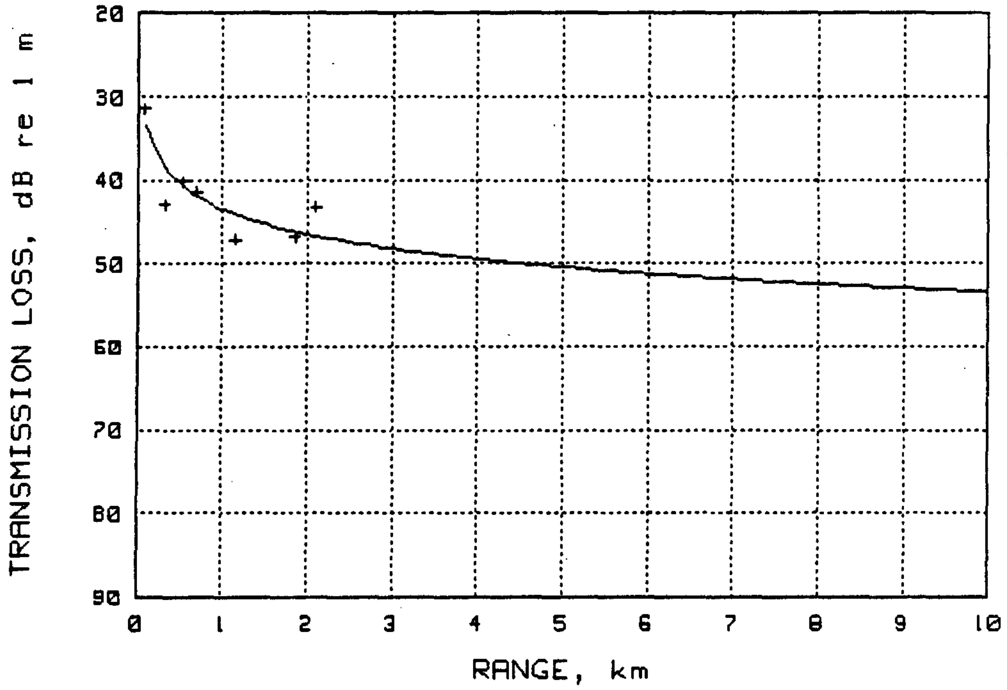
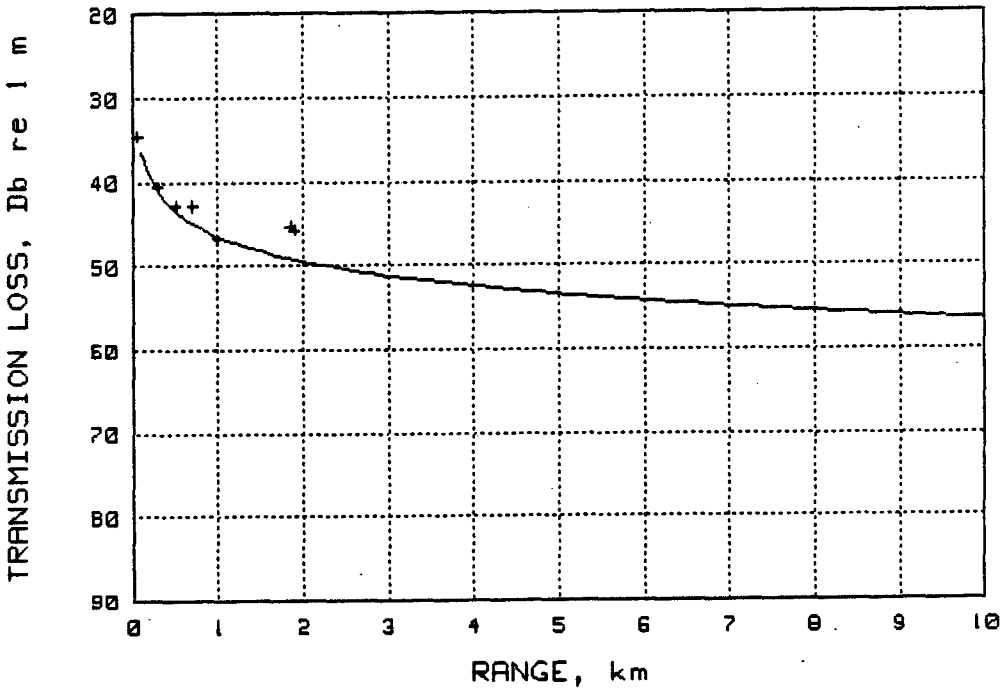


FIGURE 47. ENVIRONMENTAL DATA FOR BELCHER SITE, 9/10/85.

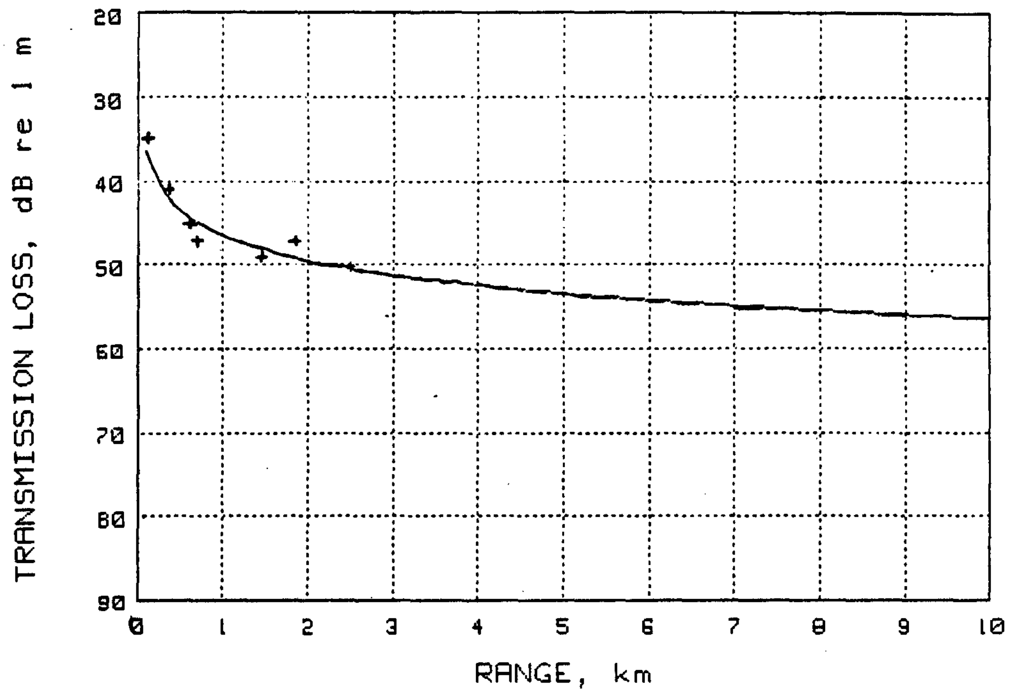


BELCHER 200 Hz Data, Curve - 10 LOG R TL Model, A=0, An=4

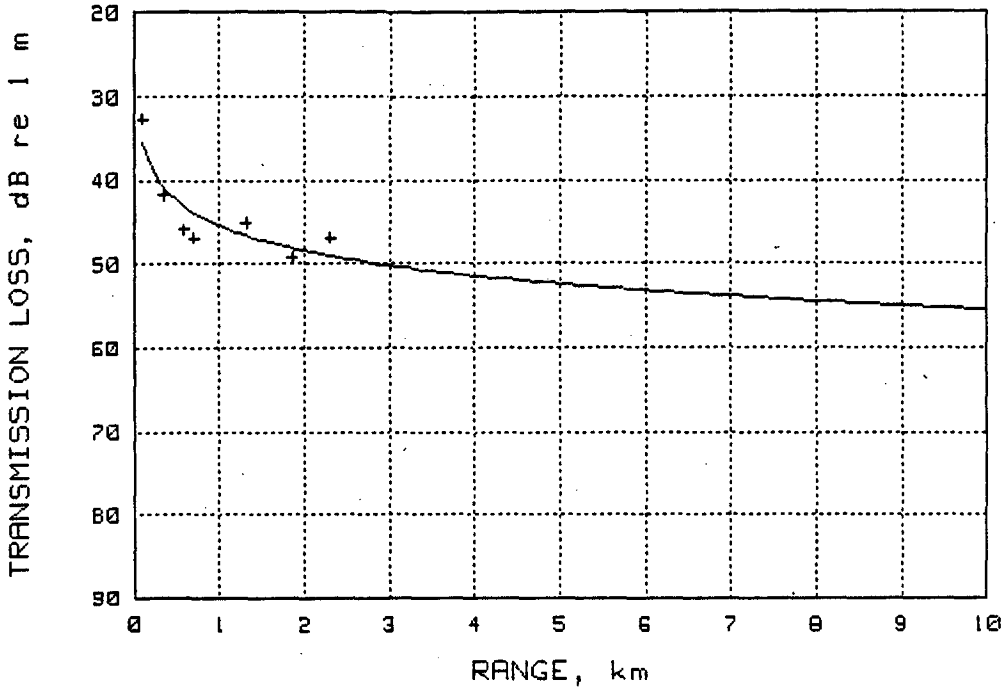


BELCHER 100 Hz Data, Curve - 10 LOG TL Model, A=0, An=1

FIGURE 48. TRANSMISSION LOSS MEASUREMENTS AT BELCHER SITE USING AN ACOUSTIC PROJECTOR AT 100 HZ AND 200 HZ.

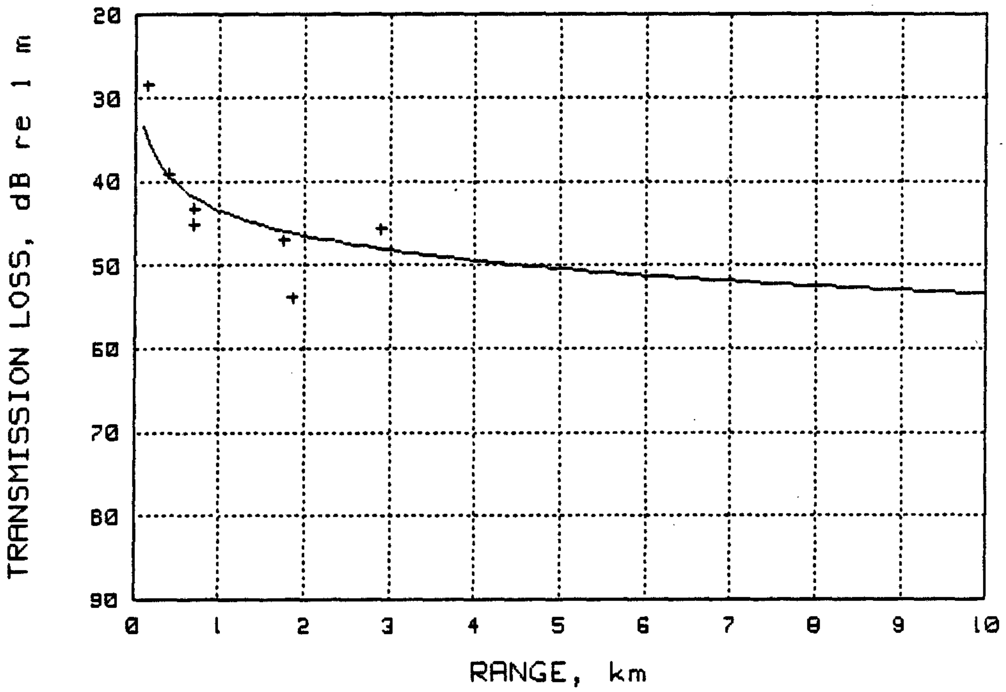


BELCHER 1 kHz Data, Curve - 10 LOG R TL Model, A-0, An-1

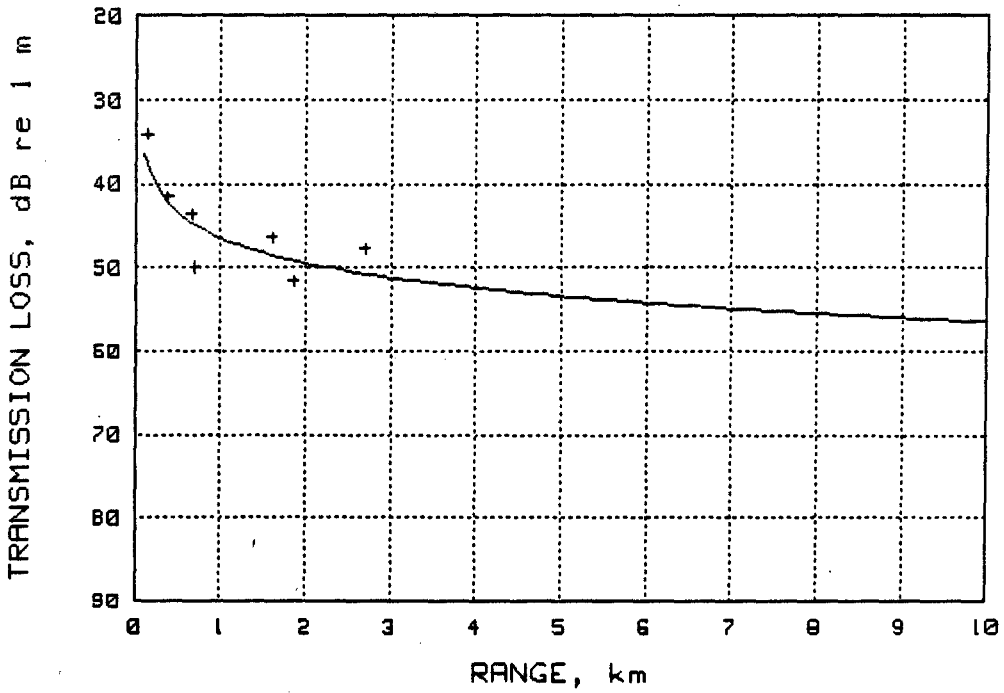


BELCHER 500 Hz Data, Curve - 10 LOG R TL Model, A-0, An-2

FIGURE 49. **TRANSMISSION LOSS MEASUREMENTS AT BELCHER SITE USING AN ACOUSTIC PROJECTOR AT 500 HZ AND 1 KHZ.**



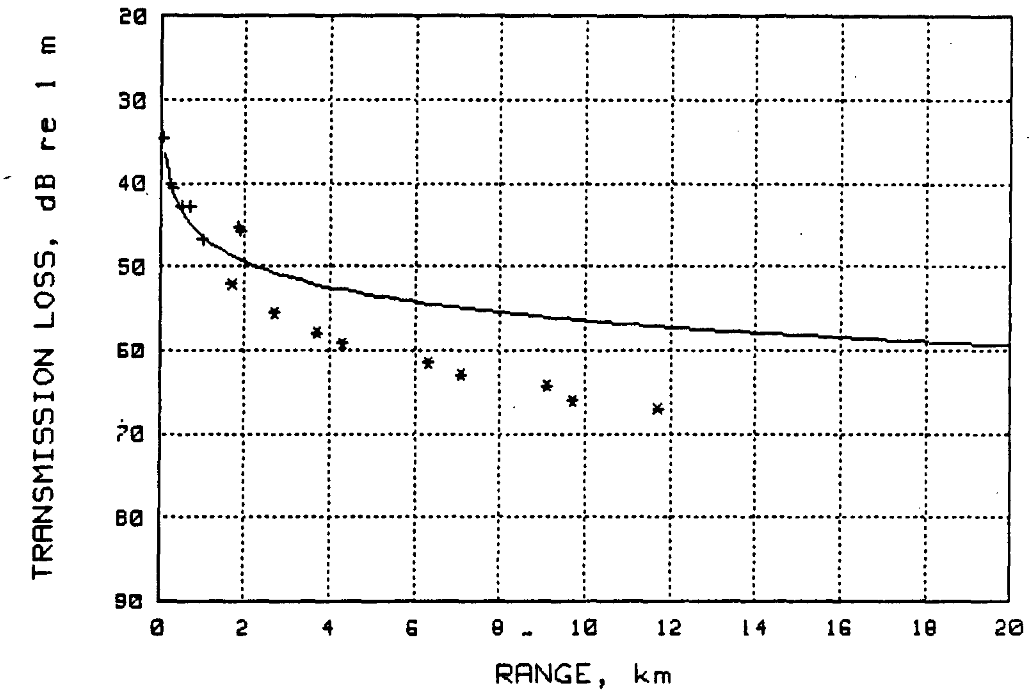
BELCHER 4 kHz Data, Curve - 10 LOG R TL Model, A-0, An-4



BELCHER 2 kHz Data, CURVE - 10 LOG R TL Model, A-0, An-1

FIGURE 50. **TRANSMISSION LOSS MEASUREMENTS AT BELCHER SITE USING AN ACOUSTIC PROJECTOR AT 2 KHZ AND 4 KHZ.**

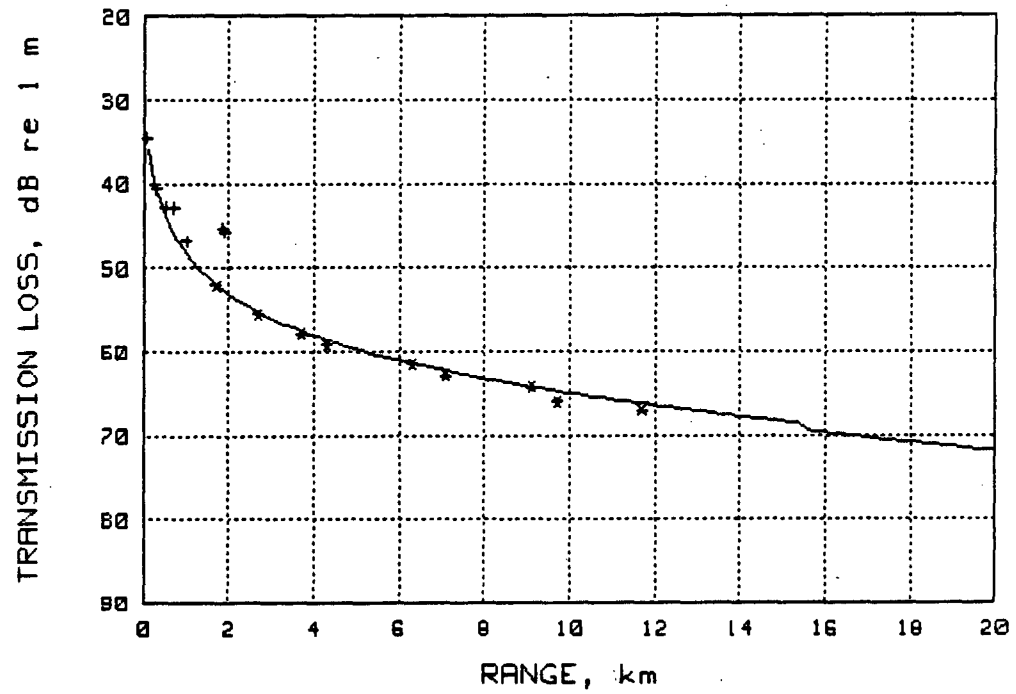
A.



BELCHER 100 Hz Data (+) and WESTERN POLARIS Air Gun Array Data (*)

Curve - 10 LOG R TL Model, A=0, An=1

B.



BELCHER 100 Hz Data (+) and WESTERN POLARIS Air Gun Array Data (*)

Curve - 'WESTON/PWS' Model, B=.4, Sin Phicrit=.7, Depth=55 m

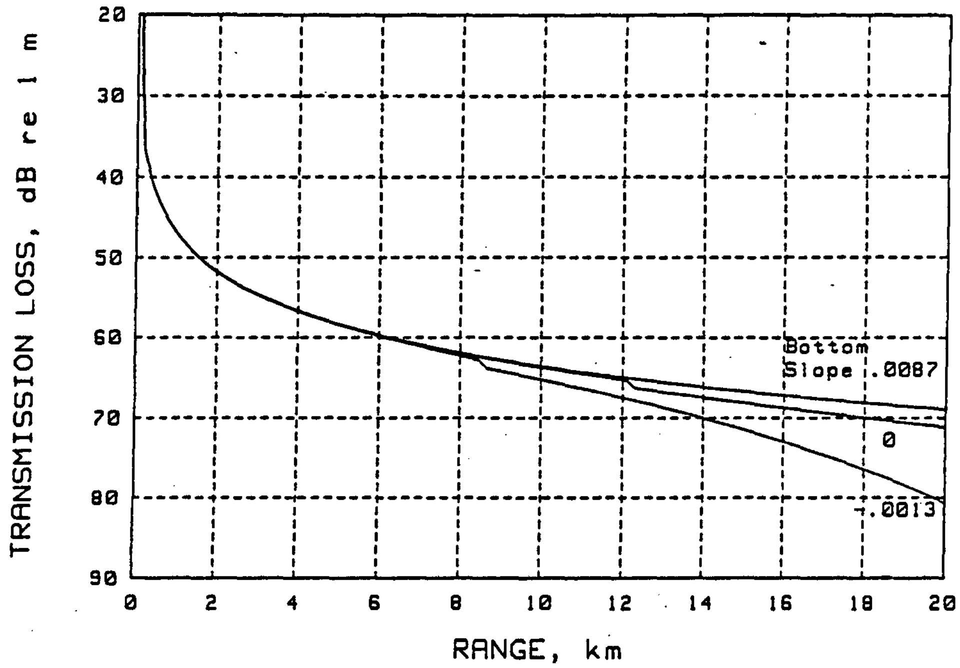
FIGURE 51. TRANSMISSION LOSS AT BELCHER SITE, LONG RANGE ESTIMATE FOR 100 HZ USING DATA OF LJUNGBLAD ET AL. (1985b) AS WELL AS DATA FROM THIS PROJECT.

projector tests at a range of 1.8 km seem to have anomalously low values of TL. Additional TL measurements will be made during the 1986 field season to obtain a better definition of the TL characteristics beyond 2 km from the site.

Since the Belcher site is located within the fall bowhead whale migration corridor (Fig. 2), it is necessary to consider the directional dependence of the TL characteristics. The general slope of the bottom toward the north and northeast is expected to cause the TL to be lower in those directions and higher in the southerly direction toward the coastline. This expected trend will be investigated during the 1986 field season. For the present report, the Weston/Smith model will be used to develop predictions of the influence of the sloping bottom on TL.

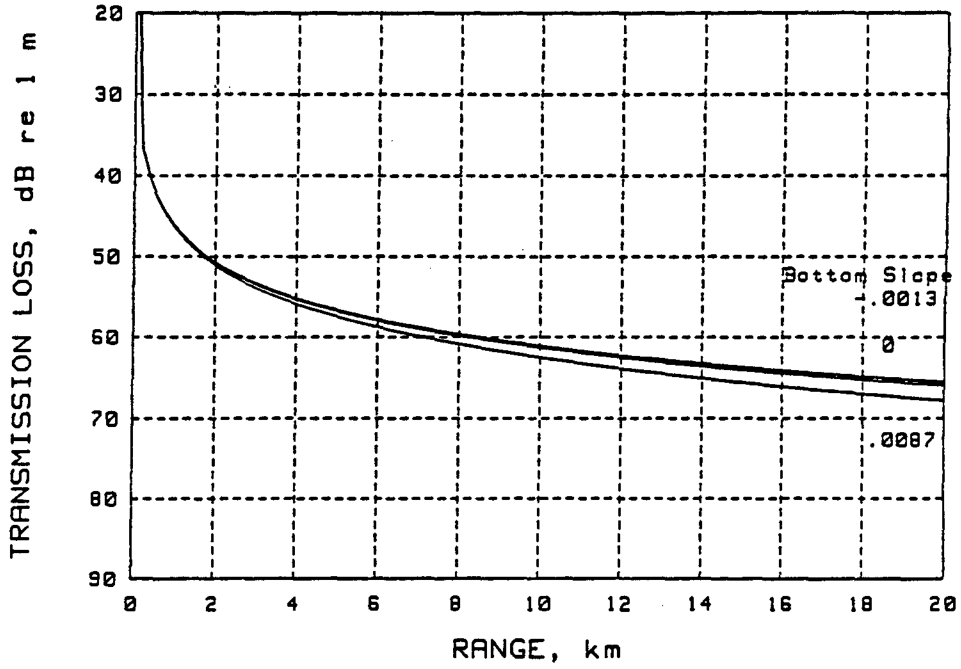
In Fig. 51, a flat or non-sloping bottom condition was used to obtain the predicted TL characteristic at the Belcher site for comparison with the air gun array TL data. Examination of chart depth information showed that an approximate slope of 0 0087 exists toward the north and an upward slope of -0.0013 exists toward the south. Figure 52A shows the effect of two sloping bottom conditions on low frequency sound (100 Hz) as compared to a zero slope condition. The diminishing depth toward the south can be seen to have a significant effect on the predicted TL. Figure 52B shows the predicted TL at 1 kHz, where the acoustic wavelength is very much less than the water depth. In this case the influence of the bottom slope is considerably less than at low frequencies. The effects of bottom slope conditions on TL prediction for 1 kHz are the opposite from the predictions for 100 Hz; at 1 kHz the highest TL occurs for <u>increasing</u> water depth to the <u>north</u>, while at 100 Hz the highest TL occurs for <u>decreasing</u> water depth to the <u>south</u>.

A.



BELCHER "Weston/Smith" Model, 100 Hz B=.5 Sin0c=.8

B.



BELCHER "Weston/Smith" Model, 1kHz B=.5 Sin0c=.8

FIGURE 52. ESTIMATED EFFECT OF BOTTOM SLOPE ON TRANSMISSION LOSS AT BELCHER SITE, BASED ON THE WESTON/SMITH MODEL.

Summary

Table 3 summarizes the values of the attenuation factors (A_s) and local anomalies (A_n) obtained from the least-squares analysis of the empirical TL data from each site. A positive or high anomaly value is due to a sound reverberation effect, resulting in a higher received sound level than would normally be obtained in very deep water. Also shown in the table is the mean square error for each analysis. The average error between the measured data and the predicted value at the same range is the square-root of the value shown in the table.

Since the TL characteristics at all of the sites showed a 10 Log R spreading loss, it is possible to compare the transmission properties of the sites by reviewing the data presented in this table. Belcher can be seen to have the lowest attenuation factors as a result of the hard bottom and deeper water than the other sites. The local anomaly at Belcher is also lower than at the other sites, primarily as a result of the deeper water. The Orion site had the highest attenuation factors and also the highest local anomaly with the values from Sandpiper being similar if not quite as high. The 4 kHz TL data for both Orion and Sandpiper were very scattered with a resulting high mean square error. The values shown in the table for A and A_n at 4 kHz at these sites thus are less accurate than the rest of the data.

TABLE 3. ACOUSTIC MODEL* PARAMETER VALUES OBTAINED FROM LEAST-SQUARES ANALYSIS OF TRANSMISSION LOSS DATA.

	1/3 OB Frequency Hz	A_s Atten. Factor dB/km	A_n, Source Anomaly dB	Mean Model Error dB (rms)
Orion Site				
	100	2.2	10	1.8
	200	3.1	12	1.5
	500	2.0	9	1.7
	1K	2.0	5	2.8
	2K	4.0	3	4.2
	4K	2.0	-8	7.1
Sandpiper Island Site				
	100	1.3	8	2.6
	200	0.5	9	1.8
	500	1.1	10	1.1
	1K	0.8	6	1.5
	2K	0.7	3	1.5
	4K	0	-5	6.7
Erik Site				
	100	0	4	1.8
	200	0.2	6	0.8
	500	0.4	4	2.1
	1K	0.1	1	1.3
	2K	1.6	4	1.1
	4K	0.2	3	1.1
Belcher Site				
	100	0	2	1.6
	200	0	4	2.5
	500	0	2	2.2
	1K	0.2	1	1.6
	2K	0	1	2.9
	4K	0.5	5	3.3

*Based on Eq. 8:

$$L_r = L_s + A_n - 10 \log H_{av} - 10 \log R - A_s R - A_v R$$
$$- 30 \text{ (dB re 1 } \mu\text{Pa)}$$

3.4 Zones of Influence on Whales*

3.4.1 Dominant Frequency Components for Each Industrial Source

The five industrial sources considered in the zone of influence analyses were a barge-mounted clam-shell dredge, a tug beginning to tow a loaded barge, a pair of tugs forcing a barge against an artificial island, drilling by a drillship, and drilling on an artificial island (Section 3.2). Figures 53A through 53D show estimated source levels of the sounds from the first four of these sources (see Section 3.2 for details, and for data from drilling on the island). Figure 53 also shows the estimated median ambient noise levels at two groups of sites (from Section 3.1). These source level and ambient noise data were used to select the 1/3-octave bands for which sound propagation calculations would be done.

When the dredge bucket was being hauled up at Erik, strong tones were recorded at various harmonics of 125 Hz, although not at 125 Hz itself (Fig. 53A). Since the sound levels of tonals are bandwidth independent, the levels in the 1/3-octave bands that contained these tones were very similar to the levels of the tones themselves. Levels at 250 Hz, 750 Hz, and 1250 Hz were especially high relative to ambient noise levels (Fig. 53A). The approximate peak 1/3-octave source levels at these three frequencies were 162, 158, and 158 dB re 1 μPa, respectively. Consequently, propagation calculations were done for these three frequency/source level combinations.

When the tug ARCTIC FOX began towing a fully-loaded barge away from the Erik dredge site, the 1/3-octave band with highest

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*By W. John Richardson, LGL Ltd., environmental research associates.

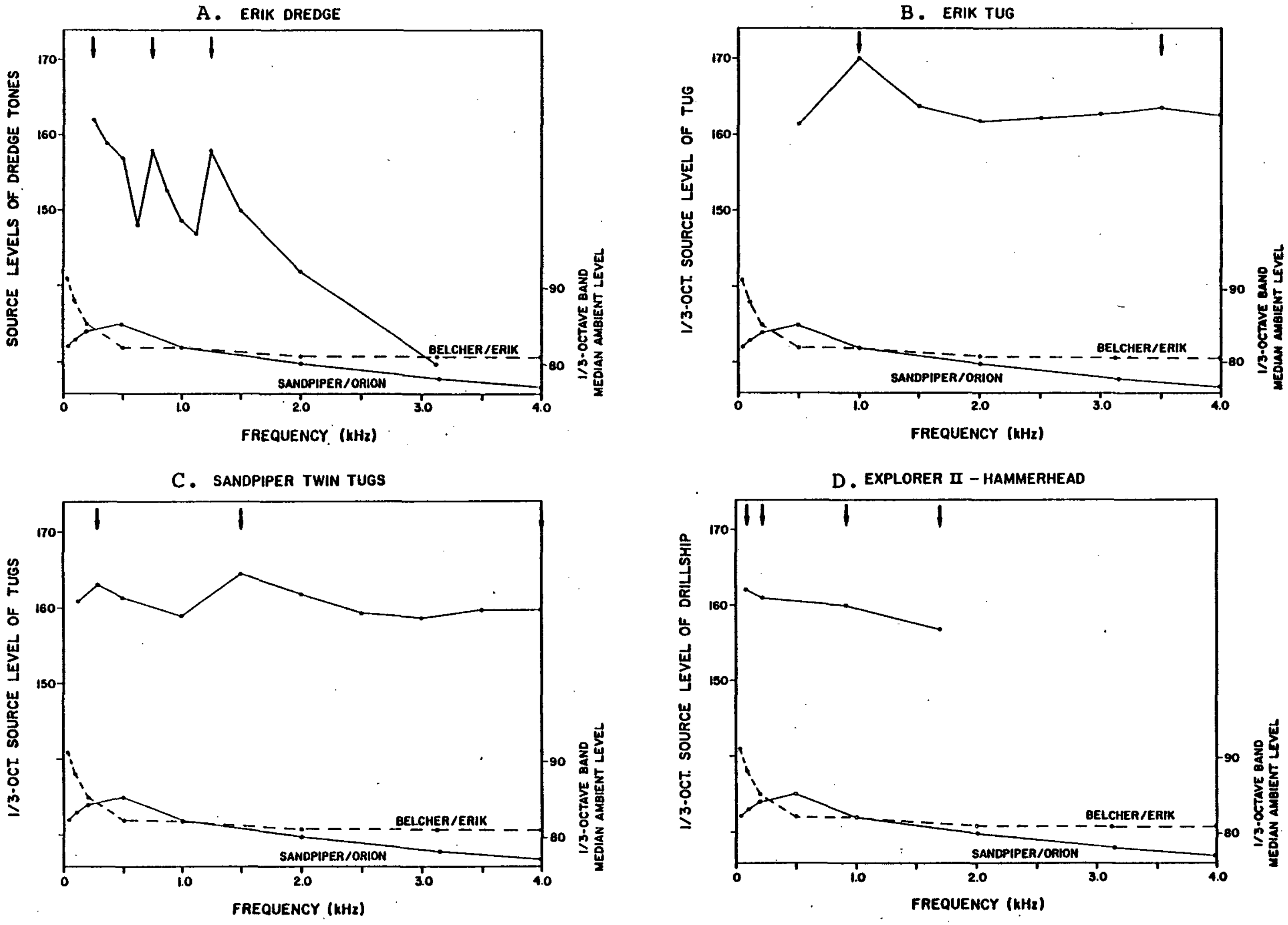

FIGURE 53. FREQUENCY DEPENDENCE OF ESTIMATED SOURCE LEVELS OF SOUNDS FROM FOUR INDUSTRIAL ACTIVITIES, PLOTTED RELATIVE TO EXPECTED MEDIAN AMBIENT LEVELS AT CORRESPONDING FREQUENCIES. THE ARROWS SHOW THE FREQUENCY/SOURCE LEVEL COMBINATIONS THAT WERE SELECTED FOR PROPAGATION CALCULATIONS.

source level (170 dB) was centered at 1000 Hz (Fig. 53B). Band levels were more or less independent of frequency from 1500 Hz to 5000 Hz. However, within this range, the band with highest level and highest signal : average ambient ratio was near 3500 Hz (164 dB). These two frequency/source level combinations were used in propagation calculations.

When two tugs held a barge against Sandpiper Island, the estimated 1/3-octave source spectrum was high, relative to the ambient noise, around 300 Hz (163 dB), 1500 Hz (164 dB), and 4000 Hz (160 dB). Propagation calculations were done for these three frequency/source level combinations.

The drillship EXPLORER II operating at Hammerhead produced high levels of sound in 1/3-octave bands near 80 Hz, 240 Hz, 920 Hz, and 1640 Hz (Fig. 53D). Estimated source levels in these four bands were 162, 161, 160, and 157 dB, respectively. Propagation calculations were done for all four of these frequency/source level combinations.

During drilling at Sandpiper Island, the dominant sound was a tone at 40 Hz (Section 3.2). The estimated source level for this tone, and for the 1/3-octave band containing it, was 145 dB. This was the only frequency/source level combination used in analyses of zones of influence around Sandpiper Island.

3.4.2 Zones of Detectability

Bowhead and gray whales are expected to be able to detect industrial sounds in the approximate range 40 or 50 Hz to 4000 Hz if the received noise level in any 1/3-octave band exceeds the ambient level in the corresponding band (see Section 2.3.1). We hypothesized that each of the five sources of industrial noise noted above was operating in turn at each of five sites. We used the site-specific Weston/Smith sound propagation models developed in Section 3.3 to predict the received levels as a function of range and bearing from these sites. The estimated ambient noise statistics from Section 3.1 were used to estimate the range at which the received level would equal the ambient level. The Figures and Tables in this section show the results for the 1/3-octave band that would be detectable farthest away. Appendix A summarizes the results for all of the 1/3-octave bands that were analyzed.

Orion. -- If the dredge, the tugboats, or the EXPLORER II drillship operated at Orion, the industrial noise level in at least one 1/3-octave band would be expected to remain above the median ambient noise level in the corresponding band out to ranges 35-45 km to the east or west (Fig. 54; Table 4). To the north, where water depth increases with increasing range, the noise from each of these operations is predicted to be above the ambient level to ranges beyond 50 km. Thus, 50% of the time, a dredge, tug or drillship operating at Orion would be expected to be detectable at distances as great as 35-45 km east or west, and >50 km north. However, these distances are greater than the maximum range where the Weston/Smith sound model is expected to give reasonably accurate results. (In Figure 54, the estimated received levels are shown as dashed lines at ranges greater than the 'maximum believable range'.) The estimated ranges where received level would equal the median ambient are especially uncertain to the north of Orion; the 'maximum believable ranges' are less on bearings where water depth increases with increasing range (north) than on bearings where water depth is constant (east, west).

The estimated ranges at which the received noise from these same industrial operations would exceed the 95th percentile ambient noise were 22-27 km to the east or west of Orion and 45 km or more to the north (Table 4; Fig. 54). Thus, 95% of the

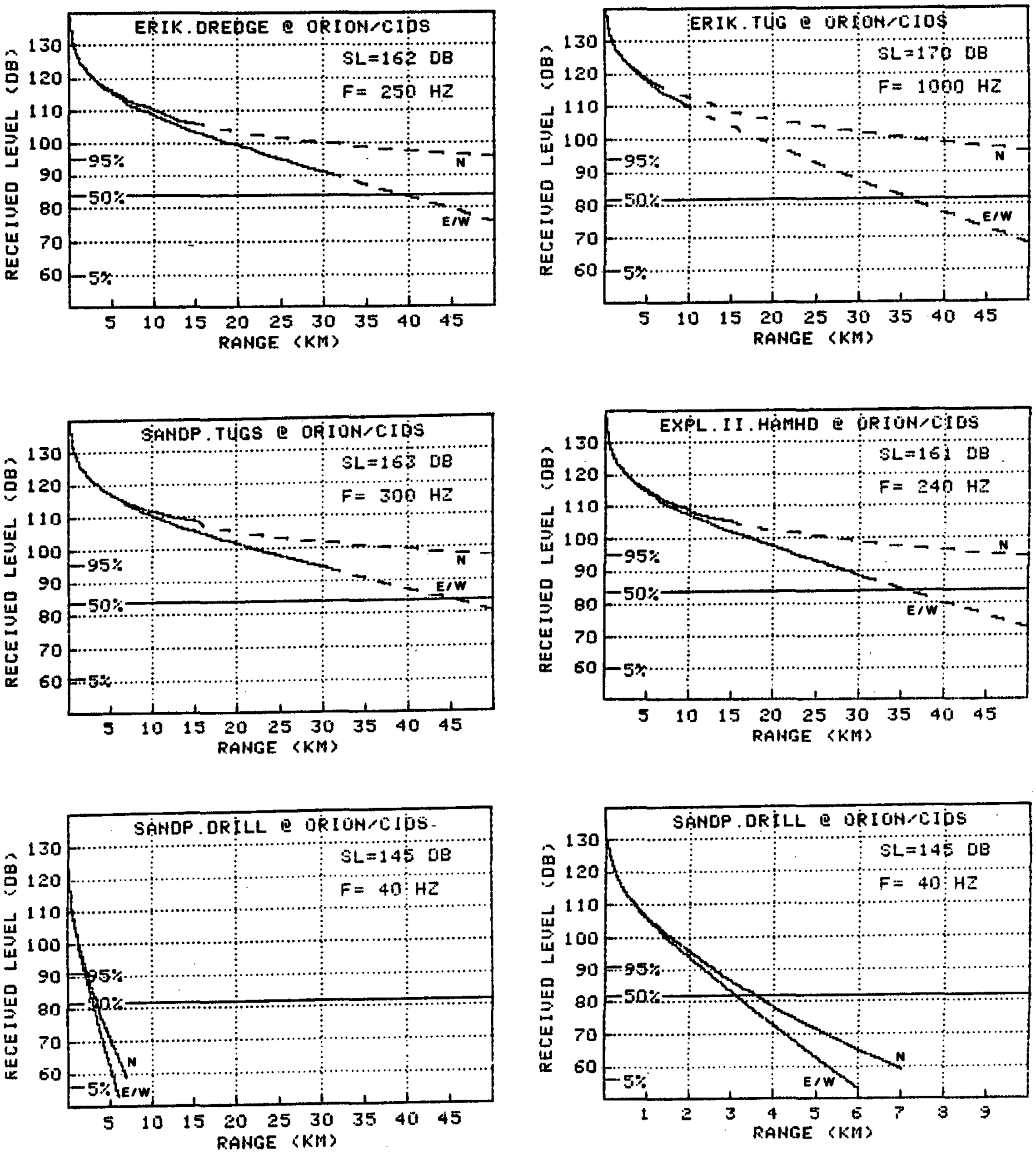

FIGURE 54. ESTIMATED RECEIVED LEVELS OF INDUSTRIAL NOISE AT VARIOUS DISTANCES FROM THE ORION SITE IF EACH OF FIVE INDUSTRIAL SOURCES WERE OPERATING THERE. ESTIMATED RECEIVED LEVELS WITH CONSTANT WATER DEPTH (WNW AND ESE OR ORION) AND FOR INCREASING WATER DEPTH (NNE OF ORION) ARE SHOWN. IN EACH GRAPH, THE INDUSTRIAL AND AMBIENT ESTIMATES ARE FOR THE 1/3-OCTAVE BAND WHOSE SOUNDS WOULD BE DETECTABLE AT GREATEST RANGE; THE SOURCE LEVEL (SL) AND CENTER FREQUENCY (F) ARE INDICATED. SOUNDS RECORDED DURING DRILLING ON SANDPIPER ARTIFICIAL ISLAND ARE PLOTTED ON TWO HORIZONTAL SCALES. ESTIMATES ARE BASED ON THE WESTON/SMITH SHALLOW-WATER SOUND PROPAGATION MODEL, WITH SITE- AND FREQUENCY-SPECIFIC ESTIMATES OF BOTTOM REFLECTIVITY AND LOCAL ANOMALY. AT RANGES WHERE THE CURVES ARE SHOWN AS DASHED LINES, THE ESTIMATED RECEIVED LEVELS ARE UNRELIABLE (SEE TEXT). EXPECTED AMBIENT NOISE LEVELS (5th, 50th, AND 95th PERCENTILES) ARE ALSO SHOWN.

TABLE 4. ESTIMATED "ZONES OF AUDIBILITY" OF UNDERWATER NOISE FROM FIVE INDUSTRIAL SOURCES IF THEY WERE AT THE ORION/CIDS SITE, ALASKAN BEAUFORT SEA. THE 1/3-OCTAVE BAND THAT WOULD BE DETECTABLE AT GREATEST RANGE IS CONSIDERED (SEE APPENDIX D FOR OTHER BANDS). THE DETECTION THRESHOLD IS ASSUMED TO EQUAL THE AMBIENT NOISE LEVEL.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at Orion (dB, 1/3 Oct. Band)			Direction from Orion	Est. Range (km) from Orion Where Sig. to Amb. Noise Ratio = 0			Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	
Dredge bucket being raised at Erik										
	250	162	60	84	95	E/W	>50	39	25	30
						N	>50	>50	>50	16
Tug beginning to tow barge at Erik										
	1000	170	60	82	94	E/W	>50	35	24	11
						N	>50	>50	>50	6
2 Tugs at Sandpiper										
	300	163	61	84	96	E/W	>50	45	27	30
						N	>50	>50	>50	15
Explorer II drilling at Hammerhead										
	240	161	60	84	95	E/W	>50	35	22	30
						N	>50	>50	45	16
Drilling at Sandpiper										
	40	145	56	82	91	E/W	5.7	3.1	2.3	63
						N	7.6	3.5	2.5	23

*The "Maximum Range of Reliability" column shows the distance (in km) beyond which the Weston/Smith propagation model may no longer provide reliable results.

time, sounds from a dredge, tugs or drillship at Orion would be potentially detectable at least 22-27 km east or west and 45 km north of Orion. Some of the 22-27 km estimates for east and west bearings were within the range where the Weston/ Smith model is believed to be reasonably accurate (dredge; tugs recorded at Sandpiper; EXPLORER II). All of the estimates for northerly bearings were well beyond the maximum range where the model can be assumed to be reliable.

The estimated ranges where the received level of dredge, tug or drillship noise would exceed the 5th percentile of ambient noise were beyond 50 km for east/west as well as north bearings. All of these estimates were well beyond the range where the model can be expected to be reliable.

Thus, if there were dredge, tugboat or drillship operations at Orion, the sounds would be expected to be above ambient levels, and potentially detectable, out to ranges of several tens of kilometers. Potential ranges of audibility would be greater to the north than to the east or west. Even under conditions of high natural ambient noise (95th percentile conditions), these industrial operations would be expected to be detectable up to about 25 km to the east or west, and farther to the north. Because of the uncertain accuracy of the propagation model for long ranges, especially to the north, all of these estimates should be taken as general guidelines, not specific predictions.

In contrast, if the 40 Hz sounds recorded from the drilling operation on Sandpiper Island were introduced into the water at Orion, their levels would be expected to drop below the median ambient level within 3 to 3.5 km from Orion (Fig. 54, Table 4). They would drop below the 95th percentile ambient noise within 2.3 to 2.5 km, and below the 5th percentile ambient noise within 6 to 8 km. All of these estimates are within the range where the

Weston/Smith propagation models are expected to be reliable. The comparatively low range of potential audibility of the 'drilling on artificial island' sounds is attributable to two factors: (1) Their source level was 12 to 25 dB less than the levels of the other sounds considered here, and (2) their expected attenuation rate in the shallow water near Orion was higher because of their low frequency and higher attenuation factors (see Table 4).

Sandpiper. -- If the five industrial sources that we are considering operated at Sandpiper and Orion in turn, each one is predicted to be detectable somewhat farther from Sandpiper than from Orion (Fig. 55; Table 5). The dredge, tug and drillship sounds in at least one 1/3-octave band would be expected to exceed the corresponding median ambient noise level at all ranges within 50 km to the east, west or north of Sandpiper. However, it should be noted that the predicted received levels at ranges of 50 km or more are not very reliable. The received levels are predicted to equal the 95th percentile ambient noise at 36 to 43 km east or west of Sandpiper, as opposed to 22 to 27 km east or west of Orion. For the dredge, Sandpiper tugs and drillship, the Weston/Smith sound propagation model is considered reasonably reliable out to a range of 43 km to the east or west, but only to 28 km to the north.

The 40 Hz sound from drilling on an artificial island would not be detectable nearly as far away. The received level is predicted to equal the 95% ambient at about 3 km, the median ambient at about 4.5 km, and the 5% ambient at about 9 km (Table 5; Fig. 55). These estimates are slightly greater than corresponding figures for the Orion site. The estimates are well within the zone where the Sandpiper sound propagation model is expected to be reasonably reliable. The estimates are also consistent with the actual measurements of Johnson et al. (1986) concerning the range of detectability of these sounds near Sandpiper Island.

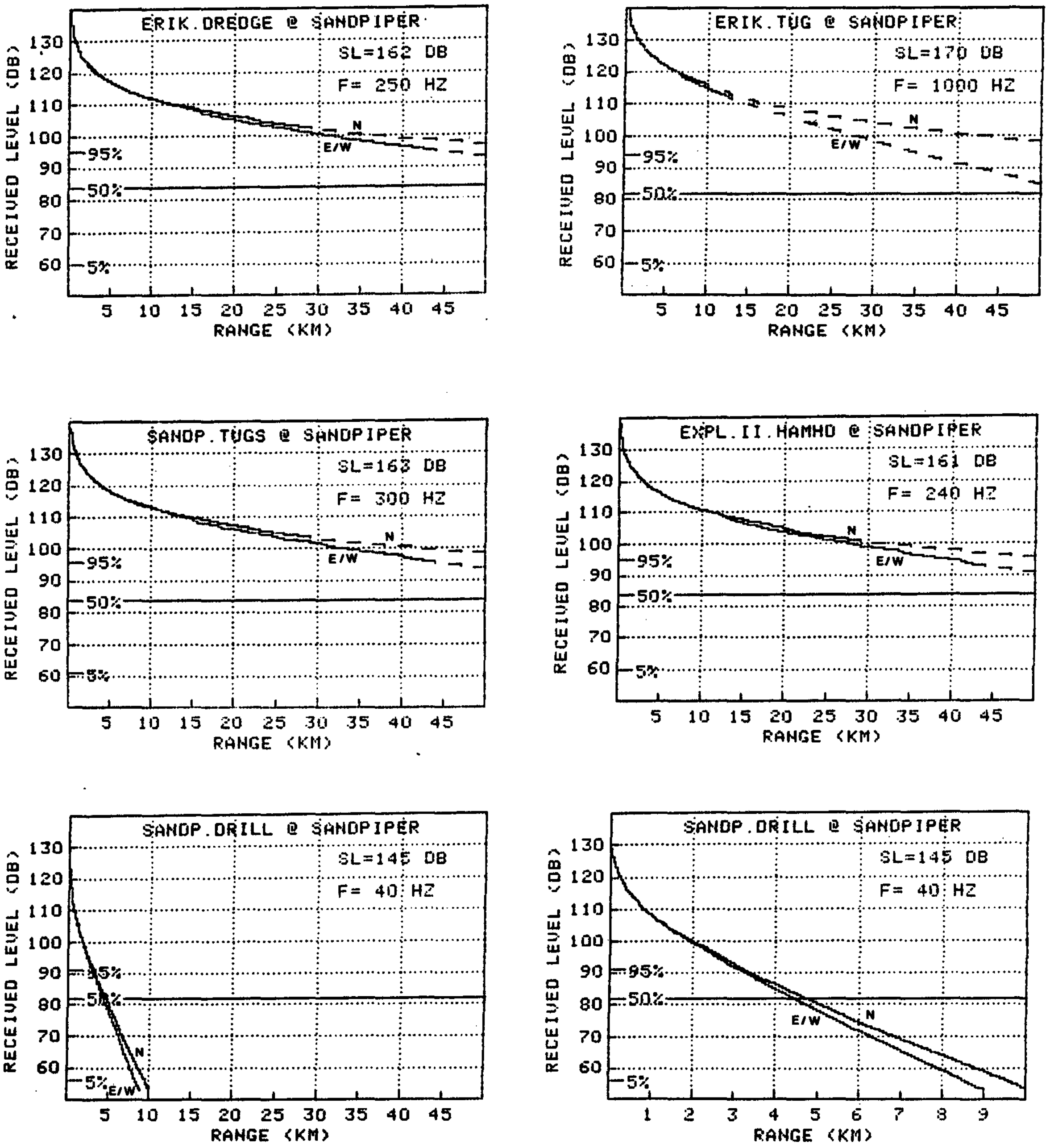

FIGURE 55. ESTIMATED RECEIVED LEVELS OF INDUSTRIAL NOISE AT VARIOUS DISTANCES FROM THE SANDPIPER SITE IF EACH OF FIVE INDUSTRIAL SOURCES WERE OPERATING THERE. PRESENTATION AS IN FIG. 54.

TABLE 5. ESTIMATED "ZONES OF AUDIBILITY" OF UNDERWATER NOISE FROM FIVE INDUSTRIAL SOURCES IF THEY WERE AT THE SANDPIPER SITE, ALASKAN BEAUFORT SEA. THE 1/3-OCTAVE BAND THAT WOULD BE DETECTABLE AT GREATEST RANGE IS CONSIDERED (SEE APPENDIX D FOR OTHER BANDS). THE DETECTION THRESHOLD IS ASSUMED TO EQUAL THE AMBIENT NOISE LEVEL.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at Sandpiper (dB, 1/3 Oct. Band)			Direction from Sandpiper	Est. Range (km) from Sandpiper Where Sig. to Amb. Noise Ratio = 0			Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	
Dredge bucket being raised at Erik										
	250	162	60	84	95	E/W	>50	>50	43	43
						N	>50	>50	>50	28
Tug beginning to tow barge at Erik										
	1000	170	60	82	94	E/W	>50	>50	36	15
						N	>50	>50	>50	11
2 Tugs at Sandpiper										
	300	163	61	84	96	E/W	>50	>50	43	43
						N	>50	>50	>50	28
Explorer II drilling at Hammerhead										
	240	161	60	84	95	E/W	>50	>50	39	43
						N	>50	>50	>50	28
Drilling at Sandpiper										
	40	145	56	82	91	E/W	8.5	4.4	3.1	63
						N	9.5	4.7	3.2	38

Hammerhead. -- If the dredge, tugs, or drillship were operating at Hammerhead, their noise would be expected to exceed the median ambient level in at least one 1/3-octave band at all ranges within 50 km. Their noise is predicted to exceed the 95th percentile ambient level up to 31 to >50 km away (Fig. 56; Table 6). These predictions are based on easterly and westerly bearings (i.e., constant water depth). Up to at least 50 km, these estimates are believed to be reasonably reliable. Predictions for increasing or decreasing water depths were not made for this site because the Hammerhead propagation model was less well defined than were the models for other sites.

As at Orion and Sandpiper, the zone of potential audibility would be much less for the 40 Hz sounds from a hypothesized drilling operation on an artificial island. The received level is predicted to equal the 95, 50 and 5 percentile ambient values at ranges of about 1.5, 3.4, and 12 km. It should be noted, however, that an artificial island of the type where these drilling sounds were recorded (Sandpiper, water 15 m deep) would not be constructed in the deeper water at Hammerhead.

Erik. -- Some bowhead whales migrate westward south of the Erik site, although in 1985 the majority apparently passed offshore of Erik (Richardson et al. 1986). Hence, we estimated received levels at various distances south of Erik (decreasing water depth) as well as east/west (constant depth) and north (increasing depth).

If the dredge, tugs or drillship were operating at Erik, their sounds would be expected to exceed the median ambient level out to ranges >50 km east, west and north of Erik. For at least one 1/3-octave band, their noise is expected to exceed the 95th percentile ambient noise up to 33 to >50 km on those bearings (Fig. 57; Table 7). The propagation model is considered reason-

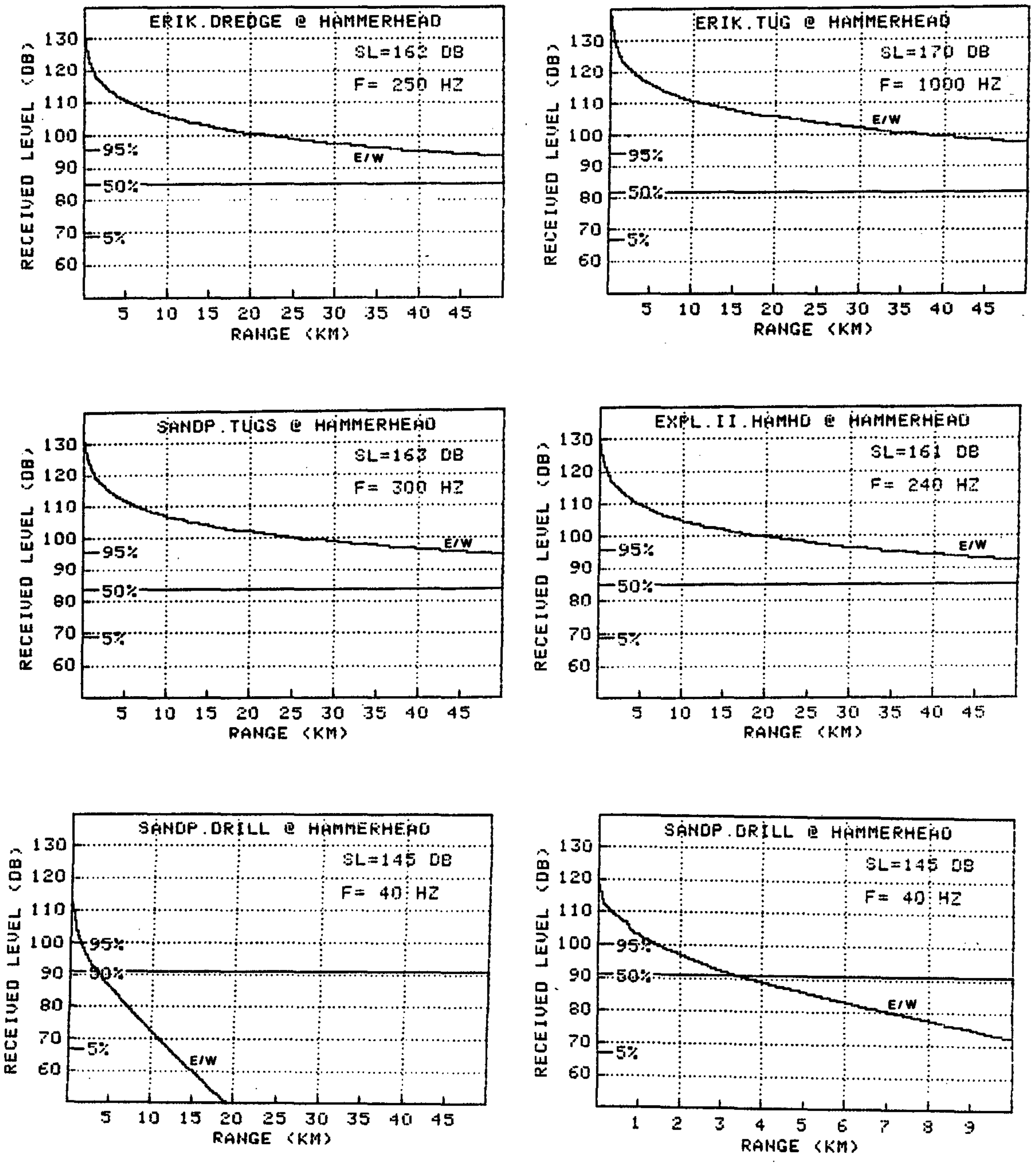

FIGURE 56. ESTIMATED RECEIVED LEVELS OF INDUSTRIAL NOISE AT VARIOUS DISTANCES FROM THE HAMMERHEAD SITE IF EACH OF FIVE INDUSTRIAL SOURCES WERE OPERATING THERE. PRESENTATION AS IN FIG. 55, EXCEPT THAT ONLY THE CONSTANT WATER DEPTH CASE IS SHOWN.

TABLE 6. ESTIMATED "ZONES OF AUDIBILITY" OF UNDERWATER NOISE FROM FIVE INDUSTRIAL SOURCES IF THEY WERE AT THE HAMMERHEAD SITE, ALASKAN BEAUFORT SEA. THE 1/3-OCTAVE BAND THAT WOULD BE DETECTABLE AT GREATEST RANGE IS CONSIDERED (SEE APPENDIX D FOR OTHER BANDS). THE DETECTION THRESHOLD IS ASSUMED TO EQUAL THE AMBIENT NOISE LEVEL.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at Hammerhead (dB, 1/3 Oct. Band)			Direction from Hammerhead	Est. Range (km) from Hammerhead Where Sig. to Amb. Noise Ratio = 0			Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	
Dredge bucket being raised at Erik										
	250	162	69	85	96	E/W	>50	>50	36	52
Tug beginning to tow barge at Erik										
	1000	170	67	82	94	E/W	>50	>50	>50	52
2 Tugs at Sandpiper										
	300	163	69	84	96	E/W	>50	>50	42	52
Explorer II drilling at Hammerhead										
	240	161	69	85	96	E/W	>50	>50	31	52
Drilling at Sandpiper										
	40	145	67	91	100	E/W	12	3.4	1.4	52

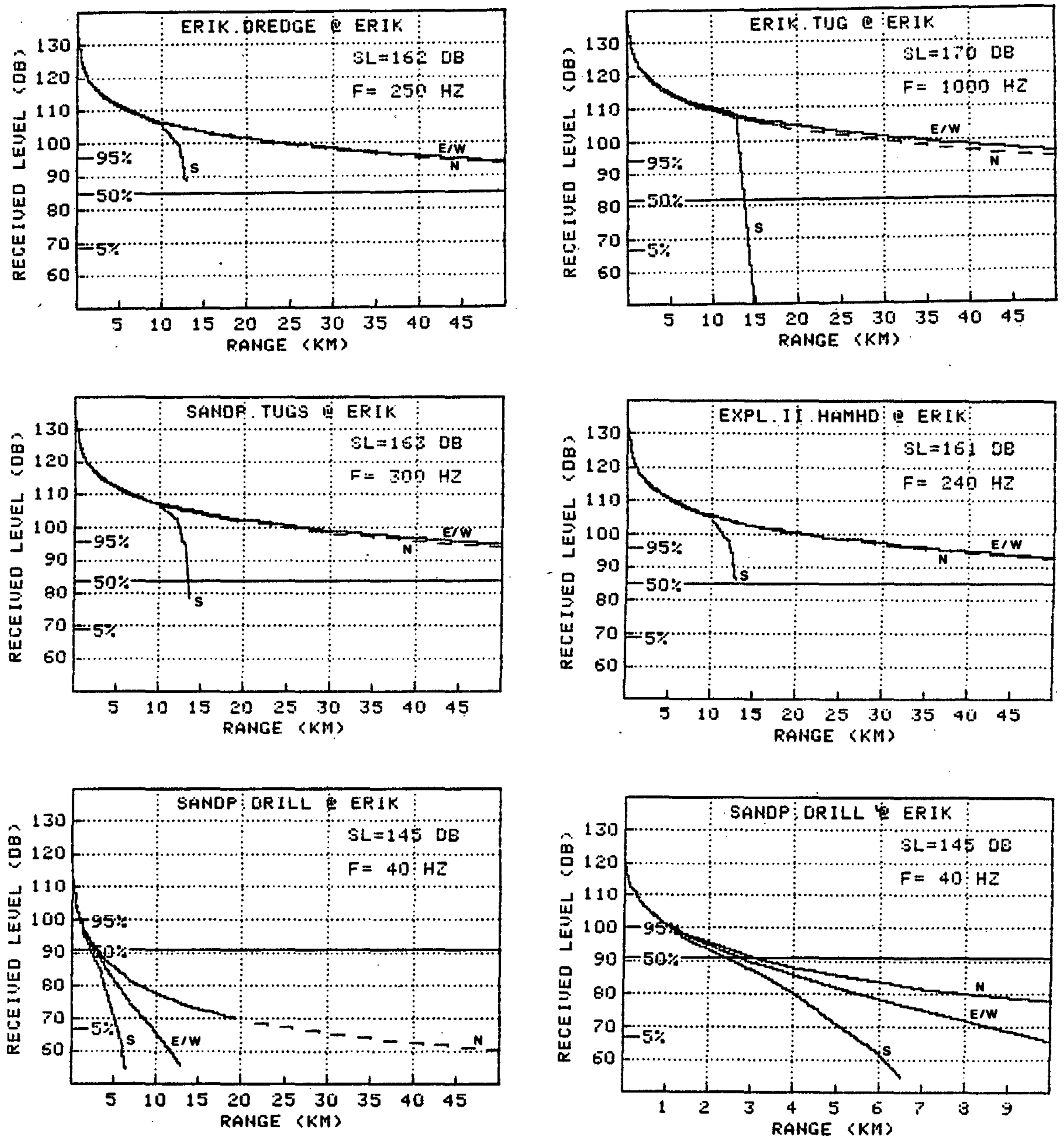

FIGURE 57. ESTIMATED RECEIVED LEVELS OF INDUSTRIAL NOISE AT VARIOUS DISTANCES FROM THE ERIK SITE IF EACH OF FIVE INDUSTRIAL SOURCES WERE OPERATING THERE. PRESENTATION AS IN FIG. 55, EXCEPT THAT ESTIMATES ARE INCLUDED FOR THE DECREASING WATER DEPTH CASE (S OF ERIK) AS WELL AS FOR THE CONSTANT AND INCRESING DEPTH CASES.

TABLE 7. ESTIMATES "ZONES OF AUDIBILITY" OF UNDERWATER NOISE FROM FIVE INDUSTRIAL SOURCES IF THEY WERE AT THE ERIK SITE, ALASKAN BEAUFORT SEA. THE 1/3-OCTAVE BAND THAT WOULD BE DETECTABLE AT GREATEST RANGE IS CONSIDERED (SEE APPENDIX D FOR OTHER BANDS). THE DETECTION THRESHOLD IS ASSUMED TO EQUAL THE AMBIENT NOISE LEVEL.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at Erik (dB, 1/3 Oct. Band)			Direction from Erik	Est. Range (km) from Erik Where Sig. to Amb. Noise Ratio = 0			Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	
Dredge bucket being raised at Erik										
	250	162	69	85	96	S	14	13	12	14
						E/W	>50	>50	39	52
						N	>50	>50	37	20
Tug beginning to tow barge at Erik										
	1000	170	67	82	94	S	15	15	15	15
						E/W	>50	>50	>50	52
						N	>50	>50	>50	19
2 Tugs at Sandpiper										
	300	163	69	84	96	S	14	14	13	14
						E/W	>50	>50	43	52
						N	>50	>50	40	20
Explorer II drilling at Hammerhead										
	240	161	69	85	96	S	14	13	12	14
						E/W	>50	>50	34	52
						N	>50	>50	33	20
Drilling at Sandpiper										
	40	145	67	91	100	S	5.5	2.4	1.1	8
						E/W	9.4	2.7	1.1	52
						N	25	2.9	1.1	20

ably reliable to >50 km east or west, but to only 20 km north. To the south, the received level of dredge, tug or drillship noise is expected to exceed both the median ambient and the 95th percentile ambient until the water depth diminishes to <10 m close to shore.

If an artificial island of the type at Sandpiper could be constructed at Erik, 40 Hz drilling sounds would be expected to be detectable out to at least 1.1 km 95% of the time, and to 2.4 to 2.9 km 50% of the time. The potential zone of audibility under quiet conditions (5th percentile ambient noise) is predicted to be much greater north of Erik (25 km) than east/west of Erik (9.4 km) or to the south (5.5 km). The greater potential zone of audibility north of Erik (25 km) than north of Orion or Sandpiper (7.6 to 9.5 km) is attributable to the greater water depth at Erik. However, it should be noted that artificial islands of the type at Sandpiper, where these drilling sounds were recorded, have not been constructed in water deeper than about 18 m. The water depth at Erik is 40 m.

<u>Belcher</u>. -- If the dredge, tugs or drillship were operating at Belcher, their sounds would be expected to exceed the median ambient level out to ranges >50 km east, west and perhaps north of Belcher. Under conditions of high ambient noise (95th percentile), the dredge, Sandpiper tugs, and drillship are expected to be detectable up to 17 to 25 km east, west and perhaps north. Even under those high noise conditions, the Erik tug might be detectable >50 km east or west and 39 km north (Fig. 58; Table 8). The Weston/Smith sound propagation model is expected to be reasonably reliable out to about 43 km east or west of Belcher, but only to about 10 km north.

To the south of Belcher, sounds from a dredge, tug or drillship are predicted to exceed the median ambient noise out to

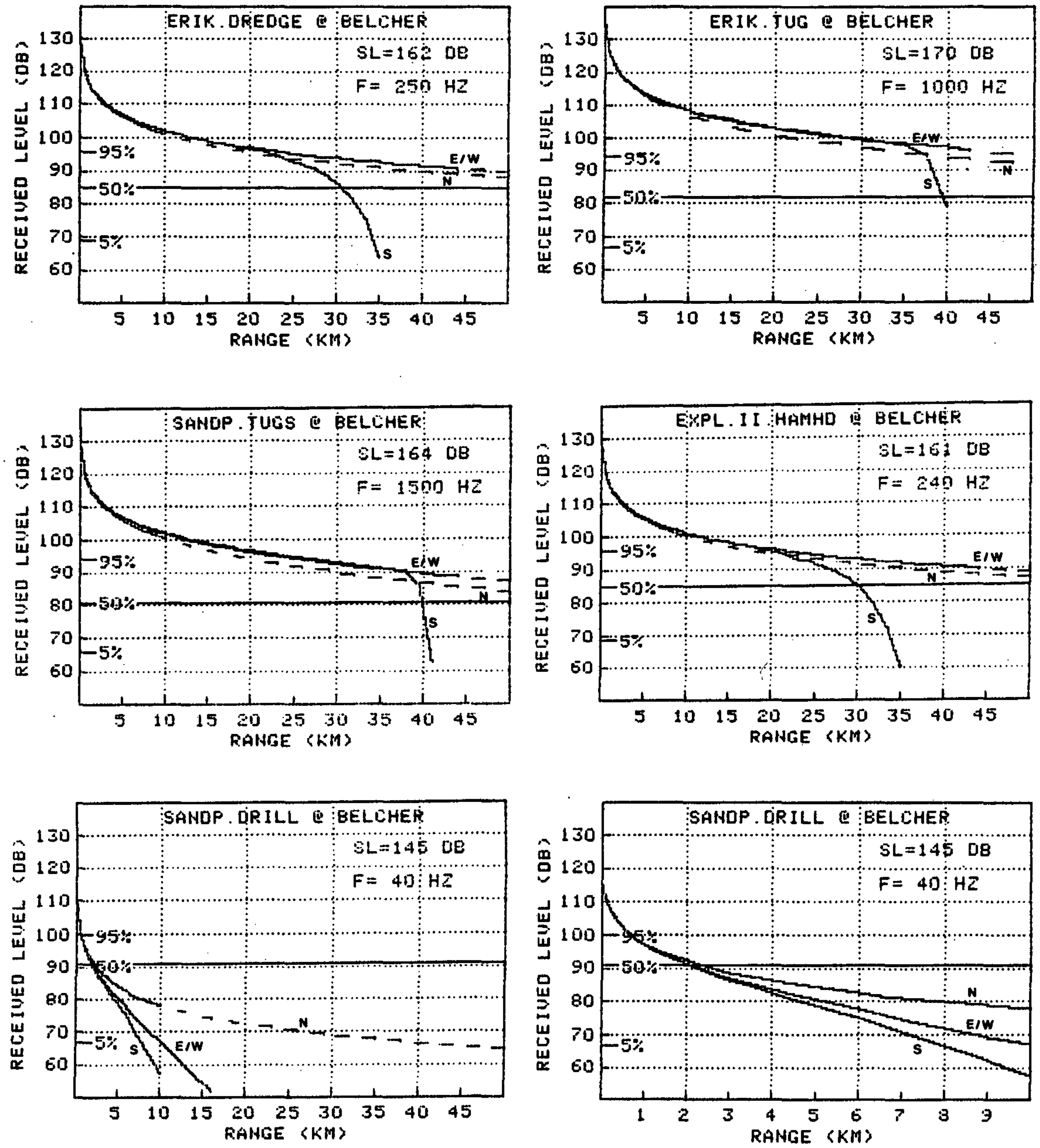

FIGURE 58. ESTIMATED RECEIVED LEVELS OF INDUSTRIAL NOISE AT VARIOUS DISTANCES FROM THE BELCHER SITE IF EACH OF FIVE INDUSTRIAL SOURCES WERE OPERATING THERE. PRESENTATION AS IN FIG. 57.

TABLE 8. ESTIMATED "ZONES OF AUDIBILITY" OF UNDERWATER NOISE FROM FIVE INDUSTRIAL SOURCES IF THEY WERE AT THE BELCHER SITE, ALASKAN BEAUFORT SEA. THE 1/3-OCTAVE BAND THAT WOULD BE DETECTABLE AT GREATEST RANGE IS CONSIDERED (SEE APPENDIX D FOR OTHER BANDS). THE DETECTION THRESHOLD IS ASSUMED TO EQUAL THE AMBIENT NOISE LEVEL.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at Belcher (dB, 1/3 Oct. Band)			Direction from Belcher	Est. Range (km) from Belcher Where Sig. to Amb. Noise Ratio = 0			Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	
Dredge bucket being raised at Erik										
	250	162	69	85	96	S	34	31	21	40
						E/W	>50	>50	22	43
						N	>50	>50	19	9.5
Tug beginning to tow barge at Erik										
	1000	170	67	82	94	S	40	40	38	40
						E/W	>50	>50	52	43
						N	>50	>50	39	9.5
2 Tugs at Sandpiper										
	1500	164	66	81	94	S	41	40	27	41
						E/W	>50	>50	25	44
						N	>50	>50	20	9.5
Explorer II drilling at Hammerhead										
	240	161	69	85	96	S	34	30	19	40
						E/W	>50	>50	19	44
						N	>50	>50	17	9.5
Drilling at Sandpiper										
	40	145	67	91	100	S	7.9	1.9	.67	28
						E/W	9.9	2.1	.67	44
						N	37	2.2	.67	9.5

a range of 30 to 40 km (Fig. 58; Table 8). Under naturally noisy conditions (95th percentile), the industrial sounds are expected to exceed ambient levels up to 19-38 km south of Belcher.

If an artificial island like that at Sandpiper could be constructed at Belcher, 40 Hz drilling sounds might be detectable at least 0.7 km away 95% of the time and 2 km away 50% of the time. The potential zone of audibility under quiet conditions (5th percentile) is predicted to be much greater: 8 to 37 km, depending on bearing (Table 8; Fig. 58). However, these estimates are all of theoretical interest only, since the water at Belcher is too deep for an island of the type at Sandpiper.

Summary. -- Our estimates of the zone of potential audibility have assumed that whales might detect an industrial noise if the received level in any one 1/3-octave band is as intense as the ambient noise in that band. Based on this criterion, the dredge, tugs and drillship were potentially detectable under average noise conditions up to several tens of kilometers east, west or north of most sites. Even when the ambient noise was higher, at the 95th percentile level, the dredge, tugs and drillship were potentially detectable at least 17 km away.

In contrast, the 40 Hz noise from drilling on an artificial island was not expected to be detectable more than a few kilometers away from any of the sites under average ambient noise conditions. At shallow sites where artificial islands of this type might be used, the sounds were not expected to be detectable more than about 10 km away even under quiet conditions.

It is important to note that these estimates are subject to considerable uncertainty. Many of the longer estimates, especially those to the north of the sites, are based on application of the Weston/Smith sound propagation model at ranges beyond those where it is expected to be reasonably reliable. Even within the range of reliability, expected received levels often diminish slowly with increasing range. Thus, small errors in assumptions about propagation loss, ambient noise levels, or the hearing abilities of whales could cause major errors in estimated zones of potential audibility. At Belcher, for example, the potential zone of audibility of the dredge, Sandpiper tugs, and drillship under median ambient conditions has been estimated as >50 km east, west and north (Table 8). However, the zone would be reduced to 19 to 34 km if the industrial noise must be 10 dB rather than 0 dB above ambient in order to be heard (Appendix A).

Additional site-specific data on long range sound propagation and ambient noise statistics would help in refining the predicted zones of audibility. However, considerable uncertainty will remain until the hearing abilities of at least one species of baleen whales can be measured.

3.4.3 Zones of Responsiveness for Bowhead Whales

The sensitivity of bowhead whales to drilling and construction noise is apparently quite variable. Some individuals showed avoidance reactions during playback tests when the signal-to-noise ratio (industrial noise : ambient noise) was as low as 16 to 24 dB in the 1/3-octave band of maximum S:N. Others showed no obvious reaction to playbacks when S:N was over 30 dB (see Table B.4 in Appendix B). In addition, numerous bowheads have been seen close enough to drillships and dredges to experience S:N ratios as high as 15 dB and 29 dB, respectively, and a few have been seen even closer to these industrial activities (Table B.3). Responsiveness is apparently at least as variable if measured in terms of absolute received levels rather than S:N ratios (Tables B.3, B.4).

Thus, no single threshold of responsiveness criterion can be identified for bowheads. We have instead calculated the ranges from five industrial activities and five sites at which the S:N ratio is expected to be 20 dB, 30 dB and 40 dB. These three criteria are considered to represent situations in which a minority of bowheads would respond (20 dB), roughly half of the bowheads would respond (30 dB), and most would respond (40 dB). In each case, the frequency band under consideration is the 1/3-octave band in which these S:N ratios would be found at greatest range. (Results for other 1/3-octave bands with high S:N are given in Appendix A.) We also present the ranges where the absolute received level in this 1/3-octave band would be 110 dB - a rough estimate of the absolute noise level at which half of the bowheads respond.

The ambient noise considered in each case is the median ambient noise, as derived in Section 3.1. The 20 dB, 30 dB, and 40 dB S:N situations would be found at greater ranges under conditions of low ambient noise, and at lesser ranges under conditions of high ambient noise. For most sites, only the 'median ambient' situation is discussed below. However, the effect of the ambient level on the zone of potential responsiveness is examined for the Orion site. For other sites, the ranges for 20 dB, 30 dB, and 40 dB S:N relative to the 5th and 95th percentile ambient noise conditions can be obtained from Figures 54 to 58, if desired.

Orion. -- Around the Orion site, zones of potential responsiveness are expected to be quite similar for the dredge, tugboats, and the EXPLORER II drillship. The industrial noise level in at least one 1/3-octave band would be expected to be at least 20 dB above the median ambient level at all ranges out to 13 to 17 km east or west and to 17-29 km north (Table 9). Beyond these ranges we would expect few, if any, bowhead whales to react

TABLE 9. ESTIMATED "ZONES OF RESPONSIVENESS" FOR BOWHEAD WHALES NEAR FIVE INDUSTRIAL SOURCES IF THEY WERE AT THE ORION SITE, ALASKAN BEAUFORT SEA. THE 1/3-OCTAVE BAND WITH THE HIGHEST INDUSTRIAL : AMBIENT NOISE RATIO IS CONSIDERED (SEE APPENDIX A FOR OTHER BANDS). FEW, IF ANY, BOWHEADS WOULD REACT TO RANGES WHERE THE INDUSTRIAL : AMBIENT NOISE RATIO IS $\leq$ 20 dB, ROUGHLY HALF WOULD REACT AT 30 dB, AND MOST WOULD REACT AT 40 dB.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated 50%ile Ambient Noise at Orion (dB, 1/3 Oct. Band)	Direction from Orion	Est. Range (km) from Orion Where Signal Exceeds 50%ile by				Est. Range (km) for Received Level 110 dB	Max. Range (km) of Reliability
					0 dB	20 dB	30 dB	40 dB		
Dredge bucket being raised at Erik										
	250	162	84	E/W	39	15	6.1	1.7	8.7	30
				N	>50	19	6.3	1.7	10.0	16
Tug beginning to tow barge at Erik										
	1000	170	82	E/W	35	16	8.4	3.1	9.9	11
				N	>50	29	11.0	3.2	14.0	6
2 Tugs at Sandpiper										
	300	163	84	E/W	45	17	7.2	2.0	10.0	30
				N	>50	23	7.5	2.0	12.0	15
EXPLORER II drilling at Hammerhead										
	240	161	84	E/W	35	13	5.3	1.4	7.6	30
				N	>50	17	5.5	1.4	9.0	16
Drilling at Sandpiper										
	40	145	82	E/W	3.1	1.3	.59	.23	.71	63
				N	3.5	1.4	.59	.23	.72	23

to the industrial noise. Many individuals would not react until or unless they were within some considerably closer range where S:N exceeded 20 dB by a substantial margin. The 13-17 km values for east and west azimuths are within the range where the Weston/Smith sound propagation model is believed to be reasonably reliable. However, the 17-29 km figures for northerly azimuths are beyond that range (Fig. 54; Table 9).

Some bowheads probably would respond to the onset of noise from dredges, tugboats or the drillship at ranges where the received level was 20 dB above ambient. If a dredge, tugboat or drillship operated at Orion under median ambient noise conditions, the 30 dB S:N level, where roughly half of the bowheads are likely to react, is expected to occur 5.3 to 8.4 km east or west, and 5.5 to 11 km north. Similarly, the 110 dB absolute noise level is expected to occur 7.6 to 10 km east or west, and 9.0 to 14 km north.

The estimated ranges of responsiveness depend rather strongly on the natural noise level. Since the 95th percentile values of ambient noise are about 10 dB above the median values (actually 9 to 12 dB), the 30 dB S:N ranges on a day with high natural ambient noise would be similar to the 40 dB S:N ranges on a day with median ambient noise, i.e., only about 1.4 to 3.2 km on a noisy day, as opposed to 5.3 to 11 km on an average day (Table 9). Since the 5th percentile values of ambient noise are more than 20 dB less than the median values, the 30 dB S:N ranges on a quiet day would be greater than the 10 dB ranges on an average day, i.e., >24 to 30 km east or west and >50 km north (Appendix A1). Again, most range estimates exceeding about 30 km east/west or 15 km north are beyond the range of reliability of the sound propagation model.

The above estimates pertain to a dredge, tugboats or a drillship. The potential zone of responsiveness to the drilling sounds recorded on an artificial island was much less. North of Orion, the S:N ratio for the dominant 40 Hz component is expected to be 40 dB at 0.2 km, 30 dB at 0.6 km, 20 dB at 1.4 km, and 10 dB at 2.3 km (Table 9: Appendix A1). An absolute level of 110 dB would be expected at 0.7 km.

Sandpiper. -- If the five industrial sources that we are considering operated at Sandpiper and Orion in turn, the zones of responsiveness are predicted to be somewhat greater around Sandpiper (Table 10 vs. 9). Predicted zones of audibility were also predicted to be somewhat larger at Sandpiper (Section 3.4.2).

For the dredge, tugboats and drillship, the predicted ranges where S:N would be 20 dB on an average day are 19 to 25 km east/west and 20 to 36 km north, i.e., about 46% greater than the corresponding ranges from Orion. Only a minority of the bowheads are expected to react to the onset of industrial sounds at those ranges. The 30 dB S:N level, where roughly half the bowheads might react, is expected to occur 6.5 to 13 km east/west and 6.5 to 14 km north of Sandpiper (Table 10; Figure 55). The 110 dB absolute noise level is expected to occur 11 to 15 km east or west, and 11 to 17 km north.

Again, sounds from drilling on an artificial island are not expected to result in responses by bowheads more than a very few kilometers away. The 40, 30, 20, and 10 dB S:N ranges from Sandpiper Island on an average day are predicted to be 0.2, 0.7, 1.7, and 3 km, respectively (Table 10; Appendix A2). An absolute level of 110 dB would be expected at 0.8 km.

Hammerhead. -- The zones of potential responsiveness around Hammerhead differed from those around Orion and Sandpiper because

TABLE 10. ESTIMATES "ZONES OF RESPONSIVENESS" FOR BOWHEAD WHALES NEAR FIVE INDUSTRIAL SOURCES IF THEY WERE AT THE SANDPIPER SITE, ALASKAN BEAUFORT SEA. THE 1/3-OCTAVE BAND WITH THE HIGHEST INDUSTRIAL : AMBIENT NOISE RATIO IS CONSIDERED (SEE APPENDIX A FOR OTHER BANDS). FEW, IF ANY, BOWHEADS WOULD REACT TO RANGES WHERE THE INDUSTRIAL : AMBIENT NOISE RATIO IS < 20 dB, ROUGHLY HALF WOULD REACT AT 30 dB, AND MOST WOULD REACT AT 40 dB.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated 50%ile Ambient Noise at Sandpiper (dB, 1/3 Oct. Band)	Direction from Sandpiper	Est. Range (km) from Sandpiper Where Signal Exceeds 50%ile by				Est. Range (km) for Received Level 110 dB	Max. Range (km) of Reliability
					0 dB	20 dB	30 dB	40 dB		
Dredge bucket being raised at Erik										
	250	162	84	E/W	>50	22	7.4	1.9	12.0	43
				N	>50	23	7.5	1.9	1.3	28
Tug beginning to tow barge at Erik										
	1000	170	82	E/W	>50	25	13.0	4.6	15.0	15
				N	>50	36	14.0	4.7	17.0	11
2 Tugs at Sandpiper										
	300	163	84	E/W	>50	24	8.7	2.3	14.0	43
				N	>50	27	8.8	2.3	15.0	28
EXPLORER II drilling at Hammerhead										
	240	161	84	E/W	>50	19	6.5	1.6	11.0	43
				N	>50	20	6.5	1.6	11.0	28
Drilling at Sandpiper										
	40	145	82	E/W	4.4	1.7	.70	.22	.81	63
				N	4.7	1.7	.70	.22	.81	38

of the greater water depth (32 m) and different bottom conditions at Hammerhead.

If the dredge, tugboats or drillship operated at Hammerhead, the range where S:N would be 20 dB on an average day is predicted to be 9 to 30 km to the east or west (Table 11; Figure 56). No predictions were made for northerly or southerly bearings because the Hammerhead sound propagation model is less well defined than the models for the other four sites. The tug recorded at Erik was the source for which the predicted zone of responsiveness was largest. The ranges where S:N would be 30 dB on an average day, i.e., where roughly half the bowheads would be expected to react, were 2.2 to 8.4 km (Table 11). The 110 dB absolute noise level would be expected to occur at 4.5 to 11 km.

The predicted zone of responsiveness to 40 Hz sounds from drilling on an artificial island was smaller for Hammerhead than for Orion or Sandpiper. The predicted ranges with 40, 30, 20, and 10 dB S:N were only < 0.01, 0.03, 0.26, and 1.2 km around Hammerhead (Table 11; Appendix A3). Similar or lower values were predicted for Erik and Belcher. It should be noted that an artificial island of the type where these drilling sounds were recorded (Sandpiper, 15 m water depth) is not likely to be built in water as deep as that at Hammerhead, Erik or especially Belcher.

Erik. -- Since some bowheads migrate westward south of the Erik site, which is northwest of Kaktovik, radii of responsiveness have been estimated for southerly, east/west, and northerly bearings from Erik.

If the dredge, tugboats or drillship were operating at Erik, their sounds would be expected to exceed the median ambient level by 20 dB out to ranges 11 to 27 km east/west, 10 to 23 km north, and 9.5 to 14 km south (Table 12). These are the approximate

TABLE 11. ESTIMATED "ZONES OF RESPONSIVENESS" FOR BOWHEAD WHALES NEAR FIVE INDUSTRIAL SOURCES IF THEY WERE AT THE HAMMERHEAD SITE, ALASKAN BEAUFORT SEA. THE 1/3-OCTAVE BAND WITH THE HIGHEST INDUSTRIAL : AMBIENT NOISE RATIO IS CONSIDERED (SEE APPENDIX A FOR OTHER BANDS). FEW, IF ANY, BOWHEADS WOULD REACT TO RANGES WHERE THE INDUSTRIAL : AMBIENT NOISE RATIO IS $\leq$ 20 dB, ROUGHLY HALF WOULD REACT AT 30 dB, AND MOST WOULD REACT AT 40 dB.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated 50%ile Ambient Noise at Hammerhead (dB, 1/3 Oct. Band)	Direction from Hammerhead	Est. Range (km) from Hammerhead Where Signal Exceeds 50%ile by				Est. Range (km) for Received Level 110 dB	Max. Range (km) of Reliability
					0 dB	20 dB	30 dB	40 dB		
Dredge bucket being raised at Erik										
	250	162	85	E/W	>50	11	2.5	.50	5.3	52
Tug beginning to tow barge at Erik										
	1000	170	82	E/W	>50	30	8.4	2.0	11.0	52
2 Tugs at Sandpiper										
	300	163	84	E/W	>50	15	3.4	.77	6.2	52
EXPLORER II drilling at Hammerhead										
	240	161	85	E/W	>50	9.3	2.2	.40	4.5	52
Drilling at Sandpiper										
	40	145	91	E/W	3.4	.26	.03	<.01	.32	52

TABLE 12. ESTIMATED "ZONES OF RESPONSIVENESS" FOR BOWHEAD WHALES NEAR FIVE INDUSTRIAL SOURCES IF THEY WERE AT THE ERIK SITE, ALASKAN BEAUFORT SEA. THE 1/3-OCTAVE BAND WITH THE HIGHEST INDUSTRIAL : AMBIENT NOISE RATIO IS CONSIDERED (SEE APPENDIX A FOR OTHER BANDS). FEW, IF ANY, BOWHEADS WOULD REACT TO RANGES WHERE THE INDUSTRIAL : AMBIENT NOISE RATIO IS $\leq$ 20 dB, ROUGHLY HALF WOULD REACT AT 30 dB, AND MOST WOULD REACT AT 40 dB.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated 50%ile Ambient Noise at Erik (dB, 1/3 Oct. Band)	Direction from Erik	Est. Range (km) from Erik Where Signal Exceeds 50%ile by				Est. Range (km) for Received Level 110 dB	Max. Range (km) of Reliability
					0 dB	20 dB	30 dB	40 dB		
Dredge bucket being raised at Erik										
	250	162	85	S	13	10	3.0	.66	6.1	14
				E/W	>50	12	2.9	.66	6.0	52
				N	>50	12	2.9	.65	5.8	20
Tug beginning to tow barge at Erik										
	1000	170	82	S	15	14	7.7	1.7	10.0	15
				E/W	>50	27	7.2	1.7	9.5	52
				N	>50	23	6.8	1.7	8.9	19
2 Tugs at Sandpiper										
	300	163	84	S	14	11	3.8	.84	6.7	14
				E/W	>50	15	3.7	.83	6.6	52
				N	>50	14	3.6	.82	6.3	20
EXPLORER II drilling at Hammerhead										
	240	161	85	S	13	9.5	2.6	.57	5.3	14
				E/W	>50	11	2.5	.57	5.2	52
				N	>50	10	2.5	.56	5.0	20
Drilling at Sandpiper										
	40	145	91	S	2.4	.26	.03	<.01	.31	8
				E/W	2.7	.26	.03	<.01	.31	52
				N	2.9	.25	.03	<.01	.31	20

ranges at which we would expect some bowheads to respond to the onset of industrial sounds. Roughly half of the most sensitive bowheads would likely respond at ranges out to 2.5 to 7 km, the distances where S:N would be about 30 dB on an average day. The received noise level would be 110 dB at 5 to 10 km. The tug recorded at Erik was the source with the largest expected zone of responsiveness.

Belcher. -- If the dredge, tugboats or drillship operated at Belcher, the radii where the expected S:N would be 20 dB on an average day would be 5 to 23 km, with little variation among azimuths (Table 13). The tug recorded at Erik had a greater zone of potential responsiveness (17 to 23 km, depending on azimuth) than any of the other sources considered (5 to 11 km). Beyond these distances, few, if any, responses by bowheads would be expected. The propagation model is considered reasonably reliable out to about 40 km east, west and south, but only to about 10 km north.

For the same industrial sources, the radii where roughly half the bowheads would be expected to respond to the onset of industrial sounds (predicted S:N 30 dB) were 5.5 km for the Erik tug and 1.2 to 2.7 km for the dredge, Sandpiper tugs, and drillship. The received noise level would be expected to be 110 dB at ranges of about 7.5 km from the Erik tug and 2.5 to 3.1 km from the dredge, Sandpiper tugs, and drillship.

Summary. -- The radius where the predicted signal-to-noise ratio is 30 dB in the 1/3-octave band of highest S:N is probably the best estimate of the average zone of potential responsiveness of bowhead whales. However, it is emphasized that some bowheads apparently do not react unless S:N is more than 30 dB whereas others react to S:N values as low as 20 dB (Appendix B).

TABLE 13. ESTIMATED "ZONES OF RESPONSIVENESS" FOR BOWHEAD WHALES NEAR FIVE INDUSTRIAL SOURCES IF THEY WERE AT THE BELCHER SITE, ALASKAN BEAUFORT SEA. THE 1/3-OCTAVE BAND WITH THE HIGHEST INDUSTRIAL : AMBIENT NOISE RATIO IS CONSIDERED (SEE APPENDIS A FOR OTHER BANDS). FEW, IF ANY, BOWHEADS WOULD REACT TO RANGES WHERE THE INDUSTRIAL : AMBIENT NOISE RATIO IS ≤ 20 dB, ROUGHLY HALF WOULD REACT AT 30 dB, AND MOST WOULD REACT AT 40 dB.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated 50%ile Ambient Noise at Belcher (dB, 1/3 Oct. Band)	Direction from Belcher	Est. Range (km) from Belcher Where Signal Exceeds 50%ile by				Est. Range (km) for Received Level 110 dB	Max. Range (km) of Reliability
					0 dB	20 dB	30 dB	40 dB		
Dredge bucket being raised at Erik										
	250	162	85	S	31	6.5	1.5	.33	3.1	40
				E/W	>50	6.4	1.5	.33	3.1	43
				N	>50	5.9	1.4	.32	2.9	9.5
Tug beginning to tow barge at Erik										
	1000	170	82	S	40	23	5.7	1.3	7.7	40
				E/W	>50	22	5.6	1.3	7.5	43
				N	>50	17	5.1	1.2	6.6	9.5
2 Tugs at Sandpiper										
	300	163	81	S	40	11	2.7	.38	3.1	41
				E/W	>50	11	2.7	.38	3.1	44
				N	>50	9.3	2.5	.38	2.9	9.5
EXPLORER II drilling at Hammerhead										
	240	161	85	S	30	5.6	1.3	.28	2.7	40
				E/W	>50	5.5	1.3	.28	2.7	44
				N	>50	5.1	1.2	.27	2.5	9.5
Drilling at Sandpiper										
	40	145	91	S	1.9	.12	.02	<.01	.16	28
				E/W	2.1	.12	.02	<.01	.15	44
				N	2.2	.12	.02	<.01	.15	9.5

For whales east or west of the five sites and the five source types considered here, the predicted distances where S:N would be 30 dB on an average day are as follows:

	Dredge	Tug at Erik	Tugs at Sandp.	Drill-ship	Drilling on Sandp.
Orion	6.1	8.4 km	7.24 km	(5.3)	0.6 km
Sandpiper	7.4	13.0	8.7	(6.5)	0.7
Hammerhead	2.5	8.4	3.4	2.2	(0.03)
Erik	2.9	7.28	3.7	2.5	(0.03)
Belcher	1.5	5.6	2.7	1.3	(0.02)

The values in parentheses represent theoretical results for situations that are not likely to occur in practice - a drillship in shallow water and an artificial island in deep water.

Another possible criterion of responsiveness is the 110 dB absolute noise level, again considering the 1/3-octave band of highest S:N. For whales east or west of the five sites, the predicted distances where the absolute noise level would be 110 dB in that 1/3-octave band are as follows:

	Dredge	Tug at Erik	Tugs at Sandp.	Drill-ship	Drilling on Sandp.
Orion	8.7	9.9 km	10.0 km	(7.6)	0.7 km
Sandpiper	12.0	15.0	14.0	(11.0)	0.8
Hammerhead	5.3	11.0	6.2	4.5	(0.3)
Erik	6.0	9.5	6.6	5.2	(0.3)
Belcher	3.1	7.5	3.1	2.7	(0.15)

The predicted zones of responsiveness based on the "110 dB absolute noise level" criterion are somewhat larger than those based on the "30 dB S:N" criterion.

Both the "110 dB absolute" criterion represent situations when about half the bowheads would be expected to respond. A few bowheads that are less sensitive to industrial noise than average would be expected to occur substantially closer to industrial sites. On the other hand, a few of the more sensitive bowheads would be expected to respond when the industrial noise to ambient noise ratio is as low as about 20 dB in the 1/3-octave band of highest S:N. For whales east or west of the five sites considered here, the predicted distances where S:N would be 20 dB on an average day are as follows:

	Dredge	Tug at Erik	Tugs at Sandp.	Drill-ship	Drilling on Sandp.
Orion	15 km	16 km	17 km	(13) km	1.3 km
Sandpiper	22	25	24	(19)	1.7
Hammerhead	11	30	15	9.3	(0.26)
Erik	12	27	15	11.0	(0.26)
Belcher	6.4	22	11	5.5	(0.12)

Regardless of the criterion chosen, the tug recorded at Erik had the greatest potential zone of influence, especially at the deeper sites (Hammerhead, Erik, Belcher). The low frequency (40 Hz) sounds from drilling on an artificial island resulted in the smallest potential radii of responsiveness. However, such an island would not be built in water as deep as that at Hammerhead, Erik or Belcher.

3.4.4 Zones of Responsiveness for Gray Whales*

General Considerations

The procedures for prediction of zones of responsiveness for gray whales near the Beaufort Sea measurement sites utilizes the results of acoustic disturbance studies reported by Malme et al. (1984) and Malme et al. (1986). The 1984 study concerned migrant whales off the California coast and the 1986 study concerned

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*Prepared by C. Malme, BBN Laboratories Incorporated.

summering and feeding gray whales in the northern Bering Sea near St. Lawrence Island. Both studies used a broadband underwater projector source for playback of selected industrial sounds and a 100 cu. in. air gun source to generate seismic survey sounds.

The drillship noise stimulus used in these studies was an EXPLORER II signature obtained in the Canadian Beaufort Sea by C.R. Greene in 1981. The 1985 EXPLORER II signature differs somewhat from the earlier one in that some of the spectrum lines have changed in frequency and source level (compare Fig. 28 and Appendix B, Fig. B.4). The dominant portion* of the overall 1985 signal is estimated to be only about 4 dB lower in source level than the earlier one. The other industrial noise signatures used in the California playback tests were considerably different in spectrum content from the industrial sources measured during the 1985 field season.

In the study of summering and feeding gray whales, whale behavior data were obtained by close observation of focal whale groups, recording surfacing-dive and blow information. In addition, tracking of the focal groups was performed using a two-vessel triangulation procedure or a land-based theodolite when weather permitted. The experimental procedure involved location of feeding whales, observation of behavior during a control period with the support vessels present, observation of behavior during an experiment period with the sound stimulus on, and observation of behavior during a post-experiment control period. Generally, several of these sequences were performed each day.

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*The dominant portion of the industrial noise signal is considered to include the 1/3-octave band with the highest sound level and all other 1/3-octave bands having levels within 10 dB of the maximum.

Limited data obtained for drillship playback sequences did not show any consistent pattern of feeding disturbance or avoidance of the sound source for levels up to 110 dB re 1 μPa. However, some whales were observed to leave the test area during an experiment when levels reached about 119 dB. These results are similar to the results of the playback tests with migrating gray whales which relate the overall level of the dominant portion of an industrial noise stimulus to a probability of avoidance (P_a) of the area near the source. The data obtained to support P_a values ranging from .1 to .9 for the overall effective stimulus bandwidth. It was not feasible to determine which portions of the industrial noise spectra resulted in behavioral response of gray whales. The results are, therefore, specific to the types of sources simulated but are not site-specific since avoidance was related to sound exposure level rather than to distance from the source.

The procedure used in estimating the zones of responsiveness for gray whales near the Beaufort Sea test sites will therefore use the EXPLORER II signature combined with measured and estimated TL values to predict the ranges at which a P_a of .1 or greater or possible feeding disturbance is expected for gray whales.

The zone of responsiveness predictions for bowhead whales discussed in the previous section considered a given ratio of industrial to ambient noise--typically 20 dB--as the criterion for observable behavioral response such as avoidance. In the gray whale tests for playback levels producing a P_a value of 0.5, the average ratio of industrial-to-ambient noise for the dominant part of the drillship playback noise spectrum was about 20 dB. The variation in ambient noise level during the California test period was not very large. The observation data were, therefore, not analyzed to determine if gray whale response was more clearly related to S:N ratio than to absolute level. Thus, an independent comparison of these two types of acoustic response measures is presently not available. In the following analysis both measures of potential acoustic response are considered.

Transmission Loss Comparisons

Sound propagation conditions can vary widely from one region to another. This is particularly true at low frequencies in shallow water. An example of the variation in TL characteristics at low frequencies is shown in Fig. 59a. Here the results of the measurements and model predictions at the shallow Sandpiper site (15 m) are compared with measured TL data for similar depths using an air gun source at the California gray whale test site and at a site in the Bering Sea near St. Lawrence Island. The probable presence of a hard layer of permafrost or overcompacted clay is considered to be the reason for the low values of TL shown for the Sandpiper site. The California and Bering Sea have a sand bottom with a possible underlying layer of rock at an undetermined depth.

Since the dominant frequency of the EXPLORER II signature in 1985 was 240 Hz, a comparison of the TL characteristics at this higher frequency for the California test site and the Belcher site is shown in Fig. 59b. The difference in TL is not as pronounced at this frequency--particularly at ranges less than 2 km.

Zones of Responsiveness Estimates

The TL characteristics for the five Beaufort sites were used to estimate the received level versus range for operation of the Explorer II drillship at each of the three deeper sites (Belcher, Erik, and Hammerhead). The resulting received level curves are

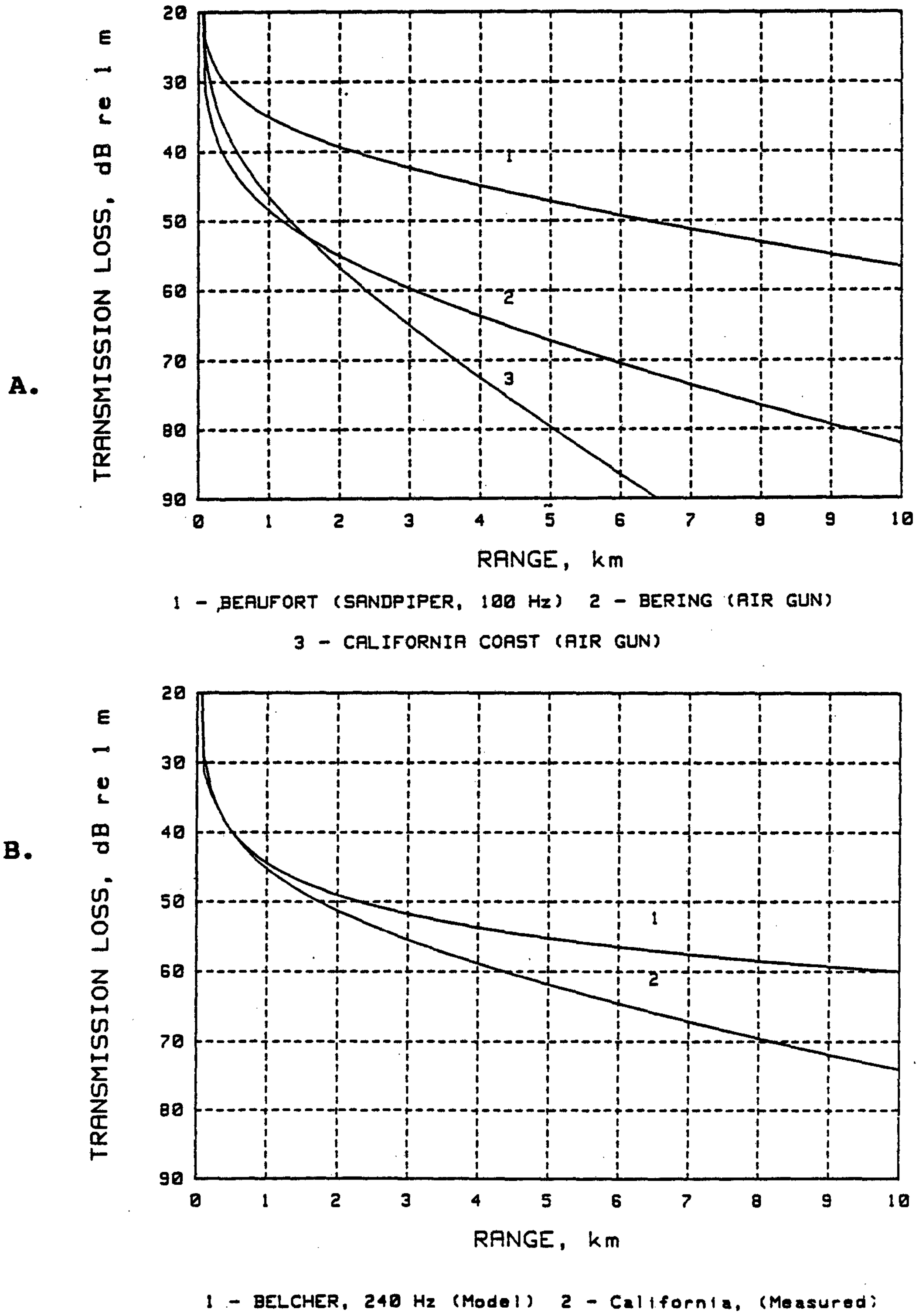


FIG. 59. COMPARISON OF TRANSMISSION LOSS CHARACTERISTICS FOR DIFFERENT AREAS.

shown in Figs. 60a through 60e. The predicted values for received level were compared with the levels associated with P_a values of 0.1 and 0.5 from the playback tests. The corresponding ranges from the drillship were estimated for each of the three sites. The results of this procedure are shown in Table 14.

To provide a direct comparison with the zone of responsiveness results for bowhead whales, the range estimates for 0, 20, 30, and 40 dB S:N ratios in the 250 Hz 1/3-octave band are also given in Table 14. This band had the highest level above the ambient noise in the drillship source spectrum. Predicted levels for the 50 percentile ambient noise spectra were used. Transmission loss data from the playback study test site in the Bering Sea (Malme et al. 1986) were used to estimate zones of responsiveness for drillship operation at that site. This was done to obtain a comparison with the Sandpiper and Orion sites in the Beaufort Sea which have a similar water depth. The results in Table 14 show that if a drillship or another industrial noise source with a comparable output is operated at the Sandpiper or Orion sites, much larger zones of responsiveness would result than for operation of the same source at the Bering Sea site.

The radius values for a 0.1 probability of feeding disturbance at a received level of 110 dB can be seen to correspond approximately to those for S:N values of about 22 to 24 dB for most sites. For a 0.5 probability of feeding disturbance and avoidance at received levels of 120 dB, the radius values correspond to those at S:N ratios of about 33 to 36 dB. For drillship noise, the 0.5 probability of disturbance and avoidance for gray whales appears to occur at about a 10 dB higher level than it does for bowheads, since 110 dB was determined to be the general noise level at which about half of the bowheads have been observed to respond.

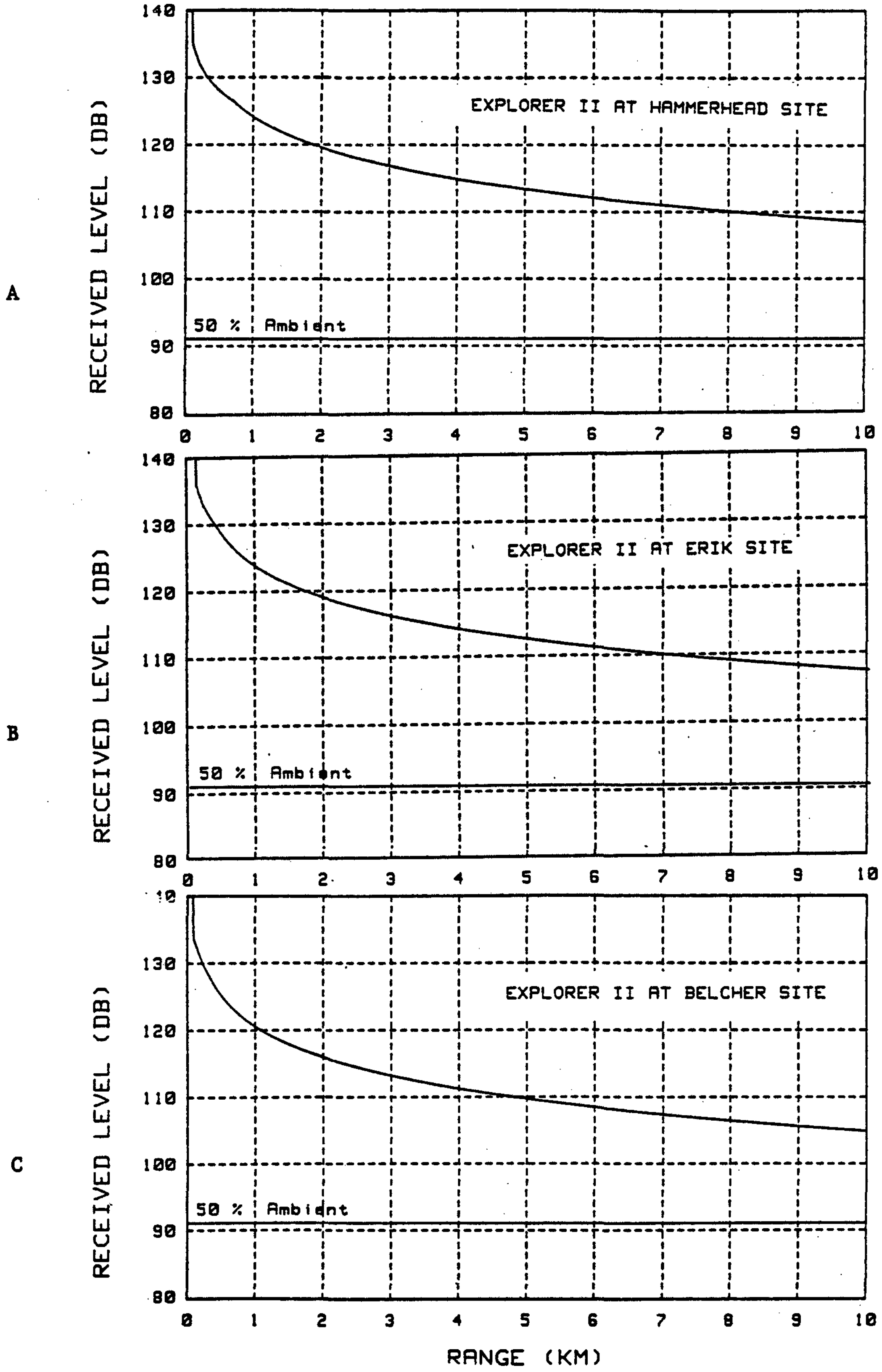
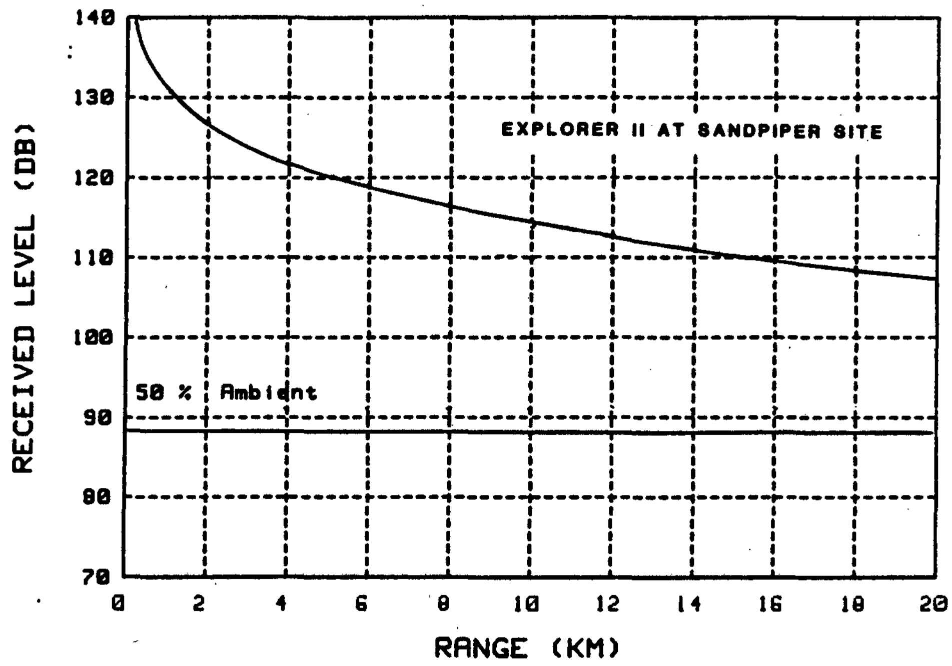


FIG. 60. RECEIVED LEVEL CHARACTERISTICS FOR EXPLORER II OPERATING AT BEAUFORT SITES.

D



E

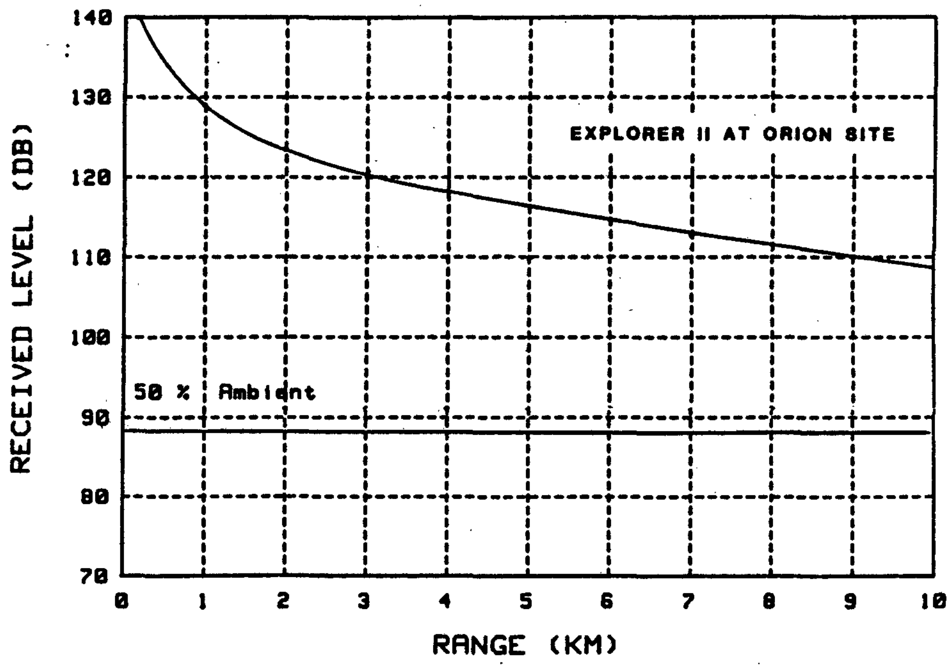


FIG. 60. (cont.) RECEIVED LEVEL CHARACTERISTICS FOR EXPLORER II OPERATING AT BEAUFORT SITES.

TABLE 14. ZONES OF RESPONSIVENESS FOR GRAY WHALES BASED ON OBSERVATIONS OF FEEDING DISTURBANCE AND AVOIDANCE RESPONSE FOR DRILLSHIP NOISE PLAYBACK (MALME ET AL. 1986).

		Estimated Range from Source Where L_r (dB re 1 µPa) is[1]		Estimated Range from Source Where 1/3 OB With Highest S:N Exceeds 50%ile Ambient by:[2]			
	P_a* L_r	0.1 110 dB	0.5 120 dB	S:N 0 dB	20 dB	30 dB	40 dB
Bering Sea Test Site (14 m) (Malme et al. 1986)		1.9 km	0.62 km	10 km	3.0 km	1.2 km	0.34 km
Belcher (55 m)	S	4.1	0.90	30	5.6	1.3	0.28
	E/W	4.1	0.90	>50	5.5	1.3	0.28
	N	4.0	0.90	>50	5.1	1.2	0.27
Erik (40 m)	S	7.9	2.0	13	9.5	2.6	0.57
	E/W	8.8	2.0	>50	11.0	2.5	0.57
	N	6.4	2.0	>50	10.0	2.5	0.56
Hammerhead (32 m)	E/W	8.0	1.8	>50	9.3	2.2	0.40
Sandpiper (15 m)[3]	E/W	15.2	6.0	>50	18.0	6.5	1.7
	N	16.0	6.0	>50	20.0	6.5	1.7
Orion (14 m)[3]	E/W	9.1	3.6	28	12.0	4.4	1.3
	N	11.2	3.7	>50	15.0	5.0	1.2

*Probability of disturbance and site avoidance as a result of the noise exposure.

NOTES: 1. The effective source level is estimated as 165 dB re 1 µPa at 1 m as determined by a power sum of the source levels in the dominant 80, 250, 1000, and 1600 Hz 1/3 octave bands (OB).

2. The 50%ile ambient noise level in the 250 Hz 1/3 OB is 85 dB at the Belcher, Erik, and Hammerhead sites (from Fig. 15). It is 84 dB at the Sandpiper and Orion sites (from Fig. 21).

3. The drillship will probably not be used at these shallow sites but the range estimates have been included for general comparison purposes.

The predicted radius of the zone of responsiveness using a criterion of 0.5 probability of disturbance and avoidance varies considerably from site-to-site as shown in Table 14. The smallest zone is predicted for the Belcher site with a 0.9 km radius. This can be compared with the 2.7 km radius predicted for a 0.5 probability of response for bowhead whales (from Table 13). The largest zone is predicted for the Sandpiper site with a 6 km radius. For bowhead whales at the same site, the predicted radius is 11 km (from Table 10).

These values of predicted zones of responsiveness have been extrapolated from transmission loss data which were obtained over considerably shorter ranges. They should be considered preliminary estimates to be used until the planned long-range sound transmission data have been obtained and analyzed.

4. CONCLUSIONS

This report presents new underwater acoustic data acquired between mid-August and mid-September 1985 at specific offshore drilling sites in the Alaskan Beaufort Sea. It also uses those new data, along with historical data concerning behavioral responses of bowhead and gray whales to acoustic stimuli to estimate site-specific zones of potential noise influence in the Alaskan Beaufort Sea. Zones of influence associated with selected industrial activities and selected industrial sites have been derived. Emphasis has been given to the bowhead whale, which is by far the more common of the two species of baleen whales observed along the North Slope.

This first year's research effort will be supplemented in the 1986 Final Report with additional acoustic measurements obtained in the summer of 1986 to provide zone-of-influence predictions which have a better statistical base. Predictions of zones of influence for migrating gray whales in the Beaufort Sea have been based upon behavioral response research performed by BBN in California and applied to Alaskan Beaufort Sea environmental conditions. Those findings have been supplemented with results of new behavioral research also performed by BBN on feeding gray whales in the Bering Sea in August 1985 and interpreted in terms of the Beaufort Sea environment.

4.1 Sites and Conditions

MMS specified that environmental acoustic data should be acquired at five offshore oil industry sites (some active and some unoccupied):

- Orion site where the Concrete Island Drilling System (CIDS) was operated by Exxon in Harrison Bay
- Sandpiper Island, a man-made gravel island operated by Shell near Prudhoe Bay

- Hammerhead Prospect, north of Flaxman Island (Unocal)
- Erik Prospect, north of Barter Island (Amoco)
- Belcher Prospect, northeast of Barter Island (Amoco)

A sixth site, Shell's Corona Prospect north of Camden Bay, was visited for measurements in 1985 and is expected to be active in 1986 providing industrial noise data. Heavy sea ice conditions prevailed in 1985 resulting in the acquisition of fewer acoustic data than originally expected. Hammerhead could not be reached at all during the planned measurement period because of ice.

In 1985, tug and dredge activity at Erik Prospect, pre-drilling preparations at Orion, and tugs at Sandpiper were the sources of noise monitored in the 16 August - 19 September time frame of this project. Greeneridge Sciences provided tape copies of 1985 drillship noise at Hammerhead and drill-rig noise at Sandpiper (since BBN was not able to make such measurements) to supplement the 1985 field data.

4.2 Acoustic Environment

Ambient noise statistics, industrial noise data, and sound transmission loss measurements were acquired and analyzed for this first year effort. The results are presented in Sec. 3. While it is important to add to the acoustic data base in 1986, several important findings have already been demonstrated.

1. The propagation of underwater sound is unusually efficient over the continental shelf of the Alaskan Beaufort Sea, demonstrating a cylindrical spreading or 10 log (range) transmission loss function over relatively short distances rather than a 15 log R or greater loss which is frequently found in similar water depths in more temperate regions. The 10 log R relationship

found in this study is consistent with recent results from the Canadian part of the Beaufort Sea.

2. It appears that the efficient sound propagation observed at the Alaskan Beaufort Sea sites is associated with the presence of sub-bottom or sub-sea permafrost and overconsolidated clay layers which provide low-loss acoustic reflection surfaces. For low frequency transmission at some sites, the effective depth apparently exceeds the actual water depth, corresponding to reported depths of permafrost and clay layers at some of the sites.

3. Sound propagation or transmission loss (TL) measurements in 1985 were limited to maximum ranges of about 5 km. After considering published 1984 data on longer range propagation of seismic pulses near some sites, the TL model developed during the analysis phase of the project permitted extrapolation beyond 5 km out to about 20 km. However, it is important to emphasize here that experimental data must be acquired in 1986 to test the validity of that extrapolation. It is entirely possible that a 10 log R loss function will not apply for all sites for distances beyond about 5-10 km and that whale behavior zones of influence may have to consider a 15 log R long distance TL function in addition to a 10 log R local loss function.

4. As a result of the initial findings regarding acoustic transmission loss in the Alaskan Beaufort Sea, migrating and feeding whales appear to be exposed to higher industrial noise levels at a given distance than would normally be expected in other geographic regions. This statement should be considered tentative until additional data are acquired in 1986.

4.3 Zones of Influence

Detailed tables and graphical presentations of the zones of potential detectability and response of endangered whales have been derived for various industrial noise signatures acquired in 1985 and various signal-to-noise conditions and absolute sound level (Sec. 3.4 and Appendix A). The analysis applied in this research has assumed that either one or both of these two criteria represent the basic causal acoustic measure(s) regarding behavioral response. Less emphasis has been given to other factors such as visual cues. For instance, both the previous bowhead and gray whale sound playback research discussed in this report considered visual cues as a possible influencing factor in the experimental protocol through observing whale behavior during vessel presence but without sound playback or seismic sound radiation.

Generally, previous research on behavioral response of bowhead whales by LGL Ltd. and gray whales by BBN has demonstrated that a 30 dB industrial noise-to-ambient noise ratio (S:N) or a 100 dB absolute noise level for bowheads (120 dB for grays) elicits changes in such variables as swimming heading, swimming speed, breathing rate, and dive times. A 20 dB signal-to-noise ratio provides less consistent and less conspicuous changes in behavior, with a minority of the individual whales reacting overtly and a majority not doing so. Three brief summary tables given in Section 3.4 for bowhead response are repeated here as Tables 15 through 17. They indicate distances from the site noted at which a few whales may respond (20 dB S:N) and where about half of the whales probably will respond (30 dB S:N) and for 110 dB absolute received level. We emphasize again that some of these estimates, especially those for a 20 dB signal-to-noise ratio, are well beyond the ranges at which transmission loss models have been verified. Hence, the

TABLE 15. MAXIMUM ESTIMATED DISTANCES FOR A 30 dB SIGNAL-TO-NOISE RATIO FOR FIVE SITES AND FIVE INDUSTRIAL NOISE SOURCES (PROBABLE WHALE RESPONSE)

	Dredge	Tug at Erik	Tugs at Sandpiper	Drill-ship	Drilling on Sandpiper
Orion	6.1 km	8.4 km	7.2 km	(5.3) km	0.6 km
Sandpiper	7.4	13.0	8.7	(6.5)	0.7
Hammerhead	2.5	8.4	3.4	2.2	(0.03)
Erik	2.9	7.2	3.7	2.5	(0.03)
Belcher	1.5	5.6	2.7	1.3	(0.02)

TABLE 16. MAXIMUM ESTIMATED DISTANCE FOR 110 dB ABSOLUTE RECEIVED NOISE LEVEL FOR FIVE SITES AND FIVE INDUSTRIAL NOISE SOURCES (PROBABLE BOWHEAD RESPONSE).

	Dredge	Tug at Erik	Tugs at Sandpiper	Drill-ship	Drilling on Sandpiper
Orion	8.7 km	9.9 km	10.0 km	(7.6) km	0.7 km
Sandpiper	12.0	15.0	14.0	(11.0)	0.8
Hammerhead	5.3	11.0	6.2	4.5	(0.3)
Erik	6.0	9.5	6.6	5.2	(0.3)
Belcher	3.1	7.5	3.1	2.7	(0.15)

TABLE 17. MAXIMUM ESTIMATED DISTANCES FOR A 20 dB SIGNAL-TO-NOISE RATIO FOR FIVE SITES AND FIVE INDUSTRIAL NOISE SOURCES (POSSIBLE BOWHEAD WHALE RESPONSE).

	Dredge	Tug at Erik	Tugs at Sandpiper	Drill-ship	Drilling on Sandpiper
Orion	15.0 km	16.0 km	17.0 km	(13.0) km	1.3 km
Sandpiper	22.0	25.0	24.0	(19.0)	1.7
Hammerhead	11.0	30.0	15.0	9.3	(0.26)
Erik	12.0	27.0	15.0	11.0	(0.26)
Belcher	6.4	22.0	11.0	5.5	(0.12)

estimates are preliminary and will be checked and revised after the 1986 field measurement results are available.

Estimates of zones of influence for gray whales relative to industrial noise in the Beaufort Sea must be based upon research performed in other geographic regions and then interpreted in the context of the Beaufort Sea given a definition of it's acoustic environment and acoustic transmission loss characteristics. Results of earlier research by BBN with migrating gray whales in California and feeding or summering gray whales near St. Lawrence Island in the Bering Sea have been used in that way for this study and the resulting Table 14 from the previous section is summarized in Table 18.

TABLE 18. ZONES OF RESPONSIVENESS FOR GRAY WHALES TO DRILLSHIP NOISE IN THE BEAUFORT SEA.

	Est. Range from Source		**Est. Range from Source**		
Prob. of Avoidance	**0.1**	**0.5**	**Sig.-to-Noise**	**20 dB**	**30 dB**
Received Level	**110 dB re 1 μPa**	**120 dB**			
Site					
Belcher	4.1 km	0.9 km		5.4 km	1.3 km
Erik	7.7	2.0		10.2	2.5
Hammerhead	8.0	1.8		9.3	2.2
Sandpiper	15.6	6.0		19.0	6.5
Orion	10.2	3.7		13.5	4.7

5. RECOMMENDATIONS

Except for item 7 below, the following recommendations, which have resulted from the 1985 field work and associated data analysis, are all related to the need for improving the yield of data during the 1986 field measurement period as well as subsequent data analysis and interpretation.

1. Long-range acoustic transmission loss (TL) data are required, ideally out to distances of 20-30 km from each of the oil industry sites that are being surveyed acoustically. As discussed previously, the TL models used in this report are supported by data out to about 5 km and extrapolated beyond that to the longer ranges using the Weston/Smith model. If the 10 log R function is, in fact, not applicable out to the longer distances, there could be major effects on the predicted sizes of zones of influence on whale behavior. Three approaches are recommended for acquisition of the needed data.

   (a) The 1985 field work used a single J-13 sound transducer for controlled TL experiments. Two such transducers operated in parallel should result in TL data out to 10-15 km, assuming ambient noise conditions similar to those encountered in 1985. BBN plans to incorporate this change into the 1986 acoustic measurement systems.

   (b) Every effort should be made to negotiate cooperation with seismic survey operators so that air gun array impulses from known sources can be received at opportune times and locations. This will complement the J-13 data by extending TL measurements to distances of 20 or more kilometers from the oil industry sites of interest.

(c) Advantage should be taken of high energy tonal noise components originating at the industrial sites to be surveyed. Those tonals that are expected to persist for long periods of time (2-3 hours) will be measured as a function of range from the site. A sonobuoy will be moored near the source (ice conditions permitting) at a fixed range to monitor the continuity of the signal level and frequency. An improved radio communications link for larger ranges will also have to be arranged.

2. Descriptions of the sub-sea permafrost and overconsolidated sediment near each site should be compiled. Obtaining those data will require discussions and cooperation with the site operators, review of MMS files and discussions with scientists at other research organizations such as U.S. Geological Survey (Menlo Park, CA) and U.S. Army Cold Regions Research and Engineering Laboratory (Hanover, NH).

3. Establish closer ties with site operators than achieved in 1985 so as to ensure a clear understanding of site noise-producing activities occurring precisely at the time of underwater noise measurements. Radio communications channel selections will have to be established with each operator.

4. Ideally, an acoustic research vessel capable of operating in greater than 2/10 ice cover should be obtained for the 1986 work. Heavy ice cover (5/10-6/10) often limited our ability to acquire TL data beyond 3-4 km in 1985.

5. Obtain access to daily or every other day ice reconnaissance and ice forecast information. Such access will need to be coordinated through Minerals Management

Service and should permit more efficient use of vessel charter time.

6. Zones of detection and responsiveness of whales will have to be recalculated and expanded based on new TL and ambient noise data and revised industrial noise source information to be acquired during this study in 1986, and during industry-funded studies in 1985 and possibly 1986.

7. Two acoustic criteria have been used in evaluating industrial noise zones of influence on whales; signal-to-noise ratio and absolute received level. There is insufficient information at the present time to allow selection of one criterion over the other regarding their relative importance. Indeed, both may be important considerations under certain conditions. The issue probably cannot be resolved until the results from more research are obtained through either more analysis of existing data files or through performance of additional measurement and observation during controlled experiments followed by detailed analysis. It is entirely possible that some indications of the relative importance of the two criteria could be developed by more analysis of existing data files, before investing in a major research effort implied by the second alternative.

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APPENDIX A

ZONE OF INFLUENCE TABLES

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APPENDIX A: SOUND PROPAGATION ESTIMATES FOR ZONE OF INFLUENCE ANALYSES

This appendix summarizes the sound propagation analyses used to derive the estimated ranges of detectability and responsiveness (see Section 3.4). The five tables in this appendix are for the five industrial sites discussed in detail in Section 3.4: Orion, Sandpiper, Hammerhead, Erik, and Belcher. For each of these sites, we have hypothesized that each of five industrial activities might occur:

- dredge bucket being raised (as recorded at Erik),
- tug beginning to tow barge (as recorded at Erik),
- two tugs in operation (as recorded at Sandpiper),
- drillship EXPLORER II drilling (as recorded at Hammerhead by Greeneridge Sciences Inc.), and
- drilling on artificial island (as recorded at Sandpiper by Greeneridge).

It should be recognized that an artificial island like that at Sandpiper would not be built at sites as deep as Hammerhead, Erik, or Belcher. Similarly, a drillship is unlikely to operate at sites as shallow as Orion or Sandpiper. Hence, some of the calculations in this appendix are of only theoretical relevance.

For each of the five industrial activities, Section 3.4.1 identifies the 1/3-octave bands in which the source levels are especially high relative to ambient levels in the same bands. One to four such 1/3-octave bands were identified for each of the five industrial sources. These bands are the ones that are likely to be detectable at longest ranges, and that will have the highest "industrial to ambient" noise ratios at any given distance. These bands are the ones considered in this appendix.

The Weston shallow-water sound propagation model (Section 3.3) has been applied for each of the five sites, five industrial source, and one-four frequency bands. For Orion and Sandpiper, we considered east and west azimuths (bottom slope 0) and north azimuths (bottom slope positive). For Erik and Belcher, we also considered south azimuths (bottom slope negative). For Hammerhead, where the sound propagation model was less well defined, we considered only the zero slope case.

The tabulated data for each run of the propagation model include:

- frequency and source level of the industrial noise in the 1/3-octave band with highest industrial-to-ambient noise ratio,
- the ambient noise levels expected in the corresponding 1/3-octave band at the site in question (5th, 50th, and 95th percentile values),
- the ranges at which the received industrial noise level would be expected to equal the 5th, 50th, and 95th percentile ambient noise (assumed "zone of audibility"),
- the ranges at which the received industrial noise level would be expected to be 10 dB, 20 dB, 30 dB. and 40 dB above the median (50th percentile) ambient noise (used to define "zone of responsiveness"),
- the ranges at which the received industrial noise level would be expected to be 100, 110, 120, and 130 dB, and
- the maximum range at which the propagation model is believed to be reasonably reliable.

Section 3.4 includes additional rationale for this approach, and an interpretation of the results.

TABLE A1. ESTIMATED RANGES AT WHICH VARIOUS NOISE LEVELS WOULD BE RECEIVED IF CERTAIN INDUSTRIAL ACTIVITIES TOOK PLACE AT THE ORION SITE (THE LOCATION OF THE CIDS IN 1985). FOR EACH INDUSTRIAL SOURCE, WE CONSIDER THE FEW 1/3-OCTAVE BANDS IN WHICH NOISE LEVELS WERE HIGHEST RELATIVE TO THE MEDIAN AMBIENT NOISE LEVEL. SEE SECTION 3.2 FOR DATA ON NOISE FROM EACH INDUSTRIAL SOURCE, SECTION 3.1 FOR DATA ON AMBIENT NOISE, AND SECTION 3.3 FOR DETAILS OF THE WESTON SOUND PROPAGATION MODEL USED TO OBTAIN THE ESTIMATED RECEIVED LEVELS.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at ORION (dB, 1/3 Oct. Band)			Slope Assumed in Model	Est. Range (km) from ORION Where Sig. to Amb. Noise Ratio = 0			Est. Range (km) from ORION where Signal Exceeds 50%ile by				Est. Range (km) from ORION where Received Level (dB re 1 uPa) is				Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	10 dB	20 dB	30 dB	40 dB	100	110	120	130	
Dredge bucket being raised at Erik	250	162	60	84	95	0	>50	39	25	26	15	6.1	1.7	19	8.7	2.9	.72	30
						.001	>50	>50	>50	>50	19	6.3	1.7	30	10.0	2.9	.72	16
	750	158	61	83	95	0	41	22	13	14	7.2	2.7	.69	9.1	3.8	1.1	.26	17
						.001	>50	>50	21	26	9.1	2.7	.69	12.0	4.0	1.1	.26	8
	1250	158	60	81	93	0	>50	30	15	17	7.7	2.3	.85	8.2	2.6	.64	.15	11
						.001	>50	>50	20	25	8.1	2.3	.55	9.1	2.6	.64	.15	6
Tug beginning to tow barge at Erik	1000	170	60	82	94	0	>50	35	24	26	16	8.4	3.1	18.0	9.9	4.0	1.1	11
						.001	>50	>50	>50	>50	29	11.0	3.2	35	14.0	4.1	1.1	6
	3500	164	58	78	90	0	>50	47	22	25	11	3.2	.78	8.4	2.4	.58	.14	11
						.001	>50	46	21	25	10	3.1	.77	8.2	2.4	.58	.14	6
Two tugs at Sandpiper	300	163	61	84	96	0	>50	45	27	30	17	7.2	2.0	22	10	3.4	.86	30
						.001	>50	>50	>50	>50	23	7.5	2.0	37	12	3.4	.86	15
	1500	164	59	81	93	0	>50	43	23	26	12	4.2	1.1	13	4.7	1.2	.29	11
						.001	>50	>50	31	37	14	4.2	1.1	16	4.8	1.2	.29	6
	4000	160	57	77	89	0	>50	35	15	18	6.6	1.8	.43	4.6	1.2	.28	.06	11
						.001	>50	34	14	17	6.4	1.8	.43	4.5	1.2	.28	.06	6

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TABLE A1. (cont.) ESTIMATED RANGES AT WHICH VARIOUS NOISE LEVELS WOULD BE RECEIVED IF CERTAIN INDUSTRIAL ACTIVITIES TOOK PLACE AT THE ORION SITE (THE LOCATION OF THE CIDS IN 1985). FOR EACH INDUSTRIAL SOURCE, WE CONSIDER THE FEW 1/3-OCTAVE BANDS IN WHICH NOISE LEVELS WERE HIGHEST RELATIVE TO THE MEDIAN AMBIENT NOISE LEVEL. SEE SECTION 3.2 FOR DATA ON NOISE FROM EACH INDUSTRIAL SOURCE, SECTION 3.1 FOR DATA ON AMBIENT NOISE, AND SECTION 3.3 FOR DETAILS OF THE WESTON SOUND PROPAGATION MODEL USED TO OBTAIN THE ESTIMATED RECEIVED LEVELS.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at ORION (dB, 1/3 Oct. Band)			Slope Assumed in Model	Est. Range (km) from ORION Where Sig. to Amb. Noise Ratio = 0			Est. Range (km) from ORION where Signal Exceeds 50%ile by				Est. Range (km) from ORION where Received Level (dB re 1 uPa) is				Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	10 dB	20 dB	30 dB	40 dB	100	110	120	130	
EXPLORER II drilling at Hammerhead	80	162	57	83	92	0	26	15	12	11	7.6	4.3	1.8	8.7	5.2	2.3	.76	63
						.001	>50	36	20	19	9.9	4.7	1.9	12.0	6.0	2.4	.77	23
	240	161	60	84	95	0	>50	35	22	24	13.0	5.3	1.4	17.0	7.6	2.5	.62	30
						.001	>50	>50	45	50	17	5.5	1.4	26.0	9.0	2.5	.62	16
	920	160	60	82	94	0	46	25	14	16	8.4	3.2	.85	9.8	4.1	1.1	.27	12
						.001	>50	>50	24	30	11.0	3.3	.85	13.0	4.2	1.1	.27	7
	1640	157	59	81	93	0	>50	31	13	15	5.4	1.4	.34	6.2	1.7	.39	.09	11
						.001	>50	43	14	17	5.5	1.4	.34	6.2	1.7	.39	.09	6
Drilling at Sandpiper	40	145	56	82	91	0	5.7	3.1	2.3	2.2	1.3	.59	.23	1.5	.71	.27	.04	63
						.001	7.6	3.5	2.5	2.3	1.4	.59	.23	1.5	.72	.27	.04	23

TABLE A2. ESTIMATED RANGES AT WHICH VARIOUS NOISE LEVELS WOULD BE RECEIVED IF CERTAIN INDUSTRIAL ACTIVITIES TOOK PLACE AT SANDPIPER ARTIFICIAL ISLAND. FOR EACH INDUSTRIAL SOURCE, WE CONSIDER THE FEW 1/3-OCTAVE BANDS IN WHICH NOISE LEVELS WERE HIGHEST RELATIVE TO THE MEDIAN AMBIENT NOISE LEVEL. SEE SECTION 3.2 FOR DATA ON NOISE FROM EACH INDUSTRIAL SOURCE, SECTION 3.1 FOR DATA ON AMBIENT NOISE, AND SECTION 3.3 FOR DETAILS OF THE WESTON SOUND PROPAGATION MODEL USED TO OBTAIN THE ESTIMATED RECEIVED LEVELS.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at Sandpiper (dB, 1/3 Oct. Band)			Slope Assumed in Model	Est. Range (km) from Sandpiper Where Sig. to Amb. Noise Ratio = 0			Est. Range (km) from Sandpiper where Signal Exceeds 50%ile by				Est. Range (km) from Sandpiper where Received Level (dB re 1 uPa) is				Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	10 dB	20 dB	30 dB	40 dB	100	110	120	130	
Dredge bucket being raised at Erik	250	162	60	84	95	0	>50	>50	43	46	22	7.4	1.9	31	12.0	3.3	.79	43
						.00035	>50	>50	>50	>50	23	7.5	1.9	36	13.0	3.3	.79	28
	750	158	61	83	95	0	>50	34	20	22	11	3.9	1.0	14	5.7	1.6	.38	20
						.00035	>50	>50	26	31	12	4.0	1.0	16	5.8	1.6	.38	14
	1250	158	60	81	93	0	>50	44	22	26	12	3.7	.91	13	4.2	1.1	.25	14
						.00035	>50	>50	26	32	13	3.7	.91	14	4.2	1.1	.25	10
Tug beginning to tow barge at Erik	1000	170	60	82	94	0	>50	>50	36	39	25	13.0	4.6	28	15.0	5.9	1.6	15
						.00035	>50	>50	>50	>50	36	14.0	4.7	42	17.0	6.0	1.6	11
	3500	164	58	78	90	0	>50	>50	29	34	16	5.2	1.4	13	4.1	1.0	.24	11
						.00035	>50	>50	29	34	15	5.2	1.4	13	4.0	1.0	.23	9
Two tugs at Sandpiper	300	163	61	84	96	0	>50	>50	43	48	24	8.7	2.3	33	14.0	3.9	.95	43
						.00035	>50	>50	>50	>50	27	8.8	2.3	41	15.0	3.9	.95	28
	1500	164	59	81	93	0	>50	>50	33	38	18	6.8	1.8	20	7.7	2.1	.50	13
						.00035	>50	>50	44	49	21	6.9	1.8	23	7.8	2.1	.50	9
	4000	160	57	77	89	0	>50	44	21	24	10	3.1	.76	7.3	2.1	.49	.11	11
						.00035	>50	43	20	24	9.9	3.1	.76	7.2	2.1	.49	.11	9

continued...

TABLE A2. (cont.) ESTIMATED RANGES AT WHICH VARIOUS NOISE LEVELS WOULD BE RECEIVED IF CERTAIN INDUSTRIAL ACTIVITIES TOOK PLACE AT SANDPIPER ARTIFICAL ISLAND. FOR EACH INDUSTRIAL SOURCE, WE CONSIDER THE FEW 1/3-OCTAVE BANDS IN WHICH NOISE LEVELS WERE HIGHEST RELATIVE TO THE MEDIAN AMBIENT NOISE LEVEL. SEE SECTION 3.2 FOR DATA ON NOISE FROM EACH INDUSTRIAL SOURCE, SECTION 3.1 FOR DATA ON AMBIENT NOISE, AND SECTION 3.3 FOR DETAILS OF THE WESTON SOUND PROPAGATION MODEL USED TO OBTAIN THE ESTIMATED RECEIVED LEVELS.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at Sandpiper (dB, 1/3 Oct. Band)			Slope Assumed in Model	Est. Range (km) from Sandpiper Where Sig. to Amb. Noise Ratio = 0			Est. Range (km) from Sandpiper where Signal Exceeds 50%ile by				Est. Range (km) from Sandpiper where Received Level (dB re 1 uPa) is				Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	10 dB	20 dB	30 dB	40 dB	100	110	120	130	
EXPLORER II drilling at Hammerhead	80	162	57	83	92	0	38	22	16	16	10	5.2	1.9	12	6.6	2.8	.77	63
						.00035	>50	29	20	19	11	5.4	2.0	13	6.9	2.8	.77	38
	240	161	60	84	95	0	>50	>50	39	41	19	6.5	1.6	27	11.0	2.9	.68	43
						.00035	>50	>50	>50	>50	20	6.5	1.6	32	11.0	2.9	.68	28
	920	160	60	82	94	0	>50	39	23	25	13	4.8	1.3	15	6.1	1.7	.40	17
						.00035	>50	>50	31	37	14	4.8	1.3	18	6.2	1.7	.40	12
	1640	157	59	81	93	0	>50	43	20	22	8.7	2.4	.58	9.8	2.8	.67	.16	12
						.00035	>50	>50	21	26	8.8	2.4	.58	9.9	2.8	.67	.16	9
Drilling at Sandpiper	40	145	56	82	91	0	8.5	4.4	3.1	3.0	1.7	.70	.22	1.9	.81	.27	.04	63
						.00035	9.5	4.7	3.2	3.1	1.7	.70	.22	1.9	.81	.27	.04	38

TABLE A3. ESTIMATED RANGES AT WHICH VARIOUS NOISE LEVELS WOULD BE RECEIVED IF CERTAIN INDUSTRIAL ACTIVITIES TOOK PLACE AT THE HAMMERHEAD SITE NORTH OF FLAXMAN ISLAND, AK. FOR EACH INDUSTRIAL SOURCE, WE CONSIDER THE FEW 1/3-OCTAVE BANDS IN WHICH NOISE LEVELS WERE HIGHEST RELATIVE TO THE MEDIAN AMBIENT NOISE LEVEL. SEE SECTION 3.2 FOR DATA ON NOISE FROM EACH INDUSTRIAL SOURCE, SECTION 3.1 FOR DATA ON AMBIENT NOISE, AND SECTION 3.3 FOR DETAILS OF THE WESTON SOUND PROPAGATION MODEL USED TO OBTAIN THE ESTIMATED RECEIVED LEVELS.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at Hammerhead (dB, 1/3 Oct. Band)			Slope Assumed in Model	Est. Range (km) from Hammerhead Where Sig. to Amb. Noise Ratio = 0			Est. Range (km) from Hammerhead Where Signal Exceeds 50%ile by				Est. Range (km) from Hammerhead Where Received Level (dB re 1 uPa) is				Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	10 dB	20 dB	30 dB	40 dB	100	110	120	130	
Dredge bucket being raised at Erik	250	162	69	85	96	0	>50	>50	36	41	11.0	2.5	.50	21	5.3	1.2	.17	52
	750	158	68	82	94	0	>50	>50	20	25	6.7	1.5	.34	8.9	2.1	.46	.06	52
	1250	158	66	82	94	0	>50	>50	17	22	6.0	1.4	.31	7.9	1.9	.42	.06	52
Tug beginning to tow barge at Erik	1000	170	67	82	94	0	>50	>50	>50	>50	30	8.4	2.0	37	11.0	2.7	.60	52
	3500	164	63	81	93	0	>50	>50	25	29	12	3.5	.83	13	4.0	.96	.22	44
Two tugs at Sandpiper	300	163	69	84	96	0	>50	>50	42	>50	15	3.4	.77	25	6.2	1.4	.20	52
	1500	164	66	81	94	0	>50	>50	32	43	15	3.9	.90	17	4.5	1.0	.23	52
	4000	160	62	81	93	0	>50	39	16	20	7.2	2.0	.45	8.1	2.3	.53	.10	44
EXPLORER II drilling at Hammerhead	80	162	68	89	99	0	>50	27	13	13	4.9	1.3	.20	12	4.3	1.1	.17	52
	240	161	69	85	96	0	>50	>50	31	36	9.3	2.2	.40	19	4.5	1.0	.13	52
	920	160	68	82	94	0	>50	>50	24	30	8.4	2.0	.44	11	2.7	.60	.10	52
	1640	157	66	81	94	0	>50	>50	14	20	5.7	1.4	.30	6.6	1.6	.35	.05	49
Drilling at Sandpiper	40	145	67	91	100	0	12	3.4	1.4	1.2	.26	0.3	<.01	1.4	.32	.03	<.01	52

TABLE A4. ESTIMATED RANGES AT WHICH VARIOUS NOISE LEVELS WOULD BE RECEIVED IF CERTAIN INDUSTRIAL ACTIVITIES TOOK PLACE AT THE ERIK SITE WHICH IS NORTHWEST OF BARTER ISLAND, ALASKA. FOR EACH INDUSTRIAL SOURCE, WE CONSIDER THE FEW 1/3-OCTAVE BANDS IN WHICH NOISE LEVELS WERE HIGHEST RELATIVE TO THE MEDIAN AMBIENT NOISE LEVEL. SEE SECTION 3.2 FOR DATA ON NOISE FROM EACH INDUSTRIAL SOURCE, SECTION 3.1 FOR DATA ON AMBIENT NOISE, AND SECTION 3.3 FOR DETAILS OF THE WESTON SOUND PROPAGATION MODEL USED TO OBTAIN THE ESTIMATED RECEIVED LEVELS.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at Erik (dB, 1/3 Oct. Band)			Slope Assumed in Model	Est. Range (km) from Erik Where Sig. to Amb. Noise Ratio = 0			Est. Range (km) from Erik where Signal Exceeds 50%ile by				Est. Range (km) from Erik where Received Level (dB re 1 uPa) is				Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	10 dB	20 dB	30 dB	40 dB	100	110	120	130	
Dredge bucket being raised at Erik	250	162	69	85	96	-.0026	14	13	12	13	10	3.0	.66	12	6.1	1.4	.29	14
						0	>50	>50	39	44	12	2.9	.66	24	6.0	1.4	.29	52
						.0028	>50	>50	37	42	12	2.9	.65	22	5.8	1.4	.28	20
	750	158	68	82	94	-.0026	15	14	14	14	6.7	1.5	.32	8.9	2.0	.44	.05	15
						0	>50	>50	19	25	6.3	1.4	.31	8.4	2.0	.43	.05	52
						.0028	>50	>50	17	22	6.0	1.4	.31	7.9	1.9	.43	.05	19
	1250	158	66	82	94	-.0026	15	15	14	14	5.8	1.3	.28	7.8	1.8	.38	.05	15
						0	>50	>50	16	21	5.5	1.3	.28	7.3	1.7	.38	.05	52
						.0028	>50	48	14	18	5.3	1.3	.28	6.9	1.7	.38	.05	18
Tug beginning to tow barge at Erik	1000	170	67	82	94	-.0026	15	15	15	15	14	7.7	1.7	14	10	2.3	.51	15
						0	>50	>50	>50	>50	27	7.2	1.7	33	9.5	2.3	.50	52
						.0028	>50	>50	>50	>50	23	6.8	1.7	29	8.9	2.2	.50	19
	3500	164	63	81	93	-.0026	15	15	15	15	13	3.9	.90	14	4.4	1.0	.24	15
						0	>50	>50	26	30	12	3.7	.89	14	4.3	1.0	.23	44
						.0028	>50	50	23	27	12	3.6	.88	13	4.1	1.0	.23	15
Two tugs at Sandpiper	300	163	69	84	96	-.0026	14	14	13	13	11	3.8	.84	12	6.7	1.5	.32	14
						0	>50	>50	43	>50	15	3.7	.83	26	6.6	1.5	.32	52
						.0028	>50	>50	40	50	14	3.6	.82	24	6.3	1.5	.31	20
	1500	164	66	81	94	-.0026	15	15	15	15	14	3.8	.84	14	4.4	.98	.20	15
						0	>50	>50	31	42	14	3.7	.84	16	4.2	.97	.20	52
						.0028	>50	>50	27	36	13	3.6	.83	15	4.1	.96	.20	17
	1600	160	62	81	93	-.0026	15	15	15	15	8.2	2.2	.49	9.3	2.5	.57	.10	15
						0	>50	40	17	20	7.7	2.1	.49	8.6	2.4	.57	.10	44
						.0028	>50	36	16	19	7.3	2.1	.49	8.1	2.4	.57	.10	15

continued...

TABLE A4. (cont.) ESTIMATED RANGES AT WHICH VARIOUS NOISE LEVELS WOULD BE RECEIVED IF CERTAIN INDUSTRIAL ACTIVITIES TOOK PLACE AT THE ERIK SITE, WHICH IS NORTHWEST OF BARTER ISLAND, ALASKA. FOR EACH INDUSTRIAL SOURCE, WE CONSIDER THE FEW 1/3-OCTAVE BANDS IN WHICH NOISE LEVELS WERE HIGHEST RELATIVE TO THE MEDIAN AMBIENT NOISE LEVEL. SEE SECTION 3.2 FOR DATA ON NOISE FROM EACH INDUSTRIAL SOURCE, SECTION 3.1 FOR DATA ON AMBIENT NOISE, AND SECTION 3.3 FOR DETAILS OF THE WESTON SOUND PROPAGATION MODEL USED TO OBTAIN THE ESTIMATED RECEIVED LEVELS.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at Erik (dB, 1/3 Oct. Band)			Slope Assumed in Model	Est. Range (km) from Erik Where Sig. to Amb. Noise Ratio = 0			Est. Range (km) from Erik where Signal Exceeds 50%ile by				Est. Range (km) from Erik where Received Level (dB re 1 uPa) is				Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	10 dB	20 dB	30 dB	40 dB	100	110	120	130	
EXPLORER II drilling at Hammerhead	80	162	68	89	99	-.0226	10	8.6	6.8	6.8	3.7	1.0	.20	6.6	3.3	.87	.17	12
						0	46	21	11	11	3.9	1.0	.20	9.7	3.4	.87	.17	52
						.0028	>50	45	14	14	4.0	1.0	.20	13	3.5	.87	.17	20
	240	161	69	85	96	-.0026	14	13	12	12	9.5	2.6	.57	12	5.3	1.2	.23	14
						0	>50	>50	34	39	11	2.5	.57	21	5.2	1.2	.23	52
						.0028	>50	>50	33	37	10	2.5	.56	20	5.0	1.2	.23	20
	920	160	68	82	94	-.0026	15	15	14	14	7.7	1.7	.37	10	2.3	.51	.06	15
						0	>50	>50	21	27	7.3	1.7	.37	9.6	2.3	.50	.06	52
						.0028	>50	>50	19	24	6.9	1.7	.37	8.9	2.2	.50	.06	19
	1640	157	66	81	94	-.0026	15	15	14	14	5.9	1.3	.29	6.8	1.6	.34	.04	15
						0	>50	>50	14	20	5.6	1.3	.29	6.4	1.5	.34	.04	52
						.0028	>50	45	13	18	5.3	1.3	.29	6.1	1.5	.34	.04	17
Drilling at Sandpiper	40	145	67	91	100	-.0226	5.5	2.4	1.1	.97	.26	.03	<.01	1.1	.31	.03	<.01	8
						0	9.4	2.7	1.1	.98	.26	.03	<.01	1.1	.31	.03	<.01	52
						.0028	25	2.9	1.1	.98	.25	.03	<.01	1.1	.31	.03	<.01	20

TABLE A5. ESTIMATED RANGES AT WHICH VARIOUS NOISE LEVELS WOULD BE RECEIVED IF CERTAIN INDUSTRIAL ACTIVITIES TOOK PLACE AT THE BELCHER SITE, WHICH IS EAST OF BARTER ISLAND, ALASKA. FOR EACH INDUSTRIAL SOURCE, WE CONSIDER THE FEW 1/3-OCTAVE BANDS IN WHICH NOISE LEVELS WERE HIGHEST RELATIVE TO THE MEDIAN AMBIENT NOISE LEVEL. SEE SECTION 3.2 FOR DATA ON NOISE FROM EACH INDUSTRIAL SOURCE, SECTION 3.1 FOR DATA ON AMBIENT NOISE, AND SECTION 3.3 FOR DETAILS OF THE WESTON SOUND PROPAGATION MODEL USED TO OBTAIN THE ESTIMATED RECEIVED LEVELS.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at Belcher (dB, 1/3 Oct. Band)			Slope Assumed in Model	Est. Range (km) from Belcher Where Sig. to Amb. Noise Ratio = 0			Est. Range (km) from Belcher where Signal Exceeds 50%ile by				Est. Range (km) from Belcher where Received Level (dB re 1 uPa) is				Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	10 dB	20 dB	30 dB	40 dB	100	110	120	130	
Dredge bucket being raised at Erik	250	162	69	85	96	-.0013	34	31	21	23	6.5	1.5	.33	13	3.1	.69	.12	40
						0	>50	>50	22	26	6.4	1.5	.33	13	3.1	.69	.12	43
						.0087	>50	>50	19	22	5.9	1.4	.32	11	2.9	.68	.12	9.5
	750	158	68	82	94	-.0013	39	37	14	18	4.3	.96	.19	5.8	1.3	.28	.03	40
						0	>50	>50	13	17	4.3	.95	.19	5.7	1.3	.28	.03	43
						-.0087	>50	42	11	14	3.9	.93	.18	5.2	1.3	.28	.03	9.5
	1250	158	66	82	94	-.0013	40	38	13	17	4.3	.95	.19	5.7	1.3	.28	.03	40
						0	>50	48	13	16	4.2	.95	.19	5.6	1.3	.28	.03	43
						.0087	>50	37	11	14	3.9	.93	.18	5.1	1.2	.28	.03	9.5
Tug beginning to tow barge at Erik	1000	170	67	82	94	-.0013	40	40	38	38	23	5.7	1.3	29	7.7	1.8	.38	40
						0	>50	>50	52	>50	22	5.6	1.3	27	7.5	1.8	.38	43
						.0087	>50	>50	39	47	17	5.1	1.2	22	6.6	1.7	.38	9.5
	3500	164	63	81	93	-.0013	40	40	22	26	9.6	2.6	.60	11	3.0	.70	.12	40
						0	>50	48	21	25	9.3	2.6	.60	10	3.0	.69	.12	43
						.0087	>50	40	18	21	8.2	2.4	.59	9.1	2.8	.68	.12	9.5
Two tugs at Sandpiper	300	163	69	84	96	-.0013	35	33	22	26	7.6	1.7	.38	13	3.1	.70	.12	40
						0	>50	>50	23	30	7.5	1.7	.38	13	3.1	.69	.12	43
						.0087	>50	>50	19	24	6.8	1.7	.38	12	2.9	.68	.12	9.5
	1500	164	66	81	94	-.0013	41	40	27	35	11	2.7	.60	13	3.2	.70	.12	41
						0	>50	>50	25	34	11	2.7	.60	12	3.1	.70	.12	44
						.0087	>50	>50	20	27	9.3	2.5	.59	11	2.9	.69	.12	9.5
	4000	160	62	81	93	-.0013	41	36	14	17	5.7	1.4	.33	6.4	1.7	.38	.05	41
						0	>50	34	14	16	5.6	1.4	.33	6.3	1.7	.38	.05	44
						.0087	>50	29	12	14	5.1	1.4	.33	5.7	1.6	.38	.05	9.5

continued...

TABLE A5. (cont.) ESTIMATED RANGES AT WHICH VARIOUS NOISE LEVELS WOULD BE RECEIVED IF CERTAIN INDUSTRIAL ACTIVITIES TOOK PLACE AT THE BELCHER SITE, WHICH IS EAST OF BARTER ISLAND, ALASKA. FOR EACH INDUSTRIAL SOURCE, WE CONSIDER THE FEW 1/3-OCTAVE BANDS IN WHICH NOISE LEVELS WERE HIGHEST RELATIVE TO THE MEDIAN AMBIENT NOISE LEVEL. SEE SECTION 3.2 FOR DATA ON NOISE FROM EACH INDUSTRIAL SOURCE, SECTION 3.1 FOR DATA ON AMBIENT NOISE, AND SECTION 3.3 FOR DETAILS OF THE WESTON SOUND PROPAGATION MODEL USED TO OBTAIN THE ESTIMATED RECEIVED LEVELS.

Type of Noise Source	Dominant Frequency (Hz)	Est. 1/3 Octave Source Level (dB)	Estimated Ambient Noise at Belcher (dB, 1/3 Oct. Band)			Slope Assumed in Model	Est. Range (km) from Belcher Where Sig. to Amb. Noise Ratio = 0			Est. Range (km) from Belcher where Signal Exceeds 50%ile by				Est. Range (km) from Belcher where Received Level (dB re 1 uPa) is				Max. Range (km) of Reliability
			5%ile	50%ile	95%ile		5%ile	50%ile	95%ile	10 dB	20 dB	30 dB	40 dB	100	110	120	130	
EXPLORER II drilling at Hammerhead	80	162	68	89	99	-.0013	21	14	7.1	7.1	2.3	.56	.09	6.5	2.0	.48	.07	35
						0	50	19	8.1	8.1	2.3	.56	.09	7.4	2.0	.48	.07	44
						.0087	>50	31	8.8	8.8	2.3	.56	.09	7.7	2.0	.48	.07	9.5
	240	161	69	85	96	-.0013	34	30	19	20	5.6	1.3	.28	11	2.7	.59	.09	40
						0	>50	>50	19	22	5.5	1.3	.28	11	2.7	.59	.09	44
						.0087	>50	>50	17	19	5.1	1.2	.27	10	2.5	.59	.09	9.5
	920	160	68	82	94	-.0013	40	38	18	23	5.8	1.3	.28	7.7	1.8	.38	.05	41
						0	>50	>50	17	22	5.7	1.3	.28	7.5	1.8	.38	.05	44
						.0087	>50	48	14	18	5.1	1.3	.28	6.7	1.7	.38	.05	9.5
	1640	157	66	81	94	-.0013	41	39	11	16	4.2	.95	.19	4.9	1.1	.23	.03	41
						0	>50	44	11	16	4.1	.95	.19	4.8	1.1	.23	.03	44
						.0087	>50	34	9.3	13	3.8	.93	.18	4.4	1.1	.22	.03	9.5
Drilling at at Sandpiper	40	145	67	91	100	-.0013	7.9	1.9	.67	.58	.12	.02	<.01	.67	.16	.03	<.01	28
						0	9.9	2.1	.67	.58	.12	.02	<.01	.67	.15	.03	<.01	44
						.0087	37	2.2	.67	.58	.12	.02	<.01	.67	.15	.03	<.01	9.5

APPENDIX B

PREVIOUS DATA ON RESPONSES OF BOWHEAD AND GRAY WHALES TO NOISE FROM OIL AND GAS INDUSTRY ACTIVITIES

W. John Richardson (LGL Ltd.) and
Charles I. Malme (BBN Laboratories
Incorporated)

APPENDIX B.
PREVIOUS DATA ON RESPONSES OF BOWHEAD AND GRAY WHALES TO NOISE FROM DRILLING AND ISLAND CONSTRUCTION*

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* By W. John Richardson (LGL Ltd.) and C. I. Malme (BBN Laboratories Incorporated)

APPENDIX B

PREVIOUS DATA ON RESPONSES OF BOWHEAD AND GRAY WHALES TO NOISE FROM DRILLING AND ISLAND CONSTRUCTION*

B.1 INTRODUCTION

The present study was designed to determine the characteristics of underwater noise around drillsites and island construction sites in the Alaskan Beaufort Sea. The present study does not include field tests of the reactions of whales to industrial noise. Previous studies of the sensitivity of whales to industrial noise, in conjunction with the new site-specific data on industrial noise, are used to estimate the potential zones of influence of the industrial sites on bowhead and gray whales occurring in the Alaskan Beaufort Sea.

Since 1976, there has been intensive offshore drilling for oil and gas in parts of the Canadian Beaufort Sea deep enough to be utilized by bowhead whales. More recently, offshore drilling has begun north of the barrier islands in the Alaskan Beaufort Sea. Several studies of bowhead whales have been conducted in these areas in recent years. A few of these studies were specifically designed to observe or to test the reactions of bowheads to drilling or island construction (Hickie and Davis 1983; Davis et al. 1985; Richardson et al. 1985b,c). Characteristics of the underwater noise near industrial sites were documented during each of these studies. In addition, many other studies of bowheads in the Canadian and Alaskan parts of the Beaufort Sea have provided data on the occurrence (or absence) of bowheads near offshore industrial sites, even though this was not an objective of most of these studies.

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Gray whales occur regularly in the Chukchi Sea northeast to Point Barrow, but are rare east of there (Rugh and Fraker 1981; Ljungblad et al. 1985). Aside from one opportunistic observation of a gray whale when reactions of bowheads to drillship noise were being tested (Richardson et al. 1985b), there have been no attempts to study the reactions of gray whales to industrial activities in the Beaufort Sea. However, controlled studies of the reactions of migrating gray whales to various industrial sounds have been conducted along the California coast (Malme et al. 1983, 1984). Follow-up work has recently been done on the reactions of feeding gray whales summering in the northern Bering Sea to industrial noise (Malme et al. 1986).

B.1.1 Scope of This Review

In this section, we summarize the available data on the occurrence, behavior and noise exposure of bowhead whales near actual and simulated drillsites and offshore construction sites in the Beaufort Sea. The objective is to determine the distances, noise levels, and signal-to-noise ratios at which bowhead whales do or do not react to underwater noise from drilling and island construction. With this information about the sensitivity of bowheads to noise, along with measurements of underwater noise fields near industrial sites in the Alaskan Beaufort Sea (present study), it should be possible to estimate the potential zones of influence of those sites on bowhead whales.

The main sources of information about sensitivity of bowhead whales to industrial noise are the few investigations that have specifically examined the distribution, behavior and noise exposure of bowheads near industrial sites (Hickie and Davis 1983; Davis et al. 1985; Richardson et al. 1985a,b,c). However, we have also examined published and unpublished data from other projects, mainly involving aerial surveys, to identify additional cases in which bowhead whales have been observed near industrial sites in the Alaskan or Canadian Beaufort Sea.

This section also contains a brief review of the situations in which migrating and feeding or summering gray whales do and do not react to various industrial sounds. Those data came from studies along the California coast (Malme et al. 1983, 1984). Data concerning the sensitivity of summering gray whales to industrial sounds is discussed in the context of the Beaufort Sea using results of the 1985 tests of the reactions of gray whales summering in the northern Bering Sea to industrial noise (Malme et al. 1986)

B.2. BOWHEADS AND DRILLING IN THE BEAUFORT SEA

B.2.1 Types of Drilling Operations

Offshore drilling can be from artificial or natural islands, platforms of various types, and drillships.

1. Artificial islands constructed of uncontained sand and gravel have been used to drill in nearshore portions of the Beaufort Sea, in areas as deep as 18 m. Such islands have gently-sloping sides, and hence are not economical in deeper water because of the huge amount of fill required. Artificial drilling islands have been constructed in both the Canadian and Alaskan parts of the Beaufort Sea. Many of these islands were in water shallower than that normally used by bowheads, but some islands have been constructed far enough offshore to be near the southern edge of the areas frequented by bowheads.

2. Caisson-retained islands and self-contained drilling caissons have been used in the Canadian Beaufort Sea since 1981, and in the Alaskan Beaufort since 1984, usually in water deeper than 18 m. Caisson-retained islands are steep-sided rings filled by sand. Self-contained caissons are steel or concrete structures ballasted down onto the bottom or onto an underwater berm.

3. Three or four ice-strengthened conventional drillships have worked in the Canadian Beaufort Sea each summer and autumn since 1976. One of these same drillships, EXPLORER II, began to work in the Alaskan Beaufort Sea late in 1984 and drilled there in 1985. These drillships have usually operated in water 25-75 m deep. In addition, during 1983-1985, a new circular drilling barge, KULLUK, was also operating in the Canadian Beaufort. KULLUK may drill in Alaskan waters in future years. Drillships are normally attended by one or more smaller support vessels. In the Beaufort Sea, drillships often are also attended by icebreakers, especially during the early and late parts of the drilling season when ice is most commonly present.

Drilling from artificial islands and caissons can occur at any time of year. Drillships, in contrast, operate only during summer or autumn when ice is absent or thin; bowhead whales may be present at these times.

B.2.2 Sightings Near Drillships

Richardson et al. (1985b,c) saw bowheads within 4-20 km of drillships on several days in August of 1981-84. Sometimes the drillship was the only potential source of disturbance to the whales. On other occasions, bowheads 8-20 km from a drillship were also exposed to sounds from various combinations of seismic exploration, helicopter and boat traffic, and island construction. In most of these cases, bowheads were seen in the same area for at least a few days (Fraker et al. 1982; Richardson et al. 1984, 1985b,c). This suggested that some whales were tolerating the presence of the drillship and other industrial activities, although there was no proof that the same individual whales were present on successive days.

On five occasions when bowheads were seen 4-20 km from drillships, the drillships and their standby vessels were the only sources of possible disturbance (Richardson et al. 1985b,c). General activities of these bowheads seemed characteristic of undisturbed bowheads (Table B-1). The whales were not heading away from the drillship on any of these five occasions. Bowheads seen 4 km from EXPLORER II were socializing even though exposed to strong drillship noise. The apparent lack of calling by whales 4 km from the ship is noteworthy, since socializing bowheads usually call frequently (Würsig et al. 1985). However, faint calls might have been present but not detected because of the high drillship noise level.

Surfacing, respiration and dive characteristics of bowheads near drillships were usually within the ranges for undisturbed whales (see Richardson et al. 1983b, p 195-8 for details). The one exception involved two whales 10-12 km from EXPLORER III on 31 Aug 1982. Their dive times were consistently long (23.4-31.0 min). However, there was no evidence that the long dives were related to the proximity of the drillship. Indeed, a sonobuoy near these whales did not detect drillship sound.

TABLE B-1. CIRCUMSTANCES OF OBSERVATIONS OF BOWHEADS NEAR DRILLSHIPS, 1981-82. THESE WERE ONLY OBSERVATIONS WHEN THE DRILLSHIP WAS THE ONLY SOURCE OF POTENTIAL DISTURBANCE (FROM RICHARDSON ET AL. 1985).

	23 Aug '81	23 Aug '81	11 Aug '82	31 Aug '82	31 Aug '82
Location – N. Lat.	70°04'	70°05'	70°50'	70°28'	70°27'
W. Long.	134°54'	134°28'	134°18'	136°51'	136°30'
Water Depth (m)	31	23	90	550	150-390
Sea State	1	1	3-4	1-2[a]	2
Aircraft Altitude (m)	457-610	610	457	457[b]	457
Duration of Obs. (min)	62	63[c]	26	113[b]	194
Drillship					
Identity	Expl. II	Expl. II	Expl. IV	Expl. III	Expl. III
Range (km)	15-20	4	17	18-19	10-12
Activity	Drilling	Drilling	Not drilling	Drilling	Drilling
Detectable[d]	Yes	Yes-strong	Yes-weak	No	No
Approx. No. of Whales	8+	3	1+	1	2
Activity of Whales	Some echelon feeding & socializing; calling	Mainly socializing; no calls detected	Unknown; some calling	Slow to medium speed travel; calling	Long dives; slow to medium travel; some calling

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[a] No whitecaps but heavy swell.

[b] Subsequent observations from 305 m a.s.l. are not considered here.

[c] Excludes subsequent observations when boats nearby.

[d] Industrial noise detected by sonobuoy dropped near whales.

Although the aforementioned cases are the only ones in which bowhead behavior has been documented near drillships, aerial surveyors have recorded numerous other sightings of bowheads within 20 km from drillships operating in the Canadian Beaufort Sea:

1. During an LGL grid survey on 13 Aug 1981, 18 whales were seen within 20 km of one or more of the three drillships operating north of the Mackenzie Delta. The closest sighting was of three whales 5 km from EXPLORER I at Kopanoar (unpubl. data; summarized in Richardson et al. 1985a, p 270).

2. Davis et al. (1982) found a number of bowheads within 20 km of EXPLORER II on 24 Aug 1981, including one only 4 km from the drillship. These whales were near those seen on previous days by Richardson et al. (1985b,c) (e.g. Table B-1).

3. In 1982, there was a sighting of one bowhead 12 km from EXPLORER IV at Kenalooak (Harwood and Ford 1983, Fig. 5), as well as the sightings listed in Table B-1.

4. In late August and early September 1983, there were several sightings of bowheads 12-20 km from the circular drilling unit KULLUK at Pitsiulak (Ljungblad et al. 1984, p A-32; Richardson et al. 1984). Some were socializing and feeding near the bottom.

4. In 1984, one bowhead was seen about 10 km from KULLUK at East Amauligak on 16 Aug (D. Rugh, U.S. Nat. Mar. Fish. Serv., pers. comm.). A bowhead calf was seen about 13 km from EXPLORER II at Havik on 12 Sept (Harwood and Borstad 1985, Fig. 9).

5. About 20 bowheads were seen 12 km from EXPLORER III at Arluk on 2 Sept 1984 (Davis et al. 1986). About 15 bowheads were seen 23 km from Arluk three days later, but the three individually identifiable bowheads found on 5 Sept apparently had not been present on 2 Sept (Davis et al. 1986).

In addition, there have been a few other sightings of single bowheads at distances of 13-20 km from drillships.

Industry personnel reported sightings of bowheads near EXPLORER IV and EXPLORER III on several occasions from mid-July to early August 1980. The distance of the whale(s) from the drillship was estimated for 7 sightings as 0.2-5 km. In 1982 and 1983, industry personnel reported 3 sightings of single bowheads near drillships, in each case at an estimated distance of 3.7 km (Richardson et al. 1985b,c).

Prior to 1985, drillships had not operated in the Alaskan Beaufort Sea during the bowhead migration period. In 1985, EXPLORER II operated north of Flaxman Island (146°W) in August and early-mid September. Intensive aerial survey and acoustic programs were conducted to search for bowheads near the drillship and to document its underwater noise; the results are expected to be available in McLaren et al., in preparation).

In summary, aerial surveyors have seen bowhead whales as close as 4-5 km from operating drillships on at least three occasions, and there have been numerous sightings at distances of 10-20 km. As documented in B.4.2, underwater noise from drillships is strong at distances of 4-5 km, and typically is detectable at and beyond 10 km. Industry personnel have reported bowheads considerably closer to drillships, as close as 0.2 km in one case. Bowheads have sometimes been seen near drillships over periods of several days, but there is no information about the duration of stay of particular individual bowheads near drillships. There has been no quantitative analysis of bowhead abundance relative to distance from drillships; it is questionable whether a meaningful analysis of this type would be possible given the low density and variable distribution of bowheads. Thus, it is not known whether the numbers of bowheads seen at various distances from drillships are the same as would occur in the absence of drillships.

B.2.3 Sightings Near Drillsites on Artificial Islands and Caissons

In the Canadian Beaufort Sea, drilling from artificial islands and caissons was not common during the late summers of 1980-84 when behavior of bowheads was studied. Most island-based drilling was done at other times of year. There was no drilling from uncontained artificial islands during the study periods of Richardson et al. (1985b,c), and there was drilling from caissons during only a few days within those field seasons. The closest bowhead sighting relative to a caisson where drilling was underway was 21 km from Tarsiut caisson-retained island on 4 Aug 1982 (Richardson et al. 1983b). However, industry personnel at Tarsiut reported two sightings during a drilling period, one only 0.2 km away. Two more bowheads were reported about 0.3 km away after drilling ended. Sound levels near Tarsiut and its attending support vessels during drilling are unknown. However, background noise levels within about 1 km from Tarsiut were quite high during periods without drilling (Greene 1985).

In the Alaskan Beaufort Sea, several artificial islands have been built north of the barrier islands northwest of Prudhoe Bay since 1982. A self-contained drilling caisson, known as the CIDS, was present farther west in Harrison Bay in late 1984 and 1985.

However, because of the "seasonal drilling restriction" and other regulatory actions related to bowhead whales, there has been little drilling from these structures during periods when bowheads were migrating westward. Site-specific studies of bowheads and of underwater sounds were conducted near Seal and Sandpiper Islands in 1984 and 1985, respectively (Davis et al. 1985; Johnson et al. in prep.).

In 1984, drilling at Seal Island continued until 22 September. While drilling was underway, bowheads were seen no nearer to Seal Island than 29 km away (Davis et al. 1985; see also Ljungblad et al. 1985). However, the whale 29 km from the island was travelling west at a location WNW of Seal Island and only about 5 km north of the barrier islands. Its closest point of approach to Seal Island was probably much less than 29 km. In 1985, drilling was not permitted at Sandpiper Island during the bowhead migration period.

In summary, there has been very little drilling from islands and caissons in either the Canadian or Alaskan Beaufort Sea during periods when bowheads were present and under study. Thus, no conclusions can be drawn about occurrence or behavior of bowheads near drilling operations of these types.

B.2.4 Reactions to Playbacks of Drillship Noise

On six occasions in 1982 and 1983, Richardson et al. (1985b,c) observed the behavior of groups of bowhead whales before, during and (in some cases) after exposure to underwater playbacks of recorded drillship noise. The drillship sounds had been recorded 185 m from the EXPLORER II drillship in 1981. Four tests provided interpretable data: two tests in 1982 and two in 1983. The whales under observation during the four successful tests were at ranges of 3-6.5 km in the most distant case, and

0.4-1.7 km in the closest case. Sonobuoys dropped amidst or near the bowheads showed that the drillship noise was clearly audible, at least to humans, at the locations of the whales (see Section B.5.2 for details).

During playbacks, general activities of the bowheads changed only slightly (Richardson et al. 1985c). In the 1982 experiments, the observers believed that the whales travelled more consistently and rapidly away from the projector than had been true in the pre-playback control periods. During one test in 1983, most whales seemed to interrupt their gradual travel toward the projector. However, in all three of these tests, the reaction was less conspicuous than the reaction of bowheads to an approaching boat. During the second test in 1983, no change in behavior was noted in real time. There was little change in surfacing and respiration behavior during drillship noise playbacks, but there was a hint of reduced dive durations during playbacks.

In both 1982 and 1983, the experiments provided weak evidence that bowheads tended to orient and move away from the noise projector during playbacks. The tendency was considered weak because some whales headed toward the projector even during playbacks, and because the results of the statistical tests were often only marginally significant (Richardson et al. 1985c). There was a greater tendency for orientation and movement away from the projector while drilling noise was being broadcast than during the pre- or post-playback periods. However, the difference between the orientations before and during playbacks was not significant in 1982 ($p>0.5$), marginal in 1983 ($p=0.05$), and very marginal overall ($p=0.1$). Considering the individual experiments, the tendency for orientation and movement away was evident in only one of two experiments in each year. A possible reason for the stronger reaction on 18 than on 22 Aug 1983 was that the ambient noise level was lower, and the signal-to-noise ratio was higher, on 18 Aug (see Section B.5.2). To the human ear, drillship sound reaching the sonobuoy and whales on 18 Aug 1983 completely dominated the underwater sound field. In contrast, water noise was still detectable along with drillship noise on 22 Aug 1983. The tendency to orient away from the source of drilling noise during playbacks did not seem to depend on range from the projector, within the range of distances studied.

Bowheads apparently called less during drillship noise playbacks than before those playbacks. However, the proportional frequencies of occurrence of the various call types were similar before, during and after playbacks (Richardson et al. 1985c).

In summary, call rates seemed lower during drillship noise playbacks, and bowheads tended to turn away from locations where drillship noise was originating. However, the effect was weak, and not all whales reacted. In 1983, dives were briefer when the water was ensonified by drillship noise than after such playbacks, but the sample sizes were very small. None of the other behavioral variables analyzed differed significantly between pre-playback and playback periods (Richardson et al. 1985c).

It is noteworthy that some bowheads reacted, although not strongly, to drillship noise at intensities similar to those several kilometers from a real drillship (see Section B.5.2 for quantitative analysis). In contrast, bowheads sometimes were found within 4-5 km of operating drillships, well within the zone where drillship noise was clearly detectable. General activities there seemed normal, and there was no conclusive evidence that the noise affected surfacing, respiration or dive cycles. The significance of this apparent difference between observations near actual drillships and during playback tests is discussed in Section B.5.3.

B.3 BOWHEADS AND ISLAND CONSTRUCTION IN THE BEAUFORT SEA

B.3.1 Types of Island Construction Operations

Several seagoing dredges have been used in the Canadian Beaufort Sea during recent open water seasons (Richardson et al. 1985a). They construct artificial islands and undersea berms from sea bottom materials. They also excavate glory holes for wells to be drilled by drillships. Two types of dredges are used in the Canadian Beaufort:

1. Suction dredges remain nearly stationary. They excavate material from the bottom near the dredge, and continuously deposit the material nearby via floating pipeline.

2. Hopper dredges are ships that excavate material at one location, load it into the ship, and carry it to a construction site. There the dredge dumps the material either through gates in the bottom of the ship or via pump-out methods. The dredging and construction sites are occasionally as much as 100 km apart.

Both suction and hopper dredges create continuous underwater noise detectable many kilometers away (Greene 1985; see Section B.4.3).

Other types of equipment besides suction and hopper dredges are often used during island construction. Clamshells aboard barges are sometimes used to excavate glory holes at drillsites, or to move fill from abandoned artificial islands onto barges for transport to new artificial islands. Tugboats and other support vessels are commonly used during island construction, e.g., to tow barges and caissons. When an artificial island is nearing completion, bulldozers and other machinery are often operated on the island. Underwater noise from most of these types of activities has been studied in the Alaskan but not the Canadian Beaufort Sea (Greene 1983; Davis et al. 1985; Johnson et al., in prep.; present study).

In the Alaskan Beaufort Sea, suction and hopper dredges have not been used to construct artificial islands. The most common method has been to use trucks to transport fill from shore over the winter ice. Thus, island construction has not, to date, been a major activity during the open water season in the Alaskan Beaufort Sea.

B.3.2 Sightings Near Island Construction Sites

Most of the available data concerning reactions of bowhead whales to island construction were acquired in the Canadian Beaufort Sea by Richardson et al. (1985b,c). Their opportunistic observations of bowheads near construction operations are reviewed here. Their controlled tests of the reactions of bowheads to underwater playbacks of dredge noise are reviewed in Section B.3.3. Some other investigators have also sighted bowheads near construction sites in the Canadian Beaufort Sea. Also, some construction activities have taken place in the Alaskan Beaufort Sea during the autumn, and bowheads have occasionally been found close enough to such activities to warrant comment.

Richardson et al. (1985b,c) described three situations in which they saw bowhead whales well within areas ensonified by dredge noise:

1. In 1980, underwater industrial noise was readily detectable 1.2 and 4.6 km from BEAVER MACKENZIE, a suction dredge operating at Issungnak (water depth 18 m). This noise was probably detectable considerably

farther away (Section B.4.3). Bowheads were seen as close as 0.8 km from the construction operation. As many as 12 bowheads were seen within 5 km during a single survey, although bowheads were not that close on all dates (Norton Fraker and Fraker 1981; Fraker et al. 1982). Industry personnel working at Issungnak reported 17 sightings of whales on 2-18 Aug 1980; several whales were estimated to be <500 m from the dredge. Sightings by industry personnel and biologists were consistent in indicating that bowheads were common within 5-10 km of Issungnak for about 17 days (Richardson et al. 1985c). Whether specific individual bowheads remained nearby for 17 days is unknown.

2. Richardson et al. (1985c) observed two bowheads 2-4 km from the suction dredge BEAVER MACKENZIE and its support vessels on 13 Aug 1983. Industry personnel reported bowheads there on 12 and 15 August. These observations were at Amerk, where the water depth is 26 m. Underwater sounds 1.85 km from the dredge were recorded on 13 Aug 1983; industrial noise was very noticeable (Greene 1984).

3. Groups of 12 and 7 bowheads were observed 13 km from 1-2 hopper dredges unloading at Minuk on 30-31 Aug 1984. The whales moved at slow to moderate speed, with no tendency to orient away from the dredges (Richardson et al. 1985c). On 30 August, when observations began 2.33 h before the dredge arrived at Minuk, general activities of the whales did not change when the dredge approached or began unloading. The whales often brought mud to the surface, indicating that near-bottom feeding was occurring during dives. Sonobuoys showed that strong dredge sounds were reaching the whales on both dates

(see Section B.4.3). Water depth was 12 m at Minuk and 13 m near the whales.

Even in the shallow waters where seagoing dredges operated, dredge noise was detectable underwater for at least several kilometers (Greene 1985; Section B.4.3). Bowheads engaged in seemingly normal activities were seen well within the zones ensonified by suction and hopper dredges. Bowheads were seen in areas with dredge noise for as much as 17 days, but it was not known whether specific individuals ever remained in an ensonified area for that long.

Various other studies in the Canadian Beaufort Sea have provided additional sightings of bowheads near dredging and/or island construction sites. Most of these authors have not commented directly on the occurrence of whales near industrial sites. The following list was compiled by comparing sighting locations with information about industrial sites compiled by Richardson et al. (1985a). In most of these cases, the exact type of industrial activity at the time of the whale sighting is uncertain:

1. In 1981, three single bowheads were seen 2-8 km from dredging and island construction operations at South Tarsiut and Tarsiut on 17 and 24 Aug (Davis et al. 1982 and unpubl. LGL data). Bowheads were seen as close as 3 km to dredging locations at both Herschel Island and Ukalerk in Sept 1981 (Davis et al. 1982 and unpubl. LGL data).
2. In 1983, a bowhead was seen 11 km from the suction dredge AQUARIUS operating at Nerlerk on 20 Aug (McLaren and Davis 1985).

3. In 1984, three groups of 2-5 bowheads were seen 5-10 km from dredging and berm construction operations in the Tarsiut area in mid and late August 1984 (Harwood and Borstad 1985; Richardson et al. 1985a; Davis et al. 1986).

Although it is uncertain whether all of these whales were exposed to industrial noise at the times when they were observed, most probably were.

There have been far fewer opportunities to observe bowheads near island construction operations in the Alaskan Beaufort Sea. Most island construction has been done in seasons when no bowheads were present, and all islands have been south of the southern edge of the main autumn migration corridor of bowheads (cf. Ljungblad et al. 1985). In the autumn of 1982 construction was continuing at Seal Island, in 12 m of water NW of Prudhoe Bay. Machinery in operation on the island included three front-end loaders, a tracked crane, a bulldozer, and a motor-driven bag-filling plant. Also, barges occasionally brought fuel and gravel to the island (Hickie and Davis 1983). Those authors conducted intensive aerial surveys near Seal Island on 13 days. Their closest bowhead sighting was 11.5 km NW of the island; others were at 15 km, 17.5 km, and various greater ranges north of the island. (Of the whales seen by Ljungblad et al. [1983] and Reeves et al. [1983], the closest was about 20 km NE of Seal Island) Acoustic monitoring showed that noise from the island was occasionally detectable as much as 9.5 km away, but only on calm days. Bowhead calls detected by acoustic buoys 4.5 and 9.5 km from the island indicated that most bowheads were substantially more than 4.5 km offshore from the island, consistent with the aerial survey results (Hickie and Davis 1983).

In summary, bowhead whales sometimes occur within a few kilometers of dredging and island construction sites in the

Canadian Beaufort Sea, well within the zones ensonified by industrial noise. Bowheads appear to engage in normal activities while within the ensonified zones. Although bowheads have been seen within such areas for periods as long as 17 days, it is not known how long individual whales remained there. It is also not known whether numbers present near construction sites were the same as would occur in the absence of industrial activities. In Alaskan waters, there have been few opportunities to observe bowheads near island construction sites. The closest sighting to such a site was 11.5 km away.

B.3.3 Reactions to Playbacks of Dredge Noise

Three dredge noise playback experiments were conducted near the Yukon coast in 1983-84 (Richardson et al. 1985c). Noise recorded 1.2 km from the BEAVER MACKENZIE suction dredge was played back underwater in the same manner as during playbacks of drillship noise (see Section B.2.4). During the first two tests, distances of whales from the projector were 0.5-2 km and 0.15-2.25 km. In the third experiment, five whales under detailed observation were only 0.1-0.8 km from the projector at the start of the playback period. During the last two experiments, sonobuoys were dropped amidst the whales; dredge sounds reaching the whales were quite prominent to the human ear (see Section B.5.2).

The overt responses of bowheads to the playbacks apparently depended on distance from the noise projector. During the test at ranges 0.5-2 km, activities were the same before, during and after the noise playback. During the test at ranges 0.15-2.25 km, general activities were again similar before, during and after the playback, but during the playback many surfacings were quite short with only 1 or 2 blows. During the test at the shortest ranges (0.1-0.8 km), bowheads ceased near-bottom feeding and swam away at moderate speed. Thirty minutes after the start of the third playback, no bowheads could be found within 2 km of the playback site. Consistent with these general observations, there was little change in headings during the first playback, but significant orientation away from the noise source during the second and third tests (Richardson et al., 1985c).

In summary, the three dredge noise playback experiments showed that bowheads often respond to the onset of strong dredge noise, even when the noise level is increased gradually over 10 min as in these experiments. Whales tended to orient away from the playback site. In 2 of 3 tests the tendency to move away was strong. Whales 0.1-0.8 km from the projector ceased feeding near the bottom and vacated the area within 2 km of the playback site within 30 min. Section B.5.3 discusses the apparent contrast between the obvious response of bowheads to some playbacks vs. their apparent tolerance of similar levels of noise from actual dredging operations.

B.4 NOISE FROM DRILLING AND ISLAND CONSTRUCTION IN THE BEAUFORT SEA

Underwater industrial noise was measured around many of the industrial sites near which bowhead whales have been observed. To provide the basis for evaluating situations in which bowheads did and did not react to industrial noise, this section reviews the relevant measurements of underwater noise. Most of these data come from the work of Greene (1985) in the Canadian Beaufort Sea. For most of these noise sources, this section includes some previously unreported measurements and equations for received noise levels in 1/3-octave bands (unpubl. data courtesy of C. Greene; compiled by LGL). The width of the 1/3-octave band around any given frequency is about 23% of that frequency. For example, the 1/3-octave bands around 50, 500 and 5000 Hz are approximately

45-56, 450-560 and 4500-5600 Hz, respectively. In contrast, most previous reports of industrial noise characteristics in the Beaufort Sea have presented the results as spectrum levels (i.e., noise power in various 1 Hz bands) and as broadband levels (total noise power over a wide range of frequencies, e.g. 20-1000 Hz).

Our emphasis on 1/3-octave band levels warrants some explanation. The hearing mechanisms of bowheads and other baleen whales have not been studied. However, if their hearing processes are like those of other mammals, noise levels in bands about 1/3 octave in width are likely to be most relevant (see Background information in Section 2, and Gales 1982b). For most mammals that have been tested, noise within (approximately) a 1/3-octave band around a particular frequency affects the ability of the mammal to detect a sound signal at that frequency. Noise at a frequency more than about 1/3 octave from the frequency of the sound signal has little effect on detectability of that signal. If we restrict attention to the frequency range within which a mammal has sensitive hearing, then to a first approximation the mammal can detect a sound if its level within any 1/3-octave band exceeds the ambient noise level in that same band. Although this statement involves several approximations and assumptions (Richardson et al. 1983a), noise data from bands about 1/3 octave wide are clearly more relevant for our purposes than are data from very narrow bands (e.g., 1 Hz spectrum levels) or from very broad bands (e.g., 20-1000 Hz).

B.4.1. Ambient Noise

Because industrial noise is only likely to be detectable when its level exceeds that of the ambient noise, a brief summary of available data on ambient noise levels in the Canadian Beaufort Sea is necessary. Over the 1980-84 period, Greene (1985) obtained 66 measurements of underwater noise at depths of 9 or

18 m at locations where industrial noise was not prominent. Most of these measurements were obtained at sea states ranging from 0 to 3; no measurements were obtained under the high sea states characteristic of storms. Greene's data for the 20-1000 Hz band, in dB re 1 μPa, were as follows:

Measurement Source	Depth (m)	n	Percentiles 10%	50%	90%
Sonobuoys	18	29	86	99	111
Hydrophone	18	22	81	99	117
Hydrophone	9	15	77	94	112

The overall median level at depths 9 and 18 m was 98 dB. For comparison, the expected levels for sea states 0, 1, 2, 4 and 6 are 87, 95, 100, 107, and 112 dB re 1 μPa. These figures are based on the standard deep-water spectrum-level curves of Knudsen et al. (1948), extended to low frequencies with an assumed slope of -5 dB/octave (Greene 1985).

Greene (unpubl.) determined the ambient noise levels in various 1/3-octave bands at 20 times on eight days in 1984 (Fig. B-1). Sea states were 0-2. The average levels in 1/3-octave bands were more or less constant below 70 Hz, and diminished at a slope of about -2.7 dB/octave over the 80-1600 Hz range (Fig. B-1). The sample of data plotted in Fig. B-1 is small, but the average 1/3-octave levels shown there are similar to expected values (Fig. B-2). If spectrum levels of ambient noise typically diminish at -5 dB/octave (Knudsen et al. 1948), then 1/3-octave band levels would be expected to diminish at -2 dB/octave (Fig. B-2; from Davis et al. 1985).

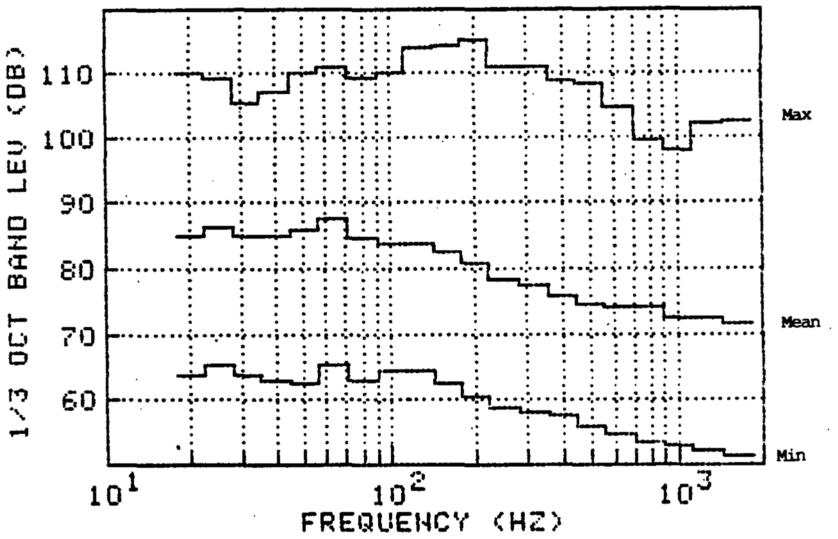

FIGURE B1. AVERAGE, MINIMUM, AND MAXIMUM AMBIENT NOISE (dB re 1 µPa) IN 1/3-OCTAVE BANDS, BASED ON MEASUREMENTS IN THE CANADIAN BEAUFORT SEA AT HYDROPHONE DEPTHS 9-18 M ON 20 OCCASIONS DURING EIGHT DAYS IN AUGUST 1984, SEA STATES 0-2. INDUSTRIAL NOISE WAS NOT PROMINENT ON ANY OF THESE OCCASIONS.

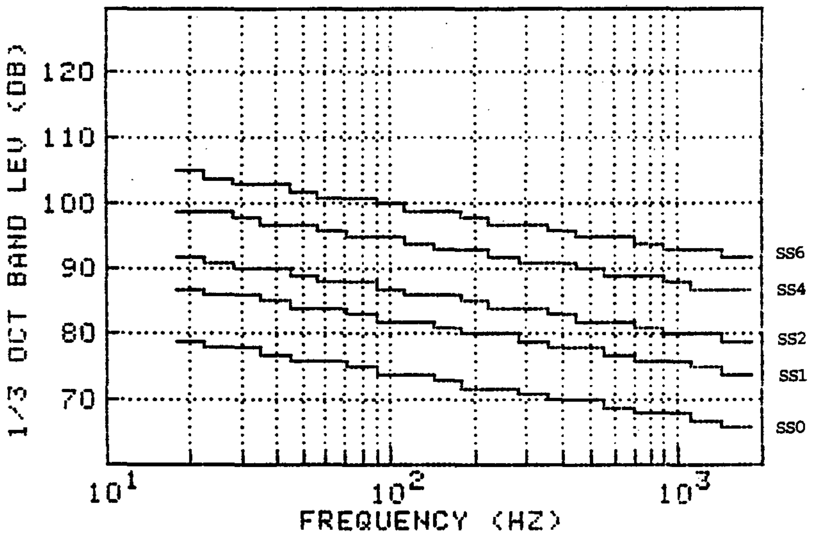

FIGURE B2. EXPECTED AMBIENT NOISE (dB re 1 µPa) IN 1/3-OCTAVE BANDS AS A FUNCTION OF SEA STATE. THESE CURVES ARE BASED ON THE DATA OF KNUDSEN ET AL. (1948) FOR HIGH FREQUENCIES AND DEEP WATER. THE CURVES ARE EXTENDED TO LOW FREQUENCIES BASED ON THE OBSERVATION THAT SPECTRUM LEVELS TYPICALLY INCREASE AT 5 dB/OCTAVE WITH DECREASING FREQUENCY (FROM DAVIS ET AL. 1985).

B.4.2. Drilling Noise

In the Canadian Beaufort Sea, bowhead whales have been seen near the conventional drillships EXPLORER I-IV and the conical drilling barge Kulluk (Section B.2.2). Noise from EXPLORER II is of particular interest because a recording of this noise was used in drillship playbacks to bowheads (Richardson et al. 1985b,c; Section B.2.4) and to gray and humpback whales (Malme et al. 1983, 1984, 1985; Section B.6). Furthermore, EXPLORER II drilled in the Alaskan Beaufort Sea in 1985, and its sounds were recorded there (McLaren et al., in prep.). To date, there has been little drilling from artificial islands and caissons when bowheads have been present, but noise propagating from these types of drillsites is also of interest.

EXPLORER II--Sounds from EXPLORER II were recorded while this ship drilled at North Issungnak, north of the Mackenzie Delta, on 6 Aug 1981 (Greene 1982, 1985). Water depth was 27 m, hydrophone depth 9 m, bit depth was 2030 m, and the supply ship CANMAR SUPPLIER III was standing by near the drillship. Sounds were recorded at six ranges from the ship, 0.19 to 7.4 km away. The received level in the 20-1000 Hz band diminished from about 134 dB to 112 dB over the 0.19 to 7.4 km range (Fig. B-3). A strong tone at 275-278 Hz was the most prominent tone at all ranges (Fig. B-4A,B). The received level in the 1/3-octave band centered at 250 Hz (which contained the 275-278 Hz tone) was high relative to levels in adjacent 1/3-octave bands, especially at the shorter ranges (Fig. B-5). The 250 Hz band also had the highest received level relative to typical ambient noise levels (cf. Fig. B-1, B-2). Thus, sounds in the 1/3-octave band around 250 Hz would probably be detectable farther away from the drillship than would the sounds in other 1/3-octave bands. The received levels in the 20-1000 Hz band and in the 1/3-octave band near 250 Hz (containing the 275 Hz tone) are compared in Fig. B-6.

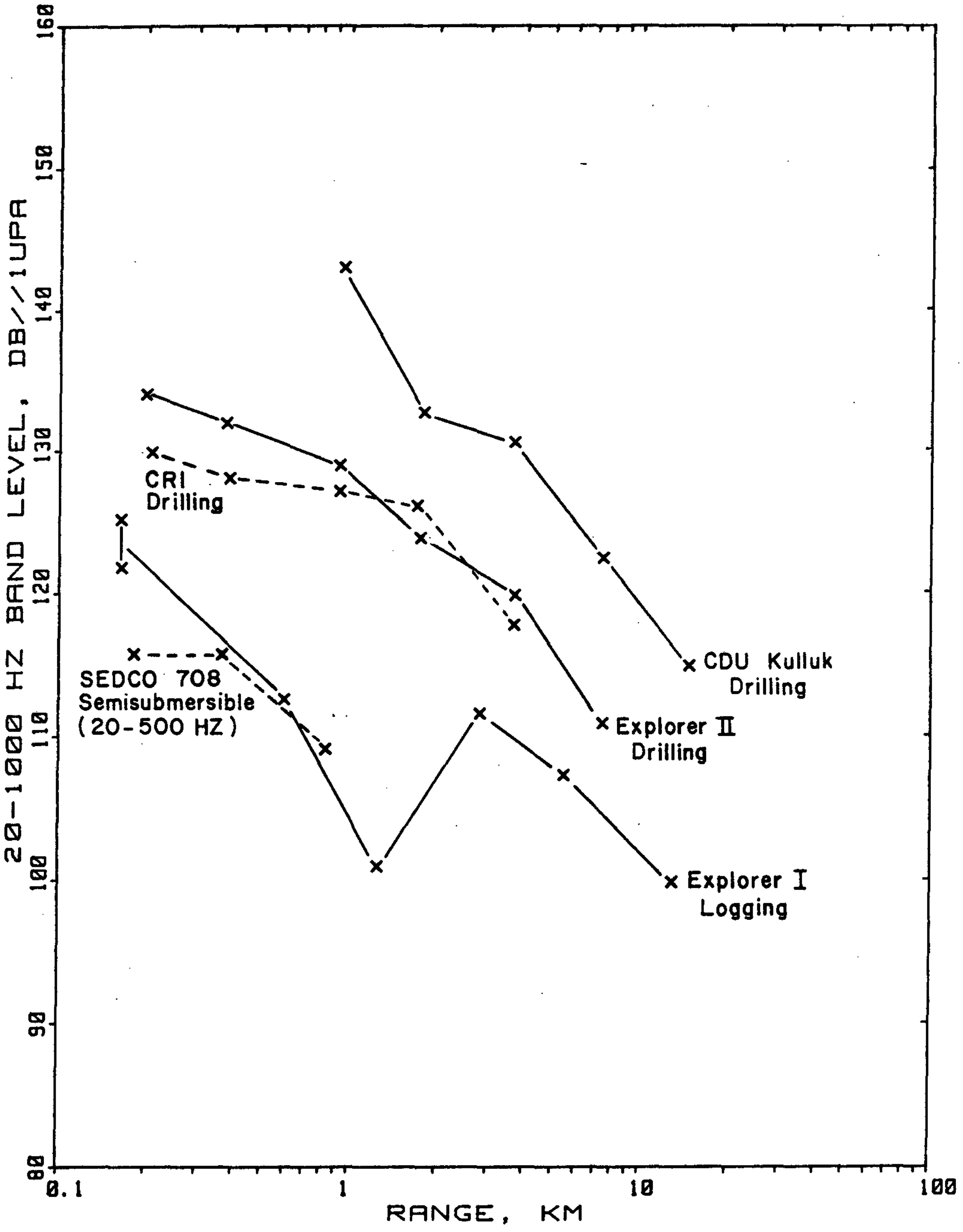

FIG. B3. RANGE DEPENDENCE OF UNDERWATER SOUND LEVELS NEAR DRILLING OPERATIONS IN THE CANADIAN BEAUFORT SEA (dB re 1 μPa IN THE 20-1000 HZ FREQUENCY BAND; FROM GREENE 1985). CRI = CAISSON RETAINED ISLAND. CDU = CONICAL DRILLING UNIT. FOR COMPARISON, LEVELS NEAR A SEMI-SUBMERSIBLE DRILLING NEAR THE ALEUTIAN ISLANDS ARE ALSO SHOWN (FROM GREENE IN PRESS). HYDROPHONE DEPTH 9-18 M IN EACH CASE.

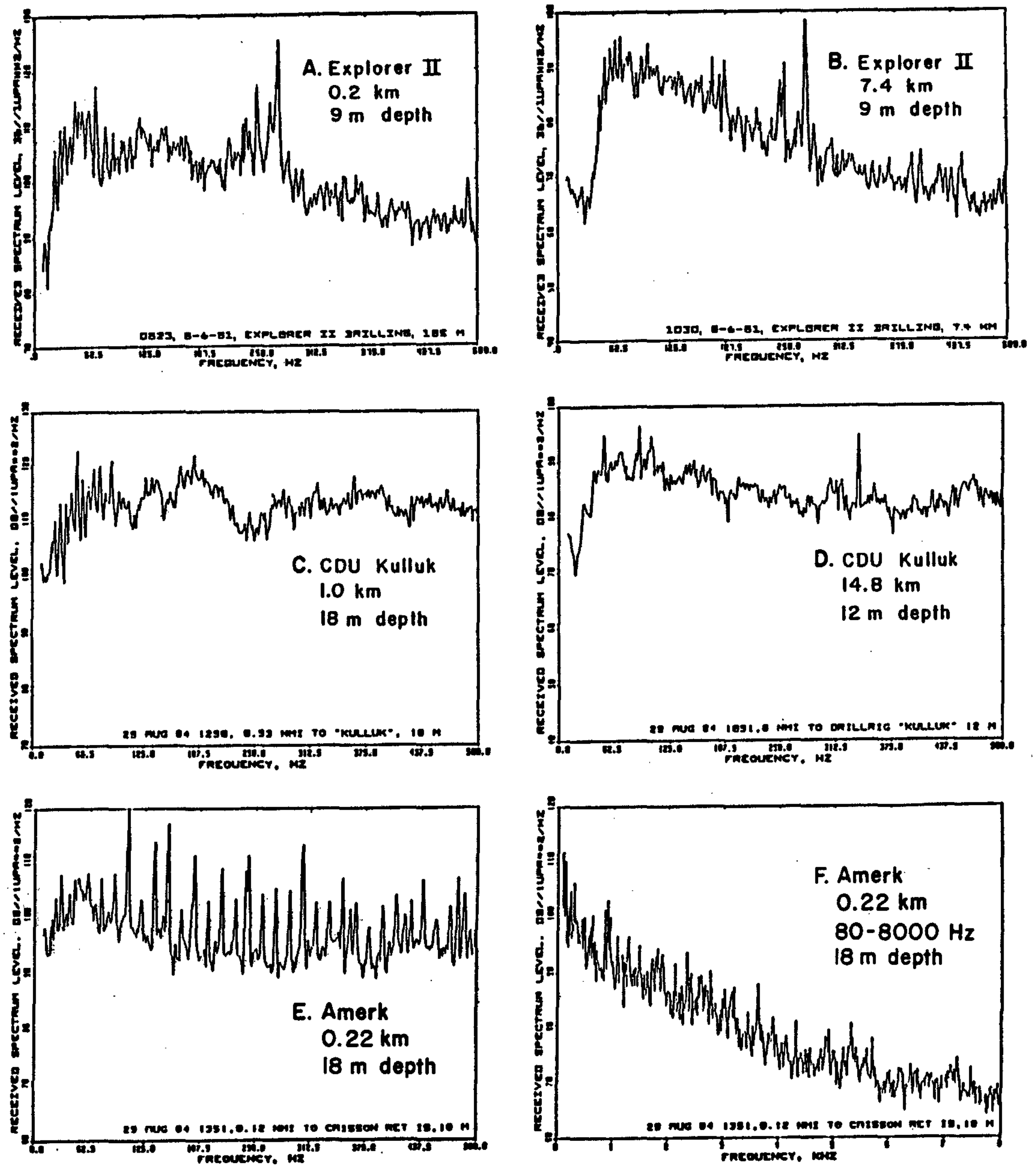

FIGURE B4. SOUND PRESSURE SPECTRA (dB re 1 µPa²/Hz) FOR DRILLING BY DRILLSHIP EXPLORER II, CONICAL DRILLING UNIT KULLUK, AND CAISSON RETAINED ISLAND AMERK, CANADIAN BEAUFORT SEA (FROM GREENE 1985). HYDROPHONE DEPTHS 9-18 M. NOTE THE VARYING VERTICAL SCALES AND, FOR F, THE EXTENDED HORIZONTAL SCALE.

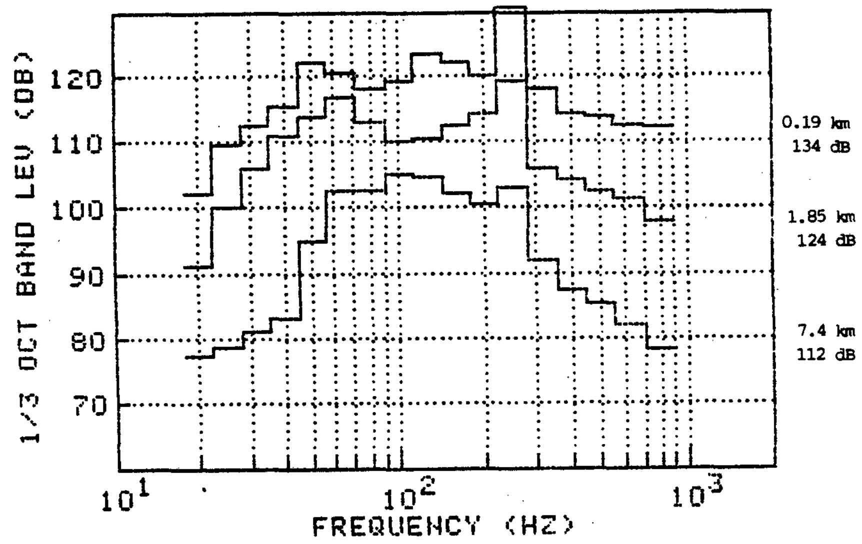

FIG. B5. MEASURED NOISE (dB re 1 µPa) IN 1/3-OCTAVE BANDS AT THREE DISTANCES FROM DRILLSHIP EXPLORER II DRILLING IN THE CANADIAN BEAUFORT SEA, 6 AUGUST 1981. WATER DEPTH 27 M; HYDROPHONE DEPTH 9 M. VALUES ALONG THE RIGHT MARGIN ARE RANGES (KM) AND RECEIVED LEVELS IN THE 20-1000 HZ BAND. BASED ON GREENE (UNPUBLISHED DATA).

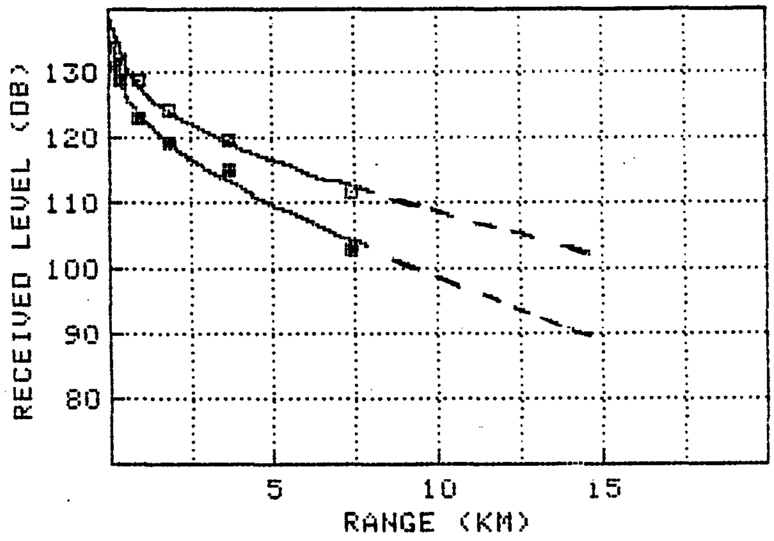

FIGURE B6. RANGE DEPENDENCE OF RECEIVED LEVELS OF NOISE (dB re 1 µPa) FROM DRILLSHIP EXPLORER II, 6 AUGUST 1981. DATA AND BEST-FIT CURVES (TABLE B2) ARE SHOWN FOR THE 20-1000 HZ BAND (OPEN SYMBOLS) AND FOR THE 1/3 OCTAVE BAND CENTERED AT 250 HZ (CLOSED SYMBOLS).

Greene (1985) found that received levels of sounds from several industrial sites in the Canadian Beaufort Sea, including EXPLORER II, could be approximated by equations of the form

$$\text{Received level} = A - B*R - 10*\log(R),$$

where the received level is in dB re 1 μPa, A and B are constants, and R is range in kilometers. Greene (1985) found that, for the 20-1000 Hz band, the received level of noise near EXPLORER II was

$$RL\ (dB) = 128.4 - 0.985*R - 10*\log(R)$$

Based on the same set of measurements, Greene (1982) found that the received level for the tone near 275 Hz was

$$RL\ (dB) = 122.9 - 1.52*R - 10*\log(R)$$

Similarly, for the 1/3-octave band around 250 Hz and including the 275 Hz tone, we calculated the following best-fitting equation:

$$RL\ (dB) = 124.9 - 1.62*R - 10*\log(R)$$

Figure B6 shows the data and fitted equations for the 20-1000 Hz band and the 1/3-octave band near 250 Hz. The average ambient level in the 1/3-octave band near 250 Hz was 78 dB (Fig. B-1). Noise from EXPLORER II would be expected to fall below 78 dB about 21 km from the ship (Fig. B-6), assuming that the equation calculated from measurements at ranges up to 7.4 km is appropriate for ranges up to 21 km. Table B-2 summarizes the equations and "range of potential audibility" estimates for EXPLORER II and the other industrial activities described below.

TABLE B-2. FITTED EQUATIONS FOR RANGE-DEPENDENCE OF THE RECEIVED LEVELS OF NOISE FROM SELECTED INDUSTRIAL ACTIVITIES IN THE CANADIAN BEAUFORT SEA, AND RANGES OF POTENTIAL AUDIBILITY.* ALL EQUATIONS ARE OF THE FORM RECEIVED LEVEL (dB re 1 uPa) = Constant - (Linear Term)*(Range in km) - 10*log(Range in km). ALL RECEIVED LEVELS ARE AT HYDROPHONE DEPTH 9-18 m. THE "AVERAGE" AMBIENT LEVEL IS FROM FIG. B-1, AND REPRESENTS SEA STATE 0-2 CONDITIONS. THE RIGHTMOST COLUMN GIVES THE RANGE AT WHICH THE RECEIVED LEVEL OF THE INDUSTRIAL SOUND WOULD BE EXPECTED TO EQUAL THE AVERAGE AMBIENT LEVEL, ASSUMING THAT THE EQUATION IS APPLICABLE TO RANGES GREATER THAN THE MAXIMUM RANGE FOR WHICH DATA WERE AVAILABLE (7.4-14.8 km, see text).

Noise Source (Water Depth)	Frequency Band (Hz)	Constant	Linear Term	Average Ambient Level	Range (km) for 0 dB S : N
DRILLING OPERATIONS					
Drillship					
EXPLORER II	20-1000	128.4	-0.985	98 dB	18 km
(27 m)	250‡	124.9	-1.62	78	>20
CDU KULLUK	20-1000	139.8	-1.266	98	>20
(31 m)	630‡	131.1	-1.686	74	>20
Caisson-ret. Island	20-1000	128.9	-0.984	98	19
(28 m)	315‡	116.4	-0.439	77.5	>>20
DREDGES					
BEAVER MACKENZIE	20-1000	127.1	-1.197	98	15
(13 m)	400‡	117.0	-0.915	76	>20
AQUARIUS	20-1000	134.7	-0.374	98	>>20
(46 m)	250‡	126.6	-0.825	78	>>20
GEOPOTES X Underway	20-1000	143.9	-0.916	98	>>20
(25 m)	80‡	140.1	-0.874	85	>>20

*From Greene (1985) and previously unpublished data of C.R. Greene analyzed by LGL (see text).

‡1/3 octave band centered at this frequency.

KULLUK--Sounds from the conical drilling barge KULLUK were recorded while this vessel drilled at East Amauligak, north of the Mackenzie Delta, on 29 Aug 1984 (Greene 1985). Water depth 14.8 km away. Several support vessels were near KULLUK. At hydrophone depths of 12-18 m, the received level in the 20-1000 Hz band diminished from 137-143 dB re 1 μPa near 1 km range to 121-123 dB at about 7.3 km and 115-119 dB at 14.8 km range (Fig. B-3). The 14.8 km data may include a significant fraction of ambient noise, given the high sea state during the recording period. Received levels were higher than those at corresponding ranges from EXPLORER II. The noise spectra were not especially distinctive; a strong tone at 333 Hz was detected only at the two longest ranges (Fig. B-4C vs. D), presumably because of some change in the industrial activities during the recording interval. Spectrum levels were unusually flat up to 750 Hz, above which the typical decrease with inreasing frequency was observed.

Received levels in 1/3-octave bands are shown for selected ranges in Fig. B-7 (based on Greene, unpubl. data). These levels were highest, relative to typical ambient noise levels in corresponding bands, at frequencies at or above 400 Hz, depending on range (cf. Fig. B-1, A-2). At moderate and long ranges, the signal-to-noise ratio was particularly high for the 1/3-octave band near 630 Hz.

Best-fitting equations for received noise levels near Kulluk vs. range have not been reported previously. For the 20-1000 Hz band and ranges up to 7.4 km, the best-fitting equation of the form RL = A - B*R - 10*log(R) is as follows:

$$RL\ (dB) = 139.8 - 1.266*R - 10*\log(R)$$

Similarly, the equation for the 1/3-octave band near 630 Hz is

$$RL\ (dB) = 131.1 - 1.686 * R - 10 * \log(R)$$

These equations, and the measurements from which they were derived, are shown in Fig. B-8. The average ambient level in the 1/3-octave band near 630 Hz was 74 dB (Fig. B-1). In this band, the received level of noise from KULLUK would not diminish to 74 dB until one reached a range exceeding 20 km (Fig. B-8). We cannot estimate the actual range at which noise from KULLUK would diminish to typical ambient levels, since the greatest range where usable measurements were obtained was only 7.4 km, and the fitted equation may not be appropriate at ranges exceeding 10 or 15 km.

Drilling on Caisson-Retained Island--On 29 Aug 1984, underwater sounds were recorded near a caisson-retained island on which drilling was underway (Greene 1985). This structure was in 26 m of water at Amerk, north of the Mackenzie Delta. The structure consisted of an octagonal steel ring (the caisson) sitting on an underwater berm and filled with sand. Three support vessels were present near the island. At hydrophone depth 18 m, the received levels in the 20-1000 Hz band diminished from 129-130 dB re 1 uPa about 0.2 km from the island to 113-114 dB at range 7.6 km and 111-112 dB 13.2 km away (Fig. B-3). Again, the 13.2 km data may include a significant fraction of ambient noise. Received levels were similar to those at corresponding distances from EXPLORER II, and less than those at corresponding distances from KULLUK (Fig. B-3). The noise spectrum contained many tones at frequencies up to at least 5.7 kHz (Fig. B-4E,F, from Greene 1985).

Received levels in 1/3-octave bands are shown for selected ranges in Fig. B-9 (based on Greene, unpubl. data). The levels in the 1/3-octave band near 315 Hz were the highest, relative to

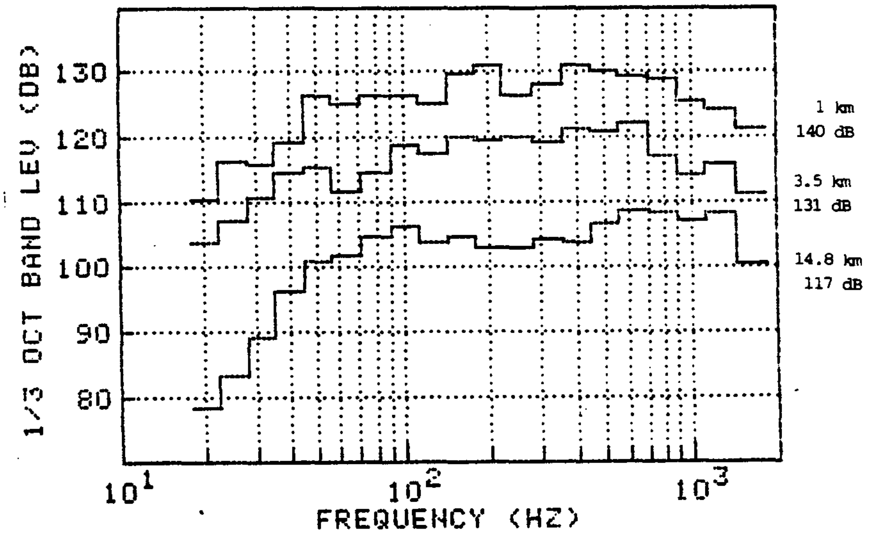

FIGURE B7. MEASURED NOISE (dB re 1 µPa) IN 1/3-OCTAVE BANDS AT THREE DISTANCES FROM CONICAL DRILLING UNIT KULLUK DRILLING IN THE CANADIAN BEAUFORT SEA, 29 AUGUST 1984. WATER DEPTH 31 M AT CDU; HYDROPHONE DEPTH 12-18 M. VALUES ALONG THE RIGHT MARGIN ARE RANGES (KM) AND RECEIVED LEVELS IN THE 20-1000 HZ BAND. BASED ON GREENE (UNPUBLISHED DATA).

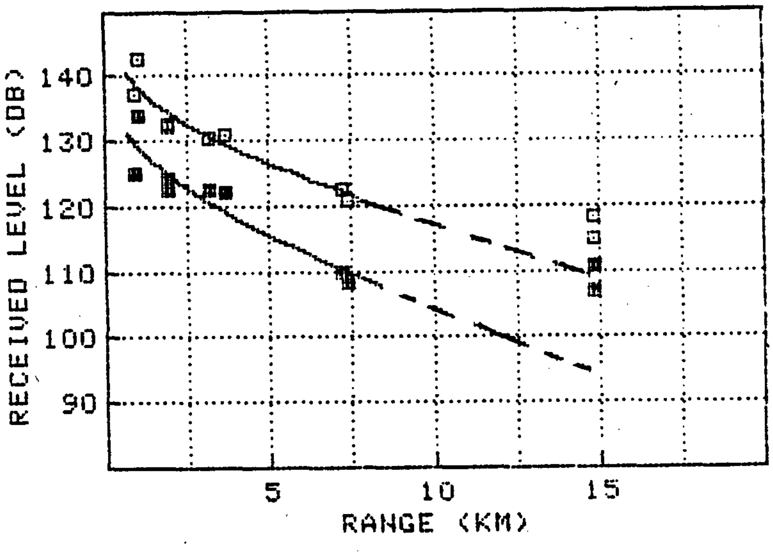

FIGURE B8. RANGE DEPENDENCE OF RECEIVED LEVELS OF NOISE (dB re 1 µPa) FROM CONICAL DRILING UNIT KULLUK, 29 AUGUST 1984. DATA AND BEST-FIT CURVES (TABLE B2) ARE SHOWN FOR THE 20-1000 HZ BAND (OPEN SYMBOLS) AND FOR THE 1/3 OCTAVE BAND CENTERED AT 630 HZ (CLOSED SYMBOLS). THE DATA FROM 14.8 KM MAY HAVE INCLUDED CONSIDERABLE AMBIENT NOISE, AND WERE NOT CONSIDERED IN FITTING THE EQUATIONS.

typical ambient noise levels in corresponding bands (cf. Fig. B-1, B2).

Best-fitting equations for received noise levels near this drillsite have not been reported previously. Inspection of the data shows that the received level was more or less independent of range at ranges less than 1 km (Fig. B-3). This probably was a result of the fact that the drilling operation was not a point source; the vessels near the drillsite probably were significant contributors to the total noise. Also, data from the longest range, 13.2 km, may have been dominated by ambient noise. Hence, only the data from ranges 0.93-7.8 km were considered in deriving the equations (Fig. B-10). For the 20-1000 Hz band, the best-fitting equation of the form $RL = A - B*R - 10*\log(R)$ was

$$RL\ (dB) = 128.9 - 0.984*R - 10*\log(R)$$

The corresponding equation for the 1/3-octave band near 315 Hz was

$$RL\ (dB) = 116.4 - 0.439*R - 10*\log(R)$$

The average ambient level in this band was 77.5 dB (Fig. B-1). The received level of noise from the Amerk drillsite would not diminish to 77.5 dB until one reached a range well over 20 km (Fig. B-10; Table B-2).

Sounds from drilling operations on artificial islands in very shallow ($\leq$ 3 m) portions of the Alaskan Beaufort Sea have been recorded by Malme and Mlawski (1979) and Cummings et al. (1981b). These measurements are of limited relevance here because of the shallow water and because the data were obtained in winter under sea ice.

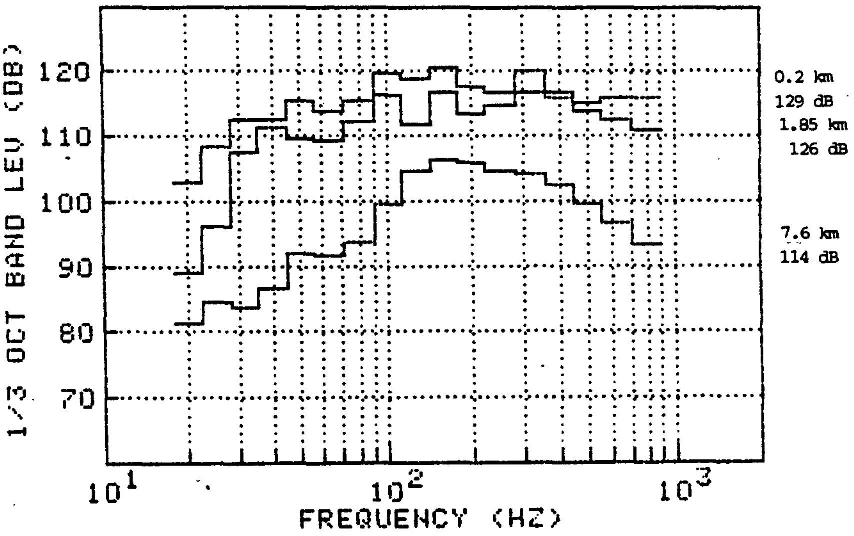

FIGURE B9. MEASURED NOISE (dB re 1 μPa) IN 1/3-OCTAVE BANDS AT THREE DISTANCES FROM DRILLING ON CAISSON RETAINED ISLAND AMERK, CANADIAN BEAUFORT SEA, 29 AUGUST 1984. WATER DEPTH 26 M AT CRI; HYDROPHONE DEPTH 18 M. VALUES ALONG THE RIGHT MARGIN ARE RANGES (KM) AND RECEIVED LEVELS IN THE 20-1000 HZ BAND. BASED ON GREENE (UNPUBLISHED DATA).

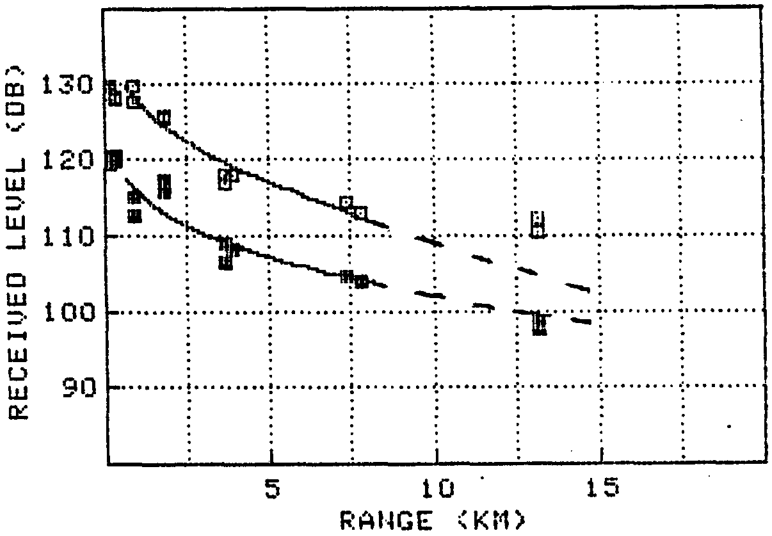

FIGURE B10. RANGE DEPENDENCE OF RECEIVED LEVELS OF NOISE (dB re 1 μPa) FROM CIASSON RETAINED ISLAND AMERK, 29 AUGUST 1984. DATA AND BEST-FIT CURVES (TABLE B2) ARE SHOWN FOR THE 20-1000 HZ BAND (OPEN SYMBOLS) AND FOR THE 1/3 OCTAVE BAND CENTERED AT 315 HZ (CLOSED SYMBOLS). EQUATIONS WERE BASED ON DATA FROM RANGES 0.93-7.8 KM (SEE TEXT).

B.4.3. Island Construction Noise

In the Canadian Beaufort Sea, bowhead whales have been seen near the suction dredge BEAVER MACKENZIE and various hopper dredges (Section B.3.2). Noise from BEAVER MACKENZIE is of particular interest because a recording of this noise was used in dredge noise playbacks to bowheads (Richardson et al. 1985c; Section B.3.3). This subsection summarizes data on the levels and characteristics of underwater noise at various distances from dredges and other construction operations.

Suction Dredge BEAVER MACKENZIE--Sounds from this dredge were recorded in 1980, 1981 and 1983. One of the 1980 recordings was used in the dredge noise playbacks. The 1981 recordings are of special interest because data were acquired at several different ranges. The spectra contained numerous tones, including a strong tone at 1775 Hz (Fig. B-11A-C).

In 1981, sounds from BEAVER MACKENZIE were recorded while this ship dredged in 13 m of water at Alerk, northeast of the Mackenzie Delta (Greene 1982, 1985). At hydrophone depth 9 m, the received level in the 20-1000 Hz band diminished from 133 dB re 1 uPa at range 0.19 km to 110 dB at 7.4 km (Fig. B-12). The signal-to-noise ratio (i.e., BEAVER MACKENZIE sounds relative to typical ambient levels) was relatively high in the 1/3-octave band near 400 Hz, although values in some other bands were not much different (Fig. B-13 vs. B-1, B-2).

Greene (1985) found that the received level in the 20-1000 Hz band was closely approximated by the equation

$$\mathrm{RL\ (dB)} = 127.1 - 1.197 * R - 10 * \log(R)$$

Similarly, a previously unreported best-fitting equation for the 1/3-octave band near 400 Hz is

$$\mathrm{RL\ (dB)} = 117.0 - 0.915 * R - 10 * \log(R),$$

based on Greene's unpublished data (Fig. B-14). Distant from

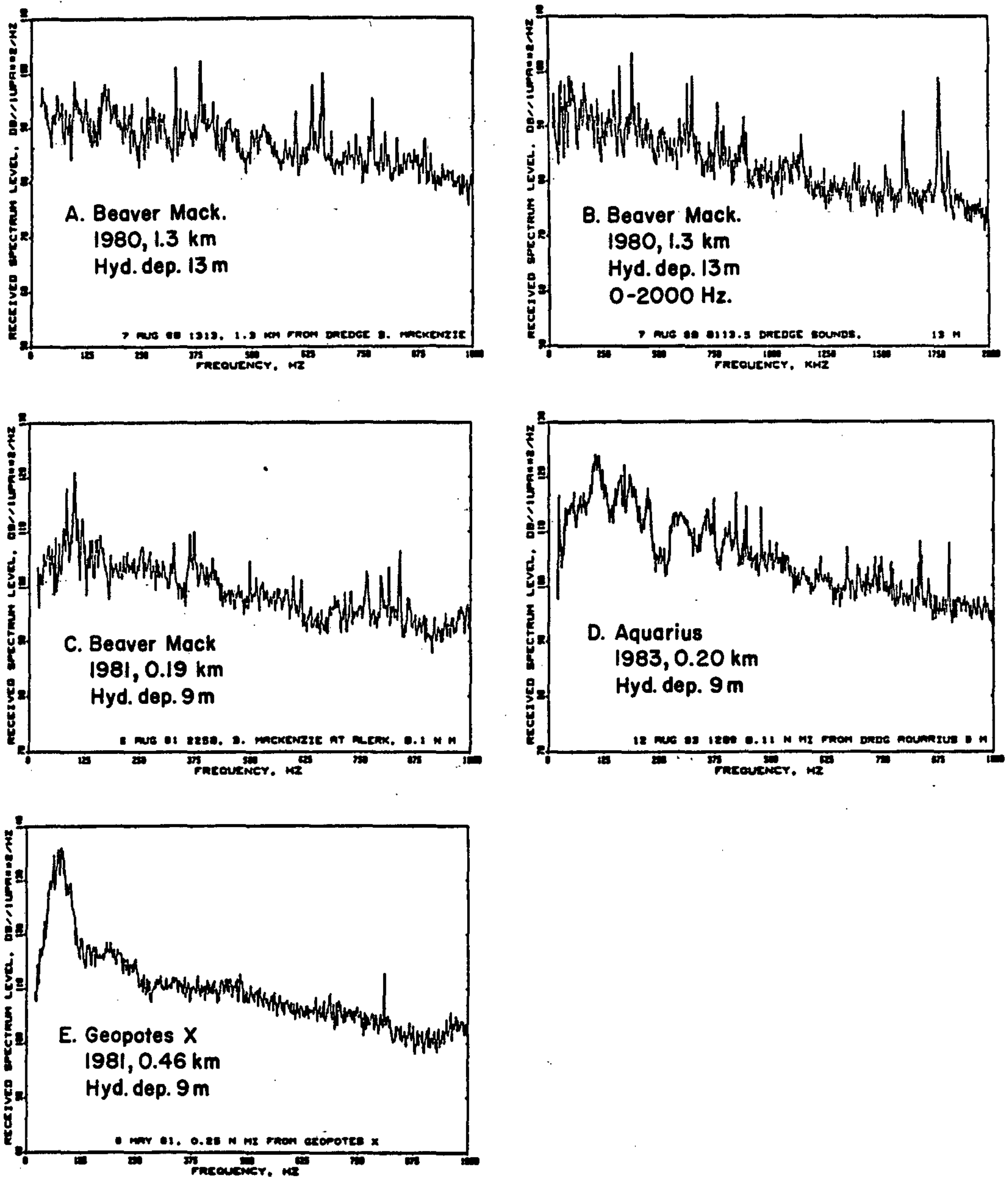

FIGURE B11. SOUND PRESSURE SPECTRA (dB re 1 $\mu Pa^2/Hz$) FOR DREDGING BY SUCTION DREDGES BEAVER MACKENZIE (A-C) AND AQUARIUS (D), AND FOR HOPPER DREDGE GEOPOTES X UNDERWAY (E), CANADIAN BEAUFORT SEA (FROM GREENE 1985 AND UNPUBLISHED). HYDROPHONE DEPTHS 9-13 M. NOTE THE VARYING VERTICAL SCALES AND, FOR B, THE EXTENDED HORIZONTAL SCALE.

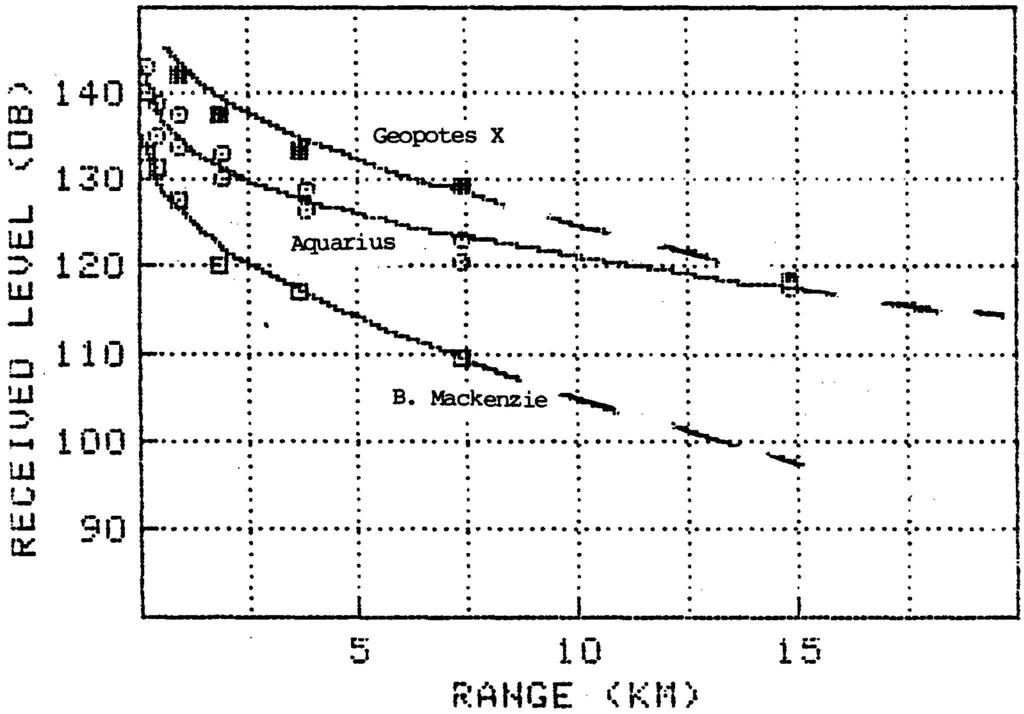

FIGURE B12. RANGE DEPENDENCE OF UNDERWATER SOUND LEVELS NEAR DREDGES IN THE CANADIAN BEAUFORT SEA (dB re 1 μPa IN THE 20-1000 HZ FREQUENCY BAND; FROM GREENE 1985 AND UNPUBLISHED). HYDROPHONE DEPTHS 9-18 M.

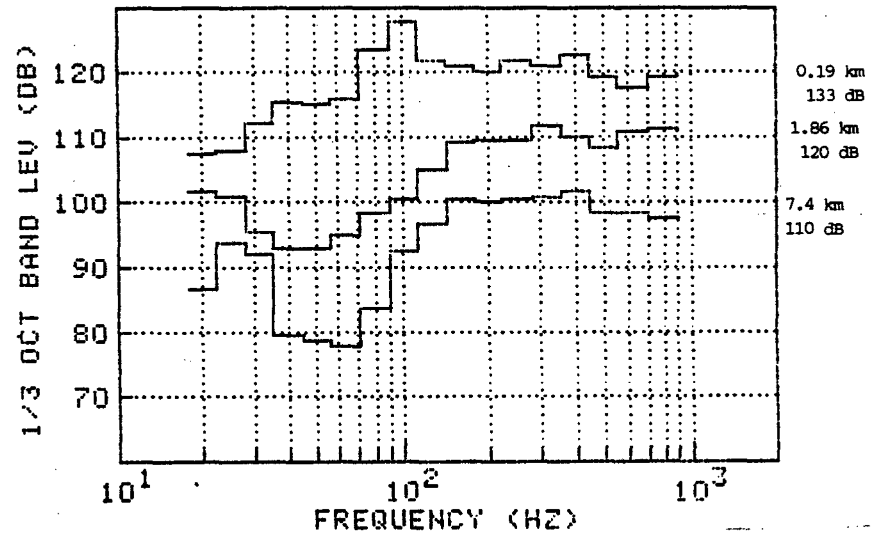

FIGURE B13. MEASURED NOISE (dB re 1 µPa) IN 1/3-OCTAVE BANDS AT THREE DISTANCES FROM SUCTION DREDGE BEAVER MACKENZIE DREDGING IN THE CANADIAN BEAUFORT SEA, 6 AUGUST 1981. WATER DEPTHS 13-15 M; HYDROPHONE DEPTH 9 M. VALUES ALONG THE RIGHT MARGIN ARE RANGES (KM) AND RECEIVED LEVELS IN THE 20-1000 HZ BAND. BASED ON GREENE (UNPUBLISHED DATA).

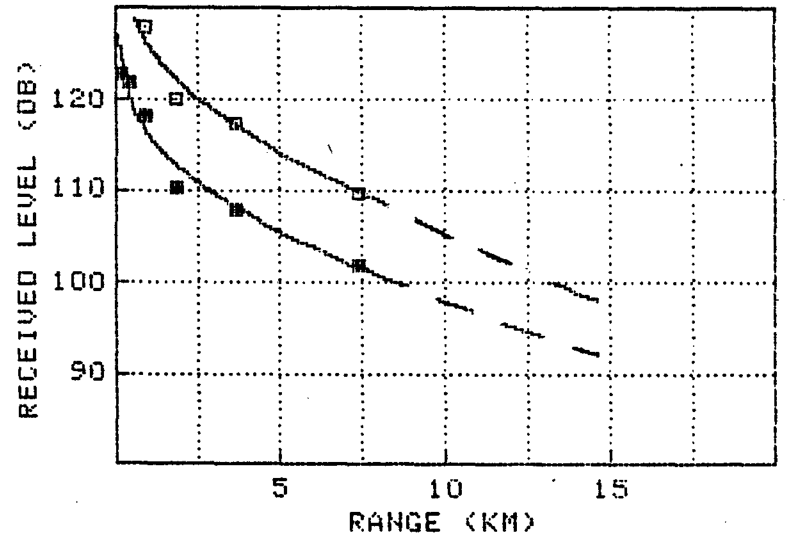

FIGURE B14. RANGE DEPENDENCE OF RECEIVED LEVELS OF NOISE (dB re 1 µPa) FROM DREDGE BEAVER MACKENZIE, 6 AUGUST 1981. DATA AND BEST-FIT CURVES (TABLE B2) ARE SHOWN FOR THE 20-1000 HZ BAND (OPEN SYMBOLS) AND FOR THE 1/3 OCTAVE BAND CENTERED AT 400 HZ (CLOSED SYMBOLS).

industrial sites, the average ambient level in the 1/3-octave band near 400 Hz was 76 dB (Fig. B-1). The received level of BEAVER MACKENZIE sounds in this band apparently remained above 76 dB out to ranges considerably greater than 20 km (Fig. B-14; Table B-2).

Suction Dredge AQUARIUS--Sounds from this suction dredge and associated vessels were recorded on 12 Aug 1983 while they were attempting to construct an undersea berm at Nerlerk, north of the Mackenzie Delta (Greene 1984, 1985). Water depth was 46 m at the dredge, increasing to 60 m at the most distant recording site 14.8 km away. Several other vessels involved in the construction operation were present near AQUARIUS. At hydrophone depths of 9-18 m, the received level in the 20-1000 Hz band diminished from 140-143 dB re 1 μPa at 0.2 km range to 118 dB at 14.8 km. Received levels near AQUARIUS were higher than those at corresponding distances from BEAVER MACKENZIE (Fig. B-12), possibly because Aquarius was a higher-capacity dredge. The noise spectrum is shown in Fig. B-11D. The signal-to-noise ratio (i.e., AQUARIUS vs. typical ambient) was relatively high in the 1/3-octave band near 250 Hz, but values in some adjacent bands were not much different (Fig. B-15 vs. B-1, B-2).

Greene (1984, 1985) developed several equations relating received noise levels in the 20-500 Hz band to hydrophone depth as well as distance from AQUARIUS. To facilitate comparison with the previous equations for other noise sources, we computed a best-fitting equation in our usual format for the 20-1000 Hz band and hydrophone depths 9-18 m:

$$RL\ (dB) = 134.7 - 0.374*R - 10*\log(R)$$

Similarly, the equation for the 1/3-octave band near 250 Hz was

$$RL\ (dB) = 126.6 - 0.825*R - 10*\log(R)$$

based on Greene's unpublished data (Fig. B-16). Distant from industrial sites, the average ambient level in the 1/3-octave

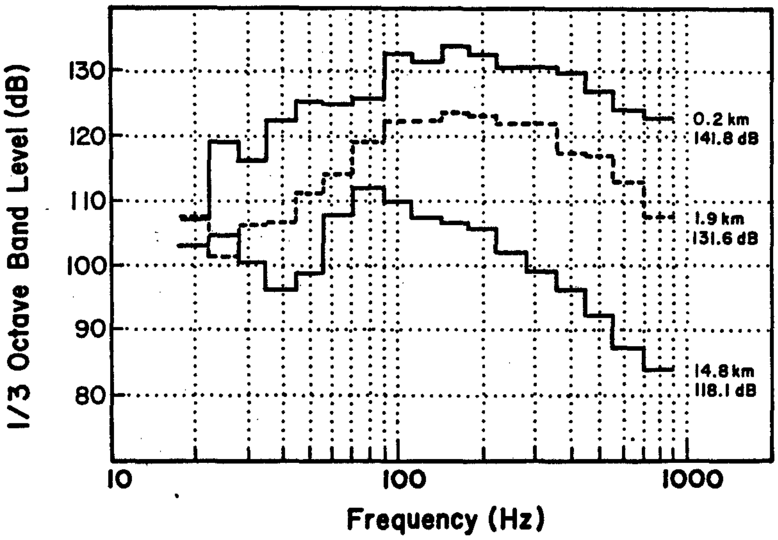

FIGURE B15. MEASURED NOISE (dB re 1 μPa) IN 1/3-OCTAVE BANDS AT THREE DISTANCES FROM SUCTION DREDGE AQUARIUS DREDGING IN THE CANADIAN BEAUFORT SEA, 12 AUGUST 1983. WATER DEPTH 46 M AT DREDGE; HYDROPHONE DEPTH 9-18 M. VALUES ALONG THE RIGHT MARGIN ARE RANGES (KM) AND RECEIVED LEVELS IN THE 20-1000 HZ BAND. BASED ON GREENE (UNPUBLISHED DATA).

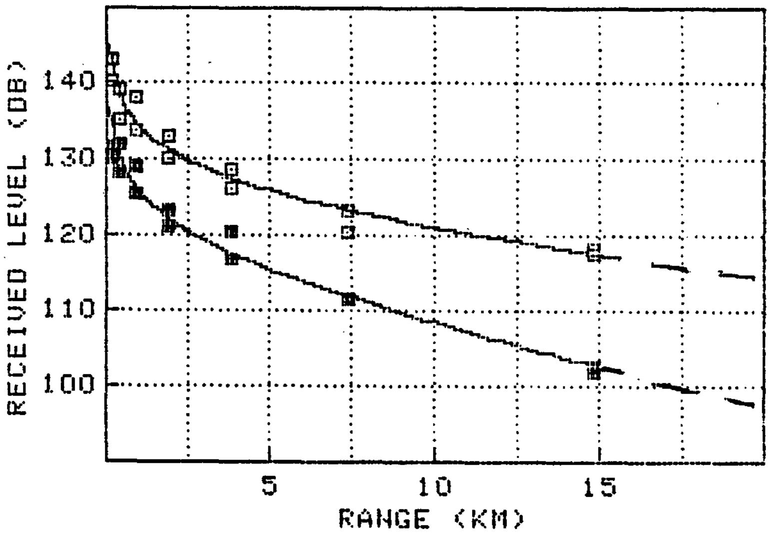

FIGURE B16. RANGE DEPENDENCE OF RECEIVED LEVELS OF NOISE (dB re 1 μPa) FROM DREDGE AQUARIUS, 12 AUGUST 1983. DATA AND BEST-FIT CURVES (TABLE B2) ARE SHOWN FOR THE 20-1000 HZ BAND (OPEN SYMBOLS) AND FOR THE 1/3 OCTAVE BAND CENTERED AT 250 HZ (CLOSED SYMBOLS).

band near 250 Hz was 78 dB (Fig. B-1). The received level of AQUARIUS sounds in this band were above 78 dB out to ranges well over 20 km (Fig. B-16; Table B-2).

Hopper Dredge GEOPOTES X Underway--Sounds from this hopper dredge, fully loaded, were recorded as it travelled from its dredging to its dumping site at 24 km/h (Greene 1982, 1985). GEOPOTES X is 136 m long, 22 m wide, draws 12 m when full, and displaces 17,981 tons. It reportedly had a damaged propeller at the time of recording, which may have contributed to the high level of underwater noise (Fig. B-11E, B-12). Water depth was 25 m. At a hydrophone depth of 9 m, received levels in the 20-1000 Hz band diminished from 150 dB at 0.46 km to 129.4 dB at 7.4 km. Received levels were higher than those at corresponding distances from the suction dredges AQUARIUS and BEAVER MACKENZIE (Fig. B-12), or any of the drillships (cf. Fig. B-3). The signal-to-noise ratio (i.e., GEOPOTES X vs. typical ambient) was highest in the 1/3-octave band near 80 Hz (Fig. B-17), as one would expect given the fact that spectrum levels peaked near 80 Hz (Fig. B-11E).

Greene (1985) found that the received levels of GEOPOTES X noise in the 20-1000 Hz band could be approximated by the equation

$$RL\ (dB) = 143.9 - 0.916*R - 10*\log(R)$$

Similarly, the best-fit equation for received levels in the 1/3-octave band near 80 Hz was

$$RL\ (dB) = 140.1 - 0.874*R - 10*\log(R)$$

(from Greene, unpubl. data; see Fig. B-18). Distant from industrial sites, the average ambient level in the 1/3-octave band

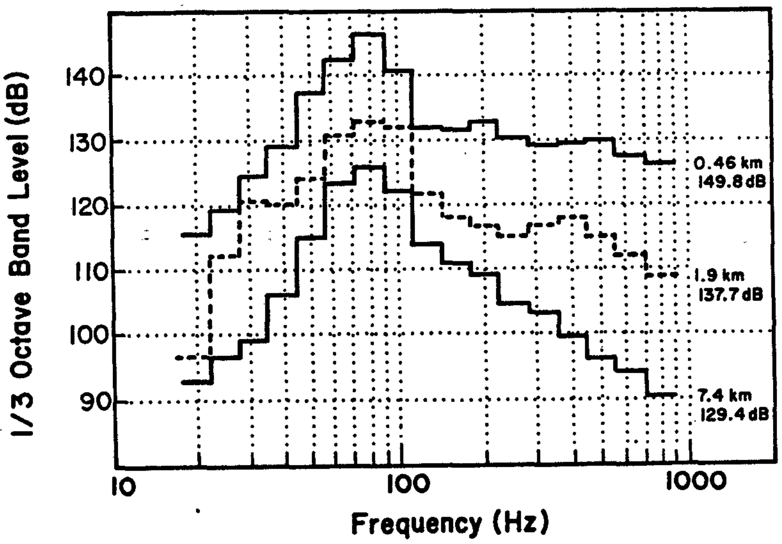

FIGURE B17. MEASURED NOISE (dB re 1 μPa) IN 1/3-OCTAVE BANDS AT THREE DISTANCES FROM HOPPER DREDGE GEOPOTES X LOADED AND UNDERWAY AT 24 KM/H IN THE CANADIAN BEAUFORT SEA, 5 AUGUST 1981. WATER DEPTH 25 M; HYDROPHONE DEPTH 9 M. VALUES ALONG THE RIGHT MARGIN ARE RANGES (KM) AND RECEIVED LEVELS IN THE 20-1000 HZ BAND. BASED ON GREENE (UNPUBLISHED DATA).

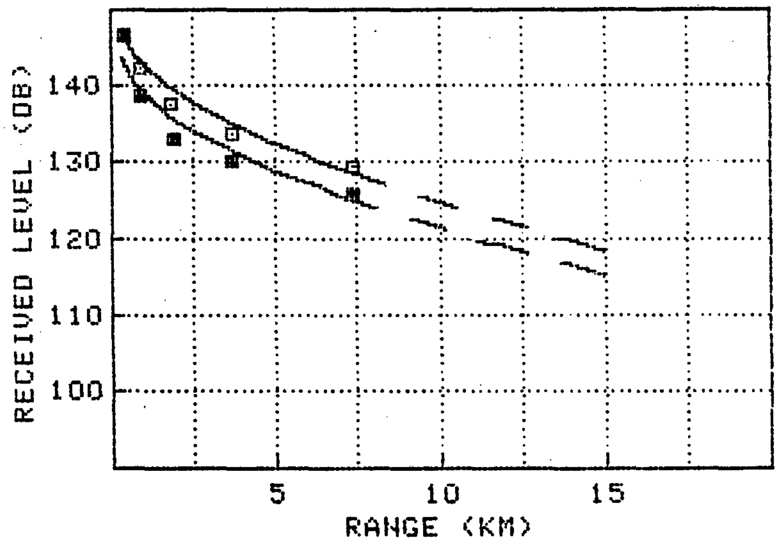

FIGURE B18. RANGE DEPENDENCE OF RECEIVED LEVELS OF NOISE (dB re 1 μPa) FROM HOPPER DREDGE GEOPOTES X UNDERWAY, 5 AUGUST 1981. DATA AND BEST-FIT CURVES (TABLE B2) ARE SHOWN FOR THE 20-1000 HZ BAND (OPEN SYMBOLS) AND FOR THE 1/3 OCTAVE BAND CENTERED AT 80 HZ (CLOSED SYMBOLS).

near 80 Hz was 85 dB (Fig. B-1). The received level of GEOPOTES X sounds in this band would not diminish to 80 dB until one reached a range far exceeding 20 km (Fig. B-18; Table B-2).

Other Construction Operations--Greene (1985) reported measurements of sounds from three hopper dredges loading and unloading. Noise levels were similar to those from AQUARIUS dredging and GEOPOTES X underway at corresponding ranges. These noise data are not summarized in detail here because, in each case, the data came from only a narrow range of distances from the dredge; thus, equations could not be derived for received level vs. range. However, it is noteworthy that prominent noise from the hopper dredge CORNELIS ZANEN was recorded near bowhead whales 13 km from the dredge (Greene 1985; Richardson et al. 1985c). This dredge was emptying by the pump-out method at the Minuk island construction site (water depth 12-13 m). The received level at range 13 km was 115-117 dB re 1 μPa in the 20-1000 Hz band--well above the average ambient level of 98 dB in this band.

There have been few measurements of sounds from construction activities, aside from dredging, near islands and caissons in the Canadian Beaufort Sea (Greene 1985). Received levels were generally lower than those at corresponding distances from most dredges. However, it was not possible to obtain repeated measurements at wide ranges of distances. Greene (1985) emphasized that radiated sound levels could vary considerably because of the varying activities of support vessels.

In the Alaskan Beaufort Sea, noises from construction of an artificial island have been recorded under the ice in winter (Greene 1983) and in very shallow open water (Cummings et al. 1981a). However, these data are of limited relevance to bowhead whales in open water 10 m or more deep. Davis et al. (1985)

provided data on underwater noise near Seal Island, in water 12 m deep, in September 1985. Although there was no construction during this period, activities at the island included arrival and departure of tugs and barges, and general housekeeping operations. Hourly measurements over a 9-day period showed that underwater noise levels near the island were highly variable. In the 20-1000 Hz band, levels at a hydrophone 1.65 km from the island ranged from 78 to 123 dB re 1 μPa, with 5th, 50th and 95th percentiles of 81, 92 and 116 dB (Davis et al. 1985). This variability was partly attributable to natural factors; in the absence of boats, sound levels were correlated with the wind speed. However, when tugboats operated at the island, noise levels at hydrophones 1.65-2.5 km away were greatly elevated. Although construction was not underway on this island, the data indicate that underwater background sound levels near occupied artificial islands can be relatively low, and that vessel traffic in support of the island may be the strongest source of noise.

B.5 SENSITIVITY OF BOWHEADS TO DRILLING AND CONSTRUCTION NOISE

B.5.1. Bowheads Near Industrial Sites

Biologists have seen bowheads as close as 4-5 km from drillships (Section B.2.2) and 0.8 km from a dredge (Section B.3.2). There was no evidence that the behavior of these whales was unusual, although it is not known whether numbers whales this close to industrial sites were the same as they would have been in the absence of industrial activity. Industry personnel have reported bowheads at even closer distances. The data in Section B.4 allow us to provide previously unreported estimates of the noise levels to which the whales seen near industrial sites were exposed (Table B-3).

Considering the three types of industrial operations listed in Table B-3, noise levels at the locations of the closest sightings by biologists are estimated as 117-127 dB re 1 μPa in the 20-1000 Hz band. No measurements of background noise were possible in these situations. Assuming that the ambient noise was at the average level of 98 dB on these occasions, the signal-to-noise (S:N) ratio for the industrial sounds at these locations was about 19-29 dB in the 20-1000 Hz band. Absolute received levels were 117-127 dB. In the 1/3-octave band with the highest S:N ratio, estimated S:N ratios at the locations of closest sightings by biologists were higher: 30-41 dB (Table B-3). Absolute levels were 104-117 dB. Industry personnel reported a few bowheads even closer to drillships and dredges than the closest sightings by biologists; estimated received levels and S:N ratios were correspondingly higher in these cases (Table B-3). It is emphasized that all of these S:N figures are only rough estimates, since actual ambient noise levels at the times when bowheads were seen close to industrial sites are unknown.

TABLE B-3. ESTIMATED NOISE LEVELS (dB re 1 μ Pa) AT LOCATIONS WHERE BOWHEAD WHALES HAVE BEEN SEEN NEAR DRILLSHIPS AND DREDGES. LOCATIONS ARE FROM SECTION B.2.2 AND B.3.2. RECEIVED LEVELS ARE FROM FITTED EQUATIONS (TABLE B-2). AVERAGE AMBIENT NOISE IS FROM FIG. B-1. THE "APPROXIMATE SIGNAL-TO-NOISE RATIO" COLUMN ASSUMES THAT AMBIENT NOISE WAS NEAR AVERAGE WHEN THE WHALES WERE SEEN.

		20-1000 Hz (dB)			1/3-Octave Band (dB)*		
	Range (km)	Rcvd. Lev.	Ave. Amb.	Approx. S:N	Rcvd. Lev.	Avg. Amb.	Approx. S:N
EXPLORER drillships							
Closest ind. rep.**	0.2	135	98	37	132	78	54
Closest biol. "	4.0	118	98	20	112	78	34
Whales numerous at	13.0	104	98	6	93	78	15
KULLUK CDU							
Closest biol. rep.**	10.0	117	98	19	104	74	30
BEAVER MACKENZIE dredge							
Closest ind. rep.**	0.1	137	98	39	127	76	51
Closest biol. "	0.8	127	98	29	117	76	41
Whales numerous at	5.0	114	98	16	105	76	29

*1/3-octave band with maximum signal-to-noise ratio; band centered at 250 Hz for EXPLORER, 630 Hz for KULLUK, and 400 Hz for BEAVER MACKENZIE.

**Closest reports by industry personnel and by biologists are shown.

The 1/3-octave bands considered in Table B-3 were centered at 250-630 Hz, well within the frequency range of bowhead calls (approx. 50-4000 Hz, Ljungblad et al. 1982; Clark and Johnson 1984; Würsig et al. 1985). Thus, it is assumed that the bowhead auditory system would be relatively sensitive to sounds at the frequencies of the industrial noise. Although hearing sensitivity of bowheads and other baleen whales has not been measured formally, they probably can detect sounds with S:N ratios as low as about 0 dB (Malme et al. 1983, 1984; Richardson et al. 1983a). Thus, industrial noise with a signal-to-noise ratio of 30-41 dB in at least one 1/3-octave band would be expected to be above the hearing threshold of a bowhead by about 30-41 dB.

The cases described above were the extremes--i.e., the situations when bowheads were seen closer to industrial operations than on any other occasion. However, bowheads were often seen as close as 13 km from the EXPLORER drillships and 5 km from the dredge BEAVER MACKENZIE. Following the same procedures as above, absolute received levels for such whales were 104-114 dB for the 20-1000 Hz band and 93-105 dB for the 1/3 octave band of greatest S:N ratio (Table B-3). Estimated S:N ratios for such whales were 6-16 dB for the 20-1000 Hz band, and 15-29 dB for the 1/3-octave band with greatest S:N ratio (Table B-3). These S:N estimates are more reliable than those given earlier for the closest whales. The present values are based on sightings of whales on several dates. Hence, use of the average ambient noise data was more appropriate here than it was for the closest whales. Similarly, bowheads seen about 13 km from hopper dredges unloading at Minuk (Section B.4.3) were exposed to about the same received noise level as those 5 km from BEAVER MACKENZIE.

Thus, it is apparently not uncommon for bowheads to tolerate continuous drilling and dredge sounds with S:N ratios as high as

15-29 dB in at least one 1/3-octave band and absolute received levels as high as 93-105 dB in that band. At least a few bowheads continue seemingly-normal activities with considerably higher levels of drilling or dredge sounds. As noted earlier, it is not clear whether all bowheads tolerate drilling and dredge sounds this intense. Results from playback experiments indicate that bowheads sometimes show avoidance reactions to sounds of this intensity.

B.5.2. Bowheads Exposed to Noise Playbacks

Richardson et al. (1985b,c) conducted six noise playback tests in which the sounds reaching bowhead whales were monitored by sonobuoys. Four of these tests involved noise from drillship EXPLORER II; two tests involved noise from suction dredge BEAVER MACKENZIE. This section examines the noise exposure data from these experiments in more detail than has been reported previously (unpubl. data of Richardson et al. 1985c and Greene 1985, re-examined by LGL).

During each playback test, the level of industrial sounds reaching the whales was well above ambient noise levels before and after the playback (Fig. B-19, B-20):

	Signal-to-Noise Ratio		Absolute Received Level	
	Closest Whales	Most Distant Whales	Closest Whales	Most Distant Whales
20-1000 Hz band	10-40 dB	3-32 dB	100-131 dB	94-122 dB
Max. 1/3-oct. band	24-49	16-41	95-123	87-114

The values for the six individual tests are given in Table B-4.

The procedure for estimating received levels and S:N ratios at the positions of the closest and most distant whales was as follows:

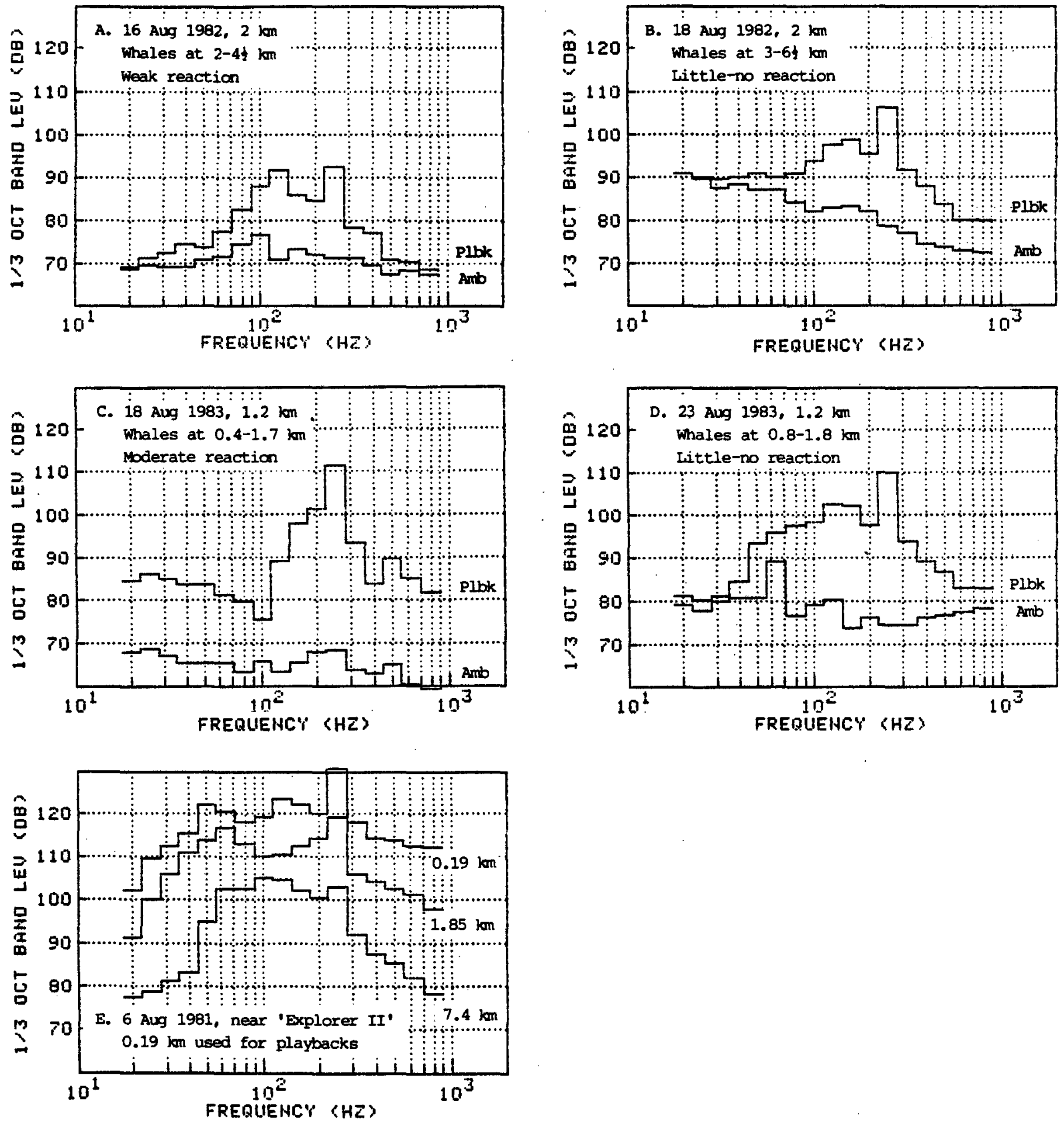

FIGURE B19. MEASURED NOISE (dB re 1 μPa IN 1/3-OCTAVE BANDS) NEAR BOWHEAD WHALES DURING DRILLSHIP NOISE PLAYBACK EXPERIMENTS (A-D) AND NEAR ACTUAL DRILLSHIP (E). FOR EACH OF FOUR PLAYBACK TESTS, RECEIVED NOISE AT THE PEAK OF THE PLAYBACK IS COMPARED WITH AMBIENT NOISE BEFORE OR AFTER THE PLAYBACK. THE PLAYBACK LEVELS WERE ALL AT LEAST AS HIGH AS THE "AMBIENT" LEVELS IN CORRESPONDING BANDS. THE NOISE RECORDING USED FOR THE PLAYBACKS HAD BEEN ACQUIRED 0.19 KM FROM EXPLORER II (E). FROM UNPUBLISHED DATA OF GREENE (1985) AND RICHARDSON ET AL. (1985c).

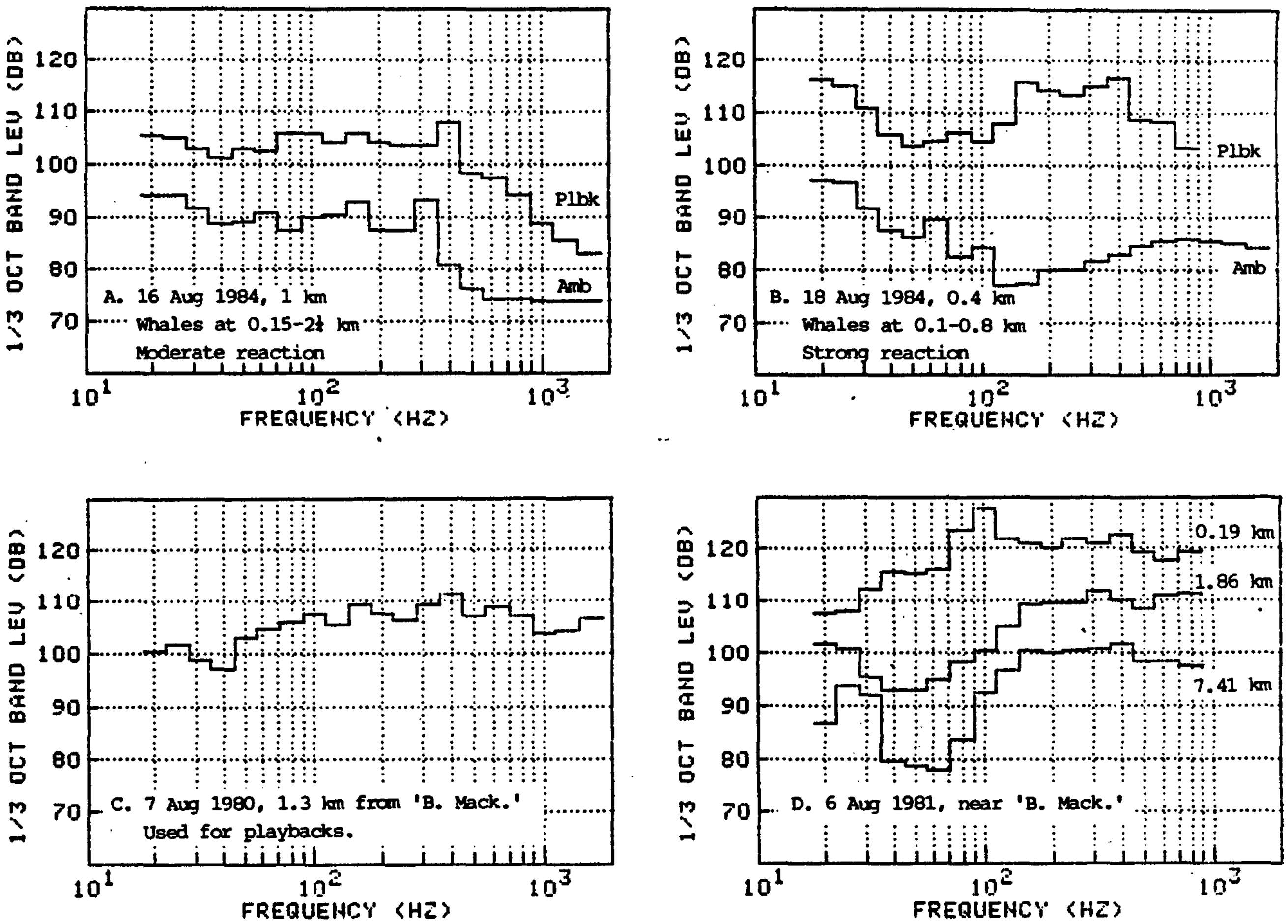

FIGURE B20. MEASURED NOISE (dB re 1 μPa IN 1/3-OCTAVE BANDS) NEAR BOWHEAD WHALES DURING DREDGE NOISE PLAYBACK EXPERIMENTS (A-B) AND NEAR ACTUAL DREDGE (C-D). FOR EACH OF TWO PLAYBACK TESTS, RECEIVED NOISE AT THE PEAK OF THE PLAYBACK IS COMPARED WITH AMBIENT NOISE BEFORE OR AFTER THE PLAYBACK. THE NOISE RECORDING USED FOR THE PLAYBACKS HAD BEEN ACQUIRED 1.3 KM FROM BEAVER MACKENZIE (C). FROM UNPUBLISHED DATA OF GREENE (1985) AND RICHARDSON ET AL. (1985c).

TABLE B-4. NOISE LEVELS AND SIGNAL-TO-NOISE RATIOS DURING PLAYBACKS OF DRILLSHIP AND DREDGE NOISE NEAR BOWHEAD WHALES (BASED ON RICHARDSON ET AL. 1985c AND UNPUBLISHED DATA). SOURCE LEVEL, AMBIENT LEVEL, AND RECEIVED LEVEL AT SONOBUOY WERE MEASURED; RECEIVED LEVELS AT OTHER RANGES WERE ESTIMATED, AS WERE THE RANGES FROM THE ACTUAL DRILLSHIP OR DREDGE AT WHICH THESE LEVELS WOULD BE RECEIVED (SEE TEXT). ALL LEVELS ARE IN dB re 1 μPa.

			20-1000 Hz Band				Max 1/3-Octave Band*			
	Source Level (dB)	Range (km)	Amb-ient (dB)	Rcvd Lev., Peak Plbk (dB)	S:N, Plbk: Amb. (dB)	Equiv Range From Ship (km)	Amb-ient (dB)	Rcvd Lev., Peak Plbk (dB)	S:N, Plbk: Amb. (dB)	Equiv Range From Ship (km)
Drillship Playbacks--No Avoidance										
18 Aug 82	164									
Sonobuoy		2	97	110	13	9.0	79	108	29	5.7
Closest Bhd		3	"	107	10	11	"	105	26	7.0
Farthest Bhd		6.5	"	100	3	16	"	96	17	11
23 Aug 83	164									
Sonobuoy		1.2	93	113	20	7.1	75	111	36	4.5
Closest Bhd		.8	"	115	22	5.8	"	113	38	3.8
Farthest Bhd		1.8	"	111	18	8.4	"	108	33	5.7
Drillship Playbacks--Avoidance Observed										
16 Aug 82	155									
Sonobuoy		2	84	100	16	16	71	95	24	12
Closest Bhd		2	"	100	16	16	"	95	24	12
Farthest Bhd		4.5	"	94	10	21	"	87	16	16
18 Aug 83	164									
Sonobuoy		1.2	78	112	34	7.7	68	111	43	4.5
Closest Bhd		.4	"	118	40	4.2	"	117	49	2.5
Farthest Bhd		1.7	"	110	32	9.0	"	109	41	5.3
Dredge Playbacks--Avoidance Observed										
16 Aug 84	161									
Sonobuoy		1	102	118	16	3.3	81	110	29	2.8
Closest Bhd		.15	"	127	25	0.8	"	119	38	.6
Farthest Bhd		2.25	"	113	11	5.5	"	105	24	5.2
24 Aug 84	161									
Sonobuoy		.4	101	125	24	1.2	83	117	34	.8
Closest Bhd		.1	"	131	30	.4	"	123	40	.24
Farthest Bhd		.8	"	122	21	1.9	"	114	31	1.5

* 1/3-octave band in which the S:N ratio was highest; centered at 250 Hz for drillship sounds, and at 400 Hz for dredge sounds.

1. The received levels of industrial noise during the playback, and of ambient noise before and/or after the playback, were measured by a sonobuoy dropped near the whales.
2. Received levels at the distances of the closest and farthest whales were estimated from the measured level, assuming that transmission loss was at the same rate as that near the actual drillship or dredge, i.e., using the 10*log(R) term and the linear terms given in Table B-2.
3. These estimates of received level were used to estimate S:N ratios, assuming that the ambient noise measured at the sonobuoy was characteristic of that at the locations of nearby whales.

Step (2) was the most speculative link in this calculation being the least supported by empirical data. Transmission loss at the playback sites undoubtedly was not identical to that at the recording sites for which the equations in Table B-2 were derived. However, errors arising from this process should be relatively small. The fitted equations were only used to adjust the sonobuoy-derived measurements for the fact that some whales were somewhat farther away than the sonobuoy whereas others were somewhat closer. The adjustments in received level and S:N never exceeded +9 dB or -12 dB relative to values at the sonobuoy (Table B-4), and the maximum error was probably substantially less than 12 dB.

During four of the six playback tests, the whales definitely oriented and moved away during the playback phase; during the other two tests there was no clear evidence of a reaction (Richardson et al. 1985b,c; summarized in Section B.2.4 and Section B.3.3). Table B-4 shows the estimated industrial sound levels and S:N ratios for each test; these data can be summarized as follows:

	Signal-to-Noise Ratio		Absolute Received Level	
	Closest Whales	Most Distant Whales	Closest Whales	Most Distant Whales
20-1000 Hz band				
Reaction	16-40 dB	10-32 dB	100-131 dB	94-122 dB
No reaction	10,22	3,18	107,115	100,111
Max. 1/3-oct. band				
Reaction	24-49	16-41	95-123 dB	87-114 dB
No reaction	26,38	17,33	105,113	96,108

For the 20-1000 Hz band, estimated S:N ratios at the locations of the whales tended to be higher in the four tests with an avoidance reaction (10-40 dB) than in the two tests without a pronounced reaction (3-22 dB), but there was some apparent overlap. The overlap was greater for the 1/3-octave band of maximum S:N ratio (16-49 dB with reactions vs. 17-38 dB without).

The results can also be examined on the basis of received levels rather than S:N ratios. For the 20-1000 Hz band, estimated received levels ranged from 94 to 131 dB re 1 uPa in tests where there was an avoidance reaction, and from 100 to 115 dB in tests with no obvious reaction (Table B-4). For the 1/3-octave band of maximum S:N ratio, received levels ranged from 87 to 123 dB in tests with a reaction, and from 96 to 113 dB in tests with no obvious reaction. Thus, there was no clear tendency for received levels to be higher in the tests where there was an avoidance reaction.

Another way in which the data can be examined is in terms of equivalent ranges from the actual drillship or dredge. Table B-4 shows the distances from the actual drillship or dredge at which one would expect to find the various levels measured or estimated during the playback experiments. These equivalent ranges are based on the equations in Table B-2. Based on data from the 1/3-octave band of maximum S:N ratio, some bowheads showed weak avoidance reactions to playbacks when received noise levels equalled those as much as 12-16 km from the drillship or 5 km from the dredge. Other bowheads apparently did not react when received noise levels equalled those as little as 4-6 km from the drillship. Corresponding figures based on the 20-1000 Hz band were slightly higher (Table B-4).

These data show that the responsiveness of bowhead whales to playbacks of drillship and dredge noise varied considerably. Bowheads sometimes reacted to sounds of a given level, e.g., 110 dB re 1 μPa, and at other times did not react to sounds with similar received levels. Considering the 1/3-octave band with maximum S:N ratio, a few whales reacted to received levels as low as about 87 dB, and a few did not react overtly at levels as high as 113 dB. Responsiveness with respect to signal-to-noise ratio also varied. Again considering the 1/3-octave with maximum S:N, a few whales reacted at S:N as low as about 16 dB and a few did not react overtly at S:N as high as 38 dB.

B.5.3 Discussion

Biologists have observed bowheads close enough to drillships and dredges for the (roughly) estimated S:N ratio to be 19-29 dB in the 20-1000 Hz band, and 30-41 dB in the 1/3-octave band of maximum signal-to-noise ratio (Table B-3). These values are generally similar to maximum S:N ratios during the two playback tests when whales showed no obvious avoidance reactions (22 dB in the 10-1000 Hz band; 38 dB in the maximum 1/3-octave band). In this respect, the observations of whales near actual industrial sites were consistent with those during playback experiments. However, during playback tests, some bowheads showed avoidance reactions when sound levels were no greater than those to which certain whales were exposed near actual drilling and dredging operations:

1. Some bowheads showed avoidance reactions when the S:N ratio was as low as about 10-16 dB in the 20-1000 Hz band, and 16-24 dB in the 1/3-octave band of maximum S:N (Table B-4). In contrast, a considerable number of bowheads have been seen close enough to drillships and dredges to experience S:N ratios at least this high (Table B-3).
2. Industry personnel have reported a few bowheads very close to drillships and dredges. In the extreme cases, estimated S:N ratios were 37-39 dB in the 20-1000 Hz band and 51-54 dB in the maximum 1/3-octave band--similar to the highest values during the playback tests.
3. Bowheads that showed avoidance reactions during playback experiments were receiving noise equivalent in level to that 2.5-16 km from the actual drillship, and 0.25-5 km from the actual dredge (or slightly farther away if 20-1000 Hz rather than 1/3-octave data are considered--Table B-4). In contrast, numerous bowheads have been seen as close as 10 km to drillships (some closer), and there have been several sightings within 0.8-5 km of dredges.

One interpretation of these data is that bowheads were more sensitive to short playbacks of drillship and dredge noise than to ongoing noise from drillships and dredges themselves. The playbacks lasted only 30-40 min, and the noise level increased from zero to maximum over only 10 min (Richardson et al. 1985c). The rapid onset of industrial sounds during playbacks may have evoked a startle reaction. Another possibility is that the whales seen close to drillships and dredges were individuals that were unusually insensitive to noise, and that the more sensitive individuals do not occur this close to industrial sites. It is not known whether bowhead numbers near dredges and drillships were reduced relative to numbers that would have been there in the absence of industrial activity. The actual explanation may involve both of these factors. A more detailed discussion of the possible reasons for greater sensitivity to playbacks appears in Richardson et al. (1985c, p 176-8).

The data presented in this section provide information about the received levels and signal-to-noise ratios at which bowhead whales tolerate vs. react to industrial noise. It is clear that there is a considerable intermediate range of levels at which responses are variable from one individual whale to another, or from time to time. It is not possible to identify a single 'threshold' noise level or S:N ratio. The data also provide further evidence that some bowheads may react to industrial noise at distances well beyond the minimum distances where a few individuals have been seen.

B.6 SENSITIVITY OF GRAY WHALES TO INDUSTRIAL NOISE

A considerable amount of research has been carried out on migrating gray whales, which are easier to study than are most other whales because of their proximity to land during migration. However, not much information is available in the literature concerning gray whale response to man-made noise. A series of field studies (Malme et al. 1983, 1984) have been performed to obtain more information about sensitivity of migrating gray whales to industrial noise exposure. Using the techniques developed in studying migrating whales, a study of summering and feeding gray whales was recently completed at a site near St. Lawrence Island (Malme et al. 1986). These studies are reviewed and their findings summarized.

B.6.1 Results from Playback Experiments With Migrating Gray Whales Using Representative Industrial Sounds

Playback experiments were conducted off the California coast at Soberanes Point near Carmel during the 1983 southbound and northbound migrations. During the study period, the southbound migration was composed of a representative sample of the general gray whale population. The northbound migration study was conducted during the period when the migrants consisted primarily of mother/calf pairs since this was considered to be potentially the most acoustically sensitive part of the population. Further experiments were carried out at the same site during the 1984 southbound migration.

A broadband underwater sound projector system was used to play back recorded industrial noise at realistic levels in the presence of the migrating gray whales. The acoustic stimuli used were signatures of a drillship, drilling platform, production platform, semi-submersible drill rig, and helicopter flyovers. The sound transmission characteristics of the test area were measured using a calibrated source so that the noise exposure levels at observed whale positions could be estimated. Ambient noise levels were measured to permit estimation of the range of potential audibility of the test signals. The whale swimming patterns were tracked using theodolite observations and general whale behavior was observed to determine if any changes occurred in response to the test stimuli.

It was demonstrated during these experiments that behavioral responses of gray whales can be elicited through acoustic playback experiments. A measure of hearing sensitivity was obtained, demonstrating that gray whales can detect the presence of anomalous sounds having a 0 dB signal-to-noise ratio in the 1/3-octave band of maximum signal level. These tests also demonstrated annoyance and startle responses from the whales. Lesser responses, which can be described as nonextreme, cautious maneuvers, were also demonstrated.

For the southbound migration experiments, a computer-implemented track deflection program was established to test for any possible changes in such parameters as distance from shore, speed, linearity of track, orientation towards the sound source, and compass heading of each whale group. Results of this analysis show that each playback stimulus caused statistically significant response compared with undisturbed whales, and each stimulus elicited a different pattern of response. Whales exposed to the playback stimuli generally showed an avoidance response, indicated by deflections from the immediate vicinity of the sound source. The other response of whales to playback was to slow down relative to undisturbed conditions. The response of slowing down during playback of industrial sounds appears to be neither an avoidance nor an annoyance response. Instead, the whales may be moving more cautiously when in the presence of such sound sources.

Migrating whales were found to respond to the presence of a noise source by small course changes at some distance from the source. This "detection" reaction often occurred at ranges where the estimated level of the noise source was equal to the local ambient noise level. In the test area this corresponded to ranges of 2 to 3 km. The result of these small course changes, as the whales approached the sound source, was an increase in the distance between the whales and the source at the closest point of approach. This "avoidance" behavior resulted in a lower sound level exposure than would have occurred had the whale maintained the original course.

The distribution of distances between the source and the migrating whale tracks was statistically analyzed by comparing the track density distributions under experimental conditions with the track density distributions for the corresponding control conditions. This procedure resulted in obtaining a "probability of avoidance" distribution which showed the change in track density near the source as a function of distance from the source. By converting the distribution of range values to a distribution of sound exposure levels, using measured sound propagation characteristics for the test area, a set of sound exposure characteristics were obtained which permitted prediction of the probability that migrating whales would avoid a region of high noise level. These sound exposure characteristics are specific for the industrial noise sources used in the experiments but are not site-specific. Thus, if the expected range of sound exposure levels can be predicted for a proposed drilling site, the potential impact zone for migrating gray whales can be estimated.

Probability of Avoidance Levels

The probability of avoidance analysis procedure showed that avoidance behavior began at broadband sound exposure levels of around 110 dB (re 1μPa) for the playback signals and was greater than 80% for regions with broadband signal levels higher than 130 dB. Some variation among the various playback stimuli was observed with the drillship producing the greatest avoidance and the production platform the lowest, for levels between 110 and 125 dB. However, for levels between 125 and 130 dB, the reactions to all playback signals were comparable.

Effective Range of Operating Sources

An estimate of the effective range of the original noise sources (from which the tape recorded signals were obtained) was made by assuming operation in the test area. The effective range for a 50% probability of avoidance for most of the playback sources was estimated as less than 100 m. The effective range for the drillship was estimated as 1.1 km. Detailed results for these measurements are presented in Section B.6.4.

B.6.2 Results from Experiments With Migrating Whales Using Seismic Sources

In addition to the playback experiments described above, the field measurements included tests using a 100 cu. in. air gun. The services of a seismic survey vessel (CECIL H. GREENE II) with a 4,000 cu. in. air gun array were also used during the northbound migration in 1983.

The experimental procedures followed with the air gun tests were identical to those used for the playback study. The main data collection and analysis effort of the study centered on the analysis of tracks of whale groups. However, a concerted effort was made to note whale group behaviors such as surface activity, milling, and breaching during control and experimental conditions so that any potential relationship to industrial sound exposure level could be determined. No significant differences in the occurrences of any of these behaviors were observed when comparing control and experimental conditions.

During the northbound mother/calf phase of the 1983 migration, the major potential disturbance used in experiments was air gun activity either from a 40-gun array or from a single air gun. The most dramatic responses of the whales to air gun array activity occurred at received levels of greater than 160 dB re 1μPa when the air gun source was within 2 km of the animals. In general, whales would slow down, turn away from the source, and increase their respiration rates when exposed to air gun impulse sounds. In several cases, groups were seen swimming into the surf zone and also apparently positioning themselves in the sound shadow of a rock, island, or outcropping.

Track Analysis Results

For the southbound migrations where relatively high sample sizes were obtained, a computer-implemented track analysis program was used to analyze the theodolite data. The results of this program were cumulative track frequency distributions which were statistically analyzed to determine significant differences between experimental and control conditions.

The probability of avoidance analysis procedure described previously showed that for the 100 cu. in. air gun, the threshold of avoidance behavior was 164 dB (effective pulse pressure re 1μPa). Levels of 180 dB were observed to produce nearly complete avoidance of the area. The air gun pulse rate was 6/min.

Effective Range

The effective range for a 50% probability of avoidance for the 100 cu. in. air gun was 400 m. For the 4000 cu. in. seismic array, the effective range for a 50% probability of avoidance with a broadside sound exposure geometry was estimated as 2.5 km. These effective ranges are based on sound propagation in the test area off Soberanes Point, California. Application of these estimates to other areas should not be made without following the procedures discussed in Malme et al. (1984).

B.6.3 Summary of Numerical Results from Playback and Air Gun Tests for Migrating Gray Whales

Stimuli Projection and Monitoring

The acoustic levels reported for the original sources of the playback stimuli varied over a wide range. Playback at source levels designed to reproduce the original signal levels was not feasible for some stimuli because of the high acoustic power required. For other stimuli, the original sound levels were low enough so that reproduction of the original level could result in whale behavioral reaction in close proximity to the playback source vessel. The close proximity of the relatively large vessel (27 m) could be a potential confounding factor in interpreting the results for the lower level stimuli.

Thus, to provide a potential behavioral reaction zone at some distance from the playback source for all of the playback sequences, the output level of the projector system was set to provide a source level which was 55 to 60 dB above the measured ambient noise level in the dominant bandwidth of the stimulus. An effective range of 2 to 3 km was obtained to the zone where the playback level became approximately equal to the ambient noise level in the dominant band of the stimulus. This procedure produced an acoustic test zone where any behavioral reaction of the migrating whales would probably occur within visual range of the observation stations but also at some distance from the playback source vessel.

The sound levels used were subsequently scaled to levels reported for the actual sources and range corrections were derived by using the transmission loss characteristics measured at the test site. This procedure is described in later discussion.

Selection and Level Calibration

Descriptive information for the five playback test examples are contained in Table B-5. As shown in the table, the acoustic recording used for each of the test stimuli was obtained at various ranges from the respective source. To standardize the playback comparison process, the reported acoustic level data were corrected to an equivalent 100 m range from the source. Since the water depth and sound propagation characteristics differed for the various sources, correction to a 100 m range represented a smaller potential error than correction to the usual 1 m range. In each case measured transmission loss data were used, if available, or the best estimate of transmission loss was used based on stated range and water depth values. In deriving the appropriate comparison with the projected playback level, a 100 m sound level estimate was also used. Thus, a scaling factor was obtained for the playback level which permitted compensation for local transmission loss characteristics and for differences between acoustic levels from the actual sources and the achievable levels from the playback projector. Table B-7 shows the differences in levels between the playback stimuli and the reported values as corrected to an equivalent 100 m range. It was convenient to operate at a

TABLE B-5. PLAYBACK STIMULI INFORMATION. (From Malme et al. 1984.)

Stimulus (Code)	Original Recording Dist. Meters	Dominant Frequencies Hz	Reported Level dB//µPa	Est. 100 m Level dB//µPa	Playback 100 m Level dB//µPa	Difference (PB-Orig) dB	Data Ref.**
Drilling Platform (HOLLY)	30	5 (t)	119	109	-	-	Gales p. 66
		13 (t)	107	97	-	-	
		80-315 (st)	99	89	125	36	
DRILLSHIP (EXPLORER II)	185	278 (t)	123	126	122	-4	Greene p. 322
		50-315 (bb)	133	136	127	-9	
Production Platform (SPARK)	9	20 (t)	134	118	93	25	Gales p. 64
		63-250 (st)	125	109	123	14	
Helicopter (Bell 212)	152 (altitude)	20 (t)	114	118*	99	-19	Greene P. 311
		32 (t)	99	103*	113	10	
		50-200 (st)	99	103*	116	13	
Semisubmersible Rig (OCEAN VICTORY)	12	28 (t)	129	111	105	-6	Gales p. 65
		63-250 (st)	119	101	123	22	

Key:

(t) tonal, (bb) broadband, (st) summed tonals.

*These values are for a flyover at 100 m altitude. Estimate based on relationships developed for aircraft-underwater sound transmission in deep water. In shallow water, levels would be higher, depending on the acoustic properties of the bottom material. Values assume a receiver position near the surface. (Barger and Sachs 1973).

**Gales (1982), Greene (1982).

relatively constant signal-to-noise ratio (S/N) at the source to have a uniform exposure region for all test stimuli. Thus, as shown in the table, the projected level was louder than the actual source level for some stimuli, and quieter than the actual source for others.

Table B-5 lists the maximum measured levels for the stimuli when they were originally recorded. These sound levels are based on the reported data for the actual tape dubs used. The reference cited was used as the basis for establishing the original sound field level because of the difficulty in recovering and preserving a calibration chain through the dubbing and playback process. The original data were used to determine the dominant spectrum components of the original sound field and the frequency region of the principal output. Because of the low frequency limitation of the playback projectors below 32 Hz, it was not possible to reproduce the required levels for sources with very low dominant frequencies. In this case, the degree to which the frequency response above 32 Hz matched the original source was examined independently by comparison of this part of the playback spectrum with the comparable part of the reported original source spectrum. This is shown as the "summed tonal level" value in Table B-5.

The sound level output produced during playback is compared with the original sound source values in the last column of the table. The comparison shows that, while low frequency components are often appreciably reduced on playback, the components above 32 Hz are generally greater than their original levels. The exception to this is the drillship stimulus where the achievable level is below that of the actual source at all frequencies.

The Influence of Playback and Air Gun Sound Levels on Migration Behavior

Analysis of track patterns and swim speed data showed that gray whales detected several of the playback stimuli at ranges where the level of the dominant part of the playback signal was comparable to the ambient noise level in the same frequency range (0 dB S/N). The principal reaction was a small change in swim direction and a drop in speed. The change in swim direction generally caused the whales to pass the vicinity of the sound source at a greater distance than would have occurred otherwise. This avoidance reaction thus results in a reduction of the sound exposure for the whales as they pass the source. The avoidance distance presumably is a function of the loudness and degree of unpleasantness (noisiness) of the sound. It is also likely to be a function of whether or not the sound might have a threat significance to the whales (such as orca sounds).

Some representative detailed tracks showing response of whale groups to drillship playback stimuli are illustrated in Fig. B-21. The contours are not concentric because of the dependence of sound transmission on bottom depth in addition to range. The bottom is non-uniformly sloping to seaward in the test area. track data shown in Fig. B-21 for a drillship playback experiment illustrate the sound exposure calculation procedure by superimposing sound contours on the track plots obtained from sighting data. Similar data, are available for the air gun source and drill-rig playbacks (Malme et al., 1984).

Sound Avoidance Analysis

Track data from theodolite sightings, as shown in Fig. B-21, are used to develop plots showing the cumulative track distributions across the migration zone at 0.5 km intervals as shown in Fig. B-22. The distance by which the whales avoid the sound

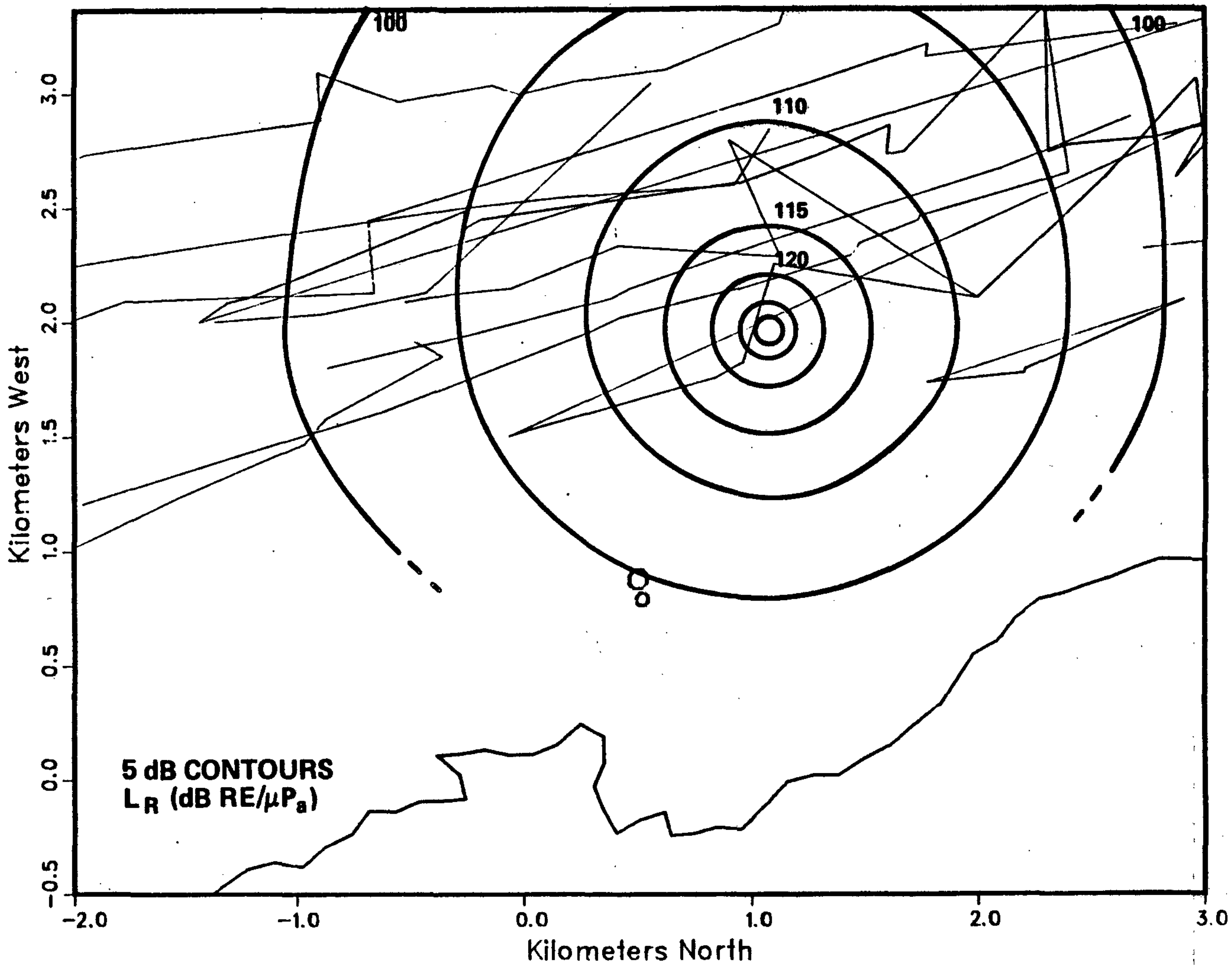

FIGURE B21. COMBINED TRACK PLOTS AND SOUND LEVEL CONTOURS FOR MIGRATING GRAY WHALES, SOUND SOURCE - PROJECTOR PLAYBACK OF DRILLSHIP NOISE (DATA FROM MALME ET AL. 1984, OBTAINED OFF SOBERANES POINT, CALIFORNIA).

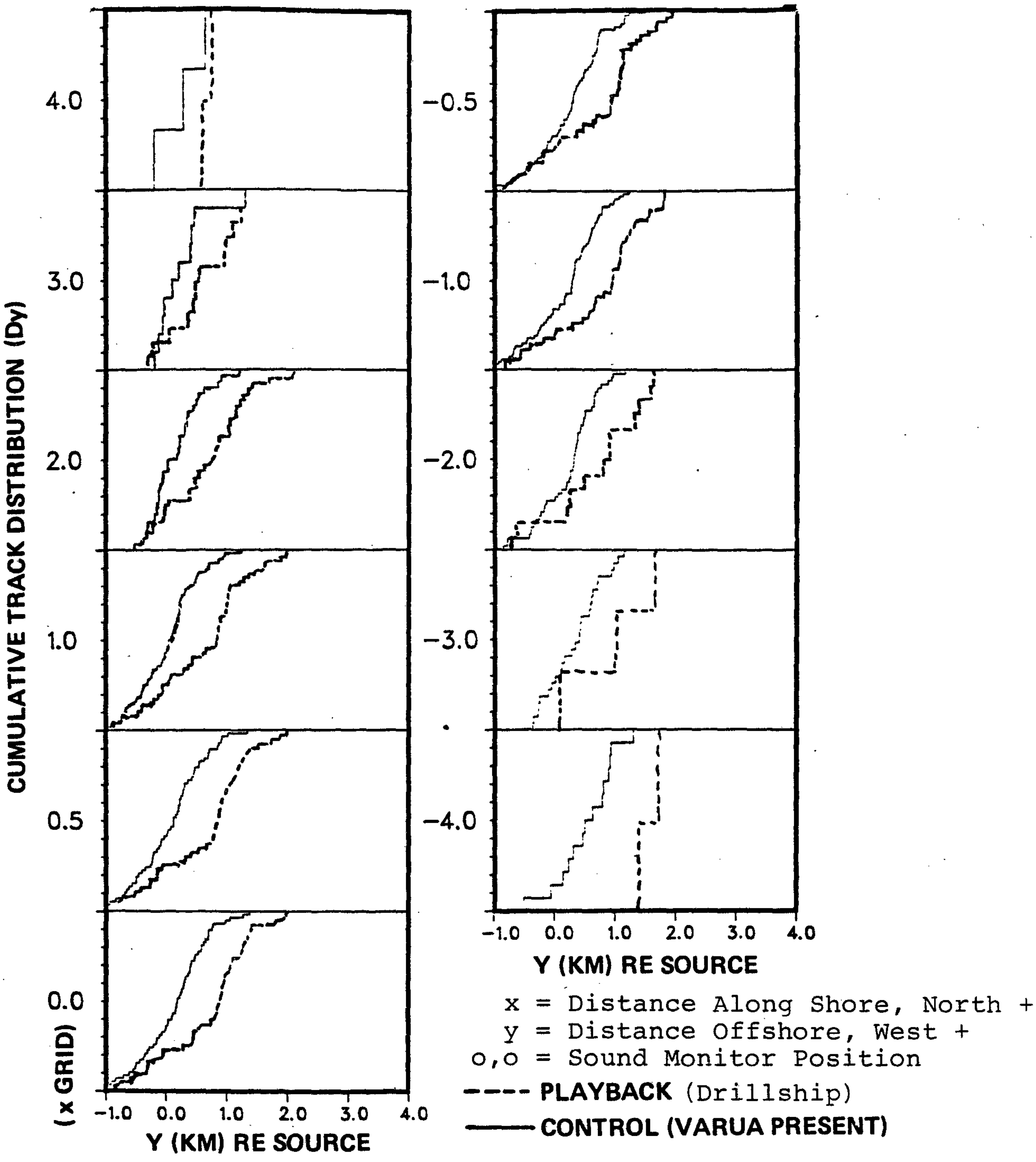

FIG. B-22. COMPARISON OF GRAY WHALE CUMULATIVE TRACK DISTRIBUTIONS FOR POOLED OBSERVATION DATA DISTRIBUTIONS MEASURED ALONG Y COORDINATE AT INDICATED X-GRID LOCATIONS DRILLSHIP PLAYBACK (FROM MALME ET AL. 1984).

source can be estimated by comparing the cumulative track distributions for a given stimulus condition with the distributions for the control condition with the source vessel present but no sound projection. Since for most tracks the point of closest approach to the source occurs along the x = 0 grid line (see Fig. B-22), only the distribution of track crossings along this line needs to be considered in making the avoidance determination. As an example, cumulative track distributions for the pooled drillship experiments are conveniently compared with the appropriate control conditions by using a direct overlay procedure as illustrated in Fig. B-22. The influence of the high sound levels near the source can be seen as a shift in the distribution near the source region from the x = 0.5 coordinate and north to 0.0 km.

Probability of Avoidance Calculations

The approximate track density function for the control conditions and for pooled data for each of the acoustic stimuli were determined using a procedure for approximate differentiation of the cumulative track distributions. A "probability of avoidance" estimate was then made using the relationship

$$P_{a(y)} = (P_c(y) - P_s(y))/P_c(y) \qquad \text{(B-1)}$$

The Probability of Avoidance is thus defined as the difference between the track density under control conditions, $P_c(y)$, and the track density under experimental conditions, $P_s(y)$, normalized by the control condition track density. Thus, if for a given value of y, the density during experimental conditions was the same as during control conditions, the probability of avoidance at that point would be 0. Conversely, if no tracks were found near the same y value under experimental conditions, the probability of avoidance would be 1.

Track density plots were derived for the playback and drillship playback tests using the summed cumulative track distributions. These plots were then compared with corresponding density distributions for control periods to obtain the probability of avoidance for each stimulus.

An example probability of avoidance plot for the drillship playback is shown in Fig. B-23. The control, test, and avoidance densities are shown in this figure for comparison.

The probability of avoidance plot shown in the figure was obtained by computer implementation of Eq. (B-1) using the data from the control and test track density plots. No editing of the density plots was performed prior to the processing. As a result, the small sample difference regions in the tails of the density plots show up as large avoidance regions because of the normalization process. The significance of the avoidance density plot values can be judged by the length of their vertical increments. If a large number of samples were present in the original distributions, the vertical increments in the density plot are small; hence a small sample size produces a large vertical increment, consequently, even a low density of whales at a given y value in the control distribution will produce a large avoidance value if it was not matched or there were no whales at that y value during the experimental conditions. In interpreting the results of the probability of avoidance analysis, the central regions near the source thus are the principal regions of interest.

Determination of Acoustic Response Characteristics

The probability of avoidance plots can be used directly to relate avoidance distances to specific sources and to sound level values. This is done by converting the source distance values

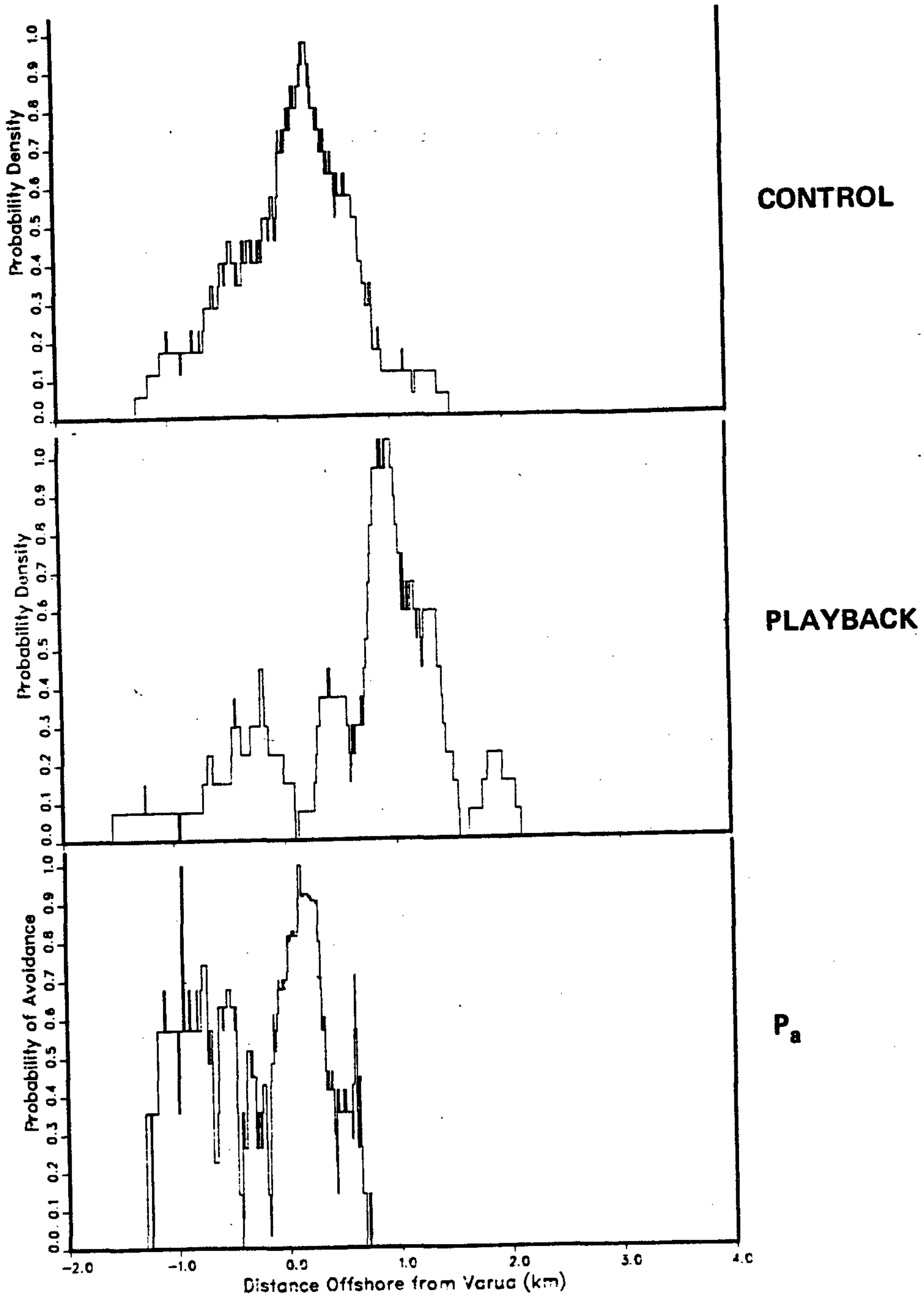

FIG. B-23. GRAY WHALE TRACK DENSITY DISTRIBUTIONS AND PROBABILITY OF AVOIDANCE DISTRIBUTION FOR COMBINED DRILLSHIP PLAYBACK OBSERVATIONS (FROM MALME ET AL. 1984). DISTRIBUTIONS ARE FOR TRACKS CROSSING THE X = 0 COORDINATE (SEE FIG. B-22).

shown in the plots to equivalent sound exposure levels by using the measured values of source level and transmission loss. By using these relationships, the probability of avoidance plots were converted to plots showing probability of avoidance versus sound exposure level. This "acoustic response characteristic" has the advantage of not being site-specific and, hence, is more generally applicable than plots which relate sound exposure level to range in a given test area. The results of this procedure were plotted for each stimulus and are shown in Fig. B-24.

Examination of Fig. B-24 shows that for the playback stimuli, the drillship sound produces an avoidance reaction at the lowest level (110 dB re 1 μPa, broadband). The production platform does not seem to produce an avoidance reaction until a broadband level of about 119 dB is reached. The other playback sounds produce reactions midway between the drillship and production platform. However, all of the playback stimuli seem to produce nearly complete avoidance at sound exposure levels of 130 dB and higher.

In contrast with the playback stimuli avoidance levels, the air gun does not seem to produce significant avoidance until effective peak pressure levels of 164 dB are reached. Nearly complete avoidance occurs at levels of 180 dB. The difference in avoidance level between the continuous sound of the playback tests (with the exception of the helicopter) and the impulsive sound (6 pulses/min.) of the air gun thus ranged from 50 to 55 dB. This is similar to the difference in sound levels reported for tests of equivalent noisiness with human subjects when comparing continuous and impulsive noise (Fidell, et al., 1970).

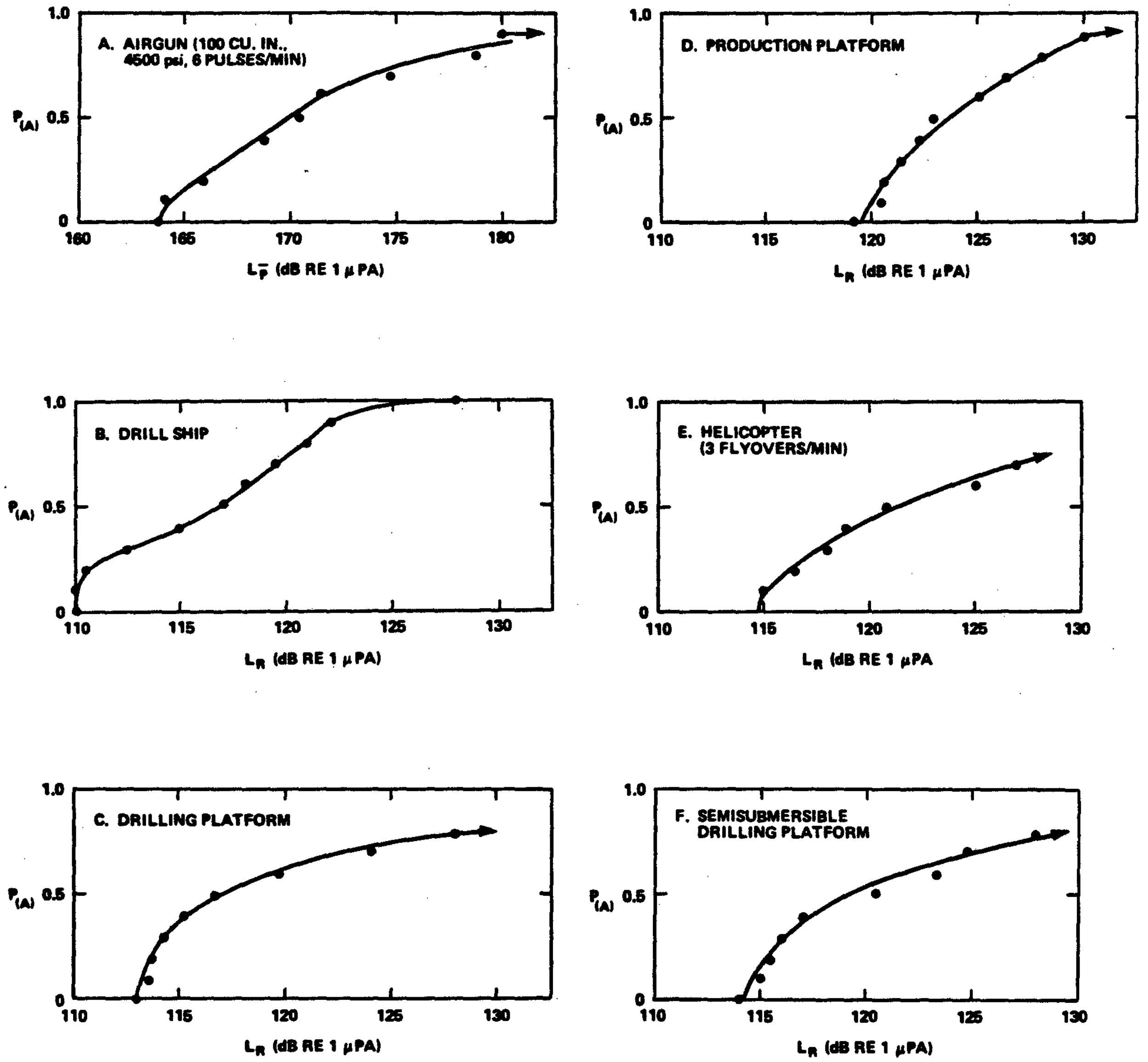

FIG. B-24. ACOUSTIC RESPONSE CHARACTERISTICS FOR PLAYBACK AND AIR GUN STIMULI SHOWING PROBABILITY OF AVOIDANCE (P_A) VERSUS SOUND EXPOSURE LEVEL (FROM MALME ET AL. 1984 FOR MIGRATING GRAY WHALES).

Application of Acoustic Response Characteristics

The acoustic response characteristics relate avoidance behavior to sound exposure levels. In this application, the data for deriving the characteristics were obtained using specific types of sounds and observing the swimming behavior of migrating gray whales. Thus, application of these characteristics to predict avoidance reaction in other areas should be limited to the same species and similar sound sources and whale activity.

Effective Range of Operating Sources

A summary of the results of the probability of avoidance analysis is given in Table B-6a for the playback stimuli and the air gun. An estimate of the effective range of the original petroleum industry sources was made by assuming that they were operating in the test area off the California coast. This was necessary because TL characteristics for the original source locations were not available (except for the drillship). The measured TL characteristic for the test area was used for ranges greater than 100 m with the assumption that the original source was at the playback source position. For ranges less than 100 m a 20 log (R) characteristic was assumed. With these assumptions, Table B-6b was developed which shows the effective range of the sources for a 0.5 probability of avoidance. Note that the effective range of most of the noise sources is estimated to be less than 100 m based on the playback spectrum exposure level.

In making this estimate of effective range, the response threshold of gray whales for low frequency noise components below 40 Hz was considered to be comparable to that in the playback range above 40 Hz. The low frequency sound exposure levels producing a 0.5 avoidance probability for each source were thus considered to be equal to the values determined using the playback data for that source. The effective range values estimated for the low frequency components should thus be

TABLE B-6a. COMPARISON OF PROBABILITY OF AVOIDANCE LEVELS FOR THE TEST STIMULI FOR MIGRATING GRAY WHALE EXPERIMENTS AT SOBERANES POINT, CALIFORNIA.

Stimulus Level, dB re 1 μPa

P_a	Drillship	Drilling Platform	Production Platform	Helicopter	Semi-submersible	Avg. Playback	Air Gun (Seismic Array)
0.1	110	114	120	115	115	115	164
0.5	117	117	123	120	120	119	170
0.9	122	>128	>129	>127	>128	>127	>180

TABLE B-6b. EFFECTIVE RANGE IN TEST AREA FOR $P_a = 0.5$

	Drillship	Drilling Platform	Production Platform	Helicopter	Semi-submersible	Air Gun	Seismic Array[5]
Sound Level at 100 m	136[1]	89 (109)[2]	109 (118)	103[2] (118)	101 (111)	180	212 (dB re 1 μPa)
Sound Level for $P_a = 0.5$	117	117	123	120	120	170	170 (dB re 1 μPa)
Required TL Change	19	-28 (-8)	-14 (-5)	-17 (-2)	-19 (-9)	10	42 (dB re 1 m)
Est. Range for $P_a = 0.5$	1.1 km	4 m (40 m)	20 m (56 m)	14 m[4] (79 m)	11 m (35 m)	400 m	2.5 km

NOTES:

1. Estimated sound level at 100 m for broadband or summed tonal components of original source included with good fidelity in playback (from Table 3.1, Malme et al. 1984).
2. Estimated sound level at 100 m of loudest low frequency tonal components of original source not reproduced adequately by playback (from Table 3.1, Malme et al. 1984).
3. These levels are estimated for a direct flyover at an altitude of 100 m.
4. These values are altitude predictions for producing 120 dB in the water at a point just below the surface for a direct flyover.
5. Data from Malme et al. 1983, array orientation-broadside.
6. Referred to transmission loss at 100 m.

conservative since it is probable that the low frequency response threshold of whales increases at low frequencies as an adaptation to the fact that levels of low frequency ambient noise in the ocean tend to increase as frequency decreases.

The values of 1.1 km for the drillship and 2.5 km for the seismic array for a 0.5 probability of avoidance show that these sources are much more important from the standpoint of potential effects on migration behavior of gray whales than are the drilling platform, production platform, semisubmersible rig, and helicopter sources which have only short range effects for the examples tested.

B.6.4 Results for Playback and Seismic Source Experiments With Summering and Feeding Gray Whales

This is a summary of the results of an investigation of the potential effects of underwater noise from petroleum industry activities on the behavior of feeding gray whales (Eschrichtius robustus) (Malme et al. 1986). The objectives of the study were to determine the character and degree of response of feeding gray whales to playbacks of industrial noise or actual seismic sound sources and to develop predictive models of the potential zones of influence of various types of industrial noise sources for important gray whale habitats such as Chirikof Basin and Unimak Pass. The noise sources used were playback of drillship sound and a single 100 cu. in. air gun. The work was performed in the Bering Sea near Southeast Cape, St. Lawrence Island, during August 17-28, 1985.

Experimental Procedure

The acoustic environment of the test area was measured by determining the propagation loss and ambient noise levels. The output source levels of the playback source and the air gun were calibrated. These measurements permitted calculation of the test stimulus level at sighted whale positions. Ambient noise in the test area was generally low and controlled by wind-generated sea noise. Sound transmission was found to be more efficient than is usual for shallow water areas with a sand/silt bottom because of the probable presence of a sub-bottom rock layer.

Whale behavior data were obtained by close observation of focal whale groups, recording surfacing-dive and blow information. In addition, tracking of the focal groups was performed using a two-vessel triangulation procedure or a land-based theodolite when weather permitted. The experimental procedure involved location of feeding whales, observation of behavior during a control period with the support vessels present, observation of behavior during an experiment period with the sound stimulus on, and observation of behavior during a post-experiment control period. Generally, several of these sequences were performed each day.

Surfacing-Dive and Blow Rate Analysis

The four basic characteristics used to describe the surfacing-dive behavior of gray whales were (1) respiration or blow interval, (2) length of surfacing, (3) length of dive, and (4) number of blows per surfacing. Blow rate was calculated from these data. For drillship sounds, blow intervals decreased and length of surfacing, length of dive, and number of blows per surfacing increased. Blow rate changed little. Recovery back to a pre-disturbance level occurred in about 30 min. after the stimulus was turned off. For air gun sounds, the characteristics changed in a reverse order. Blow intervals were increased, but length of surfacing, length of dive, and number of blows per surfacing all decreased. Blow rate did not change significantly except for high exposure levels when it increased - usually accompanied by cessation of feeding and movement away from the air gun vessel. Recovery to "normal" levels after exposure was less rapid than that for drillship sounds, requiring about one hour.

Whale Movement Analysis

Because of visibility conditions and the distance of feeding areas from shore, it was not feasible to use land-based theodolite tracking procedures except for one day. A two-vessel tracking procedure using a theodolite and binocular-compass provided sighting data which were analyzed using a computer-implemented triangulation program to determine whale distances from the sound source. the absolute position of the test geometry was determined using Loran C.

Limited data obtained for drillship playback sequences did not show any consistent pattern of feeding disturbance or avoidance of the sound source for levels up to 110 dB re 1 μPa; however, some whales were observed to leave the test area during an experiment when levels reached about 119 dB. The behavioral response of feeding gray whales to air gun sound was highly varied. At high exposure levels up to 176 dB (average pulse pressure level), some whales would continue feeding while others would stop feeding and move away from the sound source area. One whale was observed to leave a feeding area for an exposure level of about 150 dB. Most whales returned and resumed feeding after the air gun vessel had moved on.

Sound Transmission Modeling

The results of the sound propagation modeling were used for prediction of zones of influence for air gun array, air gun, and drillship sounds in the Chirikof Basin and Unimak Pass areas. The modeling procedure used both analytic and semi-empirical techniques assisted by measured data and data obtained from the literature. The whale migration corridor near Unimak Island is in shallow water near shore so it was necessary for the model to predict upslope sound propagation characteristics as well as characteristics for sound propagation in water of constant depth.

Conclusions

The data base obtained from the field study will not support the detailed statistical analysis required to obtain behavioral measures highly quantized in terms of noise exposure level. However, it is possible to assign at least two general response levels to the stimuli used in the study.

For the drillship stimulus it is recommended that 110 dB be considered as the lowest level which may possibly cause disturbance of feeding activity. This was the level that was observed to cause an onset of avoidance behavior for migrating gray whales. Until more data are available, it is recommended that 120 dB be considered as the level which will probably cause avoidance of a potential feeding area near an industrial site by more than 50% of the local gray whale population. A level of 119 dB resulted in a 0.5 probability of avoidance for the average of all the playback stimuli tested with migrating gray whales.

Because of the wide range of responses of feeding gray whales to air gun noise, it is recommended that an average pulse pressure level of 163 dB be considered the level at which the disturbance of feeding activity is possible. It is also recommended that 173 dB be considered the level at which cessation of feeding activity and temporary movement away from the feeding area are probable for at least 50% of whales exposed.

By using the sound level criteria given above together with the sound propagation model, it is possible to predict zones of influence for specific source types. For an air gun array with a peak beam pressure level of 250 dB, an average pulse pressure level of 173 dB will occur at a range of 2.6 km in the Chirikof Basin and at 2.8 km offshore of Unimak Island. For the EXPLORER

II drillship, a level of 120 dB will occur at a range of 300 m in the Chirikof Basin, and at a range of 500 m offshore of Unimak Island.

Recommendations

Augmentation of the available data is necessary to have a better statistical basis for establishing sound exposure criteria for feeding gray whales.

An extended field study should be performed early in the season when the whale population is larger and weather conditions better. The St. Lawrence Island site would be desirable for this study because of the available high ground for a theodolite station. Potentially, this would eliminate the need for a second large support vessel and reduce the cost for the project.

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Swartz, S.L., and M.L. Jones, 1980. Gray whales, Eschrichtius robustus, during the 1977-1978 and 1978-1979 winter seasons in Laguna San Ignacio, Baja California Sur, Mexico. U.S. Dept. Commer., NTIS PB80-202989, 35 p.

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APPENDIX C

THE POTENTIAL EFFECTS OF SOUND GENERATED BY OFFSHORE OIL AND GAS EXPLORATION AND DEVELOPMENT ON THE BOWHEAD WHALE, *Balaena mysticetus*, IN THE BEAUFORT SEA: AN ANNOTATED BIBLIOGRAPHY

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APPENDIX C: THE POTENTIAL EFFECTS OF SOUND GENERATED BY OFFSHORE OIL AND GAS EXPLORATION AND DEVELOPMENT ON THE BOWHEAD WHALE, *Balaena mysticetus*, IN THE BEAUFORT SEA: AN ANNOTATED BIBLIOGRAPHY

C.1 Introduction

In recent years there has been a rapid growth in the available information on the bowhead whale in the Beaufort Sea. Much of this information has come from three sources: 1) Department of the Interior (DOI) sponsored (BLM/MMS) studies on bowhead whale distribution, abundance, and behavior and the potential effects of Outer Continental Shelf exploration and development on the bowhead whale and other marine mammals; 2) Yearly spring ice counts of bowhead whales passing Pt. Barrow, Alaska, sponsored by the North Slope Borough/National Marine Fisheries Service; and 3) DOI-sponsored (BLM/MMS) anatomical studies on bowhead whales taken in the subsistence hunt.

This annotated bibliography focusses on the potential effect of underwater sound generated by Outer Continental Shelf related exploration and development activities on the bowhead whale in the Beaufort Sea. Although this bibliography is not an exhaustive review of the literature, it does cover much of the currently available information on this topic. At the end of this bibliography a list of additional research reports on the bowhead whale in the Beaufort Sea is included. These reports were not available at the time that this bibliography was prepared. They will be obtained and annotated for the final report.

Braham, H., B. Krogman, J. Johnson, W. Marquette, D. Rugh, M. Nerini, R. Sonntag, T. Bray, J. Brueggeman, M. Dahlheim, S. Savage, and C. Goebel (1980), "Population Studies of the Bowhead Whale (*Balaena mysticetus*): Results of the 1979 Spring Research Season." In Reports of the International Whaling Commission 30:391-404.

During tests conducted on the response of migrating bowhead whales to helicopter overflights, Braham et al. report that 11% of 160 whales exhibited an escape reaction to a Sikorsky H52-A helicopter flying at altitudes of 152 m and 228 m. There was no significant difference when comparison was made between responses at 152 m and 228 m.

Davis, R.A. and D.H. Thompson (1984), "Marine Mammals." In: Proceedings of a Synthesis Meeting: The Barrow Arch Environment and Possible Consequences of Planned Offshore Oil and Gas Development, J.C. Truett (ed.), p. 47-79, Oct. 30-Nov. 1, 1983, Girdwood, AK. OCSEAP, Anchorage, AK, 229 p.

Davis and Thompson present a review of bowhead whale industrial noise disturbance studies to 1983. They summarize many of the studies referred to in this annotated bibliography, particularly the work by LGL Ltd. for the U.S. Minerals Management Service.

Fraker, M.A. and P.N. Fraker (1979), "The 1979 Whale Monitoring Program MacKenzie Estuary." Unpublished report from LGL Ltd., environmental research associates, Sidney, B.C., for ESSO Resources Canada Ltd., Edmonton, Alberta, 51 p.

Brief mention is made of bowhead whales observed near ESSO operations in the offshore waters of the Canadian Beaufort Sea during 1976 through 1978. It is recommended that systematic aerial surveys should be done to compliment the sighting data by industrial personnel.

Hickie, J. and R.A. Davis (1983), "Distribution and Movements of Bowhead Whales and Other Marine Mammals in the Prudhoe Bay Region, Alaska, 26 September to 13 October 1982." In: Biological studies and monitoring at Seal Island, Beaufort Sea, Alaska, 1982, B.J. Gallaway (ed.). Unpublished report from LGL Ecological Research Associates, Inc., Bryan, TX, for Shell Oil Co., Houston, TX, 149 p.

Three methods were used to monitor marine mammals in the study area: 1) Acoustic, using two sonobuoys at Seal Island (70° 20.5'N, 148° 41.56'W) between 22 to 26 September; 2) Shore-based observations from Seal Island from 30 September to 4 October; and 3) Aerial surveys near Seal Island and Tern Island (70° 16.75'N, 147° 29.7'W) from 30 September to 13 October. A deHavilland Twin Otter flying at an altitude of approximately 152 m (a.s.l. - above sea level) was used for the aerial surveys. Bowhead whale vocalizations were heard faintly and "quite frequently" between 22 to 25 September. No bowhead whales were observed during shore-based watches. During aerial surveys between 30 September and 6 October at least 21 bowhead whales were seen with all but one sighted outside the 18 m depth contour. All whales observed were moving to the west or northwest. Based on the migration and sitribution data reported by Ljungblad and co-workers, it was concluded that "...the lack of observations of bowheads in the immediate vicinity of Seal and Tern Islands does not suggest that the animals were avoiding these islands. Rather, it indicates that bowheads were following their usual migration route which is more commonly in waters deeper than those in which these artifical islands are sited." (p. 114)

Ljungblad, D.K. (1981), "Aerial Surveys of Endangered Whales in the Beaufort Sea, Chukchi Sea, and Northern Bering Sea." Unpublished Report from Naval Ocean Systems Center, San Diego, CA, for U.S. Bureau of Land Management, Washington, D.C., NOSC TD 449, 302 p.

Ljungblad and co-workers conducted aerial surveys during the summer (April to June) and fall (September to November) 1980 in the Alaskan Beaufort Sea and adjacent waters. The survey aircraft was a Grumman Turbo Goose flown at a mean altitude of 244 m. Altitude depended upon visibility conditions. During the summer surveys, the response of bowhead whales to the aircraft became more noticeable as the whales moved northward toward Pt. Barrow and eastward past Pt. Barrow. The reaction of bowhead whales near the Bering Strait was described as "minimal." Near Pt. Barrow, approximately 70% of the whales reacted to the survey aircraft by diving. The whales sighted past Pt. Barrow all doveon approach of the aircraft. Possible reasons for this differential response pattern were noted as an increase in ice cover and hunting pressure as the whales passed Pt. Barrow. During the fall, aerial surveys suspected feeding whales near Demarcation Bay showed little response to the aircraft, however, actively migrating whales "...nearly all reacted to the aircraft by diving." (p. 39)

Ljungblad, D.K., S.E. Moore, D.R. Van Schoik, and C.S. Winchell (1982), "Aerial Surveys of Endangered Whales in the Beaufort, Chukchi, and Northern Bering Seas." Unpublished report from Naval Ocean Systems Center, San Diego, CA, for U.S. Bureau of Land Management, Washington, D.C. NOSC TD 486, 374 p.

Aerial surveys using a Grumman Turbo Goose were conducted in the Alaskan Beaufort Sea and adjacent waters during 1981. Survey altitude varied between 153 m and 305 m with a maximum altitude of 450 m if circling over bowhead whales while collecting behavioral data. Altitude depended upon visibility conditions. No comment is made on the possible effects of aircraft surveys on the behavior of bowhead whales in the Beaufort Sea. However, it is briefly mentioned that during spring surveys (April to May) no overall response by bowhead whales to the survey aircraft was observed south of the Bering Strait, even at altitudes as low as 60 m. Appendix A gives the position of each bowhead or group of bowheads sighted during all surveys along with aircraft altitude and a brief description of behavior.

Ljungblad, D.K., S.E. Moore, and D.R. Van Schoik (1983), "Aerial Surveys of Endangered Whales in the Beaufort, Eastern Chukchi, and Northern Bering Seas, 1982." Unpublished report from Naval Ocean Systems Center, San Diego, CA, for U.S. Minerals Management Service, Anchorage, AK. NOSC TD 605, 382 p.

Aerial surveys were conducted in the Alaskan Beaufort Sea and adjacent waters during the fall, 1982. Survey aircraft was a Grumman Turbo Goose flown at altitudes ranging from 40 m to 458 m, depending upon visibility conditions. Various responses to the aircraft were observed with the most responses noted during 1 to 31 August with 97% (n = 105) of the bowheads showing some sort of reaction. Responses most often included a change in speed or direction of movement, diving, or a change from "quiescent" to active behavior. During late September, most bowheads, 92% (n = 227), exhibited no apparent response to the survey aircraft. Ljungblad et al. noted that during this time period more whales appeared to be feeding than during August and the whales were in shallower, ice free waters as opposed to the whales in August which were observed in heavy ice conditions in deeper water.

Ljungblad, D.K., S.E. Moore, and D.R. Van Schoik (1984), "Aerial Surveys of Endangered Whales in the Northern Bering, Eastern Chukchi, and Alaskan Beaufort Seas, 1983: With a Five Year Review, 1979-1983." Unpublished report from Naval Ocean Systems Center, San Diego, CA, for U.S. Minerals Management Service, Anchorage, AK. NOSC TR 955, 370 p.

Aerial surveys during spring (April to May) and fall (August to October) 1983 were conducted in the Alaskan Beaufort Sea and adjacent water using a Grumman Turbo Goose at altitudes of 30 m (very short duration) to 460 m. Altitude depended upon visibility. During spring surveys, 44% (87/199) of bowhead whales observed showed some apparent response to the aircraft. Responses included abrupt dives, course change, or a cessation of some behavior noted before the aircraft was over the whales. During fall survey work, Ljungblad and co-workers noted that most apparent responses to the aircraft occurred during 1 to 15 August. The responses were generally from resting whales. Behavioral changesin resting whales would be more readily noticeable by survey personnel than perhaps other kinds of behavioral changes. Ice cover from 1 to 15 August was classified as being lighter than for the rest of the season. A behavior termed "huddling," where a group of whales would come together into close contact, was observed twice. Survey altitude at thesetimes was 305 m and 460 m. This behavior was noted as being a possible response to the survey aircraft but this interpretation remains speculative.

Ljungblad, D.K., B. Würsig, R.R. Reeves, J.T. Clarke, and C.R. Greene, Jr. (1984), "Fall 1983 Beaufort Sea Seismic Monitoring and Bowhead Whale Behavior Studies." Unpublished report for U.S. Minerals Management Service, Anchorage, AK, under Interagency Agreement No. 14-12-0001-29064, 180 p.

Ljungblad et al. attempted to conduct controlled experiments on the effects of seismic profiling on bowhead whales in the Alaskan Beaufort Sea during fall 1983. However, heavy ice conditions in the study area precluded any experiments. Aerial observations were carried out using a deHavilland Series 300 Twin Otter at an altitude of approximately 460 m (a.s.l.). The study period was 18 August to 30 September. The following criteria were used in categorizing undisturbed whales: 1) altitude of aircraft not below 457 m (a.s.l.); 2) "...no moving vessel within 5.0 km of the whales; and 3) no underwater industrial activity noise could be heard via sonobuoys monitored in the aircraft." (p. 24) Although no controlled experiments could be conducted, a limited amount of surfacing, respiration, and dive data was collected on whales exposed to seismic noise and whales that were presumably undisturbed. On the three days when usable data were collected on whales exposed to seismic activity, the operating vessels were 42 to 57 km from the whales. Results showed that: 1) the number of blows per surfacing was significantly lower for whales exposed to seismic noise; 2) blow intervals were longer (not significantly) for whales exposed to seismic noise; and 3) the length of surfacing and dive were not significantly different when the two conditions were compared, but showed a tendency to increase during seismic noise conditions. Received sound levels at the whales under observation were not given. Much of the report is devoted to giving data on the undisturbed behavior of bowhead whales. Comparisons are also made between the results of this study and other studies on the bowhead whale in the Beaufort Sea.

Ljungblad, D.K., S.E. Moore, J.T. Clarke, D.R. Van Schoik, and J.C. Bennett (1985), "Aerial Surveys of Endangered Whales in the Northern Bering, Eastern Chukchi, and Alaskan Beaufort Seas, 1984: With a Six Year Review, 1979-1984." Unpublished report from Naval Ocean Systems Center, San Diego, CA, for U.S. Minerals Management Service, Anchorage, AK. NOSC TR 1046, OCS Study, MMS 85-0018, 315 p.

Aerial surveys were conducted using a Grumman Turbo Goose during fall 1984 in the Alaskan Beaufort Sea and adjacent waters. Less than 5% of the bowhead whales observed (18/380) showed possible responses to the survey aircraft. The mean survey altitude when possible responses were observed was 200 m vs. 373 m during all other bowhead sightings. Almost all of the whales that showed possible responses were classified as lone individuals or pairs. This response rate was lower than in previous years (1979-1983).

Ljungblad, D.K., B. Würsig, S.L. Swartz, and J.M. Keene (1985), "Observations on the Behavior of Bowhead Whales (*Balaena mysticetus*) in the Presence of Operating Seismic Exploration Vessels in the Alaskan Beaufort Sea." Unpublished report from SEACO, Inc., San Diego, for U.S. Minerals Management Service, Anchorage, AK. OCS Study, MMS 85-0076, 78 p.

Ljungblad et al. conducted aerial observations of bowhead whales in the Alaskan Beaufort Sea from herschel Island to Pt. Barrow between 18 August and 3 October 1984. The survey aircraft was a deHavilland Series 300 Twin Otter flown at altitudes ≥457 m (a.s.l.). Four experiments were conducted under controlled conditions, each experiment using a different seismic vessel. Overall, no apparent behavioral changes were noted when the vessel was >10 km from the whales. Behavioral changes were detected when the whales were within 5 to 7 km of the vessel. Received sound levels at the whales was estimated to be between 142 to 164 dB re $1 \mu Pa$ during this time. Avoidance reaction by bowheads to full scale seismic operations was observed at distances from the vessel between 3.5 to 5 km with estimated received sound levels of 160 to 170 dB re 1μPa. Overall, bowhead whales showed an increase in blow interval and a decrease in the number of blows per surfacing, length of surfacing, and length of dive in the presence of seismic noise. Indications were that these changes in the surfacing and respiration characteristics of bowheads exposed to seismic noise were short-term in nature because they were approaching pre-seismic levels within 30 to 60 min. after the end of a seismic experiment. Ljungblad et al. noted that the results obtained in this study are generally consistent with those of other studies.

Moore, S.E., D.K. Ljungblad, and D.R. Schmidt (1984), "Ambient, Industrial, and Biological Sounds Recorded in the Northern Bering, Eastern Chukchi, and Alaskan Beaufort Seas During the Seasonal Migrations of the Bowhead Whale (Balaena mysticetus), 1979-1982." Unpublished report from SEACO, Inc., San Diego, CA, for U.S. Minerals Management Service, Anchorage, AK, 104 p.

Although this document is not primarily concerned with assessing the effects of industrial noise on bowhead whale behavior, it is included here because of the information it presents on bowhead whale vocalizations, ambient noise levels, and industrial noise characteristics in the Alaskan Beaufort Sea. These data are integrated into a source-path-receiver model to predict the range at which industrial noise could be detected by bowhead whales.

Reeves, R., D. Ljungblad, and J.T. Clarke (1983), "Report on Studies to Monitor the Interaction Between Offshore Geophysical Exploration Activities and Bowhead Whales in the Alaskan Beaufort Sea, Fall 1982." Unpublished report for U.S. Minerals Management Service, Anchorage, AK, under Interagency Agreement No. 41-12-0001-29064, 180 p.

Reeves, R.R., D.K. Ljungblad, and J.T. Clarke (1984), "Bowhead Whales and Acoustic Seismic Surveys in the Beaufort Sea." Polar Record 22(138):271-280.

Reeves et al. conducted aerial observations of bowhead whales in the Alaskan Beaufort Sea from 14 September to 2 October 1982. The survey aircraft was a Grumman Turbo Goose flown at an altitude of approximately 305 m (a.s.l.) depending on visibility conditions. The area surveyed was approximately 142°W to 154°W. Controlled experiments on the response of bowhead whales to seismic noise were not possible because of heavy ice conditions and regulatory area closures to seismic operations. Behavioral observations were made on six days during mid to late September. Survey aircraft altitude on these flights varied from 411 to 457 m (a.s.l.). On 14 September what was a possible reaction to the onset of seismic operations was noted within 30 min. after a seismic vessel, 33 km distant, began operations. A spread out group of whales, oriented randomly, exhibiting synchronous and asynchronous surfacing patterns, came together within 30 min. after seismic operations started. The whales oriented towards each other and surfacing patterns were described as being synchronous. A similar behavioral change occurred during observations on 24 September, however, no seismic noise was detected at this time. This "huddling" behavior was also noted by Ljungblad, Moore, and Van Schoik (1984 - see this bibliography) in possible response to the survey aircraft. Overall, results showed that bowhead whales classified as "adult" "...appeared to spend significantly longer at the surface in the presence of seismic sounds." (p. 278, Reeves, et al. 1984.) The authors note that caution must be used in interpreting the results of this study because of the lack of experimental control and the area closures to seismic operations as bowhead whales began moving through the area.

Richardson, W.J., C.R. Greene, J.P. Hickie, and R.A. Davis (1983), "Effects of Offshore Petroleum Operations on Cold Water Marine Mammals: A Literature Review." Report from LGL Ltd., Environmental Research Associates, Toronto, for American Petroleum Institute, Washington, D.C. API Report No. 4370, 248 p.

This review covering literature up to and including 1982 provides a detailed introduction to the potential effects of petroleum operations on marine mammals. The review is separated into three broad sections: Petroleum industry acoustic, non-acoustic, and cumulative impacts on marine mammals. Summaries are presented of work on the assessment of acoustic impacts on bowhead whales including the LGL work in the Canadian Beaufort Sea. The work by Ljungblad and co-workers in the Alaskan Beaufort Sea is also detailed.

The most extensive work to date on the assessment of offshore industrial noise impacts on bowhead whales is the five year study conducted in the Canadian Beaufort Sea by LGL Ecological Research Associates for the U.S. Minerals Management Service. A detailed summary of this work was prepared in 1985:

Richardson, W.J., C.R. Greene, and B. Würsig (1985), "Behavior, Disturbance Responses, and Distribution of Bowhead Whales *Balaena mysticetus* in the eastern Beaufort Sea, *1980-84: A Summary.*" Unpublished report from LGL Ecological Research Associates, Inc., Bryan, TX, for U.S. Minerals Management Service, Reston, VA. OCS Study, MMS 85-0034, 30 p.

Because of the number of reports and publications that have resulted from this long-term study, we have chosen to annotate three recent documents which will provide an overview of the results. For specific details not covered in these annotations, the yearly LGL unpublished reports to the Minerals Management Service should be consulted.

Richardson, W.J., R.A. Davis, C.R. Evans, and P. Norton (1985), "Distribution of Bowheads and Industrial Activity, 1980-84." In: Behavior, Disturbance Responses and Distribution of Bowhead Whales (*Balaena mysticetus*) in the eastern Beaufort Sea, 1980-84, W.J. Richardson (ed.). Unpublished report from LGL Ecological Research Associates, Inc., Bryan, TX, for U.S. Minerals Management Service, Reston, VA. OSC Study, MMS 85-0034, 306 p.

The database for this assessment extends beyond the distribution of bowhead whales noted during the five year LGL study on bowhead whale behavior and disturbance. It includes all systematic surveys for bowheads in the Canadian Beaufort Sea, Ljungblad and co-workers' surveys that extended into the Canadian Beaufort Sea, and photogrammetric and other studies in the Canadian Beaufort Sea. The database covers 1980 to 1984, however, information on bowhead whale distribution between 1976 to 1979 was also compiled. For each year (1980 to 1984) the following data are given in detailed maps of the study area: 1) The location and number of bowheads by 10 to 11 day periods, 1 August to 10 September, with each 10 to 11 day period divided into first five days, last 5 to 6 days (all survey routes are depicted); 2) Vessel traffic, with approximate number of trips and routes travelled, between industrial sites (these industrial sites are identified as to type); 3) Helicopter traffic between the various industrial sites with number of trips between sites (this data is limited to 1981 to 1984); 4) Location of seismic lines run, indicating the type of seismic operation, i.e., large array, sleeve exploder, etc.; and 5) Ice conditions. From this extensive examination Richardson et al. conclude that, although the data show that bowheads were present in the main offshore industrial area three of five years from 1976 to 1980 and none of four years from 1981 to 1984, and that industrial activity has gradually increased over all years surveyed, the year-to-year variability of bowhead distribution throughout the entire study area and the unknown interaction between oceanographic/ meteorological factors and prey availability, it is not possible (at this time) to equate increased industrial activity with variation in bowhead whale distribution and abundance. Richardson et al. go on to note that the seismic operations data suggest that bowheads have not abandoned those areas where seismic operations have occurred. However, they caution that the whales returning to areas where seismic operations have occurred may not be the same whales that were previously exposed.

Richardson, W.J., R.S. Wells, and B. Würsig (1985), "Disturbance Responses of Bowheads, 1980-84." Behavior, Disturbance Responses and Distribution of Bowhead Whales (Balaena mysticetus) in the Eastern Beaufort Sea, 1980-84, W.J. Richardson (ed.). Unpublished report from LGL Ecological Research Associates, Inc., Bryan, TX, for U.S. Minerals Management Service, Reston, VA. OSC Study, MMS 85-0034, 306 p.

This report presents all data from the 1980 to 1984 LGL disturbance and behavior study. We limit our discussion to non-seismic industrial noise disturbance results (1980 to 1984). See Richardson et al. (1986) (the next annotation in this bibliography) for a review of seismic noise and bowhead whale behavior.

During this study almost all aerial observations were conducted using a Britten-Normal BN-2A-21 Islander (C-GYTC). A deHavilland DHC-6-300 Twin Otter (CG-BDR) was used during part of the 1983 season. Aircraft altitude was 457 m or 610 m (a.s.l.) except during aircraft disturbance experiments or when visibility conditions necessitated a change.

Based on aircraft disturbance trials and opportunistic observations at various altitudes, Richardson et al. conclude that bowhead whales sometimes react when aircraft altitude is $\leq$ 305 m, infrequently react when the aircraft was at 457 m, and when the aircraft was $\geq$ 610 m, reaction was generally undetectable. Most reactions observed were classified as "hasty dives" with hasty surfacings, orientation changes, other activity changes, or movement out of the area (rarely) also noted. Blow intervals tended to be of shorter duration when the aircraft was circling overhead at $\leq$ 305 m vs. 457 m and/or 610 m. Richardson et al. point out the difference between the reactions observed during one overflight vs. prolonged circling. No apparent reaction was caused by single helicopter overflights at 153 m. However, the whales were below the surface on each of the five occasions that the helicopter was present.

Bowhead response to close approaches by vessels proved to be the strongest and most consistent reactions observed during the 1980 to 1984 study period. Rapid swimming away from approaching vessels was observed at 1 to 4 km. As the vessel came within a few hundred meters, the whales would turn or swim away from the vessel path or dive. Analysis of surfacing and respiration characteristics showed a decrease in surface time and number of blows per surfacing during avoidance behavior. Avoidance of the vessel was very short term, however; the resulting scattered distribution of the whales lasted longer. Variability was noted in how individual whales reacted to approaching vessels.

During opportunistic observations near active drilling sites, bowheads engaged in seemingly normal behavior patterns. Received sound levels at the whales during these observations was not known, however; measurements made at one drill site showed sound levels at 121 to 130 dB re 1μPa at 1.1 km during a period of no drilling. Playbacks of drilling noise did not cause significant changes in surfacing and respiration characteristics, however; there was a "hint" of reduced dive durations and vocalization rates. There was also a weak tendency for whales to orient away from the playback vessel. Received sound levels at the whales during these playbacks was estimated to be 100 to 125 dB re 1μPa.

During opportunistic observations of bowheads near dredging operations, no discernable reactions were noted. Bowheads were observed from 0.8 to 13 km from the dredging operations with received sound levels estimated to be 111 to 120 dB re 1μPa. During dredge noise playbacks, bowheads tended to orient away from the playback vessel and in 2 of 3 experiments, the tendency to move away was noted as "strong." During the playbacks, bowheads were 0.1 to 2.25 km away with received sound levels estimated to be 109 to 132 dB re 1μPa. During one experiment, whales apparently stopped near bottom feeding and moved > 2 km from the playback vessel over a 30 min. period. Received sound level during this experiment was estimated to be 119 to 132 dB re 1μPa.

Overall, results showed that short-term fluctuations in bowhead whale behavior do occur in response to industrial activities, particularly to those activities "...that are transient and those that are starting up." (p. 16 in Richardson, Greene, and Würsig 1985 summary report.)

Richardson, W.J., B. Würsig, and C.R. Greene, Jr. (1986), "Reactions of Bowhead Whales, Balaena mysticetus, to Seismic Exploration in the Canadian Beaufort Sea." Journal of the Acoustical Society of America, 79(4):1117-1128.

From 1980 to 1984, Richardson et al. observed the reactions of bowhead whales in the Candian Beaufort Sea to: 1) distant operating seismic vessels not under experimental control; 2) controlled approaches of seismic vessels; and 3) controlled tests using a single 0.66-l Bolt air gun.

Opportunistic observations were madeon bowhead whales exposed to seismic noise on 21 occasions. Vessel distance from whales ranged from 6 to 99 km with received sound levels at the whales estimated to be 107 to 158 dB re 1μPa. There was no evidence that bowheads moved away from active seismic vessels that were ≥ 6 km distant. There were indications that changes did occur in surfacing, respiration, and dive characteristics with fewer blows/surfacing, shorter surface and dive times, and longer blow intervals for whales exposed to seismic noise when matched results were pooled from 1980 to 1984 observations. However, because of variability, overlapping of values, contrary trends on specific occasions, and the opportunistic nature of the observations, Richardson et al. note that results should be viewed with caution. It is also noted that observations on one whale whose behavior may have been the result of aircraft disturbance strongly affected the pooled data. If the data on this whale are removed, number of blows per surfacing and surface duration, seismic vs. non-seismic, show no significant difference. Other behavioral changes occurred, including more turns and pre-dive flexes and reduced vocalization rate, however; these results are not conclusive.

Results from three moving air gun experiments show no measurable response of whales 3 to 5 km distant. However, during one of two stationary air gun experiments conducted at 2 to 4.5 km, whales oriented away when the air gun was fired. Received sound levels at the whales was estimated to be at least 124 to 131 dB re 1μPa. During the second experiment, whales were 0.2 to 1.2 km distant. The whales oriented and moved away from the vessel. Received sound levels were not measured but were "doubtlessly higher" than the previous experiment. Surfacing, respiration, and dive values were consistent with those obtained during opportunistic observations.

Multivariate analysis done to determine if distant seismic noise or single air gun affected surfacing and respiration characteristics (allowing for partial correlations to 17 variables) did not confirm the univariate trends. However, the results of the univariate analysis showing some effect of seismic operation on bowheads may be real "...given that many intercorrelated "whale activity" and environmental variables covaried in an uncontrolled fashion." (p. 1124) in the multivariate analysis. Discriminate analysis was done to compare the occurrence of various behavioral patterns in the presence and absence of distant seismic noise. Bottom-feeding and active socializing were found to be more common in the presence of seismic noise while turns were less common. However, variables such as water depth and year were not controlled for.

During a full-scale seismic experiment, whales reacted by orienting away from the vessel at the onset of firing. The vessel was 7.5 km distant. However, no other discernable change in the whales' behavior was noted. When the vessel was 3 km distant, whales stopped near-bottom feeding. The frequency of diving with flukes out decreasedwhen the vessel was approximately 1.5 km away. Two individually identifiable whales moved 2 km from their pre-seismic positions during the experiment.

At the time of the preparation of this bibliography, the following reports were not available. These reports will be requested, reviewed, and annotations will be included in the final report.

Davis, R.A., W.R. Koski, W.J. Richardson, C.R. Evans, and W.G. Alliston (1982), "Distribution, Numbers, and Productivity of the Western Arctic Stock of Bowhead Whales in the Eastern Beaufort Sea and Amundsen Gulf, Summer 1981." Unpublished report from LGL Ltd., Toronto for Sohio Alaska Petroleum Co. and Dome Petroleum Ltd. (co-managers), 134 p.

Davis, R.A., W.R. Koski, and G.W. Miller (1983), "Preliminary Assessment of the Length-Frequency Distribution and Gross Annual Reproductive Rate of the Western Arctic Bowhead Whale as Determined with Low-Level Aerial Photography, with Comments on Life History." Unpublished report from LGL Ltd., Toronto and Anchorage, for National Marine Mammal Laboratory, Seattle, WA, 91 p.

Davis, R.A., C.R. Creene, and P.L. McLaren (1985), "Studies of the Potential for Drilling Activities on Seal Island to Influence Fall Migration of Bowhead Whales Through Alaskan Nearshore Waters." Unpublished report from LGL Ltd., King City, Ontario, for Shell Western E&P Inc., Anchorage, AK, 70 p.

Davis, R.A., W.R. Koski, and G.W. Miller (1986), "Experimental Use of Aerial Photogrammetry to Assess the Long Term Responses of Bowhead Whales to Offshore Industrial Activities in the Canadian Beaufort Sea." Unpublished report from LGL Ltd., King City, Ontario, for Dept. Indian and Northern Affairs, Ottawa.

Harwood, L.A. and G.A. Borstad (1985), "Bowhead Whale Monitoring Study in the Southeastern Beaufort Sea, July-September 1984." Unpublished report from ESL Environ. Sci. Ltd., Sidney, B.C., for Envir. Stud. Revolv. Funds, Dept. Indian and Northern Affairs, Ottawa.

Harwood, L.A. and J.K.B. Ford (1983), "Systematic Aerial Surveys of Bowhead Whales and Other Marine Mammals in the Southeastern Beaufort Sea, August-September 1982." Unpublished report from ESL Environ. Sci. Ltd., Sidney, B.C., for Dome Petroleum Ltd. and Gulf Canada Resources Inc., Calgary, 76 p.

Johnson, S.R., C.R. Greene, R.A. Davis, and W.J. Richardson (1986), "Bowhead Whales and Underwater Noise Near Sandpiper Island Drillsite, Alaskan Beaufort Sea, Autumn 1985." Unpublished report from LGL Ltd., King City, Ontario, for Shell Western E&P Inc., Anchorage, AK (in review).

LGL, ESL, and ESSA (1984), "Beaufort Environmental Monitoring Project, 1983-1984 Final Report." Unpublished report for Northern Environmental Protection Branch, Dept. Indian and Northern Affairs, Ottawa, 292 p.

McLaren, P.L. and R.A. Davis (1985), "Distribution of Bowhead Whales and Other Mammals in the Southeast Beaufort Sea, August-September 1983." Environ. Stud. Revolv. Funds, Rep. No. 001. Dept. Indian and Northern Affairs, Ottawa, 62 p.

Renaud, W.E. and R.A. Davis (1981), "Aerial Surveys of Bowhead Whales and Other Marine Mammals Off the Tuktoyaktuk Peninsula, N.W.T., August-September 1980. Unpublished report from LGL Ltd., Toronto, for Dome Petroleum Ltd., Calgary, 55 p.