OCS Study
MMS 91-0037

ACOUSTIC EFFECTS OF OIL PRODUCTION ACTIVITIES ON BOWHEAD AND WHITE WHALES VISIBLE DURING SPRING MIGRATION NEAR PT. BARROW, ALASKA--1990 PHASE:

SOUND PROPAGATION AND WHALE RESPONSES TO PLAYBACKS OF CONTINUOUS DRILLING NOISE FROM AN ICE PLATFORM, AS STUDIED IN PACK ICE CONDITIONS

by

W.J. Richardson, C.R. Greene Jr., W.R. Koski and M.A. Smultea

assisted by

G. Cameron, C. Holdsworth, G. Miller, T. Woodley and B. Würsig

from

LGL Ltd., environmental research associates
22 Fisher St., POB 280, King City, Ont. L0G 1K0, Canada

for

U.S. Minerals Management Service, Procurement Operations
381 Elden St., MS2500, Herndon, VA 22070-4817

LGL Report TA848-5

October 1991

Contract 14-12-0001-30412

This study was funded by the Alaska Outer Continental Shelf Region of the Minerals Management Service, U.S. Dept. of the Interior, Anchorage, AK, under contract 14-12-00001-30412.

PROJECT ORGANIZATION

The 1990 phase of this contract was conducted by LGL Ltd., environmental research associates, assisted by subcontractor Greeneridge Sciences Inc. **LGL** organized the project as a whole, and conducted the biological aspects of the work. M. Smultea and B. Würsig of the Marine Mammal Research Program, Texas A & M University, worked with LGL on the biological components. **Greeneridge** was responsible for the physical acoustics components. The affiliations of the senior authors (in boldface) and co-authors are as follows:

W.J. Richardson, W.R. Koski, G. Cameron, C. Holdsworth,
G. Miller, and T. Woodley:
LGL Ltd., environmental research associates
22 Fisher St., POB 280, King City, Ont. L0G 1K0, Canada
(416)-833-1244

Charles R. Greene, Jr.
Greeneridge Sciences Inc.
4512 Via Huerto, Santa Barbara, CA 93110
(805)-964-9818

Mari A. Smultea and Bernd Würsig
Texas A & M University at Galveston, Dept. of Marine Biology
POB 1675, Galveston, TX 77553
(409)-740-4413

Another major contributor to the fieldwork was Kenneth Toovak Sr. of Barrow. Another major participant in the analysis was R. Blaylock of Greeneridge. Dr. John Hanna prepared Appendix A for Greeneridge.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Previous studies of the reactions of bowhead whales to noise from oil industry operations have all been conducted during late summer or early autumn, in open water or at most light ice conditions. Concern has arisen about potential reactions of bowheads to man-made noise in the leads through which bowheads migrate in spring. Particular concern has arisen about the possible effects of continuous noise from structures that might be used for oil production in or near spring lead systems.

Objectives

General Objectives

In response to this concern, the Minerals Management Service funded the present experimental study of the effects of noise from oil production activities on bowhead and (secondarily) white whales during their spring migrations around Alaska. The overall objectives of the study can be summarized as

1. To quantify sound transmission loss and ambient noise within nearshore leads off northern Alaska in spring, emphasizing propagation of underwater sounds produced by production platforms and icebreakers.
2. To quantify the short term behavioral responses of spring-migrating bowhead whales and, if possible, white whales to sounds from production platforms and icebreakers.
3. To assist and coordinate with other studies and local resource users to maximize collection of needed data and avoid conflict with subsistence whaling activities.
4. To analyze the data in order to test hypotheses concerning the effects of oil industry noises on the movement patterns and behavior of bowhead and white whales.

Specific 1990 Objectives

The specific objectives of the 1989 and 1990 phases of this project were similar. Because of the poor weather and ice conditions in 1989, and the low number of whales accessible in that year, the data on reactions to drilling platform sounds acquired in 1989 were too sparse to be conclusive. Hence, the highest priority during the 1990 field program, as in 1989, was to study the reactions of bowheads to noise from a bottom-founded drilling or production platform. When possible, reactions of white whales to this sound were to be determined as well. Underwater playback techniques were to be used to simulate the noise from an actual platform. As a lower priority, the reactions of bowheads and white whales to actual helicopter overflights were to be determined if opportunities allowed. Because of concern about the effects of low-frequency industrial sound components on bowheads, and the inability of a practical sound projector to reproduce those components, several indirect methods of addressing the importance of low frequency components were identified as objectives in 1990.

The specific objectives for the second field season, in 1990, were as follows:

1. To measure ambient noise levels and characteristics in leads and cracks along the spring migration corridor of bowhead and white whales in the western Beaufort

Sea, including infrasonic components. [Infrasounds are sounds at frequencies less than the lower limit of human hearing, generally taken to be 20 Hz.]

2. To measure and model transmission loss of underwater sound along that part of the spring migration corridor, based on playbacks of (a) test tones at selected frequencies between 50 Hz and 10 kHz, and (b) continuous drilling platform sound (*Karluk* sounds).
3. To measure the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of continuous drilling platform sound (*Karluk* and CIDS sounds).
4. To collect some of the data needed to assess the importance of the infrasonic components (<20 Hz) of industrial noise; specifically, to measure ambient noise at infrasonic frequencies, and determine whether bowhead calls contain infrasonic components.
5. To measure the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to actual helicopter overflights.
6. To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses and acoustic environment of bowheads and white whales along their spring migration corridor in the western Beaufort Sea.
7. To assist and coordinate with other studies and local resource users to maximize collection of needed data and to avoid interference with subsistence whaling and other studies.
8. To analyze the data to test hypotheses concerning the effects of the drilling platform sounds mentioned in (3) on (a) the movement patterns and (b) the behavior of bowheads and white whales visible along their spring migration corridor in the western Beaufort Sea.

Approach and Procedures

No oil production facilities have yet been constructed in or near the spring lead systems, so no recording of underwater sounds from such an operation exists. It was decided that sounds from one of the bottom-founded caissons used for exploratory drilling in the Beaufort Sea would be the most appropriate sounds to use. No recording of sounds from such a caisson operating in winter or spring ice conditions existed during the 1989 field program. Instead, as part of this project, sounds from drilling on a grounded ice platform were recorded near Prudhoe Bay in late March 1989. These sounds were used for all playback experiments in the spring of 1989. Because the 1989 sample size was inadequate, and for other reasons, it was decided to use the same drilling sounds for playbacks in 1990.

The study had to be conducted in such a manner that it did not interfere, and was not perceived to interfere, with either subsistence whaling or the spring bowhead census. Barrow is the northeasternmost community where there is spring whaling, and the census is also done just north of Barrow. After consultation with the Barrow Whaling Captains' Association, the Alaska Eskimo Whaling Commission, and the North Slope Borough's Dept of Wildlife Management, it was agreed in early 1989 that the most suitable location for playback experiments was about 60 km NE or ENE of Pt. Barrow. In 1990, it was agreed that the work could be done as close as 15 n.mi. (28 km) beyond the northeasternmost whaling camp.

The field crew consisted of two teams. *(1)* A helicopter-supported crew deployed a U.S. Navy J-11 underwater sound projector from ice pans, and used it to project recorded drilling platform sound into leads. When whales came within visible range of the projector site, the ice-based crew documented whale movements and behavior, using a surveyor's theodolite to measure the successive bearings and distances of whales from the projector. In addition, this crew measured the rate of attenuation of underwater noise with increasing distance from the source (in this case the projector). *(2)* A second crew, in a Twin Otter aircraft, located whales and suitable projector sites, documented the behavior of whales as they swam toward and past the projector, and (in 1989) obtained known-scale vertical photos of bowheads in order to identify individuals and measure their sizes. The aircraft crew also used naval sonobuoys to monitor underwater sounds near whales exposed to projected drilling sounds.

Whale observations obtained by the two crews were complementary. Ice-based observers obtained more detailed data on the paths and speeds of some whales that passed within 1-2 km of the projector, and observed whales even when there were low clouds. The aerial observers could observe whales at any distance from the projector site, and could follow them for longer distances. Aerial observers also had a much better vantagepoint for viewing the details of behavior. However, aerial observations were only useful when the cloud ceiling was at least 460 m (1500 ft) above sea level, since bowheads sometimes react to a circling observation aircraft if it flies lower than that altitude. Low cloud frequently interfered with behavioral observations in 1989, but did so less commonly in 1990.

The ice-based crew worked from the ice on 16 days between 27 April and 26 May 1990, and on 18 days between 29 April and 30 May 1989. They conducted transmission loss tests on four days in 1990 and five days in 1989. They projected *Karluk* drilling platform sounds into the water for several hours on each of 8 days in 1990 and 11 days in 1989. On 6 days in 1990 and 5 days in 1989, bowheads were observed in waters that were ensonified by the projected drilling platform sounds. The total number of bowheads seen near the operating projector was much greater in 1990. Control data on bowheads near the quiet projector were obtained on the same six dates in 1990 plus two additional non-playback days in 1990. White whales were seen near the operating projector on one day in 1990 and four days in 1989.

The aircraft-based crew conducted reconnaissance surveys on 23 days in 1990, from 29 April to 26 May; and on 24 days in 1989, from 1 to 30 May. The aerial crew conducted 29 behavior observation sessions on 12 days in 1990, and 17 sessions on 10 days in 1989. Behavioral observations totaled 46.8 h in 1990 and 25.6 h in 1989. Of these 72.4 h of observations over the two years, 43.9 h involved presumably undisturbed bowheads (control data) and 28.5 h involved potentially disturbed bowheads.

This report concerns primarily the 1990 results. A previous report presented the detailed results from 1989 (Richardson et al. 1990a, OCS Study MMS 90-0017, NTIS PB91-105486). However, the 1989 and 1990 data on bowhead behavior and reactions to noise playbacks are integrated in this report.

Physical Acoustics

Ambient Noise

Broadband levels of ambient noise usually were within the range expected for sea state zero (flat calm) to sea state four (moderate sea) spectra. The primary contributors to the ambient noise were animal calls, ice deformation noises, and small waves. High wind-driven seas could not develop with sea ice coverage exceeding 80-90%, and work in the Beaufort was rarely attempted when wind speed exceeded 20 knots (37 km/h). Ambient noise levels in the 20-1000 Hz band averaged slightly higher in 1990 (91 dB re 1 μPa) than in 1989 (85 dB). The increased amount of open water in 1990 may have been at least partly responsible.

The median ambient noise level on a 1/3-octave basis was 76-79 dB re 1 μPa for every 1/3-octave band from 12.5 through 1250 Hz, a two decade range. In contrast, third-octave levels usually tend to decline slowly with increasing frequency. Bearded seal calls were an important contributor to the ambient noise at levels from a few hundred to a few thousand Hertz. Although the median 1/3-octave levels were relatively flat across frequency, the 5th and 95th percentiles generally declined with increasing frequency.

Ambient noise levels within ¼-s intervals were very variable. When such measurements were made over various 8½-s and 1-min periods, it was found that the median of the ¼-s measurements tended to be less than the overall average for the corresponding 8½-s or 1-min period. The largest differences between median ¼-s values and the longer-term averages tended to occur on occasions with high ambient noise. These results indicate that marine mammals may be able to hear weaker sound signals than might be expected based on conventional ambient noise data averaged over several seconds or longer--especially on days with high average levels of ambient noise. Mammals may be able to hear weak signals during the instants when ambient noise is lower than average.

Transmission Loss Tests

Transmission loss (TL) tests were conducted on 1, 2, 24, and 25 May 1990. During each test, pure tones, sweeps, and a sample of *Karluk* drilling sounds were projected into the water at a base camp on the ice, and received levels were determined at distances ranging from 100 m to ~13 km.

In general, TL data derived from the three types of signals were similar; TL increased with range in the general manner expected. However, there were a few seemingly anomalous points, in most cases for tones. This was to be expected, given that received levels of tones are especially subject to constructive and destructive interference effects associated with multipath propagation.

Simple propagation models have been fitted to the 1990 TL data. Each of these models includes a logarithmic spreading loss term and a linear term accounting for absorption and scattering losses. Spreading loss at distances exceeding 100 m from the projector was found to range from 10 log (R) to 20 log (R), depending on the water depth. The linear loss terms accounted for an additional 2-4 dB/km in most cases. The linear loss coefficients found in this study were higher than those found during previous summer and autumn studies elsewhere in the Beaufort Sea during the open water season. The additional loss during this spring study was at least partly attributable to the effects of the rough underice surface. The results of the transmission loss tests were important in deriving equations to estimate the levels received by whales during the playback experiments.

Results from 1990 were comparable to those from 1989. Preliminary indications are that the bottom influence on sound transmission is about the same throughout the study area. The acoustic propagation behavior of the study area in late April and May appears to be comparable to that of the Chukchi Sea in winter.

Playback Tests

Useful disturbance tests were conducted on six days in 1990. Sounds recorded 130 m from the actual *Karluk* drillrig were used as the stimulus during all disturbance test playbacks in 1990 as well as 1989. A model J-11 underwater sound projector suspended at depth 18 m was used in every 1990 test.

For the overall 20-1000 Hz band, the average source level in 1990 was 166 dB re 1 µPa-m. The highest source level noted during a playback was 169 dB and the lowest was 163 dB. In 1989, the average source level in the 20-1000 Hz band was 165 dB. The source level of the actual *Karluk* drillrig is unknown but higher. However, propagation loss near the actual rig in very shallow water was more rapid than that in the deeper water around playback sites. As a result, during the 1990 playbacks, the 20-1000 Hz levels received <100 m (330 ft) from the projector were somewhat lower than those at corresponding distances from the actual rig. Levels 100-200 m from the projector and the actual rig were similar. Levels >200 m from the projector exceeded those at corresponding distances from the *Karluk* rig.

The J-11 projector was effective in broadcasting components of the drilling sound above 80 Hz. The projected sounds at frequencies below 80 Hz, and especially below 63 Hz, underrepresented the corresponding components of the actual *Karluk* drillrig sounds. Below 50 Hz there was little output, even though the original *Karluk* sounds contained significant energy down at least as low as 10 Hz. The inability of any practical projector to reproduce the lowest-frequency components of industrial sound is a concern, as discussed on pages 261-263. However, at distances of a few hundred meters from the projector, where some of the most interesting biological results were obtained, overall levels in the 20-1000 Hz band were similar to those at corresponding distances from the actual rig.

Levels and spectral characteristics of the projected drilling sounds as received at various distances from the projector during playback tests are given at several places in the report, as necessary to interpret the movements and behavior of whales during playback tests. The projected *Karluk* sounds were very prominent when received about 1 km from the projector. The projected sounds diminished with increasing distance, and dropped below the background noise level in the corresponding frequency band at distances ranging from about 2 to 10 km, varying from day to day.

Infrasounds

As an indirect way to assess whether bowhead hearing capabilities may extend into the infrasonic (<20 Hz) range, where the sound projector is ineffective, a preliminary analysis was done to determine whether bowhead calls include any infrasonic components. A total of 45 bowhead calls were analyzed in waterfall format spanning frequencies from 5 to 250 Hz. These calls had been recorded with equipment effective to frequencies below 5 Hz. Few calls had any energy at frequencies as low as 50 Hz, and very few--if any--had energy below 30 Hz. One of the 45 calls was accompanied by weak components at 15-32 Hz, but it is not certain that these were part of the call. This preliminary work showed that few if any of the known types of calls include components at infrasonic frequencies. This analysis did not address the possibility that bowheads might sometimes emit calls that are confined to frequencies below 20 Hz, without any accompanying higher-frequency components.

Ambient noise levels at infrasonic frequencies are of interest with respect to questions about how far away any infrasonic components from industrial noise sources might be detectable. The ambient noise analyses mentioned above extended down to 10 Hz. Ambient noise levels at 10-20 Hz were higher than those at most higher frequencies on both a spectrum level and a 1/3-octave basis. This would tend to reduce the maximum detection radius of any man-made sounds at very low frequencies.

Bowhead Whales

Movements and General Behavior

Bowheads migrated northeast and east through the study area throughout late April and May of 1989 and 1990. In 1989, the migration was often through heavy pack ice conditions. In 1990, the ice was less compacted. Even when a broad nearshore lead extended east along the landfast ice edge through the study area, the migration corridor 35+ km ENE of Pt. Barrow was mainly along the offshore side of the lead or through the pack ice north of the lead.

Bowheads visible under undisturbed conditions in May 1989, mainly amidst the pack ice, were engaged in traveling (migration), socializing, and resting. Resting bowheads were often in small areas of open water amidst heavy ice. In 1989, many bowheads apparently migrated through the study area unseen during periods of heavy ice cover and poor weather. In May 1990, when heavy ice cover was much less common, a higher proportion of the whales observed were actively migrating northeast or east. Socializing was seen occasionally, but resting was not. No surface feeding was seen, and apparent water-column feeding was rare. A number of whales were seen surfacing with mud streaming from their bodies and (rarely) from their mouths. Several behaviors that have been observed commonly in late summer and autumn were seen only infrequently in May 1989-90: pre-dive flexes, fluke-out dives, and aerial activities. A few bouts of sexual activity were observed.

Bowhead calves and their mothers were seen only in the latter half of May in 1989 and 1990. They constituted the majority of the bowheads present in the last week of May in both years. They did not migrate as strongly or consistently eastward as did other bowheads, especially in 1989 when ice conditions were heavier. In 1989, a few mother/calf pairs traveled *west* for at least a few kilometers. One mother/calf pair identified in 1989 traveled only 12 km in 44 h. Some of these pairs may have been waiting for ice conditions to ameliorate before continuing east. During travel, bowhead calves often "rode" on the backs of their mothers during 1989, but did so less often in 1990. Riding has not been seen in late summer or autumn, when the calves are older and larger.

Drilling Noise Playbacks

Because of heavy ice conditions and poor weather during much of the 1989 field season, there were only five days in 1989 when we were able to observe bowheads exposed to projected drilling noise. All data had to be collected from holes and leads amidst the pack ice rather than along the landfast ice edge. The number of bowheads seen near the sound projector in 1989 was small, but some noteworthy data were obtained.

In 1990, weather and ice conditions were much more favorable. Bowheads were observed passing the operating sound projector on six days; control data on bowheads passing the ice camp were obtained on those six days and two additional days. Numbers of bowheads passing the ice camp tended to be higher in 1990, and several times as many data on whales near the ice camp were obtained in 1990 than in 1989. Also, considerably more control data on bowheads away from any ice camp were obtained in 1990 than in 1989.

The largest quantity of data came from 13 May 1990 when, throughout the day, a stream of bowheads migrated along a long, narrow lead through otherwise-heavy pack ice. The sound projector had been set up alongside this lead at a point where it was ~200 m (655 ft) wide. Bowheads continued to pass the projector while normal *Karluk* drilling sounds were projected. One whale came within 110 m (360 ft) of the projector. Many came within 160-195 m (525-640 ft), where the received broadband (20-1000 Hz) sound levels were about 135 dB re 1 µPa. That level was about 46 dB above the background ambient level in the 20-1000 Hz band on 13 May (Figure A). However, bowhead movement patterns were strongly affected when they approached the operating projector. When bowheads were still several hundred meters away, most began to move to the far side of the lead from the projector. (This did not happen during control periods while the projector was silent.) One approaching whale temporarily reversed course when about 400 m away before resuming eastward migration past the operating projector.

The behavior of the bowheads that came within 1 km (0.62 mile) of the operating projector on 13 May was affected in several ways, and there were less consistent behavioral effects at greater distances. Univariate and multivariate analyses showed that behavior of whales 0-½ km and ½-1 km from the projector differed significantly from behavior far away. Turns became more frequent, and there were changes in surfacing and respiration cycles. These behavioral changes were similar to the types of changes noted during previous bowhead disturbance studies. The increased frequency of turns noted within 1 km was also evident at 1-2 km, and there was evidence of subtle changes in surfacing and respiration cycles at distances as great as 2-4 km (1¼-2½ miles). Sound levels at those distances are shown in Figure A.

The results from 13 May showed that migrating bowheads would tolerate exposure to high levels of continuous drilling noise in order to continue their migration. However, the data also showed that the local movement patterns and various aspects of the behavior of these whales were affected by the noise exposure.[1]

---

[1] On 13 May 1990, in addition to the playback test with normal *Karluk* drilling sounds, we also projected distorted sounds during one period while a projector was failing. The distorted sounds were less intense than the normal *Karluk* playbacks, but they were more variable and different in frequency composition. During the distorted playback, bowheads began to exhibit increased turning when they came within about 3 km (1.86 miles) of the projector. They seemed to be seeking an alternate route under the ice. In the absence of such a route, they continued toward the projector and--in at least some cases--passed within 200 m (655 ft) of it.

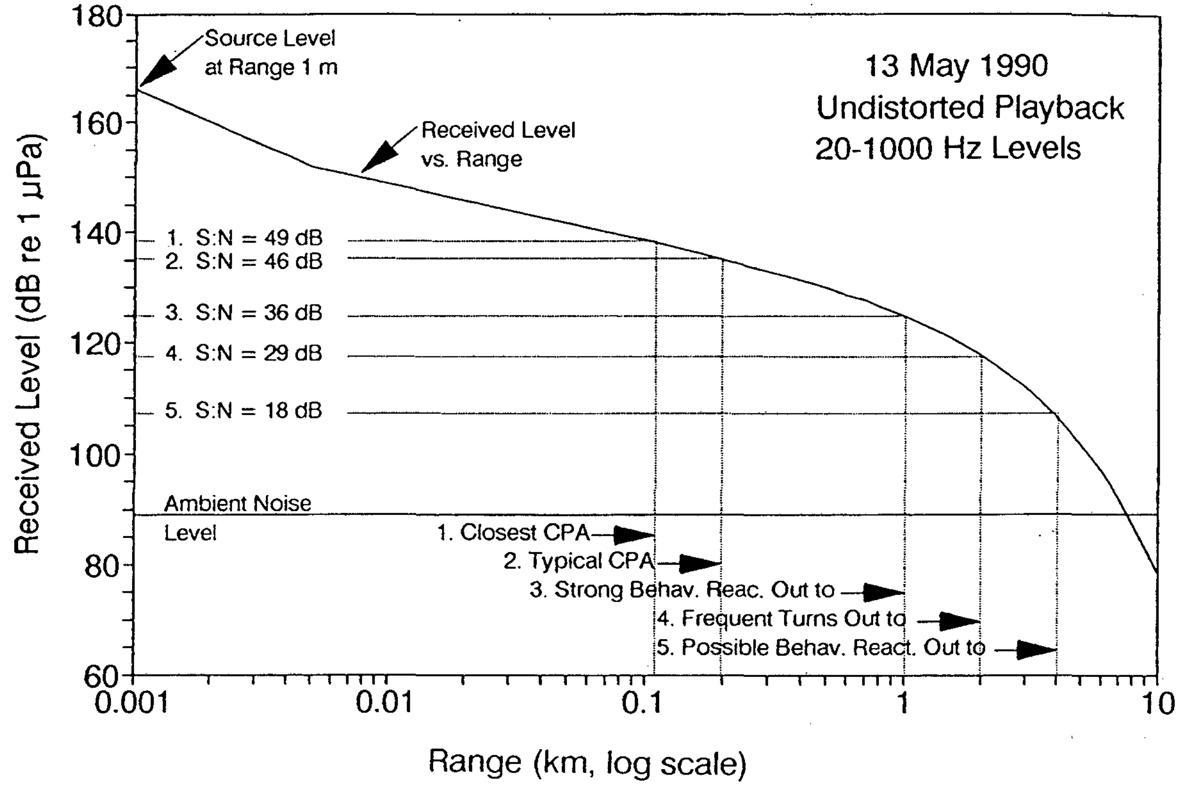


FIGURE A. Summary of major results from the 13 May 1990 playback experiment, showing received levels of *Karluk* drilling sound vs. distance from the projector, the reaction distances of bowheads, and the sound levels and signal-to-noise ratios (i.e. *Karluk* noise : ambient noise ratios) at those distances. CPA = Closest Point of Approach.

Data from other days in 1989-90 also showed that bowheads would move into the area ensonified by the sound projector, often approaching within 1 km (0.62 miles) and occasionally coming within 200 m (655 ft). The closest sighting was of a bowhead that swam to within 35 m (115 ft) of the operating projector on 10 May 1990. There was, however, evidence that some migrating bowheads diverted their courses enough to remain a few hundred meters to the side of the projector on days other than 13 May. Typically, bowheads whose initial courses would have brought them within about 500 m of the projector often diverted so as to remain >500 m to the side. Also, the frequency of turns during surfacings increased when bowheads were within 2 km (1¼ miles) of the operating projector on days other than 13 May as well as on 13 May. There was little evidence of changes in other aspects of behavior on days other than 13 May 1990.

The more conspicuous changes in movements and behavior on 13 May 1990 than on other days were presumably related to three facts: (1) On 13 May, the only available lead brought the whales within 200 m of the projector, where they were exposed to especially high sound levels. (2) The lead that channeled the whale movements on 13 May was very long, narrow and straight, making any changes in heading or behavior especially conspicuous. (3) The sample size was larger on 13 May than on any other day, making it easier to recognize effects.

There was no evidence that bowhead migration was blocked by the projected drilling sounds, and no evidence that bowheads avoided the projector by distances exceeding 1 km. We began to follow some bowheads when they were as much as 5 km (3 miles) from the operating projector, but we did not see diversion of migration paths until the whales were within a few hundred meters.

The 1989-90 data allow us to evaluate a modified and more specific version of the null hypothesis dealing with bowhead distribution and movements in relation to playbacks of platform noise. The modified null hypothesis, amended to take account of the specific characteristics of the data, is as follows (amendments are ***highlighted***):

> "Playbacks of recorded ***continuous*** noise from a bottom-founded platform ***like the Karluk drilling operation on a grounded ice pad*** will not significantly alter the migration routes or spatial distribution of bowhead whales ***visible*** in open water ***amidst the pack ice and in the seaward side of the nearshore lead system*** during spring migration ***east of*** Pt. Barrow, Alaska."

From a statistical viewpoint, this null hypothesis must be rejected. There were ***statistically significant small-scale (<1 km) alterations*** in migration routes and spatial distribution. There were also statistically significant alterations in some aspects of behavior that are related to distribution and movements (headings, turns, speed of movement). However, the demonstrated effects were localized and temporary. We conclude that the available data are consistent with this modified null hypothesis, insofar as ***biologically significant*** alterations in migration routes or spatial distribution are concerned.

The 1989-90 data on behavior allow an evaluation of a similarly-amended version of the second null hypothesis, concerning playback effects on subtle aspects of individual behavior. The 1989-90 data show that--***from a statistical viewpoint***--this null hypothesis must also be rejected. There were statistically significant changes in many aspects of individual behavior among bowhead whales approaching within 1 km of the sound projector, and a few behavioral variables were apparently affected out to 2-4 km. The ***biological significance*** of these changes in behavior is less obvious. Most aspects of behavior that were affected near the projector were affected for only about ½-1 hour.

Table A summarizes the distances from the projector at which bowheads reacted, along with the received sound levels and signal-to-noise (S:N) ratios at those distances. In this context, the S:N ratio is the difference, in decibels, between the received level of *Karluk* noise and the level of the natural ambient noise in the corresponding band.

We emphasize that all values in Table A refer to playbacks of one particular type of continuous, low-frequency sound. It should not be assumed that the same values would apply to other types of sounds.

One of the main limitations of this study is the inability of a practical sound projector to reproduce the low-frequency components of recorded industrial sounds. The *Karluk* rig emitted strong sounds down to ~10 Hz, and quite likely at even lower frequencies. It is not known whether the underrepresentation of components below 80 Hz and especially below 63 Hz during playbacks had significant effects on the responses by bowheads. Bowheads presumably can hear sounds extending well below 80 Hz, but it is not known whether their hearing extends into the infrasonic range below 20 Hz.

Table A. Reaction thresholds for bowheads exposed to playbacks of *Karluk* drilling sounds, 1989-90. The 13 May 1990 values refer to whales migrating along a narrow, constraining lead through heavy ice. The "Other" values refer to other days in 1989-90 when the ice was not as constraining.

		Closest CPA *	Typical CPA	Strong Behav. Reaction Out to	Frequent Turns Out to	Possible Behav. Reaction Out to
A. Distance						
	13 May	110 m	200 m	1 km	2 km	4 km
	Other	35 m	400 m	-	2 km	-
B. Received Level						
20-1000 Hz	13 May	138 dB*	135 dB	125 dB	118 dB	107 dB
	Other	138 *	120	-	106	106
Dominant	13 May	134 *	131	120	113	102
1/3 Octave	Other	133 *	115	-	100	100
C. Signal-to-Noise Ratio						
20-1000 Hz	13 May	49 *	46	36	29	18
	Other	44 *	26	-	12	12
Dominant 1/3	13 May	53 *	50	39	32	21
1/3 Octave	Other	49 *	32	-	17	17

* CPA = Closest point of approach. Decibel values in this column may be overestimated by as much as a few decibels, as explained in footnote 21 on page 250.

The projector adequately reproduced the overall 20-1000 Hz level at distances beyond 100 m even though components below 80 Hz were underrepresented (see p. xiv). If bowheads are no more responsive to sound components at 20-80 Hz than to those above 80 Hz, then the playbacks provided a reasonable test of bowhead responsiveness to components of *Karluk* sound above 20 Hz. No specific test of the responsiveness of bowheads to the components below 20 Hz is possible in the absence of a sound projector capable of reproducing infrasonic components. Also, this study was not designed to test the potential reactions of whales to non-acoustic stimuli detected via sight, olfaction, etc. However, in summer the responses of bowheads to actual dredges and drillships seem generally consistent with the reactions to playbacks of recorded sounds from those same sites (Richardson et al. 1990b, *Mar. Environ. Res.* 29:135-160). This observation gives us some reason for optimism that the playback method provides meaningful results.

Aircraft Disturbance

Limited observations were obtained in 1989 and 1990 on bowhead reactions to a Bell 212 helicopter. The sample size was small and most observations were unsystematic. However, one controlled overflight experiment was conducted in 1990.

Overall, the limited 1989-90 observations suggest that spring-migrating bowheads sometimes dive in response to a close approach by a turbine-powered helicopter. However, other bowheads show no obvious reaction to single passes--even at altitudes of 150 m (500 ft) or below.

There is, to date, no evidence that single helicopter overflights at altitudes of 150 m (or below) disrupt the distribution or movements of spring-migrating bowheads in any biologically significant way. However, the 1989-90 data are limited, and additional data are expected to be forthcoming from subsequent years of this project. Therefore, a final evaluation of the null hypotheses concerning effects of helicopter overflights on the distribution, movements, and behavior of bowheads is deferred until later in the project.

White Whales

Movements and General Behavior

Sightings of white whales were much more numerous than those of bowheads in May 1989. As previous workers have reported, white whales tended to be more widely scattered and slightly farther offshore than bowheads, but their migration corridors overlapped broadly. Most of the white whales seen were amidst the pack ice, although in late May a few were traveling east on the offshore side of the lead bordering the landfast ice edge.

In late April and May of 1990, white whales were seen much less regularly than in 1989. They were migrating consistently northeast and east through the pack ice or the north side of the main nearshore lead. In 1990, unlike 1989, we did not see white whales whose migration was blocked by heavy ice conditions. There was only one day in 1990 (21 May) when white whales passed the ice camp while a playback experiment was in progress.

Drilling Noise Playbacks

We observed migrating white whales close to the operating projector on four dates in May 1989. On three of these dates, at least a few white whales came within ~200 m (655 ft) of the operating projector, including a few within 50-75 m (165-250 ft). White whales that were migrating toward the projector appeared to travel unhesitatingly toward it until they came within a few hundred meters. Some white whales that came that close to the projector continued past it without apparent hesitation or turning. However, others did react temporarily to the noise, or perhaps to visual cues, at distances on the order of 200-400 m (655-1310 ft).

On 14 May 1989, a substantial proportion of the white whales that came within 200-400 m of the projector slowed down, milled, and in some cases reversed course temporarily. This interruption of migration was very obvious, but lasted only several minutes. Then the whales continued past the projector, in some cases passing within 50-100 m (165-330 ft) of it.

On the one day in 1990 when white whales were seen near the projector, several groups migrated past within ~400 m (1310 ft). The closest confirmed approach to the operating projector in either year was on 21 May 1990, when a group of four white whales approached to within 15 m (50 ft). However, they did not dive (and thus expose themselves to strong low frequency noise) until they were 64 m (210 ft) away. Another group seen on that day turned away when they came within 40 m (130 ft), and dove at that distance.

We saw no evidence that white whales reacted at distances greater than 200-400 m even though projected drilling noise was measurable as much as several kilometers away. We suspect that this was related to the poor hearing sensitivity of white whales at the low frequencies where the *Karluk* drilling sounds were concentrated. At distances beyond ~200 m, received levels of the low-frequency drilling sounds (on a 1/3-octave basis) usually were less than the measured hearing sensitivity of white whales.

The observed reactions may have been to weak artifactual components of the projected sound at frequencies above 2-3 kHz rather than to the stronger *Karluk* components between ~63 Hz and ~300 Hz. Although weak, the high-frequency components were potentially audible to white whales at somewhat greater ranges, given the much better hearing capabilities of white whales at higher frequencies.

Overall, some white whales reacted to the projected sounds at distances as great as 200-400 m (655-1310 ft), but other individuals approached considerably closer. The minimum confirmed distances from the operating projector were 15 m (50 ft) for white whales at the surface and 40 m (130 ft) during a dive. Estimated received sound levels several meters or more below the surface at these distances were as follows:

Range (m)	Range (ft)	Broadband (dB re 1 µPa)	Max. 1/3-Octave (dB re 1 µPa)
400	1310	112	106
200	655	118	112
40	130	134[a]	128[b]

[a] S:N≈36 dB

[b] S:N≈42 dB

The 1/3-octave levels of drilling sound noted above for the observed minimum and maximum reaction distances quite likely do not represent the actual acoustic reaction thresholds. Although maximum projected and received levels occurred in 1/3-octave bands near 200 Hz, the levels received 200-400 m from the projector in that frequency band appear to be too low to have been heard. Acoustic reactions are more likely to depend on reception of lower level sounds at higher frequencies where the white whale hearing apparatus is more sensitive.

The maximum acoustic reaction distance of white whales near a shallow-water drillsite like *Karluk* is predicted to be similar to that observed in our tests (a few hundred meters). Reaction distances near the actual drillsite might, in fact, be less than those near the projector if the observed reactions were to the weak high-frequency system noise rather than the drilling noise *per se*. This high-frequency noise would not be present near the actual drillsite.

Minimum reaction distances near an actual drillsite like *Karluk* probably exceed those observed near the projector (15-50 m) because of the higher noise levels and other stimuli present within ~200 m of the actual site relative to those at corresponding distances from the projector site.

The two hypotheses concerning reactions of white whales to playbacks of platform noise deal with (1) migration routes and spatial distribution, and (2) subtle aspects of individual behavior. The wording is the same as that for bowheads (see above). We can only draw conclusions about the effects of playbacks of ***continuous noise from drilling on a bottom-founded ice platform like Karluk***. Also, the data apply to white whales ***visible*** while migrating through ***pack ice and along the seaward side of the nearshore lead east of Pt. Barrow***.

We conclude that playbacks of sounds from drilling on a bottom-founded ice platform like *Karluk* have no biologically significant effects on migration routes and spatial distribution of white whales visible while migrating through pack ice and along the seaward side of the nearshore lead east of Point Barrow in spring. Furthermore, we expect that maximum reaction distances of white whales to an actual drillsite like *Karluk* (a few hundred meters) would be similar to those observed during the playback experiments. In drawing these conclusions, we consider that the observed temporary hesitation and minor changes in migration paths exhibited by some white whales within 200-400 m of the noise source were not biologically significant. Our acceptance of the amended null hypothesis is based on a "weight of evidence" approach; the available data are not suitable for a statistical test of the hypothesis.

We emphasize strongly that our conclusions relating to the "distribution and movements" hypothesis pertain only to continuous low-frequency drilling noise from a bottom-founded ice platform like Karluk. Reaction distances to some other sources of industrial noise may be very different. This is evident from the reactions of spring-migrating white whales in the Canadian high arctic to ships and icebreakers at very long distances (Finley et al. 1990, *Can. Bull. Fish. Aquatic Sci.* 224:97-117). To understand the effects of industrial noises related to oil production on spring-migrating white whales in the Beaufort Sea, we need to test their reactions to additional types of noise whose characteristics differ from those studied in 1989-90.

The available data are not adequate for a test, statistical or otherwise, of the second hypothesis, concerning effects of *Karluk* drilling noise on subtle aspects of the individual behavior of white whales.

Aircraft Disturbance

The 1989-90 observations of the movements and behavior of white whales in the presence of a Bell 212 helicopter or Twin Otter fixed-wing aircraft were largely anecdotal but generally consistent with previous evidence. Reactions to turbine-powered aircraft during the spring migration near Pt. Barrow are variable. Some individuals show no overt response to a fixed-wing aircraft or helicopter flying at low level, or to a helicopter standing on the ice edge (with engines running) within 100-200 m (330-655 ft) of the whales. Others look upward or dive abruptly when an aircraft passes over at altitudes at least as high as 460 m (1500 ft). Some white whales whose paths come within 100 m of a helicopter on the ice with its engines running may divert as much as 100 m away from the helicopter. It is not known whether these small-scale and apparently brief reactions are to the noise from the aircraft, visual cues, or both.

The two hypotheses concerning reactions of white whales to helicopter overflights deal with effects on (1) migration routes and spatial distribution, and (2) subtle aspects of individual behavior. The wording is the same as that for bowheads (see p. xviii, above). The available spring data apply only to ***Bell 212*** helicopters, and to white whales ***visible*** while migrating through ***pack ice and along the seaward side of the nearshore lead east of Pt. Barrow.***

The limited results available from 1989-90 are consistent with the null hypothesis about helicopter effects on migration routes and spatial distribution (amended as highlighted above). The data suggest that single overflights by a helicopter of the Bell 212 class do not cause blockage or biologically significant diversion of the spring migration of white whales traveling in pack ice or along the seaward side of the nearshore lead. We consider that diversion of migration routes by 100 m or 330 ft (as may have occurred on 21 May 1990) is not biologically significant. This preliminary assessment is based on the "weight of evidence"; the available data are not amenable to a statistical test. The data are limited and non-systematic, and additional data are likely to be obtained in future years of this study. Hence, a final determination as to the validity of the "distribution and movement" null hypothesis for white whales is postponed until later in the project.

The available data are not adequate for a test, statistical or otherwise, of the hypothesis concerning helicopter effects on subtle aspects of the individual behavior of white whales. It is obvious that short-term effects on their behavior do occasionally occur (hasty dives, looking at the passing helicopter). However, the available data do not allow quantification or assessment of biological significance.

ACKNOWLEDGEMENTS

We thank the Barrow Whaling Captains' Association (BWCA), Alaska Eskimo Whaling Commission (AEWC), and North Slope Borough (NSB) for their agreement that this project could be conducted near Barrow during the spring whaling season. Individuals from Barrow who provided much valuable advice or assistance in 1990 included Thomas Albert, J. Craig George, Ben Nageak and Mike Philo (NSB Dept of Wildlife Management), Edward E. Hopson and Burton Rexford (AEWC and BWCA), Rosie Habeich and Charlotte Brower (AEWC), and the management and staff of UIC-NARL.

We thank the members of the project's Scientific Review Board for their advice and constructive criticisms concerning field plans and preliminary results. The SRB members in 1990 were as follows:

Dr. Thomas Albert	North Slope Borough Dept of Wildlife Management,
Mr. Mark Fraker	BP Exploration (Alaska), Inc.,
Dr. Roger Green	University of Western Ontario,
Mr. Allen Milne	Sci. Rev. Board Chairman,
Mr. Ron Morris	Nat. Mar. Fish. Serv.,
Mr. Thomas Napageak	Alaska Eskimo Whaling Commission,
Mr. Burton Rexford	Barrow Whaling Captains' Association, and
Dr. Steven Swartz	Marine Mammal Commission.

For help in the field, we thank Kenneth Toovak Sr. of Barrow, who participated in most of the 1989-90 ice-based fieldwork. We thank Dave Gardner and Roy Dehart of NOAA (helicopter crew), and Stan Ashland and Leon Smith of Evergreen (Twin Otter pilots). The National Oceanic & Atmospheric Administration supplied the helicopter and some other equipment. We also valued the cooperation and assistance provided by the National Marine Mammal Laboratory photogrammetry field crew, led by David Rugh and David Withrow, and by their pilots Bill Steck and Jim Brown of Empire Airways.

We thank R. Blaylock of Greeneridge for conducting many of the acoustic analyses, and Dr. J. Hanna for preparing Appendix A. D. Rugh and D. Withrow (NMML) kindly provided unpublished data on their bowhead sightings near Barrow. We thank J. Groves and Carl Byers (University of Alaska) for supplying satellite imagery and weather data, and S. Cutcliffe for drafting the maps. K. Hester and B. Griffen provided much help with report production.

We thank the Alaska OCS Region, U.S. Minerals Management Service, for conceiving and funding this project, and for many constructive comments. Dr. Jerome Montague, Dr. Cleve Cowles and Jerry Imm of MMS provided invaluable assistance in initiating the work and in overcoming various obstacles. This project was conducted under Permit 670 issued by the National Marine Fisheries Service under the provisions of the Marine Mammal Protection Act and the Endangered Species Act.

GLOSSARY

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

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

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

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

ASL. Above sea level.

audiogram. A graphical depiction of auditory thresholds, showing the sound levels that are barely detectable by an animal, in the absence of significant background noise, as a function frequency.

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

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

bandpass filter. A filter with high-pass and low-pass cutoff frequencies, designed to pass only a desired band of frequencies.

bandwidth. A range of frequencies.

blow interval. The interval, in seconds, between two successive respirations within the same surfacing by a whale.

CPA. Closest Point of Approach.

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

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

continuous wave. A sound whose waveform continues with time.

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

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

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

DIFAR. A type of sonobuoy (AN/SSQ-53B) that has the ability to determine the direction of arrival of a sound.

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

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

fluke-out dive. A dive in which the whale raises its tail flukes above the surface of the water as it dives.

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

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

high-pass filter. A filter passing sounds above a specified frequency.

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

infrasound. Sound energy at frequencies too low to be directly audible to humans; generally taken to be sound at frequencies below 20 Hz.

J-11. A particular type of U.S. Navy underwater sound projector.

***Karluk*.** *Karluk* was a grounded ice platform that was constructed in 6 m of water near Prudhoe Bay, Alaska, during the winter of 1988-89. The *Karluk* ice platform was used as a drillsite during that winter. The underwater sounds projected during playback experiments in this study were recorded 130 m from *Karluk* while it was drilling during March 1989.

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

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

low-pass filter. A filter passing sounds below a specified frequency.

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

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

noise. Sounds that are not of particular interest during an acoustic study and that form the background to the sound being studied. Noise can include both natural sounds and man-made sounds.

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

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

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

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

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

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

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

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

pre-dive flex. A distinctive concave bending of the back occasionally exhibited by bowheads while they are at the surface but shortly before they are about to dive.

pressure. A physical manifestation of sound. The dimensions of pressure are force per unit area. The commonly used unit of acoustical pressure is the micropascal.

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

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

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

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

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

RL. Received Level; the level of sound reaching a location some distance from the sound source (*cf.* source level).

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

signal. A sound of interest during an acoustic study.

S:N. Signal-to-Noise ratio; the difference in level, measured in decibels, between a signal of interest (in this study, usually *Karluk* sound) and the background noise at the same location (in this study, usually ambient noise).

sonobuoy. A sound monitoring and transmitting device that includes a hydrophone, amplifier and an FM radio transmitter. Sonobuoys are designed to be dropped into the water from an aircraft. They can also be deployed from the surface. Sounds in the water can be monitored from a remote location via radio receivers.

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

sound pressure. The pressure associated with a sound wave.

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

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

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

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

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

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

spectrum level. See "sound pressure density spectrum level".

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

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

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

SSDC. Single Steel Drilling Caisson or Steel-Sided Drilling Caisson; this is a mobile bottom-founded drilling platform constructed from part of a supertanker.

surfacing. As defined in this study, a surfacing by a whale is the interval from the arrival of the whale at the surfacing following one long dive until the start of the next long dive. Periods while the animal is just below the surface between breaths (blow intervals) are not counted as dives. Equivalent to the term "surfacing sequence" used by some authors.

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

third octave. Abbreviation for one-third octave (see above).

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

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

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

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

waterfall spectrogram. A graphical depiction of the intensity of sound components at various frequencies over time. Time and frequency are shown on the X and Y axes, and intensity is shown as a third dimension. A waterfall graph usually indicates only relative power.

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

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

INTRODUCTION

The possible effects of underwater noise from offshore oil and gas activities have been a significant concern to Minerals Management Services (MMS), the National Marine Fisheries Service (NMFS), and other agencies for several years. Hence, MMS has funded studies to document the characteristics of oil industry noises and their effects on the behavior of bowhead and gray whales (e.g. Gales 1982; Malme et al. 1984; Richardson et al. 1985b; Miles et al. 1987; Ljungblad et al. 1988). The oil industry has funded related studies of the reactions of bowhead whales to oil industry operations in the Alaskan Beaufort Sea (e.g. LGL and Greeneridge 1987). These and other similar studies have been reviewed and summarized recently (Richardson et al. 1991; Richardson and Malme in press).

Prior to this study, all systematic studies of disturbance to bowheads had been done in summer or early autumn when the whales are either in open water or in loose pack ice where their movements are relatively unrestrained by ice. There had been no work on the disturbance reactions of bowheads migrating in leads through areas of heavy ice cover--the normal situation in spring. Also, there had been no systematic scientific study of the suggestion by Inupiat whalers that bowhead whales are especially sensitive to noise in the spring.

The sounds considered in the summer-autumn studies conducted in the Beaufort Sea have been those associated with some of the major offshore exploration activities, *viz* aircraft and boat traffic, marine seismic exploration, drillships, and offshore construction. Only a very limited effort has been devoted to the reactions of bowheads to icebreaking, which is a particularly noisy activity (Greene 1987a; Richardson et al. 1991). Reactions of bowheads to sounds from an oil production platform have not been studied, in part because no production platforms exist in arctic waters deeper than a few meters. Reactions of migrating gray whales to noise from a production platform were studied by Malme et al. (1984), but the type of platform involved was very different from the types likely to be used in the Arctic.

The National Marine Fisheries Service took note of the above situation in its recent Biological Opinions on lease sales in the Beaufort and Chukchi seas. NMFS believes that development and production activities in spring lead systems used by bowheads might, in certain circumstances, jeopardize the continued existence of the Western Arctic bowhead whale population (Evans 1987; Brennan 1988; Fox 1990). The possibility of significant disturbance in spring lead systems, when bowheads may have few or no optional migration routes, was one of the factors about which NMFS was concerned.

The beluga or white whale is the one other cetacean that migrates through the spring lead systems in a manner similar to the bowhead. The sensitivity of various populations of white whales to several types of human activities and underwater noises has been studied in summer in Alaska, in late spring and summer in the Mackenzie Delta area, and in spring in the eastern Canadian High Arctic. There has also been a playback study with captive white whales (Thomas et al. 1990). The sensitivity of the white whales in these situations varied widely. There was great tolerance in some situations. However, white whales exhibited strong avoidance reactions to ships and icebreakers at very great distances during spring in the eastern high arctic (LGL and Greeneridge 1986; Cosens and Dueck 1988; Finley et al. 1990). The responsiveness of white whales to underwater noise during the spring migration around western and northern Alaska has not been studied previously.

In order to answer some of these questions, MMS has funded this study. The main objectives are to determine the short-term effects of production platform noise and icebreaker noise on the movements and behavior of bowhead and white whales migrating through open leads and pack ice near Pt. Barrow, Alaska, in spring. A related objective is to determine the characteristics of sound propagation and of natural ambient noise in spring lead systems. These physical acoustic phenomena affect the received levels and prominence of man-made noise. Reactions of whales to helicopter overflights are also to be determined when possible.

This report describes results from 1990, the second year of a continuing study. The study will continue for at least one additional spring season, in 1991. In 1989, we obtained

- considerable information on physical acoustic phenomena (ambient noise and sound propagation),
- some data on reactions of bowheads and white whales to playbacks of continuous sounds from one drilling platform: a rig on a bottom-founded ice pad, and
- limited data on reactions of bowheads and white whales to aircraft.

However, weather and ice conditions in 1989 were not good, and relatively few observations of bowheads were possible. Weather and ice conditions in 1990 were much more amenable to the types of fieldwork necessary in this study. In 1990, we collected additional data on physical acoustics, limited additional data on whale reactions to helicopters, and many more data on reactions of bowheads to the same type of drilling noise used in 1989. In 1991 the top priority will be to test the reactions of bowheads to a different and more variable type of industrial noise: icebreaker sound.

The report on the first year of the study (Richardson et al. 1990a) contains much background information that is not repeated here. That report includes a summary of the distribution and movements of bowhead and white whales in spring. It also provides brief reviews of previous studies of the disturbance responses of those species, and of the possible characteristics of underwater sounds from spring production activities (pages 2-17).

Objectives and Rationale

General Objectives

In early 1988, MMS requested proposals for an experimental study of the effects of noise from oil production activities on bowhead and (secondarily) white whales during their spring migrations around Alaska. The overall objectives of the study, as defined by MMS, were

1. "To quantitatively characterize the marine acoustic environment including sound transmission loss and ambient noise within the nearshore leads of the Alaskan Chukchi Sea and Beaufort Sea in the spring.
2. "To quantitatively describe the transmission loss characteristics of underwater sound produced by production platforms and icebreakers in the spring lead study area.
3. "To quantitatively document the short term behavioral response of spring migrating bowhead and, as possible, beluga [white] whales resulting from exposure to the [above] sources (see objective 2) of production sounds.

4. "To assist and coordinate with other MMS sponsored studies and local resource users to maximize collection of needed data and avoid conflict with subsistence whaling activities.
5. "To analyze acquired and synthesized data to test the generalized null hypothesis."

Rationale for Various Study Components

The rationale for studying topics such as sound transmission loss, ambient noise levels, and received sound levels near whales requires some explanation. These data are needed in order to develop quantitative models for predicting the radii of noise detectability and noise responsiveness around the specific types of noise sources that are tested. The basic components and interrelationships of this model are illustrated in Figure 1.

The underwater noise received from an industrial source diminishes in level with increasing distance from the source. The rate of transmission loss depends on water depth, bottom conditions, ice conditions and other factors. Hence, the slope of the received level vs. range curve illustrated in the diagram can vary from place to place and time to time. The transmission loss properties of a particular study area need to be studied during the season of interest in order to make meaningful predictions of received noise levels as a function of range.

The level of the natural ambient noise has a major influence on the maximum distance to which man-made noise can be detected. Man-made noise is normally detectable by an animal (or hydrophone) if its received level exceeds the level of natural background noise at similar frequencies. The range at which the received level of man-made noise diminishes below the ambient noise level is (to a first approximation) the maximum radius of detectability (Fig. 1). Beyond that distance, the man-made noise will be weaker than the natural background noise, and is likely to be undetectable. Closer to the source of man-made noise, the received level of man-made noise will exceed the ambient noise level and the man-made noise is likely to be detectable. Ambient noise levels vary naturally from day to day as a function of wind, waves, ice conditions, calling rates by animals, and other factors. Day-to-day variations of ±10 dB or even ±20 dB are not uncommon. A 10 or 20 dB change in the ambient level has a drastic change on the range at which the received level of man-made noise falls below the ambient noise level, and thus on the radius of detectability of the man-made noise. Hence, it is important to characterize the typical ambient noise levels in the study area and season, the normal range of variation of these ambient noise levels, and the factors affecting ambient noise levels in any particular circumstance.

In most previous studies of the disturbance reactions of marine mammals, it has been found that disturbance responses do not begin until the received level of man-made noise exceeds the minimum detectable level by a substantial margin. This has proven to be the case in studies of bowhead whales, including the 1989-90 phases of this study. Thus, the received level of man-made noise diminishes below the response threshold before it diminishes below the ambient noise level and becomes inaudible (Fig. 1). In order to quantify the responsiveness of bowheads and white whales to man-made noise, it is necessary to determine the response threshold level. This will not be a constant, since whale responsiveness varies considerably. As a minimum, the average response threshold should be determined. If sample size allows, the noise levels to which various percentages of the animals react should also be

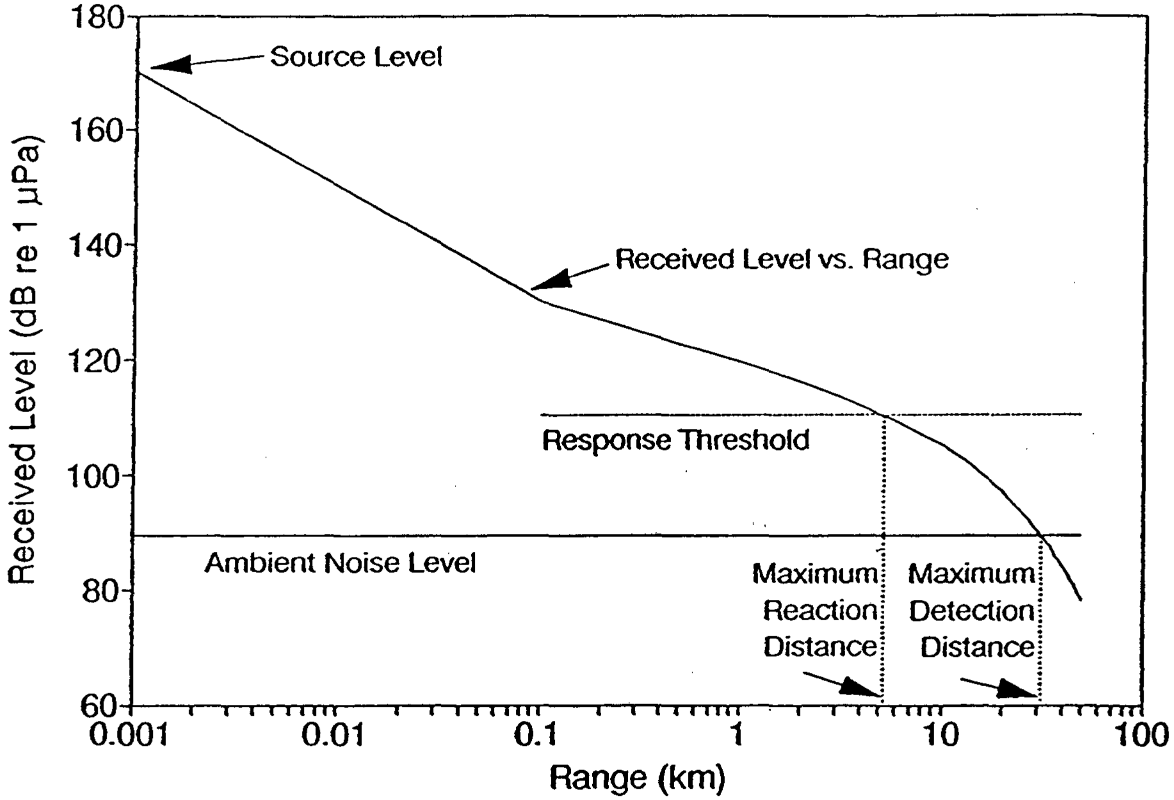


FIGURE 1. Components of a simple zone of acoustic influence model. See text for explanation.

determined. The lower the response threshold, the greater the distance at which the received level of man-made noise will diminish below that threshold.

One additional component of the zone of acoustic influence model is the source level of the man-made noise. An increase in source level will shift the received level vs. range curve upward by a corresponding amount. This shift will result in an increase in the distances at which the received level diminishes below the response threshold (= maximum reaction distance) and the ambient noise level (= maximum detection distance).

In many cases the source level of the sounds emitted during a playback experiment may be less than that of the actual industrial activity being simulated, e.g. due to projector limitations. If the source levels of the projector and the actual industrial activity are known, along with the other components of the model (Fig. 1), then it is possible to estimate the maximum reaction and detection distances around the actual industrial site based on the results collected near the projector.

Thus, by considering the source level of man-made noise, its propagation loss, the ambient noise level, and the response threshold of whales, a meaningful quantitative model of acoustic influence can be developed. This study aims to collect the types of data needed to quantify, for particular situations, the conceptual model illustrated in Figure 1 (see Fig. 95, p. 254).

Specific 1990 Objectives

The specific objectives of the 1989 and 1990 phases of this project were similar. The specific objectives for 1989 were given by Richardson et al. (1990a:17). Because of the poor weather and ice conditions in 1989, and the low numbers of whales accessible in that year, the data on reactions to drilling platform sounds acquired in 1989 were too sparse to be conclusive. Hence, the highest priority during the 1990 field program, as in 1989, was to study the reactions of bowheads to noise from a bottom-founded drilling or production platform. When possible, reactions of white whales to this sound were to be determined as well. Underwater playback techniques were to be used to simulate the noise from an actual platform. As a lower priority, the reactions of bowheads and white whales to actual helicopter overflights were to be determined if opportunities allowed. Because of concern about the effects of low-frequency industrial sound components on bowheads, and the inability of a practical sound projector to reproduce those components, several indirect methods of addressing the importance of low frequency components were identified as objectives in 1990.

The specific objectives for the second field season, in 1990, were as follows:

1. To measure ambient noise levels and characteristics in leads and cracks along the spring migration corridor of bowhead and white whales in the western Beaufort Sea, including infrasonic components.[1]
2. To measure and model transmission loss of underwater sound along that part of the spring migration corridor, based on playbacks of (a) test tones at selected frequencies

---

[1] Infrasound is sound whose frequency is too low to be heard by humans. The lower limit of useful human hearing is usually taken to be 20 Hz. In this report, we consider sounds at frequencies <20 Hz to be infrasounds.

between 50 Hz and 10 kHz, and (b) continuous drilling platform sound (*Karluk* sounds).[2]

3. To measure the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of continuous drilling platform sound (*Karluk* and CIDS sounds).[2]
4. To collect some of the data needed to assess the importance of the infrasonic components (<20 Hz) of industrial noise; specifically, to measure ambient noise at infrasonic frequencies, and determine whether bowhead calls contain infrasonic components.[1]
5. To measure the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to actual helicopter overflights.
6. To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses and acoustic environment of bowheads and white whales along their spring migration corridor in the western Beaufort Sea.
7. To assist and coordinate with other studies and local resource users to maximize collection of needed data and to avoid interference with subsistence whaling and other studies.
8. To analyze the data to test hypotheses concerning the effects of the drilling platform sounds mentioned in (3) on (a) the movement patterns and (b) the behavior of bowheads and white whales visible along their spring migration corridor in the western Beaufort Sea.

The Null and Alternate Hypotheses

MMS initially indicated that the *primary purpose* of the study was to test the following generalized null hypothesis:

> "Noises associated with offshore oil and gas production activities *will not* significantly alter the migratory movements, spatial distribution, or other overt behavior of bowhead whales during the spring migration in the eastern Chukchi and western Beaufort Seas."

MMS indicated that the *secondary purpose* of this study was to test a similar generalized null hypothesis concerning white whales.

During the planning phase of this study, the hypotheses to be assessed were made more specific in four ways: (1) the types of oil and gas activities of concern, (2) the criteria of whale behavior to be considered, (3) the geographic location and environmental circumstances of the tests, and (4) the fact that playback techniques were to be used to simulate the noise from a platform. Four null hypotheses of a more specific nature were developed for each of the two whale species.

---

[2] The original objective was to project effectively those components of *Karluk* sound above 20 Hz. This was not possible with any practical projector.

1. Playbacks of recorded noise from a bottom-founded platform will not (or alternatively will) significantly alter measures of migration routes and spatial distribution of whales in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.
2. Playbacks of recorded noise from a bottom-founded platform will not (or alternatively will) significantly alter subtle aspects of individual whale behavior in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.
3. Helicopter overflights will not (or alternatively will) significantly alter measures of migration routes and spatial distribution of whales in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.
4. Helicopter overflights will not (or alternatively will) significantly alter subtle aspects of individual whale behavior in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.

MMS indicated that greater emphasis should be placed on hypotheses (1) and (3) relating to effects on migration routes and distribution, than to hypotheses (2) and (4), relating to subtle aspects of the behavior of individual whales. However, LGL undertook to address hypotheses (2) and (4) as well, at least for bowheads. Difficulties in observing some aspects of the individual behavior of white whales from an aircraft circling at high altitude made it doubtful whether hypotheses (2) and (4) could be assessed for white whales.

Approach

This is a complex study with many interrelated tasks or components. This section provides a brief description of the overall approach. This may be helpful in understanding the relationships among the various tasks. Methods are described in more detail in a later section (METHODS).

The general concept was that reactions of bowhead and white whales to industrial noises would be tested by using an underwater sound projector to introduce recorded noise into a lead through which whales were migrating. The movements and behavior of whales would be documented as they approached and passed the sound projector. Industrial sound levels reaching the whales at various distances from the projector were to be measured with sonobuoys or hydrophones, supplemented by acoustic modeling procedures. Reactions to helicopter overflights were to be determined using an actual helicopter rather than playback techniques.

LGL is responsible for the project as a whole, and for all biological components of the work. Subcontractor Greeneridge Sciences Inc. is responsible for providing and operating acoustical equipment, and for analyzing and reporting most of the physical acoustics results. Subcontractor BBN Systems & Technologies Corp. was responsible for sound propagation modeling during 1989.

The contract was awarded to LGL in the autumn of 1988. First-year funding was provided in two stages. Initial funding covered the planning phase (October 1988 to April 1989). After it was determined that the project likely would receive the necessary approvals and permits, incremental funding was provided for the 1989 fieldwork, analysis and reporting.

1989 Planning Phase

During the planning phase, we contacted and met with representatives of three local organizations: the North Slope Borough (NSB), Alaska Eskimo Whaling Commission (AEWC), and Barrow Whaling Captains' Association (BWCA). The purposes of these communications were (1) to obtain information about local conditions that would be helpful in planning the study, and (2) to avoid any actual or perceived interference with their ongoing activities, most notably whaling and the spring bowhead census. As part of this consultation process, project personnel attended a public meeting in Barrow in January 1989 and a meeting of the BWCA in February 1989. In addition, we contacted and met with representatives of the National Marine Mammal Laboratory (NMML) aerial photogrammetry group, who were also planning to work near Barrow in the spring of 1989.

Prior to the 1989 fieldwork, the acoustic environmental conditions near Pt. Barrow during spring were reviewed, modeled and interpreted (Malme et al. 1989/1990; Richardson 1989). The main objective was to determine how far from Barrow this study would have to be conducted in order to avoid acoustic interference with whaling or the census near Barrow. In addition, Miller (1989) reviewed available literature on spring ice conditions and the spring whale migration near Barrow to assist in determining the best site for the fieldwork.

A study area was then selected based on all of the above mentioned discussions and considerations. It was decided that experimental work should be centered about 60 km northeast or east of Point Barrow. To confirm that sounds projected into the water in that region would not reach the whaling or whale census areas, two preliminary sound transmission loss tests were conducted there in late April 1989, prior to the main field season in May 1989. These tests were designed to check the acoustic predictions developed by Malme et al. (1989/1990) and Richardson (1989).

At the end of March 1989, a trip was made to Prudhoe Bay to record the sounds produced by drilling on a grounded ice platform ("*Karluk*") in 6 m of water. Production platforms similar to those that might be used in or near spring lead systems have not been constructed, and no recording of sounds from an icebound concrete or steel drilling caisson were available in early 1989. In the absence of recordings of such sounds, the under-ice noise from the *Karluk* platform was selected as having the most suitable characteristics for use during playback experiments during 1989. In order to maximize the sample size, it was decided to use this one type of industrial noise in all playback tests during 1989.

Plans for the 1989 fieldwork were reviewed and refined at a meeting of the project's Scientific Review Board (SRB) held in early April 1989. The SRB included representatives of the three concerned local groups (AEWC, BWCA and NSB) as well as independent biologists and acousticians (see Acknowledgements). MMS and project personnel also attended.

1989 Fieldwork

The main field program was conducted during May 1989 using two crews of researchers. One crew (aerial crew) conducted surveys and aerial observations of bowheads and white whales from a fixed-wing aircraft. This crew also dropped sonobuoys into the sea to document the underwater sounds near whales and other sites of interest. The second crew (ice-based crew) operated a sound projector to project recorded sounds into the sea and sound recording equipment to monitor those and other sounds. They also used a theodolite to track the movements of whales observable from the ice edge.

No open lead was present along the edge of the landfast ice NE of Barrow until 20 May in 1989, and openings in the pack ice seaward of the landfast ice edge were also scarce and small until about that date. As a result, until 20 May there was no persistent or predictable open water area, although there were transient areas of open water amidst the pack ice. Even after the nearshore lead opened on 20 May, most whales traveled through the pack ice or along the offshore side of the lead. Therefore, a suitable projector site on the pack ice had to be located each day by aerial reconnaissance. The ice-based crew spent the nights in Barrow, and used a helicopter to move to and from the chosen field location on each day when weather and ice conditions permitted.

After arriving on the pack ice each day, the ice-based crew deployed the sound projector and a monitor sonobuoy about 1 km away. Before beginning to project the drilling sounds into the sea, they recorded ambient noise levels. When the drilling sound was being projected, they monitored the transmitted sound level and recorded the noise received at the sonobuoy 1 km away. During sound playbacks, two of the ice-based observers watched for whales, documented behavioral observations, and used a theodolite to track whale movements. The highest available observation platform was usually an ice ridge, so the theodolite was only 2-5 m ASL (Above Sea Level). Because of the low elevation, most ice-based observations were restricted to whales within ~1 km of the projector. In addition, even some of the whales within a few hundred meters of the projector could not be detected because of obstruction by intervening ice.

Whales approaching the projector from greater distances were observed from a fixed-wing aircraft (Twin Otter) circling at an altitude high enough to avoid disturbing the whales (460 m ASL). The aerial observers were able to document whale movements (albeit less precisely than via ice-based theodolite), observe behavior of individual whales, determine whale distribution relative to the sound projector, and drop and monitor sonobuoys to determine sound levels at whale locations. None of these tasks could be done adequately from the ice platform when the whales were beyond ~1 km from the theodolite site.

To provide more information concerning noise attenuation in the water under different environmental conditions, three more transmission loss experiments were conducted by the ice-based crew during the main field season in May 1989. These complemented the two similar propagation tests conducted in late April 1989. These data were used in modeling studies to estimate sound levels at various distances from noise sources under different ice conditions.

1990 Planning and Fieldwork

The 1990 work was also planned in consultation with the Minerals Management Service, North Slope Borough, Barrow Whaling Captains' Association, and Alaska Eskimo Whaling Commission. In early 1990, project personnel attended a meeting in Barrow to describe the 1989 results, explain plans for 1990, and seek local advice on those plans. Results from 1989 were also presented at the North Slope Borough's "5th Conference on the Biology of the Bowhead Whale", in early April 1990. After the end of that conference, the project's Scientific Review Board met to review the draft report on 1989 work and the plans for 1990.

Because field conditions in 1989 had limited collection of data on whale reactions to *Karluk* drilling sounds and to aircraft overflights, it was agreed that additional work comparable to that in 1989 was needed. Although a recording of noise from an icebound bottom-founded caisson engaged in drilling (Hall and Francine 1990, 1991) was available to us by early 1990, it was agreed that the *Karluk* sounds should be used again in 1990. One important change that was agreed to by all concerned was that, in 1990, the sound projector could be set up as close as 15 n.mi. (28 km) beyond the northeasternmost whaling camp or 20 n.mi. (37 km) beyond the bowhead census site if there were a census.

The field approach in 1990 was essentially unchanged from that in 1989, aside from the partial relaxation of restrictions on the study area, deletion of the preliminary sound propagation test phase, and some technical improvements in equipment. Once again, there was a helicopter-supported ice-based crew and an aerial observation crew. The 1990 field season extended from 27 April to 26 May. Specific methods used in 1990 are described later (see "METHODS").

Assumptions and Limitations

A number of assumptions had to be made in designing an experimental field study that would address the general project objectives and the specific 1989 and 1990 objectives. This section lists several assumptions that may need to be made in using the results to predict the reactions of whales to actual oil industry operations. Associated with most of these assumptions are various limitations.

(1) The study area, located NE, ENE and E of Point Barrow, is assumed to be reasonably representative of locations where bowheads and white whales migrating around northern Alaska in spring might encounter oil industry activities.

> ***Limitations***: (a) All sound propagation tests and behavioral observations in 1989-90 were necessarily performed in pack ice conditions or along the south side of the pack ice (north side of the nearshore lead). The applicability of these data to whales migrating along the south side of the nearshore lead, near the landfast ice, is not verified.
>
> (b) The applicability of the 1989-90 results to the Chukchi Sea is not verified, since all 1989-90 data were necessarily obtained in the western Beaufort Sea. However, it is noteworthy that sound propagation conditions in the western Beaufort Sea during spring (this study--Richardson et al. 1990a:148) are similar to those in the Chukchi Sea during late winter-early spring (Greene 1981).
>
> (c) Water depths at many 1989-90 study locations were greater than those where bottom-founded drilling and production platforms are likely to be constructed. Water depth affects sound propagation.

(2) In order to draw conclusions about *all* whales migrating around northern Alaska in spring, it would be necessary to assume that whales visible in leads and amidst the pack ice (i.e. those studied here) react to underwater noise in about the same way as those that are not visible. The accuracy of this assumption is unknown, so we restrict our discussion (and the title of the report) to whales *visible* during spring migration.

Limitations: (a) Some whales migrate along the open nearshore lead, others through extensive leads and cracks in the pack ice, and others through closed-lead or heavy pack ice conditions. The likelihood of detecting whales differs greatly among these three habitats. Also, once detected, the likelihood of successfully observing them for a prolonged period differs greatly among habitats. Almost all 1989-90 data on reactions to noise were from whales migrating through open pack ice or along the north side of an open nearshore lead. We obtained no data on whales migrating through closed lead conditions, and very few data on whales traveling through heavy pack ice (but see 30 April 1989 results--Richardson et al. 1990a:174).

(b) Even in open pack ice, some individual whales are likely to behave in ways that make them more visible than other whales. Because observations are concentrated on the area close to the noise source, whales that come close to the source are most likely to be seen. Based on the limited observations obtainable in the difficult ice conditions encountered in 1989, we could not determine what proportion of the bowheads approached within various distances of the noise source. Based on the more extensive 1990 data collected under more favorable conditions, we consider it unlikely that many bowheads diverted around the test sites at distances beyond our effective observation radius when observing from the aircraft (see "BOWHEAD RESULTS--Larger Scale Avoidance?", p. 225). However, this conclusion comes from experiments involving playbacks of *Karluk* sounds. It would be premature to assume that there would be no long-distance reactions to playbacks of other types of sounds.

(c) Acoustic monitoring and localization methods, which have proven very valuable in studying the movements of whales migrating under the ice during spring migration past Pt. Barrow, are not nearly as useful in a study of this type. The noise emitted during playbacks would mask all but the strongest bowhead calls received near the projector site.

(3) Underwater playback of recorded underwater sounds from an industrial operation is assumed to be a useful method for evaluating the likely reactions of whales to actual industrial operations of corresponding types. In 1989-90, specifically, we assumed that playbacks of underwater sounds recorded near a drillrig on a bottom-founded ice pad were a useful method for testing the reactions of whales to an actual drilling operation of that type.

Limitations: (a) Underwater playback techniques simulate the sounds emitted by an industrial site, but exclude other stimuli to which whales may be sensitive, e.g. sight, smell, effects of physical presence on water flow. This is an advantage in the sense that it allows an assessment of the effects of noise *per se*, but a disadvantage in that the playback does not simulate all aspects of the actual industrial operation.

(b) The types of sounds available for use in this study were limited, and it is uncertain how similar the sounds from an actual drilling/production platform will be to the *Karluk* sound used here. To date, neither drilling nor production have been done in or near spring lead systems off northern Alaska. Therefore, it has not been possible to record or study the sounds emanating from such an operation. It was desirable to conduct tests of the reactions of whales to simulated industrial activities prior to the start of actual industrial activities. There is some reason for optimism that whales may react in a similar way regardless of the specific type of industrial noise used for playbacks, provided that it is continuous (Malme et al. 1984; Richardson et al. 1991). Nonetheless, any extrapolation of the 1989-90 playback results to situations involving other types of industrial sounds must be considered speculative.

(c) Sounds emitted during playbacks do not simulate the full range of sounds that an actual industrial site would emit over time. In 1989-90, we repeatedly projected a 3-minute segment of sounds emitted by the *Karluk* drillsite while it was drilling, simulating a continuous drilling operation with no interruptions. There was no attempt to simulate the noise from other activities that occur intermittently on a drillrig.

(d) Sounds emitted during playbacks do not simulate the full frequency range of sound and vibration emitted by an industrial site. Procedures used in 1989-90 provided a reasonable simulation of the components of *Karluk* sound within the 50 to 12,000 Hz band. However, the playback system underrepresented the components at frequencies below 80 Hz--especially the components below 63 Hz (see p. 88, "PHYSICAL ACOUSTICS RESULTS--Fidelity of Playbacks"). White whales are not sensitive to these low frequency components unless their levels are very high (see Fig. 100, p. 275). Hence, the inability to project them was not a problem during playback tests on white whales. It is not known whether bowhead whales are sensitive to these low frequency components. In summer, bowheads seem at least as sensitive to playbacks of drillship and dredge sounds as they are to actual drillships and dredges (Richardson et al. 1990b). This suggests that playbacks can provide relevant data.

(4) It is assumed that the presence of the observers did not bias the results significantly. Three potential problems existed (see items a-c, below), but these sources of bias were present during most control observations as well as during playbacks. Furthermore, the potential for bias of all three types is believed to be limited.

Limitations: (a) Whales are known to react to aircraft overflights in some situations; many of the 1989-90 observations were obtained from an aircraft circling above the whales. Studies in summer and autumn have shown that an observation aircraft circling over bowheads causes no significant disturbance reaction provided that it remains at an altitude of at least 460 m (1500 ft) at a low power setting, and avoids passing directly over the whales (Richardson et al. 1985a,b). Anecdotal data suggest that white whales also tolerate aircraft at that height (reviewed by Richardson et al. 1991). Limited data from this 1989-90 study suggest that sensitivity to aircraft is no greater in spring than during summer or autumn (see p. 264 and 282). Given this, and the fact that we excluded observations from periods when the aircraft was below 460 m, the presence of the aircraft is not considered to be a significant problem.

(b) The projected drillsite noise came from a small camp located on the edge of an ice pan. This camp, including the ice-based personnel, may have been visible to some of the closer whales while they were at the surface. However, reactions to visual cues would be minimized by the small size of the ice-based operation, the limitations of vision through the air-water interface, and the frequent presence of visual obstructions (ice floes) between the camp and the whales. Also, interpretation problems arising from any non-acoustic effects that do exist can be minimized by comparing behavior of whales passing the camp when the projector is operating vs. silent. This type of control was applied during the 1990 field season.

(c) It was necessary to use a small gasoline-powered generator at the ice camp during playbacks and some control periods. This emitted underwater noise. This noise was detectable underwater within a few hundred meters of the campsite during control (quiet) periods, but the generator noise was masked by the projected sound during playbacks (see p. 98). The possibility of close-range reactions to generator noise during control periods is discussed later (p. 244, "BOWHEAD RESULTS--Non-Playback Effects of Ice Camp"). That section concludes that *(i)* there may be some short-range responses to acoustic or non-acoustic cues from the camp itself, but *(ii)* these cannot explain the more pronounced responses observed during projection of industrial noise than when the projector was off. This difference must have been caused by the sound playbacks themselves.

(5) It is assumed that disturbance of whales is evident by visual observations of their distribution and movements near the noise source, and (for bowheads) visual observations of the details of their individual behaviors. Previous studies have shown that bowhead and white whales often react in visually observable ways when subjected to strong noise from actual or simulated oil industry operations.

Limitations: (a) Even the most conspicuous whales are visible for only a fraction of the time--typically less than 20% in migrating bowheads. Whales migrating past a disturbance source are often below the water and invisible when at their closest point of approach. During periods while whales are underwater or under ice, it usually is not possible to observe them directly. However, some aspects of their movements underwater or under ice often can be inferred from their diving and re-surfacing positions, headings, and times. Also, migrating whales occasionally travel at sufficiently shallow depths such that they can be seen below the surface throughout part or all of a dive in open water. This was common on some days in 1990, including the playbacks on 11, 13 and 16 May 1990.

(b) The calling rates of whales could not be compared under playback vs. control conditions. Some other studies of whales have suggested, often based on equivocal evidence, that call rates diminish in the presence of man-made noise. This could not be studied here because the majority of the calls heard in the absence of projected noise would be undetectable due to masking even if they were present during playbacks.

(c) No direct measure of physiological stress is possible during field observations of passing whales. However, in the case of bowheads, surfacing, respiration and diving cycles were monitored quantitatively. These variables may provide indirect and limited indications of stress. These variables could not be observed reliably for white whales, so we had no similar indicator for that species.

(d) No data of any type could be collected on any whales that avoided detection, e.g. by remaining amidst heavy ice. This was not considered to be a significant problem in 1990 (see limitation 2b, above).

(e) This study concerns the short-term reactions of migrating whales to one source of industrial noise. The long-term consequences with respect to the well-being of individuals and the population are not addressed directly. However, data on the short-term reactions to one noise source may provide an indication of the likely severity of the long-term effects of one or more sources of that type of noise.

STUDY AREA, WEATHER AND ICE

Selection Criteria

In choosing a study area, it was necessary to compromise between choosing (a) an area where many whales would be encountered and (b) an area where project activities would not interfere (or be perceived to interfere) with native subsistence whaling or other scientific studies.

Local Concerns

This study could not have been conducted if it had been opposed by local organizations such as the North Slope Borough, the Alaska Eskimo Whaling Commission, or the Barrow Whaling Captains' Association. Strong opposition would have occurred if the proposed study site were southwest of the northeasternmost of the spring whaling communities (Barrow). Whalers would have been strongly concerned about a proposed disturbance experiment anywhere "upstream" (south or southwest) of any whaling site. They would have been concerned that such a study might block the passage of some whales, or interfere with the subsequent timing or route of the whale migration past the whaling community. For the same reasons, the study area could not have been near Barrow itself.

In addition, for more than a decade there has been an annual spring bowhead census near Pt. Barrow. In 1988, a very intensive census effort was conducted, and in 1989 a scaled-down census effort was planned for late April and May. A minor effort was planned again for 1990 but no work was actually conducted in 1990. This census at Barrow has been very important to the local people, to U.S. regulatory agencies, and to the International Whaling Commission. The census procedures have become very precise and highly sophisticated. Present census and data analysis procedures depend on the consistent migratory behavior of the whales. Disturbance-related changes in whale behavior might include changes in swimming speeds, average distance from the ice edge, or whale headings. Changes in any one of these behaviors could significantly affect the results of the census. Also, acoustic monitoring techniques are now an important part of the census. If background noise levels were elevated because industrial sounds were being projected into the water nearby, the range of effective acoustic monitoring (and especially of call localization) would be reduced. Any real or potential interference with the census would have been unacceptable to a variety of local, national, and international interests.

Given these considerations, the project would not have received local acceptance if the proposed field site were anywhere near or southwest of Barrow. Locations well to the east of Pt. Barrow appeared to be the only locations that might be acceptable to local people and to agencies concerned about the whale census.

Specific Study Location

As part of the planning process for this study, Miller (1989) reviewed the available information on ice conditions and on whale distribution in the area east and northeast of Pt. Barrow during spring. Results of this review are summarized in Richardson et al. (1990a:2-12). Logistically, the most advantageous location for the study area and ice camp was expected to be along the landfast ice edge where a semi-permanent camp might be established. However, the literature reviewed by Miller (1989) indicated (and our 1989 and 1990 studies confirmed) that few whales are found along the landfast ice edge more than about 35 km east of Barrow. Beyond that distance, most whales have moved offshore into the seaward side of the nearshore lead or into the pack ice beyond the nearshore lead.

Thus, during most years, the best location for the sound projector would be along the landfast ice edge within 35 km of Pt. Barrow. Given that such a site might be too close to whaling and census areas, LGL recognized from the start of the planning process that the projector might have to be set up on pack ice northeast of Pt. Barrow. However, the whale migration corridor widens as the whales travel east of Pt. Barrow, reducing the numbers of whales expected to pass close to any given site. Also, logistic support becomes progressively more difficult with increasing distance to the east.

Given the above, it was desirable to work as close to Barrow as possible without causing real or perceived interference to whaling and to the census. The most appropriate distance east of Barrow was determined through an acoustic modeling study (Malme et al., p. 261-284 *in* Richardson et al. 1990a) and consultation with local Barrow organizations, individuals and scientific investigators. In 1989, to provide convincing "safety" margins and to avoid opposition from the various concerned groups, we selected an area about 60 km (32 n.mi.) NE or ENE of Pt. Barrow as the approximate location for the industrial noise playback experiments. We also undertook not to fly within 10 km of the census or whaling sites (unless these were within 10 km of Barrow's airport).

The 1989 study showed that we could conduct the work without interfering with other groups. Therefore, in 1990, after consultation with the same groups, it was agreed that we could work closer to Barrow. In 1990, it was agreed that our projector sites would be at least 15 n.mi. (28 km) northeast or east of the northeasternmost whaling camp. At any times when the bowhead census crew was working on the ice, we undertook to keep the projector at least 20 n.mi. (37 km) away. In addition, we again undertook not to fly within 10 km of the whaling or census sites except as necessary to take off or land at Barrow. The reduced distance limit in 1990 proved to be very helpful in providing more flexibility in choice of projector sites.

Ice Conditions

Sea ice dominates the Alaskan Beaufort Sea, with ice cover of almost 100% for 9 to 10 months each year (Norton and Weller 1984). There are three principal zones of ice cover in the Beaufort Sea: landfast ice, the shear zone, and the pack ice. A brief description of these zones and the annual variation in their occurrence can be found in Richardson et al. (1990a:28-29).

1989 Ice Conditions

Ice conditions in 1989 were more closed than in typical years. When the study was initiated in late April, no major lead was present either along the fast ice edge or in the area where the E-W offshore shear zone usually forms. The overall ice cover was 98 to >99%. The few open water areas consisted of small holes between ice pans, plus narrow cracks and leads that tended to be oriented NW to SE. These general ice conditions were maintained until 12 May, when winds began to shift the offshore pack ice and formed several minor offshore leads oriented SW to NE through the pack ice. Ice conditions remained about the same until 20 May, when a major nearshore lead formed across our study area. Thereafter, the landfast ice was separated from the offshore pack ice by a broad lead. That lead remained open for the remainder of the 1989 study period. The 1989 ice conditions are described in detail in Richardson et al. (1990a:29-32).

1990 Ice Conditions

Ice conditions in 1990 were similar to those in the typical years that are described in Richardson et al. (1990a:28-29). When the study was started in late April, there was a narrow nearshore lead along the fast ice edge ENE of Barrow. Little open water was present amidst the offshore pack ice north and NE of Barrow. The lead started to open at Barrow on 7 May, and was several kilometers wide by 10 May. This major lead extended across much of our study area (Plates 1 and 2). The pack ice north of the lead was generally heavy, but there were localized corridors of less-dense pack ice, especially in the first few kilometers north of the main nearshore lead.

The major nearshore lead and the pack ice farther offshore remained more or less unchanged until 20 May when strong winds moved the offshore pack ice. The lead near Barrow widened but the lead became choked with ice ~40 km ENE of Barrow. During the final few days of the 1990 study, strong winds altered the lead and pack ice conditions almost daily. The lead along the fast ice edge was reduced to 1 km in width by 25 May, and secondary leads developed in the pack north of Barrow.

Weather

The typical weather conditions at and near Barrow during spring were described by Richardson et al. (1990a:32-43). That document also describes the weather in the study area in 1989. In summary, weather and associated ice conditions in 1989 were worse than normal for conducting bowhead whale studies. Weather was clear at the end of April and in early May in 1989, but little open water was present so whales could not be studied very effectively. Unusually cold weather from 5 to 8 May 1989 (Fig. 2) froze existing open water areas and consolidated the offshore pack ice, making observations even more difficult. From 10 to 26 May 1989, low ceilings, snow and fog prevented aerial observations from altitude 460 m ASL most of the time. Observing conditions were ideal on 27-30 May 1989, but most bowheads had already migrated past Barrow by that time.

Weather conditions near Barrow in the spring of 1990 were much more amenable to a study of this type. During the last few days of April and the first six days of May, temperatures at Barrow were near normal (Fig. 3). However, during the remainder of May temperatures were consistently above normal, and "record" high temperatures[3] were recorded or equalled on several different days (Fig. 3). The Twin Otter crew was able to conduct surveys on similar proportions of the days in 1989 and 1990. However, cloud ceilings were much better in 1990. None of the 29 behavior observation sessions conducted in 1990 had to be conducted at altitudes <460 m, whereas in 1989 four of 17 sessions were conducted at <460 m, and other sessions were not initiated because of the prevailing low cloud. Because all 1990 observation sessions were from altitude 460 m, none of our 1990 aerial observation data were confounded by potential Twin Otter aircraft disturbance, contrary to the situation in 1989.

---

[3] Historical weather data against which 1990 data are compared are for the 1951-1980 period. Hence, some of the supposed record high temperatures were not true record highs.

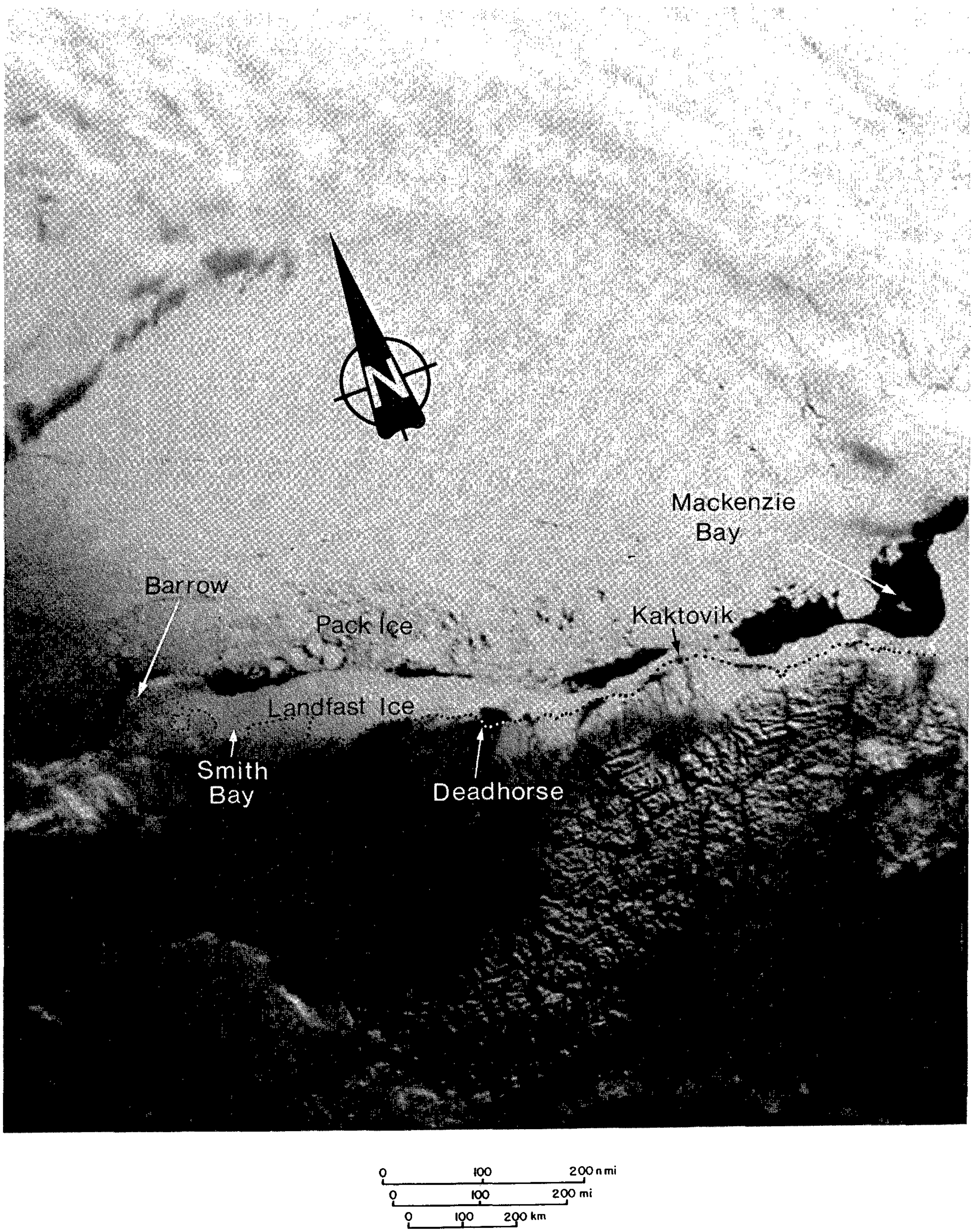


Plate 1. NOAA satellite imagery of the Beaufort Sea, 19 May 1990, showing a well-developed nearshore lead and extensive offshore pack ice.

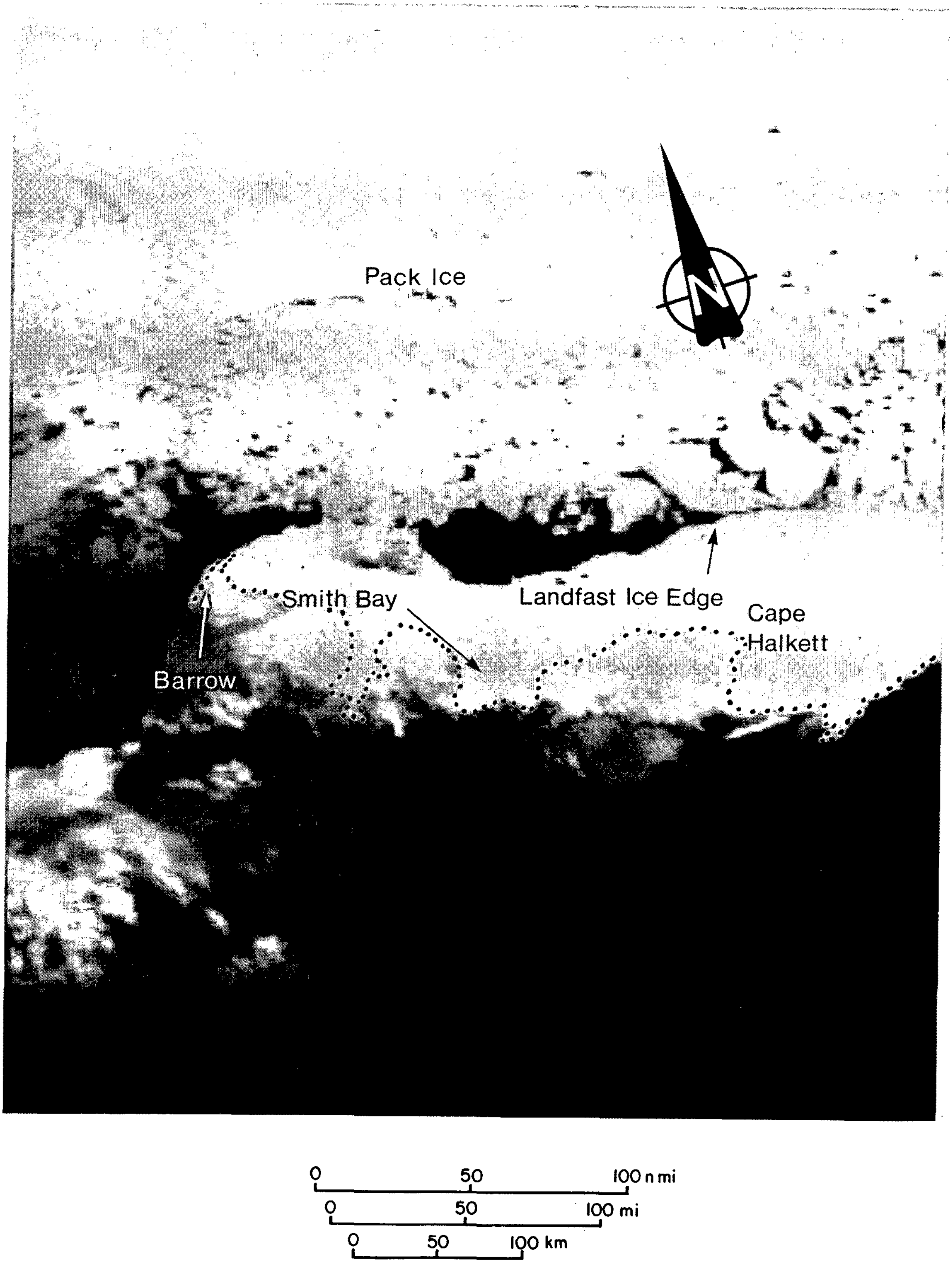


Plate 2. NOAA satellite imagery taken of the western Beaufort Sea, 19 May 1990, showing the landfast ice edge, nearshore lead, and offshore pack ice near Barrow, Alaska.

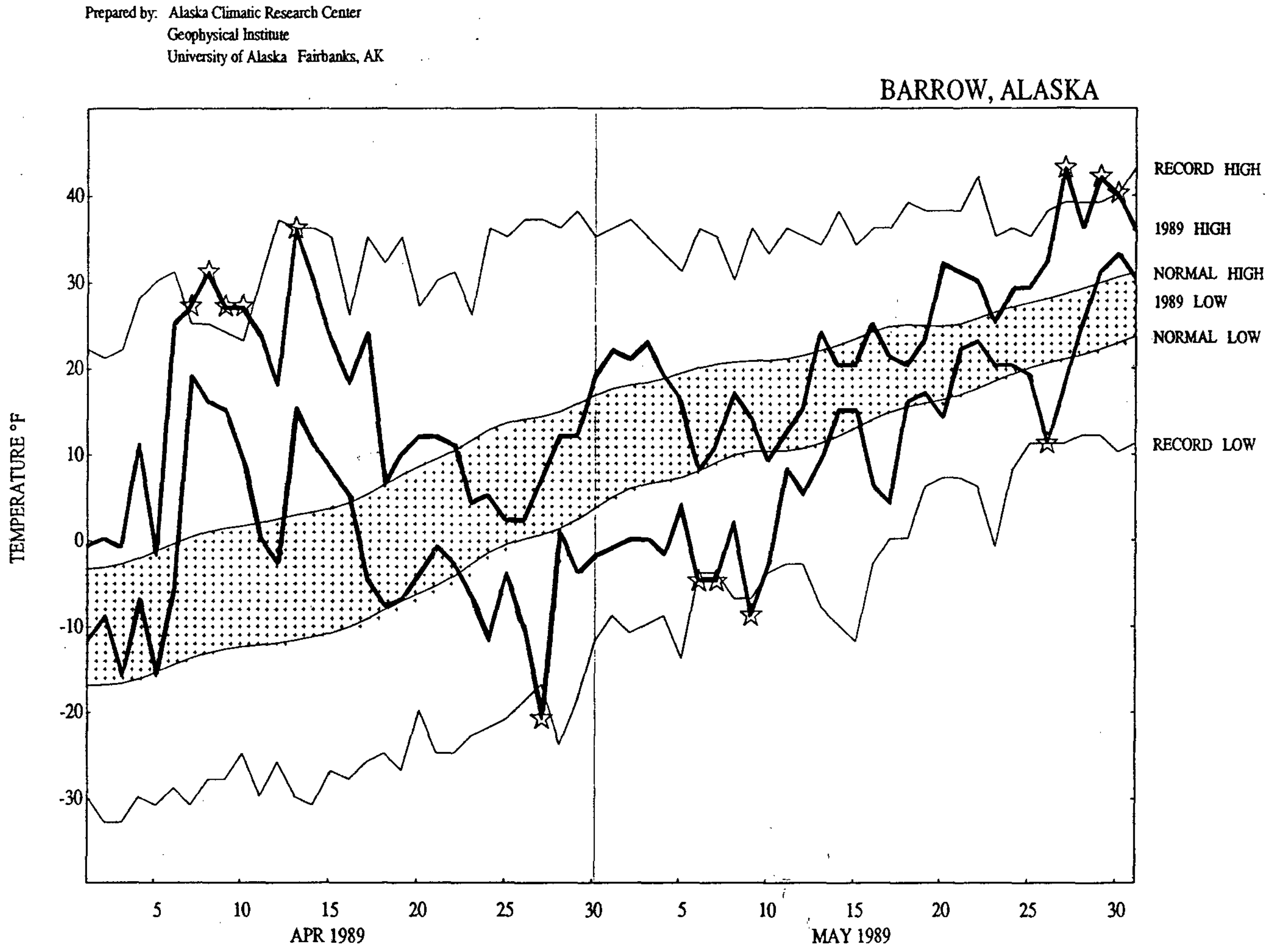


FIGURE 2. Daily weather in April and May 1989 at Barrow, Alaska. Normal and record highs and lows are based on data collected from 1951 to 1980. Stars show occasions in 1989 when the temperature was outside the range for 1951-80.

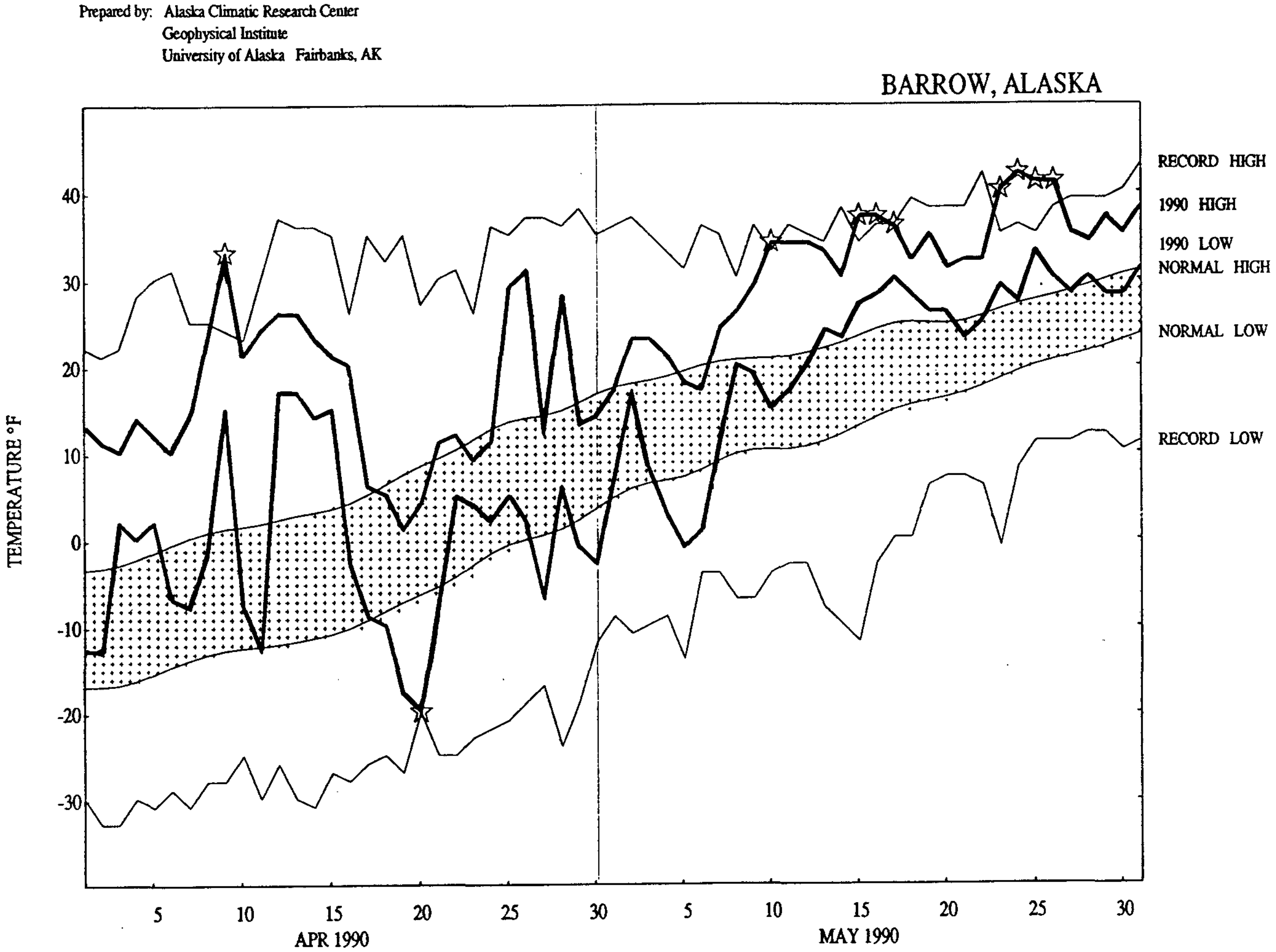


FIGURE 3. Daily weather in April and May 1990 at Barrow, Alaska. Normal and record highs and lows are based on data collected from 1951 to 1980. Stars show occasions in 1990 when the temperature was outside the range for 1951-80.

METHODS

Physical Acoustics Methods

This section is organized according to the four specific 1990 field objectives concerning, in whole or in part, physical acoustics (see p. 5-6). Those objectives were as follows:

(1) ***Ambient Noise.*** To measure ambient noise levels and characteristics in leads and cracks along the spring migration corridor of bowhead and white whales in the western Beaufort Sea, including infrasonic components.

(2) ***Transmission Loss.*** To measure and model transmission loss of underwater sound along that part of the spring migration corridor, based on playbacks of (a) test tones at selected frequencies between 50 Hz and 10 kHz, and (b) continuous drilling platform sound (*Karluk* sounds).

(3) ***Playback Experiments.*** To measure the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of continuous drilling platform sound (*Karluk* and CIDS sounds).

(4) ***Infrasonic Noise.*** To collect some of the data needed to assess the importance of the infrasonic components (<20 Hz) of industrial noise; specifically, measure ambient noise at infrasonic frequencies and determine whether bowhead calls contain infrasonic components.

Ambient Noise

Methods for measuring ambient noise in 1990 followed the practices begun in 1989, with one major improvement: use of Digital Audio Tape (DAT) recorders.

The ice-based crew recorded background noise (1) at the projector site immediately before and after each playback period, and (2) at each receiving station during each sound propagation experiment. The aircraft crew also recorded background noise via sonobuoys dropped at times or places when projected industrial noise was not present. The ice-based crew also recorded some sonobuoy signals. In assessing a recording as suitable for inclusion in the ambient noise database, we excluded recordings with known man-made sounds (aircraft, generator, and playback sounds). We included recordings with bowhead, white whale and seal calls, which are natural environmental sounds.

The ice-based crew used one type of hydrophone for ambient noise measurements: the ITC 6050C. This hydrophone includes a preamplifier next to the hydrophone. The preamplified signals were further amplified by a postamplifier with 0-60 dB gain (selectable in 10 dB steps) before being recorded. Most tape recording was via a TEAC model RD-101T digital audio tape (DAT) recorder suitable for 0-20,000 Hz; a "memo" channel permitted voice announcements by the operator without interrupting the acoustic data. The TEAC also provided a continuous record of date, time, time from the start of the tape, and event number. Sometimes a Marantz PMD430 audio cassette recorder was used (calibrated 10-10,000 Hz).

The aircraft crew used sonobuoys of three types: *(1)* AN/SSQ-41B, with omnidirectional hydrophone, effective at 10-20,000 Hz, hydrophone depth 18 m. *(2)* AN/SSQ-57A, with calibrated omnidirectional hydrophone, effective at 10-20,000 Hz, hydrophone depth 18 m or 14 m. (The standard depth is 18 m, but some units had been modified to deploy their hydrophones to depth 14 m, for use in shallow water.) *(3)* AN/SSQ-53B DIFAR (directional) sonobuoys, effective 10-2400 Hz, hydrophone depth 27 m. The radio signals from all types of sonobuoys were received at a dedicated antenna on the project's Twin Otter aircraft, amplified by a low noise RF preamplifier, and split to two Regency MX5000 wideband FM receivers. The two receivers permitted simultaneous recordings of the underwater sounds from two sonobuoys. The Regency receivers had been modified by adding an audio amplifier attached to the FM discriminator output. This amplifier had a flat audio response from 1 to 20,000 Hz. The special audio amplifier output signals were tape recorded on a second TEAC model RD-101T DAT recorder.

The ice-based crew used a similar setup to record sonobuoy signals but they used a Kenwood model RZ-1 wideband FM receiver to tune the sonobuoy channels. The Kenwood radio had been modified with the same audio frequency amplifier to provide a flat response from 1 to 20,000 Hz.

Samples of ambient noise were analyzed using Greeneridge's standard power spectrum analysis methods as applied in previous projects, including the 1989 phase of this study (Richardson et al. 1990a). The calibration range and analysis frequency range extended down to 5 Hz and up to 8000 Hz as appropriate to the sensor used. A summary of the power density spectrum analysis characteristics is as follows:

- Sample rate: 16,384 samples/second.
- Fourier transform block size: 8192 samples (0.5 s, 2 Hz bin spacing).
- Blackman-Harris minimum 3-term window applied (3.4 Hz bin width).
- 50% overlap of transform blocks.
- 8.25 seconds of data per analysis; based on averaging of transform blocks.
- Spectrum levels computed and graphed.
- 1/3rd octave and 20-1000 Hz band levels computed.

The computed results were adjusted based on the individual calibration curves for the specific pieces of equipment used in receiving and recording the signals: hydrophones, amplifiers, sonobuoys, sonobuoy receivers, tape recorders, filters, and analog-to-digital converters. Data originating from sonobuoys were corrected to allow for the strongly sloped frequency response curves of sonobuoys. This was done using either the individual calibration curve for a particular sonobuoy (57A buoys) or, where necessary, the standard curve for a given class of sonobuoys (41B and 53B buoys). For all three types of sonobuoy, sensor sensitivity is specified to be within ±2 dB of a standard value at one frequency (100 Hz).

One-third octave band levels of the ambient noise were summarized on a percentile basis. The broadband 20-1000 Hz band level was also plotted over time over the duration of the 1990 field season.

Each ambient level value derived by this method is an average over 8.25 s. The project's Scientific Review Board (SRB) also recommended investigating the shorter-term variability of the ambient noise. This would show whether there were short periods of time (<8.25 s) during which the noise level was significantly lower than the measured average level. If so, whales might, at times, be able to hear weak sounds from distant sources--sounds with received levels lower than the average ambient noise. The characteristics for short-term analyses were

- Sample rate: 2048 samples/second.
- Sample block size: 122,880 samples (1 minute).
- Block sizes for acoustic power computation: 512 and 17,408 samples (0.25 and 8.5 s).

Several methods of summarizing and presenting these data are described under "PHYSICAL ACOUSTICS RESULTS--Short-term Ambient Noise" (p. 55*ff*).

Transmission Loss

The objectives of the transmission loss (TL) measurements and modeling in 1990 were essentially the same as in 1989, and the field methods were also similar. Measurements were carried out on four days in 1990: May 1, 2, 24, and 25. We installed a J-11 underwater sound projector at a base camp. Figure 17 (p. 64) shows the locations of the four base camps and their associated receiving stations. The projector was suspended at a depth of 18 m below the edge of an ice pan. The projector's audio amplifier (250 W Bogen MT250) was powered by a 2.2 kW gasoline-powered Honda generator sitting on snow-covered ice, typically about 20 m back from the ice edge.

A cassette tape had previously been recorded with the sounds for transmission. We used three types of sounds in each of the first three transmission tests: tonal sweeps, pure tones, and sounds from the drillrig on a bottom-founded ice-platform at *Karluk*. We added a fourth sound segment for the final TL test--supply ship *Robert Lemeur* icebreaking. *(1)* The tonal sweeps were special "hyperbolic frequency modulation" (HFM) signals (Rihaczek 1986) synthesized by BBN Systems and Technologies Corp. Each 5-s sweep spanned one-third octave at a center frequency of 50, 100, 200, 500, 1000, 2000, or 5000 Hz. During each transmission, each sweep was sent four times with no pauses between sweeps. *(2)* The pure tones were at frequencies 50, 100, 200, 500, 1000, 2000, 5000, and 10,000 Hz. Each tone was transmitted for 20 s with 5 s between tones. *(3)* The *Karluk* drilling noise segment was 35 s long. *(4)* The *Robert Lemeur* segment was 44 s long. Characteristics of the *Karluk* and *Robert Lemeur* sounds were described by Richardson et al. (1990a:80-86). Each transmission of these 3 or 4 types of sounds lasted ~8 min, and the operator rewound the tape after each transmission ended.

The projected sound was monitored with an ITC model 1042 spherical hydrophone placed at a nominal distance of 2 m above the projector face. The actual distance was measured during each deployment of the J-11. The monitor hydrophone signal was tape recorded on a Marantz model PMD430 audio cassette recorder. The recordings were analyzed with the usual Greeneridge power spectrum analysis technique. The resulting levels were adjusted, assuming spherical spreading, to estimate the source level at a reference distance of 1 m. The waveform was monitored on an oscilloscope during projector operation to assure linear operation. The overall source level depended on the frequency content of the signal. It was typically near 166 dB re 1 µPa-m in 1990, vs. 165 dB in 1989.

The receiving/recording equipment consisted of an ITC model 6050C hydrophone, a postamplifier with 0-60 dB selectable gain, and a TEAC model RD-101T digital audio tape (DAT) recorder operating from a battery. The receiving station crew used a Rolotape distance measuring wheel to locate receiving sites along the edge of the ice floe at ranges 100, 200 and (if possible) 400 m from the J-11 projector. At each receiving station, the hydrophone was deployed on a faired cable to depth 18 m. Ambient noise was recorded first. The remote crew then radioed the base camp to request transmission of the taped signals. When transmissions ended, ambient noise was again recorded. At the short-range stations ($\leq$400 m range), the ambient noise was recorded both with and without operation of the generator at the base. This was done to determine the characteristics and range of detectability of the underwater components of the generator sounds.

The distant receiving stations were reached by helicopter. The crew attempted to find suitable recording stations at ranges 0.5, 1.0, 2.0, 5.0, and 7.5 n.mi. A suitable site was one along the edge of an ice floe bordered by open water or thin recently-refrozen ice. The helicopter's GNS-500 VLF navigation system was used for positioning. The GNS was not designed for such precise navigation. However, GNS readouts of the relative positions of two stations overflown at short intervals normally are accurate within a few hundred meters. When there was doubt about the accuracy of the GNS, the helicopter returned to the ice camp in order to re-calibrate the GNS. This was also helpful in allowing for the rapid drift of the ice (and thus the projector) on some days. The absolute position of the ice camp was determined more accurately using a Si-Tex model A-310 satellite navigation system. At the most distant stations, beyond hand-held radio range, the base camp crew operated the projector on a timed schedule and the remote crew sometimes recorded two transmission cycles. Water depth at each receiving station was measured with an echosounder.

Transmission loss (TL) was determined for each receiving station, sound type, and frequency. In the case of the *Karluk* and *Robert Lemeur* sounds, TL was determined for each 1/3-octave where there was significant sound energy. TL for each test sound or 1/3-octave band was found by *(1)* determining the received level (RL) via analysis methods similar to those used for ambient noise, and then *(2)* subtracting RL from the 1-m source level of the corresponding signal as determined via the monitor hydrophone near the projector.

The TL data from each test were used in regression analyses to determine an equation for TL vs. range for each frequency in the area of each test. Each regression analysis included the TL measurements based on all 3 or 4 sound types listed above--HFM sweeps, pure tones, *Karluk* and (test 4 only) *Robert Lemeur.* The fitted equations were of the general form

$$TL = A + B*R + C*\log_{10}(R)$$

where R is in kilometers but TL is the transmission loss in dB referred to range 1 m. The TL value for range 1 m (always 0 dB) was not used in the regression analysis because the equation is not appropriate for ranges less than 100 m. These equations can be used to predict TL from the source to distances ranging from ~100 m through 10 km (the approximate range of the data). ***The equations cannot be used to predict TL from the source to distances less than ~100 m.***

Coefficient C, applying to the logarithmic function of range, is expected to be near 10 for shallow water (cylindrical spreading), near 20 for deep water or very short ranges (spherical spreading), and about 15 for intermediate cases, depending also on source and receiver depths. Coefficient B, applying to the linear function of range, is determined by the combined effects of sound absorption and sound scattering; B must be positive. The constant A, added to B, provides the transmission loss value between 1 m and 1 km. As a rough estimate, we would expect the loss at 1 km to be less than 60 dB [$20*\log_{10}(1000)$] because spreading loss would be spherical for short ranges, transitioning toward cylindrical by range 1 km.

This type of generalized regression equation was fitted to the data for each frequency separately for each 1990 TL test. Then the process was repeated with preselected values of C--10, 15 and 20--on the assumption of cylindrical, intermediate or spherical spreading (respectively) within the distance range for which we had data. The results were assessed in terms of goodness-of-fit and physical appropriateness, given the known water depths. The most appropriate fitted equations were graphed, along with the individual data points, and were used to tabulate estimates of TL vs. range and frequency at the four test sites.

Playback Experiments

All playback experiments in 1990 used the same recording of *Karluk* drilling noise as had been used for the 1989 experiments. Consideration was given to switching to drilling sounds recorded near the CIDS Concrete Island Drilling System by Hall and Francine (1990). However, it was decided that it would be preferable to obtain a more adequate sample size of whale observations in the presence of the sound type used for playbacks in 1989--the *Karluk* sounds. Also, there were doubts about the appropriateness of the available recordings of CIDS sounds for use in playback experiments.

Playback Procedures.--The playback experiments in 1990 were conducted in a manner similar to that in 1989, but with a slightly higher source level. During all playback experiments, we projected underwater sounds that had been recorded 130 m from Chevron's *Karluk* ice-founded drillrig in March 1989 (Richardson et al. 1990a:80*ff*). A model J-11 underwater sound projector was suspended over the ice edge at depth 18 m. An ITC model 1042 spherical hydrophone was mounted 2 m above the projector face to monitor the signals projected. A 250 W Bogen MT250 amplifier drove the J-11. A Sony TC-D5M cassette recorder played a 3-min loop tape of the continuous *Karluk* sounds. A Marantz PMD430 audio cassette recorder was used to record the monitor hydrophone signal and signals received from a sonobuoy deployed ~1 km away.

One specific objective of the 1990 field work was to project effectively the components of drilling sounds above 20 Hz (p. 6). The limitations of the J-11 projector and other practical broadband projectors prevented meeting this objective as completely as desired. The J-11 and other practical projectors cannot reproduce infrasonic components of industrial sound, i.e. components at frequencies below 20 Hz. Also, between 80 Hz and 20 Hz, the J-11 reproduces recorded sound progressively less well with decreasing frequency. Between 80 and 50 Hz, the recorded sound is reproduced, but at a proportionately lower level than that at frequencies above 100 Hz. Below 50 Hz, there is little effective output from the J-11 (see "PHYSICAL ACOUSTICS RESULTS--Fidelity of Playbacks", p. 88). In 1990, the field crew drove the J-11 with slightly stronger power levels than in 1989. The result was slightly higher source levels at all frequencies. However, sound components at frequencies below 80 Hz were proportionately underrepresented, and those at frequencies below 63 Hz were seriously underrepresented. In 1991, a J-13 projector was used in an attempt to improve performance at low frequencies.

Measured Sound Levels During Playbacks.--Sonobuoys deployed by hand and by aircraft were used to monitor the levels and characteristics of the projected *Karluk* sounds as received at different distances from the projector, including near whales.

A sonobuoy was installed manually at a nominal distance of 1 km from the projector prior to each playback of drilling noise. The helicopter was used for transportation to this site. Usually we used a Sparton Defense Electronics AN/SSQ-41B wideband sonobuoy modified to use external batteries for longer life. Also, its cutoff circuits had been disabled to allow operation for more than the usual maximum of 8 h. Hydrophone depth was 9 m. On some days, we used a Sparton AN/SSQ-57A sonobuoy that was standard except that the hydrophone depth was 14 m. Both types of sonobuoys provided useful data from 10 to 20,000 Hz.

Sounds received by each of these types of buoys were telemetered on VHF frequencies between 162.25 and 173.5 MHz. A calibrated Kenwood model RZ-1 wideband FM receiver, modified for flat audio response from 1 to 20,000 Hz, was set up at the base camp to monitor the sounds received at the manually-deployed sonobuoy. A low-noise RF preamplifier was positioned at the antenna to improve weak RF signal reception. The same telemetered sonobuoy signals were often received and recorded aboard the project's Twin Otter aircraft. Sounds projected during playback experiments were monitored and recorded with this remote installation. This provided received level data at one known range (~1 km) in addition to the known level at the projector.

Sonobuoys were dropped from the Twin Otter aircraft, usually at locations near whales, during playback experiments and at certain other times. This allowed us to measure the levels and spectral characteristics of sounds reaching whale locations. It also allowed us to monitor whale calls. We used Sparton AN/SSQ-57A sonobuoys with standard hydrophone depth 18 m or modified depth setting 14 m. DIFAR sonobuoys, Sparton model AN/SSQ-53B, were also used. These directional sonobuoys employ sensors at depth 27 m and span the frequency range 10-2400 Hz. Signals from all types of sonobuoys were received via a dedicated antenna on the Twin Otter. A low-noise RF preamplifier preceded two calibrated Regency MX5000 wideband FM receivers. They had been modified for flat audio response from 1 to 20,000 Hz.

The approximate distances of the manually-deployed and air-dropped sonobuoys from the ice camp were determined via the helicopter's and Twin Otter's GNS navigation systems. Distances to sonobuoys within ~1.5 km of the ice camp usually could be checked via theodolite sightings of the sonobuoy from the base camp or by measuring the acoustic travel time from projector to sonobuoy. Travel time could be measured when signals from the monitor hydrophone (~2 m from projector) and sonobuoy were recorded simultaneously on the same recorder at the base camp. When two sonobuoys were monitored simultaneously, as was sometimes done from the aircraft, their relative distances from the projector were measured based on the difference in arrival times of projected sound components at the two buoys.

Sound Levels Received by Whales During Playbacks.--Equations to predict received levels vs. distance were developed for each playback test. These equations were based on (1) measured sound levels during that test and (2) transmission loss models derived from the four TL experiments during 1990.

Measured water depths at the playback sites influenced the choice of equation. In the shallowest water, i.e. depth <50 m, a spreading loss term of 10*log(R) corresponding to cylindrical spreading was appropriate. For depths 50 to 200 m, an intermediate spreading loss term of 15*log(R) was appropriate. For depths >200 m, spherical spreading--represented by

20*log(R)--was assumed to apply. These depth zones were selected after examining the measured received levels vs. range during disturbance and transmission loss tests.

Two or three frequency bands were considered when describing sound exposure: *(1)* The 20-1000 Hz band, which included all significant energy from the *Karluk* playback.[4] *(2)* The one-third octave band centered at 200 Hz, which was generally the strongest one-third octave band in the *Karluk* spectrum. Occasionally, due to frequency-dependent propagation effects, the level in the one-third octave band centered at 160 or 250 Hz was slightly stronger than that near 200 Hz. In these cases, the band around 160 or 250 Hz was considered. *(3)* For the first disturbance test on 13 May, the one-third octave band centered at 1250 Hz was also considered. The first J-11 projector used on the 13th had developed a slow leak. Its output level gradually decreased and signal distortion increased. For part of this period the one-third octave band near 1250 Hz contained the strongest projected sounds. The adjacent one-third octave bands, centered at 1000 and 1600 Hz, were also considered in determining the strongest received levels during the first test on the 13th.

The specific procedures used to develop suitable transmission loss models for each playback day are described in Appendix B. Different procedures were used on different days, depending on circumstances and the available data. During the analyses and computations, all sound levels were specified to the nearest 0.1 dB re 1 µPa. For presentation in tables, the results are rounded to the nearest integer dB.

For each playback test, the sound levels in the above-described frequency bands were calculated as functions of range. Estimated sound levels based on transmission loss models were graphed in relation to distance from the projector. These estimates were tabulated for standard distances of 0.2, 0.5, 1.0, 2.0, and 4.0 km, and for the distances of closest approach by bowheads. Average measured ambient noise levels were also tabulated to permit assessing the signal-to-noise ratios. It should be noted that the ambient levels varied by as much as 20 dB during measurements on any given day.

Infrasonic Components of Ambient Noise and Bowhead Calls

Because of concerns about the possibility that bowheads are sensitive to frequencies lower than those that can be reproduced adequately by the J-11, we wanted to obtain information concerning the sources, transmission and reception of sounds at low frequencies, including infrasonic frequencies (<20 Hz). Of the several possible avenues of investigation, two were practical in 1990. We measured the infrasonic components of the natural ambient noise, and we undertook a preliminary assessment of bowhead calls to see if they included infrasonic components. *(1)* The levels of ambient noise at infrasonic frequencies are relevant to any attempt to evaluate how far away an infrasonic component of an industrial noise might be audible above the natural background noise at corresponding frequencies. *(2)* If bowhead calls contain infrasonic components, there would be increased reason for believing that bowheads can hear those frequencies.

---

[4] The original *Karluk* sounds included components below 20 Hz, but these were not reproduced during playbacks via the J-11 projector.

In measuring ambient noise levels, the methods used for the sonic frequency range were also used for the lower frequencies. The calibrations and analyses were extended to 10 Hz for the sonobuoys and 5 Hz for the ITC 6050C signals. This permitted inclusion, in the ambient noise statistics, of band levels for third-octave bands centered at 12.5 and 16 Hz.

Waterfall spectrum analysis was used to examine bowhead calls for infrasonic and other low-frequency components. This approach is useful in determining whether, at the times when bowheads emit their known types of calls, there are also infrasonic components that have not previously been recognized. The characteristics for waterfall spectrum analysis were as follows:

- Sample rate: 1024 samples/second.
- Fourier transform blocksize: 1024 samples (1 Hz bin spacing).
- Blackman-Harris minimum 3-term window applied (1.7 Hz bin width).
- 87.5% overlap of transform blocks.
- 1 second of data analyzed and displayed per spectrum displayed.
- Typically, 9.45 seconds of data were displayed in a waterfall plot showing frequencies 5 to 250 Hz.

The results concerning infrasonic and other low-frequency components of bowhead calls are given under "PHYSICAL ACOUSTICS RESULTS--Bowhead Calls" (p. 91).

Aerial Reconnaissance and Surveys

General Approach

Aerial reconnaissance and surveys were a necessary component of the work required to meet specific objective 3, "To measure the short-term behavioral responses of ... whales ... to underwater playbacks...". Aircraft-based work was also important in addressing specific objective 6, "To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses and acoustic environment...".

Aerial surveys were necessary to find the best location for the projector site each day and to determine the number and spatial distribution of whales moving east near the projector site. Because the projector had to be established on the pack ice, it was not prudent to leave the ice-based crew on the ice overnight. The first priority each day was to find a suitable location on the pack ice for the sound projector. Ideally, this location would have been a large multi-year ice pan along an open E-W lead through which bowheads and white whales were migrating.

Each day when conditions were suitable for flying, a reconnaissance survey of the study area was conducted to document ice conditions, including the locations and orientations of leads, and to determine the distribution, numbers, general activities and directions of movement of whales. The flight route depended on ice conditions. In general, a series of widely-spaced transects was flown initially to determine the overall ice conditions and the locations and orientations of leads. A location for the sound projector was then selected. While the projector was being set up, additional surveys were conducted as far as 20 km west and southwest of the projector site. These additional surveys followed any prominent leads that whales might follow toward the projector site.

The need to avoid disturbing whales near Barrow necessitated setting up the projector ≥28 km east of the northeasternmost whaling camp (see specific objective 7, p. 6, and "STUDY AREA--Specific Study Location", p. 14).

Survey Methods and Data Recording

Aerial surveys were conducted from 29 April to 26 May 1990 in a DHC-6-300 Twin Otter aircraft. The Twin Otter is a high-wing aircraft powered by two turboprop engines. The aircraft was equipped with a GNS 500A Very Low Frequency navigation system, a radar altimeter, an inverter for 120 V/60 Hz power, three bubble windows (right center, left center, left rear), and an intercom system for communication among the four observers and two pilots. An aircraft with a ventral camera port was not available in 1990, so no photogrammetry work was possible. Also, the aircraft did not have a long-range fuel tank, so flights were limited to a maximum of about 4.5 h.

The aircraft was flown at ~200 km/h airspeed and, when possible, at 460 m (1500 ft) above sea level (ASL). When ceilings were lower than 460 m, the maximum possible altitude below the cloud layer was maintained. During the mid-day periods when a NMFS-National Marine Mammal Lab crew was conducting low-altitude photogrammetric work with another Twin Otter in the same region, we normally either flew at 460 m altitude or stayed on the ground. This avoided some aircraft safety concerns, and fulfilled a condition of the research permit issued by NMFS for this project (see specific objective 7, p. 6).

Four observers were present during almost all surveys. During surveys, they recorded observations onto audio cassette recorders. During surveys, one observer (right front) was in the co-pilot's seat, two were at bubble windows on the left and right sides of the aircraft two rows behind the pilot's seat, and the fourth was at a rear-left window. For each whale sighting, observers recorded the time, location, number, species, general activity, orientation, and ice conditions. Ice conditions were noted throughout the survey, particularly whenever a change in ice type or percent cover occurred. Aircraft position was recorded manually from the GNS whenever sightings were made and whenever the aircraft changed course.

When a whale was sighted, the observer notified other members of the crew over the intercom. Most bowhead whales were circled at least briefly to obtain information on the activity of the whale and to determine whether additional whales were present nearby. White whales usually were not circled, but large groups of white whales were circled to obtain more accurate counts and heading information.

No standardized surveys were conducted by helicopter. However, locations and headings of bowheads seen from the project's Bell 212 helicopter during ferry flights were noted.

Behavioral Observations

Aerial Observations

On 29 occasions in late April and May 1990, the aerial observation procedures of Richardson et al. (1985a,b, 1990a) were used to observe the behavior of bowhead or white whales, as required to meet specific objectives 3 and 5 (p. 6). Four observers in the Twin Otter aircraft circled high above the whales. In 1990, the aircraft always circled at 460 m ASL, which is high enough to avoid significant aircraft disturbance to bowheads, at least during summer and autumn. (Results from this study in 1989-90 suggest that sensitivity to the observation aircraft was no greater during spring than during previous summer and autumn work--see p. 264 and 282.) Airspeed during circling was ~165 km/h. The 29 behavioral observation sessions in 1990 ranged from 0.5 h to 3.5 h in duration, and totalled 46.8 h. For some analyses, we combined these data with those from the 17 observation sessions in 1989, which ranged from 0.1 to 3.3 h in duration and totalled 25.6 h (Richardson et al. 1990a).

The locations of the 29 observation sessions in 1990 are shown on Figure 5 (p. 42). Whenever possible, aerial observations were conducted near the ice camp in coordination with broadcasts of drilling platform sounds or associated control observations. Locations where coordinated ice-based plus aerial observations were obtained are shown in Figure 4 (p. 41).

Throughout each observation session, two observers on the right side of the aircraft dictated standardized behavioral observations via the intercom into a single tape recorder. These observers were in the co-pilot's seat and the seat two rows behind it. During each surface/dive sequence by bowheads, they described the same behavioral attributes as were recorded in our previous behavioral studies (Würsig et al. 1984, 1985; Richardson et al. 1985b, 1987b, 1990a; Koski and Johnson 1987).

The third observer, also on the right side during behavioral observations, operated an 8-mm video camera whenever whales were at the surface. Videotaping was through a flat window at the right-rear of the aircraft. A high-resolution (Hi8) camera was used, initially a Canon A1 Mk 1 with 8-80 mm lens and 1.4x teleconverter. From 21 May onward, a Sony CCD-V99 with 11-88 mm lens and 1.4x teleconverter was used. The video camera was usually operated with manual focusing and 1/1000 s shutter speed to provide sharp images when viewed in stop-frame mode. The time was displayed on each video frame. The behavioral dictation on the intercom was recorded onto the audio channel of the video tape recorder. The Hi8 cameras, used for the first time in 1990, provided greatly enhanced resolution over the Beta and standard 8-mm systems that we have used previously for this purpose.

In 1990, we resumed using a fourth observer on the observation aircraft, after using only three observers in 1989. The fourth observer surveyed for bowheads during reconnaissance periods, operated the sonobuoy receiving and recording system (see "PHYSICAL ACOUSTICS METHODS--Ambient Noise", p. 20), and assisted with behavioral observations when not busy with the sonobuoy system. The addition of this observer in 1990 proved to be very beneficial. In 1990, it was common for several bowheads to be simultaneously at the surface within the observation circle. The presence of the third observer allowed us to collect simultaneous and detailed data on more whales than could have been documented in his absence. It also avoided the necessity for the third observer to interrupt videotaping and project coordination activities to operate the sonobuoy system. This resulted in more complete videotape and sonobuoy records than would have been possible otherwise.

Behavioral data were transcribed from audiotape between flights, and the videotape was examined then or after the field season for details not noted during the real-time behavioral dictation. The combined data were coded numerically as in our previous work (see Richardson and Finley 1989:25-28 for details). These records were hand checked, and then typed into an

IBM-compatible microcomputer for computerized validation and analysis. Statistical analyses of the resulting behavioral data were done with the BMDP program system, version PC-90.

The numbers of bowhead surfacings and dives for which we have at least partial behavioral data are as follows:

	1989		1990	
	Surfacings	Dives	Surfacings	Dives
Presumably undisturbed whales	258	157	556	373
Potentially disturbed whales*				
Drilling noise playbacks	127	104	287	149
Aircraft at <460 m ASL	56	32	5	4
Sonobuoy drop	4	4	0	0
Other or combination	34	32	9	2
Subtotal	221	172	301	155
Total, undisturbed + disturbed	479	329	857	528

* Includes observations during 30-min or 15-min "post-disturbance" periods.

Ice-based Observations

Observations of bowheads and white whales were obtained by ice-based observers to help meet specific objectives 3, 5 and 6 (p. 6). When no whales were present, ringed and bearded seals were observed opportunistically. Upon arrival at the daily observation site, the theodolite was set up on the highest ice perch within ~300 m of the projector and ~20 m of open water. The observation site was usually on an ice ridge 2-5 m ASL. Two observers used binoculars to scan waters within ~2 km. When whales were sighted, one observer used a land surveyor's theodolite to track whales and observe their behavior. Observations were dictated to the second observer, who recorded all relevant data onto data sheets, into a field notebook, or into a cassette recorder.

A digital theodolite was used to measure successive positions of whales and seals in relation to the sound projector. In 1990 we used a Lietz/Sokkisha Model DT5A with 10 second precision. The height of the theodolite above sea level was determined each day by taking a gravity-referenced horizontal reading from a vertical stadia rod at the projector location. Theodolite bearings were measured in degrees, minutes and seconds from the horizontal zero (usually referenced to magnetic north) and a vertical zero referenced to gravity. Most ice ridges on which the theodolite was placed were less stable than desired. To control for error, the horizontal and vertical zeros were checked every 30 min (approx.) and after tracking episodes, and were reset if off by greater than one minute of arc.

The distances of whales from the theodolite were calculated initially by simple trigonometry, without correction for the curvature of the earth. This error is small for the combinations of perch heights and short (<2 km) distances involved in most of the 1990 observations of whales (Table 1). A whale 500 m from observers at a height of 2 m ASL would be only 5 m farther away than the distance calculated by the simple formula. However, for the small number of observations where the error associated with earth curvature would otherwise have been >5%, the distances were corrected by using a computer program that applied an iterative formula modified by E. Carlson from J.I. Wolitzky *in* Würsig (1978).

Table 1. Underestimation of distances calculated from theodolite data when curvature of earth corrections are not used.*

Theodolite Height	Distance from Theodolite				
	100 m	500 m	1000 m	1500 m	2000 m
1 m	0 m	10 m	96 m	433 m	N/A
2	0	5	41	163	490 m
3	0	3	27	98	273
4	0	3	21	73	191
5	0	2	17	56	143

* Formula modified by E. Carlson from J.I. Wolitzky *in* Würsig (1978)

Another potential error results from the refraction caused by temperature gradients in the air above the water (Sonntag and Ellison 1987). This error could be significant for low perch heights and whales more than ~1 km away when wind conditions are calm and air temperatures are low. The lack of reliable data on vertical temperature gradients in the air over leads prevents an evaluation of refraction error.

After the theodolite was set up, the relative locations of the projector, the manually-deployed sonobuoy, and the ice edge across the lead were documented by theodolite readings. These readings were repeated at ~2 h intervals to document shifts in ice configuration. Depending upon the width of the lead and the height of the perch, the waters within ~2 km of the theodolite were scanned intermittently with binoculars. When an animal was sighted, its bearing and depression angle were determined using the theodolite. Theodolite readings were recorded when the crosshairs were aligned with the waterline of the surfacing animal. An attempt was made to obtain a reading each time an animal surfaced for a blow. At each of these points, the time was also noted. Animals were tracked until they were no longer in view.

Additional notes were made in real time of initial and final sightings of all animals, including estimated distance and magnetic bearing from the projector, group size and composition, general behavior, direction of movement and subsequent shifts in direction, blow times, sighting conditions, presence of other species, and any other occurrences of interest, including aircraft flying overhead. These notes were made whether or not the theodolite and/or projector were in operation.

Playback Experiments

Playbacks were conducted to meet specific objective 3, "To measure the short-term behavioral responses of ... whales ... to underwater playbacks of the continuous drilling platform sound...". Drilling platform sounds were projected from a mobile ice-based camp that was established on the pack ice each day when weather and ice conditions were suitable. During one playback day in 1990 (9 May), observations of whales were obtained only from the ice camp because low cloud cover prevented aerial observations from altitude ≥460 m. During five days of playbacks (10, 11, 13, 16 and 21 May 1990), observations of whales were obtained by both the ice-based and aircraft-based crews. Bowheads were observed within 2 km of the operating sound projector during all six of these days. White whales were observed within 2 km during only one day in 1990--21 May.

In 1990, we made a greater effort than in 1989 to photograph the ice conditions around each projector site. Such photographs are needed to prepare maps of whale movements past the projector. At least once and usually twice during each day with coordinated aerial and ice-based work, the aircraft climbed to an altitude of 3000-5000 ft (cloud ceiling permitting). Oblique and near-vertical photographs of the area were taken from several angles using 35-mm cameras with 35-mm wide angle and 17-mm very wide angle lenses. Some examples appear as Plates later in this report. In addition, Polaroid photographs of the ice and leads were taken at the same times to provide prints onto which notes could be made immediately.

Playback Equipment and Procedures

Each day when weather and ice conditions permitted, the ice camp was established on the pack ice along a lead. When possible, the camp was placed to the east or northeast of whales located by aerial reconnaissance. The sound projector and ancillary equipment, the sound recording and monitoring equipment, and the theodolite were set up. This process normally required 1-2 hours after arrival at the site. The theodolite crew then watched for approaching whales, supported by the aerial crew whenever feasible. If no whales were seen close to the projector, it was started. To avoid startle reactions, we did not intentionally start the projector when bowheads were within 1 km. From 13 May onward, the sound level was increased gradually over 1 min (13 May) or 5 min (16, 21 May).

A single broadband J-11 projector was used for all playback experiments. The J-11 can produce a source level for *Karluk* of about 167 dB re 1 μPa-m without distortion. Its effective bandwidth is rated as 20-12,000 Hz, but its output is greatly reduced below 63 Hz and slightly reduced between 63 and 80 Hz (see "PHYSICAL ACOUSTICS RESULTS--Fidelity of Playbacks", p. 88). The J-11 was powered by a 250 W Bogen MT250 power amplifier. The J-11 and its ancillary equipment were portable by helicopter, which allowed us to conduct "single-day" experiments at changing locations.

To operate the amplifier and other electronic equipment for a significant length of time, it was necessary to use a generator instead of batteries. In 1990, the generator was operated during most control periods as well as during playbacks to ensure that control and playback periods differed only by the emission of sound from the projector during playbacks. The 2.2 kW gasoline-powered Honda generator produced significant airborne noise. Little of this noise was transmitted into the water because of attenuation by the snow-covered ice. Underwater sound from the generator would not have been detectable by whales during playback experiments, but might have been detected by whales close to the ice camp during control periods while the generator was operating (see p. 98, "PHYSICAL ACOUSTICS RESULTS--Generator Noise"; p. 244, "BOWHEAD RESULTS--Non-playback Effects of Ice Camp"; and, for 1989 data, Richardson et al. 1990a:97).

It was important to obtain the most accurate possible data on the relative positions of whales and the sound projector. These data were needed to plot whale movements and to estimate received sound levels when these were not measured directly by sonobuoys. When whales were within ~1 km of ice-based observers and within their field of view, the most precise positional data were obtained with the theodolite. However, for whales observed from the air, other procedures were necessary.

The absolute location of the ice camp was determined using the VLF navigation systems on the Twin Otter and helicopter (usually accurate within about 1 km in 1990) and using a Si-Tex model A-310 satellite navigation receiver at the ice camp (accuracy 0.1-0.2 km). The position of the ice camp often changed substantially during an experiment due to wind- and current-induced drifting of the ice. To account for this, all whale sightings and movements were plotted relative to the sound projector. To help determine whale positions relative to the ice camp, the observation aircraft was often flown from the location where whales had just dived to the ice camp. By flying directly over these two positions within a short interval, the aircraft's VLF navigation system provided accurate (±0.3 km) data on the whale-to-projector distance and bearing even though absolute position readouts from the VLF system were less precise. In addition, during playbacks we frequently recorded the position of the whale according to the aircraft's VLF navigation system, and we made visual estimates of the distance from the whale to the projector during most whale surfacings. Whale-to-projector bearings were estimated by reference to the aircraft's gyrocompass. Upon our return to the Barrow airport after each flight, we recorded the amount of drift in the absolute GNS readout during the flight. In 1990 it was usually 1 km or less.

Acoustical Monitoring

Sound levels reaching whales during playback experiments were measured and/or estimated using several techniques, as described under "Measured Sound Levels During Playbacks" and "Sound Levels Received..." (p. 23-25). By having a variety of monitoring capabilities, we were able to obtain the necessary data on sound exposure levels in a wide variety of field situations, including situations where some methods were impractical. The transmission loss measurements from 1989 and 1990, along with mathematical models of transmission loss, provided estimates of received level at places and times where direct measurements of sounds reaching whales were not available.

Behavioral Observations

To maximize the power of the observations in assessing the hypotheses, we planned to use whales approaching the sound projector as their own controls. Our intent was to compare the behavior of the same whales when they were at various distances from the projector. This approach reduces the complications caused by differences in the natural activities of different individual whales. We planned to begin observing the movements and behavior of whales when they were far enough from the projector that they could not hear it or, at the least, were not likely to react to it.[5] We then intended to observe their movements and behavior as they approached and passed the projector.

---

[5] Previous studies of bowheads and other baleen whales have shown that they generally show no discernible reaction to steady sounds that are weak but presumably detectable (Richardson et al. 1991).

Because the projector had to be reestablished on the ice each day, the projector often began operating while whales were already under observation from the aircraft. To eliminate observer expectancy biases, we prevented the two primary behavioral observers in the aircraft from knowing whether the sound projector was operating. This "blind" observation protocol for the primary observers was fully achieved in 1990. The third observer on the aircraft (project director) was in radio communication with the acoustician on the ice, and was aware of projector status. The fourth observer on the aircraft was usually aware of projector status because he was monitoring the signals received by sonobuoys, which detected the projected drilling sound when it was present. The 3rd and 4th observers did not discuss projector status with the primary behavioral observers until after the behavioral data had been transcribed from audiotape onto dataforms by those primary observers.

In addition, the ice-based crew recorded whale behavior and movements with the aid of the theodolite during playback experiments. Because of the low vantage point from the ice, ice-based observers could not see whales unless they were within ½-2 km of the projector (depending on ice conditions). The most valuable data obtained from the ice-based observations were data on the closest point of approach to the projector and on the tracks of whales that approached or passed the projector. More precise data of these types could be obtained by theodolite than by aerial observations. Also, ice-based observers sometimes were able to collect data when aerial observations were impractical because of low cloud ceiling (9 May 1990) or limited aircraft endurance.

Because of their proximity to the projector site and their involvement in its deployment and retrieval, the ice-based observers sometimes were aware of projector status (on or off). However, most of their data were theodolite readouts, which do not involve subjective judgments. Thus, observer bias would not be a problem in these data. Furthermore, the ice-based biologists often were unaware of projector status. The generator was operated during both playback and control periods. During control periods as well as playbacks, the tape recorder used to play back the *Karluk* sounds was operated, and the *Karluk* sounds were played over a monitor speaker in the tent at the ice camp. With this procedure, only the acoustician at the camp knew whether *Karluk* sounds were also being projected into the water.

To determine the reactions of whales to the drilling sounds, we planned to conduct three types of comparisons of whale movements and behavior: *(1)* For whales that approach and pass the operating projector, examine movements and behavior as a function of distance from the projector, allowing each animal or group to serve as its own control. *(2)* Compare the movements and behavior of whales passing the ice-based crew at times when the projector is operating vs. silent. *(3)* Compare the movements and behavior of whales seen near the operating projector vs. those seen at times and locations when the ice-based crew is absent.

In 1989, because there were few opportunities for playbacks, we decided to operate the projector on each day when whales were passing it. Thus, few data of the type needed for comparison (2) were obtained in 1989. In 1990, control observations with the ice camp present were obtained during parts of most days with playbacks, and on two days when there were no playbacks (29 April and 19 May). Thus, all three types of control data were obtained in 1990.

GENERAL CHRONOLOGY OF 1990 FIELD ACTIVITIES

Daily Chronology, 1990

The ice-based crew arrived at Barrow on the evening of 25 April and organized and tested the sound projection and recording equipment on 26 April. On 27 April a transmission loss experiment was attempted but slush ice and technical difficulties caused the test to be aborted (Table 2). The aerial observation crew set up and tested their data recording equipment before the Twin Otter aircraft arrived.

On 28 April a storm warning was issued for the Barrow area. The Twin Otter arrived at Barrow and the aircraft-based crew installed their electronic equipment in the Twin Otter.

The Twin Otter crew conducted a reconnaissance of the area ENE and NE of Barrow on 29 April. They found a nearshore lead that was several kilometers long and oriented WNW to ESE along the landfast ice edge ENE of Barrow. Several bowheads were found moving along a mostly refrozen secondary lead extending ENE from the main nearshore lead. The first behavior observation session of the year was conducted on 6 scattered bowheads in the secondary lead (Table 3). The ice-based crew set up the ice camp beside a small opening along the northern side of the secondary lead (Fig. 4). However, the projector remained quiet during this day (control observations). The Twin Otter crew conducted a second behavior observation session near and to the WSW of the ice camp (location B2 *in* Fig. 5).

The Twin Otter crew conducted surveys ENE of Barrow on each day from 30 April to 4 May and found little open water and no bowheads. In the absence of whales, the ice-based crew conducted transmission loss tests on 1 and 2 May. Then, on 4 May, they projected *Karluk* drilling platform sounds into the water along a small refrozen lead amidst the pack ice, in the hope that whales might approach (Table 2, Fig. 4). However, no whales were seen near the camp.

On 5 May the Twin Otter crew found a single bowhead traveling along a long thin lead in the pack ice and followed this whale for over an hour (B3 *in* Fig. 5). The ice-based crew set up along this lead during this time, but no additional bowheads were seen. A combination of fog and high winds prevented any useful work on 6-8 May (Table 2).

On 9 May the Twin Otter crew conducted a survey during conditions of low ceilings; they found 12 scattered bowheads and directed the ice-based crew to the north side of the main nearshore lead where several bowheads had been sighted (Fig. 4). The ice-based crew obtained ~27 observations of bowheads passing when the projector was quiet and when *Karluk* sounds were being projected. Aerial observations were not possible during this playback experiment because the cloud ceiling was <460 m near the projector. However, migrating whales were observed farther west where the sky was clear (B4, B5 *in* Fig. 5).

On 10 May many bowheads were sighted moving across the main lead and entering a secondary lead along the north side of the main lead. The ice-based crew set up along the secondary lead, and observed bowheads moving past the sound projector both during playback and control periods. Because of variable cloud conditions and ceilings at different locations and

Table 2. Summary of daily activities and weather and ice conditions, 27 April-25 May 1990.

	Ice-based Crew								Aircraft-based Crew			
Date	Ferry Flights	Transm. Loss Test	*Karluk* Projections	Number of Bowheads	Location	Other	Overall Ice Conditions	Cloud Ceiling/ Visibility	Survey (h)	Behavior Obs. Sess. (h)	Location	Other
27 Apr	2			0	71°30′ 155°38′	Ice reconnaissance. Attempted TL test but faulty equipment.	99% Small to medium-sized openings, but no leads.	Clear or high cloud.				
28 Apr	0					Equipment maintenance.	99%	Poor weather was forecast.				Aircraft arrives at Barrow.
29 Apr	2			2	71°32′ 154°59′	Control obs. No projections.	97% Lead along landfast ice NE of Barrow.	Clear	3.4	3.3	71°31′ 155°03′	Obs. of presumably undisturbed behavior.
30 Apr	3			0	71°31′ 154°44′	Refrozen lead. TL test but faulty equipment.	97% New ice formed overnight.	Clear	1.8		Survey ENE of Barrow.	
1 May	1	#1		(1)*	71°37′ 156°09′	One bowhead sighted near a TL station. Bowheads also heard.	97%	Hazy with low cloud. Poor vis.	1.7		Survey ENE of Barrow.	
2 May	2	#2		0	71°34′ 155°02		97%	Ceiling 150-450 m. Variable vis.	1.5		Survey ENE of Barrow.	
3 May	0					Equipment maintenance.	97%	Ceiling 180-300 m.	2.6		Survey ENE of Barrow.	
4 May	4		P1	0	71°36′ 155°49′	*Karluk* playback; bowheads heard but not seen. Broadcast into E end of minor refrozen lead.	97%	Fog in mid AM, then clear. Some fog in SE part of study area in PM.	3.5		Survey ENE of Barrow.	
5 May	2		P2	0	71°35′ 155°27′	*Karluk* broadcast into narrow, refrozen lead.	95% New cracks forming.	Light fog in AM. Low cloud in PM.	2.7	1.7	71°36′ 155°30′	Obs. of presumably undisturbed behavior.
6 May	1			0		Flight aborted due to fog. Analyzed TL data.	95% Lead W of Barrow ≈300 m wide.	Fog.	0.4		Survey ENE of Barrow.	
7 May	0					Analyzed data.	95%	Fog.				Poor weather, no flying.
8 May	0					Analyzed data.	95%	Fog.				Poor weather, no flying.

Continued...

Table 2. Continued.

	Ice-based Crew								Aircraft-based Crew			
Date	Ferry Flights	Transm. Loss Test	*Karluk* Projections	Number of Bowheads	Location	Other	Overall Ice Conditions	Cloud Ceiling/ Visibility	Survey (h)	Behavior Obs. Sess. (h)	Location	Other
9 May	2		P3	27	71°36' 155°29'	*Karluk* broadcast along N side of narrow lead amidst pack ice.	90%	Fog.	2.7	2.3	71°31' 156°02'; 71°30' 156°08'	Obs. of presumably undisturbed behavior. Sonobuoy disturbance.
10 May	2		P4	30	71°35' 155°16'	*Karluk* broadcast along E side of large open lead.	85% 5-10% ice in 4 km-wide lead ENE of Barrow.	Fog in AM. Some fog and low cloud in PM.	1.8	5.5	71°33' 155°24' 71°36' 155°17'	Obs. of presumably undisturbed behavior. *Karluk* projection experiment with pre- and post-plbk control obs.
11 May	2		P5	12	71°35' 155°29'	*Karluk* broadcast along NW side of large open lead.	85% 0-50% pans in lead along landfast ice.	High overcast, patchy fog. Good vis.	2.5	5.1	71°31' 155°40' 71°33' 155°30'	*Karluk* projection experiment with pre-plbk control obs. Post-plbk control obs. followed by helicopter overflight experiment.
12 May	1			0		Flight aborted due to fog. Analyzed data.	85%	Fog until mid PM, then high overcast and good vis.	1.1	3.1	71°31' 155°23'	Obs. of presumably undisturbed behavior.
13 May	2		P6, P7	138	71°26' 154°47'	*Karluk* broadcast along N side of a narrow primary lead.	95%	High overcast and good vis. in AM. Occas. low cloud in PM.	4.0	5.7	71°26' 154°47'	Distorted *Karluk* and normal *Karluk* projection experiments with post-plbk control obs.
14 May	0						95%	Fog.				Poor weather, no flying.
15 May	0						90%	Fog.				Poor weather, no flying.
16 May	2		P8	54	71°26' 154°08'	*Karluk* broadcast along S side of open lead amidst pack ice.	90%	Fog until mid AM, then good weather.	4.4	3.8	71°26' 154°12'; 71°27' 154°08'	*Karluk* projection experiment with pre- and post-plbk control obs.
17 May	1			0		Flight aborted due to fog. Analyzed data.	90%	High cloud and strong winds, then rain.	1.8			
18 May	0						90%	Fog.				Poor weather, no flying.
19 May	2			1	71°34' 155°09'	Control obs. No projections.	90%	Ceiling 100-180 m, then clearing.	2.3		Survey ENE of Barrow.	

Continued...

Table 2. Concluded.

	Ice-based Crew								Aircraft-based Crew			
Date	Ferry Flights	Transm. Loss Test	*Karluk* Projections	Number of Bowheads	Location	Other	Overall Ice Conditions	Cloud Ceiling/ Visibility	Survey (h)	Behavior Obs. Sess. (h)	Location	Other
20 May	0						85%	Ceiling and vis. marginal all day. Snowshowers in AM and winds to 55 km/h in PM.				Poor weather, no flying.
21 May	2			0	71°35' 155°31'	Control obs. No projections.	85% Wide lead E to 155°50', then very narrow.	Clear. Winds 20 to 25 kt.	2.3	5.5	71°34' 155°48'; 71°36' 155°43'; 71°37' 155°49'	Obs. of presumably undisturbed behavior. *Karluk* projection experiment with pre-plbk obs.
			P9	2	71°36' 155°48'	*Karluk* broadcast into hole amidst pack ice at second ice camp location.						
22 May	0						80%	Poor weather all day.	0.5		Survey ENE of Barrow.	
23 May	0						80%	Fog and snow in AM. Extensive fog bank across most of study area.	2.0	2.0	71°44' 156°36'; 71°35' 156°14'	Obs. of presumably undisturbed behavior. Boat (outboard) disturbance at end of session.
24 May	2	#3		(3+)	71°36' 154°57'	Bowhead and white whales heard at various TL stations.	80% Main lead reduced to ≤1 km wide from W of Barrow to 155°45'.	High cloud, good visibility except for continuous fog in E part of study area.	4.0	3.5	72°04' 155°13'	Obs. of presumably undisturbed behavior.
25 May	1	#4		0	71°34' 155°26'		80% Major secondary leads present ENE of Barrow.	High cloud. Good visibility.	2.9	5.0	71°58' 155°24'; 72°06' 154°58'	Obs. of presumably undisturbed behavior.
26 May	0						80%	High, thin cloud. Much fog offshore to N and E.	2.4		Survey ENE of Barrow.	Obs. of presumably undisturbed behavior.

* Numbers in parentheses indicate whales observed during ferry flights or TL tests.

Table 3. Summary of aerial behavioral observation sessions, 1990.

Date 1990	Behavior Obs. Sess.	Location	Obs. Period	No. of Bowheads		General Activity	Predominant Orientation °T	Predominant Speed of Travel	Size Classes	Disturbance	Water Depth (m)	Sea State	% Ice	
				circle	area								in circle	overall
29 Apr	1	71°31′ 155°04′	11:39- 12:49	4	6	feeding/ social/ travel	various	slow	mother yearling & unknown	none	18	1	85	97
29 Apr	2	71°31′ 155°01′	14:42- 17:21	2	5	travel	080-100	slow	adult & unknown	none	18	0	80	97
5 May	3	71°35.5′ 155°30′	12:17- 14:00	1	1	travel	various	medium	unknown	none	165	1	90	95
9 May	4	71°30.5′ 156°02′	21:14- 22:21	3	7	travel	various	medium	1 adult subadult & unknown	none to 22:00:56; then sonobuoy drop	28	2	<<1	90
9 May	5	71°29.7′ 156°08′	22:23- 23:34	7	9+	travel	070-090	medium	unknown	none	20	2	<<1	90
10 May	6	71°33.2′ 155°23.5′	13:39- 14:43	4	9+	mainly social & sexual/ small amt. travel	various	various	adult subadult & unknown	none	48	1	5	85
10 May	7	71°35.5′ 155°15′	14:48- 15:36	≈3-4	≈8-10	travel	various	medium	subadult & unknown	none to 15:32:09; then *Karluk* plbk	66	1	10	85
10 May	8	71°35.5′ 155°18′	15:42- 16:29	3	6	social/ travel	various	medium	subadult adult & unknown	*Karluk* plbk throughout	86	1	5	85
10 May	9	71°35.7′ 155°19′	18:06// 21:02 (2.80 hr)	10	25	social/ travel/ resting/ breach	various	various	unknown	*Karluk* plbk until 20:50:30; then post-plbk	91	0-1	5	85

Table 3. Continued.

Date 1990	Behavior Obs. Sess.	Location	Obs. Period	No. of Bowheads circle	No. of Bowheads area	General Activity	Predominant Orientation °T	Predominant Speed of Travel	Size Classes	Disturbance	Water Depth (m)	Sea State	% Ice in circle	% Ice overall
11 May	10	71°31.5′ 155°38′	11:45–13:04	6-7	8	travel/ occ. social	various	medium	adult & unknown	none	21 (later)	0-1 <1-5	2;	85
11 May	11	71°31.4′ 155°43′	13:48–14:45	1	± 5	travel	050	medium	unknown	none	19	0	25 (0-SE; 50-NW)	85
11 May	12	71°32.6′ 155°30′	15:55–17:26	5	8	travel/ some social	060-080	medium	adult subadult & unknown	none to 16:27:29; *Karluk* plbk 16:27:30–17:48:15	20	1	2 (0-5)	85
11 May	13	71°32.8′ 155°30′	17:54–19:14	2	3	travel/ some rest, social	various	medium	unknown	none to 18:56:23; then helic. overflight	22	1	5 (1-15)	85
12 May	14	71°31.2′ 155°22.6′	16:10–19:14	3	6	travel/ some feeding	060-090	medium	2 adults & unknown	none	20	1	5 (0-15)	85
13 May	15	71°26.1′ 154°47.4′	12:47–15:23	5	9	travel	various	medium	4 adults & unknown	none to 13:00:39; then *Karluk* plbk (distorted)	27	1	88	95
13 May	16	71°26.1′ 154°47.3′	16:41–18:41	6	18	travel/ some social	110-140	slow-medium	1 subadult 5 adults & unknown	*Karluk* plbk throughout	27	1	88	95
13 May	17	71°26.1′ 154°47.3′	18:43–19:47	3	8	travel/ occ. social	120	slow-medium	subadult 2 adults & unknown	*Karluk* plbk until 18:46; post-plbk 18:46-19:16	27	1	88	95
16 May	18	71°26′ 154°12′	12:28–12:58	6	12	travel/ social	100-110	slow-medium	2 adults 1 subadult & unknown	none	29	1-2	60	90

Continued...

Table 3. Concluded.

Date 1990	Behavior Obs. Sess.	Location	Obs. Period	No. of Bowheads circle	No. of Bowheads area	General Activity	Predominant Orientation °T	Predominant Speed of Travel	Size Classes	Disturbance	Water Depth (m)	Sea State	% Ice in circle	% Ice overall
16 May	19	71°26.5′ 154°07′	13:26- 15:19	3-8	15-18	travel/ very small amt. social	100	medium	adult	pre-plbk; *Karluk* plbk begins 14:10:16	40	1-2	40	90
16 May	20	71°27′ 154°08′	17:38- 19:05	5	6	feeding/ some travel/ breach	various	none-medium	adult subadult & unknown	*Karluk* plbk until 17:50:00; post-plbk 17:50-18:20	40	1	80	90
21 May	21	71°35′ 155°45′	8:48// 11:24 (2.10 hr)	(a) 2 (b) 2 (c) 2	(a) 10 (b) 10 (c) 5	travel	various	medium	2 calves 2 mothers subadult & unknown	none	(a) 150 (b) 205 (c) 205	(a) 3 (b) 3 (c) 3	(a) 5 (b) 60 (c) 60	85
21 May	22	71°36′ 155°48′	13:14- 14:32	2	2	travel	030-060	medium	adult & unknown	*Karluk* plbk throughout	210	3	75	85
21 May	23	71°37′ 155°49′	14:35- 16:41	2	4	travel	various	slow-medium	2 adults & unknown	*Karluk* plbk until 15:57:23; post-plbk to 16:27	220	3	75	85
23 May	24	71°44′ 154°36′	09:11- 10:12	1	1	unknown	various	slow	unknown	none	82	1	50	80
23 May	25	71°35′ 156°14′	18:30- 19:28	2	4	travel/ riding	060-090	medium	1 calf 1 mother	none to 19:25; then whaling boat	160	1	5	80
24 May	26	72°04′ 155°13′	18:31- 22:00	2	2	travel	various	more slow than medium	1 calf 1 mother	none	330	1	80	80
25 May	27	71°57′ 155°23′	11:06- 13:00	2	4	rest/feed	various	slow	2 calves 2 mothers	none	285	2	85	80
25 May	28	71°59′ 155°24′	15:05- 15:38	2	2	rest	various	none-slow	1 calf 1 mother	none	230	1	85	80
25 May	29	72°06′ 154°58′	15:46- 18:11	2	5	rest, aerial & unknown to 16:18; then travel	various	various	2 calves 2 mothers & unknown	none	475	0-1 2	90 until 17:10; 60 after 17:10	80

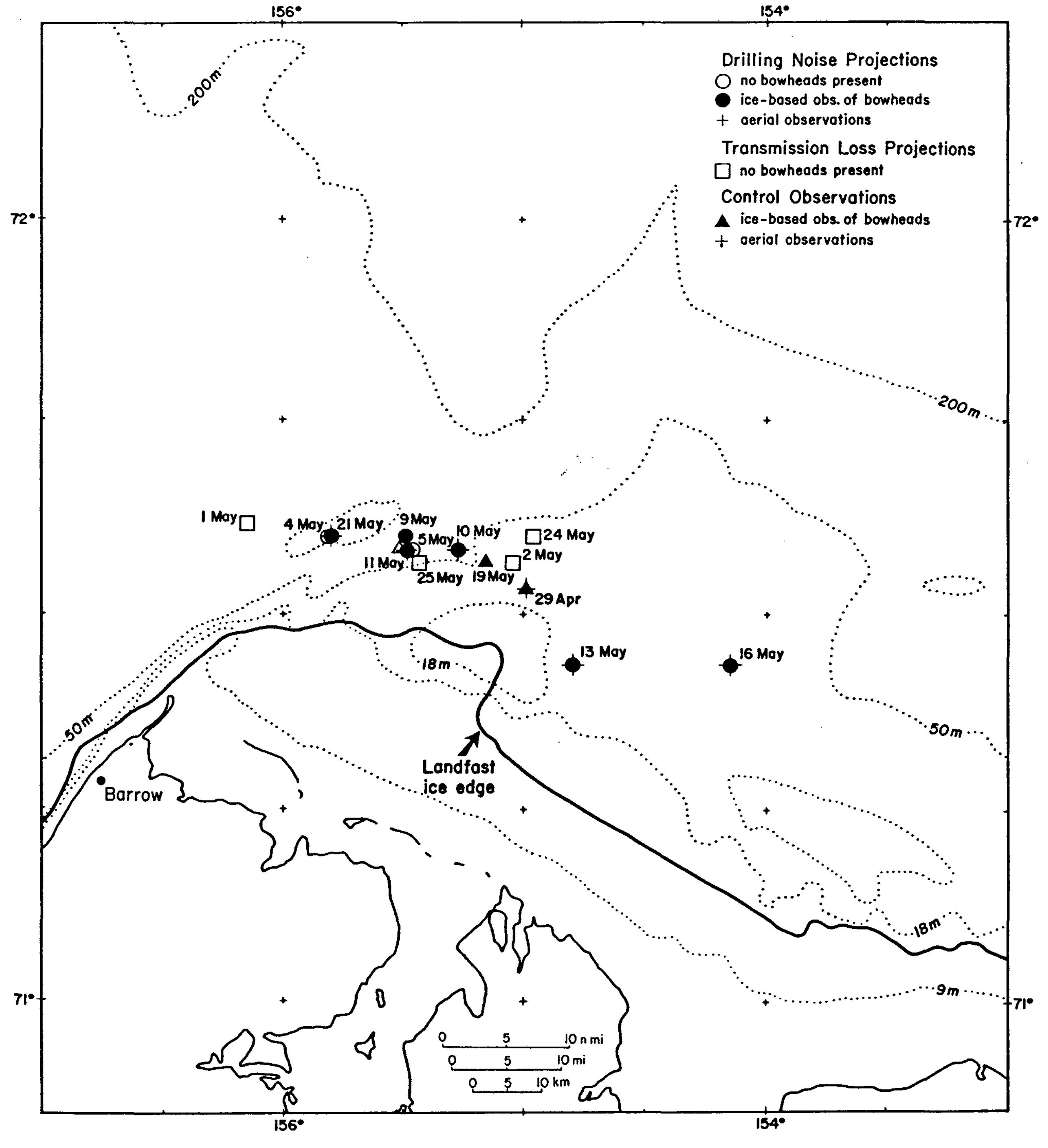


FIGURE 4. Locations where ice-based crews conducted transmission loss tests, broadcast drilling sounds, and made control observations, 29 April-25 May 1990. Solid symbols represent days when bowheads were observed. Locations are approximate because of ice drift during the course of each day's work.

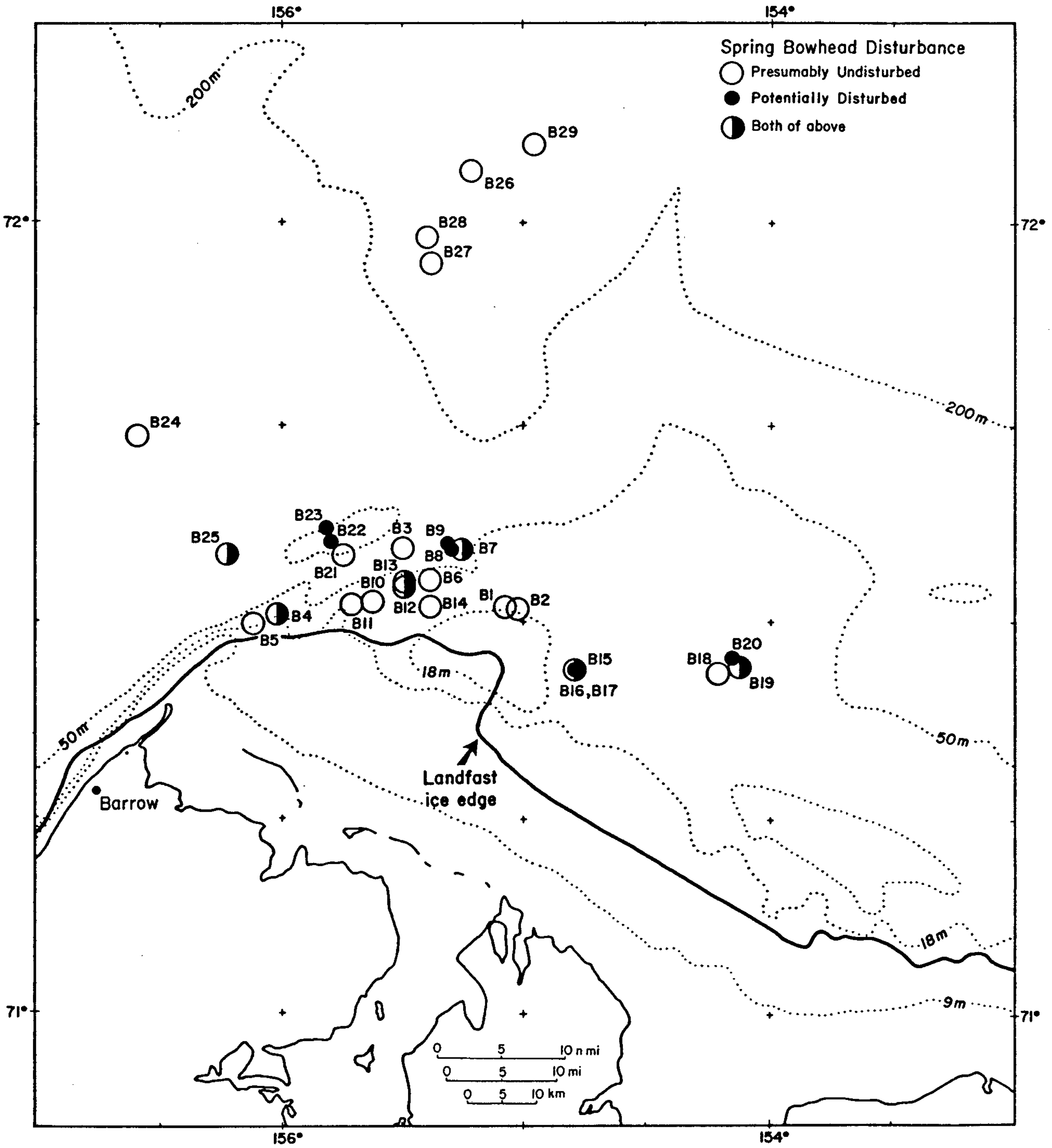


FIGURE 5. Locations where behavior of bowhead whales was observed by the aerial crew, 29 April-25 May 1990. Numbers (prefixed by a B) refer to behavior observation session numbers referenced in Table 3.

times, the Twin Otter crew obtained behavioral observations on whales both near and away from the ice camp location (Table 3; B6-B9 *in* Fig. 5).

On 11 May, the ice-based crew set up on the south side of an ice pan drifting near the north side of the main lead. Observations of bowheads were obtained when the projector was silent and when it was playing *Karluk* drilling sounds. However, few bowheads were seen near the ice camp; most whales were migrating past ~3 km farther south in the middle of the main nearshore lead. The Twin Otter crew conducted 4 observation sessions (B10-B13 *in* Fig. 5), but none of the whales that were followed passed closer than 2 km from the projector location under either quiet or playback conditions. Near the end of the day, a helicopter overflight experiment was done; the project's Bell 212 helicopter was directed to fly at 150 m altitude over bowheads that were being observed from the Twin Otter circling at 460 m altitude.

The ceilings were low for most of 12 May, but the Twin Otter crew flew in the late afternoon and obtained extensive control data on the migratory behavior of a group of whales traveling east in the main lead (B14 *in* Fig. 5).

On 13 May, the ice camp was established along a long thin lead that extended ESE from the eastern end of the main nearshore lead. Large numbers of migrating bowheads were observed by the ice-based and aerial crews when the projector was silent and when it was projecting *Karluk* drilling platform sounds (Table 2). For part of the day, the projected sounds were distorted because the projector was failing. Later in the day a replacement projector was used and normal drilling sounds were projected. The aircraft-based crew observed whales migrating past the projector during 3 observation sessions (Table 3). Some bowheads were followed from as far as 6 km west to 4 km east of the projector (B15-B17 *in* Fig. 5).

Low cloud and fog prevented flying on 14 and 15 May. The first Twin Otter flight on 16 May was unsuccessful due to fog; however, during the second flight, large numbers of whales were found moving east and NE through a secondary lead amidst the pack ice 100 km east of Barrow. The ice camp was set up on a pan toward the eastern end of this lead (Fig. 4) and observations were obtained of bowheads passing the projector before and during playbacks of drilling sounds. The aircraft-based crew followed bowheads as they approached and receded from the projector (Table 3; B18-B20 *in* Fig. 5).

A survey by the Twin Otter on 17 May found 5 bowheads and 150 white whales near the eastern end of the main lead and in the pack ice east of there; however, poor weather prevented behavioral studies. The poor weather conditions continued throughout 18 May. On 19 May ceilings were too low for aerial observations of behavior but visibility was good. The Twin Otter crew conducted a survey and directed the ice-base crew to an area of loose pack ice north of the main lead (Fig. 4) where they obtained limited control observations.

Poor weather and very strong winds prevented fieldwork on 20 May (Table 2). The weather improved on 21 May although the winds remained strong (40-45 km/h). The aerial crew found bowheads migrating through the main lead and entering a series of small openings in the pack ice north of the main lead. The ice-based crew was directed to this area, and a *Karluk* drilling noise playback was conducted (Fig. 4). Two bowheads and many white whales were observed from the ice camp, and several bowheads were followed from the Twin Otter

(Table 3; B21-B23 *in* Fig. 5). This was the only day in 1990 when we observed white whales near the operating projector.

Weather conditions were poor on 22 May and variable on 23 May. The Twin Otter crew was able to conduct two brief observation sessions on bowheads by finding whales in clear areas amidst the fog (B24-B25 *in* Fig. 5). On 24 May the ice-based crew conducted a third transmission loss test (Fig. 4) after the Twin Otter crew were unable to find bowheads. For 3.5 h in the late afternoon, the Twin Otter crew observed a mother-calf pair in the pack ice 103 km north of Barrow (B26 *in* Fig. 5).

The field season had been scheduled to end on 24 May. However, the budget situation allowed another 2 or 3 days of fieldwork, and there were still bowheads in the area. Hence, the season was extended for two more days.

On 25 May the ice-based crew conducted a fourth transmission loss test in the pack ice just north of the main lead (Fig. 4). The Twin Otter crew conducted three observation sessions on mother-calf pairs far north in the pack ice, near 72°N (Table 3; B27-B29 *in* Fig. 5). Aerial reconnaissance failed to locate whales closer to Barrow where disturbance tests could be conducted.

Two brief surveys were conducted on 26 May but low fog over much of the offshore area prevented any useful work.

Summary of 1990 Field Activities

The ice-based crew worked from the ice on 16 days between 27 April and 26 May in 1990. They conducted transmission loss tests on four days and projected *Karluk* drilling platform sounds into the water for several hours on each of 8 days. On 6 days, bowheads were observed in waters that were ensonified by the projector broadcasting drilling platform sounds. However, on one of these days (11 May) bowheads did not approach closer than 2 km from the operating projector. Whales were seen by the ice-based observers near the operating projector on 9, 10, 11 (2 km), 13, 16 and 21 May 1990. Bowheads were observed near the quiet projector on those six dates plus 29 April and 19 May.

The aircraft-based crew conducted reconnaissance surveys on 23 days from 29 April to 26 May, of which the surveys on 20 d were effective. The aerial crew conducted 29 behavior observation sessions on 12 days. The aerial crew observed bowheads near the operating projector on 10, 13, 16 and 21 May, and also followed whales within 3.5 km of the operating projector on 11 May.

Ice conditions and whale migration patterns in 1990 were similar to "normal" patterns, and there were several good opportunities to conduct tests of the reactions of migrating bowhead whales to projected industrial sounds. Far more data on the movements and behavior of bowheads near the operating projector were obtained in 1990 than in 1989. The improved success was attributable to the better ice conditions, better weather conditions (including frequent high ceilings), and the presence of many bowheads during some days when weather and ice conditions were suitable for aerial and ice-based work. However, fewer white whales were present in 1990 than in 1989, so the 1990 data on white whales provide only a limited supplement to the 1989 results.

The mobility of the projector site and of the behavioral observation platforms (ice camp and aircraft) was essential. Although large numbers of bowheads were seen migrating eastward during this study, no or very few data would have been collected in either year had the projector and observation platforms been restricted to the fast ice edge within our study area. In addition, the corridors followed by bowheads changed almost daily. No one location amidst the pack ice would have provided the quantity of biological data that we were able to collect during this study.

PHYSICAL ACOUSTICS RESULTS

The main results of the physical acoustics effort are presented in three subsections: ambient noise, transmission loss (p. 63), and the question of infrasonic components in bowhead calls (p. 91). These three topics relate to specific objectives 1, 2 and 4, respectively (*cf.* p. 5-6). This section also includes an analysis of the effectiveness of the J-11 sound projector in reproducing *Karluk* drilling noise during playbacks ("Fidelity of Playbacks", p. 88). A final subsection describes the noise from the generator used on the ice (p. 98). Generator noise is described because it is relevant in interpreting whale behavior near the ice camp. Physical acoustic data on "Noise Exposure" during playback tests (specific objective 3) are incorporated into later sections describing whale responses to playbacks (p. 125, 139, 146, 187, 199, 215).

Ambient Noise

Ambient noise data were collected via sonobuoys prior to and after playback tests, and via an over-the-ice-edge 6050C hydrophone during transmission loss tests.

Broadband Levels and Spectra

Ambient noise measurements in the 20-1000 Hz band during May 1990 are summarized in Figure 6. That figure also shows the levels expected during sea state 0, 2 and 6 conditions in temperate oceans. These expected values are based on the data of Knudsen et al. (1948), extended down to 20 Hz by extrapolation and integrated over the 20-1000 Hz band. Except for the extraordinarily low levels observed on 2 May 1990, most ambient levels were within the range expected for sea state zero (flat calm) to sea state four (moderate sea) spectra.

The primary contributors to the ambient noise in May 1990 were animal calls, ice deformation noises, and small waves slapping against ice. High wind-driven seas could not develop because ice usually covered at least 80-90% of the sea. Also, because of logistic and safety considerations on the pack ice, we rarely attempted to work when the wind speed exceeded 35 km/h. Thus, no measurements were made under the meteorological conditions when--in an open water area--high noise would be expected.

Ambient noise levels tended to be slightly higher in May 1990 than during the spring of 1989 (*cf.* Richardson et al. 1990a:110). The 65 measurements during 1989 ranged from 70 to 103 dB re 1 µPa in the 20-1000 Hz band, or 73-102 dB excluding the single highest and lowest measured levels. The average in 1989 was 85 dB. The 61 measurements in 1990 ranged from 54 to 107 dB (67-107 dB without the extremes), and averaged 91 dB.

An important playback test was conducted on 13 May 1990. Eleven ambient noise measurements were obtained via sonobuoys at times when playbacks were not in progress. The 20-1000 Hz band levels ranged from 82 to 93 dB re 1 µPa. These values were generally on the low side of the noise levels observed during the 1990 field season (Fig. 6). Figure 7 shows the power density spectra for the times on 13 May 1990 when the maximum and minimum overall levels of ambient noise were measured. Figure 68 (p. 190) shows 1/3-octave band level data for ambient noise on 13 May.

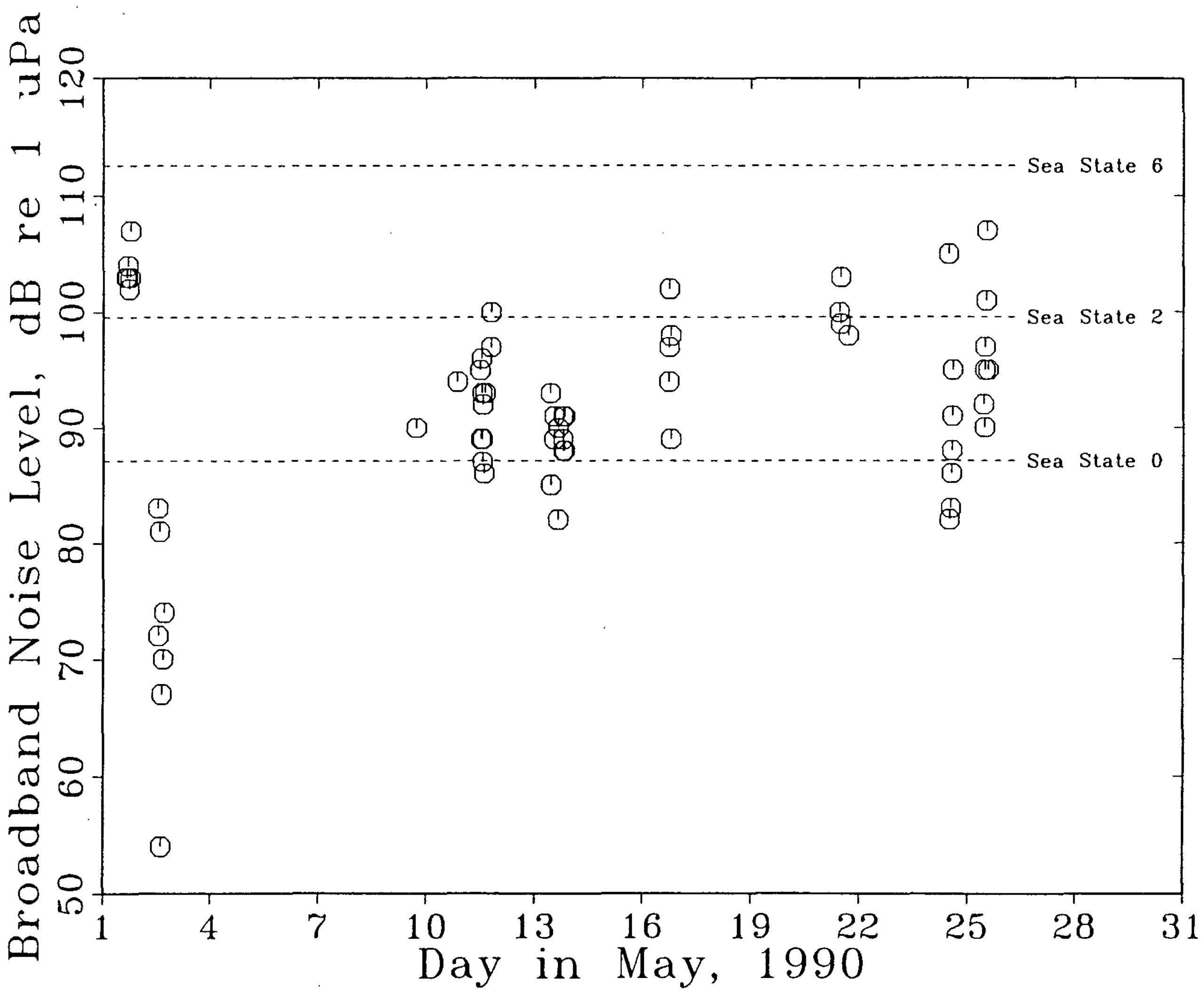


FIGURE 6. Broadband ambient noise levels (20-1000 Hz) measured during the 1990 field season, plotted against date. Several measurements were made on most days, resulting in the apparent vertical structure. Variable ice noise and intermittent animal calls account for much of the variability. No measurements were made during storms, although the wind speed on 21 May was 37-46 km/h. Cases including man-made sounds are excluded. Dashed horizontal lines show predicted ambient noise levels (20-1000 Hz) at sea states 0 (calm), 2 (light wind) and 6 (storm), from Greene (1987a).

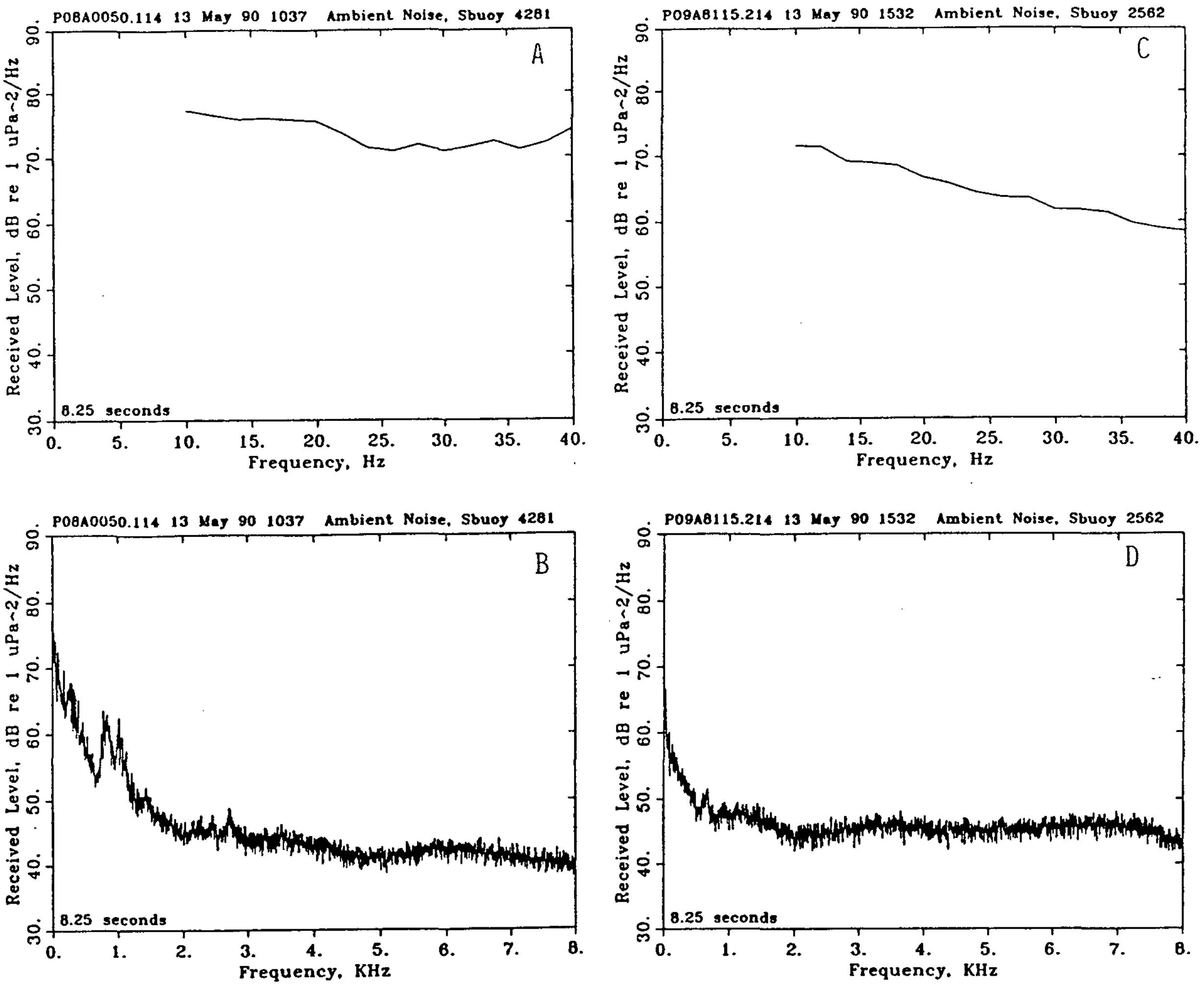


FIGURE 7. Examples of ambient noise power density spectra measured on 13 May 1990, a day of playbacks to whales. Spectra are shown for the times of highest (**A**,**B**) and lowest (**C**,**D**) observed levels. The data came from measurement sites 5.5 km (10:37) and 1.6 km (15:32) from the ice camp (projector off). Highest level observed was 93 dB in 20-1000 Hz band at time 10:37: (**A**) 0-40 Hz; (**B**) 0-8 kHz. Lowest level observed was 82 dB in 20-1000 Hz band, bearded seals noted, at time 15:32: (**C**) 0-40 Hz; (**D**) 0-8 kHz.

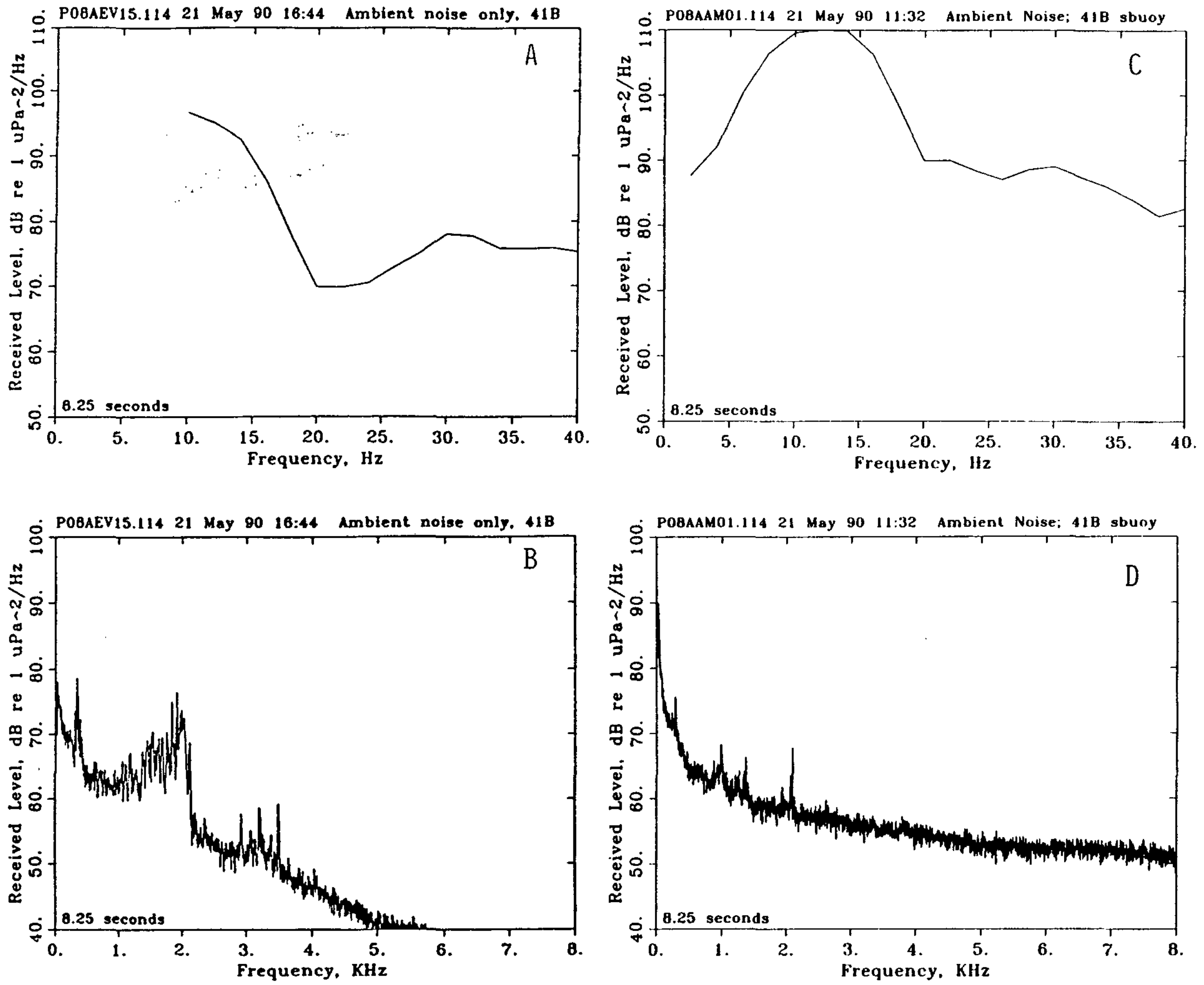


FIGURE 8. Examples of ambient noise power density spectra measured on 21 May 1990, a day of playbacks to whales. Spectra are shown for the times of lowest (A,B) and highest (C,D) observed levels at a measurement site ~400 m from the ice camp (projector off). Lowest level observed was 98 dB in 20-1000 Hz band at time 16:44: (A) 0-40 Hz; (B) 0-8 kHz. Highest level observed was 103 dB in 20-1000 Hz band at time 11:32: (C) 0-40 Hz; (D) 0-8 kHz. Note that the vertical scale for (A) and (C) differs from the scale for (B) and (D).

Figure 8 presents corresponding maximum and minimum power density spectra measured in the absence of playbacks on 21 May 1990. That was a playback day with higher overall levels of ambient noise than any other day of measurement in 1990 (Fig. 6). The measured levels of ambient noise on 21 May ranged from 98 to 103 dB re 1 µPa in the 20-1000 Hz band. The wind speed was 37-46 km/h, and the ice drifted rapidly. There were whitecaps even in the small open water areas where the sonobuoys were deployed.

Ambient noise levels were measured several times on each day of transmission loss (TL) testing: 1, 2, 24 and 25 May 1990. For contrast, we present ambient noise power density spectra from TL test #2, on 2 May, when the noise levels were generally low (Fig. 9), and from TL test #4, on 25 May, when the noise levels were generally high (Fig. 10). Note the difference in the vertical scales on these two sets of diagrams. On these two days, 20-1000 Hz band levels were 54-83 and 90-107 dB re 1 µPa, respectively. Additional ambient noise data from the TL tests are given a later section on TL test results (p. 63*ff*).

One-Third Octave Band Ambient Noise

Based on the 61 ambient noise measurements from 1990, we determined the minimum, 5%, 10%, 50%, 90%, 95% and maximum levels for each 1/3-octave band. There were 33 measurements from sonobuoys (Table 4B; Fig. 11A) and 28 measurements from ice-based 6050C hydrophones (Table 4C; Fig. 11B). The medians for the two sets of data were similar. The most notable differences are the appreciably lower minimum and 5th-percentile levels from the hydrophones. This is accounted for by the inclusion of the extraordinarily low levels measured by hydrophone during TL test #2 on 2 May. Both datasets, but especially the sonobuoy data, show a tendency for the levels in the 1/3-octave bands centered at 12.5 and 16 Hz (infrasonic ambient noise) to rise above the general shallow trend for rising level with decreasing frequency. Figure 12 shows the one-third octave percentile spectra for all 61 ambient noise samples; Table 4A shows the corresponding numerical values.

Models of wind-driven ambient noise spectra generally show decreasing levels with increasing frequency (Knudsen et al. 1948; Wenz 1962; Ross 1976). However, Ross's spectra include a level portion below about 400 Hz. In his model, one-third octave band levels below 400 Hz decrease slightly with decreasing frequency. In our data from the Beaufort Sea during May, the median level is 76-79 dB re 1 µPa for every one-third octave band from 12.5 through 1250 Hz, a two decade range. This is an interesting result. At 20-40 Hz, 1/3-octave levels near 76-79 dB are expected based on the extrapolated sea state zero (calm sea) curves of Knudsen et al. (1948). However, for the band centered at 800 Hz, the Knudsen sea state zero value is only 69 dB, as opposed to the median of 78 dB found in this study (Table 4A). The observed 78 dB figure is the level expected for a sea state between 1 and 2.

Calls from bearded seals, bowhead whales, and white whales no doubt partially account for the sustained median 1/3-octave sound level across such a wide frequency range. Calls from bearded seals, in particular, are very frequent and prominent in the study area during spring. Interestingly, both the 5th and 95th percentiles showed more tendency to decline with increasing frequency than did the median values (Fig. 12). Perhaps the animal calls are absent during the quietest times and are overidden by ice and/or wave noise during high-noise times.

Table 4. Extreme and percentile one-third octave band levels for 61 ambient noise measurements obtained via sonobuoys (n = 33) and ice-based hydrophone (n = 28) during 1-25 May 1990.

A.	All						
	Max	95%	90%	50%	10%	5%	Min
10 Hz	113	108	104	79	67	57	47
12.5 Hz	115	104	99	77	67	57	47
16 Hz	113	99	95	78	67	58	48
20 Hz	101	95	93	77	65	58	47
25 Hz	97	95	93	77	65	62	45
31.5 Hz	97	94	93	77	68	63	44
40 Hz	96	93	93	76	69	62	43
50 Hz	97	94	92	77	67	61	42
63 Hz	95	93	91	77	67	61	42
80 Hz	96	92	90	79	65	59	41
100 Hz	95	91	89	78	67	59	40
125 Hz	95	91	89	77	67	58	40
160 Hz	96	91	90	78	65	58	39
200 Hz	95	91	89	78	64	57	40
250 Hz	96	90	89	77	63	55	39
315 Hz	96	89	88	78	63	55	39
400 Hz	96	88	86	79	63	54	40
500 Hz	97	91	85	78	64	57	40
630 Hz	101	89	86	77	65	57	39
800 Hz	96	86	85	78	64	57	39
1000 Hz	95	87	86	78	62	53	39
1250 Hz	94	88	85	77	62	52	39
1600 Hz	94	90	87	76	62	53	41
2000 Hz	95	86	85	76	61	52	41
2500 Hz	92	86	84	74	55	51	41
3150 Hz	92	84	82	73	54	51	41
4000 Hz	91	84	82	73	50	50	41
5000 Hz	90	83	79	72	51	50	42
6300 Hz	89	83	79	70	52	50	42
20-1000 Hz	107	104	103	92	82	72	54

61 Samples

B.	Sonobuoys						
	Max	95%	90%	50%	10%	5%	Min
10 Hz	113	105	95	82	68	65	65
12.5 Hz	115	105	99	78	67	65	65
16 Hz	113	100	94	78	67	65	64
20 Hz	101	89	85	76	65	60	58
25 Hz	96	89	88	76	66	62	62
31.5 Hz	96	92	90	76	70	68	67
40 Hz	93	90	89	76	70	69	65
50 Hz	92	90	89	76	69	67	65
63 Hz	94	90	90	77	70	68	67
80 Hz	93	89	89	79	71	69	65
100 Hz	93	88	87	78	69	68	67
125 Hz	89	88	88	77	70	67	67
160 Hz	96	89	88	80	71	68	65
200 Hz	93	89	88	79	70	68	64
250 Hz	96	88	87	78	71	69	62
315 Hz	91	89	87	80	71	69	63
400 Hz	92	87	86	79	71	69	63
500 Hz	92	86	84	78	71	70	66
630 Hz	96	86	85	79	71	69	66
800 Hz	91	85	85	78	71	70	65
1000 Hz	87	86	83	78	71	70	65
1250 Hz	89	86	85	79	71	68	64
1600 Hz	92	90	87	78	70	67	63
2000 Hz	95	86	85	77	71	69	68
2500 Hz	90	86	85	77	67	66	64
3150 Hz	88	84	82	76	67	60	54
4000 Hz	85	84	82	74	63	51	47
5000 Hz	84	80	80	73	62	53	49
6300 Hz	84	81	81	73	59	56	52
20-1000 Hz	103	100	99	92	87	85	82

33 Samples

C.	Hydrophones						
	Max	95%	90%	50%	10%	5%	Min
10 Hz	112	108	104	75	57	54	47
12.5 Hz	104	101	99	77	57	54	47
16 Hz	99	97	95	76	58	56	48
20 Hz	99	95	94	77	58	58	47
25 Hz	97	95	94	77	57	56	45
31.5 Hz	97	94	94	78	54	53	44
40 Hz	96	94	93	79	54	53	43
50 Hz	97	94	94	77	56	54	42
63 Hz	95	93	92	77	54	54	42
80 Hz	96	92	91	76	56	53	41
100 Hz	95	91	91	77	58	52	40
125 Hz	95	91	91	76	53	52	40
160 Hz	96	90	90	77	56	51	39
200 Hz	95	90	89	76	56	51	40
250 Hz	95	90	90	76	54	51	39
315 Hz	96	89	88	76	50	50	39
400 Hz	96	86	85	79	51	50	40
500 Hz	97	91	85	77	53	51	40
630 Hz	101	89	87	77	53	50	39
800 Hz	96	86	85	77	52	51	39
1000 Hz	95	88	86	75	52	52	39
1250 Hz	94	87	85	74	52	51	39
1600 Hz	94	84	84	73	51	51	41
2000 Hz	93	83	82	72	51	51	41
2500 Hz	92	84	83	72	51	50	41
3150 Hz	92	82	81	71	51	50	41
4000 Hz	91	82	78	70	50	50	41
5000 Hz	90	78	77	69	50	50	42
6300 Hz	89	77	76	69	50	50	42
20-1000 Hz	107	105	104	91	70	67	54

28 Samples

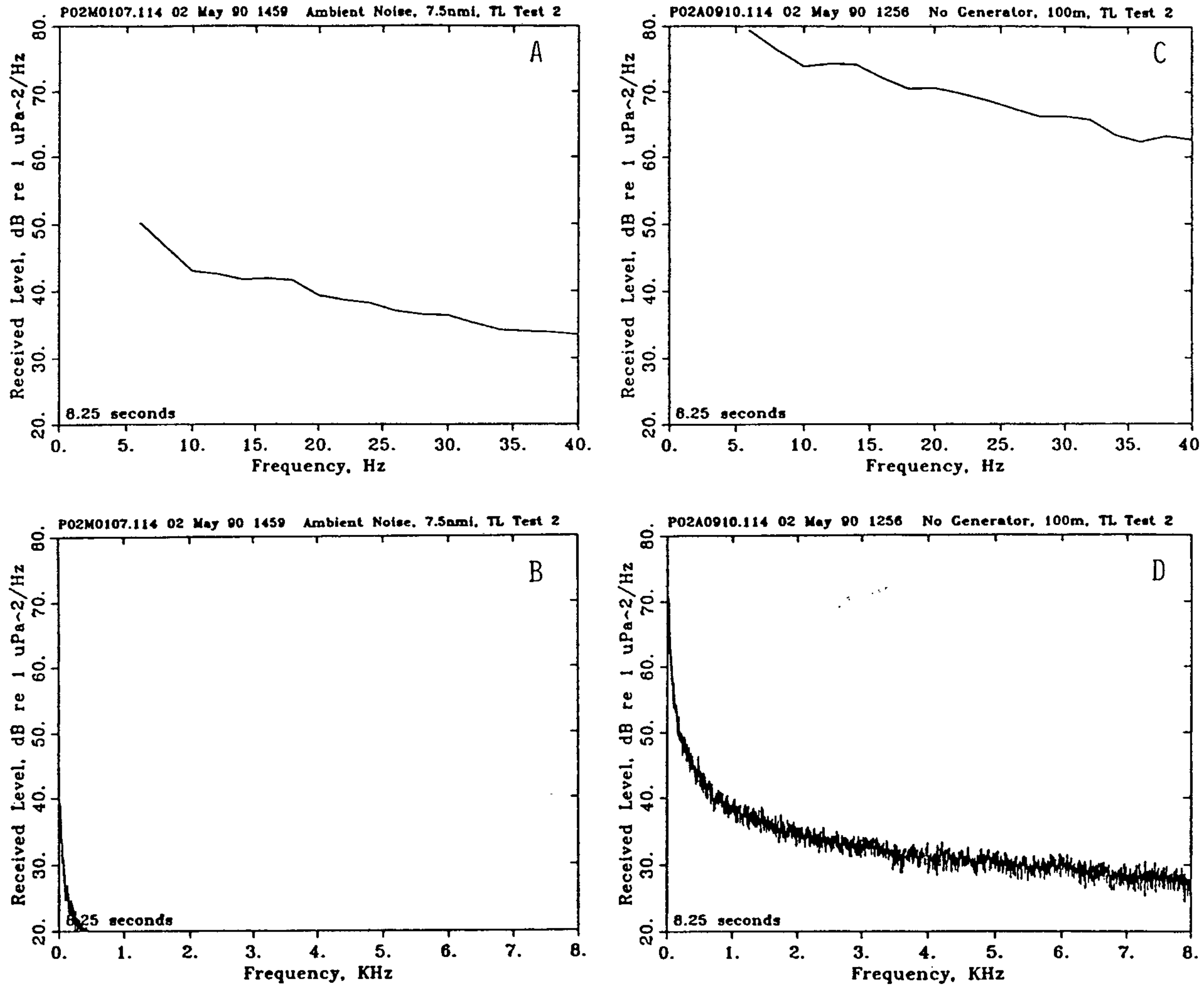


FIGURE 9. Examples of ambient noise power density spectra measured during transmission loss test #2 on 2 May 1990. Spectra are shown for the times of lowest (**A**,**B**) and highest (**C**,**D**) observed levels. Lowest level observed was 54 dB in 20-1000 Hz band at time 14:59: (**A**) 0-40 Hz; (**B**) 0-8 kHz. Highest level observed was 83 dB in 20-1000 Hz band, at time 12:56: (**C**) 0-40 Hz; (**D**) 0-8 kHz.

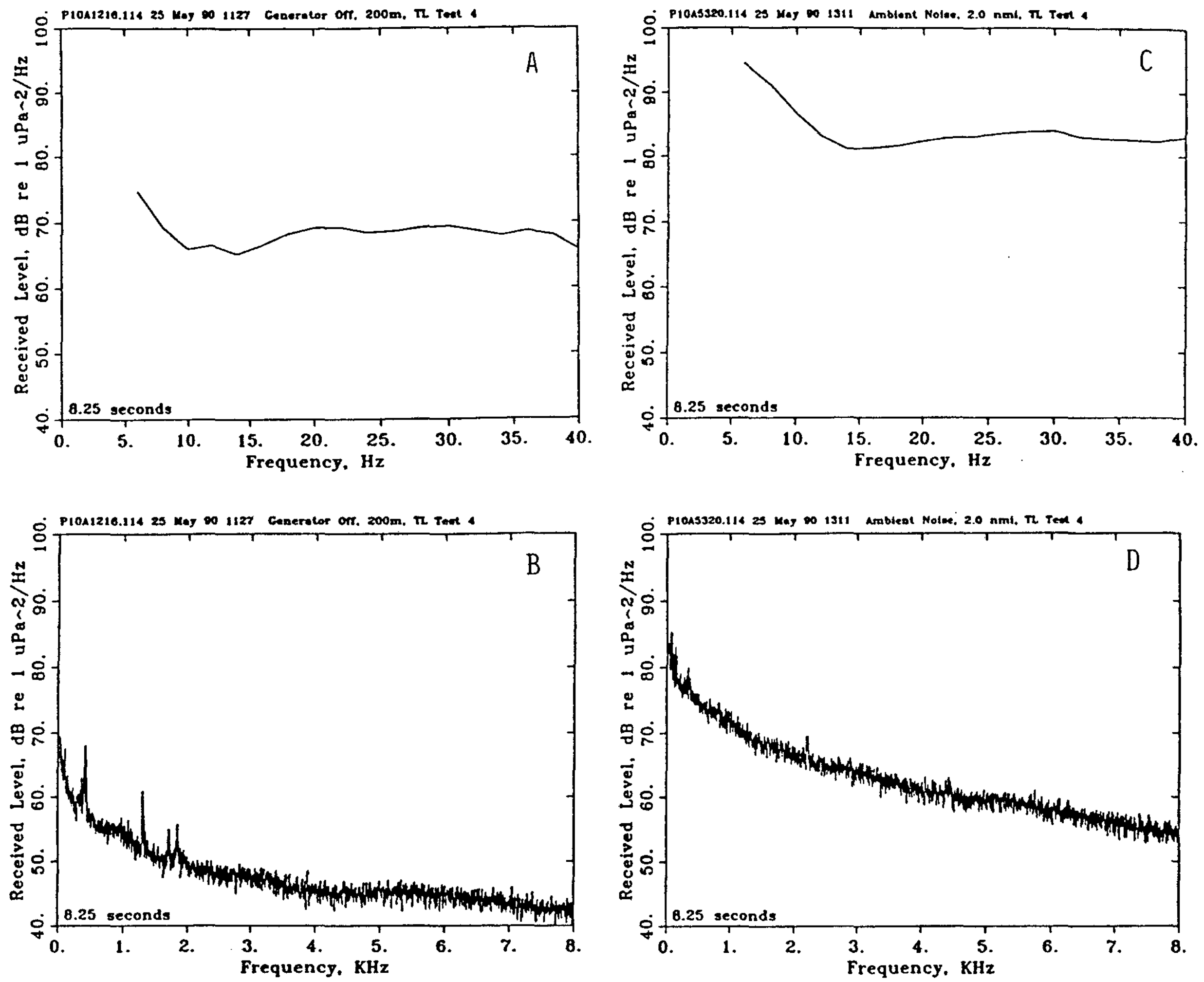


FIGURE 10. Examples of ambient noise power density spectra measured during transmission loss test #4 on 25 May 25 1990. Spectra are shown for the times of lowest (**A**,**B**) and highest (**C**,**D**) observed levels. Lowest level observed was 90 dB in 20-1000 Hz band at time 11:27: (**A**) 0-40 Hz; (**B**) 0-8 kHz. Highest level observed was 107 dB in 20-1000 Hz band, at time 13:11: (**C**) 0-40 Hz; (**D**) 0-8 kHz.

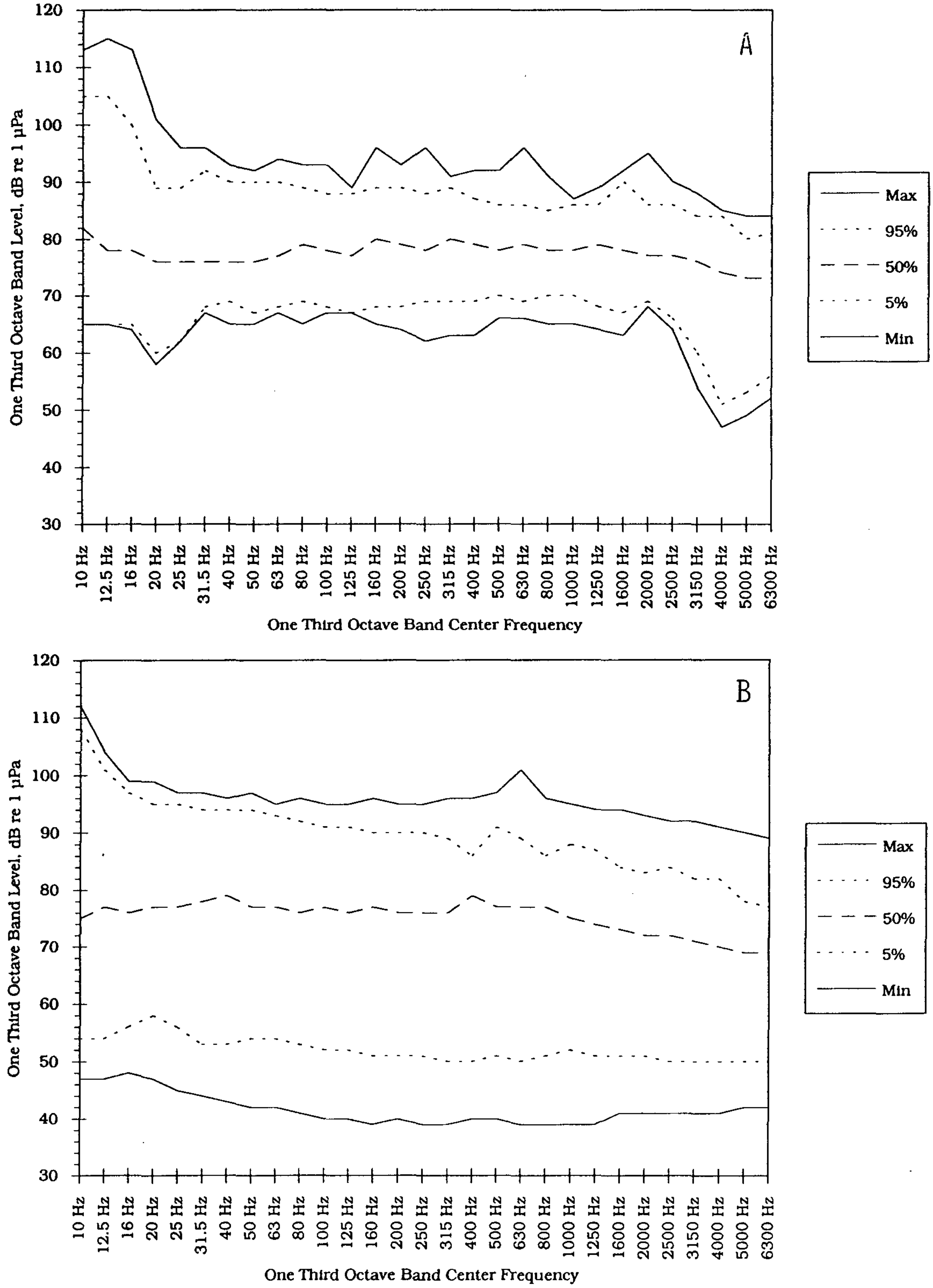


FIGURE 11. Extreme and percentile one-third octave band levels of ambient noise in 1990 for (**A**) sonobuoy data (n=33), and (**B**) 6050C hydrophone data (n=28).

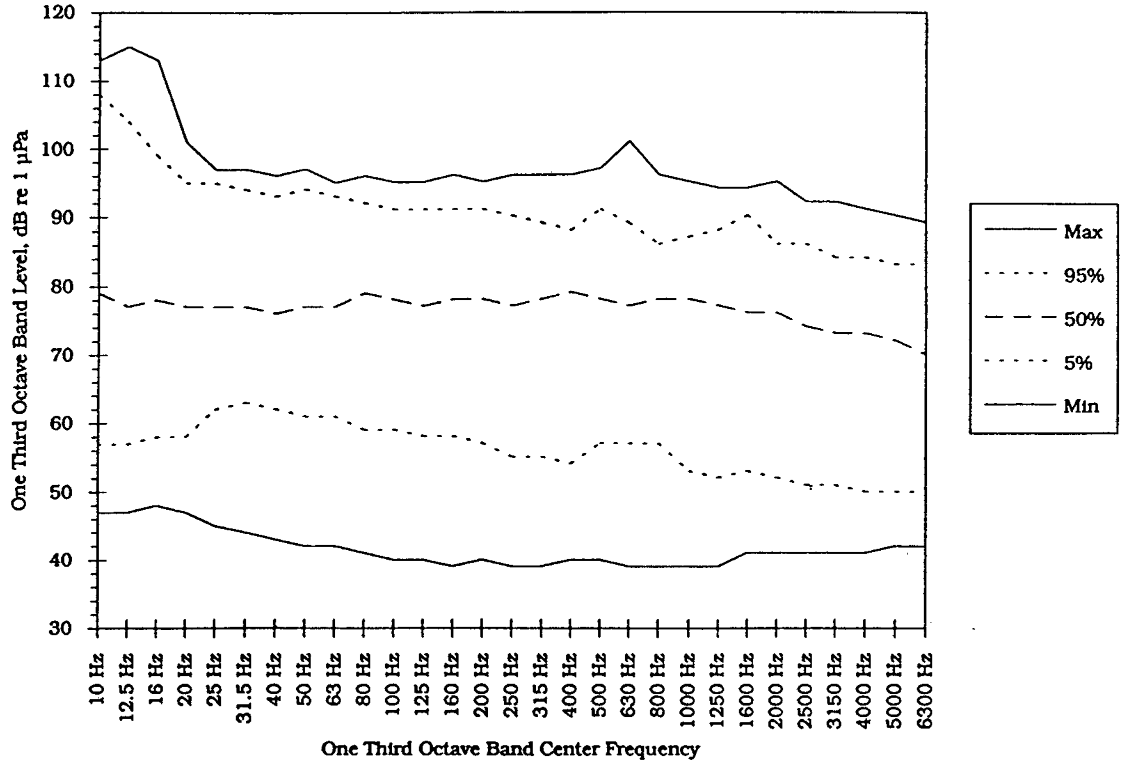


FIGURE 12. Extreme and percentile one-third octave band levels of ambient noise for 61 measurements of ambient noise taken in 1990.

Short-term Ambient Noise Powers

We compared short-term (¼ s), mid-term (8½ s) and long-term (60 s) averages of the broadband power (see "METHODS", p. 20-21). The primary question was whether the short-term ambient noise values were sufficiently variable that animals might be able to detect weak sound signals during brief intervals of low ambient noise. These quieter periods might not be evident from a noise measurement process based on longer-term averaging. The frequency of occurrence of various ¼-s powers is of particular interest. If the distribution of ¼-s powers is skewed such that most ¼-s powers are below the long-term average, this would indicate that animals are exposed, at most instants, to less ambient noise than suggested based on long-term average values.

Analysis of 33 one-minute ambient noise samples recorded during TL and disturbance tests in May 1990 revealed that every one showed considerable variability (e.g. Fig. 13, 14). Thus, animals may, at many instants, be able to perceive weaker sounds than would be predicted based on long-term averages of ambient noise power. Furthermore, every distribution of ¼-s powers was skewed, usually with a long "tail" extending upward toward high levels. The median of such a distribution is lower than its mean, suggesting that more than half the time the short-term ambient noise would be less than the long-term average.

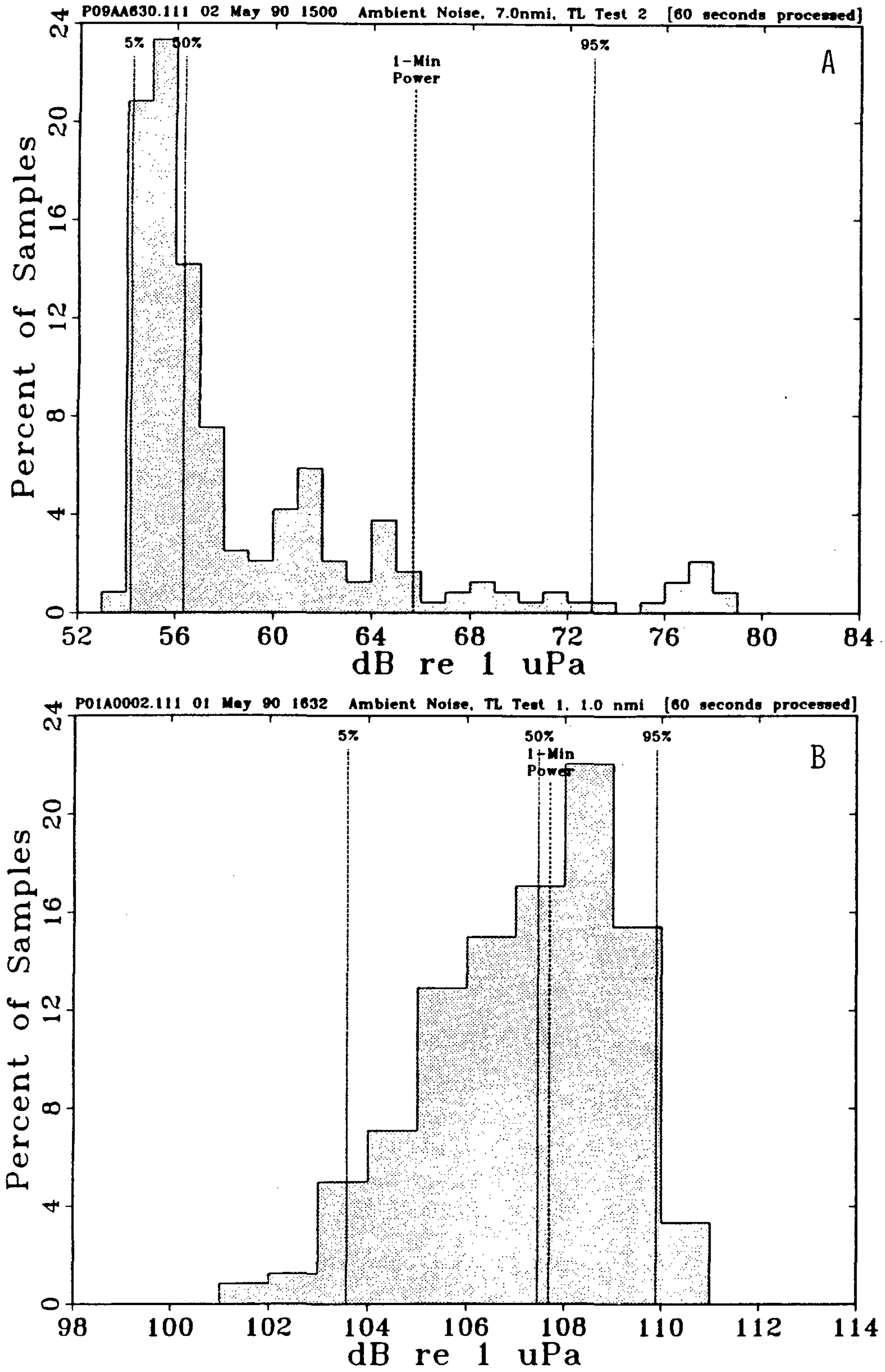


FIGURE 13. Two histograms of ambient noise power levels averaged for ¼-s and taken consecutively over a 1-minute period. The "1-min power" is the average power; the percentiles apply to the distribution of ¼-s power levels. (A) is from a quiet time during TL test #2, 15:00 on 2 May 1990. (B) is from a noisier time during TL test #1, 16:32 on 1 May 1990.

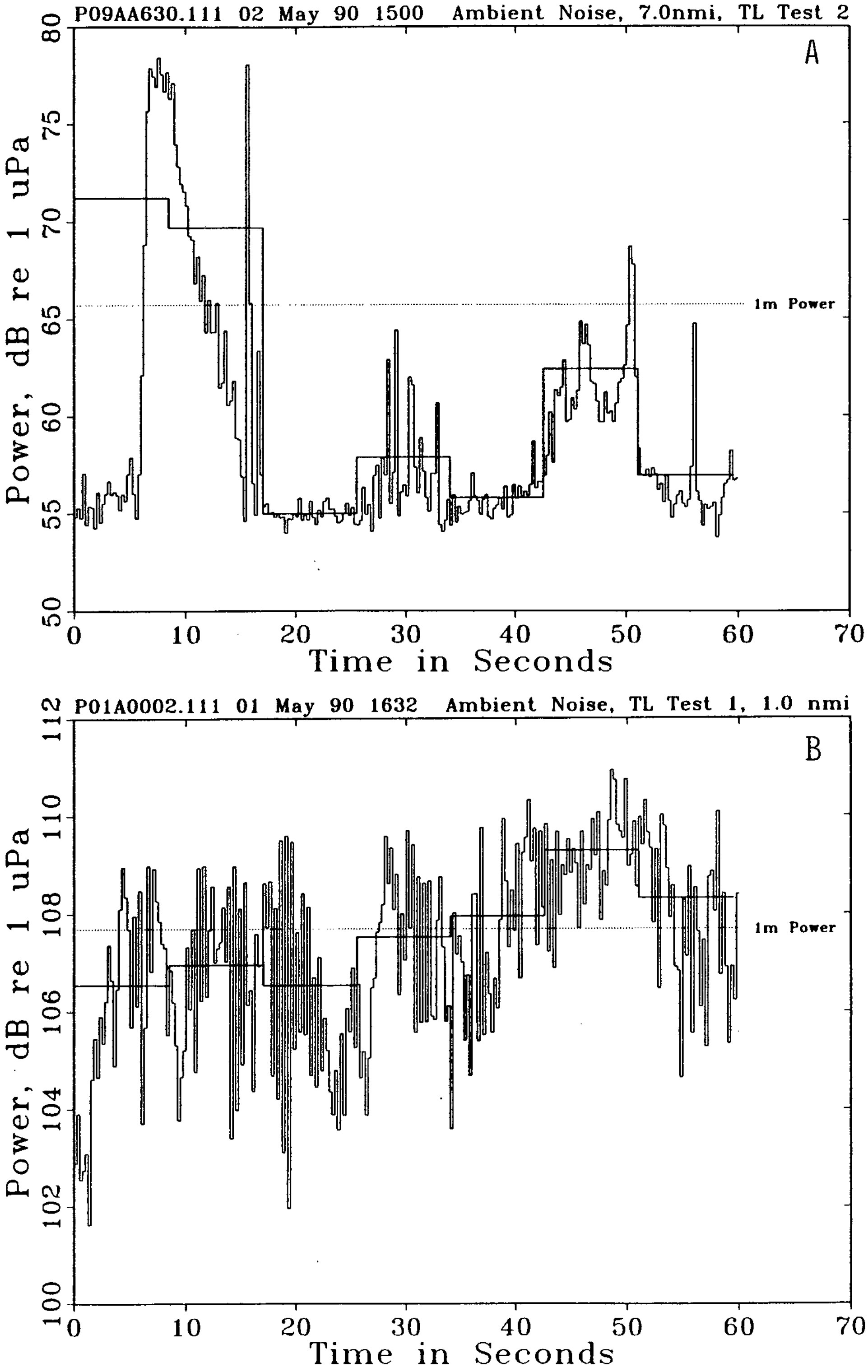


FIGURE 14. Time series plots of ¼-s and 8½-s ambient noise powers over two 1-min periods. These plots show the same data summarized in Figure 13. (A) Low noise case on 2 May 1990 at 15:00. (B) High noise case on 1 May 1990 at 16:32.

Figure 13 presents two such distributions. Figure 13A is for a quiet time on 2 May. The 1-minute power is 66 dB re 1 µPa, as is the mean of the ¼-s and 8½-s powers. The three averages must always be the same, as they are based on the same data. However, the power during 90% of the ¼-s intervals was below the 1-min power. Figure 13B is the distribution for a noisier time on 1 May. The 1-minute power is 107 dB. Just over half of the ¼-s powers were below the 1-min power.

Figure 14 shows ambient noise vs. time for the two samples summarized in Figure 13. These graphs illustrate the sequence and variability of the levels based on ¼-s and 8½-s averaging. The explanation for the skewed distributions in Figure 13 is readily apparent from Figure 14, which shows the same data. In the first case, the ¼-s powers were below the 1-min power for the majority of the 1-min interval (Fig. 14A). In the second case, there were about the same number of ¼-s powers above and below the 1-min power, but the levels extended farther below than above (Fig. 14B). These results account for the right and left skew, respectively, in Figures 13A and 13B.

Figure 15 shows a summary of the relationships among ¼-s, 8½-s and 1-min noise power measurements. The scatter diagrams show the percentage of shorter noise power measurements that were less than the longer term measurement for the same ambient noise sample, plotted against the longer term value. In only a few cases was the percentage less than 50%. The percentages were not clearly related to the longer-term ambient noise power in any of the three analyses; the correlation coefficients ranged from 0.05 to 0.12.

Figure 16 shows the difference between the longer-term average power and the median of the shorter-term powers for the same noise sample. These differences are plotted against the longer-term average power. All differences are near zero or positive, indicating that the longer-term average power was similar to or higher than the corresponding shorter-term median. There is a slight trend toward larger differences at higher longer-term power levels; the correlation coefficients ranged from 0.20 to 0.33 (Fig. 16). This trend was evident when the longer-term average power was above ~90 dB. Thus, at times when the ambient noise level is high, the level during a majority of the short intervals (e.g. ¼ s) is less than the average level during longer intervals (8½ s or 1 min).

In this project we have generally used averaging times of 8¼-8½ s for ambient noise analyses. Hence, the relationships between the ¼-s and the 8½-s results are important. In the great majority of the 8½-s samples, over 50% of the ¼-s powers were less than the corresponding 8½-s power (Fig. 15C). In a few of the 8½-s samples, the ¼-s power was less than the 8½-s value during over 90% of the ¼-s intervals. In these cases a strong but short spike of noise contributed most of the power received during the 8½-s interval. Correspondingly, in all but a few cases the 8½-s power was greater than the median ¼-s power (Fig. 16C). In one 8½-s interval the difference was 18 dB, but most differences were ≤3 dB.

Thus, for a substantial percentage of short time intervals (e.g. ¼-s intervals), the ambient noise level in our study area in spring is several decibels lower than is shown by measurements averaged over 8½ s or 1 min. If whales can sense man-made sounds within intervals much shorter than 8 s, then whales may detect man-made sounds whose levels are slightly weaker than typical ambient noise levels measured over ~8 s. Thus, weak man-made sounds may often be faintly detectable at somewhat greater distances than would be predicted based on ambient noise levels measured over ~8 s intervals. Likewise, at any given distance from a source of man-made noise, the ratio of the man-made noise to the background ambient noise may often be slightly higher than is estimated based on ambient noise measurements over ~8 s intervals.

Discussion of Ambient Noise Results

The average ambient noise level measured in 1990 was significantly higher than that in 1989. For the 20-1000 Hz band, the difference between the averages was 6 dB. One possible explanation is that, in 1989, ice cover was essentially 100% for an extended period of time, while in 1990 there was more open water. Thus, in 1990 there was more noise from waves lapping against the ice floes. It does not seem as likely that there were more animal calls or noisy ice interactions in 1990. The relatively "soft" collisions of loose ice, which dominated in 1990, may be less noisy than is ice under stress while pressure ridges are forming, as was common in 1989 (Greene 1981).

One-third octave band level statistics have not been compiled for the 1989 data. However, the results from 1990 are significant in revealing an almost flat median spectrum for one-third octave bands from 12.5 through 1250 Hz. We speculate that this may be due to the high frequency of occurrence of animal calls across a wide frequency range. There are occasional bowhead calls at low frequencies, frequent and prolonged bearded seal calls at a broad range of medium frequencies, and occasional white whale calls at higher frequencies.

Comparison with Other Studies.--Levels of ambient noise measured during the spring of 1990 tended to be somewhat lower than those in other areas where whale/acoustics work has been done:

1. During summer (August) studies in the Canadian Beaufort Sea during 1980-84, the median ambient noise level was 99 dB re 1 µPa in the 20-1000 Hz band (Greene 1985). This was 9 dB higher than the median in the spring of 1990. The summer median was close to the level expected from sea state two, based on the Knudsen curves extended to low frequencies.
2. Miles et al. (1987) reported ambient noise statistics for six sites in the Alaskan Beaufort Sea. Measurements were made for brief periods in late summer and early autumn (September and October). The levels also corresponded to nominal sea state two values.
3. Measurements were made during late September 1984 near Seal Island, Alaskan Beaufort Sea, while a drillrig on this artificial island was in standby mode (Davis et al. 1985). The median level in the 20-1000 Hz band was ~93 dB, or 2 dB below the level expected for sea state one. Similar measurements at Sandpiper Island in Sep-Oct 1985 gave median levels of 93-100 dB in the 20-1000 Hz band (Johnson et al. 1986). However, these data included some man-made sounds from Sandpiper Island.
4. Moore et al. (1984) measured ambient noise over the Alaskan continental shelf from the northern Bering Sea to the central Beaufort Sea during the spring and autumn. They found no significant difference between average spring and autumn levels. Measured levels at 500 Hz corresponded to levels expected at sea states ranging from below two to six.

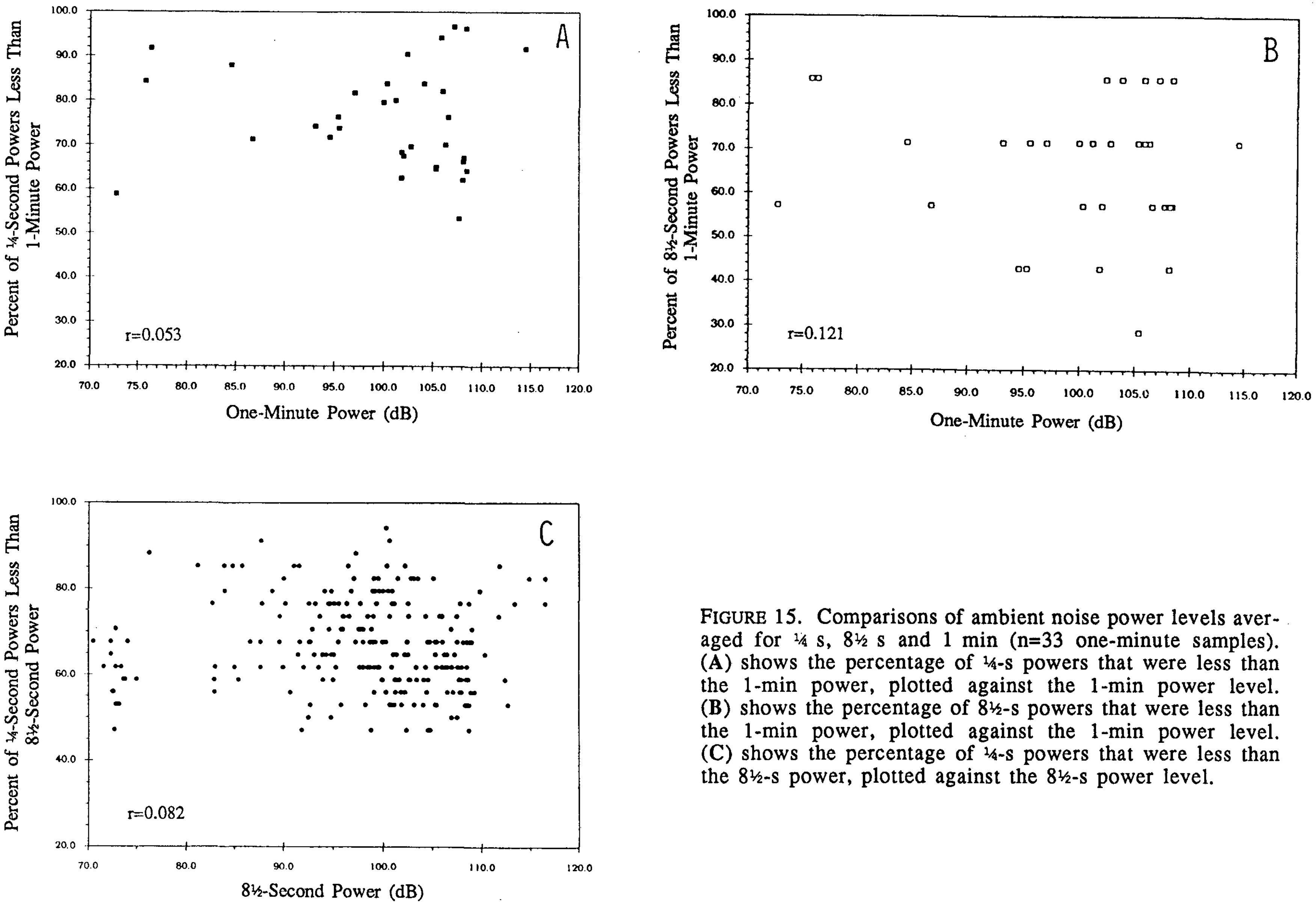


FIGURE 15. Comparisons of ambient noise power levels averaged for ¼ s, 8½ s and 1 min (n=33 one-minute samples). (**A**) shows the percentage of ¼-s powers that were less than the 1-min power, plotted against the 1-min power level. (**B**) shows the percentage of 8½-s powers that were less than the 1-min power, plotted against the 1-min power level. (**C**) shows the percentage of ¼-s powers that were less than the 8½-s power, plotted against the 8½-s power level.

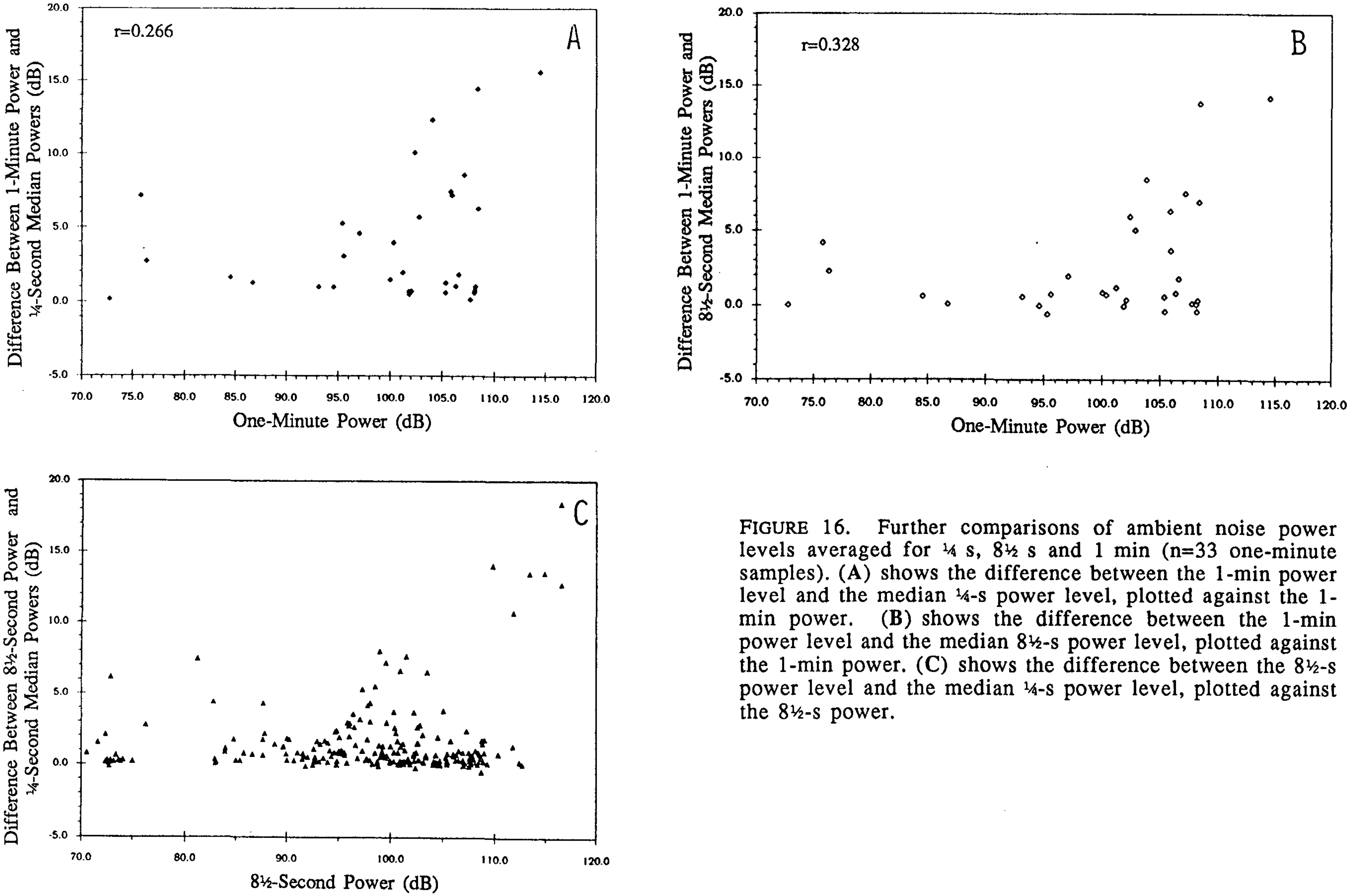


FIGURE 16. Further comparisons of ambient noise power levels averaged for ¼ s, 8½ s and 1 min (n=33 one-minute samples). (A) shows the difference between the 1-min power level and the median ¼-s power level, plotted against the 1-min power. (B) shows the difference between the 1-min power level and the median 8½-s power level, plotted against the 1-min power. (C) shows the difference between the 8½-s power level and the median ¼-s power level, plotted against the 8½-s power.

5. During January, ambient noise off the coast of California below Carmel was dominated by noise from coastal shipping at frequencies <125 Hz and from snapping shrimp above 1000 Hz (Malme et al. 1984). Thus, the ambient noise there was very different in origin and character from that in the Beaufort Sea during May. At 500 Hz, the one-third octave band level off California was 82-87 dB re 1 µPa, corresponding to sea state 2-3.

In summary, the average ambient noise level in the western Beaufort Sea during May 1990, although 5 dB higher than in May 1989, was generally lower than other reported measurements.

Infrasonic Ambient Noise.--Ambient noise levels at frequencies below 20 Hz (infrasounds) have been reviewed by Wenz (1962) and more recently by Buckingham (1990) and D'Spain et al. (1991). Infrasounds arise from natural seismic and volcanic activities, surface waves, ice deformation, some species of baleen whales, and turbulence associated with water movement. These are natural sources of infrasonic ambient noise. Shipping also contributes energy at infrasonic frequencies; propeller blade rates are often below 20 Hz. Few measurements of infrasonic ambient noise have been reported. Unbiased measurements of this type are difficult to obtain because of self-noise created by sensor motion. It is difficult to tell whether measured infrasonic noise represents actual noise in the medium or a sensor artifact.

D'Spain et al. (1991) studied infrasonic energy at frequencies 0.5-20 Hz. They used Swallow floats (neutrally buoyant) at great depths (e.g. 2960 and 5700 m) in deep water west of California. They show a spectral density level of ~110 dB re 1 µPa^2/Hz at 0.5 Hz (attributed to microseisms), decreasing to ~75-80 dB at 5 Hz, and then remaining roughly flat up to 15 Hz. Above 15 Hz the levels rose to a peak of ~95 dB at ~19 Hz. A peak at 9.5 Hz was attributed to shipping, which also contributed to the peak at 19 Hz. A peak at 17.5 Hz was attributed to a blue whale, as was part of the energy in the overall 17-20 Hz band. Many calls by blue and fin whales are at or below 20 Hz (Cummings and Thompson 1971; Edds 1982, 1988; Watkins et al. 1987). However, there is no published evidence that bowhead whale calls include components that low in frequency.

Our hydrophone data from May 1990 reveal one-third octave band levels of 47-112 dB re 1 µPa in the band centered at 10 Hz; the median level for that band was 75 dB (Fig. 11B, Table 4C). The conversion factor to obtain the approximate spectral density level at 10 Hz from the 1/3-octave level centered at 10 Hz is -3.6 dB. Thus, on a spectral density basis, the 10-Hz noise recorded in this study was 43-108 dB re 1 µPa^2/Hz with median 71 dB. That compares with 75-80 dB for deep measurements in a deep ocean with shipping (D'Spain et al. 1991). Additional measurements of Beaufort Sea infrasonic ambient noise are needed, perhaps using a technique for identifying and removing the self-noise components (Buck and Greene 1980).

Short-term Ambient Noise Levels.--The short-term vs. long-term power computations for ambient noise were done for the first time in 1990. The results indicate that ambient noise tends to "spike" for short periods. Thus, short-term (¼ s) values are highly variable. Also, long-term averages (~1 min) tend to be higher than median mid-term (~8 s) values, and mid-term averages tend to be higher than median short-term (~¼ s) values. Thus, ambient noise levels during many brief intervals are less than the values obtained by averaging over ~8 s or longer.

As a result, marine mammals may be able to detect slightly weaker sound signals than would be predicted based on conventional measurements of ambient noise, which usually involve averaging over at least several seconds. Several types of weak sound signals might be detectable only during instants when the ambient noise level is low: calls by conspecifics, other natural environmental sounds, or various man-made sounds.

Transmission Loss Tests

Transmission loss tests were conducted on 1, 2, 24, and 25 May 1990. Figure 17 shows the locations of the four projector sites and the longer-distance receive sites for each test.

Transmission Loss Test #1

TL test #1 was conducted on 1 May. Water depth at the projector station was 166 m, and the depths at the receiver sites varied from 166 to 212 m:

Site	Range	Depth	Site	Range	Depth
Projector	0.0 km	166 m	Receiver	1.22 km	183 m
Receiver	0.14	166	Receiver	3.54	183
Receiver	0.23	166	Receiver	8.83	192
Receiver	0.63	166	Receiver	12.89	212

Figure 18 and Table 5 present the transmission loss results for the tones, sweeps and *Karluk* drillrig sounds. Table 6 presents the *Karluk* source and received levels from which the *Karluk* TL values were derived. *Karluk* data are tabulated only for the 1/3-octave bands where there was significant output of energy. Table 6 also shows the ambient noise data obtained during TL test #1, by one-third octave bands. These ambient noise data are the minimum, average and maximum values based on measurements at each receive site. Summaries by frequency are presented later. The ambient noise level on this date was high (Fig. 6), which tended to mask the test sounds (see Fig. 101A on p. 276).

Transmission Loss Test #2

TL test #2 was conducted on 2 May 1990. Water depth at the projector station was 40 m, and depths at receiver sites varied from 38 to 54 m:

Site	Range	Depth	Site	Range	Depth
Projector	0.0 km	40 m	Receiver	4.30 km	43 m
Receiver	0.105	40	Receiver	10.33	54
Receiver	0.20	40	Receiver	13.32	38
Receiver	1.13	42			

Tables 7 and 8 and Figure 19 present the results, which are summarized by frequency later. The ambient noise level on this date was very low (Fig. 6), and even the weaker components of the test sounds were detectable unusually far away (see Fig. 101B on p. 276).

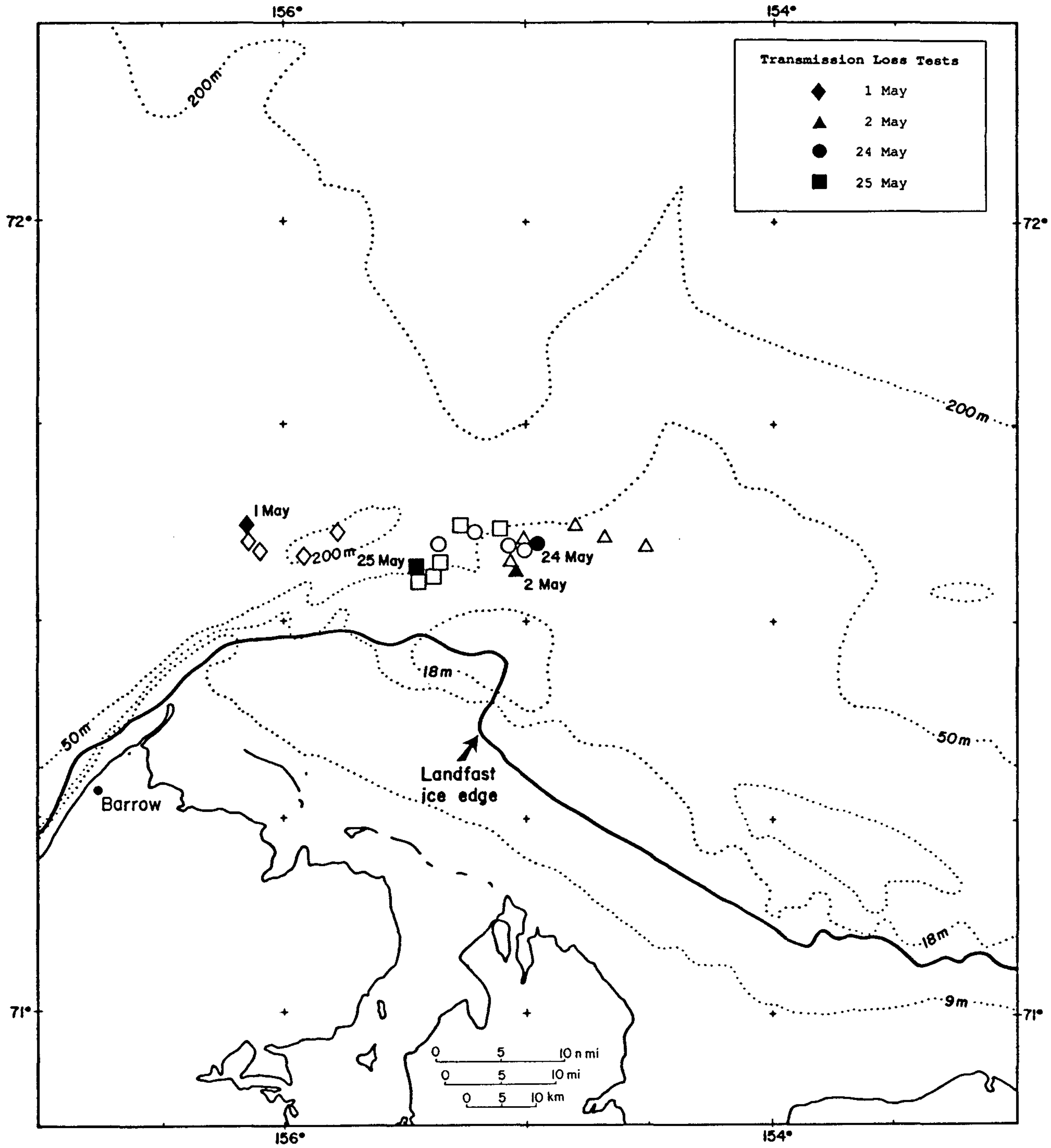


FIGURE 17. Projector (solid symbols) and receiving station sites (corresponding open symbols) during transmission loss tests #1-#4, May 1990.

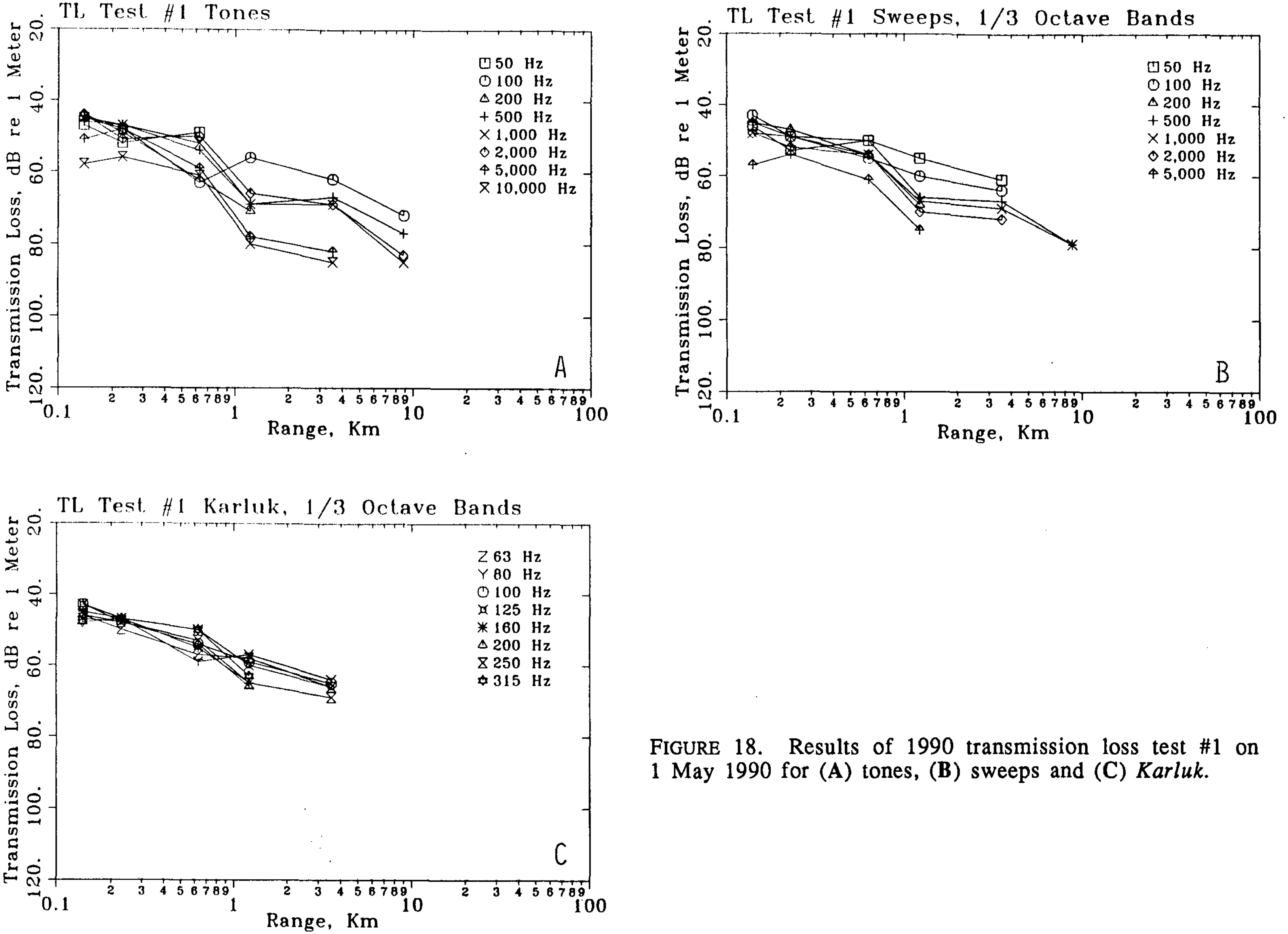


FIGURE 18. Results of 1990 transmission loss test #1 on 1 May 1990 for (**A**) tones, (**B**) sweeps and (**C**) *Karluk*.

Table 5. Transmission loss measurements by frequency and range for the tones, sweeps and *Karluk* sounds during test #1, 1 May 1990.

Range, Km	0.001	0.14	0.23	0.63	1.22	3.54	8.83
Range, nmi	0.00054	0.074	0.12	0.34	0.66	1.91	4.77
Tones:							
50 Hz	0	47	52	49			
100 Hz	0	45	48	63	56	62	72
200 Hz	0	44	49		71		
500 Hz	0	46	47	54	69	67	77
1,000 Hz	0	45	47	52	69	69	85
2,000 Hz	0	44	51	50	66	69	83
5,000 Hz	0	51	48	59	78	82	
10,000 Hz	0	58	56	61	80	85	
Sweeps:							
50 Hz	0	46	53	50	55	61	
100 Hz	0	43	49	55	60	64	
200 Hz	0	45	47	54	68		
500 Hz	0	45	49	50	66	67	79
1,000 Hz	0	48	49	54	67	69	79
2,000 Hz	0	48	52	54	70	72	
5,000 Hz	0	57	54	61	75		
Karluk:							
20 Hz	0						
25 Hz	0						
31.5 Hz	0						
40 Hz	0						
50 Hz	0						
63 Hz	0	46	50	57	58	66	
80 Hz	0	45	47	59	57	64	
100 Hz	0	43	48	54	59	65	
125 Hz	0	43	47	50	60	66	
160 Hz	0	45	47	55	65		
200 Hz	0	46	48	54	66		
250 Hz	0	47	48	53	65	69	
315 Hz	0	48	47	50	63		
400 Hz	0	46	45	48			
500 Hz	0	45	45	48	58		
630 Hz	0	44	48	47	55		
800 Hz	0	45	43	47			
1000 Hz	0		41	48			
1250 Hz	0						
1600 Hz	0						
2000 Hz	0						
2500 Hz	0						
3150 Hz	0						
4000 Hz	0						
5000 Hz	0						
6300 Hz	0						
20-1000 Hz	0	45	47	53	61	68	

Table 6. Received level measurements by one-third octave frequency band for *Karluk* sounds transmitted during test #1. Measurements that were dominated by ambient noise have been omitted. The minimum, maximum and average ambient noise levels measured at the receive sites are also given for the same bands.

Range, Km	0.001	0.14	0.23	0.63	1.22	3.54	Ambient Noise		
Range, nmi	0.00054	0.08	0.12	0.34	0.66	1.91	Min	Max	Avg
20 Hz	143						92	99	94
25 Hz	142						92	97	94
31.5 Hz	141						93	97	94
40 Hz	140						91	96	94
50 Hz	142						91	96	93
63 Hz	156	110	106	99	98	90	90	94	92
80 Hz	156	111	109	97	99	92	89	94	91
100 Hz	157	114	109	103	98	92	88	95	91
125 Hz	157	114	110	107	97	91	87	95	91
160 Hz	159	114	112	104	94		86	96	90
200 Hz	160	114	112	106	94		85	95	89
250 Hz	158	111	110	105	93	89	84	93	88
315 Hz	148	100	101	98	85		83	93	87
400 Hz	142	96	97	94			83	93	86
500 Hz	141	96	96	93	83		81	91	85
630 Hz	140	96	92	93	85		80	89	83
800 Hz	135	90	92	88			80	86	82
1000 Hz	130		89	82			78	88	81
1250 Hz	124						77	87	80
1600 Hz	120						75	86	80
2000 Hz	122						74	82	78
2500 Hz	117						72	82	76
3150 Hz	120						69	81	74
4000 Hz	118						67	78	72
5000 Hz	115						66	77	71
6300 Hz	116						66	76	70
20-1000 Hz	166	121	119	113	105	98	102	107	104

Table 7. Transmission loss measurements by frequency and range for the tones, sweeps and *Karluk* sounds during test #2, 2 May 1990.

Range, Km	0.001	0.1	0.2	1.13	4.3	10.33	13.32
Range, nmi	0.00054	0.057	0.11	0.61	2.32	5.58	7.19
Tones:							
50 Hz	0	47		49	74		
100 Hz	0	38	43	53	70		
200 Hz	0	37	43	60	68	110	
500 Hz	0			62	70	107	124
1,000 Hz	0	31	41	58	66	94	121
2,000 Hz	0	43	44	53	60	101	
5,000 Hz	0	39	48	55	59		
10,000 Hz	0	34	41	39	53		
Sweeps:							
50 Hz	0	45		48	73		
100 Hz	0	38	42	52	71		
200 Hz	0	37	42	58	68		
500 Hz	0	41	43	63	70	107	121
1,000 Hz	0	35	42	52	65	95	114
2,000 Hz	0	40	46	56	62	94	
5,000 Hz	0	45	50	58	64		
Karluk:							
20 Hz	0	46		56	67		
25 Hz	0	40		49	65		
31.5 Hz	0	39		49	69		
40 Hz	0	40		49	69		
50 Hz	0	46		48	71		
63 Hz	0	42		49	76		
80 Hz	0	37	40	49	75		
100 Hz	0	38	42	51	72		
125 Hz	0	40	47	52	71		
160 Hz	0	38	39	51	66		
200 Hz	0	37	42	57	66		
250 Hz	0	41	47	55	69		
315 Hz	0	39	49	53	68		
400 Hz	0	39	46	55	66		
500 Hz	0	42	43	63	73		
630 Hz	0	39	45	56	69		
800 Hz	0	37	41	51	71		
1000 Hz	0	39	44	41	62		
1250 Hz	0	39	46	48			
1600 Hz	0	43	49	57	59		
2000 Hz	0	43	48	57	63		
2500 Hz	0	41	48	56	61		
3150 Hz	0	44	50	62			
4000 Hz	0	48	55	63	71		
5000 Hz	0	49	54	66			
6300 Hz	0	50	54	64			
20-1000 Hz	0	38	42	52	68		

Table 8. Received level measurements by one-third octave frequency band for *Karluk* sounds transmitted during test #2. Measurements that were dominated by ambient noise have been omitted. The minimum, maximum and average ambient noise levels measured at the receive sites are also given for the same bands.

Range, Km	0.001	0.1	0.2	1.13	4.3	Ambient Noise		
Range, nmi	0.00054	0.06	0.11	0.61	2.32	Min	Max	Avg
20 Hz	123	77		67	56	47	77	64
25 Hz	124	84		75	59	45	76	63
31.5 Hz	131	92		82	62	44	74	61
40 Hz	135	95		86	66	43	72	60
50 Hz	141	95		93	70	42	72	59
63 Hz	155	113		106	79	42	71	58
80 Hz	156	119	116	107	81	41	70	57
100 Hz	155	117	113	104	83	40	69	57
125 Hz	155	115	108	103	84	40	68	56
160 Hz	157	119	118	106	91	39	67	56
200 Hz	159	122	117	102	93	40	66	56
250 Hz	158	117	111	103	89	39	66	55
315 Hz	148	109	99	95	80	39	65	54
400 Hz	143	104	97	88	77	40	64	54
500 Hz	142	100	99	79	69	40	64	55
630 Hz	141	102	96	85	72	39	66	56
800 Hz	133	96	92	82	62	39	64	55
1000 Hz	129	90	85	88	67	39	62	54
1250 Hz	128	89	82	80		39	62	52
1600 Hz	124	81	75	67	65	41	62	53
2000 Hz	123	80	75	66	60	41	61	53
2500 Hz	119	78	71	63	58	41	61	52
3150 Hz	119	75	69	57		41	61	51
4000 Hz	119	71	64	56	48	41	61	51
5000 Hz	118	69	64	52		42	61	51
6300 Hz	119	69	65	55		42	61	52
20-1000 Hz	165	127	123	113	97	54	83	72

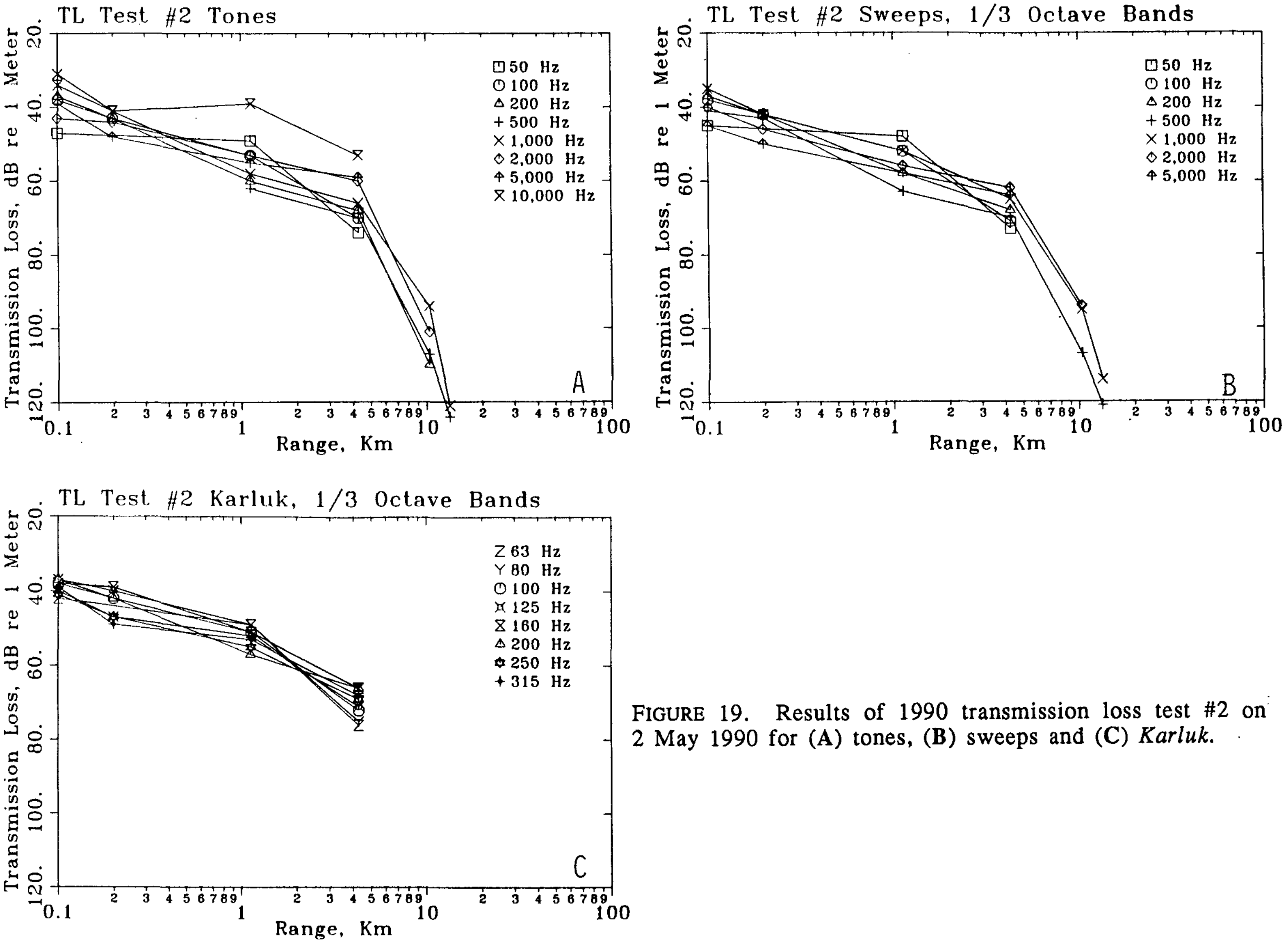


FIGURE 19. Results of 1990 transmission loss test #2 on 2 May 1990 for (A) tones, (B) sweeps and (C) *Karluk*.

Transmission Loss Test #3

TL test #3 was conducted on 24 May 1990. Water depth at the projector site was 44 m, and depths at receiver sites varied from 44 to 140 m:

Site	Range	Depth	Site	Range	Depth
Projector	0.0 km	44 m	Receiver	1.48 km	49 m
Receiver	0.10	44	Receiver	3.70	55
Receiver	0.20	44	Receiver	8.89	110
Receiver	0.93	45	Receiver	14.10	140

Tables 9 and 10 and Figure 20 present the results, which are summarized by frequency later. Ambient noise levels were moderate (Fig. 6; see also Fig. 101C on p. 277).

Transmission Loss Test #4

TL test #4 was conducted on 25 May. Water depth at the projector site was 51 m, and depths at receiver sites varied from 50 to 105 m:

Site	Range	Depth	Site	Range	Depth
Projector	0.0 km	51 m	Receiver	1.78 km	50 m
Receiver	0.10	51	Receiver	3.11	54
Receiver	0.20	51	Receiver	8.56	105
Receiver	0.93	53	Receiver	12.74	70

Figure 21 and Tables 11 and 12 present the results. During this test, a sample of sound from the icebreaker *Robert Lemeur* was projected, along with the three types of sounds used during previous TL tests. The results are summarized by frequency and test area in the following section. Ambient noise levels were relatively high (Fig. 6; see also Fig. 101D on p. 277).

Transmission Loss by Frequency and Test Area

For modeling purposes, it is important to group the TL data from each test by frequency. Graphs in this section show the TL data grouped by frequency and test. Curves based on fitted propagation equations have been plotted with the data except for three cases in which regression analysis produced no physically acceptable equation.

Although the tones, sweeps and *Karluk* drillrig sounds were transmitted over the same paths, the TL values derived for a given frequency via these three types of signals sometimes differ. Differences are caused by differences in signal bandwidth and by interference (constructive or destructive) between multipaths. The latter effect is especially important for tones. However, it is reassuring that the TL values for a given frequency and range usually agreed reasonably closely for the different types of test sounds.

Graphs of the TL data, by frequency, are presented for TL test #1 in Figures 22 and 23. The fitted regression equations were determined as described in the METHODS section (p. 22-23). Table 13 gives the coefficients of these equations. The data based on the three types of

Table 9. Transmission loss measurements by frequency and range for the tones, sweeps and *Karluk* sounds during test #3, 24 May 1990.

Range, Km	0.001	0.1	0.2	0.93	1.48	3.7	8.89
Range, nmi	0.00054	0.054	0.108	0.5	0.8	2.0	4.8
Tones:							
50 Hz	0	54		56	60		
100 Hz	0	32	37	53	55		74
200 Hz	0	53	49	48	61		77
500 Hz	0	41	48	47	61	73	79
1000 Hz	0			59	67	69	85
2000 Hz	0	32	47		57	65	
5000 Hz	0	38	50	52	64	76	
10000 Hz	0	35		41	64		
Sweeps:							
50 Hz	0	51			61	67	
100 Hz	0	40	46		61	68	
200 Hz	0	43	48	48	63	71	77
500 Hz	0	41	45	48	60	71	77
1000 Hz	0	43	50	54	66		82
2000 Hz	0	40	44	48	61		
5000 Hz	0	41	44	49	62		
Karluk:							
20 Hz	0						
25 Hz	0						
31.5 Hz	0						
40 Hz	0				60		
50 Hz	0	49			62		
63 Hz	0	42	45	50	62		
80 Hz	0	39	47	50	61		
100 Hz	0	40	46		61		
125 Hz	0	37	45	50	59		
160 Hz	0	39	46		60		
200 Hz	0	44	48		64		
250 Hz	0	41	44	48	62		
315 Hz	0	39	43	47	60		
400 Hz	0	45	48				
500 Hz	0		46				
630 Hz	0		46		53		
800 Hz	0		47		56		
1000 Hz	0			48			
1250 Hz	0			44			
1600 Hz	0			43			
2000 Hz	0		47				
2500 Hz	0		51				
3150 Hz	0						
4000 Hz	0						
5000 Hz	0						
6300 Hz	0						
20-1000 Hz	0	40	46	52	61		

Table 10. Received level measurements by one-third octave frequency band for *Karluk* sounds transmitted during test #3. Measurements that were dominated by ambient noise have been omitted. The minimum, maximum and average ambient noise levels measured at the receive sites are also given for the same bands.

Range, Km	0.001	0.1	0.2	0.93	1.48	Ambient Noise		
Range, nmi	0.00054	0.05	0.11	0.5	0.8	Min	Max	Avg
20 Hz	124					74	96	84
25 Hz	125					73	94	82
31.5 Hz	131					72	91	79
40 Hz	136				76	72	91	78
50 Hz	142	93			80	71	91	78
63 Hz	156	114	111	106	94	70	91	77
80 Hz	156	117	109	106	95	70	89	77
100 Hz	155	115	109		94	69	88	76
125 Hz	155	118	110	105	96	69	88	76
160 Hz	158	119	112		98	69	87	76
200 Hz	159	115	111		95	68	86	75
250 Hz	156	115	112	108	94	68	85	74
315 Hz	146	107	103	99	86	66	85	76
400 Hz	137	92	89			66	85	78
500 Hz	136		90			65	97	78
630 Hz	138		92		85	65	101	76
800 Hz	134		87		78	66	91	75
1000 Hz	130			82		65	86	73
1250 Hz	123			79		64	85	72
1600 Hz	119			76		63	84	73
2000 Hz	120		73			62	83	71
2500 Hz	116		65			63	83	71
3150 Hz	115					63	83	71
4000 Hz	117					61	83	71
5000 Hz	114					60	83	71
6300 Hz	114					62	83	71
20-1000 Hz	165	125	119	113	104	82	105	92

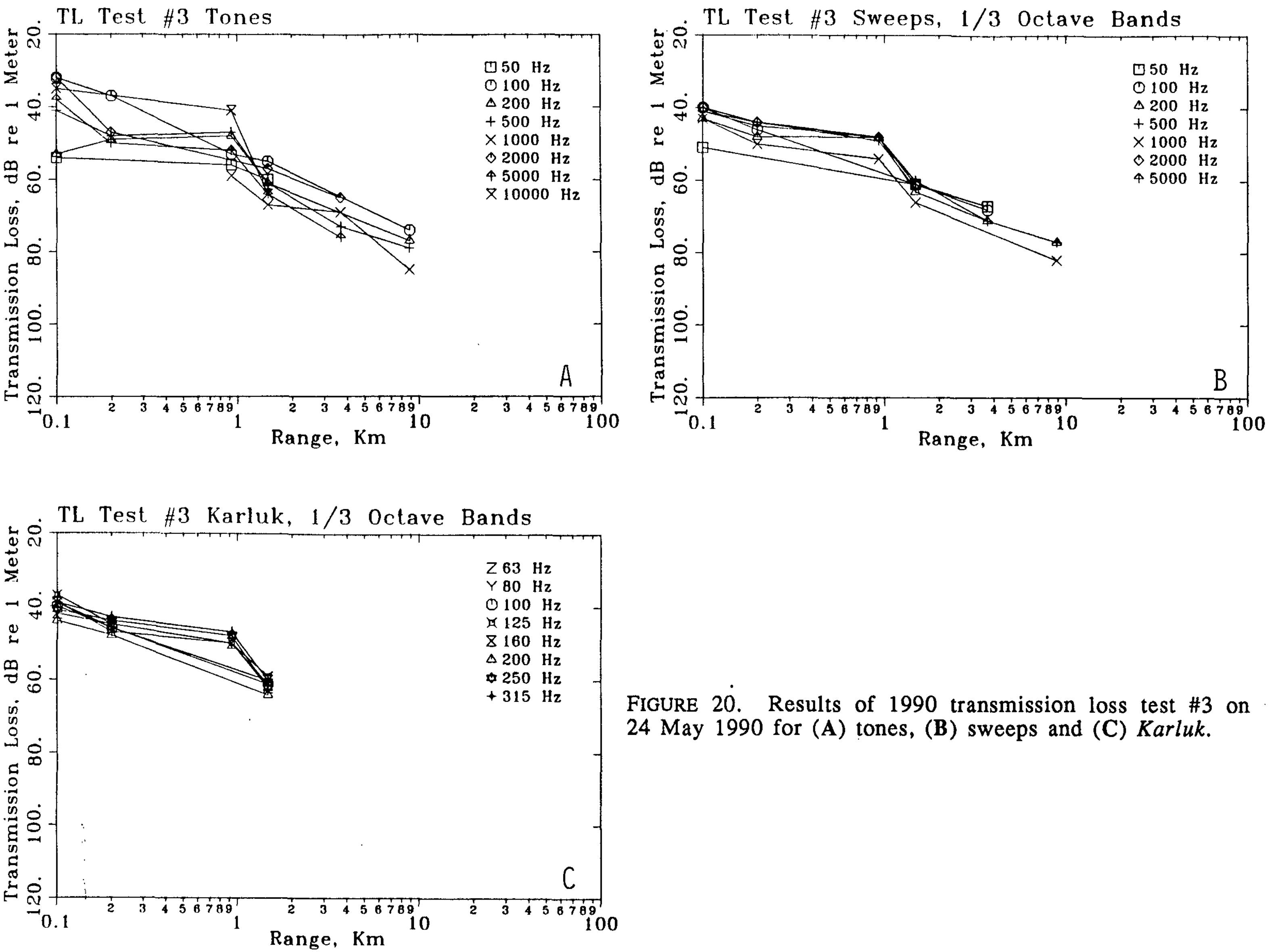


FIGURE 20. Results of 1990 transmission loss test #3 on 24 May 1990 for (A) tones, (B) sweeps and (C) *Karluk*.

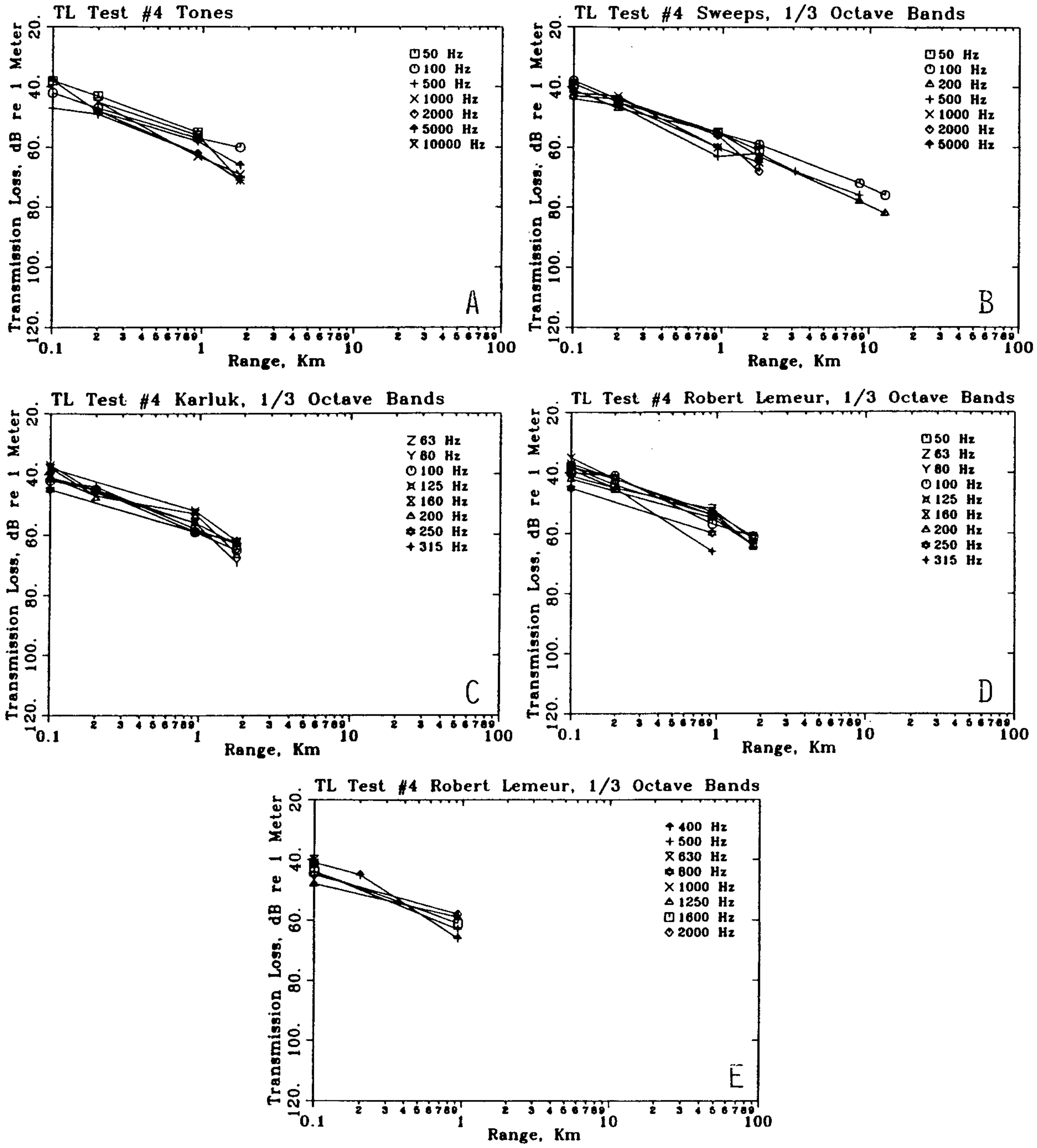


FIGURE 21. Results of 1990 transmission loss test #4 on 25 May 1990 for (A) tones, (B) sweeps, (C) *Karluk* and (D,E) *Robert Lemeur*.

Table 11. Transmission loss measurements by frequency and range for the tones, sweeps, *Karluk* sounds and *Robert Lemeur* sounds during test #4, 25 May 1990.

Range, Km	0.001	0.1	0.2	0.93	1.78
Range, nmi	0.0005	0.054	0.108	0.5	0.96
Tones:					
50 Hz	0	38	43	55	
100 Hz	0	42	47	57	60
200 Hz	0				
500 Hz	0	47	49	62	71
1000 Hz	0		45	63	69
2000 Hz	0		48	62	
5000 Hz	0	38	48	58	66
10000 Hz	0		45	56	71
Karluk:					
20 Hz	0	45			
25 Hz	0	41		43	
31.5 Hz	0	41		49	
40 Hz	0	38	42	51	
50 Hz	0	39	45	54	
63 Hz	0	41	47	53	66
80 Hz	0	37	46	56	69
100 Hz	0	42	45	59	65
125 Hz	0	38		52	62
160 Hz	0	38	47	53	66
200 Hz	0	41	45	56	63
250 Hz	0	45		59	62
315 Hz	0	42	44	58	63
400 Hz	0	40	43	58	
500 Hz	0	39	42	57	
630 Hz	0	39			
800 Hz	0	39			
1000 Hz	0				
1250 Hz	0				
1600 Hz	0				
2000 Hz	0				
2500 Hz	0				
3150 Hz	0				
4000 Hz	0				
5000 Hz	0				
6300 Hz	0				
20-1000 Hz	0	39	47	54	64

Range, Km	0.001	0.1	0.2	0.93	1.78	3.11	8.56	12.74
Range, nmi	0.0005	0.054	0.108	0.5	0.96	1.68	4.62	6.88
Sweeps:								
50 Hz	0	39	45	55	61			
100 Hz	0	38	44	55	59		72	76
200 Hz	0	41	47	55	63		78	82
500 Hz	0	44	46	63	62	68	76	
1000 Hz	0	42	43	60	65			
2000 Hz	0	43	44	56	68			
5000 Hz	0	39	45	60	65			
Robert Lemeur:								
20 Hz	0	46	49					
25 Hz	0	43						
31.5 Hz	0	43						
40 Hz	0	38	43	54				
50 Hz	0	38	44	54				
63 Hz	0	39	45	52	62			
80 Hz	0	35	42	54	64			
100 Hz	0	40	41	57	61			
125 Hz	0	37		53	61			
160 Hz	0	38	42	53	64			
200 Hz	0	42		55	64			
250 Hz	0	45		60				
315 Hz	0	41	45	66				
400 Hz	0	41	45	66				
500 Hz	0	44		63				
630 Hz	0	40						
800 Hz	0	41						
1000 Hz	0	41						
1250 Hz	0	48		59				
1600 Hz	0	44		61				
2000 Hz	0	45		58				
2500 Hz	0	44						
3150 Hz	0	42						
4000 Hz	0	47						
5000 Hz	0	44						
6300 Hz	0							
20-1000 Hz	0	40	46	56	65			

Table 12. Received level measurements by one-third octave frequency band for *Karluk* and *Robert Lemeur* sounds transmitted during test #4. Measurements that were dominated by ambient noise have been omitted. The minimum, maximum and average ambient noise levels measured at the receive sites are also given for the same bands.

	Karluk					Robert Lemeur					Ambient Noise		
Range, Km	0.001	0.1	0.2	0.93	1.78	0.001	0.1	0.2	0.93	1.78			
Range, nmi	0.00054	0.054	0.108	0.502	0.799	0.00054	0.05	0.11	0.50	0.80	Min	Max	Avg
20 Hz	127	82				125	79	76			76	93	83
25 Hz	125	84		82		124	81				76	92	84
31.5 Hz	130	89		81		127	84				77	92	85
40 Hz	136	98	94	85		134	96	91	80		76	93	85
50 Hz	143	104	98	89		144	106	100	90		77	97	85
63 Hz	154	113	107	101	88	150	111	105	98	88	76	98	84
80 Hz	155	118	109	99	86	154	119	112	100	90	76	96	83
100 Hz	155	113	110	96	90	154	114	113	97	93	76	95	83
125 Hz	155	117		103	93	153	116		100	92	76	95	82
160 Hz	159	121	112	106	93	157	119	115	104	93	76	95	82
200 Hz	159	118	114	103	96	157	115		102	93	76	94	82
250 Hz	157	112		98	95	157	112		97		75	95	83
315 Hz	147	105	103	89	84	153	112	108	87		75	96	83
400 Hz	137	97	94	79		151	110	106	85		75	96	82
500 Hz	138	99	96	81		149	105		86		76	96	81
630 Hz	138	99				142	102				76	95	83
800 Hz	128	89				140	99				76	96	83
1000 Hz	127					141	100				75	95	83
1250 Hz	128					138	90		79		74	94	81
1600 Hz	123					136	92		75		73	94	79
2000 Hz	124					133	88		75		72	93	80
2500 Hz	119					125	81				72	92	80
3150 Hz	118					121	79				72	92	78
4000 Hz	119					120	73				72	91	77
5000 Hz	117					119	75				72	90	76
6300 Hz	118					119					70	89	76
20-1000 Hz	165	126	118	111	101	165	125	119	109	100	90	107	97

signals are similar, and TL increases with range in the general manner expected (Fig. 22, 23). However, there are a few seemingly anomalous points, in most cases for tones. This behavior for tones is not surprising because of the opportunities for severe cancellation by destructive interference of multipath arrivals.

Similar graphs for TL test #2 are presented in Figures 24 and 25; for TL test #3 in Figures 26 and 27; and for TL test #4 in Figures 28 and 29. Table 13 presents a complete summary of transmission loss results by test and frequency.

Appendix A describes a more detailed model for sound transmission in a range-invariant medium, i.e. assuming constant water depth and the same bottom reflection properties along the entire transmission path. Appendix A also shows how well the sweep data from 1990 fit that model. The results relate transmission loss to the parameter Range/(2*Depth). After a single average depth has been assigned to each test, this scaling procedure permits, for each frequency, a single plot of the data from all four TL tests. Separate plots are required for each frequency because, in general, the bottom affects different frequencies differently. The results in Appendix A are consistent and encouraging. It remains for future effort to include the 1989, 1991 and any later TL data that may become available for the test area northeast of Pt. Barrow.

Comparison of the 1990 results with the 1989 results (Richardson et al. 1990a:106-148) is straightforward. By calculating the parameter Range/(2*Depth) for the 1989 data and plotting them on the graphs in Appendix A, the two data sets can be compared. This was done for sweep data from 1989 TL test #4. Actual water depths were 119-142 m, and an average depth of 130 m was assigned. Results from 1989 TL test #4 were in good agreement with those from the four 1990 TL tests.

Many measurements of received sound levels vs. distance from a source have been reported previously for the Canadian Beaufort Sea (Greene 1985) and the Alaskan Beaufort Sea (Greene 1987a). The measurements were made during summer and early autumn with no ice or at most light ice, in contrast to the heavy ice encountered during May northeast of Pt. Barrow. The cited reports contain simple regression equations fitted to the received level data. These equations are similar or identical in form to those fitted in this study. Typically, after allowance for spreading losses with a 10 log (Range) term, the linear loss coefficients for no-ice or light-ice conditions in summer or autumn were 1-2 dB/km. In contrast, many of the linear coefficients during this spring study were 3-5 dB/km, especially in water <50 m deep (Table 13, coefficient B). The larger coefficients in spring than in summer/autumn are attributable to the heavy, rough nature of the ice cover in spring. Underwater sound is expected to propagate better without rough ice, other conditions being equal.

C.I. Malme, *in* Richardson et al. (1990a:141-148), compared the May 1989 transmission loss results from this project with other results from the Beaufort and Chukchi Seas and off the California coast. Because the 1990 results reported here compare well with the 1989 results, Malme's comparison is valid for the 1990 results as well. His comparison confirmed that "ice cover has a significant influence on shallow water transmission loss". He noted that sound propagation losses in the western Beaufort Sea in May were higher than had been observed in the central and eastern Beaufort during summer. Although ice is undoubtedly an important factor in spring, part of the higher loss rate found in this study may be attributable to increased bottom loss in the western Beaufort relative to the central and eastern Beaufort. Detailed

Table 13. Coefficients for the equations fitted to the 1990 transmission loss (TL) results, by test and frequency. The tabulated coefficients are for the equation

$$TL = A + B*R + C*\log(R)$$

where R is in km and TL is in dB re 1 m.

Frequency	Coefficient			n	Correl. Coeff.	St. Err. (dB)	Measurement Ranges (km)
	A	B	C				
TL TEST #1 (water depths 166-212 m)							
50	No eq'n, B was negative			8			0.14-3.54
100	No eq'n, B was negative			16			0.14-8.83
200	55.5	8.546	15	11	0.863	2.463	0.14-1.22
500	57.3	0.752	15	16	0.492	3.979	0.14-8.83
1000	57.2	1.236	15	14	0.637	4.749	0.14-8.83
2000	59.6	1.053	15	11	0.572	4.197	0.14-8.83
5000	64.0	3.637	15	9	0.607	5.504	0.14-3.54
20-1000	57.0	0.876	15	5	0.707	1.417	0.14-3.54
TL TEST #2 (water depths 38-54 m)							
50	48.3	3.896	10	11	0.788	5.846	0.1-4.3
100	47.8	3.886	10	12	0.992	0.899	0.1-4.3
200	47.9	4.453	10	13	0.950	4.580	0.1-10.33
500	51.8	4.326	10	16	0.973	5.323	0.1-13.32
1000	44.7	4.222	10	16	0.970	5.482	0.1-13.32
2000	50.1	3.135	10	14	0.914	5.247	0.1-10.33
5000	No eq'n, B was negative			11			0.1-4.3
20-1000	48.0	3.180	10	4	0.999	0.345	0.1-4.3
TL TEST #3 (water depths 44-110 m)							
50	55.9	1.224	10	10	0.219	6.394	0.1-3.7
100	50.6	1.982	10	12	0.736	4.857	0.1-8.89
200	55.2	1.494	10	14	0.709	4.735	0.1-8.89
500	52.3	2.100	10	13	0.844	4.383	0.1-8.89
1000	57.2	1.882	10	11	0.740	5.953	0.1-8.89
2000	49.8	3.010	10	9	0.650	4.459	0.1-3.7
5000	50.1	5.575	10	9	0.872	3.865	0.1-3.7
20-1000	50.1	5.214	10	4	0.853	2.542	0.1-1.48
TL TEST #4 (water depths 50-105 m)							
50	53.8	1.665	15	13	0.738	0.844	0.1-1.78
100	56.0	0.298	15	18	0.425	2.186	0.1-12.74
200	56.2	0.809	15	13	0.857	1.955	0.1-12.74
500	59.1	0.539	15	15	0.305	3.803	0.1-8.56
1000	55.3	4.958	15	8	0.856	2.330	0.1-1.78
2000	56.9	3.294	15	8	0.631	2.628	0.1-1.78
5000	55.6	3.633	15	9	0.797	2.085	0.1-1.78
20-1000	54.8	2.868	15	8	0.784	1.767	0.1-1.78

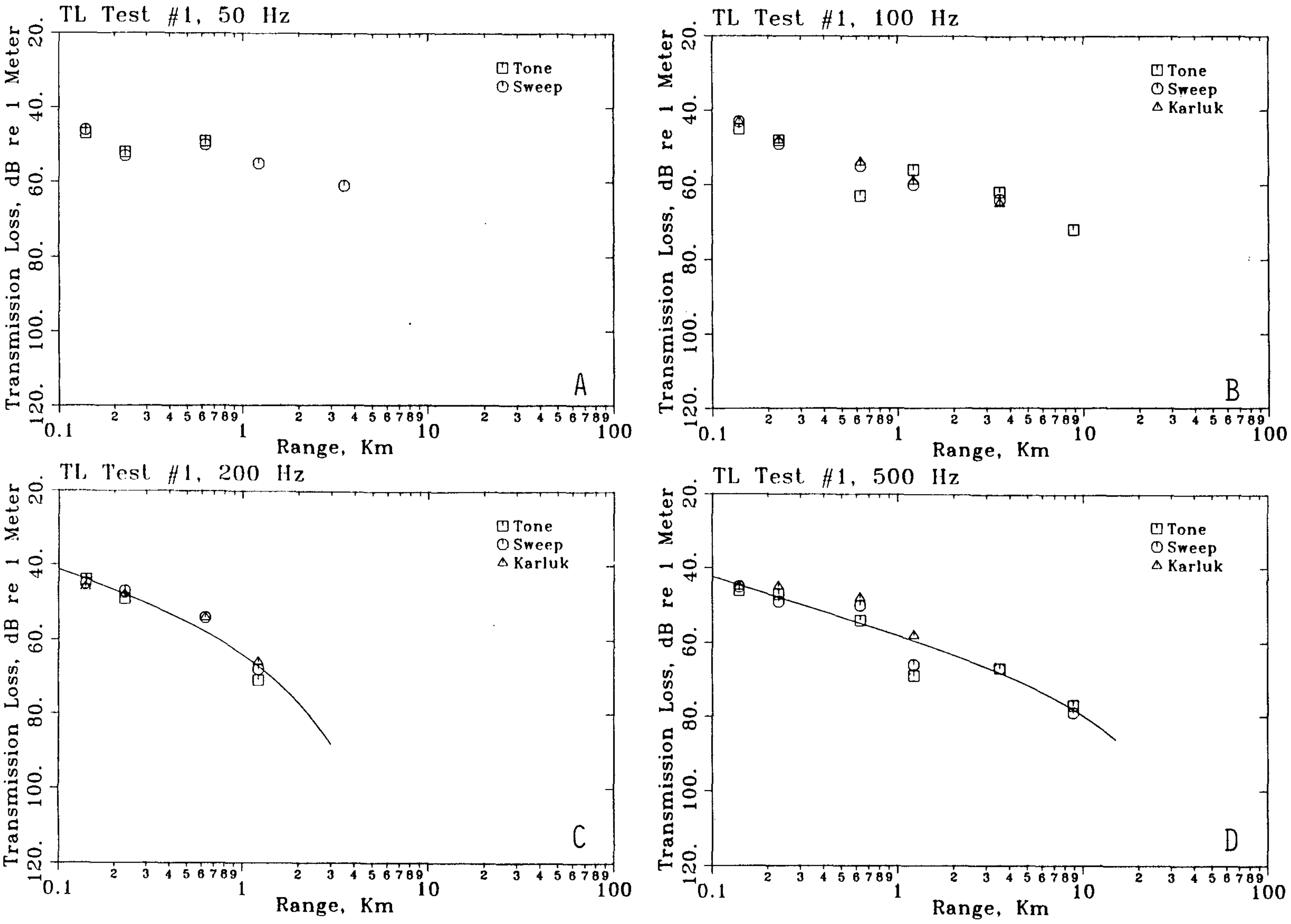


FIGURE 22. TL test #1, 1 May 1990, summary for (A) 50 Hz; (B) 100 Hz; (C) 200 Hz; (D) 500 Hz.

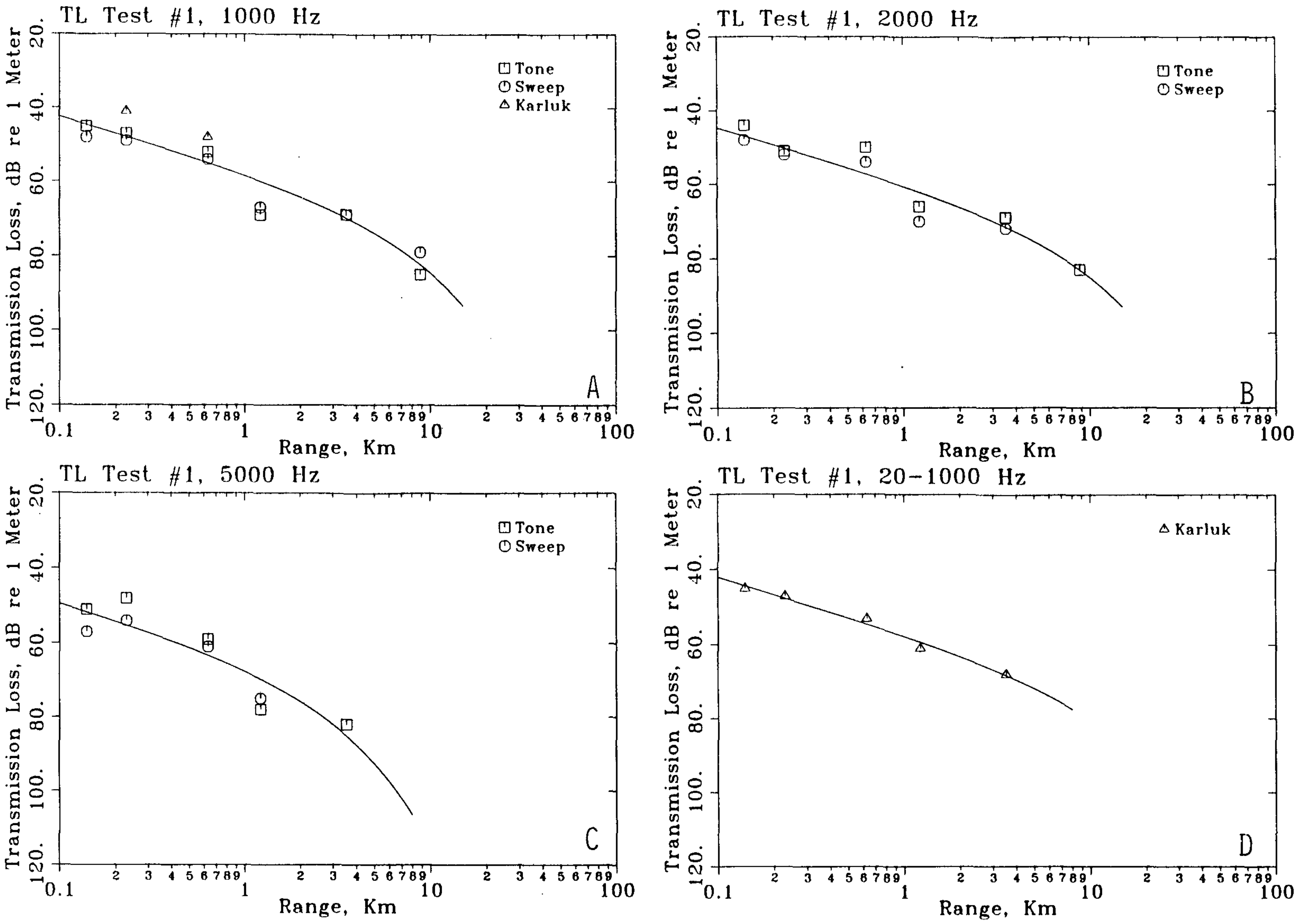


FIGURE 23. TL test #1, 1 May 1990, summary for (A) 1000 Hz; (B) 2000 Hz; (C) 5000 Hz; (D) 20-1000 Hz.

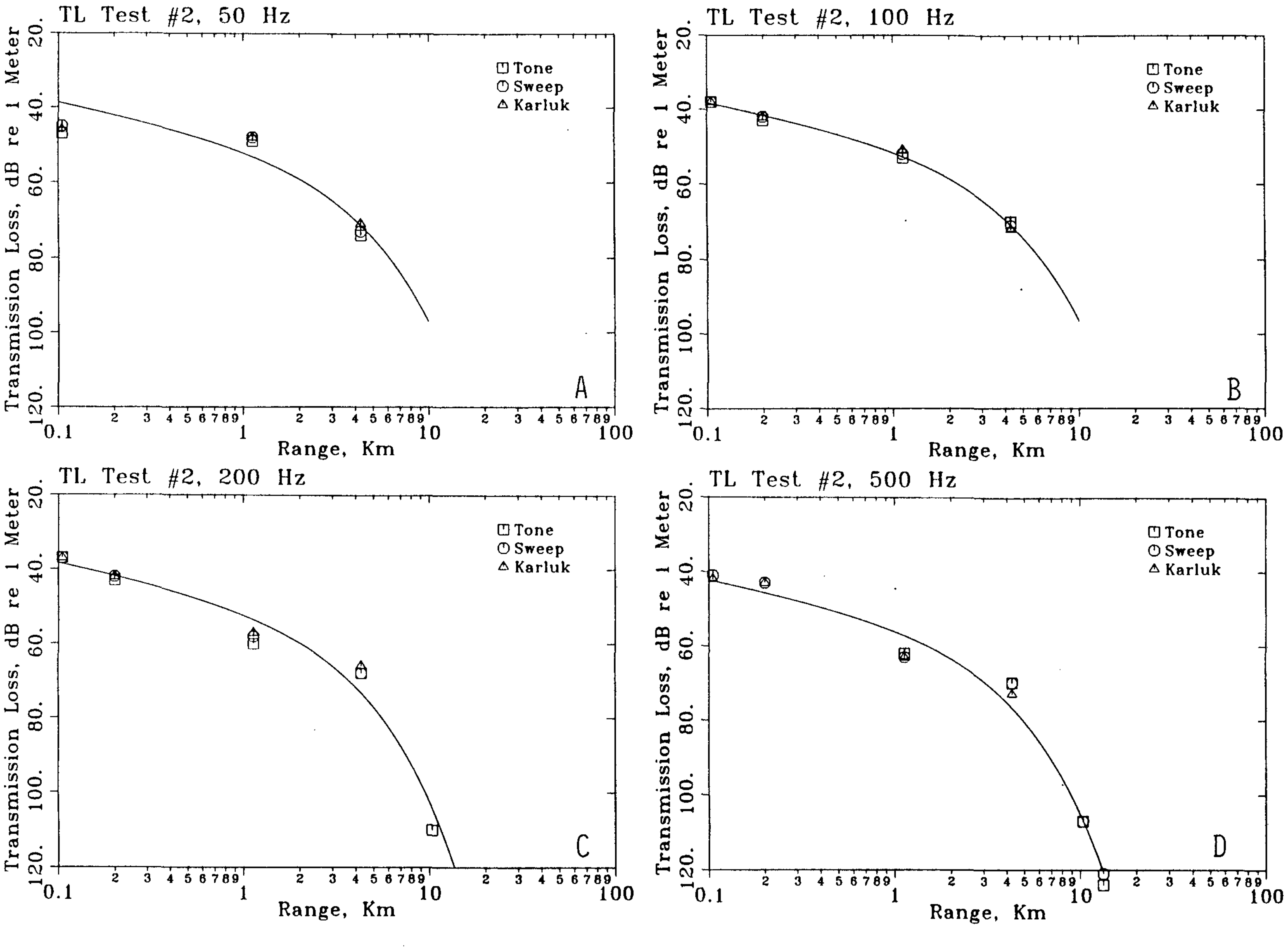


FIGURE 24. TL test #2, 2 May 1990, summary for (A) 50 Hz; (B) 100 Hz; (C) 200 Hz; (D) 500 Hz.

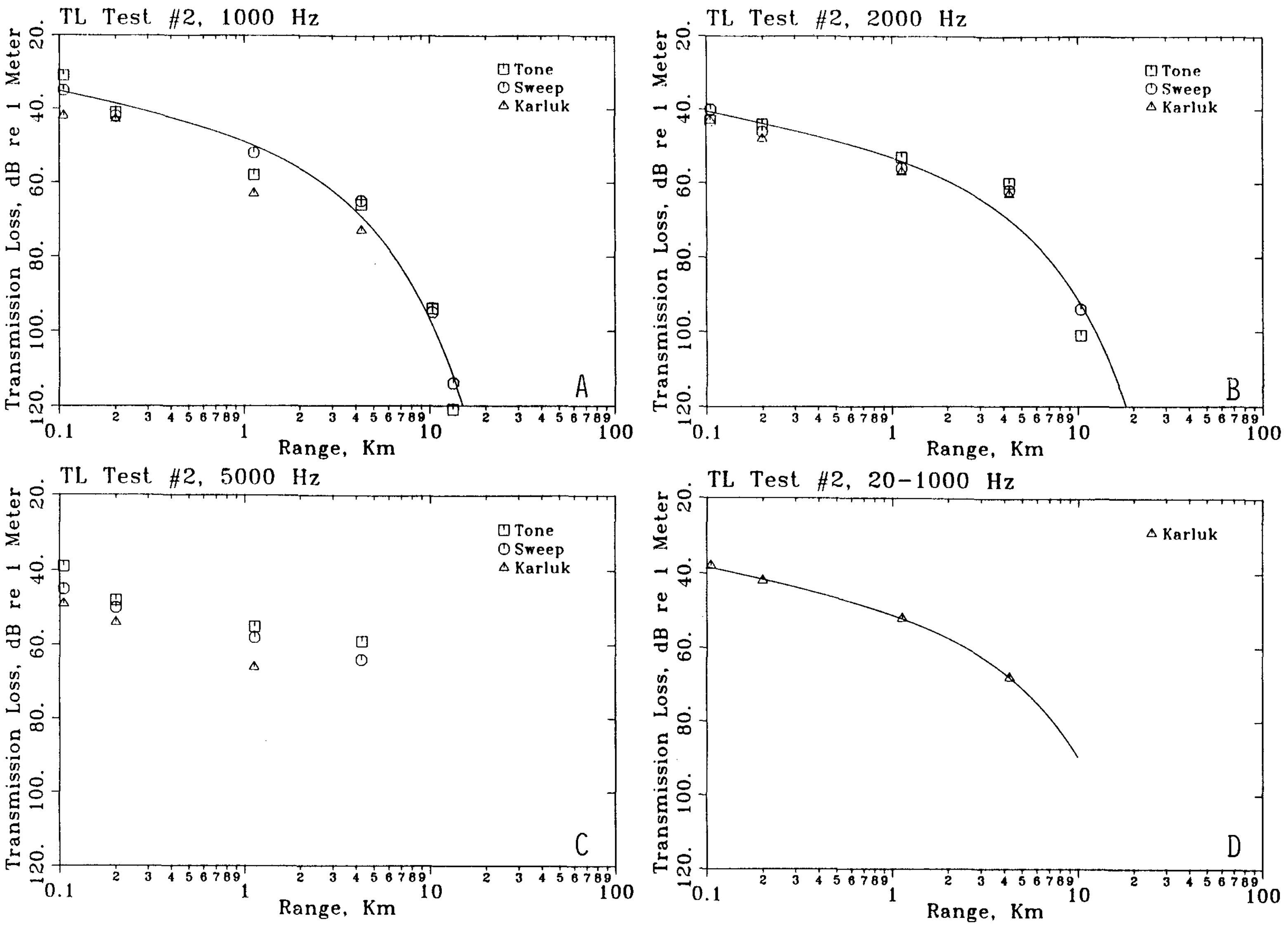


FIGURE 25. TL test #2, 2 May 1990, summary for (A) 1000 Hz; (B) 2000 Hz; (C) 5000 Hz; (D) 20-1000 Hz.

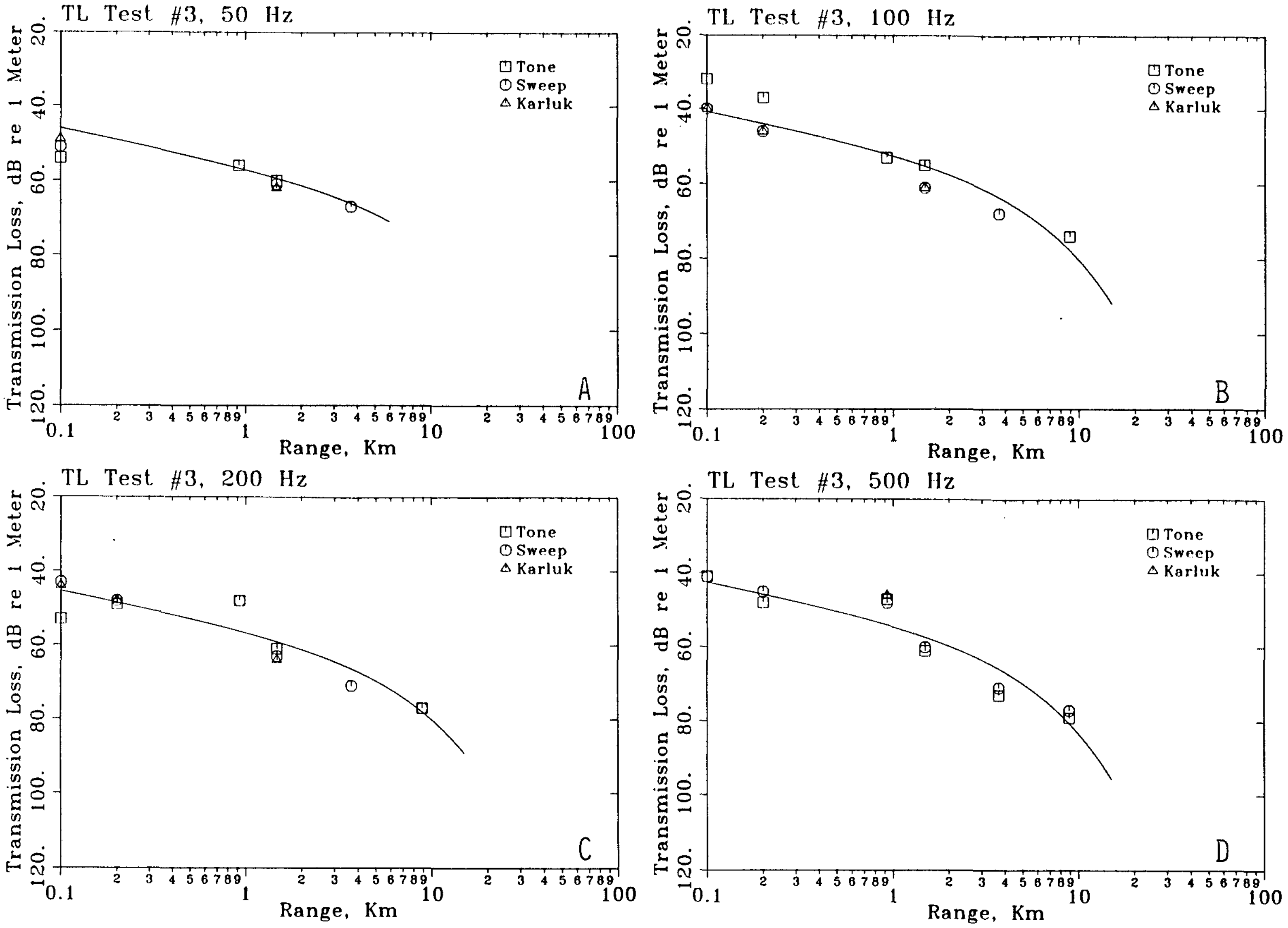
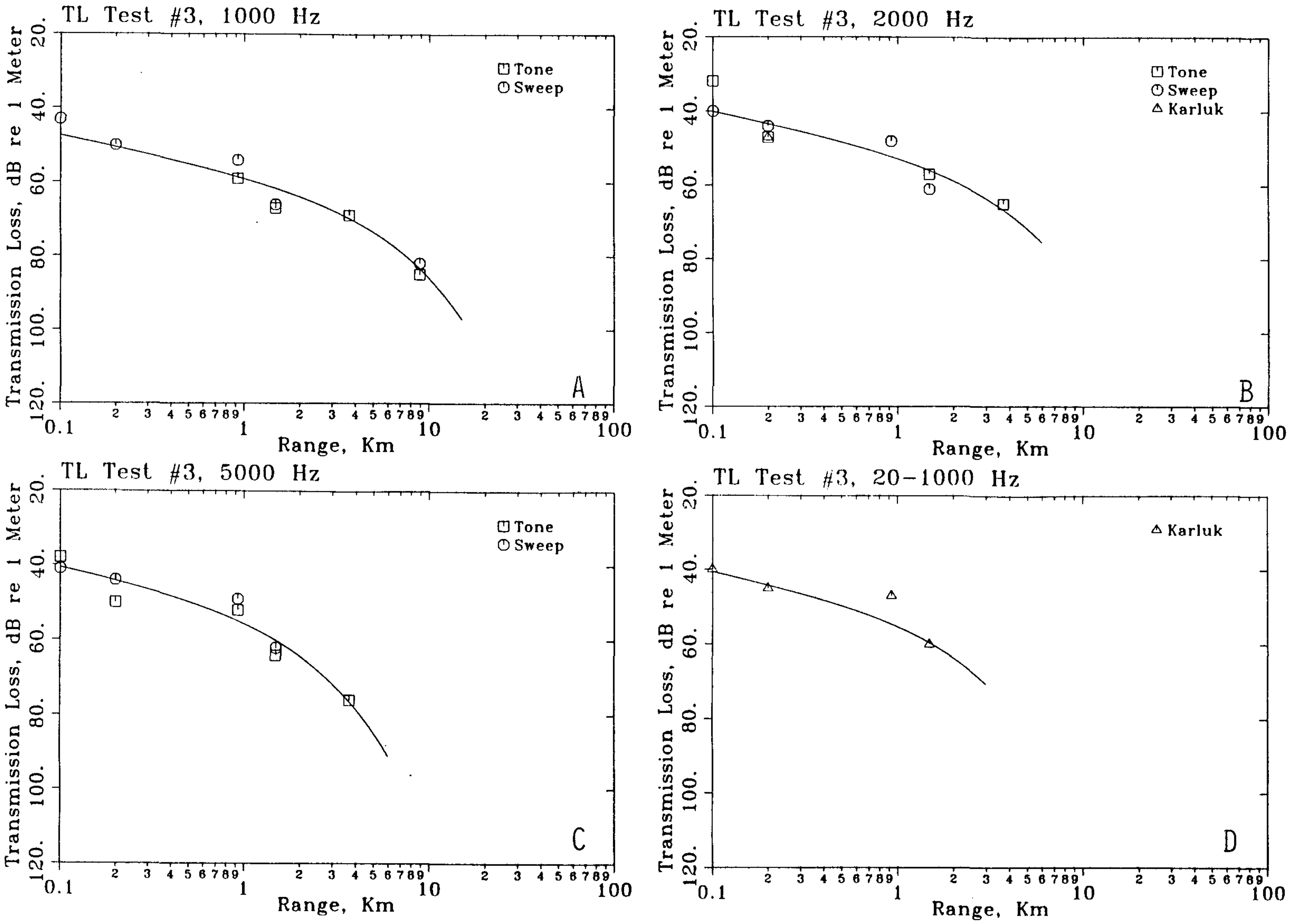


FIGURE 26. TL test #3, 24 May 1990, summary for (A) 50 Hz; (B) 100 Hz; (C) 200 Hz; (D) 500 Hz.


TL Test #3, 1000 Hz

TL Test #3, 2000 Hz

TL Test #3, 5000 Hz

TL Test #3, 20-1000 Hz

FIGURE 27. TL test #3, 24 May 1990, summary for (A) 1000 Hz; (B) 2000 Hz; (C) 5000 Hz; (D) 20-1000 Hz.

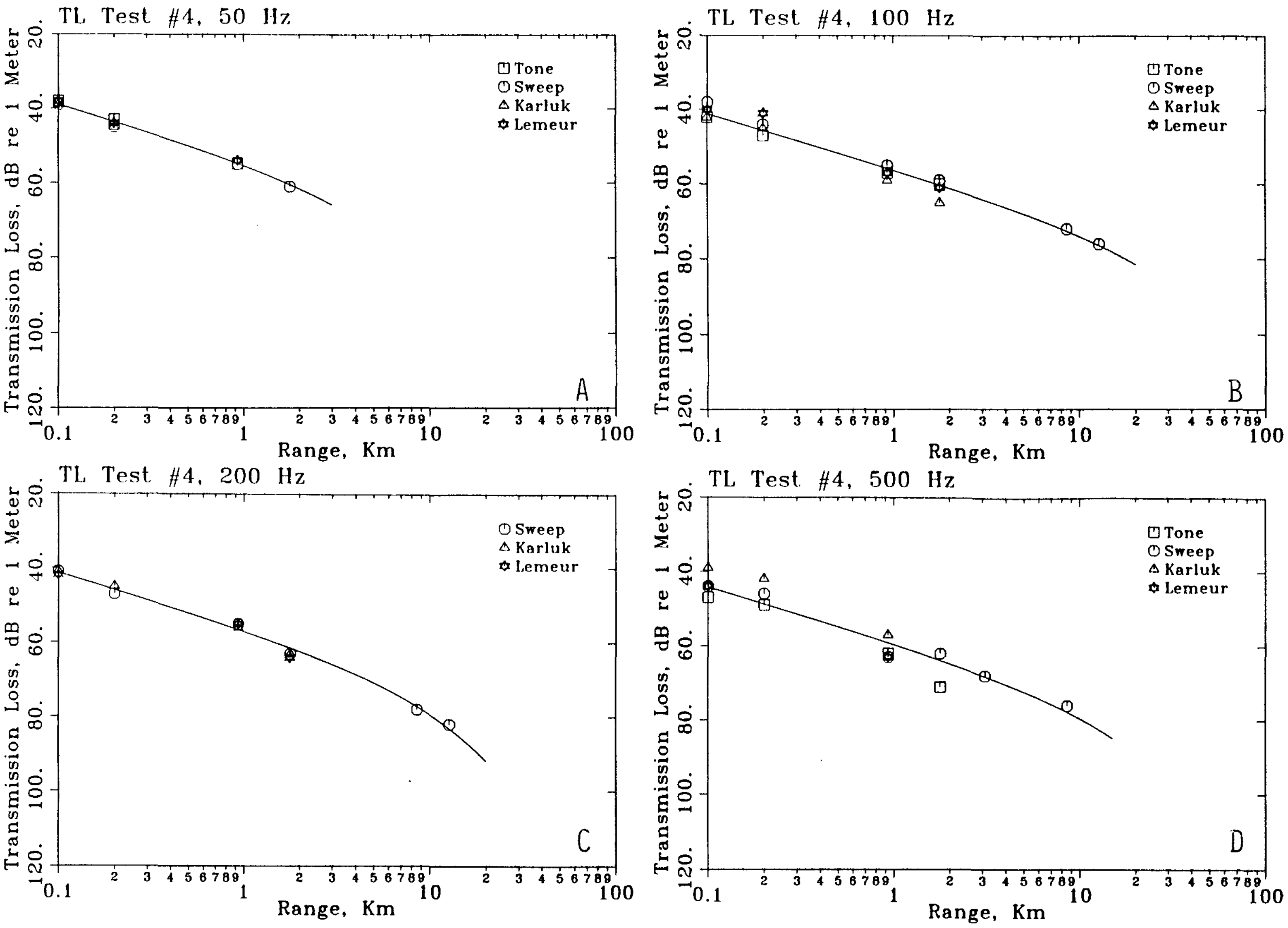


FIGURE 28. TL test #4, 25 May 1990, summary for (A) 50 Hz; (B) 100 Hz; (C) 200 Hz; (D) 500 Hz.

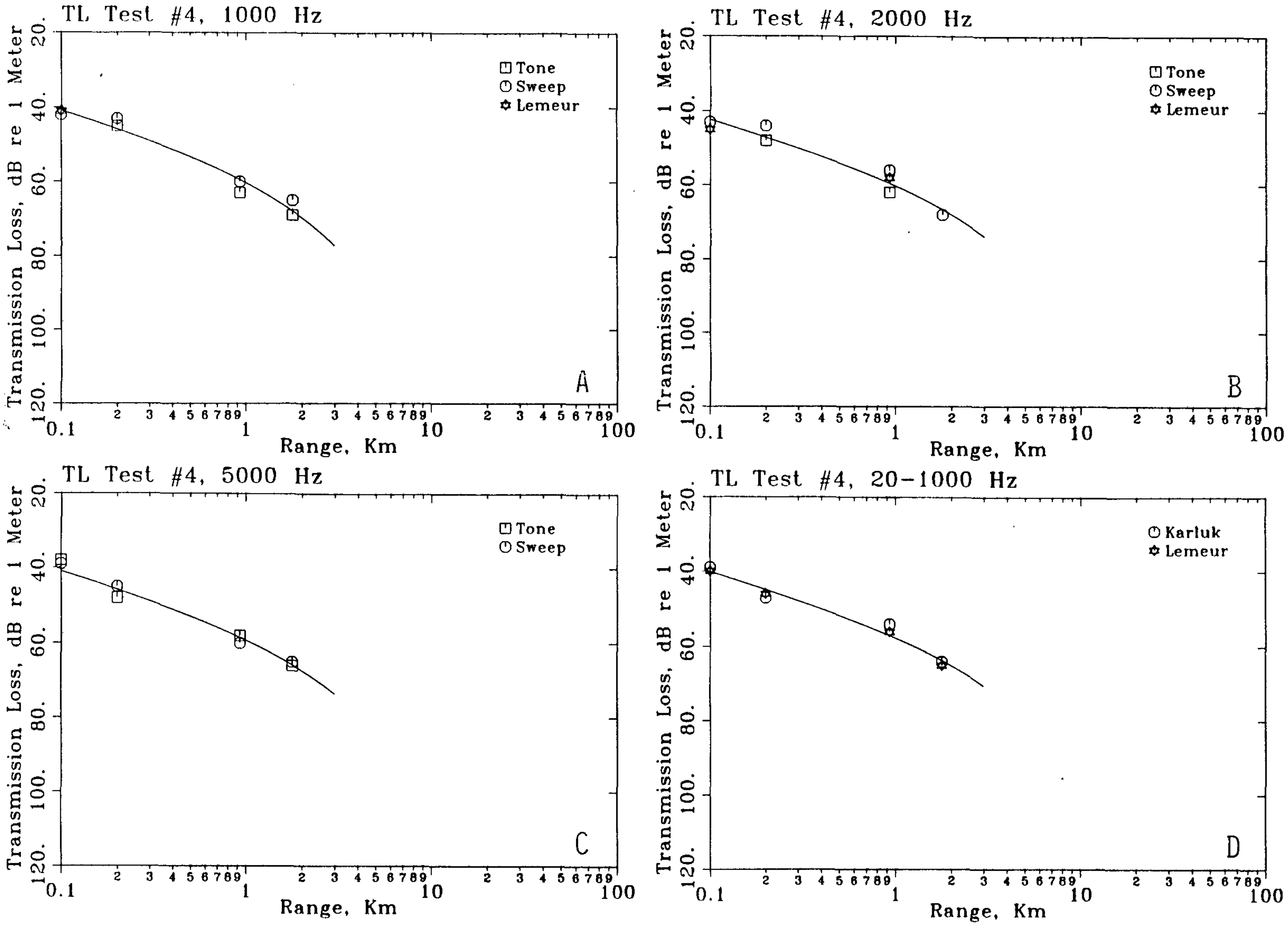


FIGURE 29. TL test #4, 25 May 1990, summary for (A) 1000 Hz; (B) 2000 Hz; (C) 5000 Hz; (D) 20-1000 Hz.

analysis of combined results from all years of this study might provide insight into this question.

Malme noted that "The general similarity between transmission loss in our study area in the western Beaufort Sea during spring and in the Chukchi Sea during late winter - early spring (Greene 1981) is also noteworthy." This similarity suggests that reactions of whales to man-made noise may occur at similar distances from noise sources in these two areas, assuming that reaction thresholds and other factors are similar.

Fidelity of Playbacks

The sound projector used for the 1990 (and 1989) playback experiments was a U.S. Navy model J-11. The J-11 is a broadband, low efficiency electrodynamic transducer with voice coil, magnet and diaphragm. The specified operating frequency range is 20-12,000 Hz (USRD 1982). However, at frequencies below 100 Hz the output capability is reduced because of diaphragm displacement limitations. Thus, users must be careful not to apply too large a drive voltage. If they do, the transducer will distort or, ultimately, perforate the diaphragm. The recorded *Karluk* sounds contained relatively high levels at frequencies below 100 Hz. Thus, it is important to describe the differences between the projected *Karluk* sounds and the original *Karluk* sounds. The original sounds were described in Richardson et al. (1990a:80*ff*).

Fidelity of Original Recording

One aspect of the overall fidelity question is the faithfulness of our original recording to the actual *Karluk* sounds. The Sony model TCD-5M audio cassette recorder used at *Karluk* on 30-31 March 1989 has two potential limitations: accuracy of recording speed and evenness of frequency response:

- The recording speed, which affects the accuracy of the recorded sound frequencies, is within a few percent. If the recording speed were off by 2%, for example, a 100 Hz tone would be recorded as a 98 or 102 Hz tone. We know of no reason, in terms of whale behavior, why a small speed inaccuracy (if it occurred) would affect the quality of the playback experiments.
- The frequency response limitation may be more important. The response of the recorder is calibrated to 10 Hz but falls off notably at frequencies below 20 Hz. Any drillsite sounds at frequencies below 10 Hz would not be recorded faithfully, and those at 10-20 Hz would be proportionally weaker than in the actual *Karluk* sound. In particular, any sound components corresponding to the rotary table rotation frequency (~60-120 rpm, or 1-2 Hz) would not be present in the recording (Hall and Francine 1991). It is possible that such sounds, sometimes called infrasonic sounds, were generated by the drillrig at *Karluk*. The rig was installed on a bottom-founded ice platform for one winter's operation. Vibrations from the rotary table/drillstring assembly may have coupled into the ice and the bottom and might have been detectable in the shallow water (6-7 m) of the lagoon around the drillsite.

It should be noted that the frequency limitations of the sound recorder used at *Karluk* in 1989 had no net effect on the playback results. The J-11 projector used for playbacks would not have been able to reproduce sounds at frequencies below 20 Hz even if they had been recorded faithfully (see "Frequency Content of Playbacks", below).

Playback Levels

Another question concerns the overall levels of the playback sounds as compared with the overall levels of the original *Karluk* sounds. This question was addressed in the report on the 1989 fieldwork (Richardson et al. 1990a:99-103). The source level of the J-11 (~166 dB re 1 μPa-m) did not approach that of *Karluk*. However, the playbacks were in deeper water than was the original *Karluk* site. Hence, sound propagation was more efficient during playbacks.

- In 1989, broadband sound levels (20-1000 Hz) received at ranges ~200-500 m from the J-11 were comparable to those at similar ranges from *Karluk* itself. Levels received at less than 200 m range were stronger near *Karluk* itself than at comparable ranges near the playback site. Levels received at ranges greater than 200-500 m were stronger near the playback site than around *Karluk* (see Fig. 99 on p. 274).
- In 1990, a similar pattern was evident, but the crossover distance was slightly less--at 100-200 m (Fig. 30). Within 100 m, levels in the 20-1000 Hz band were apparently higher near *Karluk* itself. Beyond 200 m, received levels in that band were higher near the playback site than at corresponding distances from *Karluk* itself.

The closer crossover distance in 1990 was probably attributable to the slightly higher average source level of the projector in 1990 than in 1989.

These comparisons refer to sounds above 20 Hz. The drillsite emitted strong sound at frequencies as low as 10-20 Hz, and probably lower. The sound projector did not (see below). If data on received levels at frequencies below 20 Hz were available and included in Figures 30 and 99, levels near the actual drillsite would be higher by an unknown but significant amount. Levels near the projector would be essentially unchanged from those shown in Figures 30 and 99, given the limitations of the projector below 20 Hz.

Frequency Content of Playbacks

Figure 31A shows the frequency composition of the *Karluk* sounds, by one-third octave bands, as originally recorded at three distances from the drillsite. The recording made 130 m from the drillsite was the one used for playbacks. Although the strongest third-octave levels occur at 63-250 Hz, there are significant levels at frequencies at least down to 10 Hz, the lowest frequency recorded (see above).

Figure 31B compares the levels 130 m from the actual *Karluk* rig (black squares) with source and received levels 1 m and 100 m from the J-11 projector during playbacks. Comparison of the shapes of curves shows that the components below 80 Hz, and especially below 63 Hz, were underrepresented in the projector output and in received levels 100 m from the projector (Fig. 31B). Above 80 Hz, the received level curves are more or less parallel to the curve for the original recording. Below 80 Hz, and especially below 63 Hz, the received level curves fall away rapidly. Even so, it is noteworthy that--during *Karluk* playbacks--the J-11 emitted strong signals at frequencies as low as 63 Hz. The source levels were >150 dB re 1 μPa-m for the one-third octave bands centered at 63-315 Hz.

In all third-octave bands from 80 to 1000 Hz, the average received level at 100 m during the 1990 playbacks was within 3 dB of that 130 m from the actual rig (Fig. 31C,D). If the

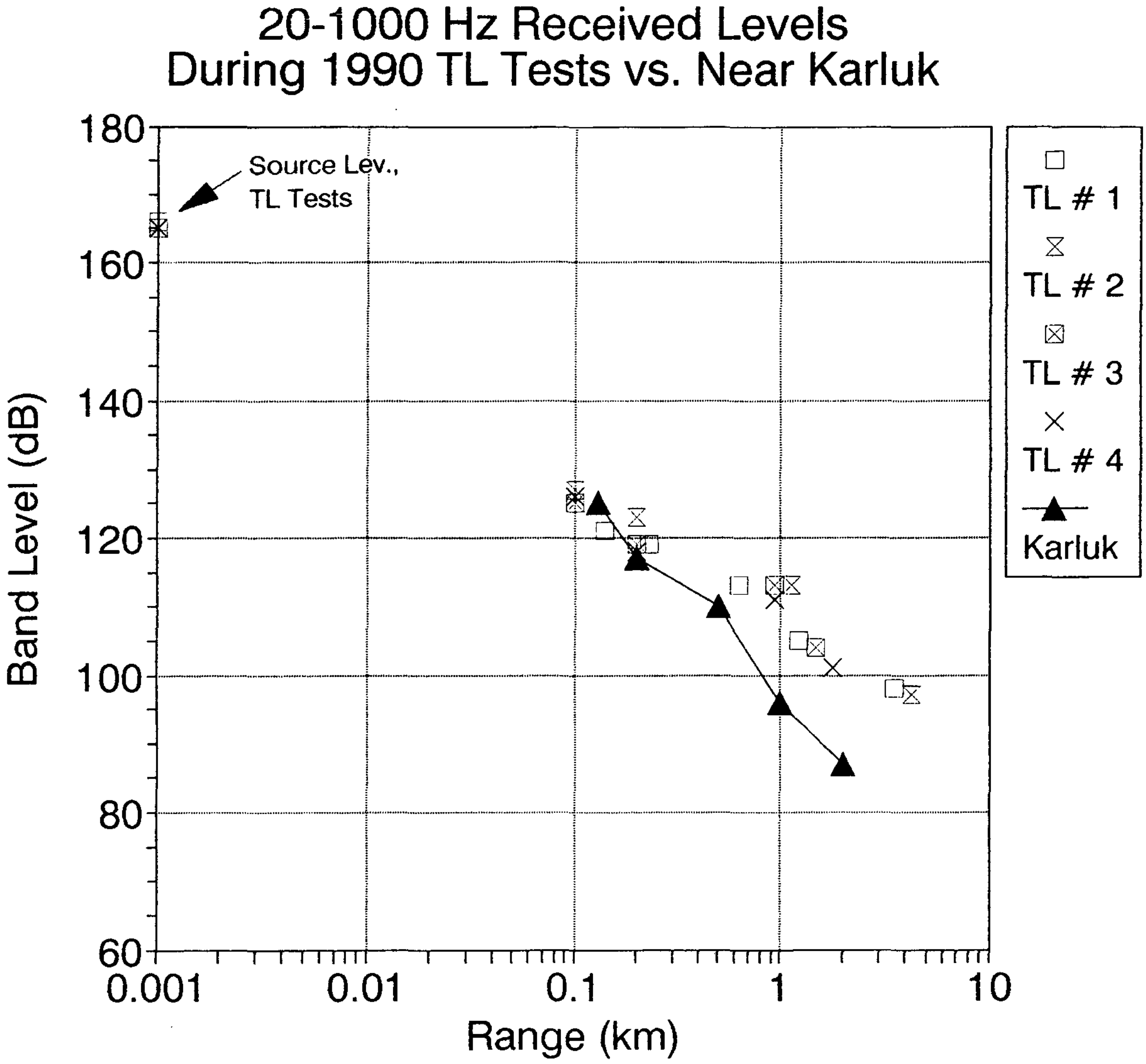


FIGURE 30. Received levels of *Karluk* drilling sound, 20-1000 Hz band, as a function of distance from the actual drillsite in March 1989 (black triangles) and from the sound projector during four transmission loss tests in May 1990 (open symbols). See Figure 99 (p. 274) for corresponding 1989 data.

projected sounds perfectly reproduced those from *Karluk* itself, levels 100 m from the projector would be expected to be 1-2 dB above those 130 m from *Karluk* itself. Between 80 and 1000 Hz, the actual differences were from -1.3 dB to +2.7 dB. However, the output of the J-11 deteriorated rapidly below 80 Hz. At 20 Hz, the difference had increased to 30.5 dB.

Figure 31C,D shows that the J-11 projector reproduced the *Karluk* sounds reliably over a high proportion of the frequency scale. However, the J-11 underrepresented sounds below 80 Hz, and especially those below 63 Hz, and it provided no effective playback of infrasounds--those components at <20 Hz.

Do Bowhead Calls Contain Infrasonic Components?

The absence of any direct information about bowhead hearing abilities as a function of frequency is an important limitation in evaluating the reactions of bowheads to actual or simulated industrial sounds. It is not known whether bowheads can hear sounds below the lower limit of human hearing, which is ~20 Hz. This is an important question in this project, given the limitations of the J-11 projector at low frequencies. If bowhead calls contain infrasonic components, then bowheads likely can hear sounds at those frequencies. It is known that many calls by blue and fin whales contain components at or below 20 Hz (see citations on p. 62). However, it is not known whether bowheads call at these infrasonic frequencies.

Forty-five bowhead calls of the usual types audible to humans were analyzed in waterfall format spanning frequencies from 5 to 250 Hz (e.g. Fig. 32, 33). Thirty-four of these calls were recorded on 4 May 1990; the remainder were recorded on 1 May (3), 24 May (6) and 25 May (2). Many other bowhead calls were recorded. However, this sample seemed sufficient to determine whether many bowhead calls contain energy at frequencies below 20 Hz. All of the calls analyzed were recorded via the ice-based 6050C hydrophone and the TEAC RD-101T DAT recorder. This system assured adequate frequency response down to 5 Hz or below. The usual type of waterfall display, as in Figure 32, provides only a qualitative look at the sound distribution.[6] However, the waterfalls in Figure 33 have been specially processed to show calibrated spectra, corrected for the frequency response curve of the hydrophone.

Few calls had any energy at frequencies as low as 50 Hz, and very few--if any--had energy below 30 Hz. In the case shown in Figures 33A, 34A and 35A, the lowest frequency component that appeared to be associated with the call was at 32 Hz. A component at 5-7 Hz came and went throughout the data from this date. It was not associated with any particular bowhead call. The source of this background noise component is uncertain.

The most interesting of the 45 calls analyzed is shown in Figures 33B, 34B and 35B. This call was accompanied by lower-frequency components than any of the others. Weak sound components at 15-32 Hz began to appear at time 1.03 s (Fig. 34B), a small fraction of a second before the much stronger call components at higher frequencies. The infrasonic components

---

[6] Our standard waterfall displays are not corrected for the declining response of the 6050C hydrophone at low frequencies. Hence, the lowest frequency components, those below 20 Hz, appear weaker in these waterfalls than they actually are. Also, waterfall amplitudes are the *magnitudes* of the Fourier transforms; they are not scaled in dB or any logarithmic form.

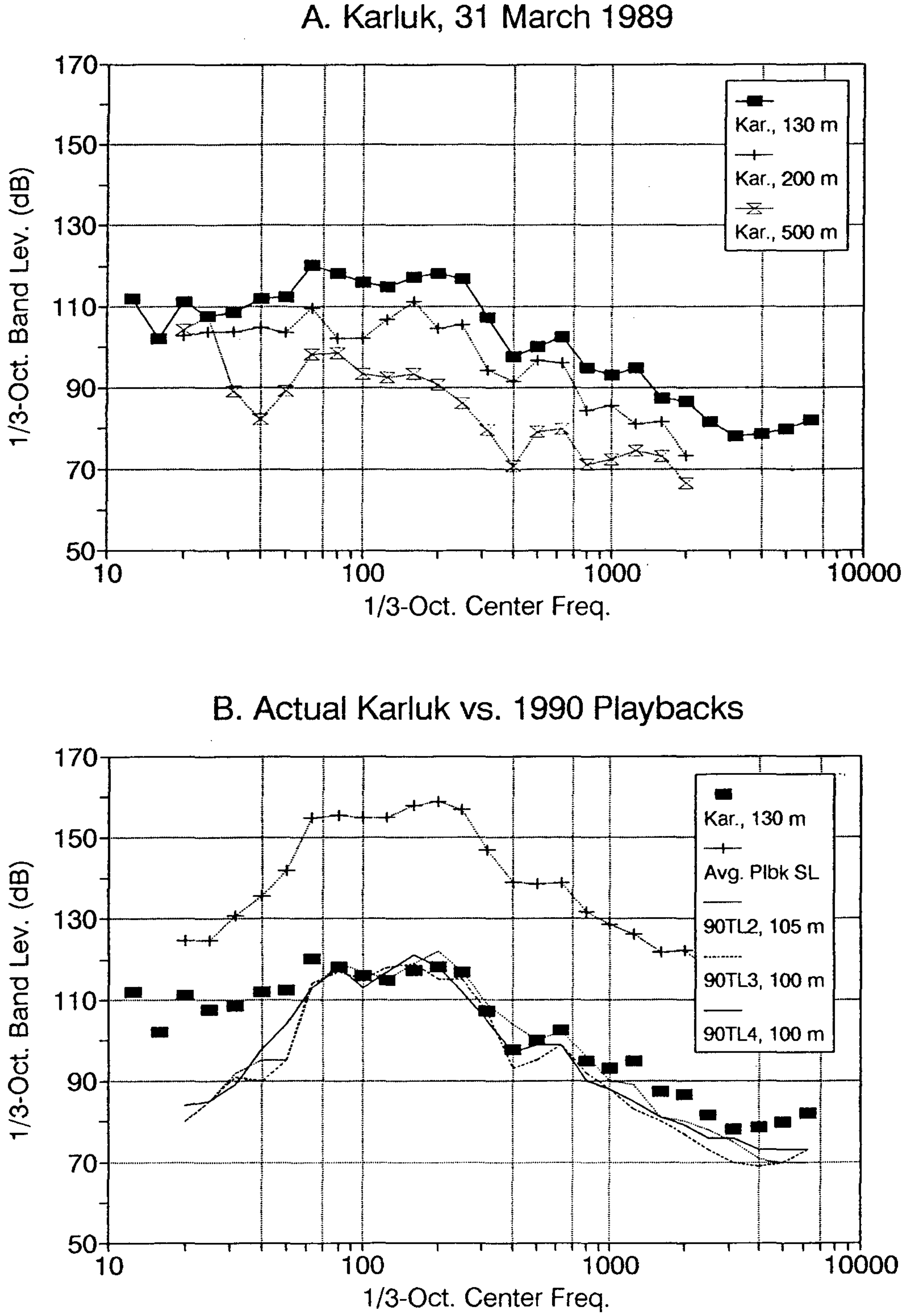
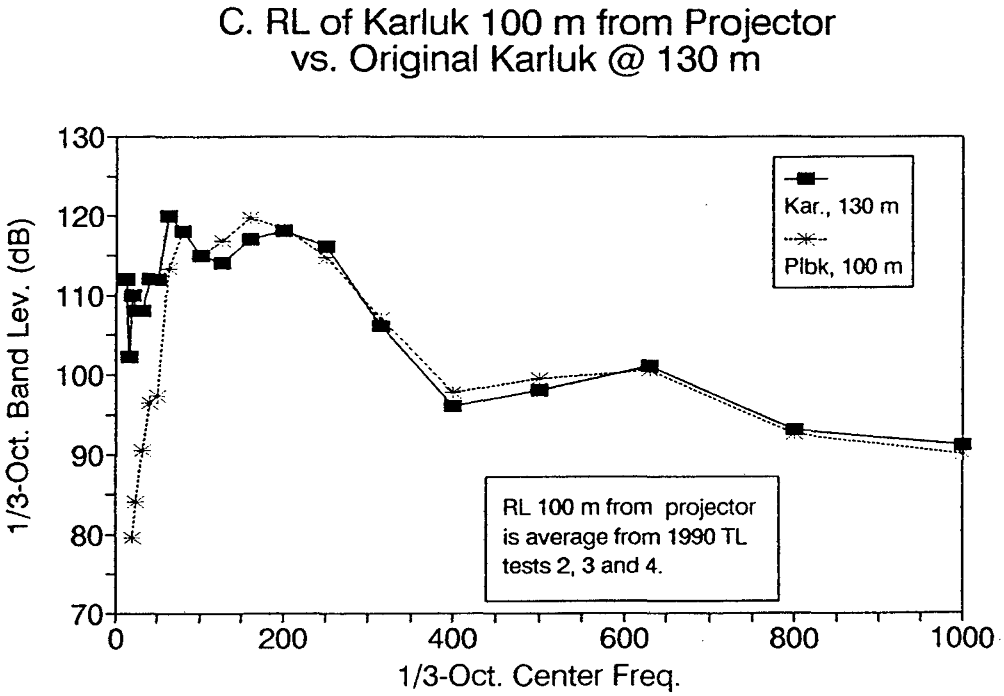


FIGURE 31A,B. Comparison of the *Karluk* drilling noise spectrum as originally recorded 130 m from the actual drillsite in March 1989 and as projected and received during transmission loss tests in May 1990. (A) One-third octave band levels of *Karluk* drilling sound as received at three distances from the actual *Karluk* drillsite in March 1989. (B) One-third octave band levels during *Karluk* playbacks via the J-11 projector in May 1990, including average source spectrum at 1 m and three examples of received spectra 100 m from the projector; the black squares [repeated from (A)] show the data 130 m from Karluk itself.



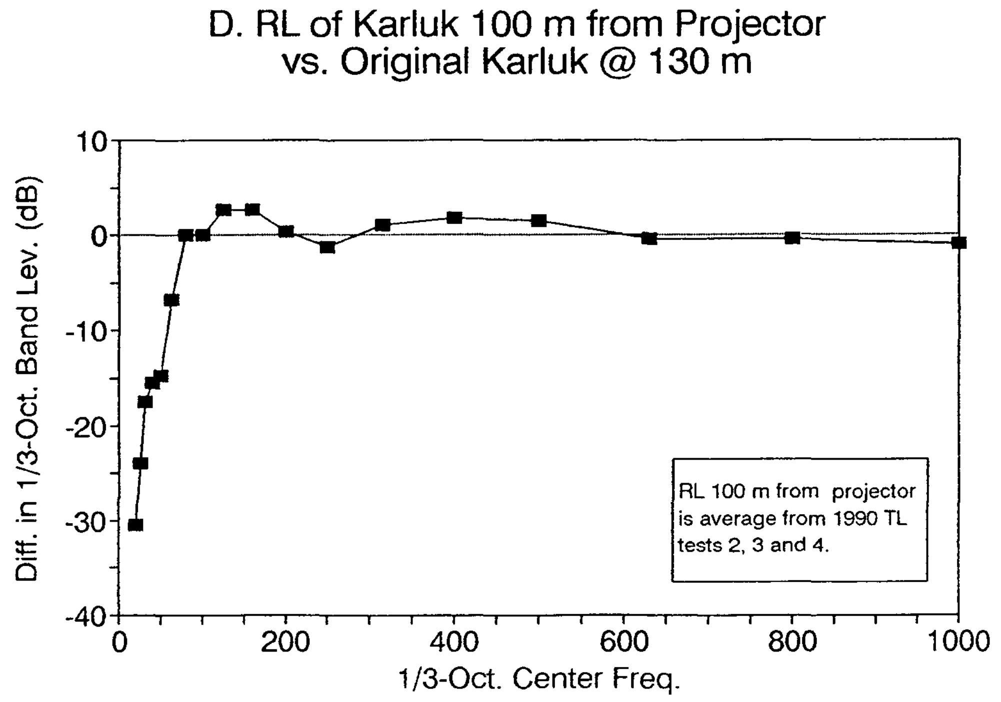


FIGURE 31C,D. Further comparison of the *Karluk* drilling noise spectrum as originally recorded 130 m from the actual drillsite in March 1989 and as received at range 100 m during transmission loss tests in May 1990. (C) Average received levels 100 m from the projector during three 1990 TL tests (shown individually in Fig. 31B) and received levels 130 m from *Karluk* itself. (D) Differences between these two sets of received levels.

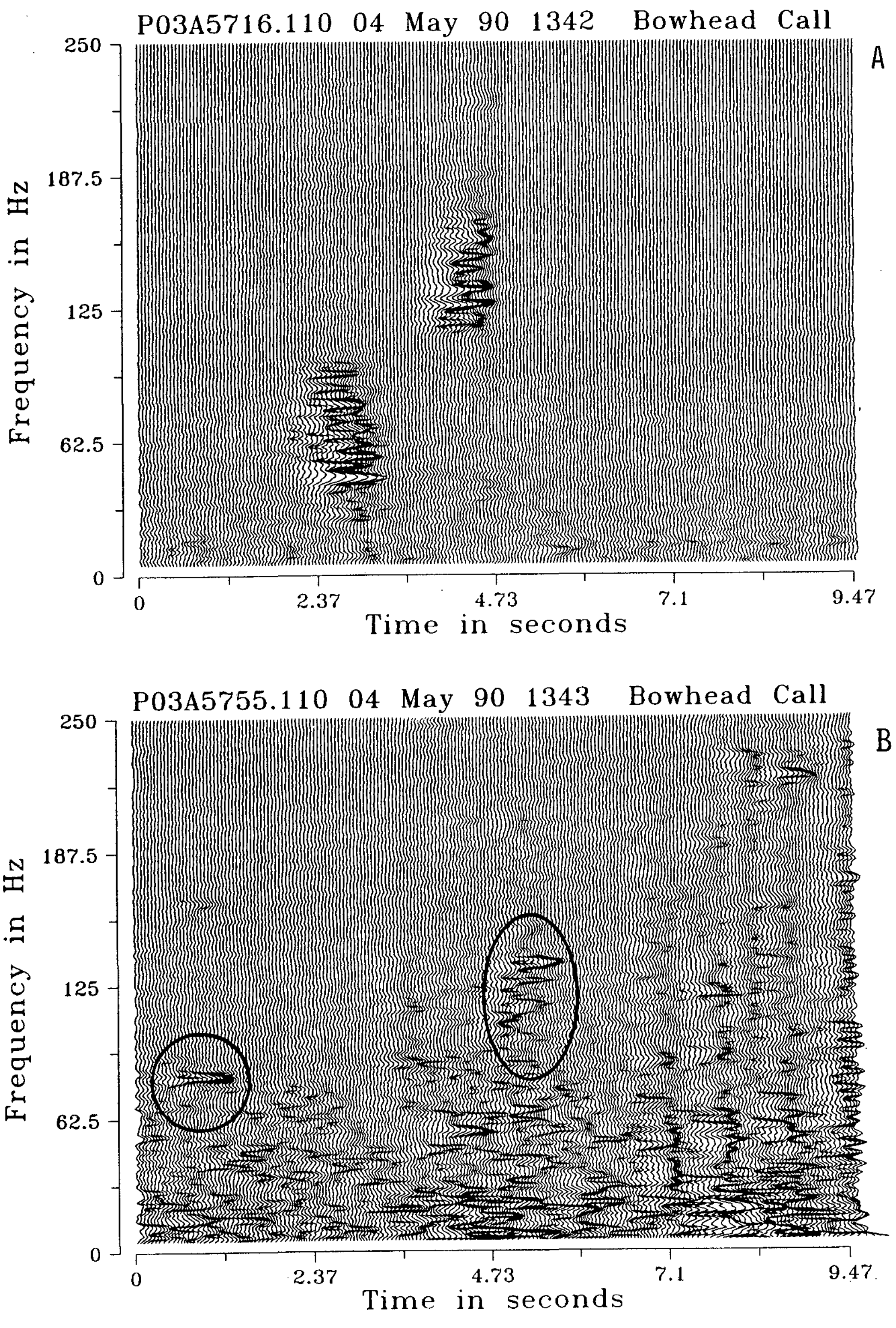
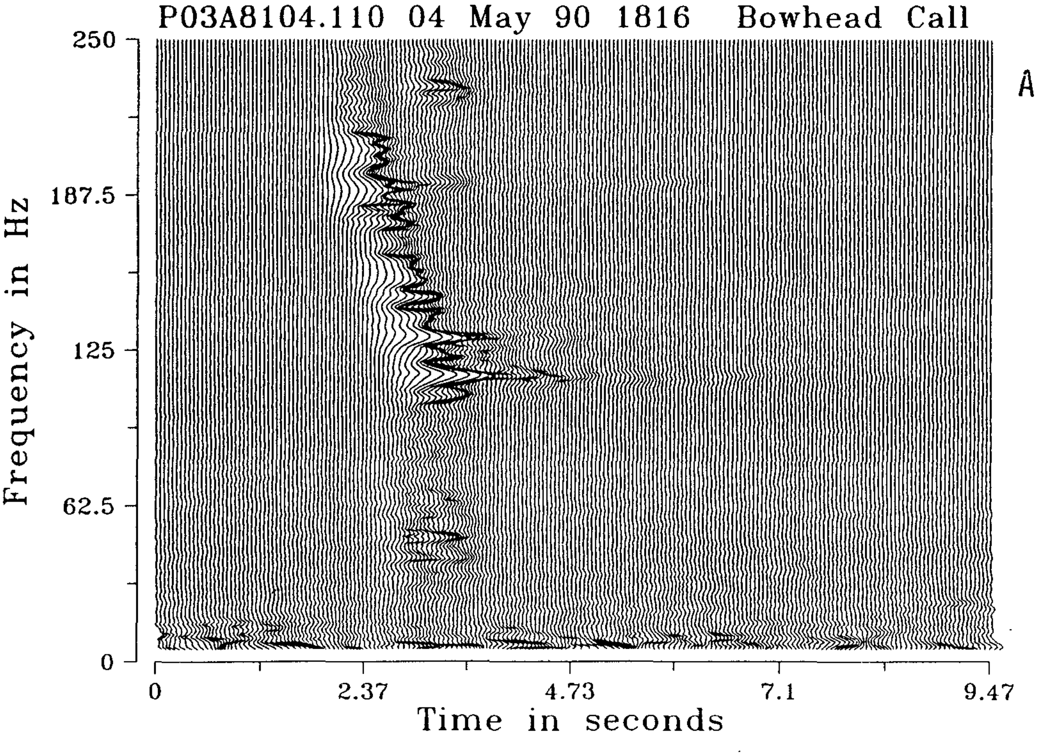


FIGURE 32. Two examples of waterfall spectra for bowhead calls showing components in the frequency range 5-250 Hz: (**A**) a strong call in relation to the ambient noise; (**B**) weak calls (circled).



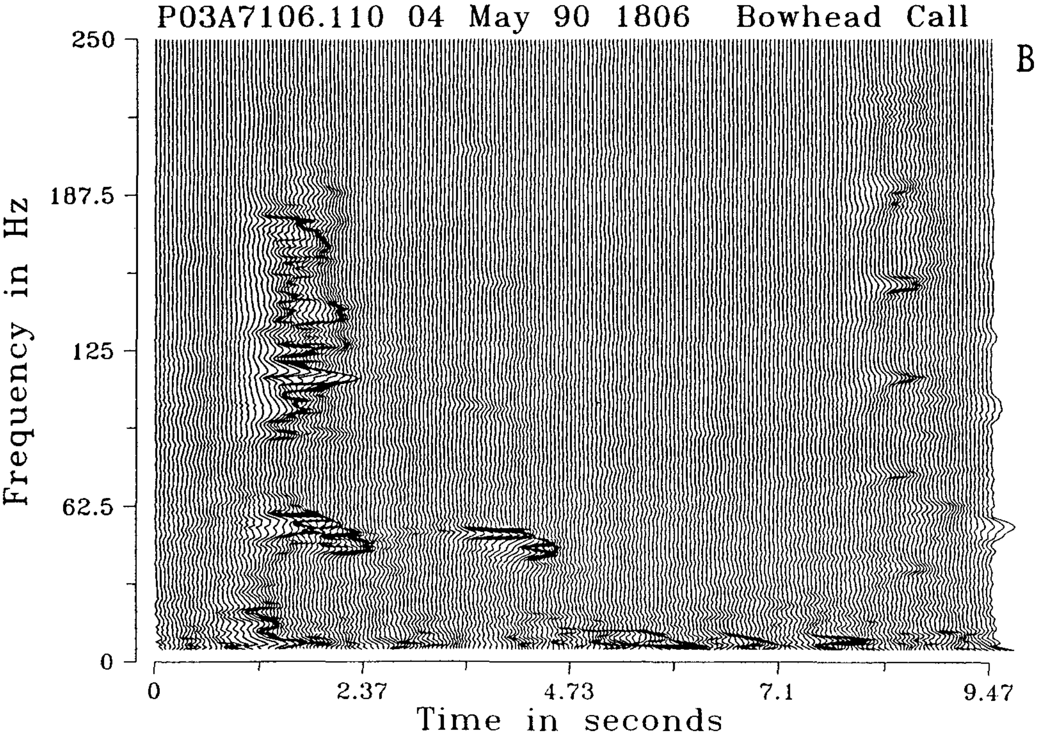


FIGURE 33. Two additional examples of waterfall spectra for bowhead calls showing components in the frequency range 5-250 Hz. (**A**) shows components as low as 32 Hz. (**B**) shows components as low as 15 Hz beginning about 1.03 s into the waterfall.

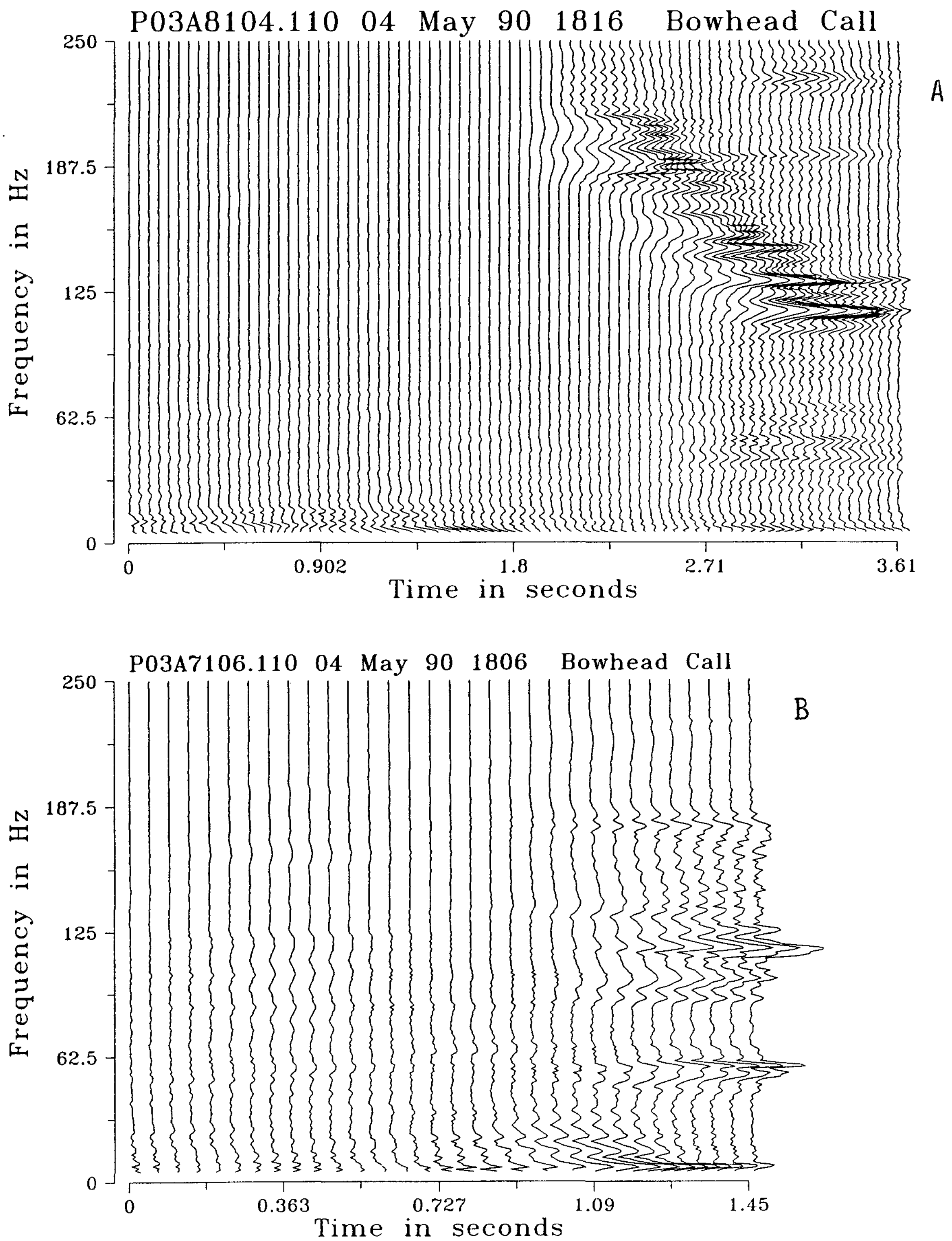
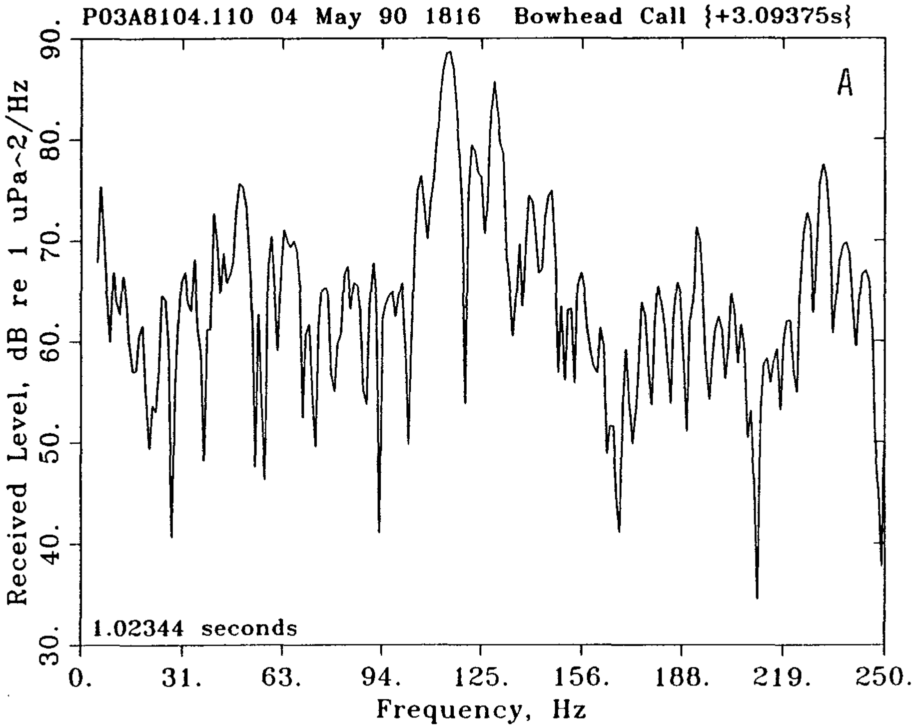


FIGURE 34. Expanded, calibrated waterfall spectrograms for the same bowhead calls shown in Figure 33. (**A**) shows the 3.6-s period that includes the lowest frequency components of the call in Figure 33A. (**B**) shows the 1.45-s period that includes the lowest frequency components of the call in Figure 33B. Both (**A**) and (**B**) start at the same point in time at which the corresponding waterfalls in Figure 33 start.



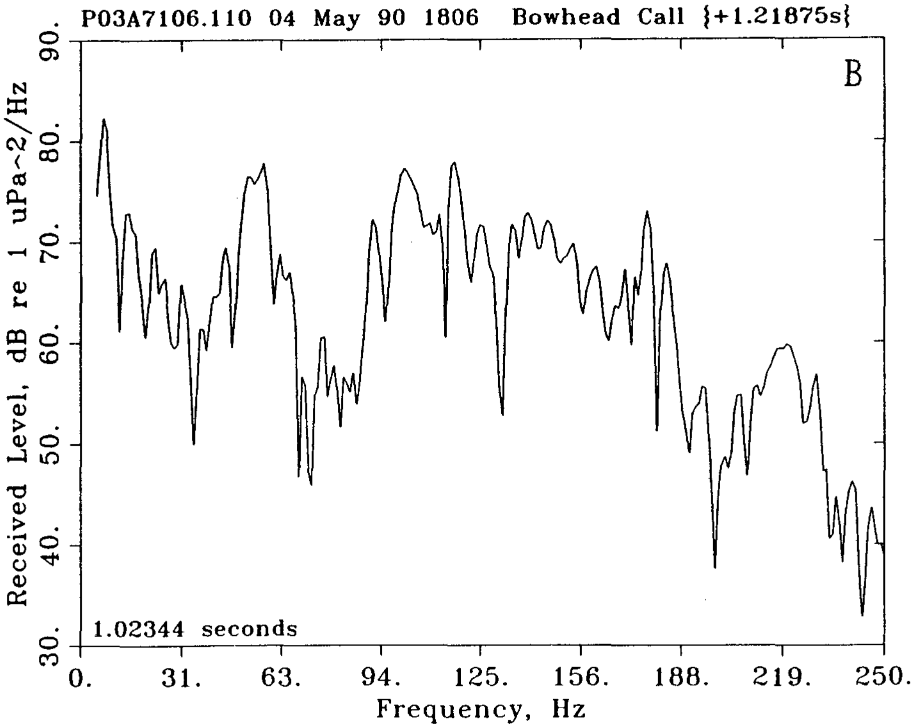


FIGURE 35. Calibrated received spectral densities for short segments of the bowhead calls shown in Figures 33 and 34. (A) corresponds to the call in Figures 33A and 34A at time 3.09 s. (B) corresponds to the call in Figures 33B and 34B at time 1.22 s. The peak at the extreme left of each spectrum (7 Hz) is thought to be ambient noise and not part of the calls.

faded away by time 1.36 s, when levels at frequencies above 50 Hz had increased sharply. We cannot determine with certainty whether the components at 15-32 Hz were emitted by the bowhead or were non-biological sounds. A strong component at 7 Hz persisted, but it was at the frequency where sound energy came and went seemingly independently of the bowhead vocalizations, as described above for a call recorded 10 min later (*cf.* Fig. 33A, 34A, 35A).

These results suggest that bowhead calls of the types usually heard by humans rarely if ever contain significant energy below 30-40 Hz. However, Figure 34B indicates that a small minority of the calls at frequencies audible to man may be accompanied by previously-unrecognized infrasonic components. Many more calls, recorded over a wide range of times and places, should be analyzed. It is premature to evaluate whether the previously-known types of bowhead calls ever contain infrasonic components. Also, we need to develop and apply techniques for evaluating the origin of low-frequency sounds that arrive simultaneously with bowhead calls. Directional processing over both infrasonic and sonic frequencies is an obvious possibility.

Our preliminary analysis does not address the possibility that bowheads might sometimes emit calls that are confined to frequencies below 20 Hz. An analysis of the low frequency sounds accompanying "normal" calls might not detect any purely infrasonic calls even if they occurred.

Generator Noise

During ice camp operations in 1990, a 2.2-kw portable electric generator operated on the ice surface. Usually there was snow on the surface. Heat from the generator melted the snow until the generator was in contact with the ice. Although the generator "feet" included rubber shockmounts, there was considerable vibration on the ice.

The generator was operated during most control periods (no playback) as well as during playbacks. This was done to ensure that the only difference between playback and control periods was the presence of the projected underwater sound. During playbacks, underwater sounds from the generator were completely masked at all distances and frequencies by the much stronger sounds from the projector (Richardson et al. 1990a:97). However, during control periods bowheads approaching the ice camp may have detected sounds from the generator. In order to interpret the data from control periods (p. 232, 244*ff*), we need know how far away from the ice camp these sounds might have been detectable.

In underwater sound spectra from periods without playbacks, the generator sound appeared as a harmonic family of tones at nominal frequencies of 62, 126 and 188 Hz (Fig. 36). The spectrum analysis cell-spacing was 2 Hz, so the tones were represented in the nearest even-frequency cell. The nominal fundamental frequency was probably just under 63 Hz. The generator speed, and thus the frequencies of the harmonic family of tones, varied slightly.

Transmission loss tests in 1990 provided opportunities to measure the background noise with the generator on and off at measured distances from the projector. (The generator was at about the same distances as the projector.) Generator tones were detected as much as 1130 m away on one occasion, but not even at the minimum measurement range of 100 m on one other occasion. These extreme results demonstrate the influence of variations in ambient noise level

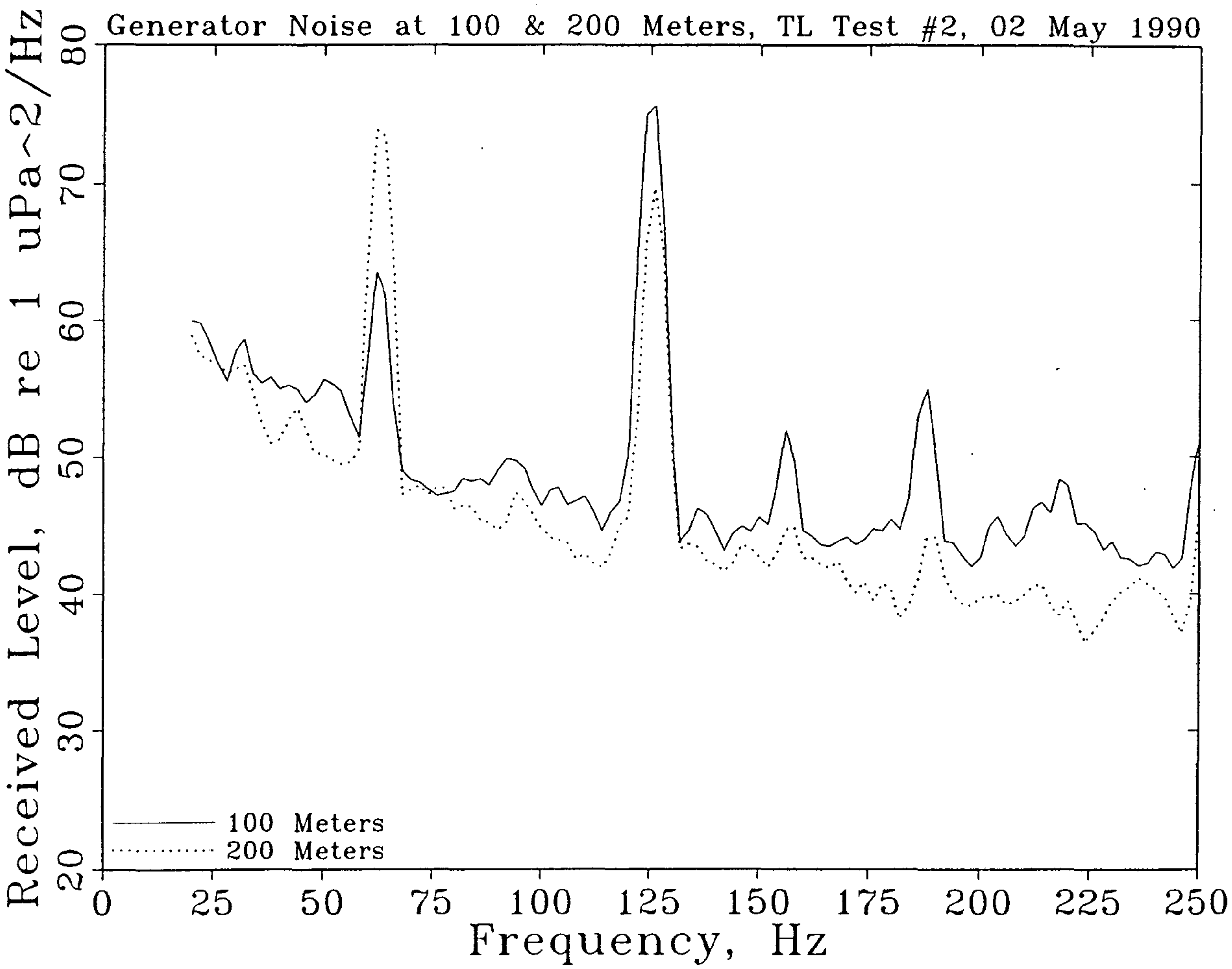


FIGURE 36. Generator tones as received at ranges 100 and 200 m from the ice camp during a day with low ambient noise (2 May 1990; projector off). Note that the plotted levels are spectral densities, in dB re 1 μPa²/Hz, in contrast to the tonal levels listed in the accompanying table.

on the detectability of sounds. The following table shows the received levels of the tones, in dB re 1 μPa[7], during transmission loss tests in 1990:

Freq. (Hz)	Tonal Level, dB re 1 μPa, at range				Ambient, 1/3-Oct. at 63 Hz
	100 m	200 m	930 m	1130 m	
TL Test #1	------No tones detected------				92 - 94
TL Test #2					61 - 71
63	69	79		68	
126	81	75		-	
156	56	-		-	
188	60	48		-	
250	57	54		-	
314	52	-		-	
TL Test #3					70 - 91
62	-	76	71		
126	72	-	66		
TL Test #4					77 - 81
62	78	-	-		
126	73	-	-		

TL test #2 on 2 May 1990 occurred under very low noise conditions (Fig. 6). For the third octave centered at 63 Hz, the ambient noise level was only 61-71 dB. Figure 36 shows results from ranges 100 and 200 m. Smaller peaks corresponding to subharmonics are manifest. The behavior of the 62 Hz tone was inconsistent; the level was higher at range 200 m than at 100 m (79 vs. 69 dB). This is probably explained by multipath interference effects. At range 1130 m only the 62 Hz tone was detectable; its level there was 68 dB re 1 μPa, only 1 dB less than at range 100 m. No tones were detectable at the next range studied, 4300 m.

In summary, during relatively quiet periods in 1990 we detected the generator tones at ranges out to 900-1100 m, although levels at such long distances were low. In contrast, during relatively noisy ambient noise conditions (and during playbacks) the generator tones were not detectable even at 100 m. Considering the short-term variability of the background noise (see p. 55*ff*), bowheads often might have detected faint generator sounds at ranges up to 500-1500 m during periods with no playbacks. During playbacks, underwater sounds from the generator were not detectable more than a few meters away; they were masked by the much stronger sounds from the projector (Richardson et al. 1990a:97).

In 1991 the generator was suspended off the ice on bungie cords. Preliminary analyses reveal no detectable tones even at range 100 m in 1991.

---

[7] These units are not the same as the spectral densities (dB re 1 $\mu Pa^2/Hz$) shown in Figure 36. The effective analysis bandwidth for Figure 36 was 3.4 Hz, and the spectral densities must be adjusted by 5 dB [10 log(3.4)] to obtain the power levels shown in the table.

BOWHEAD WHALE RESULTS

This section begins with a general description of the spring bowhead migration east of Pt. Barrow as observed in this study. Thereafter there is a section on bowhead behavior in the absence of human disturbance ("control" data). These data address part of specific objective 6, "To document ... the movements, behavior, basic biology ... of bowheads ...". These "normal behavior" data are also needed as background information for the analysis of reactions to disturbance (specific objectives 3 and 5), covered in later subsections within this section.

This report deals primarily with results from the 1990 fieldwork. However, to maximize sample size, the sections on responses to noise playbacks take account of the limited 1989 data as well as the 1990 data. Hence, it is useful to include a general description of the 1989 as well as the 1990 spring migration, and to include relevant 1989 as well as 1990 "control" data on undisturbed bowheads. Additional information about the 1989 results, beyond that summarized here, can be found in Richardson et al. (1990a).

Distribution and Movements of Bowheads

Bowheads in General

Spring 1990.--Bowhead whales were seen from our first day of aerial surveys (29 April) until the last day (26 May). Bowheads were found on most days with surveys during this period, with the notable exception of the 30 April - 6 May period. Numerous bowheads were present on 29 April and from about 8 May to 21 May. After 21 May, numbers declined, and mother-calf pairs predominated. In general, the main migration corridor through our study area tended to be farther south in 1990 than in 1989. East of 156°W longitude, most of the 1990 sightings were concentrated in an west-to-east band near 71°30'N latitude (Fig. 37). In contrast, most 1989 sightings east of 156°W were in a WSW to ENE band north of that latitude (Fig. 38).

We did not conduct surveys prior to 29 April in 1990, but the National Marine Mammal Lab (NMML) crew conducting aerial photogrammetry flights in the same study area saw only a few bowheads on 26, 27 and 28 April (D. Rugh, pers. comm.). On 29 April, we saw about 16 bowheads traveling eastward through the pack ice, with some socializing. They were in an area of loose-moderate pack ice within a few kilometers north of the main nearshore lead.

Bowhead sightings were very scarce during the following six days; we saw only one bowhead during over 16 hours of aerial surveys on 30 April-6 May. That whale was also migrating east through the pack ice. Likewise, the NMML crew saw few bowheads in our study area during that period. However, on 5 and 7 May there were reports of large numbers of bowheads moving northeast through the Chukchi Sea near Icy Cape and Point Lay. Two bowheads were taken at Wainwright on 6 and 7 May.

Many bowheads traveled through the study area from 8 May (NMML sightings) through 21 May. Bowheads were struck by Barrow hunters on 9, 10, 13 (n=2), 14, 17 and 19 May; four of these whales were landed. Throughout this period, there was a major nearshore lead extending about 50 km northeast and east of Barrow. West of 155°W longitude, most of the

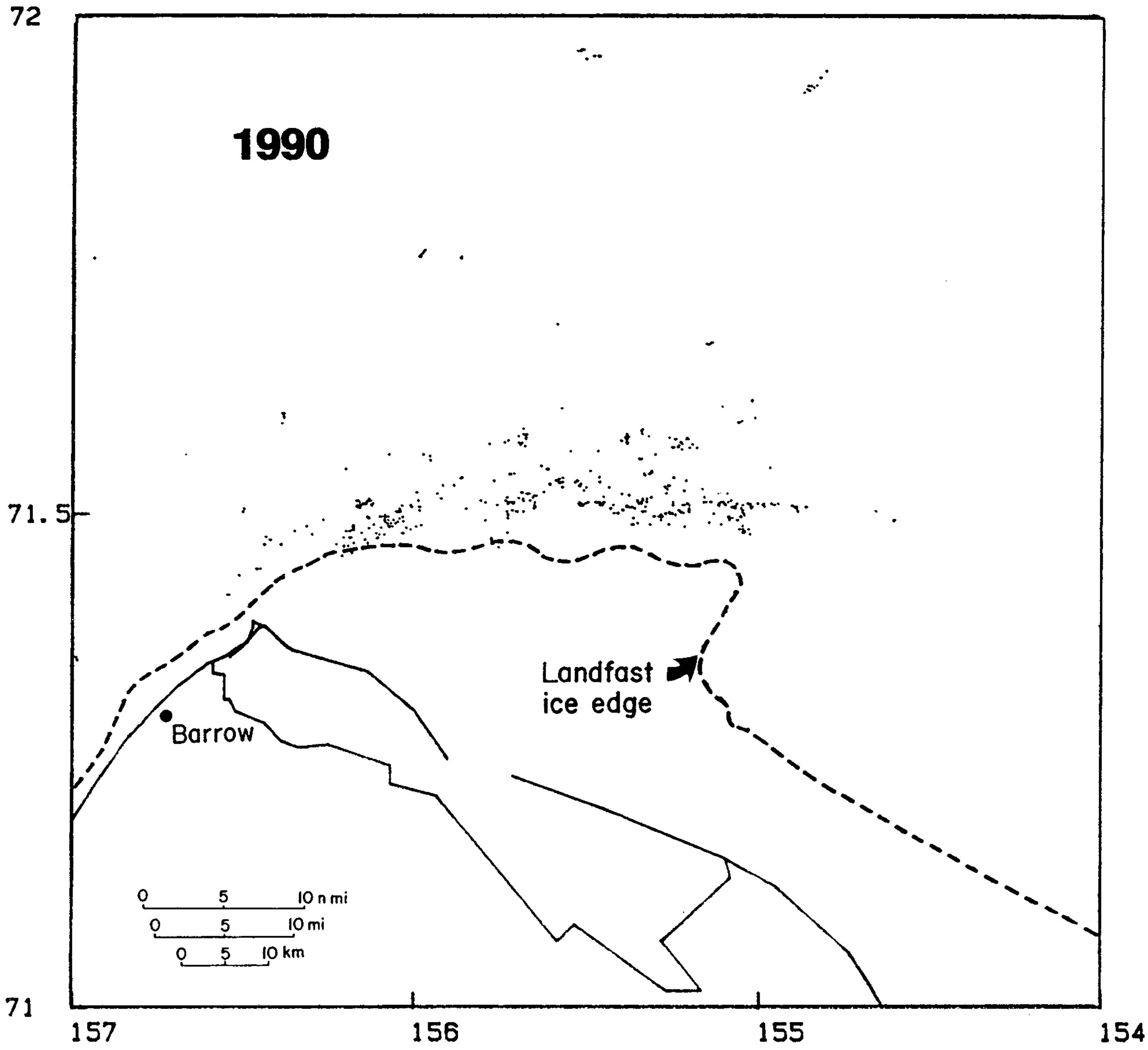


FIGURE 37. Locations where bowheads were photographed during spring photogrammetric surveys conducted by the U.S. National Marine Mammal Laboratory in 1990 (NMML unpubl. data, courtesy D. Withrow, NMML).

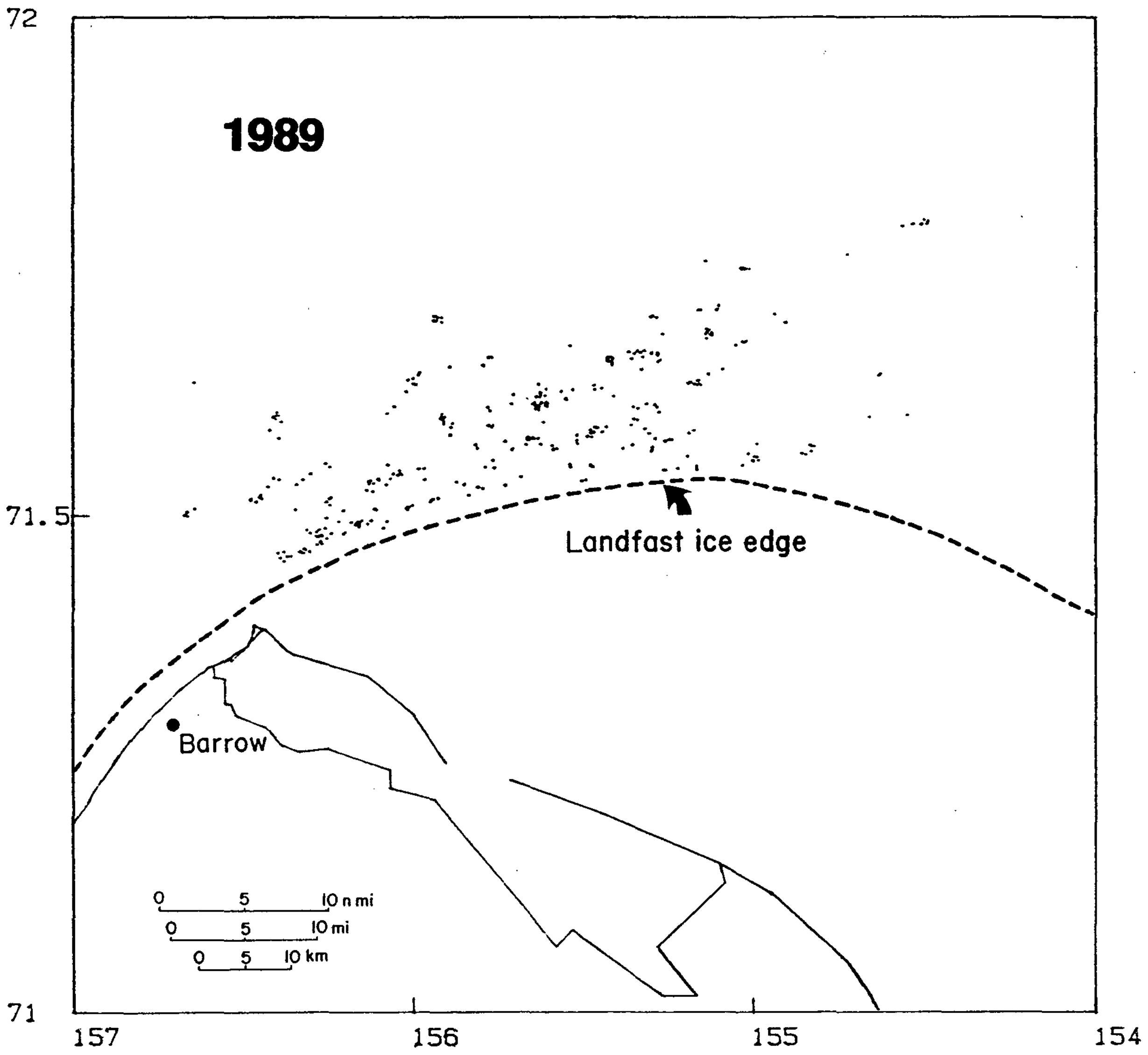


FIGURE 38. Locations where bowheads were photographed during spring photogrammetric surveys conducted by the U.S. National Marine Mammal Laboratory in 1989 (NMML unpubl. data, courtesy D. Withrow, NMML).

bowheads seen by us were moving east along the middle or northern side of this lead, or through pack ice within a few kilometers north of the north side of the lead. The lead became narrower as it progressed eastward. Its orientation (as seen by an eastbound whale) turned gradually to the right, following the landfast ice edge. The whales tended to continue eastward out into the pack ice as the lead veered to the right. East of about 155°W, most if not all bowheads were north of the nearshore lead, which in that area was oriented to the southeast and was south of the whale migration corridor. Most whales traveled consistently east or northeast; there was little socializing and very little resting or apparent feeding.

During the 9-21 May period, the best opportunities for noise playback experiments were along the north side of the nearshore lead or on the rather loose pack ice just north of the lead. Hence, we did relatively little reconnaissance for whales farther north. One cannot determine, from our mid-May data, whether some bowheads also traveled northeast farther offshore, as had occurred at this time in 1989. However, it was clear that a dominant migration corridor in mid-May of 1990 was eastward near 71°30'N. In contrast, during mid-May of 1989 there was much heavier ice along that corridor, and most bowheads traveled northeastward along a more offshore corridor (*cf.* Richardson et al. 1990a:151).

After 21 May, the number of bowheads present in the study area was greatly reduced. We saw only about 18 bowheads during 24 hours of flying on 22-26 May. Most of these bowheads were mother-calf pairs, and most of them were in pack ice farther north in the study area (see "Mothers and Calves", below). The NMML crew obtained similar results during the 22-26 May period (D. Withrow, pers. comm.).

Spring 1989.--In 1989, the effective field season was from 29 April to 30 May. Six bowhead whales were seen on 29-30 April and 39 during the first 10 days of May (see Richardson et al. 1990a:52 for map). Ice cover was extensive during this period, and the visible whales tended to be concentrated in the few open-water areas amidst the pack ice. Directions of movement of the visible whales were influenced by the orientation of open areas. The predominant orientation of whales was northeast, but a few bowheads were moving NNW along leads oriented NNW-SSE. The bowheads observed were primarily migrating or socializing; a few whales were resting.

More bowheads (70) were sighted during the 11-20 May 1989 period than during the previous and following periods. The main E-W lead along the fast ice edge within our study area did not start to form until the end of the period (20 May). Narrow leads oriented NE-SW developed amidst the pack ice at the start of this period and whale sightings were scattered throughout these leads. Sightings were more dispersed and farther offshore during mid-May than during early or late May. Almost all bowheads that were moving were oriented in a northeast direction along a corridor oriented to the NE, and the sighting locations tended to become farther and farther north as one moved eastward. This was not the case in 1990; the migration corridor in mid-May 1990 was oriented east through shallower waters. Most whales observed during mid-May of 1989 were migrating and few were socializing or resting.

A well-defined E-W "nearshore" lead was present along the landfast ice edge during the 21-30 May 1989 period. Most of our bowhead sightings in late May 1989 were along the north side of this lead or amidst the pack ice just north of the lead. Only 54 bowheads were recorded, although survey effort by the Twin Otter crew increased to 23.7 h during this period from 15.5 h during the previous period. Most of the survey effort and sightings were on 26-29 May. A high proportion of the bowheads passing on those dates were cows with calves. Whales sighted during this period were migrating, engaged in local movements, or resting. Most of those that were migrating were traveling generally eastward along the northern (offshore) side of the nearshore lead or through the pack ice north of that lead. However, many of the cow/calf pairs that were sighted were oriented in other or random directions.

The NMML photogrammetry crew photographed bowheads in the same area from mid April to early June 1989. They also found that bowheads were widely scattered in 1989. Their sightings were less concentrated along the southern edge of the migration corridor in 1989 (Fig. 38) than in 1990 (Fig. 37) or 1985-87 (NMML maps *in* Richardson et al. 1990a:8-10).

Prior to 20 May in 1989, there was no well-defined lead along the fast ice or in the offshore shear zone within our study area. As a result, the bowhead migration corridor was apparently wider in 1989 than in 1990 or in most other years. Hence, numbers of bowheads passing any one location within our study area were smaller in 1989 than in 1990. The heavy ice conditions and frequent low cloud in 1989 also made it more difficult to locate, observe and follow bowheads then than in 1990.

The more northerly and more dispersed migration corridor in 1989 than in 1990 was reflected in the headings of the bowheads observed during behavioral observation sessions (Fig. 39). In 1989, bowheads seen during undisturbed periods were commonly headed NW-NNE as well in the expected NE-ESE directions. In 1990, the great majority of the headings were in the sector from NE to ESE (Fig. 39). Headings of mothers and calves, which were especially variable in both years, are not considered here.

Mothers and Calves

Spring 1990.--The 1990 results were consistent with earlier evidence in showing that mother-calf pairs tend to pass the Pt. Barrow area near the end of the spring migration period. A few mother-calf pairs were migrating past by mid-May of 1990, but the peak of the 1990 mother-calf migration near Barrow was from 19 May onward.

Observers at the ice camp may have seen a calf pass the ice camp on 9 May 1990, and did see a mother-calf pair on 13 May. The first mother-calf pair seen from our aircraft was seen on 19 May. Mother-calf pairs were seen on all subsequent days with aerial surveys--21, 23, 24, 25, 26 May (Fig. 40). On ***19-21 May***, there were still many other whales aside from the vanguard of mother-calf pairs; on those two days our aerial observers saw three mother-calf pairs plus ~25 other bowheads. Two of the others seen on 19 May were a probable mother-yearling pair. On ***23-26 May***--the last four days of our 1990 field season--numbers of bowheads present in the study area were low as compared with earlier in May. Almost all bowheads seen on 23-26 May 1990 were mother-calf pairs (~10 adults, 8 calves).

Similarly, the National Marine Mammal Lab crew, who were conducting aerial photogrammetry work in the same area, saw their first mother-calf pair for 1990 on 12 May. They also saw numerous mother-calf pairs from 19 May onward, mostly far offshore (D. Withrow, pers. comm.).

Some of the adults seen in mid- and late May without calves may have been pregnant females with near-term fetuses. A female with a 3.9-m fetus was harvested at Barrow on 19 May 1990 (George et al. 1991). Likewise, a female with a 4.0-m fetus was taken there on 15 May 1989 (George et al. 1991).

The 11 mother-calf pairs observed from our aircraft in 1990 were seen in two parts of the study area (Fig. 40). *(1)* The four pairs seen on 19-23 May were near or just north of the north edge of the main nearshore lead crossing the study area. One of these pairs was traveling east along the north side of the main lead, paralleling the pack ice edge. Three pairs were in the relatively loose pack ice just north of the main lead; at least two of those pairs were traveling NE. *(2)* The seven pairs seen on 24-26 May were about 50 km farther north in areas that were

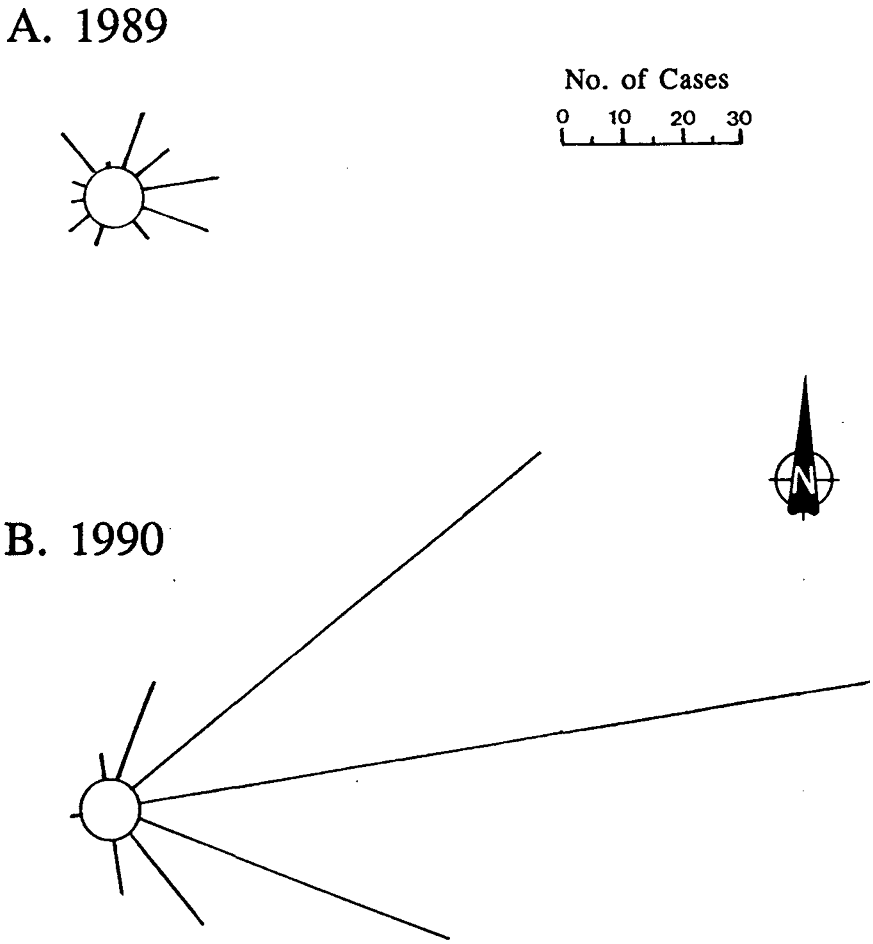


FIGURE 39. Headings (True) of undisturbed bowheads seen from the aircraft during behavioral observation sessions in (A) 1989 and (B) 1990. Each surfacing of a whale contributes one case to this figure. Mothers and calves are excluded.

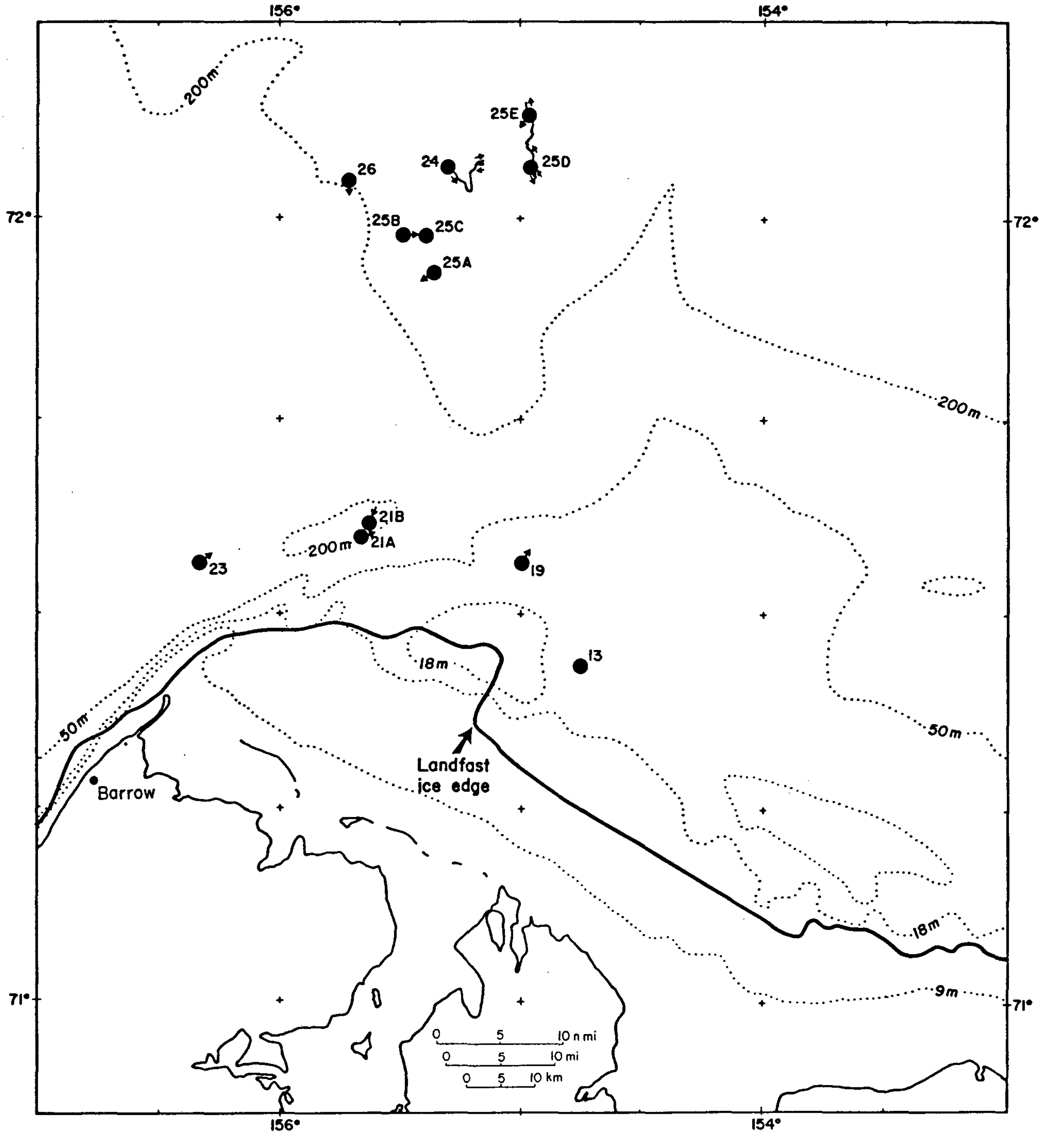


FIGURE 40. Locations where bowhead mothers and calves were seen by aerial and ice-based observers during this project, May 1990. Numbers are dates in May; A-E denote multiple mother/calf pairs seen on one date.

80% or more covered by pack ice. Of the five pairs whose activities were documented, three were actively traveling through the pack ice, but on widely different headings (N, E, S), and two were not traveling.

Spring 1989.--In 1989, as in 1990, mothers and calves moved through the study area later than most other bowheads. The first mother/calf pair sighted by us in 1989 was seen from the ice camp on 16 May. However, mothers and calves were not common until 23 May. During the period 23-29 May 1989, 67% (36 of 54) of the bowheads recorded were either mothers or calves (excluding a mother and yearling sighted on 24 May). In contrast, during the period 29 April-19 May 1989, only 3.5% (4 of 115) were mothers or calves.

Mothers and calves tended to be found along the north side of the lead that was present along the fast ice edge during the last third of May 1989 (Richardson et al. 1990a:152). Migrating mothers and calves tended to migrate along or just north of the pack ice edge. Mothers and calves engaged in other activities (resting or local travel) were found amidst pack ice north of the lead and in the open water of the lead.

Behavior of Undisturbed Bowheads

In ***1990***, we observed the behavior of bowheads during 29 behavioral observation sessions on 12 days from 29 April to 25 May (Table 3). Total aerial observation time was 46.8 hours--almost twice as much as in 1989. The estimated number of bowheads within the area being circled (typically about 2-3 km in diameter) ranged from 1 to 10 (median = 3 whales). On the occasion with 10 whales inside the observation circle (10 May), there were as many as 25 bowheads within 5 km of the center of the circle. Water depths at observation sites ranged from 18 to 475 m, based on the NOAA bathymetric chart for the area. Observations in shallow water (<50 m deep) were much more common in 1990 than in 1989. Almost all 1990 data from waters ≥100 m deep were obtained late in the field season (21-25 May), and many of those data pertained to mother-calf pairs. Ice cover within the observation circle ranged from 0 to 90%; observations with <80% ice were much more common in 1990 than in 1989. Sea states ranged from 0 to 3. Because of the greater amount of open water in 1990, sea states tended to be slightly higher in 1990.

In ***1989***, we observed the behavior of bowhead whales during 17 behavioral observation sessions on 10 days from 3 to 29 May (Richardson et al. 1990a:75). Total observation time was 25.6 h. The estimated number of whales within the area being circled was 1-5 (median = 2). On one day (3 May) there were as many as 15 whales within 5 km. Water depths at observation sites were 40-280 m. Ice cover within the observation circle ranged from 0 to 99%, but was usually 80-95%. Largely because of the dampening effect of ice on wave action, sea states were invariably low in 1989 (0-2).

In 1989, most behavioral observations were amidst pack ice well north of the landfast ice edge (Richardson et al. 1990a:73). The large amount of ice often made it very difficult or impossible to resight traveling bowheads when they surfaced after a long dive. Hence, we obtained few data on dive durations of traveling whales in 1989.

The present section is based on observations when bowheads were not exposed to any known source of human disturbance. Observation periods counted as presumably undisturbed were those when the observation aircraft was at an altitude of at least 460 m (≥1500 ft), no other aircraft were nearby, the underwater sound projector was not operating, and there had been no known potential disturbance within the preceding 30 min period.[8] In ***1990***, of the 46.8 h of behavioral observations, 31.6 h were under "presumably undisturbed" conditions. These 31.6 h of presumably undisturbed observations came from 25 observation sessions on 12 days. In ***1989***, of the 25.6 h of behavioral observations, 12.3 h were under "presumably undisturbed" conditions. These 12.3 h of presumably undisturbed observations came from 12 observation sessions on 8 days.

General activities of the bowheads varied. The majority were migrating actively toward the northeast or east. However, some were actively socializing or (in 1989) resting more or less motionless. There was rarely any evidence of feeding. Some of the mothers and calves seen during late May were migrating actively in the expected directions, but others were resting or traveling in other directions.

Surfacing, Respiration and Diving Behavior

Definitions and Criteria.--We determined the durations of surfacings and dives, the number of blows per surfacing, and the intervals between successive visible blows within a surfacing. Most definitions and criteria were the same as in our previous related studies (e.g. Dorsey et al. 1989). In particular, a surfacing is again defined as the interval from the first arrival of a whale at the surface after a long dive to the time when the whale descends below the surface for the next long dive. A surfacing usually includes several blows, and is equivalent to a "surfacing sequence" as defined by some other authors.

There were two changes in procedures relative to our earlier work:

- Occasions when the whales's blowholes rose above the surface in the pattern usually associated with a blow, but no blow was seen, were recorded as "presumed blows". Such cases seemed to be more common in 1990 than in 1989. These cases were treated as actual blows when determining blow intervals and number of blows per surfacing. Ice-based observers noted that these whales were in fact blowing; the invisible blows were audible.
- The primary measure of blow interval in this report is the "median blow interval for a surfacing". In other recent analyses we have used mean, not median, blow intervals. The median is less affected by occasional extreme values, or by missed blows.

Table 14 summarizes the surfacing, respiration and dive data for bowheads engaged in various activities--resting, traveling, socializing, and various combinations. This table excludes all potentially disturbed whales, and also excludes calves and their mothers. Previous analyses have shown that the surfacing, respiration and dive cycles of calves and mothers differ from those of "other bowheads" (e.g. Richardson et al. 1990a:161). Since none of the 1990 data on reactions of bowheads to drilling noise playbacks involved mothers or calves, the appropriate control data are those for "other bowheads".

---

[8] Whales near the ice camp were considered "presumably undisturbed" when the generator was operating, provided the projector had been silent for >30 min.

Table 14. Surfacing, respiration and dive behavior of undisturbed bowheads, excluding calves and mothers, observed from a Twin Otter aircraft in spring, 1989 and 1990.

		Individual Blow Interval (s)			Median Blow Interval (s)			# of Blows/ Surfacing			Duration of Surfacing (min)			Duration of Dive (min)		
Year	Group Activity	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n
1990	Resting	-	-	0	-	-	0	-	-	0	-	-	0	-	-	0
	Travel	**19.54**	**8.95**	**874**	**20.10**	**7.25**	**197**	**4.87**	**3.27**	**194**	**1.39**	**1.07**	**200**	**7.20**	**5.61**	**161**
	Social	13.50	3.21	8	13.67	2.31	3	4.00	-	1	0.83	0.27	2	-	-	0
	Tr & Social	16.31	7.31	103	16.53	8.11	36	3.68	3.11	19	0.85	0.90	20	3.92	2.24	17
	Tr & Feed	17.64	7.25	28	18.21	6.28	7	6.50	2.38	4	1.50	0.71	4	1.43	-	1
	All	19.19	8.75	1048	19.46	7.41	248	4.87	3.35	222	1.37	1.10	231	6.94	5.45	183
1989	Resting	95.64	141.34	85	53.45	62.70	10	7.60	3.65	5	4.64	2.79	5	13.70	13.19	6
	Travel	**16.71**	**8.39**	**115**	**17.53**	**6.96**	**29**	**5.50**	**3.56**	**6**	**1.81**	**1.07**	**9**	**-**	**-**	**0**
	Social	21.76	15.46	125	21.76	13.78	37	1.50	0.71	2	0.24	0.29	2	1.02	-	1
	Tr & Social	19.91	12.34	32	22.00	10.85	3	-	-	0	-	-	0	-	-	0
	Tr & Feed	-	-	0	-	-	0	-	-	0	-	-	0	-	-	0
	All	34.15	70.99	423	23.54	25.31	86	7.24	5.02	17	2.68	2.08	21	11.89	12.96	7
1989-90	Resting	95.64	141.34	85	53.45	62.7	10	7.60	3.65	5	4.64	2.79	5	13.7	13.19	6
	Travel	**19.21**	**8.93**	**989**	**19.77**	**7.25**	**226**	**4.89**	**3.27**	**200**	**1.40**	**1.07**	**209**	**7.20**	**5.61**	**161**
	Social	21.26	15.13	133	21.15	13.42	40	2.33	1.53	3	0.53	0.41	4	1.02	-	1
	Tr & Social	17.16	8.85	135	16.95	8.31	39	3.68	3.11	19	0.85	0.90	20	3.92	2.24	17
	Tr & Feed	17.64	7.25	28	18.21	6.28	7	6.50	2.38	4	1.50	0.71	4	1.43	-	1
	All	23.49	39.33	1471	20.51	14.40	334	5.04	3.53	239	1.48	1.26	252	7.12	5.90	190
1989-90	Rest vs. Tr.				t' = 1.70, df = 9 ns			t = 1.83, df = 203 (*)			t' = 2.59, df = 4 (*)			t' = 1.20, df = 5 ns		
	Tr. vs. Tr. + Soc.				t = 2.19, df = 263 *			t = 1.55, df = 217 ns			t = 2.22, df = 227 *			t' = 4.68, df = 45 ***		

Notes: t' = t-statistic not assuming equal population variances; ns → P>0.1; (*) → 0.1 ≥P>0.05; * → 0.05≥P>0.01; ** → 0.01≥P>0.001; *** → P≤0.001.

The blow interval data are presented in two ways: (1) considering each individual blow interval as a unit, and (2) considering the median of all blow intervals within a single surfacing as a unit. In method (1), the sample size is the total number of blow intervals recorded, whereas in method (2) it is the number of surfacings during which one or more blow intervals were recorded. The sample sizes are smaller for median blow intervals (method 2) than for individual blow intervals (method 1). Also, standard deviations often are smaller for method 2 than for method 1. Durations of successive individual blow intervals within a surfacing are presumably not independent. Hence, statistical comparisons of blow intervals are based on the median blow intervals.

Even when each surfacing or dive contributes only one observation to the analysis, there is still concern about possible lack of independence between successive surfacings or dives of a single whale (e.g. Machlis et al. 1985; Hoekstra and Jansen 1986). Because it is frequently impossible to determine whether a given whale has been observed previously, there is no way to obtain a single average value of each variable for each individual animal. Hence, in analyses in which each surfacing or dive contributes one observation, we place little emphasis on differences that, by standard statistical methods, are only marginally significant (e.g. $0.1 > P > 0.01$). Also, we refer to these P values as "nominal P" values (P_n).

Traveling.--Traveling whales (calves and mothers excluded) constituted the largest proportions of the bowheads observed during undisturbed periods and during drilling noise playbacks. Data on traveling whales seen during the undisturbed periods are important as control data for the playbacks, and are highlighted in Table 14. Most of the data used here came from 1990. Traveling whales were often observed in 1989, but most of those were mothers, calves, or whales seen during playbacks; those categories of whales are excluded from this analysis.

Considering the two spring seasons together, an average surfacing-dive cycle by an undisturbed traveling bowhead consisted of a 1.40 min surfacing and a 7.20 min dive (Table 14). There was an average of 4.9 blows per surfacing. Intervals between successive blows within a surfacing averaged 19.2 s.

The average dive duration reported here (7.20 min) may be realistic for bowheads traveling along open leads or through loose pack ice. However, it probably underestimates the overall average dive duration for traveling bowheads during spring migration. We were rarely able to resight identifiable bowheads when they resurfaced after long dives under areas of extensive ice, so these long dives are underrepresented in our sample. In this study, the longest documented dive by an undisturbed whale was a 31.5 min dive by a whale traveling along the nearshore lead on 12 May 1990. This dive was similar in duration to the longest dives reliably documented during several other studies: in the summer of 1980-84 in the Canadian Beaufort Sea (31.0 min, Dorsey et al. 1989), in the late summer/early autumn of 1985-86 near the Alaska/Yukon border (31.6 min, Richardson et al. 1987b:343), and in late summer in Baffin Bay (31.6 min, Richardson and Finley 1989:63).

Resting.--Resting whales (calves and mothers excluded) were observed only in 1989. They surfaced for an average of 4.64 min, dove for 13.7 min, and were observed to blow 7.60 times per surfacing (Table 14). These mean values were higher than for traveling bowheads, but sample sizes for resting whales were small and the differences were, at most, only marginally significant (Table 14). Intervals between successive blows averaged 95.6 s, much longer than intervals for traveling bowheads. The mean number of blows per surfacing may be underestimated and the mean blow interval overestimated, since some blows by resting bowheads are invisible (Carroll and Smithhisler 1980; LGL unpubl. data). Resting bowheads do not exhibit the upward rolling motion characteristic of blowing by moving whales, so invisible blows by resting whales will not always be recognizable as "presumed blows" via that criterion.

Socializing.--Socializing whales (calves and mothers excluded) blew, on the average, once every 21.3 s while at the surface. This value is similar to the mean for traveling animals but much less than that for resting bowheads (Table 14). The other variables were rarely recorded for socializing whales. However, more data were available for whales that socialized as they traveled. Their surfacings and dives were relatively short (averaging 0.85 and 3.92 min, respectively), with relatively few blows per surfacing (mean 3.7). Short surfacings and dives with relatively few blows per surfacing are typical for socializing bowheads (Dorsey et al. 1989; Richardson and Finley 1989:58).

Feeding and Surfacing with Mud.--Feeding apparently was not common during spring migration through our study area in either 1989 or 1990. The few data in Table 14 for whales "traveling plus feeding" pertain to whales engaged in presumptive water-column feeding. On rare occasions, whales dove repeatedly at one location, suggestive of water-column feeding. However, there was no specific proof of water-column feeding, and defecation was observed only once (3 May 1989). We saw no evidence of surface feeding.

Traveling whales sometimes seemed to have mud on their bodies when they surfaced. It is not known why or how often they contacted the bottom. On one day (16 May 1990), much mud was seen streaming out through the baleen of a small whale during one surfacing. It and three other whales near it had mud streaming from their bodies during one or more surfacings in water ~40 m deep.[9] On another day (12 May 1990), there was evidence of brief bottom or near-bottom feeding by three whales that had been observed for 2.7 h as they traveled east along the middle of the main nearshore lead. Mud was observed coming from the mouths of whales during four surfacings on this date; water depth was ~14 m.

Other Behavioral Variables

Several other behavioral variables were recorded consistently during aerial observation sessions. This section summarizes the results for five of these variables in the absence of disturbance (Tables 15, 16). Data of these types can be useful in recognizing alterations in behavior in the presence of disturbance. Mothers and calves are excluded, for the same reason as in the previous subsection.

Pre-dive Flex.--The pre-dive flex is a concave bending of the back that often occurs 10-20 s before bowheads dive. Although sample sizes for most categories of whales were small, pre-dive flexes were quite uncommon during the spring of 1989 and even rarer in 1990 (Table 15). For traveling whales, there were pre-dive flexes during only 3 of 239 surfacings (1.3%) when a flex, if present, would have been noted. In some previous studies, pre-dive flexes have been much more common (Würsig et al. 1985).

---

[9] These observations of mud on 16 May 1990 were 0.45-0.9 km from the ice camp during or within 20 min after the end of a drilling noise playback.

Table 15. Frequency of pre-dive flexes, fluke-out dives, and aerial behaviors during surfacings by undisturbed bowheads, excluding mothers and calves, as observed from a Twin Otter aircraft, spring 1989-90. The units of observation are surfacings by an individual whale.

	Pre-dive Flex			Flukes Out as Diving			Aerial Behaviors						
Year and Group Activity	No	Yes	Total	No	Yes	Total	None	Roll	Flip-Slap	Tail Slap	Breach	2 or 3 Types	Total
1990													
Rest			0			0							0
Travel	215	2	217	206	21	227	230	1	0	4	1	0	236
Social	2	0	2	4	0	4	4	0	0	0	0	0	4
Tr+soc	22	0	22	30	0	30	24	2	0	0	0	0	26
Tr+feed	5	0	5	5	0	5	7	0	0	0	0	0	7
Other/Unk	4	0	4	5	1	6	5	0	0	0	0	0	5
All	248	2	250	250	22	272	270	3	0	4	1	0	278
1989													
Rest	8	1	9	10	0	10	12	0	0	0	0	0	12
Travel	21	1	22	23	1	24	30	0	0	0	0	0	30
Social	13	1	14	14	0	14	27	11	0	0	0	0	38
Tr+soc	3	0	3	2	1	3	3	0	0	0	0	0	3
Tr+feed	0	0	0	0	0	0	0	0	0	0	0	0	0
Other/Unk	6	1	7	6	2	8	7	0	0	1	0	0	8
All	51	4	55	55	4	59	79	11	0	1	0	0	91
1989+1990													
Rest	8	1	9	10	0	10	12	0	0	0	0	0	12
Travel	236	3	239	229	22	251	260	1	0	4	1	0	266
Social	15	1	16	18	0	18	31	11	0	0	0	0	42
Tr+soc	25	0	25	32	1	33	27	2	0	0	0	0	29
Tr+feed	5	0	5	5	0	5	7	0	0	0	0	0	7
Other/Unk	10	1	11	11	3	14	12	0	0	1	0	0	13
All	299	6	305	305	26	331	349	14	0	5	1	0	369

Fluke-out Dives.--Bowheads and other whales often raise their flukes out of the water at the end of a surfacing as they are diving. However, in the spring of 1989-90, only about 8% of the dives were fluke-out dives. Results were similar for both years (Table 15). For traveling whales, the 1989-90 figure was 8.8% (22 of 251). In contrast, during autumn migration, bowheads raised their flukes ~27% of the time in the Alaskan Beaufort Sea and ~58% of the time in Baffin Bay (Richardson and Finley 1989:43).

Aerial Behaviors.--Aerial activities are those in which a part of the body is raised above the surface of the water. These behaviors include breaches, flipper and tail slaps, rolls, and various combinations (Würsig et al. 1985, 1989). During a roll along the longitudinal axis of the body, at least one flipper is raised above the surface. Amongst undisturbed whales (mothers and calves excluded) observed during the springs of 1989-90, rolls were seen during 3.8% of the surfacings (14 of 369, Table 15). Most of these rolls involved whales engaged in social interactions. Tail slaps were less commonly seen (5 of 369 surfacings, 1.4%). Breaches by undisturbed bowheads were rare (Table 15).

Table 16. Frequency of turns and various swimming speeds during surfacings by undisturbed bowheads, excluding mothers and calves, as observed from a Twin Otter aircraft, spring 1989-90. The units of observation are surfacings by an individual whale.

Year and Group Activity		Turns					Estimated Speed at Surface							
		None	Right	Left	Mult- iple	Total	None	Slow	Med- ium	Fast	Moving Unkn Speed	Mill	Change Speed	Total
1990														
	Rest					0								0
	Travel	158	21	18	15	212	1	6	204	3	33	0	16	263
	Social	0	0	0	1	1	0	2	0	0	2	1	0	5
	Tr+soc	15	3	4	1	23	0	1	25	0	8	0	3	37
	Tr+feed	1	2	1	0	4	0	0	3	0	5	0	0	8
	Other/Unk.	2	0	1	2	5	0	3	2	0	0	0	1	6
	All	176	26	24	19	245	1	12	234	3	48	1	20	319
1989														
	Rest	5	0	3	2	10	7	1	0	0	0	0	3	11
	Travel	10	1	0	0	11	0	12	11	0	0	0	3	26
	Social	2	4	4	4	14	6	5	5	1	1	0	3	21
	Tr+soc	0	3	0	0	3	0	0	3	0	0	0	0	3
	Tr+feed					0								0
	Other/Unk.	6	0	0	0	6	5	2	0	0	0	0	1	8
	All	23	8	7	6	44	18	20	19	1	1	0	10	69
1989+1990														
	Rest	5	0	3	2	10	7	1	0	0	0	0	3	11
	Travel	168	22	18	15	223	1	18	215	3	33	0	19	289
	Social	2	4	4	5	15	6	7	5	1	3	1	3	26
	Tr+soc	15	6	4	1	26	0	1	28	0	8	0	3	40
	Tr+feed	1	2	1	0	4	0	0	3	0	5	0	0	8
	Other/Unk.	8	0	1	2	11	5	5	2	0	0	0	2	14
	All	199	34	31	25	289	19	32	253	4	49	1	30	388

Turns.--The frequency of turns during surfacings depended on whale activity (Table 16). Traveling whales only infrequently changed heading during a surfacing (25% of 223 surfacings). Resting whales often turned slowly (50% of 10 surfacings), and socializing whales usually turned (87% of 15). The frequency of turns by whales that socialized intermittently as they traveled (42% of 26 surfacings) was intermediate between the frequencies for traveling (25%) and socializing (87%) whales.

Swimming Speed.--Speed during a particular surfacing cannot be determined quantitatively during aerial observations. However, as in previous related studies, we recorded relative speed during each surfacing on an ordinal "none, slow, medium, fast" scale. Not surprisingly, the few resting whales were usually classified as having no forward speed, traveling whales were usually moving at medium speed during surfacings, and socializing whales had the most variable speeds during surfacings (Table 16).

In 1990, the speeds of traveling whales were almost always categorized as medium, whereas in 1989 slow and medium speeds were recorded with almost-equal frequency (Table 16). Year to year comparisons of a somewhat subjective variable like "estimated speed" must be done with caution. However, the same observers were involved in both years, and they had experience in categorizing speed in years prior to 1989. Hence, we suspect that the difference was real. The difference was probably related to the heavier ice conditions and generally smaller areas of open water in 1989. We suspect that, when a bowhead surfaces in a small area of open water, it tends to slow down in order to allow a sufficient number of respirations before reaching the end of the open water area.

On several occasions in 1990, we were able to follow recognizable individual bowheads for several kilometers. The majority of these data concerned mother-calf pairs or whales exposed to noise playbacks. However, on 5 May we followed a single undisturbed whale for 1.0 h as it swam 4.3 km eastward along a narrow lead; the average "ground" speed (ignoring any current) was 4.4 km/h. The speed of this whale during each of its surfacings was recorded as medium. On 12 May we followed a group containing several recognizable whales for 2.1 h as they swam steadily eastward for 12.3 km along the main nearshore lead, i.e. average "ground" speed 5.9 km/h.[10] Speed during almost all surfacings within this 2.1-h period was recorded as medium.

Sexual Activity

Several generally low-intensity but distinct bouts of actual or presumed sexual activity were seen in the study area on 3 and 6 May 1989, and more active sexual activity was seen on 10 May 1990. The 1989 observations were described in Richardson et al. (1990a:163,166).

On 10 May 1990, a group of five bowheads engaged in active sexual activity and other social interactions as they traveled gradually northeast near the north (pack ice) side of the main nearshore lead. At one time the extended penises of two males were seen at the same time as the two whales oriented toward a third whale. That third whale was often belly-up, seemingly attempting to avoid the two males. At other times, whales were visible belly-up below the third whale. This active sexual activity was evident from at least as early as 13:47 until at least 14:27, and other social interactions continued thereafter.

Our brief but clear views of social-sexual activity in early May of 1989-90 reinforce the general impression that mating occurs often in spring, and wanes in frequency thereafter (Nerini et al. 1984; Koski et al. in press). However, much mating by whales of this population was seen in September-October 1988 in the eastern Beaufort Sea (Würsig et al. 1990).

Mother and Calf Behavior

Activities.--In 1989, we observed the behavior of three mother/calf pairs during periods when no source of potential disturbance was present. The first two pairs were migrating steadily eastward along the north edge of the main nearshore lead on 27 May 1989. These calves were relatively large (4.8 m and 4.9 m long). The third pair was observed on 27, 28 and

---

[10] These whales were also followed for an additional 0.5 h, but during that time they began to bring mud to the surface and slowed down to about 2.6 km/h.

29 May 1989. These animals, including a small 4.0 m calf, were lingering in the area; they were not traveling consistently eastward, perhaps because heavy ice was present to the east. A fourth pair, whose behavior was not observed systematically, moved 12.6 km WSW between the times they were photographed on 17 and 18 May. A fifth pair swam several kilometers westward during a drilling noise playback; it is not known whether they would have done so in the absence of the playback. Additional details about these 1989 observations are in Richardson et al. (1990a:166*ff*).

In 1990, the behavior of five presumably undisturbed mother/calf pairs was observed systematically for a total of 9.3 h during five different aerial observation sessions on 23-25 May. (Several other pairs were seen briefly.) Of the five pairs studied, two were actively migrating throughout the observations, one pair changed behavior from milling in one area to active migration, and the other two pairs were not actively migrating:

1. An actively migrating mother and calf were observed under undisturbed conditions for 0.9 h on 23 May ("23" *in* Fig. 40, p. 107). They traveled steadily ENE at medium speed in the largely open water of the main nearshore lead, but within a few hundred meters of the pack ice edge forming its north side. During most dives, the mother remained faintly visible below the surface, and the calf "rode" on her back (see below for discussion of riding).
2. An actively migrating mother and calf were observed for 3.5 h on 24 May. They were traveling east through moderately heavy pack ice, averaging 80% cover, far offshore NNE of Pt. Barrow ("24" *in* Fig. 40). Their observed speeds were slow to medium, with a net speed of 1.5 km/h based on the initial and final positions. The actual average speed was somewhat greater because the route through the ice was circuitous. Speeds and headings were more variable than those of the mother/calf pair seen in open water. The headings varied in such a way that the whales did not have to travel more than a few hundred meters under continuous ice. The mother and calf sometimes surfaced synchronously, but the calf often surfaced by itself at intermediate times. The calf swam actively; it was not seen to "ride" the mother.
3. On 25 May a mother and calf were found milling in small openings amidst heavy pack ice (90% cover) far offshore NE of Pt. Barrow ("25D" *in* Fig. 40). The mother may have been feeding during her dives. She may also have been searching, in some unknown manner, for a route through the pack ice. The calf spent more time at the surface. It breached several times, and sometimes nursed when the mother was at the surface. About 1 h after we found the whales in that area, they began traveling. They initially moved NNE and NE, skirting through cracks and other openings along the west side of a very large ice pan (several kilometers in diameter) that obstructed the direct eastward route. Upon reaching the north end of the large pan, the whales turned north along a major lead through the pack ice. They passed only about 100 m to the side of another mother/calf pair migrating in the opposite direction ("25E" *in* Fig. 40). Neither pair changed course or hesitated when passing the other pair. Only one brief episode of riding was visible. The overall average speed after active migration began was 4.7 km/h (6.8 km in 1.44 h). The average speed while moving through heavy pack ice was slightly less than that in the open lead (4.2 vs. 5.4 km/h).
4. Another mother and calf seen on 25 May were not actively migrating during 1.9 h of observation in an open area within heavy pack ice well offshore ("25A" *in* Fig. 40).

The calf spent more time at the surface than did the mother, which was suspected to be feeding below the surface. Activities at the surface included rest, slow travel, nursing, and tailslaps by the calf.

5. Another mother/calf pair seen in the same area on 25 May were resting almost totally motionless during 0.5 h of observation.

Thus in 1990, as in 1989, only a fraction of the mother/calf pairs were actively migrating to the northeast or east when seen. Mothers and calves in areas with much pack ice seemed especially likely to be engaged in other activities.

Riding Behavior.--In 1989, young calves that were actively traveling with their mothers usually were "riding" on the back of the mother (Richardson et al. 1990a:169). The calf appeared to lie on the back of the mother, pointed in the same direction as the mother, with rostrum slightly behind the mid-back of the mother. A calf engaged in "riding" appears to expend little energy in swimming; it seems to be pulled along by hydrodynamic forces created by the mother. The cases visible from the observation aircraft involved calves that were visible just below or at the surface, supported by mothers that were within a few meters of the surface. Depending on the depth of the whales, water clarity, and lighting conditions, the mother may or may not be visible when a "riding" calf is seen at or just below the surface. It is not known whether similar behavior occurs when both calf and mother are too deep to be seen from above.

In 1990, riding by calves at and near the surface was much less common. Of the three migrating mother/calf pairs observed systematically in 1990, consistent riding was evident in only one case--on 23 May 1990 (see above). Several other mother/calf pairs were seen briefly during reconnaissance surveys in 1990; riding was not evident in most of these cases. It is not known why riding was less common in 1990 than in 1989.

Surfacing, Respiration and Diving Behavior.--We examined the surfacing, respiration and diving (SRD) cycles of mothers and calves that were traveling when seen. Most of these whales were actively migrating, but some may have been traveling for some other reason. The sample sizes for mothers and calves engaged in activities other than traveling were too small for meaningful analysis.

We first examined the data from traveling whales that were *not* engaged in nursing (Fig. 41). The SRD cycles of traveling mothers were similar to those of other traveling "non-calves". However, the traveling calves had significantly shorter blow intervals, surface times, and dive durations than did their mothers (Fig. 41).

For traveling calves, nursing dives were even shorter than other dives, averaging 0.91 vs. 2.75 minutes in duration (Table 17). Other SRD variables were similar for traveling calves that were and were not nursing (Table 17). The presence or absence of nursing did not significantly affect the SRD cycles of traveling mothers (Table 17).

In 1990, "riding" was seen too infrequently to allow a comparison of the SRD cycles of mothers and calves that were and were not riding. In 1989, blow intervals for calves were longer when they were riding than when actively swimming (Richardson et al. 1990a:172).

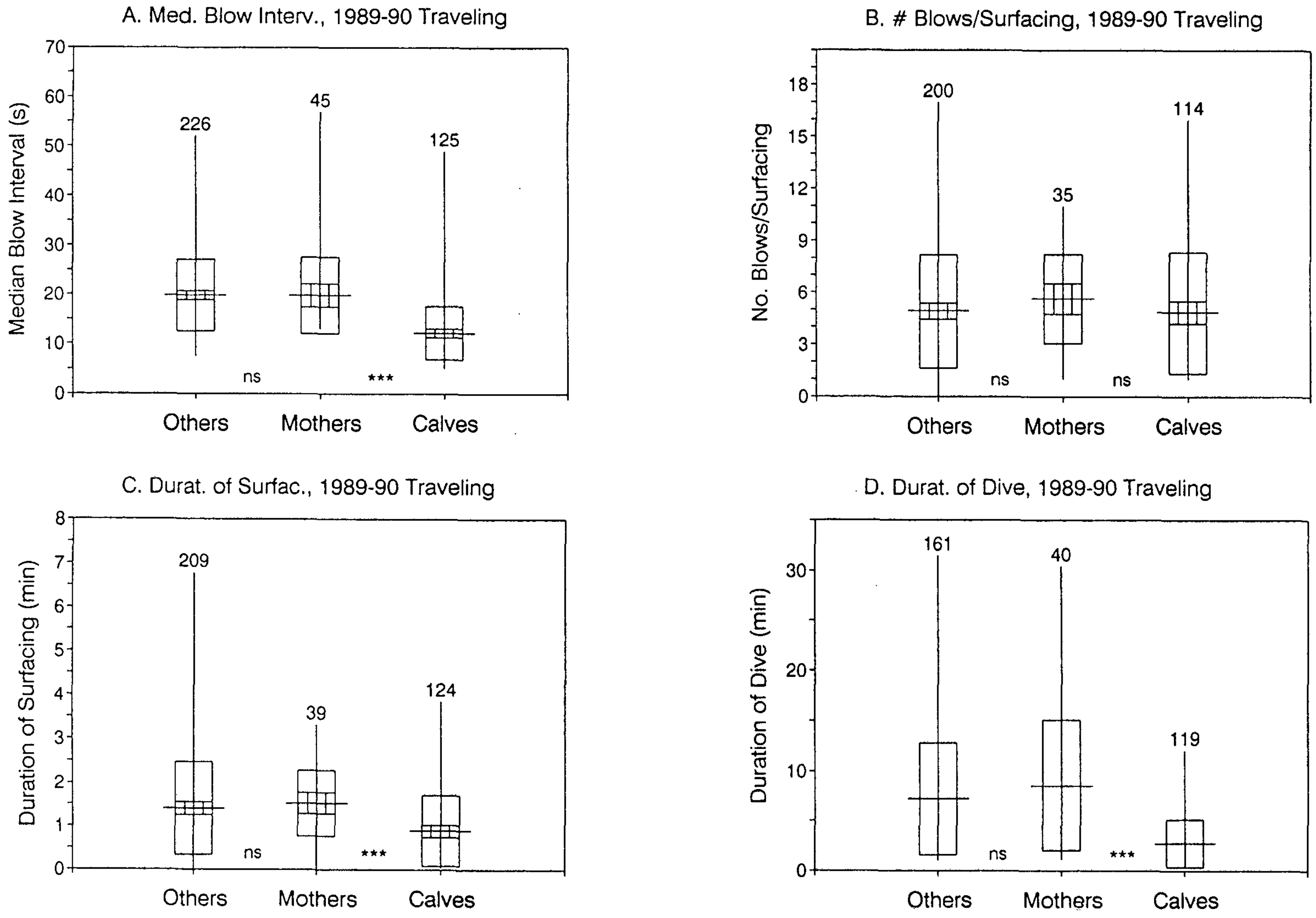


FIGURE 41. Surfacing, respiration and dive behavior for traveling bowheads--mothers, calves and others--seen from the aircraft during 1989-90. Mothers and calves engaged in nursing are excluded. The mean, range, ± 1 s.d. (open rectangle), ± 95% confidence interval (hatched rectangle) and sample size are shown. Significance levels are for t-tests comparing others vs. mothers and mothers vs. calves (from Table 17).

Table 17. Surfacing, respiration and dive behavior of undisturbed traveling bowheads--calves, mothers, and others--as observed from a Twin Otter aircraft in spring, 1989-90 combined.

Whale Category (Traveling Whales only)		Individual Blow Interval (s)			Median Blow Interval (s)			# of Blows/ Surfacing			Duration of Surfacing (min)			Duration of Dive (min)		
		mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n
Calves																
Not nursing	(1)	12.60	7.28	528	12.14	5.36	125	4.82	3.50	114	0.89	0.81	124	2.75	2.40	119
Nursing	(2)	13.88	6.60	59	14.59	6.78	16	3.57	2.41	23	0.63	0.57	23	0.91	1.08	25
Mothers																
Not nursing	(3)	18.37	6.30	191	19.79	7.75	45	5.60	2.59	35	1.52	0.75	39	8.55	6.54	40
Nursing	(4)	24.23	20.26	66	26.17	16.38	15	4.92	2.47	13	2.13	1.34	14	11.27	5.78	9
Others	(5)	19.21	8.93	989	19.77	7.25	226	4.89	3.27	200	1.40	1.07	209	7.20	5.61	161
					t	df	P	t	df	P	t	df	P	t	df	P
t-tests	(1) vs. (2)				1.67	139	(*)	1.63	135	ns	1.47	145	ns	5.97′	85	***
	(3) vs. (4)				1.46′	16	ns	0.82	46	ns	1.61′	16	ns	1.15	47	ns
	(1) vs. (3)				7.24	168	***	1.22	147	ns	4.31	161	***	5.49′	43	***
	(2) vs. (4)				2.54′	19	*	1.60	34	ns	3.98′	16	**	5.34′	8	***
	(3) vs. (5)				0.02	269	ns	1.22	233	ns	0.67	246	ns	1.32	199	ns

Notes: ′ = t-statistic not assuming equal population variances; ns → P>0.1; (*) → 0.1 ≥P>0.05; * → 0.05≥P>0.01; ** → 0.01≥P>0.001; *** → P≤0.001.

Other Behavioral Variables.--The same categorical variables that were recorded for whales other than mothers and calves (p. 112*ff*) were also recorded for mothers and calves.

Pre-dive flexes were rarely exhibited by mothers observed during the springs of 1989-90. Flexes were noted during only 2 of 85 surfacings by mothers (Table 18A). Likewise, flexes were only seen during 6 of 305 surfacings by other non-calves (Table 15). No calf was ever seen to exhibit a pre-dive flex in spring (0 of 241 surfacings, Table 18B).

Fluke-out dives were rare for mothers (1 of 89 dives, Table 18A) and infrequent for other non-calves (26 of 331 dives, Table 15). This difference in frequency is marginally significant ($chi^2=5.28$, df=1, $P<0.05$). Calves raised their flukes above the water during 14 of 259 dives (Table 18B). Among calves, fluke-out dives were more common in 1990 (9%) than in 1989 (1%; $chi^2=7.56$, df=1, $P<0.01$).)

Aerial behaviors, including breaches, tail slaps, and flipper slaps or rolls were not seen in the case of mothers observed in spring. Breaches, tail slaps and flipper slaps were seen occasionally in the case of calves (Table 18B) as well as in other non-calves (Table 15). Among calves, aerial behaviors were seen more often in 1990 than in 1989.

Turns were infrequent in the cases of mothers and calves engaged in traveling, as was also true for other non-calves that were traveling (Table 19 vs. 16). During traveling, turns occurred during 21%, 22% and 25% of the surfacings by mothers, calves and others, respectively. Sample sizes were small for mothers and calves engaged in other activities.

Swimming speeds by traveling mothers and calves were most commonly categorized as medium. However, a substantial minority of the traveling mothers and calves were categorized as moving slowly (Table 19). In contrast, few of the other non-calves that were traveling were moving slowly; the great majority were moving at medium speed (Table 16). These estimates of swimming speeds were based on partly-subjective judgments by the aerial observers.

More specific data on speeds of several presumably undisturbed mother/calf pairs were determined based on successive readouts from the aircraft's VLF navigation system. We considered only those pairs whose positions were determined over a period of at least 1 h. We excluded cases when the navigation data were suspect.

The two mother/calf pairs observed in 1989 during steady eastward migration in largely open water were traveling at speeds of 5.1 and 4.8 km/h, averaged over about 2 h. These whales were judged to be traveling at medium speed during most surfacings. The net motion of the third pair seen in 1989--the pair that lingered in the area for at least 2 days--was only 12 km NE over a 44.2 h period. The fourth pair moved 12.6 km WSW in 19.1 h.

In 1990, one mother/calf pair migrating steadily through heavy pack ice had a net speed of only 1.5 km/h, partly but not entirely due to its circuitous route through the ice. Another pair averaged 4.7 km/h, part of the time in moderately heavy pack ice. More details about the movements of these pairs are given in the descriptions of cases 2 and 3 on p. 116.

Table 18. Frequency of pre-dive flexes, fluke-out dives, and aerial behaviors during surfacings by undisturbed bowhead mothers (A) and calves (B) observed from a Twin Otter aircraft, spring 1989-90. The units of observation are surfacings by an individual whale.

Year and Group	Activity	Pre-dive Flex			Flukes Out as Diving			Aerial Behaviors						
		No	Yes	Total	No	Yes	Total	None	Roll	Flip-Slap	Tail Slap	Breach	2 or 3 Types	Total
A. MOTHERS														
1990														
	Rest	3	0	3	3	0	3	3	0	0	0	0	0	3
	Travel	31	1	32	32	0	32	33	0	0	0	0	0	33
	Feed	5	0	5	5	0	5	5	0	0	0	0	0	5
	Other/Unk	2	0	2	2	0	2	2	0	0	0	0	0	2
	All	41	1	42	42	0	42	43	0	0	0	0	0	43
1989														
	Rest	0	0	0	0	0	0	0	0	0	0	0	0	0
	Travel	26	1	27	30	1	31	32	0	0	0	0	0	32
	Feed	0	0	0	0	0	0	0	0	0	0	0	0	0
	Other/Unk	16	0	16	16	0	16	16	0	0	0	0	0	16
	All	42	1	43	46	1	47	48	0	0	0	0	0	48
1989+1990														
	Rest	3	0	3	3	0	3	3	0	0	0	0	0	3
	Travel	57	2	59	62	1	63	65	0	0	0	0	0	65
	Feed	5	0	5	5	0	5	5	0	0	0	0	0	5
	Other/Unk	18	0	18	18	0	18	18	0	0	0	0	0	18
	All	83	2	85	88	1	89	91	0	0	0	0	0	91
B. CALVES														
1990														
	Rest	12	0	12	9	4	13	9	0	0	3	0	0	12
	Travel	101	0	101	100	4	104	102	0	0	2	0	0	104
	Feed	24	0	24	19	5	24	21	0	0	1	0	2	24
	Other/Unk	7	0	7	8	0	8	2	0	0	0	4	1	7
	All	144	0	144	136	13	149	134	0	0	6	4	3	147
1989														
	Rest	0	0	0	0	0	0	0	0	0	0	0	0	0
	Travel	49	0	49	58	1	59	58	0	0	1	0	0	59
	Feed	0	0	0	0	0	0	0	0	0	0	0	0	0
	Other/Unk	48	0	48	51	0	51	51	0	0	0	0	0	51
	All	97	0	97	109	1	110	109	0	0	1	0	0	110
1989+1990														
	Rest	12	0	12	9	4	13	9	0	0	3	0	0	12
	Travel	150	0	150	158	5	163	160	0	0	3	0	0	163
	Feed	24	0	24	19	5	24	21	0	0	1	0	2	24
	Other/Unk	55	0	55	59	0	59	53	0	0	0	4	1	58
	All	241	0	241	245	14	259	243	0	0	7	4	3	257

Table 19. Frequency of turns and various swimming speeds during surfacings by undisturbed bowhead mothers (A) and calves (B) observed from a Twin Otter aircraft, spring 1989-90. The units of observation are surfacings by an individual whale.

Year and Group	Activity	Turns					Estimated Speed at Surface							
		None	Right	Left	Mult-iple	Total	None	Slow	Med-ium	Fast	Moving Unkn Speed	Mill	Change Speed	Total
A. MOTHERS														
1990	Rest	3	0	0	1	4	1	2	0	0	0	0	1	4
	Travel	22	5	5	0	32	1	5	20	0	1	0	10	37
	Feed	2	2	1	0	5	0	4	0	0	0	0	1	5
	Other/Unk.	1	0	0	1	2	0	1	0	0	0	0	1	2
	All	28	7	6	2	43	2	12	20	0	1	0	13	48
1989	Rest	0	0	0	0	0	0	0	0	0	0	0	0	0
	Travel	23	0	2	0	25	1	9	9	0	4	0	4	27
	Feed	0	0	0	0	0	0	0	0	0	0	0	0	0
	Other/Unk.	10	1	5	0	16	1	4	0	0	2	0	2	9
	All	33	1	7	0	41	2	13	9	0	6	0	6	36
1989+1990	Rest	3	0	0	1	4	1	2	0	0	0	0	1	4
	Travel	45	5	7	0	57	2	14	29	0	5	0	14	64
	Feed	2	2	1	0	5	0	4	0	0	0	0	1	5
	Other/Unk.	11	1	5	1	18	1	5	0	0	2	0	3	11
	All	61	8	13	2	84	4	25	29	0	7	0	19	84
B. CALVES														
1990	Rest	9	1	0	2	12	1	9	1	0	1	0	2	14
	Travel	79	13	9	2	103	2	12	67	0	17	0	12	110
	Feed	17	3	1	3	24	1	9	0	0	13	0	1	24
	Other/Unk.	2	0	2	3	7	0	2	1	0	3	0	1	7
	All	107	17	12	10	146	4	32	69	0	34	0	16	155
1989	Rest	0	0	0	0	0	0	0	0	0	0	0	0	0
	Travel	39	2	3	4	48	0	20	12	0	13	0	7	52
	Feed	0	0	0	0	0	0	0	0	0	0	0	0	0
	Other/Unk.	40	1	2	2	45	3	17	2	0	5	0	1	28
	All	79	3	5	6	93	3	37	14	0	18	0	8	80
1989+1990	Rest	9	1	0	2	12	1	9	1	0	1	0	2	14
	Travel	118	15	12	6	151	2	32	79	0	30	0	19	162
	Feed	17	3	1	3	24	1	9	0	0	13	0	1	24
	Other/Unk.	42	1	4	5	52	3	19	3	0	8	0	2	35
	All	186	20	17	16	239	7	69	83	0	52	0	24	235

Daily Playback Results, 1990

Specific objective 3 was to measure the short-term behavioral responses of whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of continuous drilling sound. All playback experiments in 1990 used a recording of sounds from the *Karluk* drilling operation on an ice platform. This was the same recording used during the 1989 playback experiments described by Richardson et al. (1990a).

In this section we describe each day's observations of bowheads exposed to projected drilling sounds during 1990. Bowhead movements near the ice camp are described and mapped for the noise playback periods and control periods on those days. The daily accounts include considerable information about ice conditions, since movements of the whales (and our ability to monitor them) were strongly influenced by ice. Measurements and estimates of sound levels at various distances from the projector are described. Detailed information about behavior is given only for 13 May 1990, when the sample size was large enough to warrant analysis of the single day's results. Brief daily accounts are also included for two control days when bowheads were observed near the ice camp but no playback experiments were conducted (29 April and 19 May), and for days when there was a playback but no bowheads were seen near the ice camp.

Similar daily accounts for 1989 appear in Richardson et al. (1990a:174-197), and are not repeated here.

A subsequent section of this report summarizes and integrates all of these results, taking account of previously-reported 1989 data as well as the 1990 data. That summary includes the behavioral data from all days aside from 13 May 1990, and for all days combined.

29 April 1990 (Control Only)

The ice camp was set up on the west side of a square-shaped opening in the heavy pack ice; this opening was almost entirely covered with thin new ice (Fig. 42). The opening was along a corridor of small openings and brash that extended ENE into the pack ice from the main nearshore lead, which was located several kilometers to the southwest along the edge of the land-fast ice. The projector was not operating on this day. Two bowhead whales were observed from the ice camp; the first was watched for 2 min as it rested on the surface 420 m south of the projector. The second whale was seen briefly as it rested 230 m south of the projector.

The aircraft-based crew observed bowheads along the corridor to the WSW of the ice camp. Six bowheads variously engaged in apparent feeding, socializing or traveling were observed for brief periods before the ice camp was set up. Four or five traveling bowheads were observed briefly after the ice camp was established.

4 May 1990 Playback (Few Whale Data)

The ice camp was set up along the north side of a secondary lead that was oriented NW to SE. The lead was covered with thin newly-frozen ice and was 300-350 m wide. The projector broadcast *Karluk* drilling platform sounds from 13:53:30 to 18:01:45 with short interruptions at 16:05:55 and ~16:49. No bowheads were seen near the projector on this day

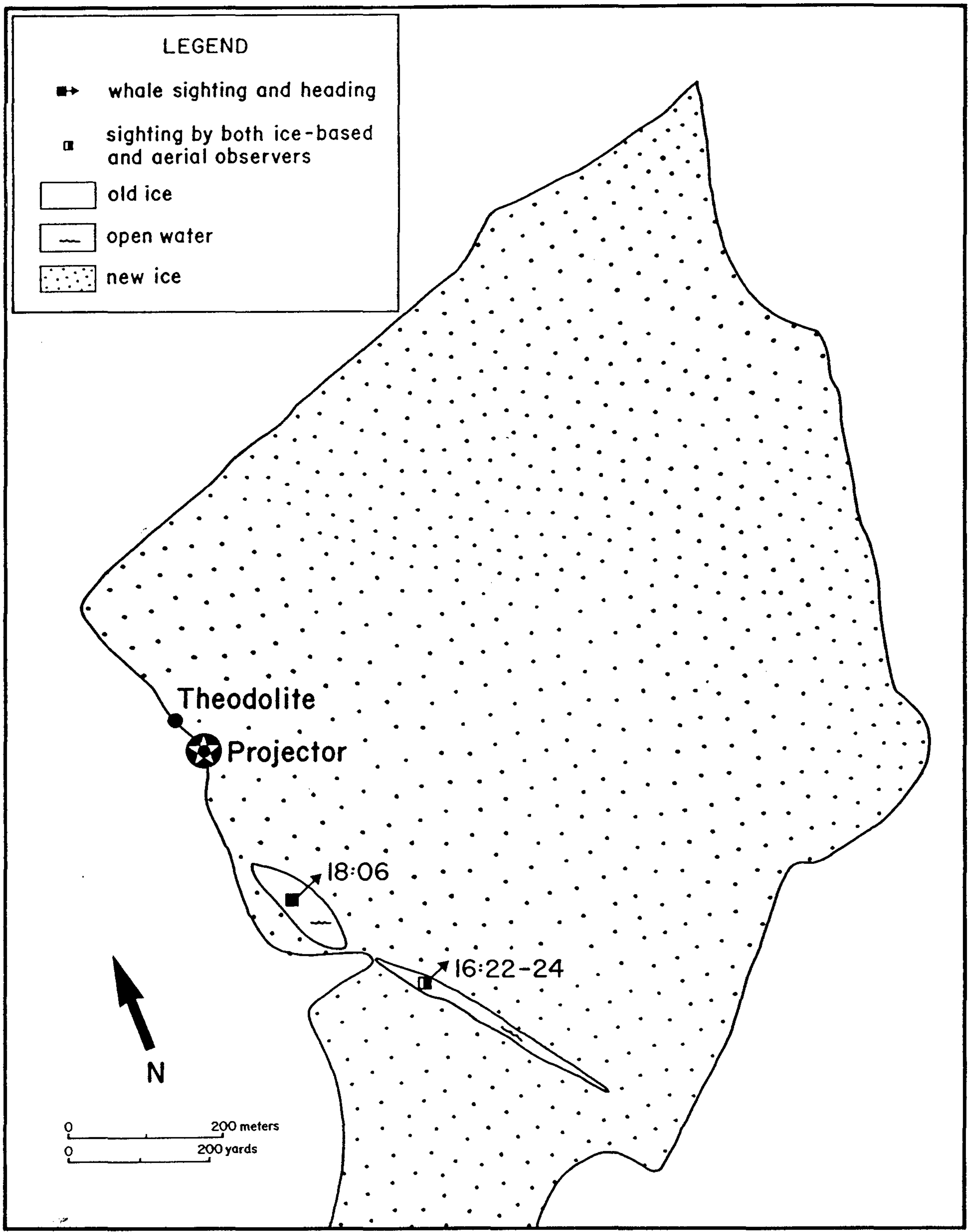


FIGURE 42. Ice conditions and bowhead whale sightings recorded by ice-based observers, 29 April 1990. The projector was silent throughout and whale positions are plotted from theodolite readings relative to the projector.

by either the aerial or ice-based crews. However, a hydrophone detected a strong bowhead call at 13:40, before the projections were started, and two series of exhalations were heard in the air at 18:23 and 18:29, shortly after the projector was turned off.

5 May 1990 Playback (Few Whale Data)

The ice camp was set up and drilling sounds were projected in an area of thin ice bordering a long narrow lead in the pack ice. No bowheads were seen after the ice camp was set up although the aerial observers had followed a single bowhead past the future projector site 10 min before the ice crew arrived. This whale was followed for 1 h as it traveled along the long narrow lead.

9 May 1990 Playback

The ceiling was low on this day and the Twin Otter crew returned to Barrow after conducting a survey and directing the ice-based crew to an area where bowheads were present. The ice camp was set up along a secondary lead (Fig. 43) just north of the main nearshore lead. We projected drilling sounds from 15:45 to 20:48 with two brief interruptions at 17:23 and 19:35.

Ice-based Observations.--Four bowheads were sighted during control observations. Two bowheads were observed before drilling sounds were projected; they were 350 m south and 410 m SW of the projector (Table 20; Fig. 43). About 30 min after the playback of drilling sounds stopped, two more bowheads (1 group) were sighted traveling ENE 107 m SSE of the projector. Based on these sighting locations and the observed headings of the whales, their closest points of approach to the ice camp probably ranged from about 100 to 350 m.

A total of 22 bowheads (17 groups) were sighted during periods when drilling sounds were being projected. Almost all of these were 600-1500 m SSW to S of the projector when seen (Fig. 43). An additional bowhead was seen swimming NE 240 m north of the projector during one of the brief intervals when the projector was turned off. This whale would have been subjected to drilling sounds at very close range (probably <300 m) before the projector was turned off at 19:35. The closest approach of a bowhead to the operating projector involved a mother/young pair (probably a mother and yearling) that were first sighted 180 m north of the projector. They swam toward the projector and dove under the ice at a distance of 132 m.

All bowheads seen during control periods were traveling on tracks that brought them within 410 m, and probably within 350 m, of the ice camp. In contrast, during the playback period, only 3 bowheads (2 groups) were seen within 410 m; the remaining 19 bowheads (15 groups) were farther away. These results suggest that some bowheads migrating near the ice camp may have altered course to avoid close approach to the projector while it was broadcasting drilling noises. However, aside from one whale that turned away when it came within 600 m at time 19:03, ice-based observers could not detect bowheads far enough away to document directly any southward diversion of the migration track that may have occurred as the whales approached the ice camp.

Noise Exposure.--On 9 May 1990, a 57A monitor sonobuoy was deployed manually 0.6 km southeast of the ice camp. Distance from the projector to the sonobuoy was determined both

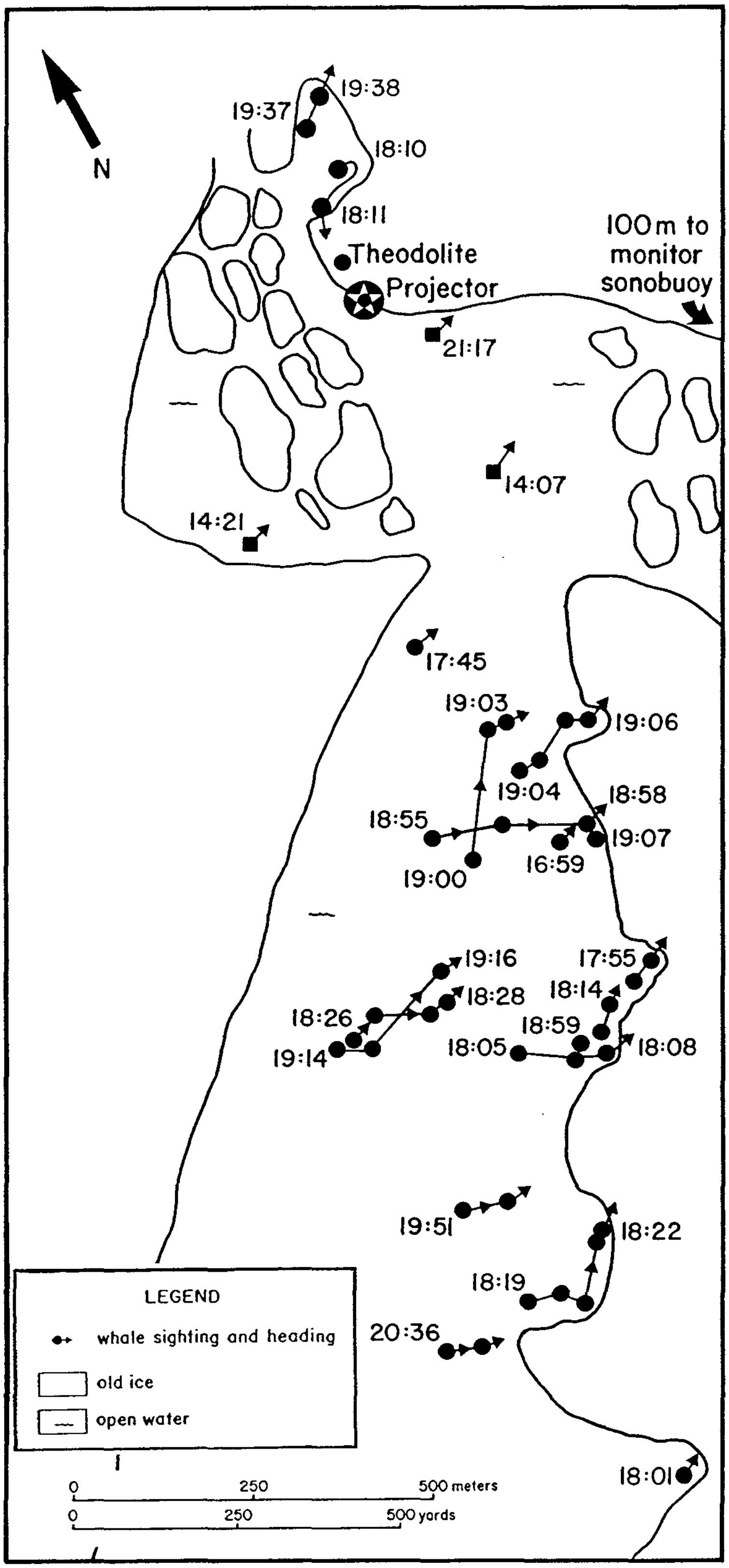


FIGURE 43. Ice-based observations of bowhead whale tracks relative to the sound projector amidst the pack ice NE of Barrow, Alaska, 9 May 1990. Closed circles represent sightings during playback of drilling platform sounds and closed squares represent sightings when the projector was silent.

Table 20. Summary of sightings of bowheads passing close to the sound projector on 9 May 1990 when the projector was silent and when it was operating amidst the pack ice NE of Barrow. Only sightings with CPA within 1 km of the projector are included in this table.

Time	Radial Distance Followed From Projector (m)[a]	CPA (m)	Determination of CPA[b]	Sound Levels[c]	Nature of Track
Silent Projector					
14:07	single sighting	<350[d]	2	NA[e]	S of projector heading ENE
14:21	single sighting	<410	1	NA	SSW of projector heading E
21:17	single sighting	107	1	NA	S of projector heading E
Operating Projector					
16:59	single sighting	780	1	109 / 101	S of projector heading E under ice
17:45	single sighting	<470	1	>112 / >105	SSW of projector heading E
17:55	-1020 to -990	<990	1	>107 / > 99	S of projector heading ENE under ice
18:11	+180 to +132	<132	1	>121 / >113	Mother/yearling. Surfaced N of projector heading E; turned and swam toward projector. Heading toward projector when they dove.
18:26	-1010 to -960	960	1	107 / 99	SSW of projector heading E in mid lead
18:55	-725 to -765	725	1	109 / 101	S of projector heading ESE under ice
19:03	-770 to -600	600	1	111 / 103	Initially heading NE (10° right of projector); turned to E when 600 m away.
19:04	-675 to -645	640	1	110 / 102	S of projector heading E under ice
19:14	-1010 to -925	<925		>108 / >100	S of projector heading ENE in mid lead
19:37	+240 to +280	240[f]	1	117 / 109[f]	Angling away from silent projector; projector was broadcasting 2 min earlier.

[a] - indicates that whales are ≥135° and ≤315°T from the projector (approaching); + indicates that whales are ≤135° or ≥315° from the projector (moving away).

[b] 1 = measured by theodolite or tape, 2 = visual estimate, 3 = estimate based on nearby surfacings, 4 = estimates based on distant surfacings (possibly unreliable).

[c] Estimated received level (dB re 1 µPa) of projected noise at CPA. Left: level in the 20-1000 Hz band. Right: level in the dominant 1/3-octave band.

[d] < indicates that whales were heading toward the projector when last seen.

[e] NA is not applicable.

[f] The projector was silent but the whale was probably at a similar distance from the projector when it was operating 2 min earlier.

by theodolite and by acoustic travel time. Because aerial observations near the ice camp were not possible on this date, there was no air-dropped sonobuoy at another distance.

The measured source level of the projected *Karluk* sounds was 165 dB re 1 µPa in the 20-1000 Hz band, with the strongest sounds in the 1/3-octave bands centered at 160, 200 and 250 Hz (158-159 dB in each--Fig. 44). At 0.6 km range, the 1/3-octave band levels from at least 40 to 800 Hz were above the ambient noise levels in the corresponding bands (Fig. 44). At 0.6 km range, the received levels were 110 dB for the 20-1000 Hz band and 103 dB for the 1/3-octave band centered at 200 Hz. These received levels were about 20 dB and 27 dB, respectively, above the natural ambient noise levels in the corresponding bands.

The results from the transmission loss tests, along with the direct measurements at 0.6 km range, were used to develop equations suitable for predicting received level vs. distance from the projector on 9 May. Appendix B describes how the equations were derived. The equations for the 20-1000 Hz band and the 1/3-octave band centered at 200 Hz were as follows:

$$RL_{20\text{-}1000\ Hz} = 107.9 - 0.88\ R - 15 \log (R)$$

$$RL_{200\ Hz} = 100.0 - 0.88\ R - 15 \log (R)$$

Figure 45 shows the received levels predicted by these two equations in relation to distance from the projector and ambient noise.

Most bowheads seen during the 9 May playback had CPA distances 0.6-1.5 km from the projector, but one whale came within 300 m and a pair came within 132 m. Those with CPA=1.5 km would have received levels of ~104 dB broadband and ~96 dB in the 1/3-octave band centered at 200 Hz. Those received levels at 1.5 km range were ~14 dB and ~20 dB above the natural ambient noise levels in the corresponding band. Whales with CPA=0.6 km were exposed to levels 6-7 dB stronger than those at 1.5 km. The mother/young pair seen closest to the projector (180→132 m) would have received ~121 dB in the 20-1000 Hz band and ~113 dB near 200 Hz:

		Type	20-1000 Hz			Dominant 1/3-Octave			
	Distance (km)	of Data	Drill. (dB)	Amb. (dB)	S:N (dB)	Freq. (Hz)	Drill. (dB)	Amb. (dB)	S:N (dB)
Source level	0.001	Meas.	165	90	75	200	159	76	83
Buoy-57A	0.6	"	110	"	20	"	103	"	27
CPA mother/young	0.13	Est.	121	"	31	"	113	"	37
"Distant" whales	1.5	"	104	"	14	"	96	"	20

Received levels for the other whales that occurred within 1 km of the projector during the playback are summarized in Table 20.

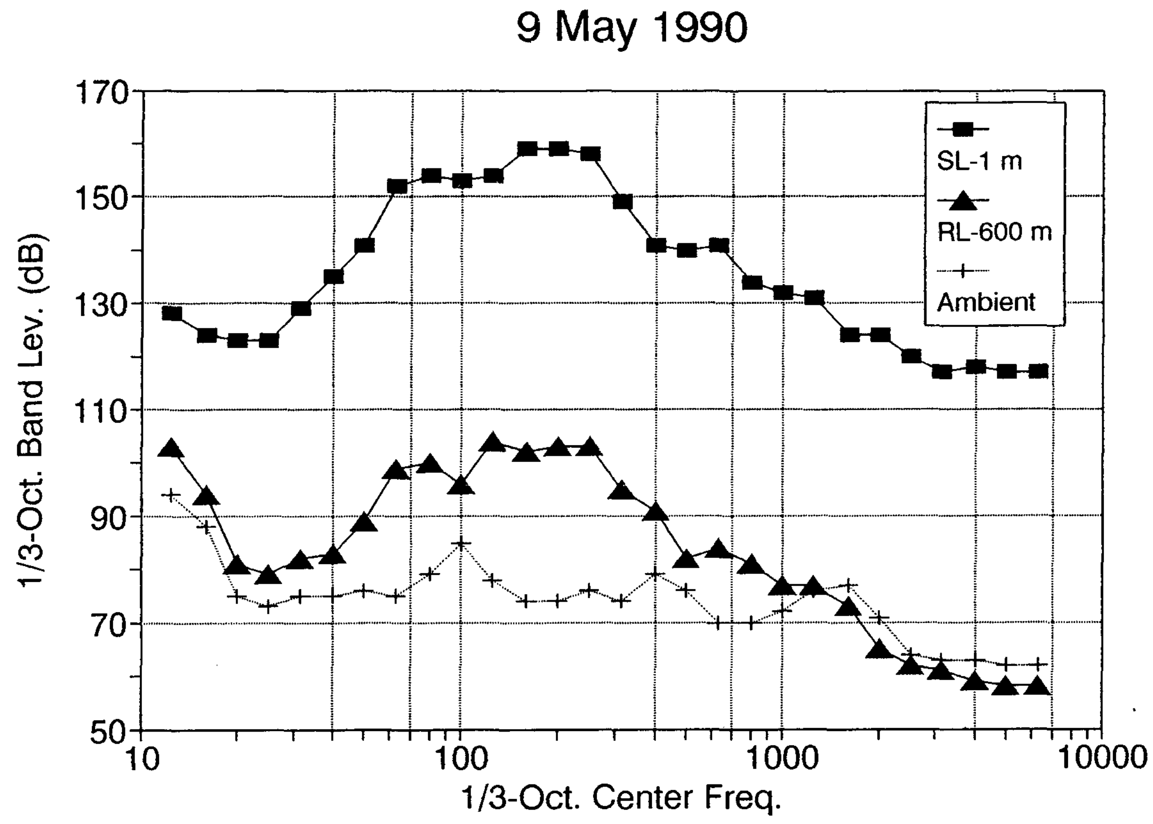


FIGURE 44. Third-octave levels of sounds 1 m from the projector (squares) and at a sonobuoy 0.6 km from the projector (triangles) during playback on 9 May 1990, time 17:26. Plus signs show ambient noise levels at the sonobuoy 2 min earlier when projector was not operating. Data are in dB re 1 µPa.

Explanatory notes: The following explanations apply to this and other similar diagrams later in the report. *(1)* Because of projector limitations, components of the drilling sounds below 80 Hz, and especially below 63 Hz, are underrepresented in the J-11 projector output relative to the original recording of *Karluk* drilling sounds (see "PHYSICAL ACOUSTICS RESULTS--Fidelity of Playbacks"). *(2)* For each 1/3-octave band, the level received at the sonobuoy during the playback is the sum of the received drilling sound plus the natural ambient noise in that band. *(3)* In some frequency bands, the received level at the sonobuoy during the playback (here triangle) is similar to or slightly below the ambient noise level recorded when the projector was off (plus). In those bands, the drilling noise has attenuated to inaudibility by the time it reaches the sonobuoy. *(4)* At some frequencies, the level of drilling noise plus ambient noise (here triangle) is slightly below the level of the ambient noise alone (plus). In these cases the ambient noise had apparently decreased slightly during the interval (here 2 min) between the two measurements. This degree of short-term fluctuation in ambient noise level is common (see Fig. 14, p. 57).

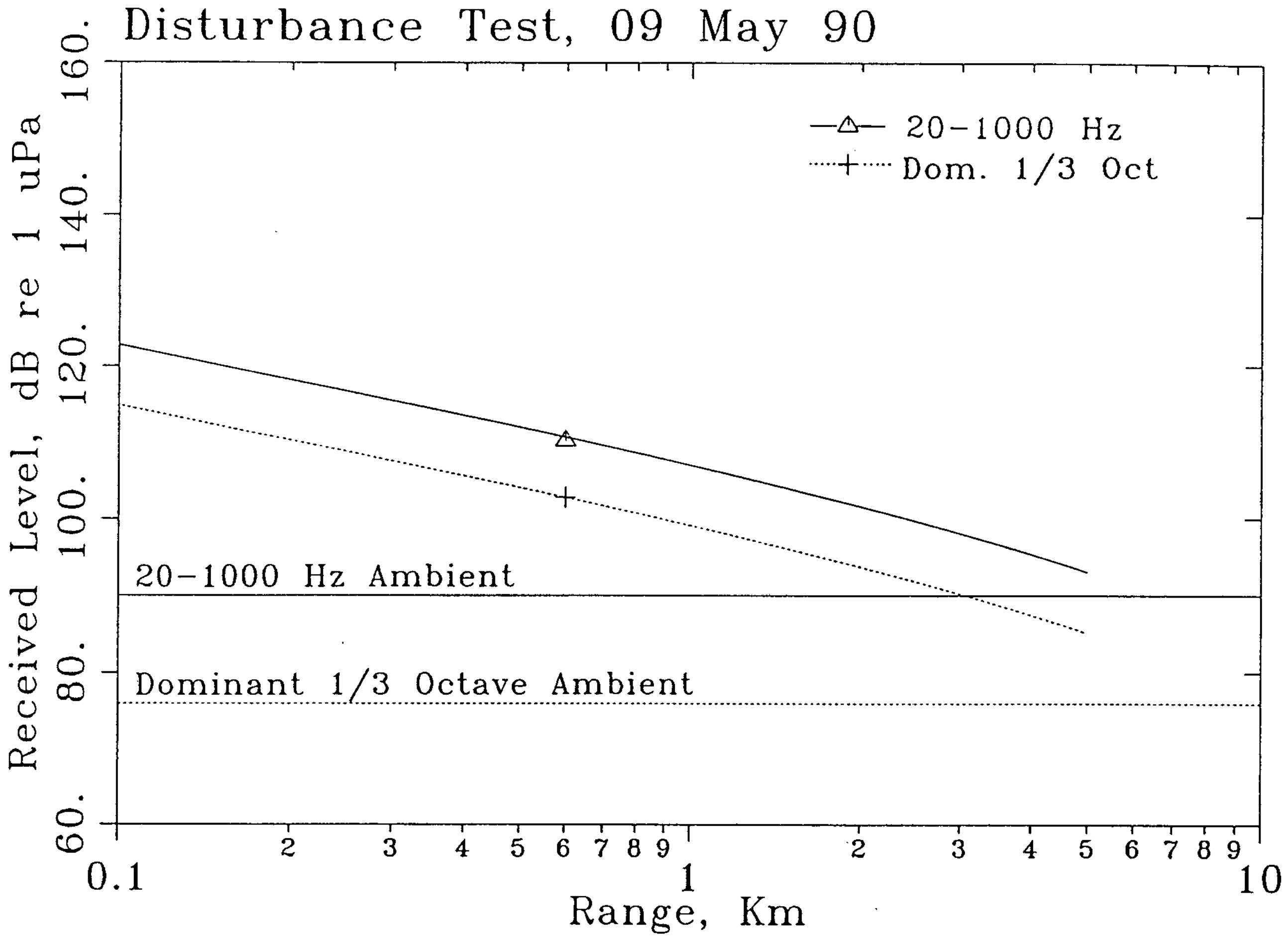
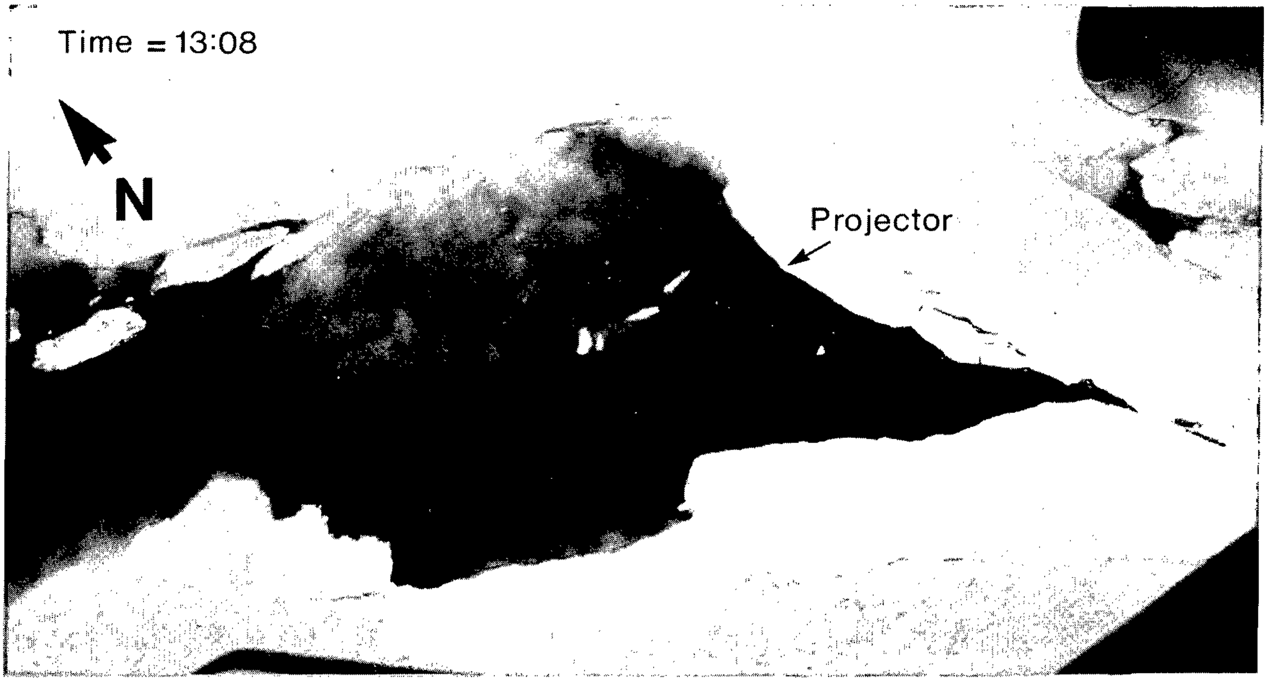


FIGURE 45. Measured and estimated received sound levels vs. range during the *Karluk* disturbance test on 9 May 1990. The triangle and plus show the measurements via a sonobuoy at 0.6 km range. The descending curves show the values estimated by the equations given in the text. The average ambient noise levels for the 20-1000 Hz band and the dominant 1/3-octave band are shown as the two horizontal lines.

10 May 1990 Playback

The ice camp and projector were set up northeast of the main E-W nearshore lead along a secondary lead (0.7-1.2 km wide) that was oriented WNW to ESE. The camp was set up on an oval-shaped pan that blocked the secondary lead. This pan rotated slowly counter-clockwise during the day as the secondary lead slowly closed (Plate 3). East of the ice camp, the secondary lead was congested with brash ice and small pans, but several small open-water areas were present; these would have permitted whales to migrate easily through the continuation of the secondary lead east of the camp. Drilling sounds were projected from 15:32:10 to 20:50:30. Whales approached the projector site from the SW, initially in the main nearshore lead and then in the secondary lead west of the projector. The bowheads near the projector were traveling and/or socializing with some apparent sexual behavior.



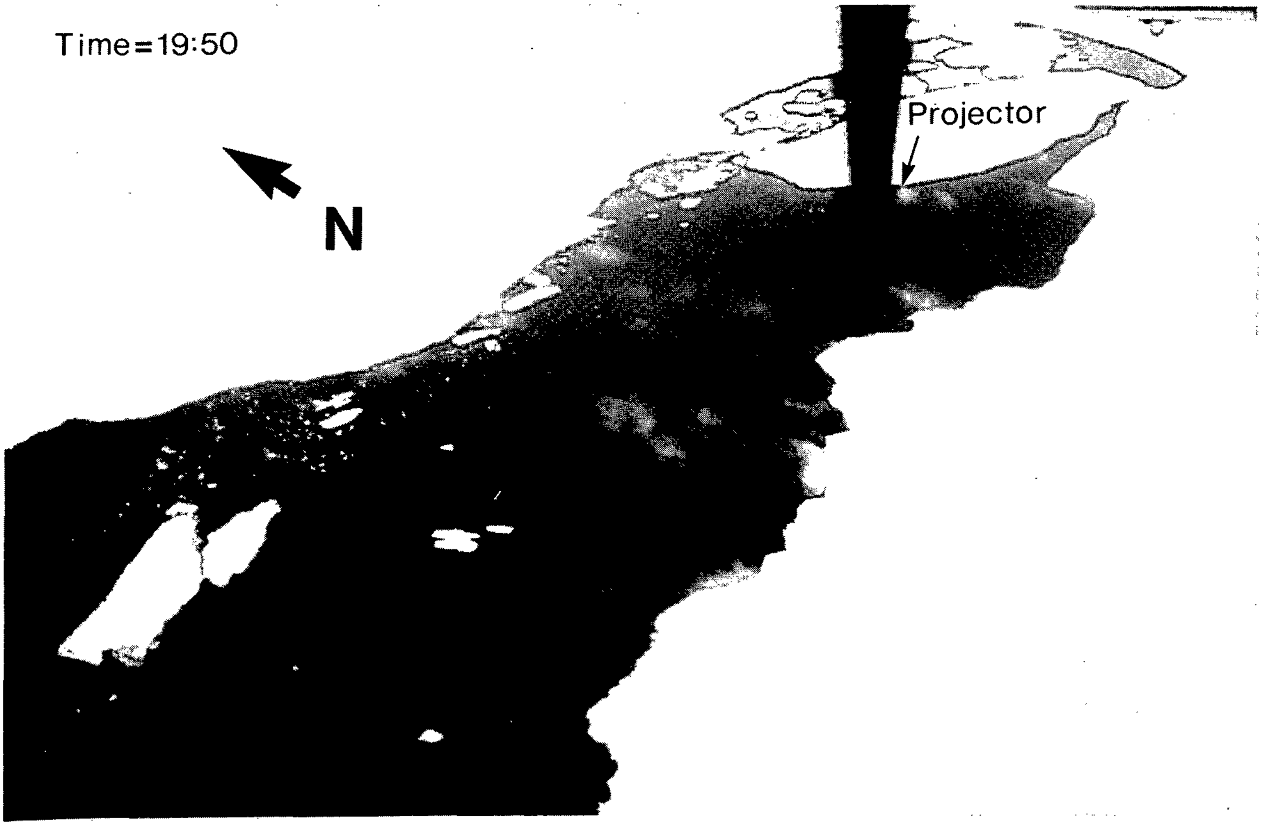


Plate 3. Ice conditions near the projector site at two times on 10 May 1990. Note the considerable shift in the position and orientation of the ice pan with the projector between 13:08 (upper panel) and 19:50 (lower panel).

Ice-based Observations.--Pre-playback control observations were conducted at the ice camp from 14:03 to 15:32:09. Two groups of bowheads (containing 3 and 1 individuals) were observed NNW of the ice camp (Fig. 46). The first of these groups milled 575 m NNW of the camp for about 20 min; one whale of this group tailslapped at least five times. The second group consisted of a single subadult whale that was moving ENE and that dove under the ice 60 m north of the silent projector. This was the second closest approach of a bowhead to the projector site on this day (Table 21). Although the projector was silent, the generator was running.

A total of 22 bowheads (20 groups) were sighted by the ice-based crew during the 15:32:10 to 20:50:30 period while drilling sounds were projected. In general, bowheads appeared to enter the lead along the south ice edge, moved NE through the lead, and passed the ice camp to the NW. When the projector was broadcasting drilling sounds, whales tended to move north or NE to the north side of the lead while they were west of the projector (Fig. 47; see also the aerial observations shown in Fig. 49, 50). In contrast, when the projector was silent some whales traveled east or NE closer to the projector (Fig. 46, see also the aerial observations in Fig. 48).

The closest confirmed approach of a bowhead to the operating projector on this day (and on any day of the 1989 and 1990 studies) was by a single subadult that moved SSE along the edge of the pan from 105 m to 35 m north of the projector at 17:36 (Table 21; Fig. 47). The distance was measured using a surveyor's measuring wheel (Rolotape model 400, accuracy 0.25% claimed by manufacturer). Another bowhead was observed at 20:08 moving ESE and directly toward the projector 115 m from it (distance measured by theodolite). Neither of these latter bowheads showed any evidence of avoidance or disturbance reaction to the operating projector.

Four single bowheads were observed during the post-playback period from 20:50:31 to 21:51. One of these whales was sighted moving ENE 250 m west of the projector (Fig. 46); this whale continued on its ENE heading until it dove under the ice camp pan about 100 m north of the projector site (distance estimated). Another bowhead was observed swimming east 300 m SSW of the ice camp; this whale was overflown by the Bell 212 *en route* from the monitor sonobuoy to the ice camp and is discussed in the section on "Bowhead Reactions to Aircraft".

Aerial Observations.--Three behavioral observation sessions were conducted near the ice camp on 10 May. These were in the secondary lead west and WSW of the camp.

The first session near the camp was conducted in the secondary lead at and just to the west of the ice camp. Observations extended from 14:48 to 15:36. The projector was silent until 15:32:10, when playback of *Karluk* sounds began. Eight to ten bowheads and about 35 white whales were traveling eastward along the northern half of the secondary lead during this period (Fig. 48). Many of these whales passed close to the silent projector or were last seen heading toward the projector at distances <500 m (Table 21). One bowhead 225 m NW of the projector was under observation when the projector was turned on at 15:32:10.[11] The whale remained at the surface and initially turned right about 60° toward the projector; it then turned

---

[11] The projector operator was not aware of the presence of this whale.

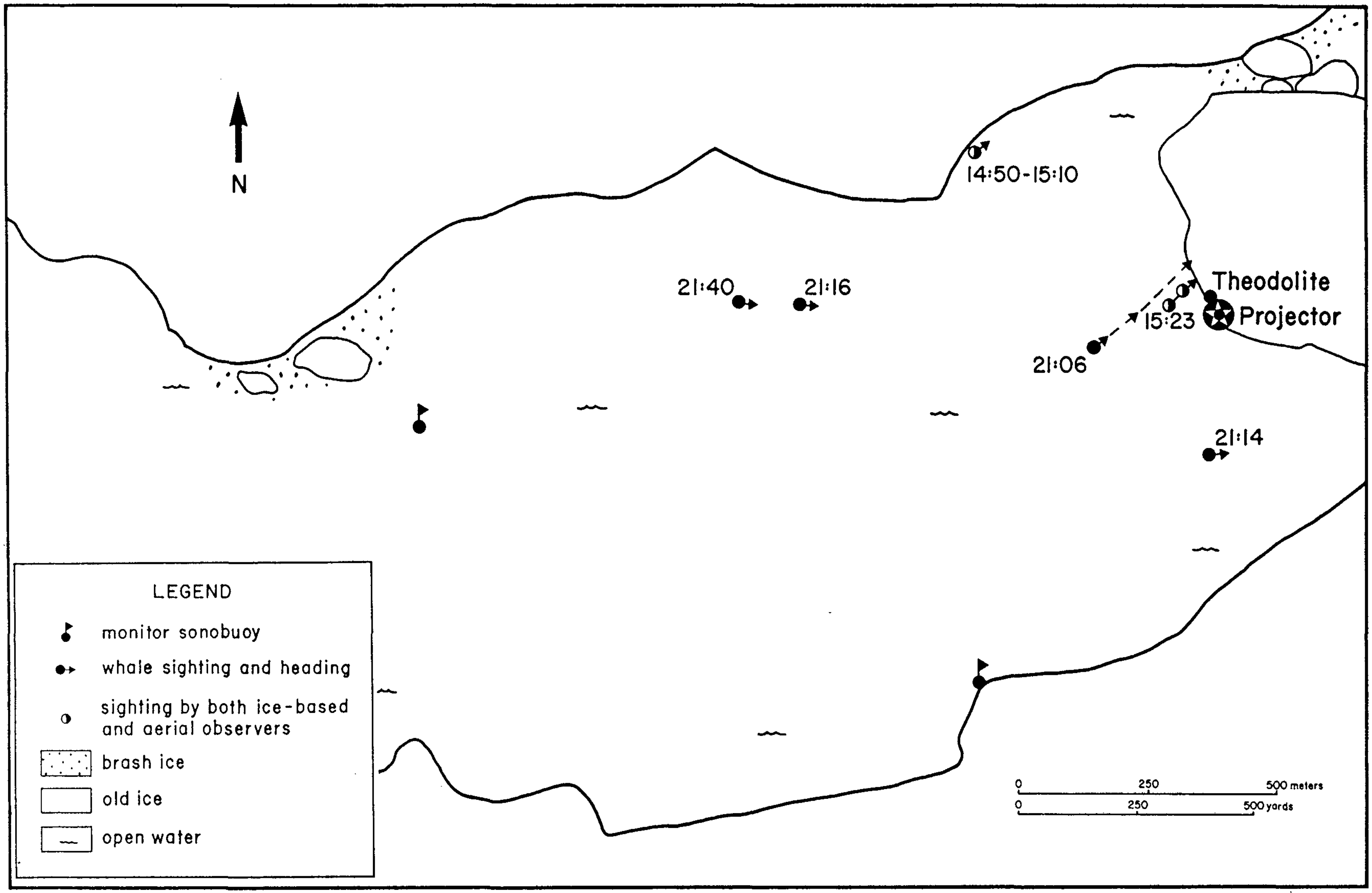


FIGURE 46. Ice-based observations of bowhead whale tracks relative to the silent sound projector amidst the pack ice NE of Barrow, Alaska, 10 May 1990. The sonobuoy along the south side of the lead stopped recording at 15:36 and the sonobuoy in the lead was deployed from the Twin Otter at 18:02. The projector was silent before 15:32 and after 20:50.

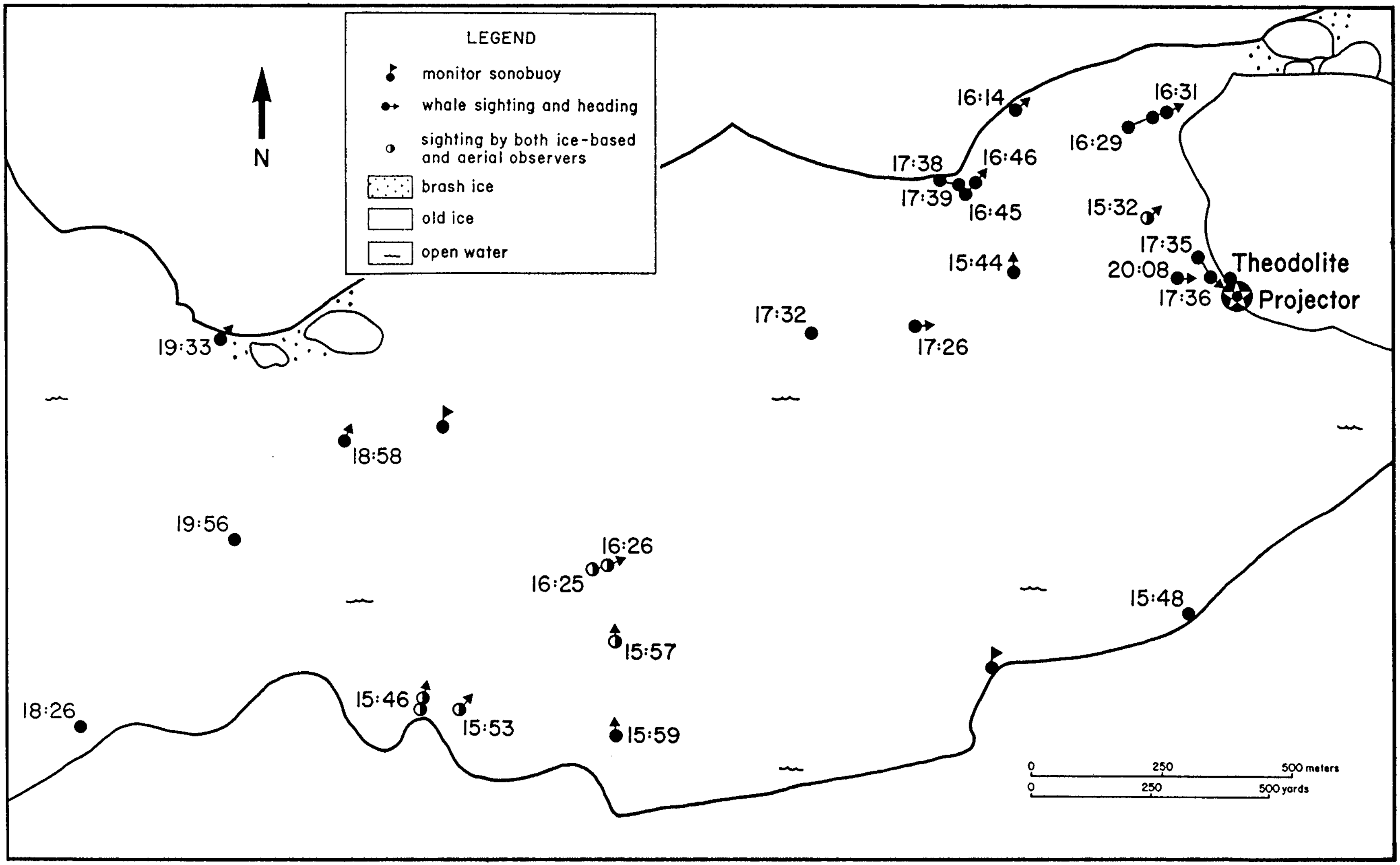


FIGURE 47. Ice-based observations of bowhead whale tracks relative to the sound projector broadcasting drilling platform sounds amidst the pack ice NE of Barrow, Alaska, 10 May 1990. The sonobuoy along the south side of the lead stopped recording at 15:36 and the sonobuoy in the lead was deployed from the Twin Otter at 18:02. The projector operated from 15:32 to 20:50.

Table 21. Summary of sightings of bowhead whales passing close to the sound projector on 10 May 1990 when the projector was silent and when it was operating amidst the pack ice NE of Barrow. Only sightings with CPA within 1 km of the projector are included in this table.

Time	Radial Distance Followed From Projector (m)[a]	CPA (m)	Determination of CPA[b]	Sound Levels[c]	Nature of Track
Silent Projector--Ice-based observations					
21:06	-250 to +100	100	1	NA[e]	Steady NE heading
21:14	single sighting	300	2	NA	Traveling E south of projector.
21:16	single sighting	<810	2	NA	W of projector heading E toward projector
21:40	single sighting	<925	2	NA	W of projector heading E toward projector
Silent Projector--Aerial observation					
14:49	single sighting	<400[d]	2	NA	W of projector heading E; heading was 20° to right of projector
14:51	single sighting	<500	2	NA	NW of projector heading SE directly at the projector
14:55[f]	single sighting	480	1	NA	Following ice edge E
15:01	single sighting	<500	2	NA	WNW of projector heading E
15:03	-1100 to -900	<900	2	NA	W of projector moving E; last seen heading NE
15:03	-700 to -600	<600	2	NA	NW of projector heading ENE
15:07	+350 to +350	<350	2	NA	Changing headings, last seen angling toward the projector from N
15:08	single sighting	<400	2	NA	NE of projector heading E
15:10-12	-500 to -490	490	2	NA	Follow ice edge E, 1 of 3 whales circles toward ice camp then continues track
15:24[f]	-100 to -60	60	1	NA	Did not change heading as it traveled E
15:24	single sighting	<200	2	NA	SSW of projector heading NE
15:30	single sighting	<250	2	NA	SSW of projector heading ENE
15:31	-850 to -800	<800	2	NA	W of projector heading E and ESE
Operating Projector--Ice-based observations					
15:44	single sighting	435	1	121 / 116	W of projector heading N
15:48	single sighting	620	1	119 / 114	S of projector along ice edge; no heading recorded

Continued...

Table 21. Concluded.

Time	Radial Distance Followed From Projector (m)[a]	CPA (m)	Determination of CPA[b]	Sound Levels[c]	Nature of Track
16:14	single sighting	565	1	120 / 114	NW of projector along ice edge; heading NE
16:31	+390 to +380	380	1	122 / 117	NNE of projector heading ENE
16:45	-560 to -545	<545	1	>120 / >115	NW of projector heading NE along the ice edge
17:26	single sighting	<625	1	>119 / >114	Mid lead heading E toward projector
17:32	single sighting	825	1	117 / 112	W of projector in mid lead; no heading recorded
17:36	-105 to -35	<35	1	>138 / >133	Follow ice edge SSE and dives toward projector
17:38	-600 to -565	<565	1	>120 / >114	WNW of projector following ice edge E
20:08	single sighting	<115	1	>130 / >125	WNW of projector heading E almost at projector
Operating Projector--Aerial observations					
15:32[f]	-230 to -200 to -250	200	1	127 / 121	Whale turned toward projector when it was started up; then turned and swam NNE away from projector
16:14	-1700 to -800	500	4	121 / 115	W of projector heading ENE
16:20	-1900 to +420	350	4	123 / 118	W of projector heading ENE
16:21	-1600 to +380	360	3	123 / 117	W of projector; travel NE to N side of lead then travel E along N ice edge

---

[a] - indicates that whales are ≥180° from the projector (approaching); + indicates that whales are ≤180° from the projector (moving away).

[b] 1 = measured by theodolite or tape, 2 = visual estimate, 3 = estimate based on nearby surfacings, 4 = estimates based on distant surfacings (possibly unreliable).

[c] Estimated received level (dB re 1 µPa) of projected noise at CPA. Left: level in the 20-1000 Hz band. Right: level in the dominant 1/3-octave band.

[d] < indicates that whales were heading toward the projector when last seen.

[e] NA is not applicable.

[f] This whale was also seen by the ice-based observers.

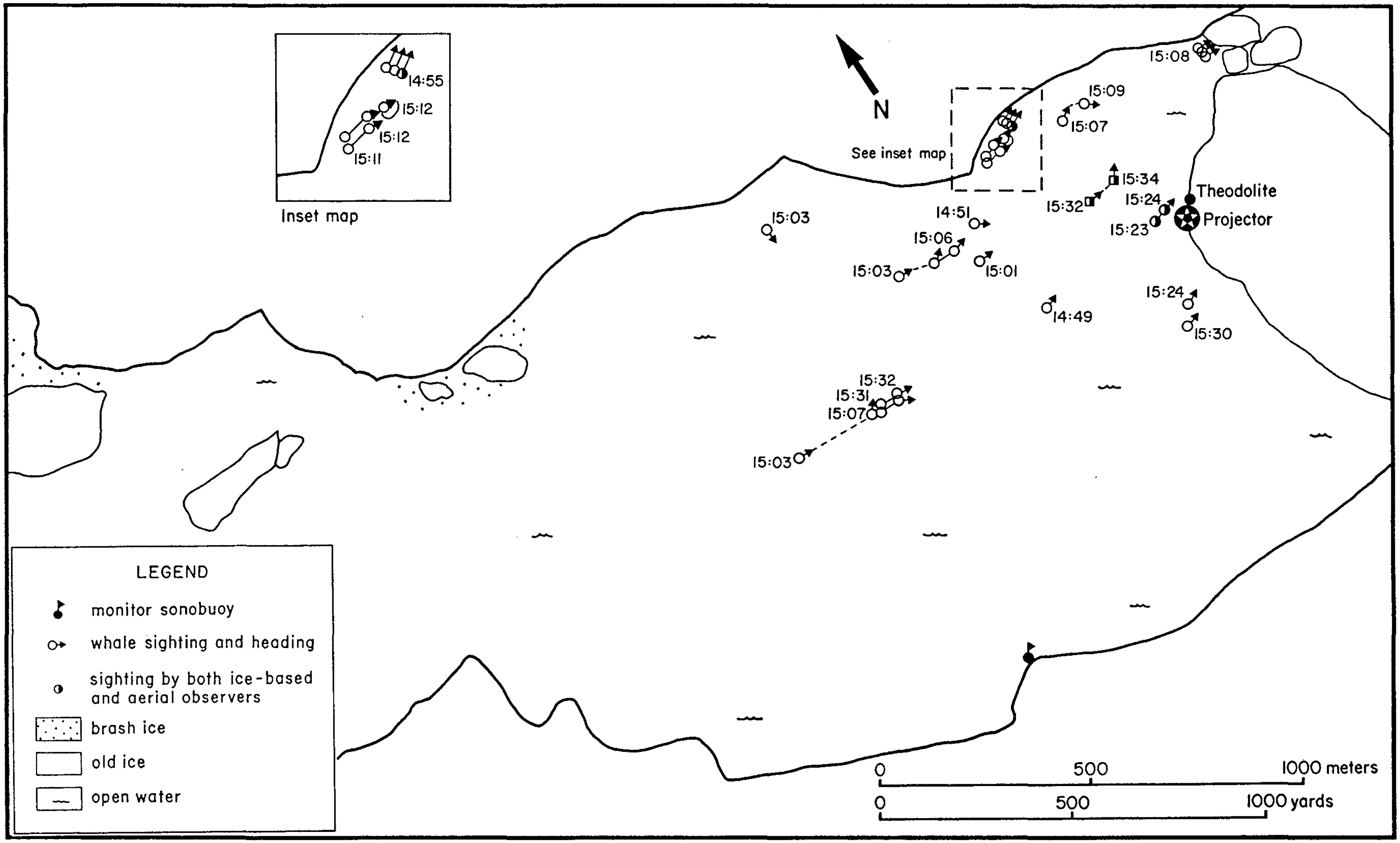


FIGURE 48. Aerial observations of bowhead whale tracks seen prior to the playback experiment amidst the pack ice NE of Barrow, Alaska, 10 May 1990. Sightings are plotted relative to the silent sound projector. The whale seen at 15:32-15:34 (indicated by squares) was being observed when the playback was started. Dashed lines connecting whale symbols represent presumed paths of whales while they were below the surface.

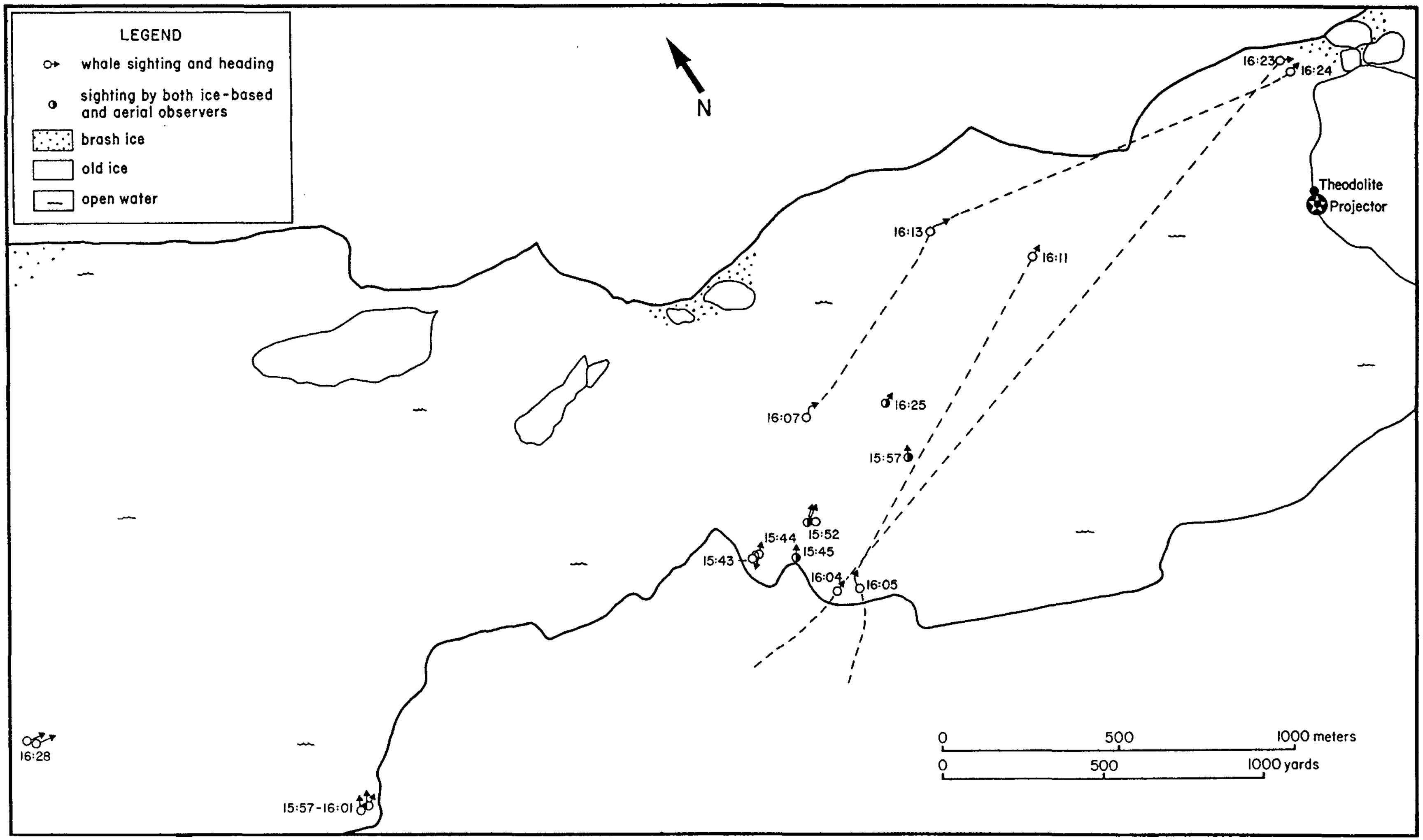


FIGURE 49. Aerial observations of bowhead whale tracks relative to the sound projector broadcasting drilling platform sounds amidst the pack ice NE of Barrow, Alaska, 10 May 1990, times 15:42-16:29. Dashed lines connecting whale symbols represent presumed paths of whales while they were below the surface.

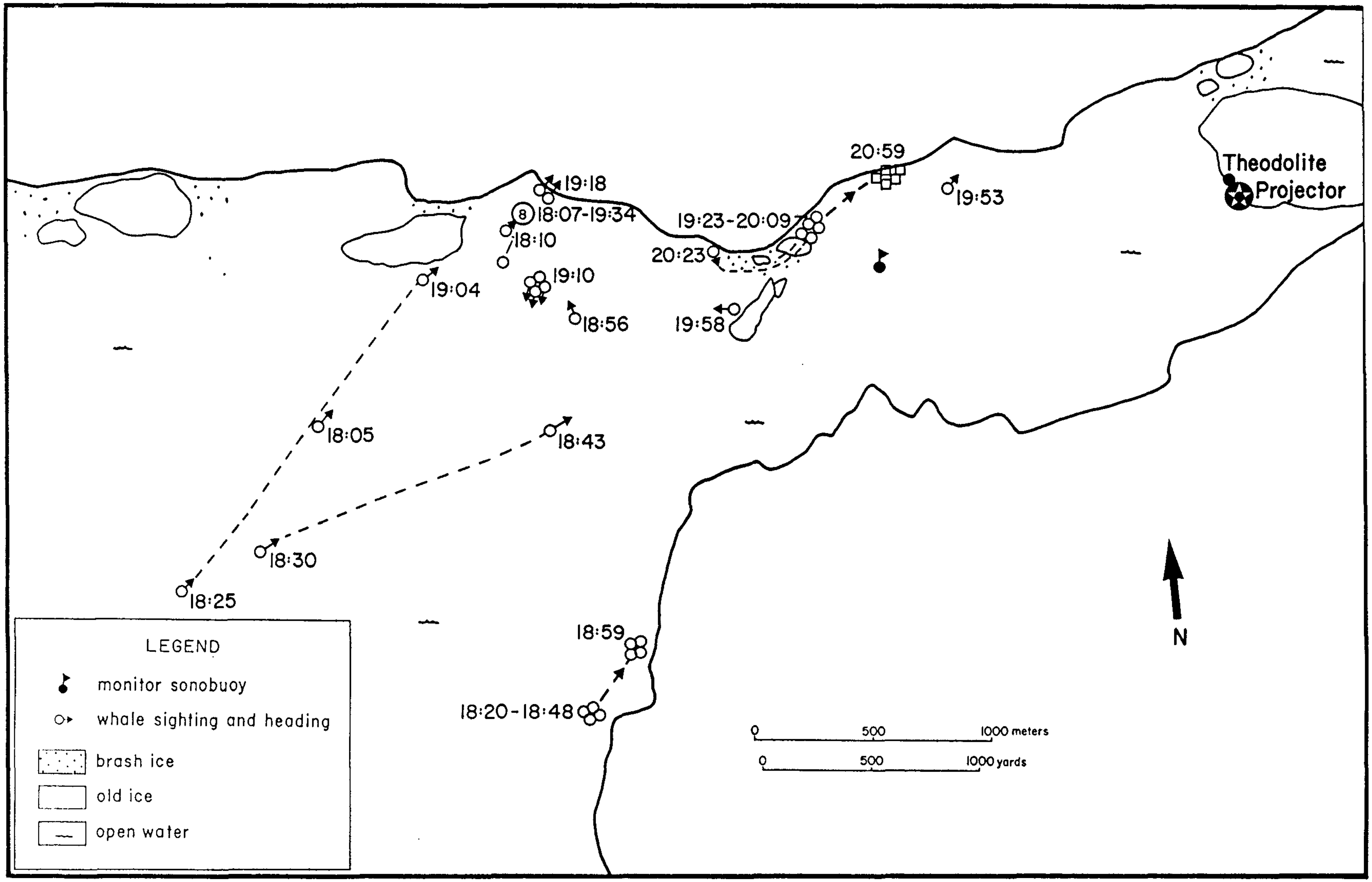


FIGURE 50. Aerial observations of bowhead whale tracks relative to the sound projector amidst the pack ice NE of Barrow, Alaska, 10 May 1990, times 18:05-21:02. The projector was broadcasting drilling platform sounds until 20:51; open squares indicate sightings when the projector was silent. Dashed lines connecting whale symbols represent presumed paths of whales while they were below the surface.

left about 120° so that it was headed almost away from the projector. It then swam away from the projector while remaining at the surface. Approximately 2 min after the projector was turned on, the whale dove and was not recognized again.

The second behavior observation session near the camp was from 15:42 to 16:29; the projector was broadcasting drilling platform sounds throughout. Whales observed during this period were actively socializing or traveling. Those that were traveling continued to move through the northern half of the lead. However, in contrast to results from the pre-playback control period, no whales were observed heading toward the projector (Fig. 49). The bowheads that were observed during this period passed 300-400 m to the north of the operating projector (Table 21).

The third behavior observation session near the camp was from 18:06 to 21:02. The projector was broadcasting drilling noise until 20:50:30. Bowheads that were observed were along the north side of the secondary lead, and were engaged in socializing or a mixture of socializing, resting and traveling (Fig. 50). A group of 8-10 bowheads remained 3 km west of the projector in a small bay along the north side of the secondary lead; these whales socialized more or less continuously throughout this observation session and the previous session. Whales joined and left this group throughout the afternoon and evening.

Noise Exposure.--On 10 May 1990, a 41B sonobuoy was air-dropped into the lead 1.6 km west of the projector at 18:02, to replace the manually-installed buoy, which had failed. By the end of the playback experiment the buoy had drifted to 1.4 km from the projector, as determined by the acoustic travel time. The broadband level (20-1000 Hz) of *Karluk* drilling sounds was 165 dB re 1 μPa-m at the source and 112 dB re 1 μPa at the sonobuoy 1.4-1.6 km away. The broadband ambient level after the playback ended was 94 dB, for a *Karluk* : ambient ratio of 18 dB at a range of 1.4-1.6 km from the projector.

The source levels of the projected *Karluk* sounds were strongest in the 1/3-octave bands centered at 160, 200 and 250 Hz (157-160 dB in each--Fig. 51). At 1.4 km range, the 1/3-octave band levels from at least 40 to 1000 Hz were above the ambient noise levels in the corresponding bands (Fig. 51). At 1.4 km range, the received levels were 112 dB for the 20-1000 Hz band and 107 dB for the 1/3-octave band centered at 160 Hz. These received levels were about 18 dB and 19 dB, respectively, above the natural ambient noise levels in the corresponding bands.

The results from the transmission loss tests, along with the direct measurements at 1.4-1.6 km range, were used to develop equations suitable for predicting received level vs. distance from the projector on 10 May. Appendix B describes how the equations were derived. The equations for the 20-1000 Hz band and for 1/3-octave bands centered near 200 Hz were as follows:

$$RL_{20\text{-}1000\ \mathrm{Hz}} = 116.4 - 0.81\ R - 15\log(R)$$

$$RL_{200\ \mathrm{Hz}} = 111.0 - 0.81\ R - 15\log(R)$$

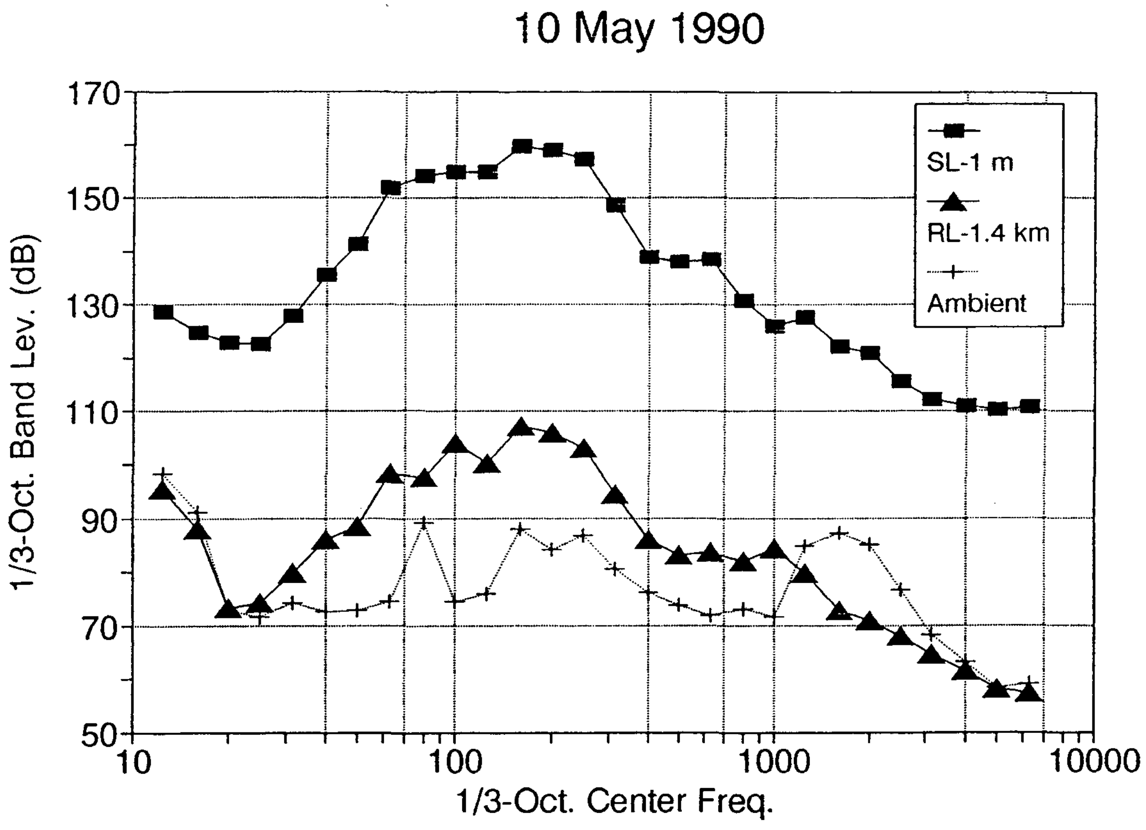


FIGURE 51. Third-octave levels of sounds 1 m from the projector (squares) and at a sonobuoy 1.4 km from the projector (triangles) during playback on 10 May 1990, time 20:49. Plus signs show ambient noise levels at the sonobuoy 2 min later when projector was not operating. Data are in dB re 1 µPa. For additional explanatory notes, see the caption to Figure 44.

Figure 52 shows the received levels predicted by the above two equations in relation to distance from the projector and ambient noise. Estimated received levels for several distances of specific interest, along with the measured values at 1 m and 1.4 km, were as follows:

		Type	20-1000 Hz			Dominant 1/3-Octave			
	Distance (km)	of Data	Drill. (dB)	Amb. (dB)	S:N (dB)	Freq. (Hz)	Drill. (dB)	Amb. (dB)	S:N (dB)
Source level	0.001	Meas.	165	94	71	160	160	88	72
41B Buoy	1.4	Meas.	112	"	18	"	107	"	19
CPA, closest whale	0.035	Est.	138	"	44	"	133	"	45
CPA, 2nd " "	0.115	"	130	"	36	"	125	"	37
"Startled" whale	0.200	"	127	"	33	"	121	"	33
Various whales at	0.350	"	123	"	29	"	118	"	30
to	0.625	"	119	"	25	"	114	"	26

Most bowheads seen near the projector during the 10 May playback had CPA distances 350-625 m from the projector, but one whale came within 35 m and another came within 115 m. The estimated broadband received levels at 35 and 115 m were ~138 and ~130 dB re 1 µPa in the 20-1000 Hz band. Corresponding *Karluk* noise : ambient noise ratios were ~44 and ~36 dB, respectively. Considering the dominant 1/3-octave band, the received levels at 35

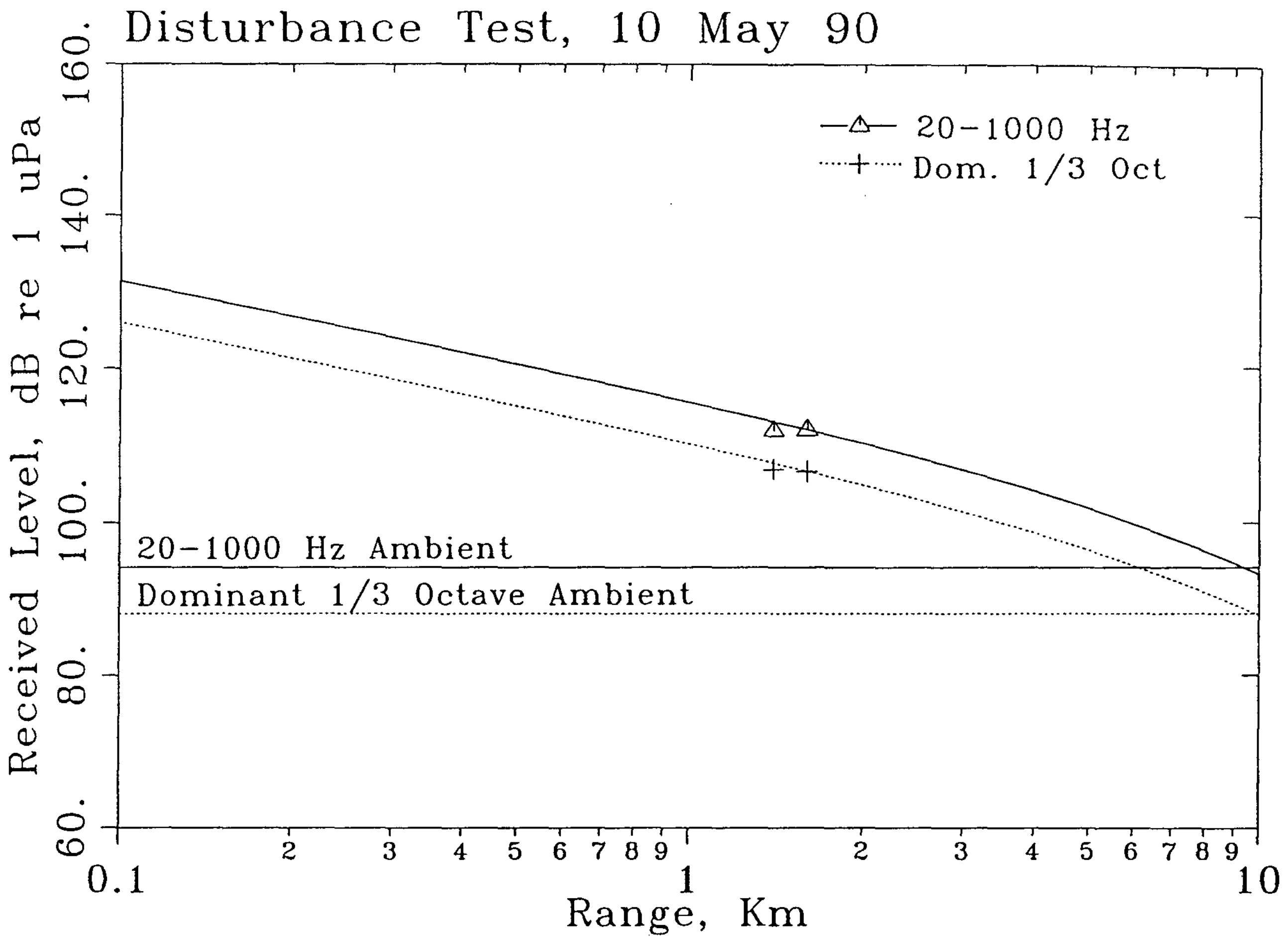


FIGURE 52. Measured and estimated received sound levels vs. range during the *Karluk* disturbance test on 10 May 1990. The triangles and pluses show the measurements via a sonobuoy at 1.4-1.6 km range. The descending curves show the values estimated by the equations given in the text. The average ambient noise levels for the 20-1000 Hz band and the dominant 1/3-octave band are shown as the two horizontal lines.

and 115 m were ~133 and ~125 dB, and the *Karluk* : ambient ratios were ~45 and ~37 dB. It should be noted that received levels within a few meters of the surface, where these whales were when they were seen, may have been a few decibels less than estimated by the above equations. Received levels of low frequency sounds (like the *Karluk* drilling sounds) tend to be reduced within a few meters of the surface because of pressure release effects (Urick 1983).

One bowhead was 200-225 m from the projector when it started broadcasting *Karluk* sounds. This whale turned sharply toward and then away from the projector at the onset of the playback, possibly exhibiting a type of startle response. This whale was potentially exposed to a broadband level of ~127 dB and a peak 1/3-octave level of ~121 dB (*Karluk* : ambient ~33 dB). However, because this whale was at the surface, the actual received levels may have been slightly less.

The numerous bowheads with CPA distances of 350-625 m would have received levels of ~119-123 dB broadband and ~114-118 dB in the dominant 1/3-octave band (Table 21). Those received levels were ~25-30 dB above the natural ambient noise levels in the corresponding bands. Estimated received levels for all whales seen within 1 km of the projector during the playback are listed in Table 21.

11 May 1990 Playback

The ice camp was set up on the SE side of a large ice pan near the north side of the main nearshore lead. This pan rotated counter-clockwise by 60° during the day. Distorted drilling sounds were projected briefly from 15:26 to 15:40 and normal drilling sounds were broadcast from 16:28 to 17:48. The Twin Otter crew observed bowheads migrating ENE along the middle of the lead south of the ice camp. Most whales seen during both control and playback periods passed 1.5 km or more south of the projector. Near the end of the day, a helicopter overflight experiment was conducted on two bowheads that had been followed for ~1 h with the projector silent (see "Bowhead Reactions to Aircraft", p. 264).

Ice-based Observations.--A total of 11 bowheads (8 groups) were observed from the ice camp while the projector was silent. The closest sightings to the projector were 200 m away (19:10) and 535 m away (13:00, Table 22). All other sightings were >1500 m away. The two long tracks shown in Figure 53 may have been straighter than shown; estimates of long distances are imprecise when theodolite height is low.

Only one bowhead was seen from the ice camp when the projector was operating; it was approximately 2000 m SE of the projector.

Aerial Observations.--Four behavioral observation sessions were conducted by the Twin Otter crew on 11 May 1990. The first session (control) started along the pack ice edge SW of the ice camp at 11:45. A group of 4-6 traveling bowheads (with 1 or 2 others joining them for a brief period) was followed northeastward along the pack ice edge for a short distance (Fig. 54). They then turned to the right and traveled ENE across the open lead, passing several kilometers south of the ice camp. The projector was silent.

During the second session (also control), starting at 13:48, a single bowhead was followed along the pack ice edge and then ENE into the open lead (Fig. 54). The session was terminated due to fuel limitations when the whale was still >5 km SW of the camp. The projector was silent.

During the third session, starting at 15:59, a group of 3-5 bowheads was followed from ~8 km SW of the ice camp to ~4.0 km SSE of the ice camp (Fig. 54). The projector was initially off, but it was turned on at 16:28 when the whales were approaching at a distance of about 5.2 km. There was no change in course when the projector was turned on, and these whales did not deviate from their straight-line path past the projector. Drilling sounds were being projected at 17:10 when the whales were at their closest point of approach, 3.5-3.6 km from the projector.

Two more bowheads were followed from SW of the projector (starting at 17:54) to SSE of the projector after the drilling noises had stopped. They followed a path similar to the paths

Table 22. Summary of sightings of bowhead whales passing close to the sound projector on 11 May 1990 when the projector was silent and when it was operating along the north side of the nearshore flaw lead NE of Barrow. Ice-based observations of bowheads with CPA up to 2 km and aerial observations of bowheads with CPA up to 3.5 km from the projector are included in this table but all distances >1000 m should be considered approximate.

Time	Radial Distance Followed From Projector (m)[a]	CPA (m)	Determination of CPA[b]	Sound Levels[c]	Nature of Track
Silent Projector--Ice-based observations					
12:47	-2780 to -1820	1650	1	NA[e]	SSW to S of projector heading E
13:00	+535 to +571	<535[d]	1	NA	E of projector heading ENE
18:40	single sighting	<1520	1	NA	SSW of projector heading ENE
19:10	single sighting	200	2	NA	SSW of projector heading NNE
Silent Projector--Aerial observations					
18:48[f]	-6000 to -3000[f]	3000[f]	2	NA	SSW of projector in open lead heading NE then ENE
Operating Projector--Ice-based observations					
17:18	single sighting	2000	2	114 / 110	SE of projector, heading unknown
Operating Projector--Aerial observations					
17:10	-7200 to +3900	3500	2	109 / 104	SSW to SSE of projector in open lead heading NE to ENE

[a] - indicates that whales are ≥135° and ≤315°T from the projector (approaching); + indicates that whales are ≤135° or ≥315°T from the projector (moving away).

[b] 1 = measured by theodolite or tape, 2 = visual estimate, 3 = estimate based on nearby surfacings, 4 = estimates based on distant surfacings (possibly unreliable).

[c] Estimated received level (dB re 1 μPa) of projected noise at CPA. Left: level in the 20-1000 Hz band. Right: level in the dominant 1/3-octave band.

[d] < indicates that whales were heading toward the projector when last seen.

[e] NA is not applicable.

[f] These whales were overflown with a Bell 212 helicopter at 18:56.

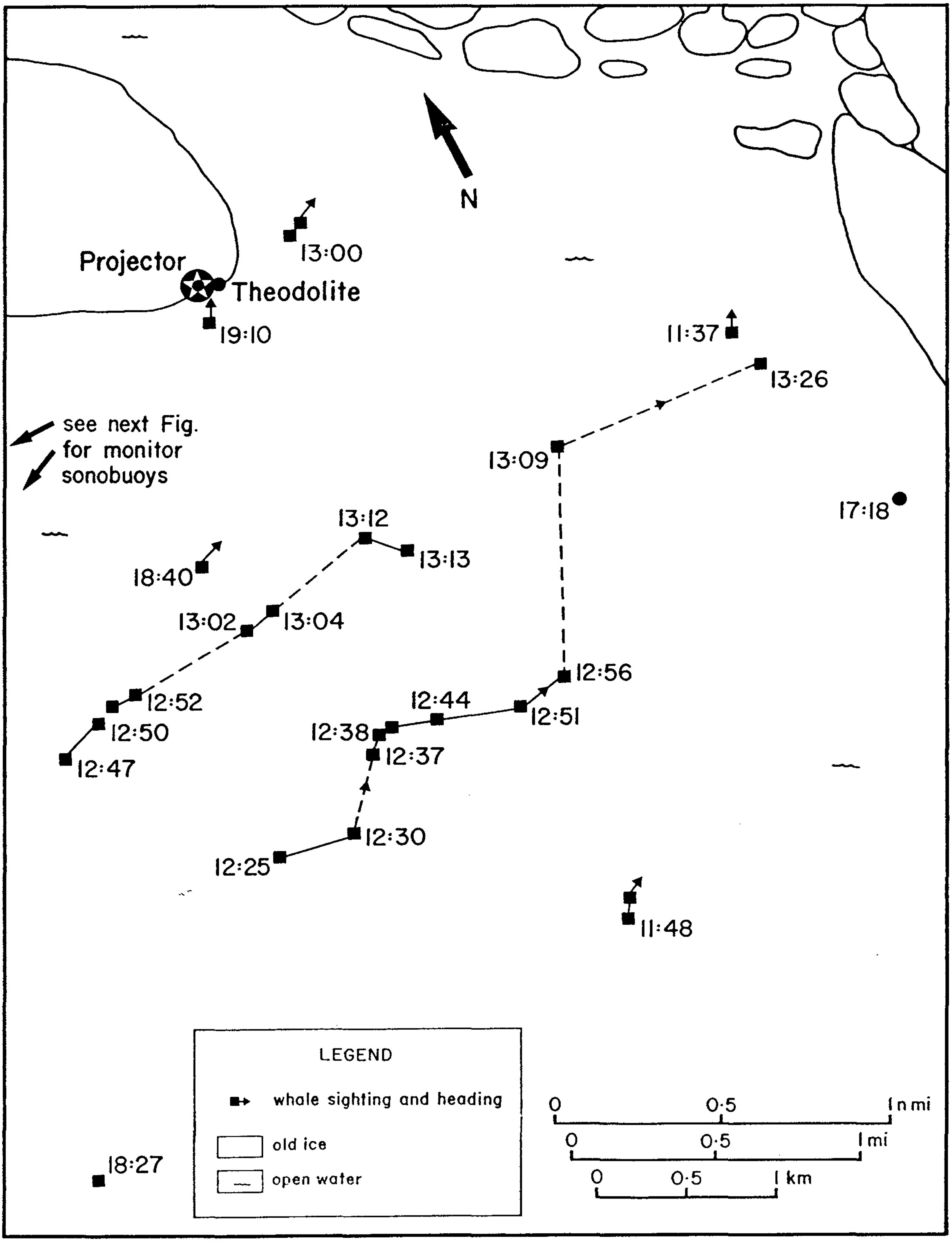


FIGURE 53. Ice-based observations of bowhead whale tracks relative to the sound projector amidst the pack ice NE of Barrow, Alaska, 11 May 1990. The circle represents the one sighting when the projector was broadcasting drilling platform sounds. The two long tracks may have been straighter than shown; estimates of long distances are imprecise when theodolite height is low.

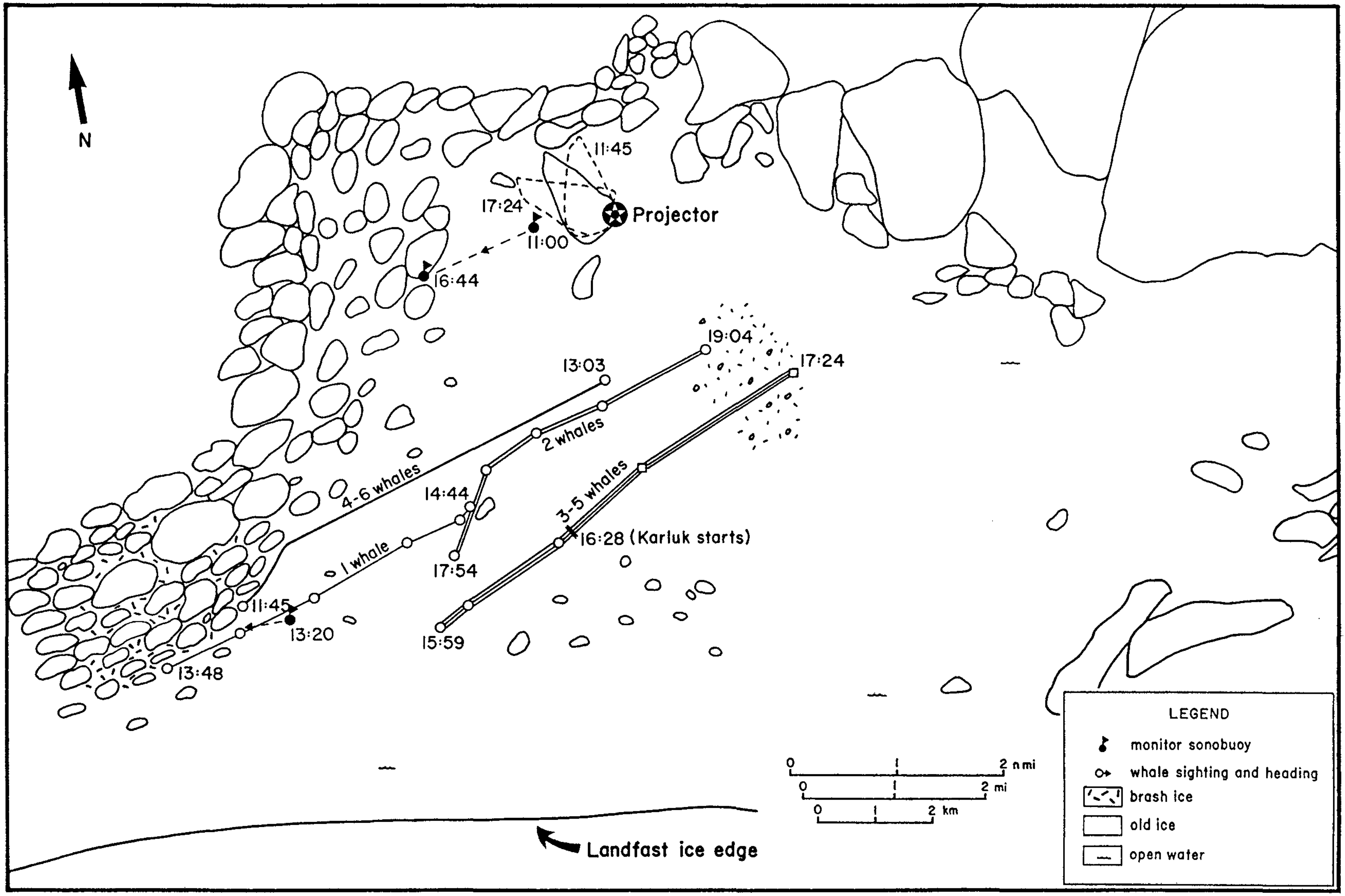


FIGURE 54. Aerial observations of tracks of groups of bowhead whales relative to the sound projector amidst the pack ice NE of Barrow, Alaska, 11 May 1990. *Karluk* drilling sounds were projected from 16:28 to 17:48.

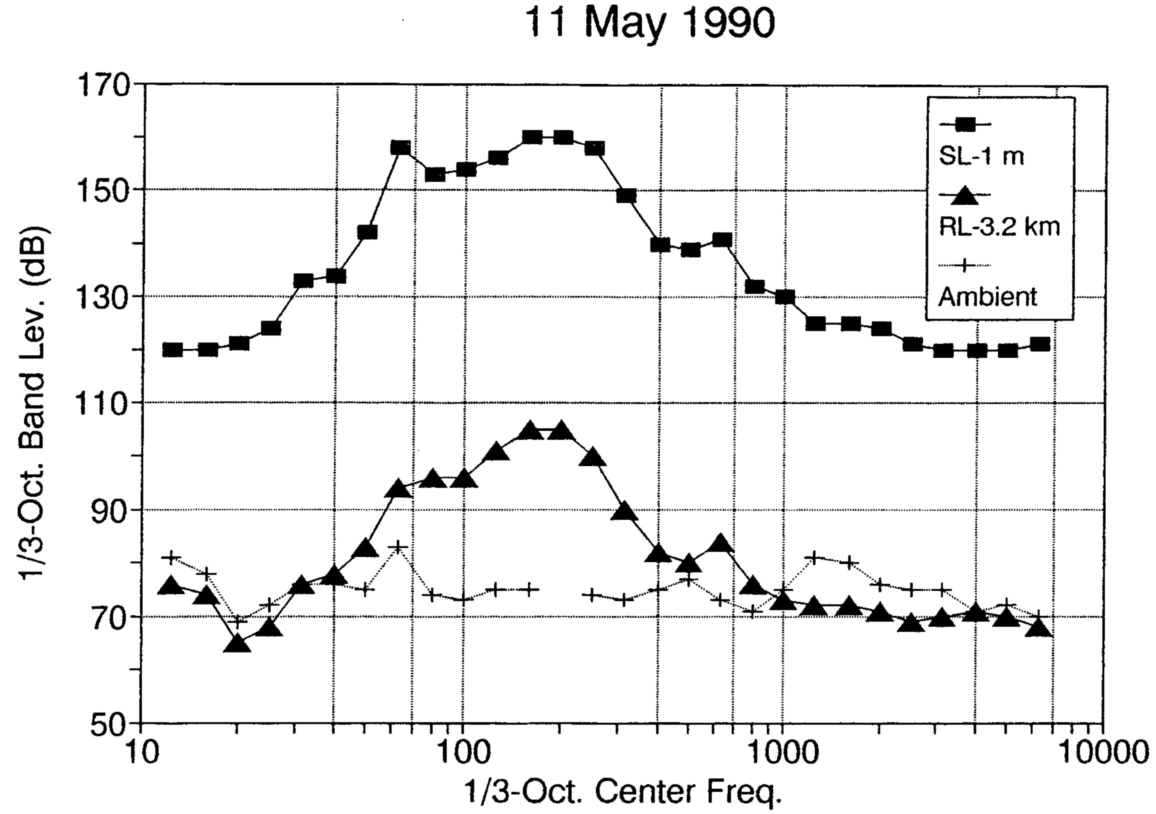


FIGURE 55. Third-octave levels of sounds 1 m from the projector (squares) and at a sonobuoy 3.2 km from the projector (triangles) during playback on 11 May 1990, time 16:35. Plus signs show ambient noise levels at the sonobuoy at 15:22 when projector was not operating. Data are in dB re 1 μPa. For additional explanatory notes, see the caption to Figure 44.

of the previous three groups (Fig. 54). At 18:56, near the end of the session, a helicopter overflight experiment was conducted on these whales (see "Bowhead Reactions to Aircraft").

Noise Exposure.--On 11 May 1990, a 57A buoy was deployed manually ~1.4 km west of the ice camp at 11:00, along the edge of an ice pan separate from the one supporting the camp. The two pans subsequently drifted apart. During the playback period in late afternoon, this sonobuoy was 3.2-3.6 km from the camp, based on the acoustic travel time. A 53B DIFAR buoy was air-dropped along the pack-ice edge about 9 km southwest of the ice camp at 13:20. It was 9.6-9.9 km from the projector during the playback.

The broadband source level of the projected *Karluk* drilling sounds was 166 dB, and the 1/3-octave bands with the strongest levels were centered at 160 and 200 Hz (159.5 dB for each; Fig. 55). The broadband received level 3.2 km away was 110 dB, which was ~19 dB above ambient. At that distance, the 1/3-octave band levels from about 50 Hz to 630 Hz were above the ambient levels in the corresponding bands (Fig. 55). The strongest 1/3-octave received levels were those centered at 160 and 200 Hz (Fig. 55; 105 dB for each; S:N = ~27 dB).

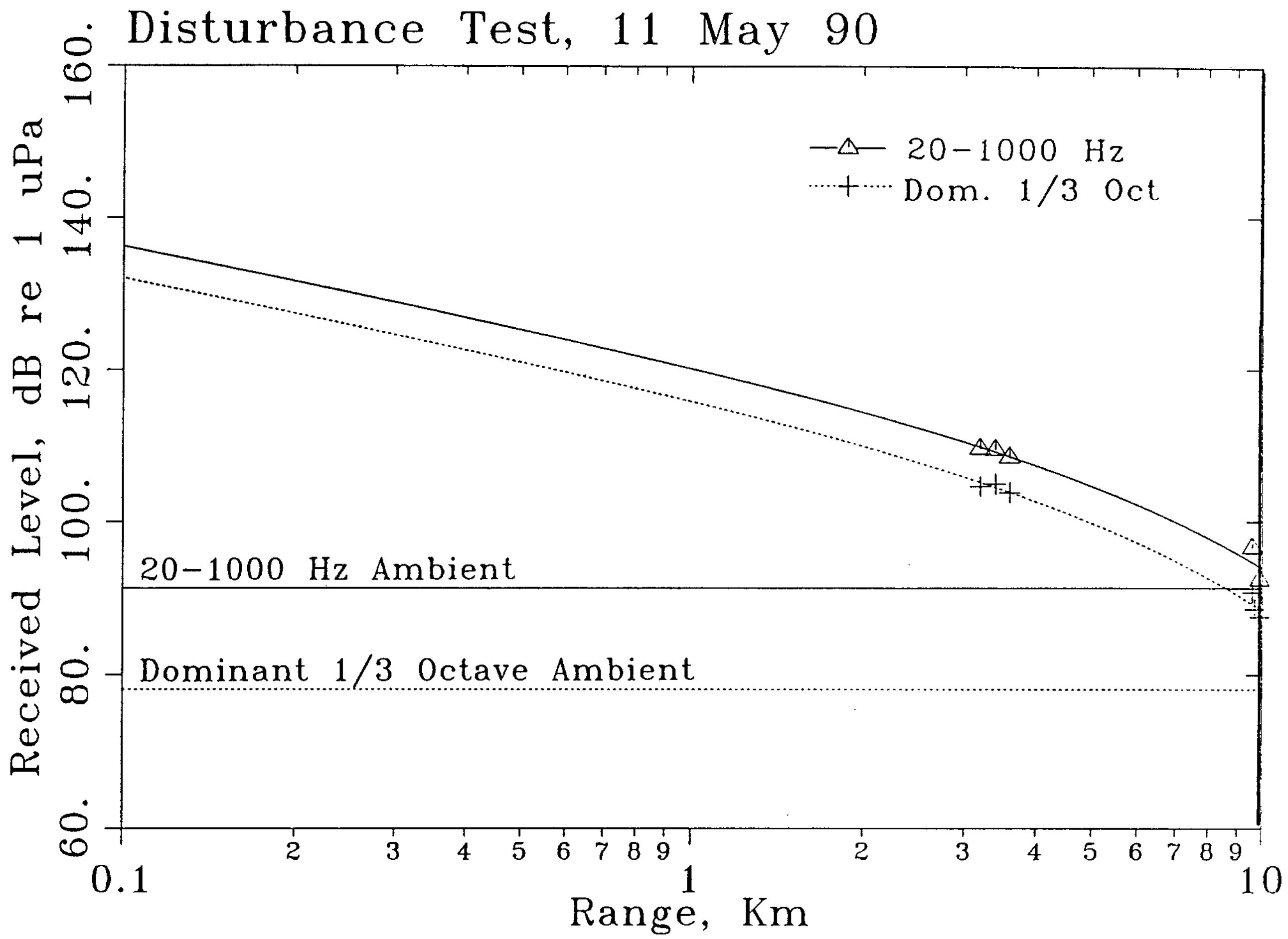


FIGURE 56. Measured and estimated received sound levels vs. range during the *Karluk* disturbance test on 11 May 1990. The triangles and pluses show the measurements via two sonobuoys. The descending curves show the values estimated by the equations given in the text. The average ambient noise levels for the 20-1000 Hz band and the dominant 1/3-octave band are shown as the two horizontal lines.

The results from the transmission loss tests, along with the direct measurements at 3.2-3.6 km and 9.6-9.9 km range, were used to develop equations suitable for predicting received level vs. distance from the projector on 11 May:

$$RL_{20\text{-}1000\ Hz} = 121.4 - 1.24\ R - 15 \log (R)$$

$$RL_{200\ Hz} = 117.2 - 1.37\ R - 15 \log (R)$$

Appendix B describes how the equations were derived. Figure 56 shows the received levels predicted by these equations in relation to distance from the projector and ambient noise. Estimated received levels for two distances of specific interest, along with measured values at 1 m and 3.2 km, were as follows:

		Type	20-1000 Hz			Dominant 1/3-Octave			
	Distance (km)	of Data	Drill. (dB)	Amb. (dB)	S:N (dB)	Freq. (Hz)	Drill. (dB)	Amb. (dB)	S:N (dB)
Source level	0.001	Meas.	166	91	75	160/200	160	78	82
57A Buoy	3.2	Meas.	110	"	19	160/200	105	"	27
Bhds @ CPA	3.5	Est.	109	"	18	"	104	"	26
Bhd @ CPA	2	Est.	113	"	22	"	108	"	30

The CPA distance for the bowheads observed from the aircraft during the 11 May playback was 3.5 km. The drilling sounds there would be expected be ~1 dB weaker than those at the sonobuoy 3.2 km from the projector. However, levels at the whale location might have been slightly higher than calculated because there was no ice between the projector and the whales, whereas there was ice along part of the path between the projector and the sonobuoy. The bowhead seen ~2 km from the ice camp by ice-based observers was probably exposed to levels ~3 dB higher than those measured 3.2 km from the ice camp.

13 May 1990 Playback

The ice camp was set up along a long, narrow, straight secondary lead that extended ESE from the eastern end of the main nearshore lead (Plate 4). The camp was placed here after our aerial reconnaissance found that many bowheads were traveling along this narrow lead. Along the ~8 km stretch where the secondary lead was well defined, its width varied from 300 m at the western end to 125 m east of the ice camp. The lead was ~200 m wide at the ice camp, which was ~6 km east of the western end of the well-defined part of the secondary lead.

The long, narrow lead formed an obvious migration corridor for eastbound bowheads, and heavy ice north and south of this lead appeared to greatly limit the alternative routes available to bowheads. To the north of the secondary lead, there was a large and continuous pan 15-20 km long and >8 km wide. This pan apparently prevented whales in the long narrow lead from diverting to the north or northeast. There was also a large pan south of the narrow lead. However, 3.8 km west of the camp a tertiary lead branched to the south from the ice camp lead (Plate 4). This tertiary lead provided the only obvious alternative corridor into which bowheads in the ice camp lead might turn. However, the ice camp lead was along the southern edge of the usual bowhead migration corridor, and the water depth was only ~27 m. Hence, we would not have expected bowheads to turn south along the tertiary lead under undisturbed conditions.

Distorted *Karluk* drilling sounds were projected from the ice camp from 13:01 to 15:06, and normal drilling sounds were projected from 16:10 to 18:46. During the first of these periods the J-11 projector was gradually failing, and the sounds were becoming progressively weaker and less *Karluk*-like. A backup J-11 was then deployed and used during the second playback period.

Ice-based Observations.--Large numbers of bowheads moved by the ice camp throughout the day. About 138 bowhead whales were estimated to have passed the ice camp during the 9.1 h while it was present. This is an approximation because of uncertainties in discriminating "new" and "repeat" sightings, and the likelihood that some passing whales were missed.

A total of ~27 bowheads (~18 groups or singletons) were sighted during the period of control observations from 11:30 to 13:01. Most of the whales sighted were traveling east along

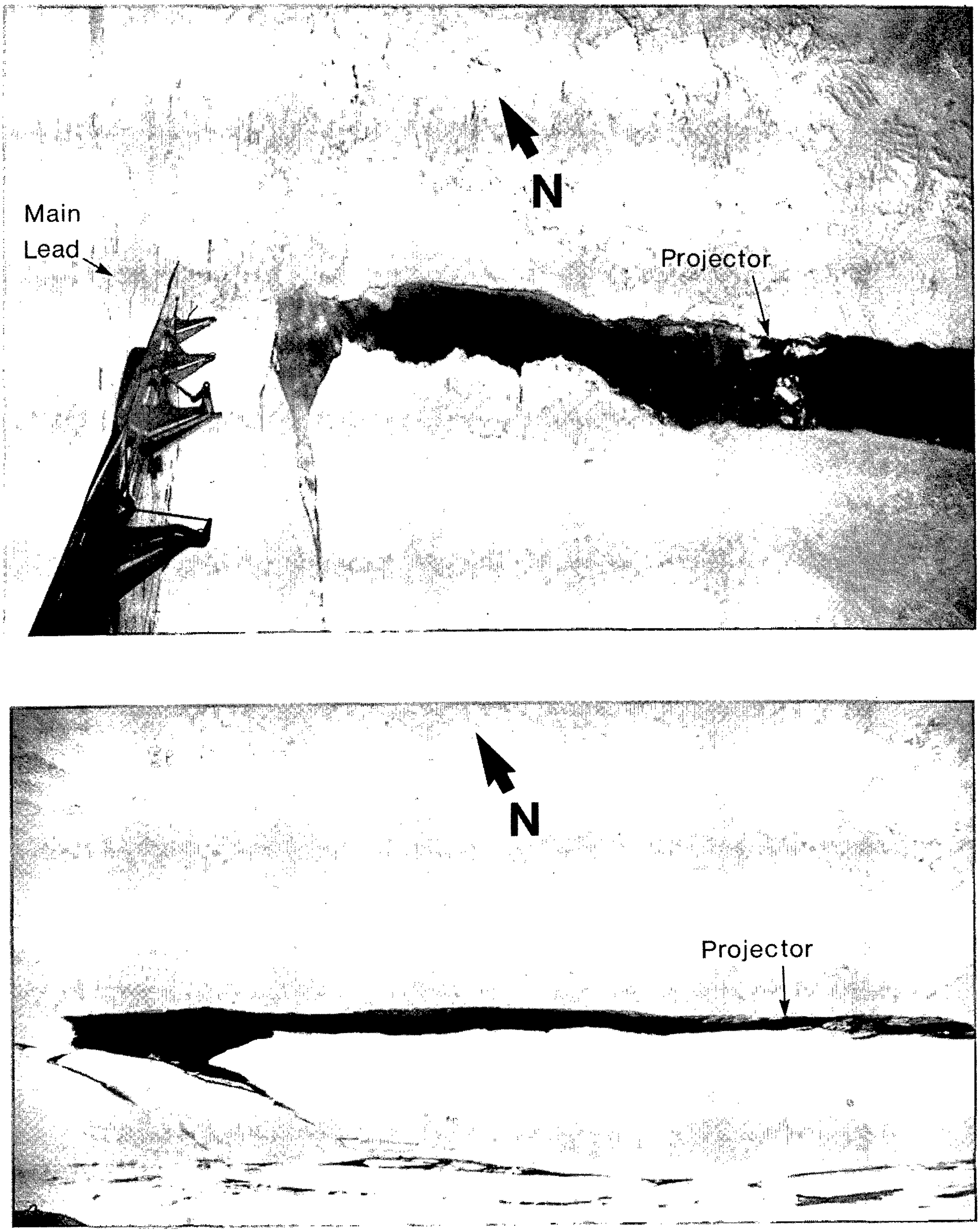


Plate 4. Ice conditions near the projector site on 13 May 1990, as viewed from two directions. Note the main nearshore lead on the left of the upper panel. Whales approached the projector site from the middle of the main nearshore lead, swimming along the long, narrow lead. **Note**: photos are mounted with north upward, although that was not the direction in which the camera was pointed.

the northern half of the lead (Fig. 57A). The closest approaches to the projector were 50 m (estimated) and 85-90 m (measured by theodolite) (Table 23A). Because there was a shelf of new ice south of the projector (stippled area on Fig. 57), whales could not surface closer than 40 m from the projector.

From 13:01 to 15:06, when the projector was broadcasting distorted drilling sounds, ~28 bowheads (~19 groups or singletons) were sighted by observers at the ice camp. Whales seemed to approach the projector from the west along the northern half of the lead, as they did during the preceding control period. However, when they were ~1 km west of the projector, some of them appeared to pause, reorient toward the north, and continue eastward after some hesitation. As they approached to within 400 m of the projector, they crossed the lead to the southern side (Fig. 57B). The closest whales seen were 206, 207 and 248 m (measured by theodolite) from the projector and along (or oriented toward) the southern edge of the lead (Table 23C). The headings of all of these whales indicated that their CPA distances were somewhat closer to the projector (~155-190 m) than their closest observed positions (Table 23C). However, there were no sightings near the north edge of the lead adjacent to the projector, contrary to results during the preceding control period.

There were few sightings during the quiet period between the two playback periods. Nineteen minutes after the projector was turned off, a single bowhead was observed traveling SE 450 m SE of the projector close to and along the south side of the lead (Fig 57C). This whale was probably ~1 km west of the projector (or closer) when the distorted noise was turned off (assuming that it traveled at 4.5 km/hr).

Two bowheads were seen during the control period from 15:36 (30 min after cessation of noise) to 16:10. The first was seen 240 m SSE of the projector and in the middle of the lead (Fig. 57C; Table 23A). The other was 1 km WNW and along the northern ice edge.

Undistorted drilling sounds were projected from 16:10 to 18:46, and ~65 bowheads (~40 groups or singletons) were observed during this period. As during previous periods, bowheads approaching from the west were seen primarily along the northern edge of the lead and were oriented parallel to the lead until they approached within ~1 km of the projector. When whales approached to 500-750 m from the projector, they generally turned right and crossed the lead to the south side before passing the projector (Fig. 57D,E). The closest observed whale was 123 m south of the projector at 18:35. Given its heading, its actual CPA distance was probably ~110 m just before it was seen. Several whales were seen ~200 m SW and S from the projector as they passed it but their CPA was probably closer. Based on headings, interpolated positions and multiple theodolite locations for these whales, their CPAs were probably ~175-195 m from the projector (Table 23E).

Fifteen bowheads (10 groups or singletons) were seen from the ice camp after the projector stopped broadcasting drilling sounds. One of these whales was observed 400 m SE of the projector and in the central part of the lead 14 min after the projector was shut off (Fig. 57E); this whale was probably within 1 km of the projector when it was operating. All bowheads sighted during this period were in the northern or central part of the lead. Once the projector was shut off, whales traveled along the northern ice edge past the projector rather than crossing to the south side of the lead. A group of two whales passed 62 m (measured by theodolite)

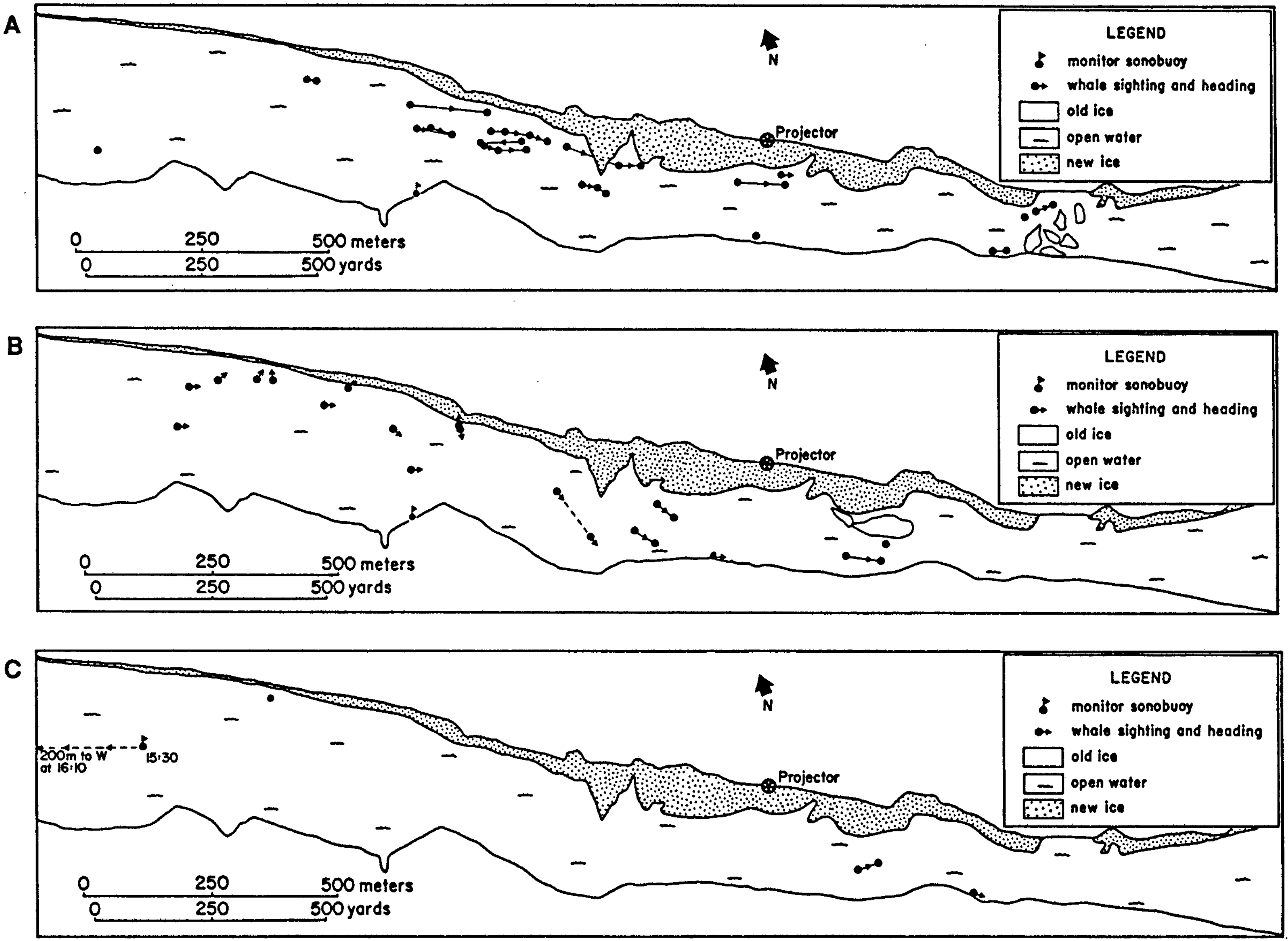


FIGURE 57. Ice-based observations of bowhead whale tracks passing the sound projector amidst the pack ice NE of Barrow, Alaska, 13 May 1990. (**A**) projector silent, 11:30 to 13:01; (**B**) distorted drilling platform sounds, 13:01 to 15:06; (**C**) projector silent, 15:06 to 16:10. Dashed lines represent presumed paths of whales while they were below the surface.

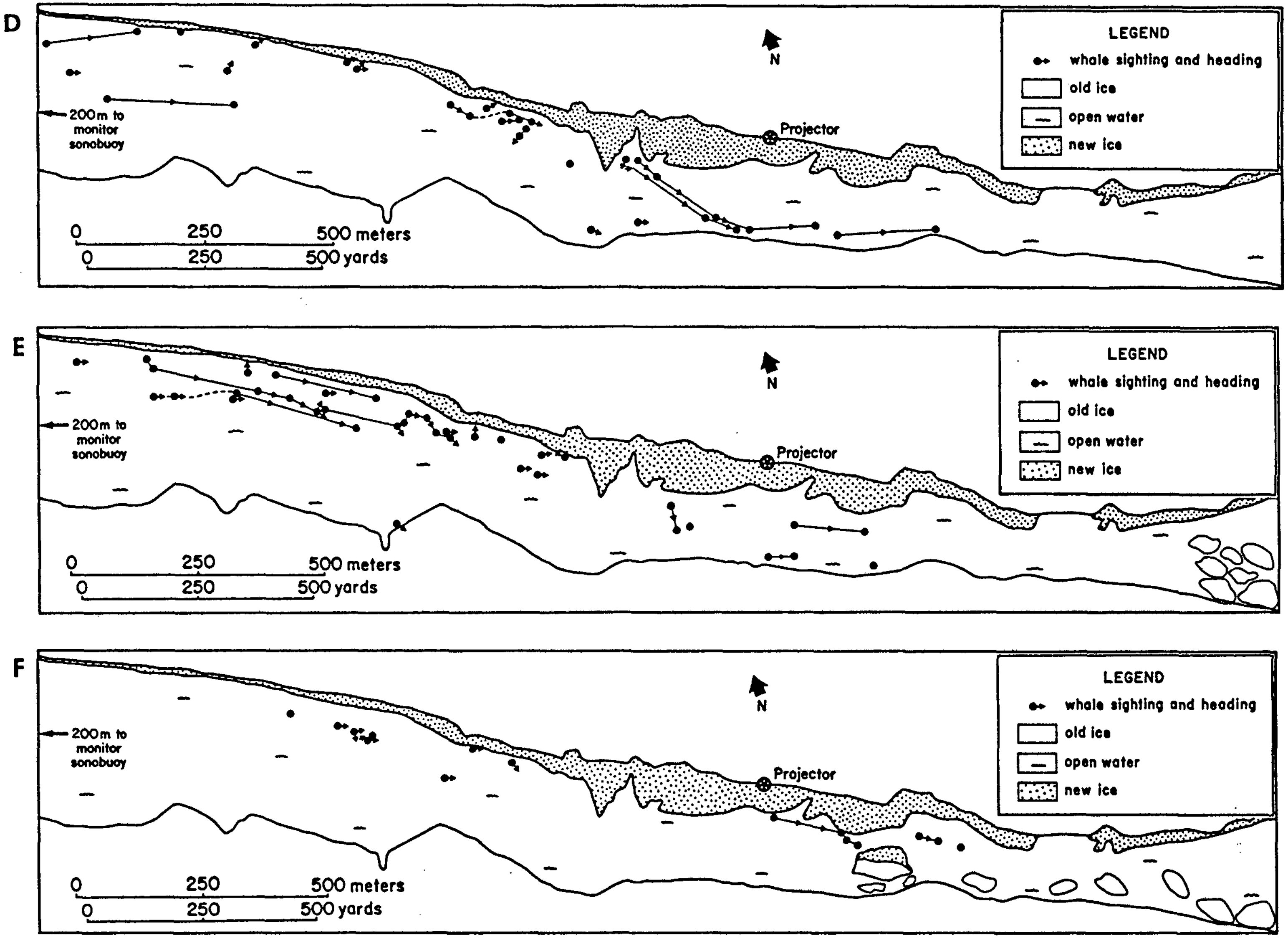


FIGURE 57. Continued. (D) and (E) normal drilling platform sounds, 16:10 to 17:35 and 17:35 to 18:46; (F) projector silent, 18:46 to 20:35.

Table 23. Summary of sightings of bowhead whales passing close to the sound projector on 13 May 1990 when the projector was silent and when it was operating on the north side of a long narrow lead amidst the pack ice NE of Barrow. Only sightings with CPA within 1 km of the projector are included in this table.

Time	Radial Distance Followed From Projector (m)[a]	CPA (m)	Determination of CPA[b]	Sound Levels[c]	Nature of Track
A. Silent Projector--Ice-based observations					
11:17	single sighting	100	2	NA[e]	S of projector; no heading recorded
11:26	single sighting	187	1	NA	SSW of projector along S ice edge
11:30	-695 to -548	<548[d]	1	NA	NW of projector along N ice edge heading ESE
11:34	-374 to -335	<335	1	NA	WSW of projector heading SE in mid lead
11:38	-535 to -429	<429	1	NA	Following N side of lead
11:40	+496 to +518	<496	1	NA	Heading ESE along S side of lead
11:56	-550 to -472	<472	1	NA	Traveling ESE in mid lead
12:06	single sighting	50	2	NA	S of projector heading SE along ice edge
12:10	single sighting	<530	1	NA	Along N side of lead; no heading recorded
12:13	single sighting	<896	1	NA	Along N side of lead heading ESE
12:18	-685 to -616	<616	1	NA	Mid lead heading ESE
12:20	-387 to -266	<266	1	NA	Following along N ice edge heading ESE
12:28	-481 to -562	481	1	NA	Mid lead heading WSW away from projector
12:31	+553 to +581	<553	1	NA	Following N side of lead heading E
12:37	-100 to +90	85	3	NA	S of projector heading ESE
15:53	+240 to +260	<240	1	NA	Mid lead heading E
16:07	single sighting	1000	2	NA	Along N side of lead
19:45	-857 to -792	-792	1	NA	Along N side with various headings
20:16	single sighting	957	1	NA	Along N side of lead; no heading recorded
20:16	single sighting	506	1	NA	Along N side of lead heading E
20:25	single sighting	600	2	NA	Along N side of lead heading ESE
B. Silent Projector--Aerial observations[f]					
19:08[f,g] (#17-1)	-2000 to +1800	60	3	NA[f]	Along N side of lead heading ESE
19:13[f,g] (#17-2&3)	-2000 to +150	60	1	NA[f]	Along N side of lead heading ESE

Continued...

Table 23. Continued.

Time	Radial Distance Followed From Projector (m)[a]	CPA (m)	Determination of CPA[b]	Sound Levels[c]	Nature of Track
C. Operating Projector (Distorted)--Ice-based observations					
13:09	-290 to -268	<268	1	>132 / >128	W of projector in mid lead crossing SE to S side of lead
13:22	single sighting	<837	1	>122 / >118	NW of projector along N side of lead heading E under ice
13:25	single sighting	<736	1	>122 / >118	WNW of projector heading SSE toward S ice edge
13:29	+248 to +300	155	3	131 / 126	Moving ESE along south side of lead E of camp
13:32	single sighting	500	2	123 / 118	single sighting
13:36	-226 to -206	190	3	128 / 122	W of projector moving SSE toward S side of lead
13:40	single sighting	180	3	127 / 122	SSW of projector along S side of lead moving SSE
13:46	175 to 288	<288 (175)	1 (2)	>123 / >117	SE of projector in mid lead; seen closer to projector but distance and heading not recorded
13:55	single sighting	877	1	114 / 107	NW of projector near N side of lead heading ESE
15:24[h]	single sighting	<452	1	NA[h]	SSE of projector heading SE; was probably <1 km from the operating projector earlier
D. Operating Projector (Distorted)--Aerial observations					
14:03[g] (#15-2)	-5200 to +4100	<996	1	>111 / >104	Follow N side of lead to 1 km NW; headed under ice heading ENE and next seen 2.4 km ESE of projector
14:13[g] (#15-3)	-5700 to +4100	<370	1	>114 / >109	Generally follow N side of lead but dove under ice to E several times when <1 km W of the projector; when 400 m WNW of projector crossed to S side of lead and dove heading S. Next seen 17 min later 1300 m ESE of projector.

Continued...

Table 23. Continued.

Time	Radial Distance Followed From Projector (m)[a]	CPA (m)	Determination of CPA[b]	Sound Levels[c]	Nature of Track
14:13[g] (#15-4)	-5700 to +4100	<370	1	>114 / >109	Follow center of lead; turned toward N side of lead when <1 km WNW of projector; when 400 m NNW of projector crossed to S side of lead and dove heading S near the S side of the lead
14:14 (#15-6)	single sighting	<370	1	>114 / >109	Along N side of lead, heading toward projector when it dove
14:15 (#15-1)	-2100 to +4200	<370	1	>114 / >109	Follow N side of lead but dove E under ice when <1 km NW of projector. Heading S when it dove along the N ice edge WNW of projector
E. Operating Projector (Normal)--Ice-based observations					
16:29	single sighting	408	1	131 / 127	WNW of projector mid lead
16:31	single sighting	<406	1	>131 / >127	W of projector moving SE angling under ice edge on S side
16:33	-542 to -510	<510	1	>130 / >125	WNW of projector heading ESE then turns to ENE as it dives under ice on N side
16:37	+236 to +370	195	3	135 / 131	SSE of projector heading ESE along ice edge on S side
17:03	-273 to +193	176	3	136 / 131	Initially WNW of projector along N side of lead; crossed to S side of lead and passed projector along S side of lead
17:12	-489 to -501	489	1	130 / 126	WNW of projector along N ice edge heading W
17:16	single sighting	837	1	126 / 122	Two whales along ice edge N side of lead; one heading E other heading ESE
17:17	single sighting	<314	1	>133 / >128	W of projector along S ice edge heading ESE
17:25	-294 to -192	185	3	136 / 131	Initially WNW of projector along N side of lead; turned to W then back to E then SSW and crossed to south side of lead and headed ESE
17:29	single sighting	<574	1	>129 / >125	WNW of projector along N ice edge heading E under the ice

Continued...

Table 23. Continued.

Time	Radial Distance Followed From Projector (m)[a]	CPA (m)	Determination of CPA[b]	Sound Levels[c]	Nature of Track
17:30	single sighting	<857	1	>126 / >122	NW of projector along N ice edge heading E under the ice
17:32	single sighting	<501	1	>130 / >125	SE of projector among small pans along S ice edge heading ESE
17:33	-641 to -482	<482	1	>130 / >126	WNW of projector along N ice edge heading SSE
17:43	single sighting	<888	1	>126 / >121	NW of projector along N ice edge heading ESE
17:45	single sighting	<455	1	>131 / >126	WNW of projector mid lead heading ESE
17:47	single sighting	<579	1	>129 / >124	NW of projector along N ice edge heading NNE
17:49	single sighting	640	1	128 / 124	NW of projector heading ESE
17:56	single sighting	<708	1	>128 / >123	W of projector along S ice edge heading SE under ice
18:06	-993 to -784	<784	1	>127 / >122	NW of projector along N ice edge heading E
18:08	-1245 to -629	<629	1	>128 / >124	NW of projector along N ice edge heading E. Changed direction several times when 750 m WNW of projector and heading SSE when last sighted.
18:24	single sighting	<489	1	>130 / >126	WNW of projector mid lead heading ESE
18:34	+123 to +230	110	3	138 / 134	S of projector in mid lead heading SE
19:00[1]	single sighting	400[1]	1	131 / 127	SSE of projector along S ice edge heading SE
F. Operating Projector (Normal)--Aerial observations					
17:43 (#16-11)	-2400 to -400	400	2	131 / 127	Initially followed N side of lead ESE. In mid lead when 420 m WNW of projector; turned S and heading S when dove under ice S side of lead.
17:44 (#16-13)	-2400 to +1300	<180 (seen at 450)	4	>136 / >131	Travel through middle of lead toward; slowed and moved to N side as passed projector but no deviations noted.
17:45 (#16-22)	single sighting	<450	2	>131 / >126	NW of projector along ice edge; heading ENE as it dives (50° left of projector).
17:45 (#16-23 & 45)	single sighting	<530	2	>130 / >125	NW of projector near ice edge; heading E as it dives (40° left of projector).

Continued...

Table 23. Concluded.

Time	Radial Distance Followed From Projector (m)[a]	CPA (m)	Determination of CPA[b]	Sound Levels[c]	Nature of Track
17:47 (#16-24)	single sighting	<510	2	>130 / >125	Mid lead; no heading recorded.
17:48 (#16-1)	-6000 to +2700	<180	4	>136 / >131	NW of projector along N ice edge heading ESE. Dives 800 m WNW of projector and next seen 2700 m ESE.
17:53 (#16-25)	single sighting	<400	2	>131 / >127	WNW of projector heading ENE; dives under points of new ice.
17:56[g] (#16-2)	-6000 to +2700	160	1	136 / 132	Travel along N side of lead to 200 m WNW; turned S and crossed to S side of lead; followed S side of lead until past projector; later seen in mid lead or N side of lead.
17:56[g] (#16-12)	-2400 to +2700	160	1	136 / 132	Travel along N side of lead; in mid lead when 420 m WNW of projector; turned N and reappeared 10 min later 75 m NE and heading ESE; when 180 m W of projector turned S, crossed to S side of lead and followed S ice edge ESE. Surfaced briefly 300 m SSE of projector close to S ice edge and later in mid lead far to ESE of projector.
17:58 (#16-21)	-1500 to -400	<400	2	>131 / >127	Travel along N side of lead; dove under ice heading 20° left of projector (ESE).
17:59[g] (#16-27&28)	-240 to -210	190	3	135 / 131	WSW of projector heading S then turn to ESE and follow S ice edge.
17:59 (#16-26)	single sighting	<300	2	>133 / >128	SSE of projector heading ESE along S ice edge.

---

[a] - indicates that whales are ≥180°T from the projector (approaching); + indicates that whales are ≤180° from the projector (moving away).

[b] 1 = measured by theodolite or tape, 2 = visual estimate, 3 = estimate based on nearby surfacings, 4 = estimates based on distant surfacings (possibly unreliable).

[c] Estimated received level (dB re 1 µPa) of projected noise at CPA. Left: level in the 20-1000 Hz band. Right: level in the dominant 1/3-octave band (centered near 200 Hz in each case).

[d] < indicates that the whale was heading toward the projector when last seen.

[e] NA is not applicable.

[f] The projector was operating until 18:46 when the whales were ≈1.9 km W of the projector.

[g] These whales were also seen by the ice-based observers.

[h] This whale was sighted 24 minutes after the projector was turned off.

[i] This whale was sighted 14 minutes after the projector was turned off.

from the silent projector while closely following the shelf of new ice; these whales were also observed from the air (see Table 23B and below).

Aerial Observations.--Three groups of bowheads were followed by observers in the circling Twin Otter aircraft as those whales swam along the lead past the ice camp. Figure 58 shows their paths when they were within ~1.5 km of the projector. Figure 59, consisting of a pair of facing fold-out pages, shows their paths along the entire length of the observation area.

The first group, consisting of five bowheads, was followed from 12:47 to 15:23 as they moved from 5.2 km WNW to 4.2 km ESE of the projector. Distorted drilling sounds were projected during all but the first 13 min and last 17 min of this session. Four of the whales followed the northern ice edge and one followed the center of the lead as they traveled east toward the projector (Fig. 59A). As they approached within ~3 km of the projector, the whales traveled very close to the ice edge while at the surface, and turned to head NE under the ice when they dove (Fig. 58A, 59A). Despite their NE headings as they started their dives, they surfaced to the ESE of their previous positions until they had approached to 400 m from the projector. At this point, four whales (two at the surface; two visible below the surface) headed south toward the south side of the lead and dove out of sight (Fig. 58A, 59A). After a long dive, all of these whales surfaced >1 km east of the projector along the north side of the lead (Fig. 59A). They continued to move ESE along and parallel to the north side of the lead. There was no resumption of the turning and northeastward dives under the ice. We followed these whales until they were 4.2 km E of the projector, by which time the distorted playback had ended.

Normal drilling sounds were broadcast throughout the second behavioral observation session from 16:41 to 18:41. Six bowheads were followed from 6.0 km west to 2.7-2.9 km east of the projector; they were among a larger group that totalled about 18 whales. As most of the whales moved eastward along the lead toward the projector, they remained along the northern edge (Fig. 59B). Although whales occasionally dove under the northern ice edge at an acute angle, most whales followed the lead eastward. When the whales approached to 0.8 km, some of them slowed and dove ENE under the ice at a slight angle to the ice edge. When they approached to 400 m, one whale changed direction several times. It briefly reversed course and moved westward, away from the projector, before resuming an ESE course (Fig. 58B, 59B). All whales under observation turned to the south a few hundred meters west of the projector, crossed the lead, and passed the projector along the southern edge of the lead. Thus, they remained as far as possible from the projector while remaining within the lead.

After passing the projector, most whales did not resurface until they were >1 km east of the projector (Fig. 59B). Of these, two had been identified earlier west of the projector; they are shown by the triangle and square symbols in Figure 59B. East of the projector, the whales hugged the northern edge of the lead and angled ENE under the ice when they dove.

Three bowheads were followed from 2.0 km WNW to 1.8 km ESE of the projector during the third session on 13 May 1990. The playback of drilling sounds stopped 3 min after the session started, and when the whales were 1.9 km from the projector. The projector was silent for the rest of the day. Throughout the session, the whales traveled along and parallel to the northern edge of the lead (Fig. 59C). They did not attempt to head NE under the ice, and they did not cross to the south side as they passed the projector (Fig. 58C; *cf.* 58A,B). The

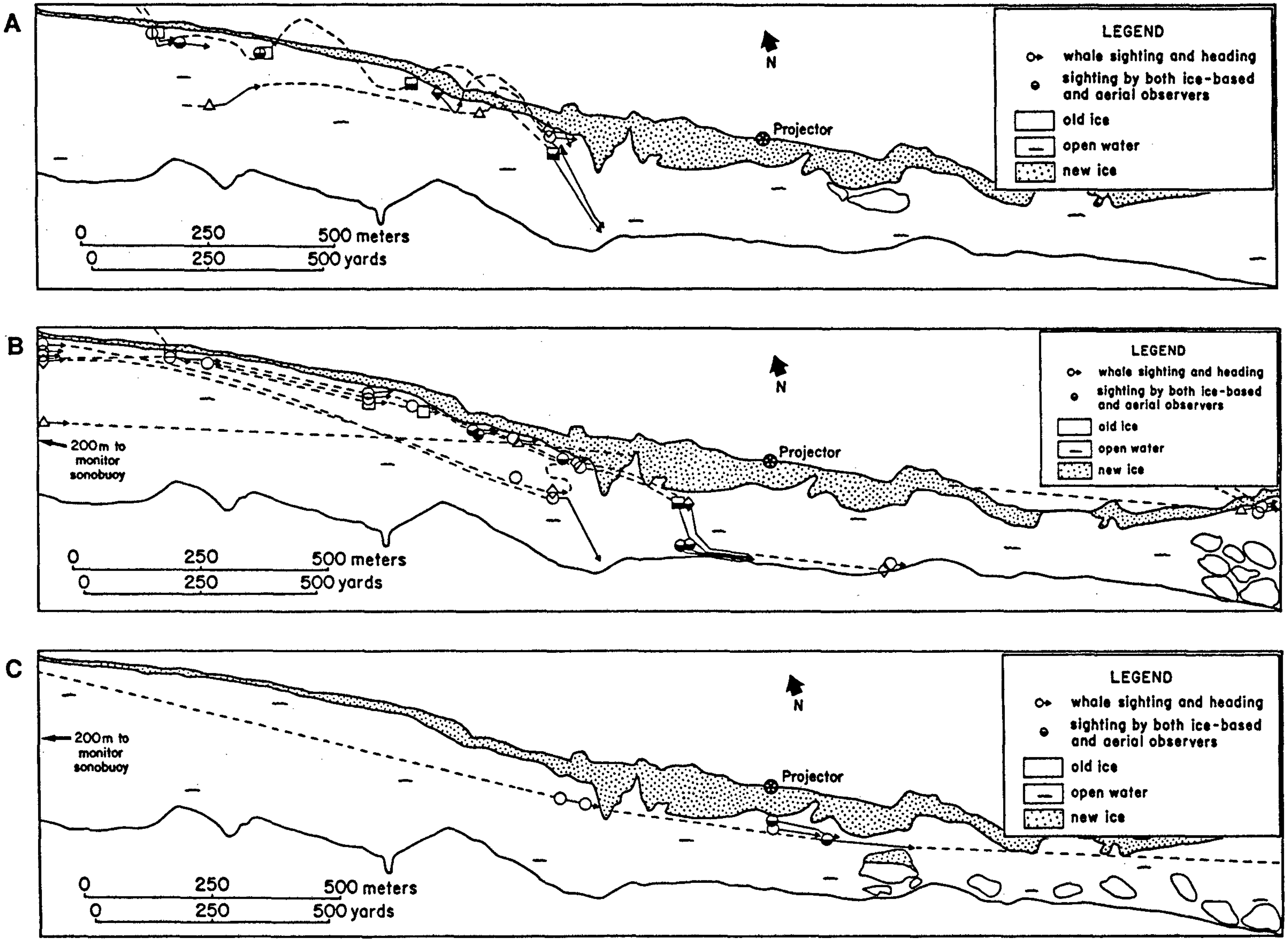


FIGURE 58. Aerial observations of bowhead whale tracks passing the sound projector amidst the pack ice NE of Barrow, Alaska, 13 May 1990. (A) distorted drilling platform sounds, 13:54 to 14:15; (B) normal drilling platform sounds, 17:30 to 18:18; (C) projector silent, 19:03 to 19:14. Circles represent various unidentifiable whales that were not followed over long distances; other symbol shapes represent specific identified whales. Half-filled symbols represent whale sightings noted by ice-based as well as aerial observers. Dashed lines represent presumed paths of whales while they were below the surface. Sometimes the path was too irregular to allow us to estimate where the whale traveled during a dive; in these cases the symbols are not connected. See Fig. 59 for a broader view.

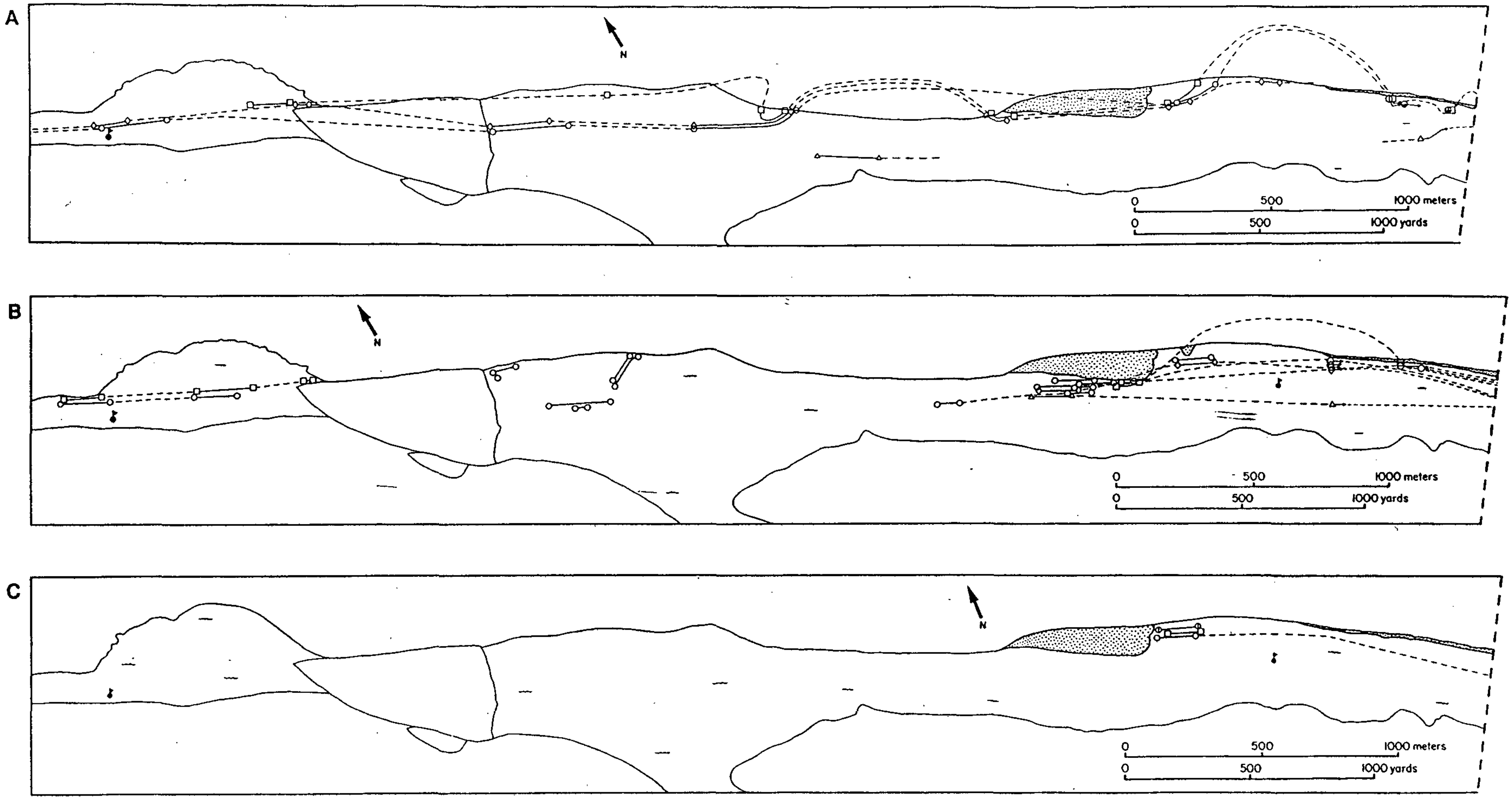


FIGURE 59. Aerial observations of bowhead whale tracks relative to the sound projector amidst the pack ice NE of Barrow, Alaska, 13 May 1990. (A) distorted drilling platform sounds, 12:47 to 15:23; (B) normal drilling platform sounds, 16:41 to 18:41; (C) projector silent, 18:43 to 19:47. Circles represent various unidentifiable whales that were not followed over long distances; other symbol shapes represent specific identified whales. Half-filled symbols near the projector represent whale sightings noted by ice-based as well as aerial observers. Dashed lines represent presumed paths of whales while they were below the surface. Sometimes the path was too irregular to allow us to estimate where the whale traveled during a dive; in these cases the symbols are not connected.

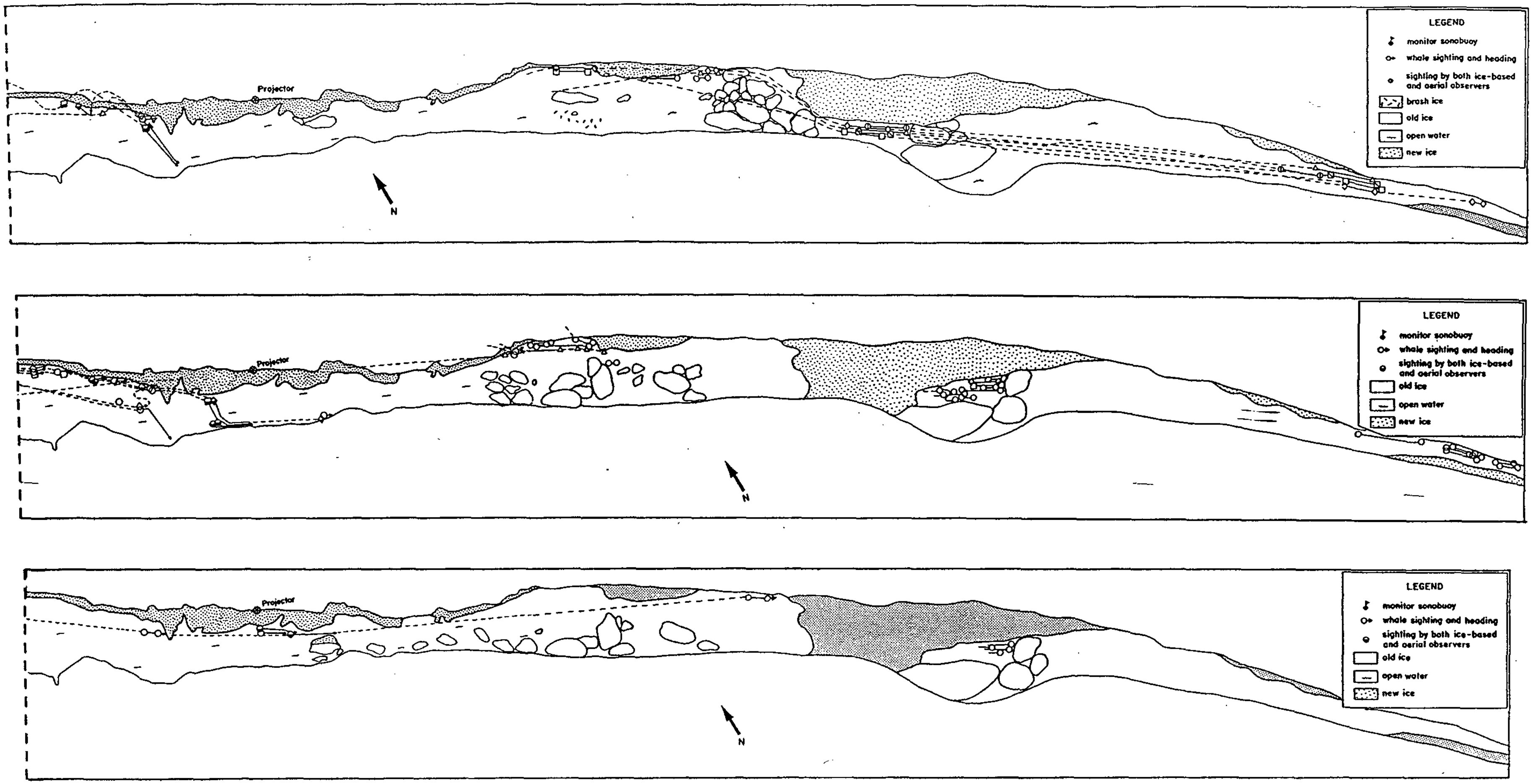


FIGURE 59. Continued.

CPA of all three whales to the projector was 60 m, in comparison to 160-190 m for whales passing when the projector was broadcasting drilling sounds (Table 23B vs. F).

As noted above, bowheads approaching the projector site moved along the north or central parts of the lead when they were >½-1 km west of the projector, but crossed to the south side when within a few hundred meters of the operating projector. During both the distorted and undistorted playbacks, the only whales seen in the southern third of the lead were within 1 km of the projector; almost all of these were within ½ km (Fig. 60A,B). Table 24 gives a more detailed breakdown of these data.

The net speeds of movement of the whales observed on this date indicate that some but not all whales were delayed for brief periods of time by the presence of the operating projector (Table 25). During the playback experiments, several whales traveled at average speeds <4 km/h as they approached the operating projector at distances >2 km and 2→0 km. After the whales passed the projector, all recorded speeds were >4 km/h.

These decreases in net speed along the axis of the lead appear to have resulted from whales temporarily slowing down and/or angling under the ice. Only one of the whales followed by the aircraft reversed course and moved westward away from the projector for a few minutes (whale #16-12, Fig. 58B, 59B). Its net speed of travel when it was 2→0 km west of the projector (3.3 km/h, Table 25) was the slowest observed on this date. After it passed the projector, its rate of travel was higher, and similar to speeds of the other whales followed on 13 May. There was no evidence of hesitation for more than a few minutes by any whale that approached the projector on 13 May.

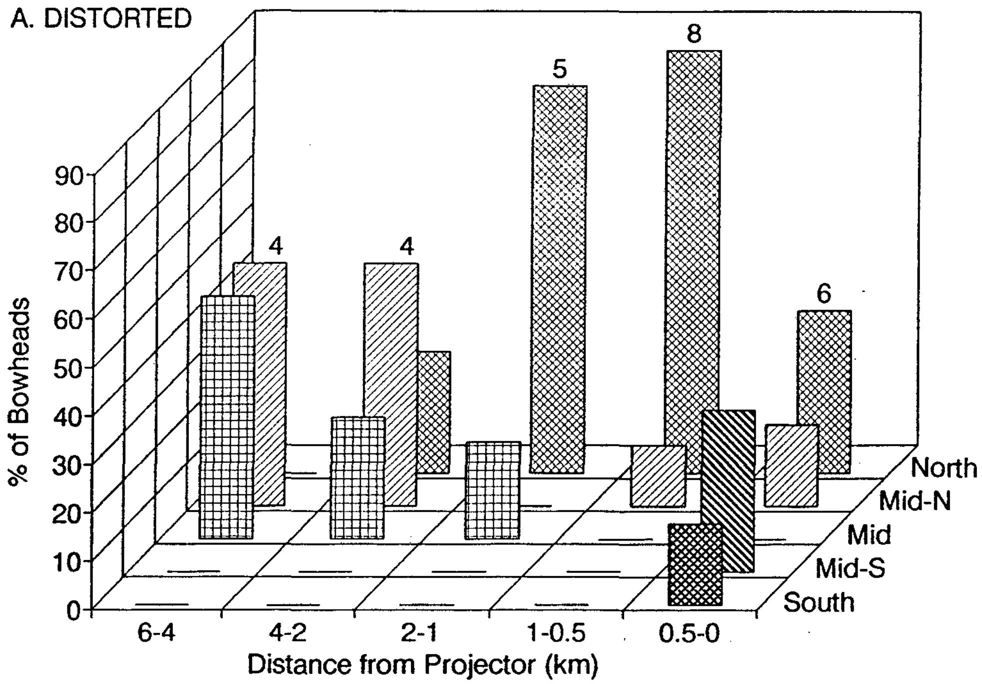
<u>Surfacing, Respiration and Dive Cycles.</u>--On 13 May 1990, the number of whales observed systematically from the circling aircraft was high enough to justify a day-specific analysis of whale behavior in relation to the presence of projected sounds and to distance from the projector. Most analyses were done by observation session, *viz* distorted *Karluk* playback, undistorted playback, and "control". During the "control" session, bowheads were followed from 2 km west to 2 km east of the ice camp. However, projection of *Karluk* sounds did not stop until 3 min after the start of observations, when the approaching whales were ~1.9 km away. In this case, the meaning of the term "control" is stretched (hence the use of quotation marks).

Correlations between behavioral variables and distance from the ice camp were calculated in two ways: (1) considering distance *per se*, in kilometers, and (2) considering the logarithm of distance. The latter approach was used because sound levels received from a point source like the J-11 projector diminish (to a first approximation) with the logarithm of distance from the projector. For each of these two methods, correlation coefficients of behavioral variables and distance were calculated for bowheads that were (a) approaching the projector and (b) moving away from the projector, and also for (c) all whales, either approaching or receding (Table 26).

Undistorted Karluk playback: Considering all whales, either approaching or receding, the number of blows per surfacing and the duration of surfacing both increased significantly[12] with

---

[12] References to significant differences refer to "nominally significant", ignoring potential problems associated with repeated observations of the same individual whales.



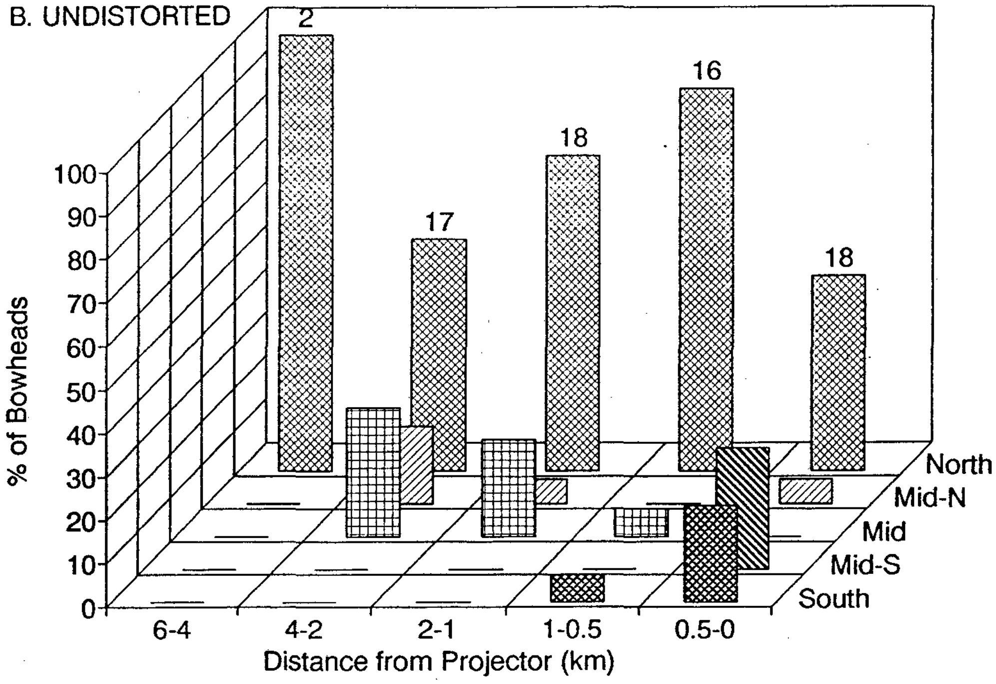


FIGURE 60. Positions of bowhead whales across the lead vs. distance from the projector during (**A**) distorted and (**B**) undistorted playbacks on 13 May 1990. Positions are categorized as being in the north, middle or south thirds of the lead, or as moving between mid and north or between mid and south. The sample sizes are the numbers of whales within the five distance categories. For each distance category, the five bars show the percentages of the whales in five north-south positions. Only whales approaching the projector from the west are counted, and a given whale is counted only once per distance category. Corresponding numerical data are in Table 24.

Table 24. Positions of whales across the lead vs. distance from the projector, 13 May 1990. Positions are categorized as being in the north, middle or south thirds of the lead, or as moving between mid and north or mid and south. Only whales approaching the projector are counted, and a given whale is counted only once per distance category. Air+Ice includes whales seen from the air or from both the air and the ice.

Position in Lead	Observation Platform	Distance from Projector (km)				
		6-4	4-2	2-1	1-0.5	0.5-0
A. DISTORTED						
N	Air+Ice	0	1	3	4	2
	Ice only	-	-	1	3	0
Mid-N	Air+Ice	2	2	0	1	0
	Ice only	-	-	0	0	1
Mid	Air+Ice	2	1	0	0	0
	Ice only	-	-	1	0	0
Mid-S	Air+Ice	0	0	0	0	2
	Ice only	-	-	0	0	0
S	Air+Ice	0	0	0	0	0
	Ice only	-	-	0	0	1
B. UNDISTORTED						
N	Air+Ice	2	9	7	5	3
	Ice only	-	-	6	9	5
Mid-N	Air+Ice	0	3	1	0	1
	Ice only	-	-	0	0	0
Mid	Air+Ice	0	5	1	1	0
	Ice only	-	-	3	0	0
Mid-S	Air+Ice	0	0	0	0	3
	Ice only	-	-	0	0	2
S	Air+Ice	0	0	0	0	2
	Ice only	-	-	0	1	2
C. CONTROL						
N	Air+Ice	0	0	3	0	3
	Ice only	-	-	0	6	3
Mid-N	Air+Ice	0	0	0	0	0
	Ice only	-	-	0	0	1
Mid	Air+Ice	0	0	0	0	0
	Ice only	-	-	0	1	1
Mid-S	Air+Ice	0	0	0	0	0
	Ice only	-	-	0	0	2
S	Air+Ice	0	0	0	0	0
	Ice only	-	-	0	0	1

Table 25. Speeds of travel of bowhead whales as they approached and passed the projector on 13 May 1990.

	Speed (km/h)			
	Distance and Direction from Projector			
Whale #	>2 km West	0 to 2 km West	East of Projector	Overall Average
Distorted Drilling Platform Sound				
15-1	3.8	3.5	5.2	4.1
15-2	3.6	3.5	6.5	4.4
15-3	3.6	4.1	4.7	4.2
15-4	4.7	5.2	5.2	4.9
Normal Drilling Platform Sounds				
16-1	4.6	NA	NA	NA
16-2	4.8	5.4	4.5	4.8
16-12	NA	3.3	4.4	NA
16-11 & 13	NA	3.8	NA	NA
16-21	NA	4.9	NA	NA
Projector Silent[a]				
17-1	NA	5.4	5.6	NA
17-2 & 3	NA	4.6	NA	NA

[a] The projector was turned off as observations were started on these whales 1.9 km from the projector.

increasing distance from the projector (Table 26; Fig. 61). Conversely, median blow interval decreased significantly with increasing distance. These data indicate that bowheads close to the operating projector tended to have relatively short surfacings with fewer blows per surfacing and longer intervals between successive blows. This is the same pattern that has been noted in summer and autumn when bowheads were exposed to several types of simulated or real industrial disturbance (Richardson et al. 1985b, 1986, 1990b). For each of these three measures of behavior, results based on the "linear distance" and "logarithm of distance" methods were similar (Table 26).

The nominal significance levels (P_n) shown in Table 26 are two-tailed levels. One could argue that it would be justified to calculate one-tailed P values, given that the pattern of results in previous studies allowed a prediction of the direction of any effect. If this procedure were followed, the nominal significance levels of the trends noted above would be higher.

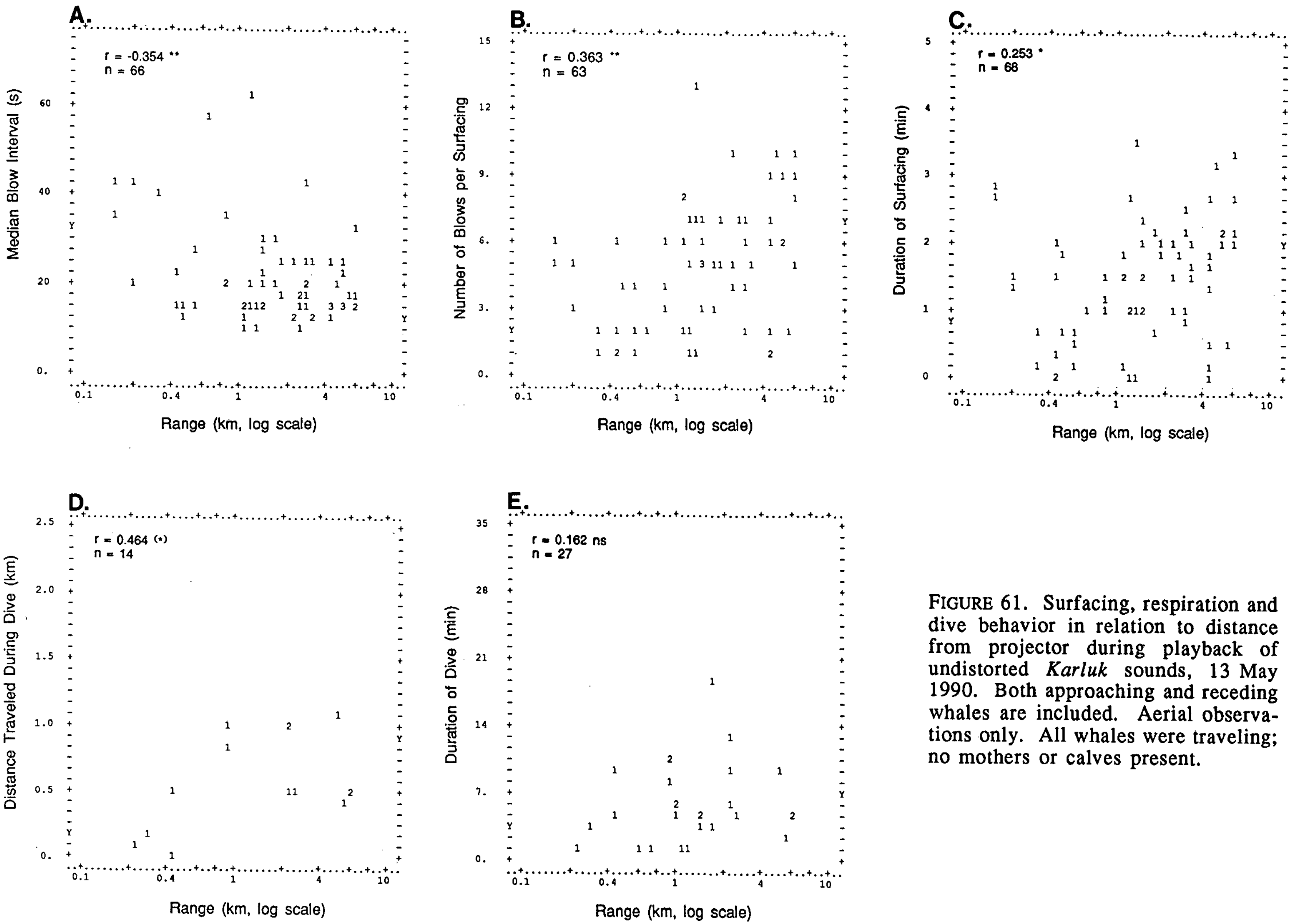


FIGURE 61. Surfacing, respiration and dive behavior in relation to distance from projector during playback of undistorted *Karluk* sounds, 13 May 1990. Both approaching and receding whales are included. Aerial observations only. All whales were traveling; no mothers or calves present.

Table 26. Surfacing, respiration and dive behavior in relation to distance from projector (R), 13 May 1990. Correlations are shown for three observation sessions: (a) with distorted *Karluk* playback, (b) with undistorted *Karluk* playback, and (c) "control" (ice camp present but no playback or other disturbance while whales were near projector). P_n is nominal 2-tailed significance level of the correlation coefficient. Aerial observations only. All whales were traveling; no mothers or calves present.

			Approach			Recede			All Whales		
Variable		Session	r	n	P_n	r	n	P_n	r	n	P_n
Median Blow Interval	vs. R	Distort.	0.244	29	ns	0.310	17	ns	0.235	46	ns
		Karluk	-0.307	46	-	0.020	20	ns	-0.270	66	-
		"Control"	-0.002	5	ns	0.531	4	ns	0.111	9	ns
"	vs. log R	Distort.	0.157	29	ns	0.280	17	ns	0.132	46	ns
		Karluk	-0.342	46	-	-0.216	20	ns	-0.354	66	--
		"Control"	-0.136	5	ns	0.392	4	ns	-0.078	9	ns
# Blows Per Surfacing	vs. R	Distort.	0.221	27	ns	-0.205	16	ns	0.145	43	ns
		Karluk	0.364	47	+	0.370	16	ns	0.358	63	++
		"Control"	0.370	5	ns		2		0.085	7	ns
"	vs. log R	Distort.	0.231	27	ns	-0.161	16	ns	0.209	43	ns
		Karluk	0.320	47	+	0.484	16	(+)	0.363	63	++
		"Control"	0.123	5	ns		2		-0.021	7	ns
Duration of Surfacing	vs. R	Distort.	0.260	28	ns	0.286	16	ns	0.273	44	(+)
		Karluk	0.222	50	ns	0.568	18	+	0.314	68	++
		"Control"	0.125	5	ns		2		-0.221	7	ns
"	vs. log R	Distort.	0.250	28	ns	0.285	16	ns	0.271	44	(+)
		Karluk	0.131	50	ns	0.610	18	++	0.253	68	+
		"Control"	-0.174	5	ns		2		-0.365	7	ns

Continued...

Table 26. Concluded.

			Approach			Recede			All Whales		
Variable		Session	r	n	P_n	r	n	P_n	r	n	P_n
Distance Trav. dur. Dive	vs. R	Distort.	0.073	20	ns	0.198	10	ns	0.170	30	ns
		Karluk	0.219	14	ns		0		0.219	14	ns
		"Control"	0.971	4	+		1		0.943	5	+
"	vs. log R	Distort.	-0.087	20	ns	0.297	10	ns	0.104	30	ns
		Karluk	0.464	14	(+)		0		0.464	14	(+)
		"Control"	0.984	4	+		1		0.950	5	+
Duration of Dive	vs. R	Distort.	0.021	25	ns	-0.161	10	ns	-0.003	35	ns
		Karluk	0.007	25	ns		2		0.045	27	ns
		"Control"	0.806	4	ns		1		0.678	5	ns
"	vs. log R	Distort.	-0.192	25	ns	-0.045	10	ns	-0.179	35	ns
		Karluk	0.159	25	ns		2		0.162	27	ns
		"Control"	0.840	4	ns		1		0.699	5	ns

ns → P>0.1; (+) or (-) → 0.1≥P>0.05; + or - → 0.05≥P>0.01; ++ or -- → 0.01≥P>0.001.

Durations of dives were not significantly related to distance from the operating projector (Table 26; Fig. 61). However, there was an indication that distance traveled during dives tended to be shorter close to the projector ($r_{\log R}$=0.464, n=14, $0.1>P_n>0.05$).

The above trends are based on all whales observed during the playback of undistorted *Karluk* sounds on 13 May 1990. Considering only the approaching whales, the trends were similar for all behavioral variables except duration of surfacing (Table 26). For approaching whales, there was no clear evidence that duration of surfacing was related to distance from the projector.

In the case of whales moving away from the projector ("Receding"), the sample size was low. For duration of surfacing vs. distance, there was a significant and strong correlation. For number of blows per surfacing, the correlation coefficients vs. distance (r_R=0.370; $r_{\log R}$=0.484) were similar to those for approaching and all whales, but the trends were non-significant because of the lower sample size. Median blow interval was not significantly related to distance, and there were few data on dive duration and none on distance traveled during dives.

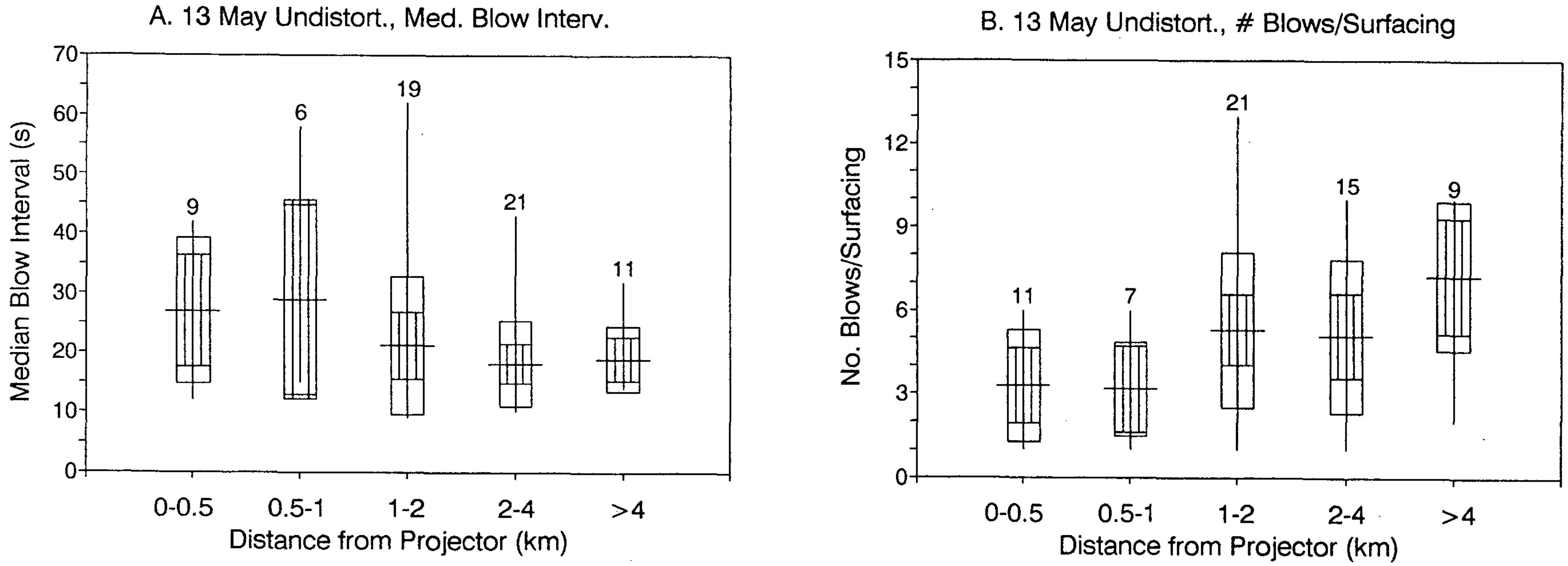
It is important to determine the distance from the projector within which unequivocal behavioral effects were evident. It is not possible to determine this in an objective way from scatter diagrams like Figure 61. Prior to the start of the 1989 phase of this project, we selected the following "distance from projector" categories for use in analyses of disturbance effects: ≤½ km, ½-1 km, 1-2 km, 2-4 km, and >4 km. The boundaries between categories are roughly logarithmic, reflecting the roughly logarithmic decline in received sound levels with increasing distance. Figure 62 shows the same surfacing and respiration data as Figure 61, but categorized by distance. (Dive data were omitted because Fig. 61 revealed no clear dependence on distance from projector.)

Analyses of variance (ANOVA) supplemented by orthogonal contrasts and multiple comparisons were used to evaluate the distances within which behavioral effects were evident (Table 27). There is no single, universally-applicable method for determining which treatment categories (here distance categories) differ from other categories (Steel and Torrie 1960; Zar 1984; Mead 1988). We have used two methods to assist in interpreting the ANOVA results:

1. Orthogonal contrasts comparing, successively, each distance category with the ***more***-distant categories pooled. The question being addressed is, "How close to the projector do bowheads come before their behavior is significantly different than that at greater distances?" Each ANOVA involves 5 distance categories, and thus has 4 numerator degrees of freedom. That, in turn, permits four contrasts, (a) - (d):

		Contrast Coefficients				
	Distances Compared	≤½	½-1	1-2	2-4	>4
(a)	2-4 km vs. >4 km	0	0	0	-1	1
(b)	1-2 km vs. >2 km	0	0	-2	1	1
(c)	½-1 km vs. >1 km	0	-3	1	1	1
(d)	≤½ km vs. >½ km	-4	1	1	1	1

These tests assume that there is no effect at distances beyond 4 km, i.e. data from >4 km are treated as control data. To a first approximation, the first of these successive tests that detects a nominally significant effect defines the maximum distance out



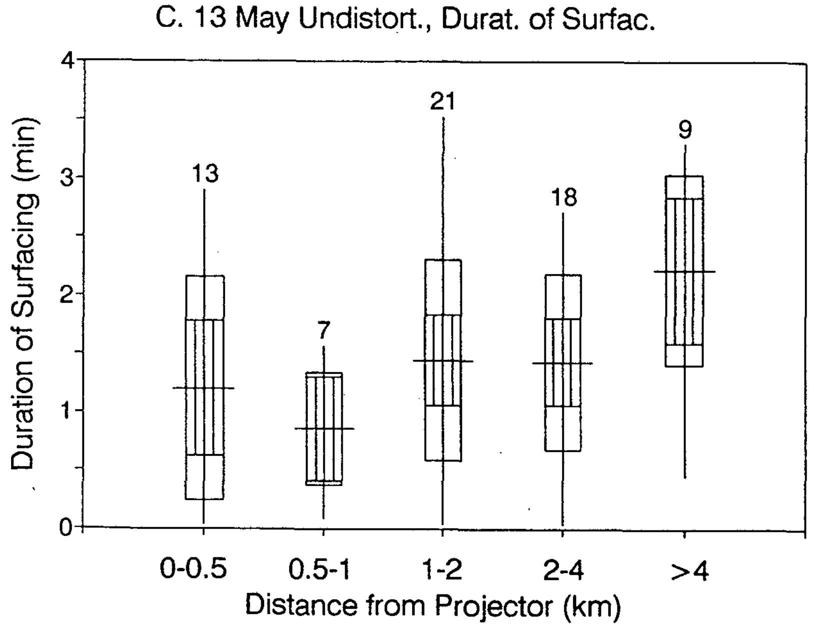


FIGURE 62. Surfacing and respiration behavior by distance category from projector during playbacks of undistorted *Karluk* sounds, 13 May 1990. Same data as in parts A-C of previous graph. The mean, range, ± 1 s.d. (open rectangle), and ± 95% confidence interval (hatched rectangle) are shown.

Table 27. ANOVA and related analyses of distance from operating projector vs. (A) surfacing and respiration variables and (B) behavioral factors, 13 May 1990, undistorted playback. Same data as in Figures 62 and 65. See text for details.

	1-way ANOVA on 5 distance categories	Orthogonal Contrasts, various distances (km) vs. all greater distances (km)		Bonferroni Tests[1], various distances (km) vs. >4 km	
A. ORIGINAL VARIABLES					
Median Blow Inverval.	(*)[2]	2-4 vs. >4	ns	2-4 vs. >4	ns[3]
		1-2 vs. >2	ns	1-2 vs. >4	ns
	var ≠	½-1 vs. >1	*	½-1 vs. >4	ns
		<½ vs. >½	ns[4]	<½ vs. >4	ns
Number of Blows per Surfacing	**	2-4 vs. >4	*	2-4 vs. >4	ns
		1-2 vs. >2	ns[4]	1-2 vs. >4	ns
	var =	½-1 vs. >1	*[4]	½-1 vs. >4	**
		<½ vs. >½	*[4]	<½ vs. >4	**
Duration of Surfacing	*	2-4 vs. >4	*	2-4 vs. >4	(*)
		1-2 vs. >2	ns[4]	1-2 vs. >4	(*)
	var =	½-1 vs. >1	*[4]	½-1 vs. >4	**
		<½ vs. >½	ns[4]	<½ vs. >4	*
B. BEHAVIORAL FACTORS					
Factor One	***	2-4 vs. >4	ns	2-4 vs. >4	ns
		1-2 vs. >2	ns	1-2 vs. >4	ns
	var =	½-1 vs. >1	(*)	½-1 vs. >4	ns
		<½ vs. >½	***	<½ vs. >4	**
Factor Two	*	2-4 vs. >4	ns	2-4 vs. >4	ns
		1-2 vs. >2	ns	1-2 vs. >4	ns
	var =	½-1 vs. >1	*	½-1 vs. >4	*
		<½ vs. >½	ns[4]	<½ vs. >4	(*)
Factor Six	***[5]	2-4 vs. >4	ns	2-4 vs. >4	ns[3]
		1-2 vs. >2	ns[4]	1-2 vs. >4	ns
	var ≠	½-1 vs. >1	***	½-1 vs. >4	(*)
		<½ vs. >½	*[4]	<½ vs. >4	ns

ns P>0.1; (*) 0.1≥P>0.05; * 0.05≥P>0.01; ** 0.01≥P>0.001; *** P≤0.001.

[1] Alpha adjusted to allow for conducting 4 comparisons.

[2] Brown-Forsythe method for unequal variances (Dixon 1990:193) gives P>0.1.

[3] Bonferroni tests for this variable are computed not assuming equal variances.

[4] This contrast may not be meaningful because behavior varied significantly with distance at distances beyond the cutpoint.

[5] Brown-Forsythe method for unequal variances (Dixon 1990:193) gives P<0.01.

to which noise effects extend. For example, if (a) and (b) are non-significant but (c) is significant, then the behavioral variable is similar at 1-2, 2-4 and >4 km, but different at ½-1 km than at those greater distances. When one test in this sequence is significant, any subsequent tests in the sequence may not be meaningful because behavior varied significantly with distance at distances beyond the distance cutpoint.

2. Bonferroni tests comparing each distance category with the ***most***-distant category (>4 km). For each variable there are four such-tests (2-4, 1-2, ½-1 and ≤½ km vs. >4 km). Each test is meaningful regardless of the significance of the other three tests. In the Bonferroni method, alpha values are adjusted to ensure that the probability of finding one or more seemingly-significant differences when the null hypothesis is true is less than α. Thus, the error-rate is experiment-wise, not comparison-wise.

These tests were done with the BMDP7D program (Dixon 1990). All significance levels are approximate because these tests do not allow for the fact that the data contain repeated observations of the same whales.

The surfacing and respiration data by distance category are shown in Figure 62, and the results of the statistical comparisons are listed in Table 27A:

- Correlation analysis showed that *median blow intervals* were significantly related to distance (Fig. 61). However, the effect was no more than marginally significant when analyzed by ANOVA. This difference in results is understandable; ANOVA is inherently less powerful than correlation when the categories compared by ANOVA are arbitrary subdivisions of a continuum--in this case distance. Insofar as any effect is evident by ANOVA, it appeared to begin when whales came within ~1 km (Table 27A).

- Mean *number of blows per surfacing* was significantly different at 2-4 km than at >4 km, according to the orthogonal contrast. This apparent effect at 2-4 km range was not confirmed by the more conservative Bonferroni test with experiment-wise error rate (Table 27A). Both methods showed that this variable was significantly different within 1 km of the operating projector than at greater distances.

- *Duration of surfacing* followed a pattern similar to number of blows per surfacing. Values were significantly different at 2-4 km than at >4 km according to the orthogonal contrast. The more conservative Bonferroni test did not confirm this effect at $\alpha=0.05$, although it did suggest that there was a marginally significant effect ($P<0.1$) at 2-4 km. Both methods showed that surfacing durations tended to be significantly affected within 1 km of the operating projector.

Thus, during the undistorted playback on 13 May 1990, surfacing and respiration cycles of bowheads were definitely different within 1 km of the operating projector than at greater distances. In addition, there was some evidence of a weaker effect on number of blows per surfacing and duration of surfacing at distances out to the 2-4 km category.

Distorted Karluk playback: There were no strong correlations between any of the five surfacing, respiration or dive variables listed in Table 26 and distance from the sound projector during playback of distorted *Karluk* sounds. Duration of surfacing was the only variable for which there was even a marginally significant trend: surfacings tended to be longer with increasing distance, as was also the case during the undistorted *Karluk* playback. A possible reason for the absence of strong correlations was the fact that the distorted *Karluk* sounds became progressively weaker as the J-11 projector gradually failed. Since the majority of the data were collected as whales approached the projector, the diminishing source level as the whales approached partially offset the usual increase in received level with diminishing distance.

"Control" data: The sample size was small for the "control" observation session on 13 May 1990, so the results must be interpreted cautiously. There was no evidence of significant relationships between distance from the ice camp and median blow interval, number of blows per surfacing, or duration of surfacing (Table 26). However, these tests had little power to detect a significant trend even if one was there, given the low sample size (n = 7-9).[13]

Thus, it is also useful to consider all control data obtained in 1989-90 when the camp was present within a few kilometers but there was no playback or other source of disturbance. These data showed no relationship between distance from the ice camp and number of blows per surfacing or duration of surfacing (see Fig. 88B,C and Table 39, p. 234, 230). However, there were no control data for distances much less than 2 km, so this lack of correlation may not be meaningful. For 1989-90 as a whole, there was a *positive* association with median blow interval (see Fig. 88A); this trend in the overall 1989-90 control data was in the opposite direction to the negative trend seen during the undistorted *Karluk* playback on 13 May (Table 39 vs. 26).

Unexpectedly, distance traveled during dives and (to a lesser degree) dive duration tended to be higher at greater distances from the camp during the "control" period on 13 May. The repeatability of these trends is unknown, given the low sample size (n=5, Table 26). Considering all control data collected in 1989-90, there was a weak *negative* relationship between duration of dive and distance (see Table 39 and Fig. 88D, later). This weak trend was in the opposite direction to that found during playbacks of undistorted *Karluk* sounds on 13 May.

Thus, the trends noted for surfacing, respiration and dive variables during playbacks on 13 May 1990 were *(1)* consistent with the types of trends found during previous disturbance studies, and *(2)* they were not repeated in the control data either for 13 May (low n) or for 1989-90 as a whole.

Headings and Turns.--The whales observed on 13 May were all moving along a long, narrow and straight lead oriented toward about 120° True. Hence, any deviation of whale headings from that direction was indicative of a whale that was not heading directly along the lead.

During the undistorted *Karluk* playback, there was a negative correlation between headings and distance from the sound projector. This was true for approaching whales, receding whales, and all whales taken together (Table 28). Far from the projector, most bowheads oriented along the lead (~120°T). Closer to the projector, the headings tended to be greater than 120° (Fig. 63A). Thus, close to the projector, there was an increased tendency to orient to the right of the lead's axis, i.e. toward the south side of the lead. During the distorted *Karluk* playback,

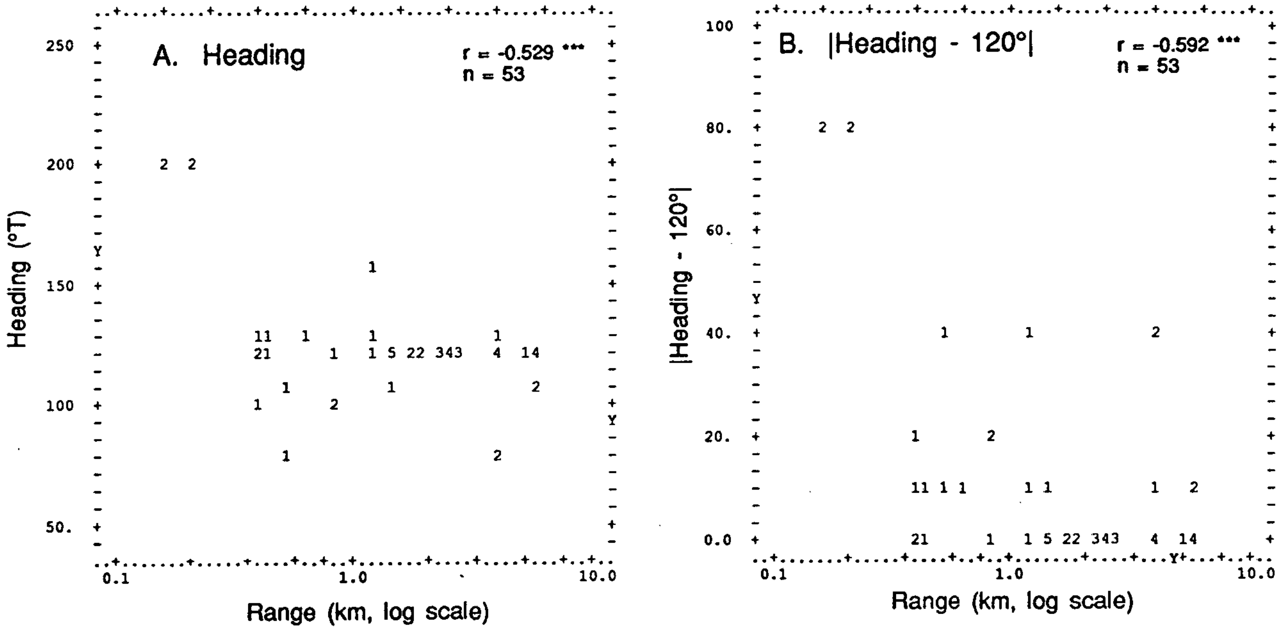
---

[13] With n=8, $|r|$ must be ≥ 0.707 to be significant at the $\alpha=0.05$ level.

Table 28. Headings and turns during surfacings in relation to distance from projector (R), 13 May 1990. Correlations are shown for three observation sessions: (a) with distorted *Karluk* playback, (b) with undistorted *Karluk* playback, and (c) "control" (ice camp present but no playback or other disturbance while whales were near projector). P_n is nominal 2-tailed significance level of the correlation coefficient. Aerial observations only. All whales were traveling; no mothers or calves present.

			Approach			Recede			All Whales		
Variable		Session	r	n	P_n	r	n	P_n	r	n	P_n
Heading	vs. R	Distort.	-0.345	32	(-)	0.421	17	(+)	-0.208	49	ns
		Karluk	-0.327	53	-	-0.301	25	ns	-0.311	78	--
		"Control"	0.000	6	ns	-0.119	4	ns	0.103	10	ns
"	vs. log R	Distort.	-0.326	32	(-)	0.474	17	(+)	-0.213	49	ns
		Karluk	-0.529	53	---	-0.436	25	-	-0.491	78	---
		"Control"	0.000	6	ns	0.114	4	ns	0.201	10	ns
|HEAD-120°|	vs. R	Distort.	-0.308	32	(-)	-0.340	17	ns	-0.313	49	-
		Karluk	-0.349	53	--	-0.373	25	(-)	-0.329	78	--
		"Control"	0.000	6	ns	-0.119	4	ns	0.103	10	ns
"	vs. log R	Distort.	-0.350	32	-	-0.408	17	ns	-0.380	49	--
		Karluk	-0.592	53	---	-0.366	25	(-)	-0.518	78	---
		"Control"	0.000	6	ns	0.114	4	ns	0.201	10	ns
Degrees of Turn	vs. R	Distort.	-0.407	28	-	-0.490	16	(-)	-0.426	44	--
		Karluk	-0.424	50	--	0.145	18	ns	-0.017	68	ns
		"Control"	-0.508	5	ns		2		-0.410	7	ns
"	vs. log R	Distort.	-0.312	28	ns	-0.543	16	-	-0.378	44	-
		Karluk	-0.633	50	---	0.219	18	ns	-0.027	68	ns
		"Control"	-0.573	5	ns		2		-0.529	7	ns

ns → $P>0.1$; (+) or (-) → $0.1 \geq P > 0.05$; + or - → $0.05 \geq P > 0.01$; ++ or -- → $0.01 \geq P > 0.001$; +++ or --- → $P \leq 0.001$.



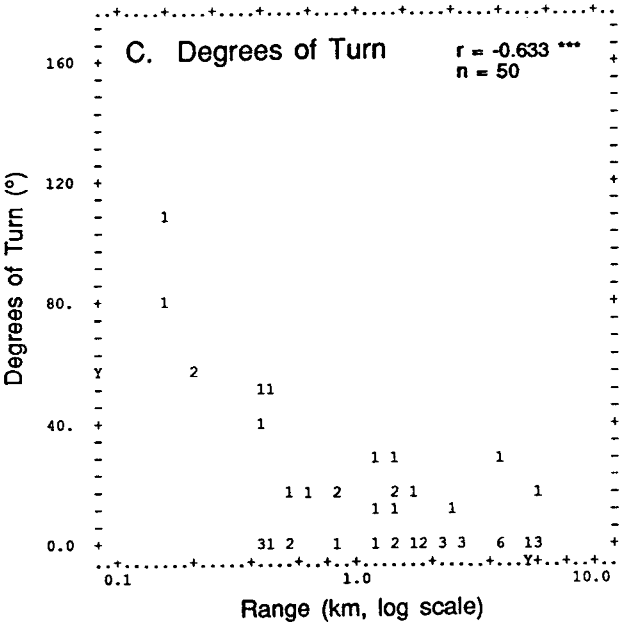


FIGURE 63. Headings and degrees of turn in relation to distance from projector during playback of undistorted *Karluk* sounds, 13 May 1990. Only approaching whales are included. Aerial observations only. All whales were traveling; no mothers or calves present.

there was some evidence of a similar effect for whales approaching the projector, although not for receding whales.

Another measure of heading was the absolute value of the deviation of the heading from 120°T (i.e., |Heading-120°|). This measure would be 0° for a whale swimming along the lead, and *x*° for a whale whose heading was either *x*° left or *x*° right of 120°T. During the undistorted playback, this measure was highly significantly correlated with distance from the projector (Table 28; Fig. 63B). As distance from the projector decreased, there was a strong tendency for increased deviation (left or right) from 120°T. The same effect was evident, although less strongly, during the distorted playback.

The above two indices, heading and |Heading-120°|, were both based on whale headings as recorded at the start of each surfacing. We also recorded the degrees of turn during surfacings. During the undistorted playback, the extent of turning during surfacings became notably higher as the whales approached the projector ($r_{\log R} = -0.633$, n=50, $P_n<0.001$; Fig. 63C). There was evidence of a similar trend during the distorted playback as well (Table 28).

The distance at which these significant trends became evident is not easily defined, given the small sample size close to the projector. During the undistorted playback, the effect was evident within 300 m for all three heading and turn variables, based on n=4 surfacings observed at <300 m. However, there was little evidence of an effect on heading or degrees of turn at distances beyond 300 m (Fig. 63). During the distorted playback, the apparent effect on headings and turns extended somewhat farther, since there was evidence of an effect even though the closest usable observations were at 370 m.

The sample size during the "control" observation session was small. However, in the absence of projected noise, there was no hint of a relationship between distance from the ice camp and Heading or |Heading-120°|, contrary to the results for the undistorted and distorted playback periods. There was, however, a tendency for more turning as whales approached the ice camp during the "control" period ($r_{\log R} = -0.573$, n=5, $P_n>0.1$) as well as during playbacks.

Table 29 shows the frequency of turns during surfacings as a function of distance from the ice camp. During the undistorted *Karluk* playback, whales approaching the projector but still >2 km away turned only infrequently (turns during 3 of 19 surfacings, 16%). Turns occurred during 7 of 13 surfacings (54%) at 1-2 km, and during 11 of 18 surfacings (61%) within 1 km. The frequency of turns 1-2 km away was statistically indistinguishable from that <1 km away (chi^2=0.16, df=1). However, the frequency of turns >2 km away was significantly less than that at 1-2 km (chi^2=5.20, df=1, $P_n<0.05$) and at 0-2 km (chi^2=8.64, df=1, $P_n<0.01$). These results suggest that the undistorted *Karluk* playback caused increased turning by approaching whales at distances as great as 2 km.

During the distorted playback, there was an indication that turning was more frequent and began even farther away. Turns occurred during 0 of 7 surfacings >4 km away, 7 of 9 surfacings at 2-4 km, 7 of 7 at 1-2 km, and 4 of 7 at ≤1 km.

These numerical analyses corroborate our previously-stated interpretation that, as bowheads approached the operating projector on 13 May, they tended (1) to exhibit more frequent and larger turns, and (2) to avoid the projector by moving to the south side of the lead or under the

Table 29. Frequency of turns and various swimming speeds during surfacings by bowheads observed from a Twin Otter aircraft, 13 May 1990. Distances from ice camp in left column are in parentheses for approaching whales and not in parentheses for whales moving away. The units of observation are surfacings by an individual whale. All whales were traveling; no mothers or calves present.

	Turns					Estimated Speed at Surface							
Situation & Distance in km	None	Right	Left	Mult-iple	Total	None	Slow	Med-ium	Fast	Moving Unkn Speed	Mill	Change Speed	Total
Distorted Karluk													
(>4)	7	0	0	0	7	0	1	5	0	2	0	1	9
(2-4)	2	0	7	0	9	0	0	8	0	0	0	1	9
(1-2)	0	2	2	3	7	0	0	7	0	0	0	0	7
(.5-1)	1	0	1	1	3	0	0	2	0	1	0	0	3
(0-.5)	2	2	0	0	4	0	0	4	0	0	0	0	4
0-.5	0	0	0	0	0	0	0	0	0	0	0	0	0
.5-1	0	0	0	0	0	0	0	0	0	0	0	0	0
1-2	2	1	1	1	5	0	0	6	0	0	0	0	6
2-4	9	1	0	0	10	0	0	10	0	0	0	0	10
>4	0	0	1	0	1	0	0	1	0	0	0	0	1
Total	23	6	12	5	46	0	1	43	0	3	0	2	49
Undistorted Karluk													
(>4)	10	1	1	0	12	0	0	12	0	2	0	0	14
(2-4)	6	0	1	0	7	0	0	10	0	0	0	0	10
(1-2)	6	3	2	2	13	0	0	11	0	0	0	2	13
(.5-1)	3	2	2	0	7	0	5	2	0	0	0	0	7
(0-.5)	4	1	3	3	11	0	3	6	0	1	0	1	11
0-.5	1	0	1	0	2	0	0	2	0	0	0	0	2
.5-1	0	0	0	0	0	0	0	0	0	0	0	0	0
1-2	4	1	3	0	8	0	0	5	0	0	0	3	8
2-4	2	0	1	1	4	0	4	3	0	0	0	1	8
>4	0	0	3	1	4	0	0	5	0	0	0	2	7
Total	36	8	17	7	68	0	12	56	0	3	0	9	80
"Control"													
(>4)	0	0	0	0	0	0	0	0	0	0	0	0	0
(2-4)	2	0	0	0	2	0	0	1	0	0	0	2	3
(1-2)	0	0	0	0	0	0	0	0	0	0	0	0	0
(.5-1)	0	0	0	0	0	0	0	0	0	0	0	0	0
(0-.5)	1	0	1	1	3	0	2	1	0	0	0	0	3
0-.5	1	0	0	0	1	0	0	1	0	0	0	0	1
.5-1	0	0	1	0	1	0	0	0	0	0	0	0	0
1-2	0	0	0	0	0	0	0	1	0	0	0	0	1
2-4	0	0	0	0	0	0	0	2	0	0	0	0	2
>4	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	4	0	2	1	7	0	2	6	0	0	0	2	10

ice north of the lead. These trends had been evident in real-time during the observations on 13 May, and they are corroborated by the correlation analyses as well as the maps of whale tracks (Fig. 59, p. 160).

Other Behavioral Variables.--The estimated ***swimming speeds*** of traveling bowheads were almost always "medium" during undisturbed conditions in 1990 (Table 16, p. 114). Similarly, during the distorted *Karluk* playback on 13 May, estimated speeds were usually medium (Table 29). This applied within 1 km of the operating projector (medium for at least 6 of 7 surfacings) as well as farther away. During the undistorted *Karluk* playback, speeds were again usually medium. However, when bowheads approached within 1 km, speeds during 8 of 18 surfacings were estimated as "slow". There had been no "slow" estimates for approaching whales at ranges >1 km (Table 29). By itself, the significance of this apparent "slowing down" by approaching whales would be difficult to assess:

- Slow movement was also seen when bowheads were traveling away from the operating projector at range 2-4 km, and when they were approaching within ½ km of the quiet ice camp during the "control" period (Table 29).
- Determination of estimated speed is partly subjective, and involves categorization of a continuum of speeds. Hence, this variable is probably more subject to observer expectancy bias than are most other variables.

However, as noted earlier, there also was evidence from the successive positions of a few whales that speeds of whales moving eastward away from the projector were higher than those of whales approaching the projector (Table 25, p. 166). Thus, we conclude that net speeds of bowheads approaching the projector on 13 May were indeed somewhat reduced.

No ***pre-dive flexes*** were seen at any time on 13 May, consistent with results from most other days in 1990 (*cf.* Table 15, p. 113).

Fluke-out dives occurred for 11% of the dives during the distorted playback, 1% during the undistorted playback, and 33% (3 of 9) during the "control" period (Table 30). For undisturbed traveling bowheads during 1990 as a whole, the flukes were raised 9% of the time (*cf.* Table 15). The frequency of fluke-out dives during the undistorted playback was significantly less than for undisturbed traveling bowheads during 1990 as a whole ($\text{chi}^2=5.51$, $P_n<0.05$). However, during the undistorted playback, fluke-out dives were absent among approaching whales more than 1 or 2 km away as well as for those within 1 or 2 km. This suggests that the near-absence of fluke-out dives on this occasion may not have been related to the playback.

Aerial behavior was rare among undisturbed traveling whales in 1990 (seen during only 3% of 236 surfacings, Table 15). Aerial activity was rare on 13 May 1990 as well. The only observed cases were three surfacings with tail slaps during the "distorted *Karluk* playback" period (Table 30).

Table 30. Frequency of pre-dive flexes, fluke-out dives and aerial behavior during surfacings by bowheads observed from a Twin Otter aircraft, 13 May 1990. Distances from ice camp in left column are in parentheses for approaching whales and not in parentheses for whales moving away. The units of observation are surfacings by an individual whale. All whales were traveling; no mothers or calves present.

	Pre-dive Flex			Flukes Out as Diving			Aerial Behaviors						
Situation & Distance in km	No	Yes	Total	No	Yes	Total	None	Roll	Flip-Slap	Tail Slap	Breach	2 or 3 Types	Total
Distorted Karluk													
(>4)	7	0	7	7	0	7	9	0	0	0	0	0	9
(2-4)	9	0	9	8	1	9	9	0	0	0	0	0	9
(1-2)	7	0	7	5	2	7	7	0	0	0	0	0	7
(.5-1)	3	0	3	3	0	3	3	0	0	0	0	0	3
(0-.5)	4	0	4	4	0	4	3	0	0	1	0	0	4
0-.5	0	0	0	0	0	0	0	0	0	0	0	0	0
.5-1	0	0	0	0	0	0	0	0	0	0	0	0	0
1-2	5	0	5	4	1	5	4	0	0	1	0	0	5
2-4	10	0	10	9	1	10	9	0	0	1	0	0	10
>4	1	0	1	1	0	1	1	0	0	0	0	0	1
Total	46	0	46	41	5	46	45	0	0	3	0	0	48
Undistorted Karluk													
(>4)	11	0	11	12	0	12	14	0	0	0	0	0	14
(2-4)	10	0	10	10	0	10	10	0	0	0	0	0	10
(1-2)	13	0	13	13	0	13	13	0	0	0	0	0	13
(.5-1)	7	0	7	7	0	7	7	0	0	0	0	0	7
(0-.5)	11	0	11	11	0	11	11	0	0	0	0	0	11
0-.5	2	0	2	2	0	2	2	0	0	0	0	0	2
.5-1	0	0	0	0	0	0	0	0	0	0	0	0	0
1-2	8	0	8	8	0	8	8	0	0	0	0	0	8
2-4	7	0	7	8	0	8	8	0	0	0	0	0	8
>4	7	0	7	6	1	7	7	0	0	0	0	0	7
Total	76	0	76	77	1	78	80	0	0	0	0	0	80
"Control"													
(>4)	0	0	0	0	0	0	0	0	0	0	0	0	0
(2-4)	3	0	3	0	3	3	3	0	0	0	0	0	3
(1-2)	0	0	0	0	0	0	0	0	0	0	0	0	0
(.5-1)	0	0	0	0	0	0	0	0	0	0	0	0	0
(0-.5)	3	0	3	3	0	3	3	0	0	0	0	0	3
0-.5	1	0	1	1	0	1	1	0	0	0	0	0	1
.5-1	0	0	0	0	0	0	0	0	0	0	0	0	0
1-2	1	0	1	1	0	1	1	0	0	0	0	0	1
2-4	0	0	0	1	0	1	2	0	0	0	0	0	2
>4	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	8	0	8	6	3	9	10	0	0	0	0	0	10

All Behavioral Variables Combined.--It is often difficult to evaluate changes in behavior when, as in this study, many different intercorrelated measures of behavior are recorded. One useful approach in such situations is the following two-stage procedure: (1) Use factor analysis to reduce the behavioral variables to a smaller number of uncorrelated indices of behavior. (2) Evaluate the relationships between these few behavior indices and the environmental circumstances--in this case the playbacks of drilling noise.

We used factor analysis to reduce 14 intercorrelated measures of behavior (Table 31) into a smaller number of uncorrelated indices or factors. Prior to factor analysis, four of the original measures of behavior were logarithmically transformed to reduce skewness. Several other measures were adjusted, relative to the original coding system, to ensure that their scales were at least ordinal. The observations included in the factor analysis are described in the caption to Table 31. The data were not restricted to 13 May 1990, since we wanted to use the same behavior indices in a subsequent analysis for all dates (see p. 240). Principal components were extracted from the correlation matrix, and the six components whose eigenvalues exceeded 1.0 were subjected to Varimax rotation. These 6 components accounted for 68% of the variance represented by the 14 original variables.

Relationships between the original variables and the 6 derived behavior factors (indices) are shown in Table 31. Each factor was strongly ($|r|>0.5$) related to two or three of the original variables. The underlying behavioral attribute indexed by each factor is identified, insofar as possible, at the bottom of Table 31. Factors 1-4 were readily interpretable. The variables heavily weighted by Factors 5-6 were not previously recognized as being interrelated.

Table 32, showing the relationships between behavior factors and distance from the ice camp, does not include any control data from 13 May. Limited "control" data were collected on 13 May but on that day there were no "control" surfacings for which we knew all of the 14 variables necessary to compute factor scores. In the absence of such data, Table 32 includes control data from all other days in 1989-90 when behavior of traveling bowheads was observed near the quiet ice camp.

On 13 May 1990, there were strong relationships between some of the behavior indices (factors) and the logarithm of distance from the sound projector (Table 32, Fig. 64).

- The propensity to turn while at the surface (Factor 1) was higher close to the projector than far away during the undistorted playback ($P_n<0.001$) and, to a lesser degree, during the distorted playback ($P_n<0.05$). There was no such tendency in the pooled 1989-90 control data (Table 32).

- Short surfacings with few blows per surfacing (Factor 2) tended to occur close to the projector during the undistorted playback ($P_n<0.05$) but not to any significant degree during the distorted playback. Again, there was no such trend in the pooled 1989-90 control data.

- Slow travel and underwater blows (Factor 6) tended to occur close to the projector during the undistorted playback ($P_n<0.001$) but not during the distorted playback. The association with slow travel was noted earlier (*cf.* Table 29). Interpretation of this

Table 31. Weighting placed on 14 behavioral variables by six behavior factors; dominant variables are in boldface[a]. Based on aerial observations of 276 surfacings by traveling bowheads during undisturbed and playback conditions, 1989-90. Mothers and calves are excluded.

Original Variable	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4	FACTOR 5	FACTOR 6
No. blows / surfacing (log)	*0.061*	**0.983**	*-0.068*	*0.032*	*0.091*	*0.021*
Duration of surfacing (log)	*0.236*	**0.870**	*0.010*	*0.007*	*-0.185*	*0.163*
Median blow interval (log)	0.254	-0.405	*0.104*	*-0.149*	**-0.539**	0.327
Turn (1,2) or not (0)	**0.935**	*0.138*	*0.054*	*0.060*	*0.106*	*-0.040*
Degrees of turn (log °/10+1)	**0.936**	*0.109*	*0.031*	*0.074*	*0.120*	*-0.019*
Speed (0-3)	*-0.052*	*-0.032*	*0.189*	*0.057*	*0.081*	**-0.740**
Group size	*0.023*	*-0.025*	**0.754**	*-0.155*	*-0.195*	*0.049*
Socialize (1,2) or not (0)	*0.109*	*0.008*	**0.636**	*0.202*	*0.248*	*-0.044*
Flukes out (1) or not (0)	*0.101*	*0.051*	*-0.175*	**0.787**	*-0.162*	*-0.094*
Paralleling ice edge (1) or not (0)	*0.115*	*-0.024*	*-0.087*	*-0.221*	**0.665**	*0.137*
Emerge from under ice (1) or not (0)	*0.208*	*-0.141*	*0.038*	*0.126*	0.404	*-0.080*
Visible below surface (1) or not (0)	*-0.055*	*-0.109*	**0.589**	*-0.005*	-0.480	*-0.105*
Underwater blow (1) or not (0)	*-0.164*	*0.122*	*0.180*	*0.215*	*0.120*	**0.740**
Tail slap (1) or not (0)[b]	*0.040*	*-0.000*	*0.190*	**0.741**	*0.126*	*0.229*
Interpretation	Turn (+) or not (-)	Surfacing long (+) or short (-)	Group (1) or alone (-)	Flukes (1) or not (0)	Paralleling ice/short blow int. (+) or not (-)	Slow & UWB (+) or Faster & no UWB (-)
% of Variance Explained by Factor						
Rel. to all 14 original var.	14.2	14.1	10.6	9.9	9.7	9.5
Rel. to all 6 factors	20.9	20.7	15.6	14.5	14.3	14.0

---

[a] The weighting placed on each variable by a factor is proportional to the absolute value of the correlation coefficient between the variable and factor. Correlation coefficients for variables heavily weighted ($|r| \geq 0.5$) are in boldface, for those moderately weighted ($0.5 > |r| \geq 0.25$) are in normal type, and for those lightly weighted ($|r| < 0.25$) are in italics.

[b] Other types of aerial activities were not seen among traveling bowheads in 1989-90.

Table 32. Behavior factors in relation to distance from projector (R), 13 May 1990. There were no usable control data for 13 May 1990[a], so all 1989-90 control data (camp present but no playback) are shown. P_n is nominal 2-tailed significance level of the correlation coefficient. Aerial observations only. All whales are traveling; no mothers or calves present.

			Approach			Recede			All Whales		
Behavior Factor		Situation	r	n	P_n	r	n	P_n	r	n	P_n
Factor 1	vs. log R	Distorted *Karluk*	-0.206	22	ns	-0.480	15	(-)	-0.367	37	-
Turn (+) or		Undistorted *Karluk*	-0.710	39	---	-0.088	8	ns	-0.631	47	---
not (-)		All 13 May *Karluk*	-0.532	61	---	-0.346	23	ns	-0.514	84	---
		All '89-'90 Control	0.127	32	ns	-0.326	4	ns	0.098	36	ns
Factor 2	vs. log R	Distorted *Karluk*	0.067	22	ns	0.167	15	ns	0.193	37	ns
Surfacing long (+)		Undistorted *Karluk*	0.328	39	+	0.587	8	ns	0.370	47	+
or short (-)		All 13 May *Karluk*	0.249	61	(+)	0.493	23	+	0.326	84	++
		All '89-'90 Control	0.149	32	ns	0.833	4	ns	0.057	36	ns
Factor 3	vs. log R	Distorted *Karluk*	0.241	22	ns	0.155	15	ns	0.241	37	ns
Group (1)		Undistorted *Karluk*	0.124	39	ns	0.159	8	ns	0.130	47	ns
or alone (-)		All 13 May *Karluk*	0.155	61	ns	0.102	23	ns	0.157	84	ns
		All '89-'90 Control	-0.706	32	---	0.117	4	ns	-0.485	36	--
Factor 4	vs. log R	Distorted *Karluk*	-0.184	22	ns	0.022	15	ns	-0.077	37	ns
Flukes (1)		Undistorted *Karluk*	0.420	39	++	0.107	8	ns	0.371	47	++
or not (0)		All 13 May *Karluk*	0.067	61	ns	0.112	23	ns	0.089	84	ns
		All '89-'90 Control	0.605	32	+++	0.187	4	ns	0.478	36	++
Factor 5	vs. log R	Distorted *Karluk*	0.070	22	ns	-0.442	15	(-)	-0.012	37	ns
Paralleling ice/		Undistorted *Karluk*	0.203	39	ns	-0.121	8	ns	0.164	47	ns
Short BI (+)		All 13 May *Karluk*	0.145	61	ns	-0.358	23	(-)	0.086	84	ns
or not (-)		All '89-'90 Control	0.211	32	ns	-0.452	4	ns	-0.125	36	ns
Factor 6	vs. log R	Distorted *Karluk*	0.139	22	ns	0.259	15	ns	0.162	37	ns
Slow & UWB		Undistorted *Karluk*	-0.581	39	---	-0.150	8	ns	-0.539	47	---
(+) or Faster		All 13 May *Karluk*	-0.380	61	--	-0.012	23	ns	-0.356	84	---
& no UWB (-)		All '89-'90 Control	-0.472	32	--	-0.597	4	ns	-0.292	36	(-)

---

[a] Although there were control observations from 13 May 1990, there were no control surfacings with known values for all 14 variables needed to compute factor scores.

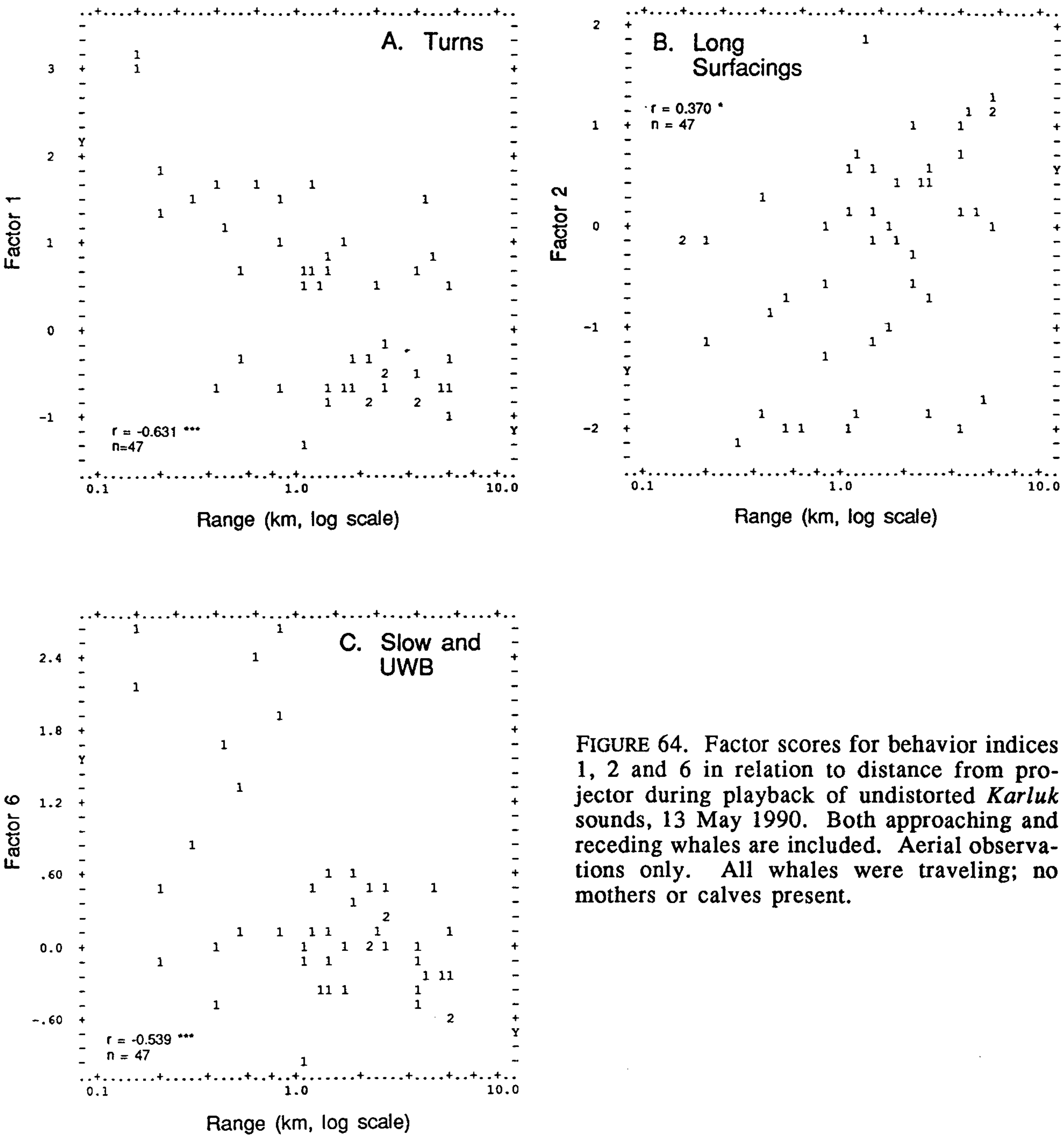


FIGURE 64. Factor scores for behavior indices 1, 2 and 6 in relation to distance from projector during playback of undistorted *Karluk* sounds, 13 May 1990. Both approaching and receding whales are included. Aerial observations only. All whales were traveling; no mothers or calves present.

trend is confounded by the fact that a similar (although weaker) trend was evident for the pooled 1989-90 control data (Table 32).

- There was evidence that raised flukes and flipper slaps (Factor 4) were more likely to occur far from the projector than near it during the undistorted playback. However, given the rarity of both behaviors on 13 May (Table 30), and the presence of a similar trend in the pooled 1989-90 control data, this apparent trend may have been unrelated to the *Karluk* playback.

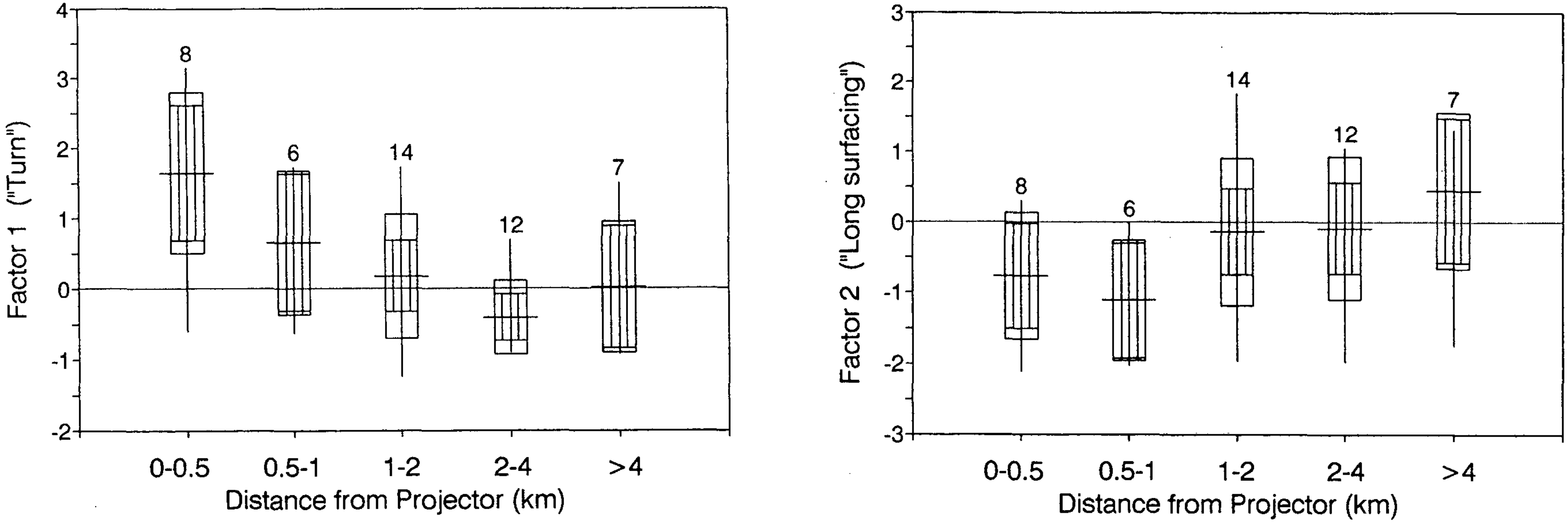
- Factors 3 and 5 were not significantly ($P_n \leq 0.05$) related to distance from the projector on 13 May.

Thus, some of the behavioral indices derived by factor analysis, like some of the original behavioral variables, were significantly related to distance from the projector during the undistorted *Karluk* playback on 13 May (Fig. 64; Table 32). The results were clearest for Factors 1 and 2, for which there were no parallel trends in the pooled 1989-90 control data. Factors 1 and 2 represented the occurrence and magnitude of turns, and the duration and number of blows per surfacing. Values of these original variables were also correlated with distance from the operating projector on 13 May (see earlier).

The three most meaningful behavioral indices (factors) were summarized according to the standard distance categories noted earlier. The results (Fig. 65) were consistent with results based on individual surfacing and respiration variables (*cf.* Fig. 62). Values of Factor 1 at ranges >½ km were statistically indistinguishable from one another, but different from values at ≤½ km. Values of Factors 2 and 4 at ranges >1 km were statistically indistinguishable, but different from values at ½-1 km (Table 27B, p. 172). Hence, this method of analysis confirms earlier indications that the undistorted playback on 13 May affected some aspects of behavior at distances as great as ½-1 km.

This method of analysis provided no evidence that behavior of bowheads >1 km from the operating projector was affected by projected *Karluk* noise. As noted earlier, there was evidence of a possible weak effect on number of blows per surfacing and duration of surfacing at distances as great as 2-4 km (p. 173; Table 27A). Also, there was evidence that turns were more frequent as much as 1-2 km away during the undistorted playback, and even farther away during the playback of distorted *Karluk* sounds (p. 178). The overall analysis based on behavioral factors did not confirm that noise effects extended out to distances >1 km. However, the data do not rule out the possibility of a weak effect at a distance somewhat greater than 1 km during the undistorted playback on 13 May 1990. Despite the relatively large quantity of data collected in this observation session, the sample sizes in specific distance categories were low, limiting the power of the analysis to identify effects.

Summary, 13 May 1990.--In the absence of playbacks, most bowheads seen on this date moved on a constant ESE heading along the north edge of a long, narrow lead. They remained along the north edge of the lead as they passed within 50-100 m of the ice camp, which was on the north edge. However, during playbacks, bowheads began to exhibit turning and hesitation when they came within 1-2 km. Many dove at an angle under the north edge of the ice. These whales must have changed course under the ice in order to return to the lead. When they came within a few hundred meters of the operating projector, most whales moved across


A. 13 May 1990, Undistorted, Factor 1

B. 13 May 1990, Undistorted, Factor 2

C. 13 May 1990, Undistorted, Factor 6

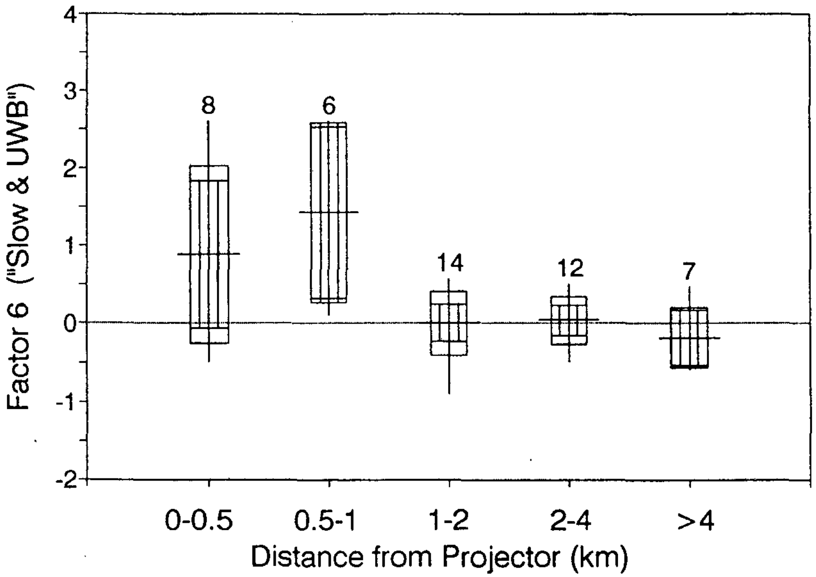


FIGURE 65. Factor scores for behavior indices 1, 2 and 6 by distance category from projector during playbacks of undistorted *Karluk* sounds, 13 May 1990. Same data as in preceding graph. The mean, range, ± 1 s.d. (open rectangle), and ± 95% confidence interval (hatched rectangle) are shown.

to the south side of the lead, the side farthest from the projector. Whales that were at the surface at their closest points of approach were typically 160-195 m from the projector at CPA, although one whale came as close as 110 m. Once they had passed the projector, they tended to make a long dive, to resume a faster and more normal rate of travel, and to resume straight-line travel--often along the north edge of the lead. Bowhead migration was not blocked, and was held back by no more than several minutes.

Several quantifiable aspects of behavior were different for whales 0-½ km and ½-1 km from the operating projector than they were >1 km away. Behavioral variables that were affected when whales were within 1 km during undistorted playbacks included duration of surfacing, number of blows per surfacing, median blow interval, headings, frequency and magnitude of turns, speeds, and various multivariate indices of behavior. The frequency of turning seemed to be affected as much as 1-2 km away during the undistorted playback, and 2-4 km away during the distorted playback. There was equivocal evidence of a possible weak effect on number of blows per surfacing and duration of surfacing at distances as great as 2-4 km during the undistorted playback.

Noise Exposure.--On 13 May 1990, source levels were determined via a hydrophone adjacent to the projector, and received levels were measured at three sonobuoy locations. *(1)* A standard 57A sonobuoy was manually deployed ~3.5 km west of the camp along the south edge of the lead at 10:36; it operated until 13:19. *(2)* A replacement standard 57A buoy was air-dropped 1.3 km west of the camp in mid-lead at 15:30. It had drifted to 1.7 km west by 16:12 and 2.4 km west by 18:46, as determined by acoustic travel time. *(3)* A more distant 57A (modified for 14 m hydrophone depth) was air-dropped 5.8 km west of the camp at 10:36. This was west of the "tertiary" lead that branched off to the south from the long, narrow lead. This distant buoy remained 5.5-6.0 km from the ice camp throughout the day, based on acoustic travel time data.

Source levels and spectra: The broadband source level (20-1000 Hz) during the distorted playback was initially 164 dB re 1 µPa-m, diminishing rapidly to 150-152 dB and ultimately to 147 dB by the end of that playback (Fig. 66). Initially the spectrum shape for the projected sounds was similar to the normal shape during other *Karluk* playbacks. The strongest components were initially in the 1/3-octave bands centered near 200 Hz, as normal (Fig. 67). However, the source levels in those bands decreased rapidly during the distorted playback, while the source levels at various higher frequencies (peaking near 1500 Hz) were, proportionally, much more prominent than normal (Fig. 67). The "14:08" curve in Figure 67 shows the spectrum of the projected sounds when the aerial observers were watching whales pass the malfunctioning projector. Later during the distorted playback there was also a strong peak at 63 Hz. Source level data are summarized in Table 33.

The broadband source level during the subsequent undistorted playback with a different J-11 projector was 166 dB, with the usual spectrum shape peaking in the 1/3-octave bands centered at 160 or 200 Hz (Fig. 67).

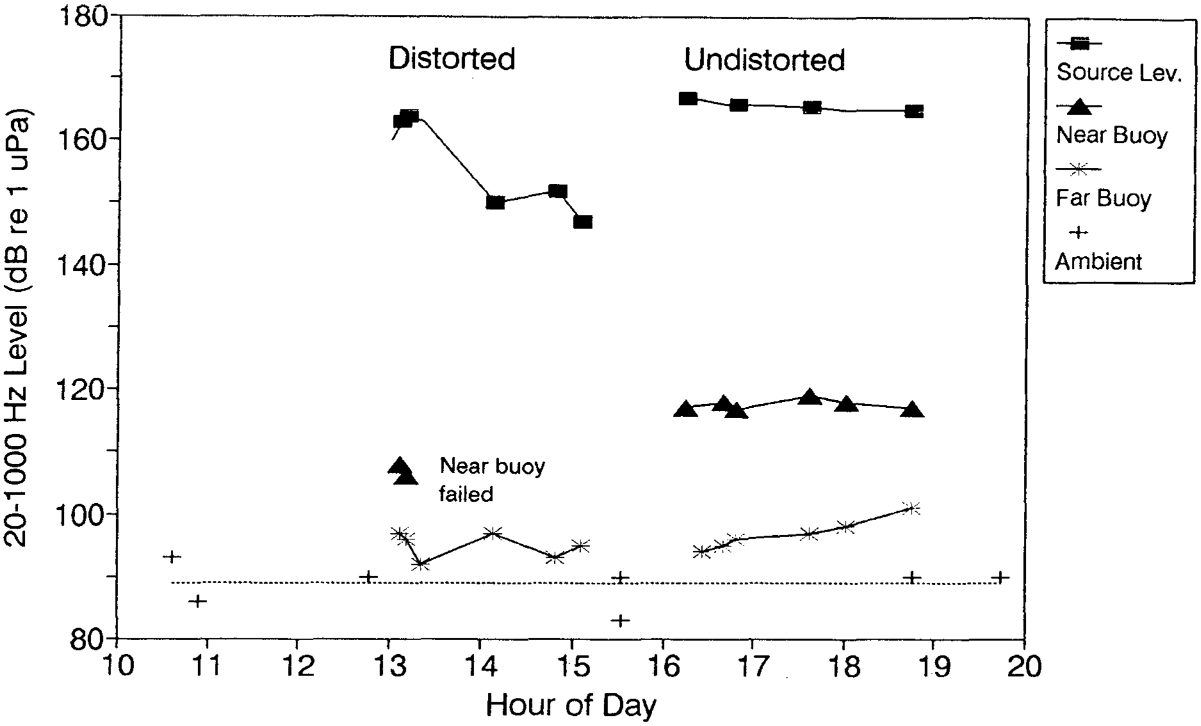


FIGURE 66. Broadband (20-1000 Hz) levels of projected sound on 13 May 1990 at the source and as received at near buoys (1.7-3.5 km away) and at a far buoy (~5.8 km away). Distance from projector to near buoy was 3.5 km during the distorted playback and 1.7→2.4 km during the undistorted playback. The background ambient level is also shown. Distorted playback, 13:00-15:06; undistorted playback, 16:10-18:46.

Table 33. Measured sound levels and estimated signal-to-noise ratios during distorted and undistorted playbacks, 13 May 1990.

		Distance (km)	Type of Data	20-1000 Hz Drill. (dB)	20-1000 Hz Amb. (dB)	20-1000 Hz S:N (dB)	Dominant 1/3-Octave Freq. (Hz)	Dominant 1/3-Octave Drill. (dB)	Dominant 1/3-Octave Amb. (dB)	Dominant 1/3-Octave S:N (dB)
Source levels										
Distort.,	13:11	0.001	Meas.	164	89	75	200	159	81	78
"	14:08	"	"	150	"	61	1250	144	79	65
"	14:49	"	"	152	"	63	1250	150	"	71
"	15:05	"	"	147	"	58	1600	145	"	66
Undist.,	16:14	"	"	167	89	78	160	161	81	80
"	18:44	"	"	165	"	76	200	159	"	78
Nearer Buoys										
Distort.,	13:07	3.5	Meas.	108	89	19	250	104	81	23
Undist.,	16:40	1.7	"	118	89	29	200	114	81	33
"	17:37	"	"	119	"	30	200	113	"	32
"	18:45	"	"	117	"	28	200	112	"	31
Farther Buoy										
Distort.,	13:07	~5.8	Meas.	97	89	8	315	93	78	15
"	14:49	"	"	93	"	4	2500	91		
"	15:05	"	"	95	"	6	630	89	79	10
Undist.,	16:40	"	"	95	89	6	160	91	81	10
"	17:37	"	"	97	"	8	160	91	"	10
"	18:45	"	"	101	"	12	160	93	"	12

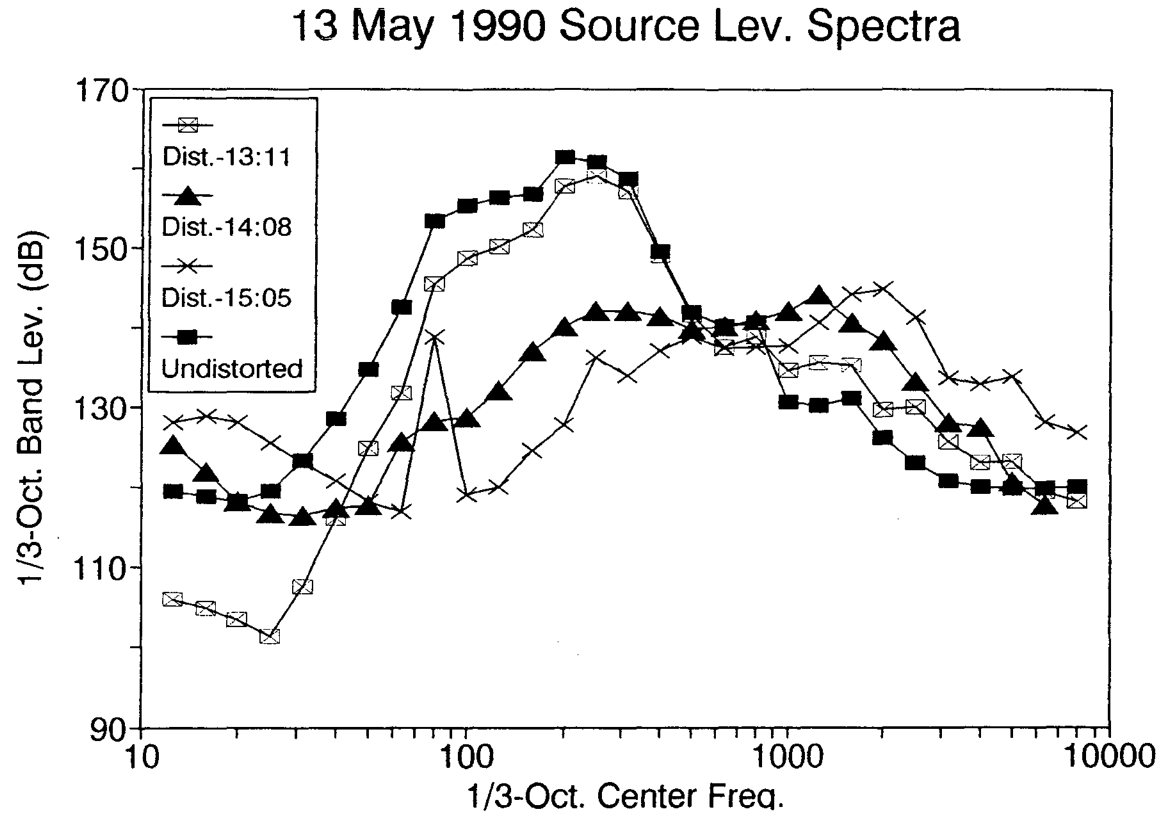


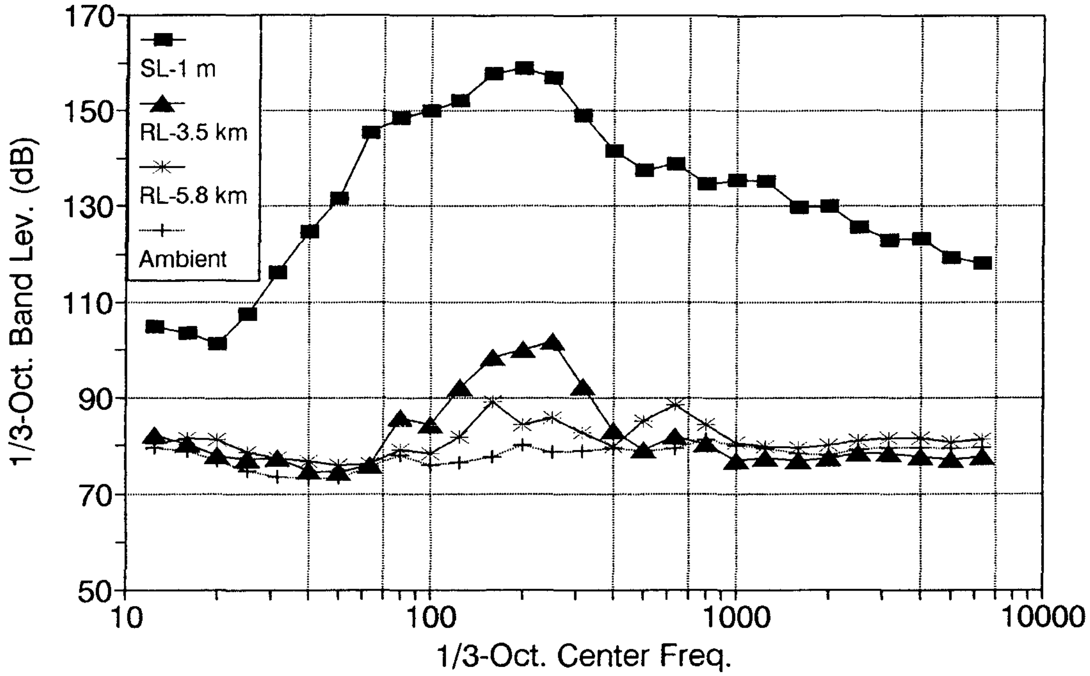
FIGURE 67. Third-octave source levels of projected sounds at four times on 13 May 1990--three times during the distorted *Karluk* playback and once during the subsequent undistorted playback. Triangles show projected sounds when the aerial observers observed bowheads near the malfunctioning projector. Data are in dB re 1 µPa at 1 m.

Measured received levels and spectra: Received levels and spectra varied through the day in approximate parallel with the variations in source level and spectrum.

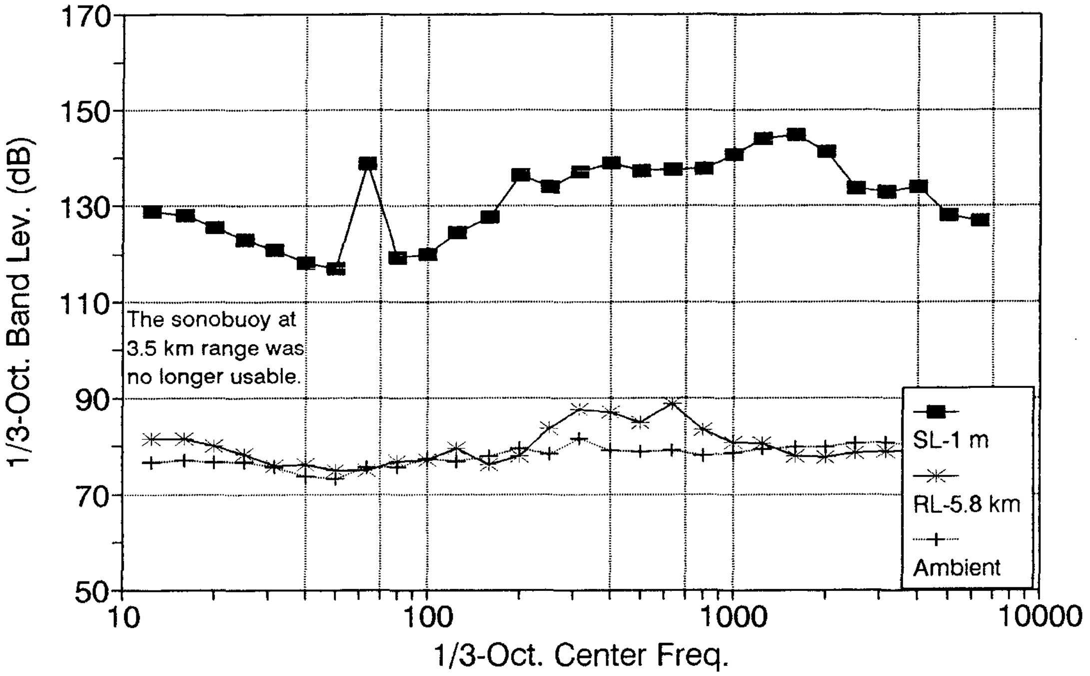
At the start of the distorted playback, the broadband (20-1000 Hz) received level was 106-108 dB at the buoy ~3.5 km from the projector and 97 dB at the buoy ~5.8 km from the projector. The received spectrum peaked in the usual frequency range near 160-250 Hz, and was barely above ambient 5.8 km from the projector (Fig. 68A). The broadband ambient level was fairly consistent through the day (Fig. 66). When estimating signal-to-noise ratios, we have assumed that the day's average of 89 dB for the 20-1000 Hz band applied throughout the day (Table 33).

The closer buoy failed early during the distorted playback. Broadband levels received at the distant (5.8 km) buoy remained in the 92-97 dB range--slightly above ambient--throughout that playback (Fig. 66). During the middle and later parts of the distorted playback, the received spectrum at 5.8 km range barely exceeded the ambient spectrum, and did so only at unusually high frequencies--250 to 800 Hz (Fig. 68B).

A. 13 May 1990--Distorted--Start



B. 13 May 1990--Distorted--End



The sonobuoy at 3.5 km range was no longer usable.

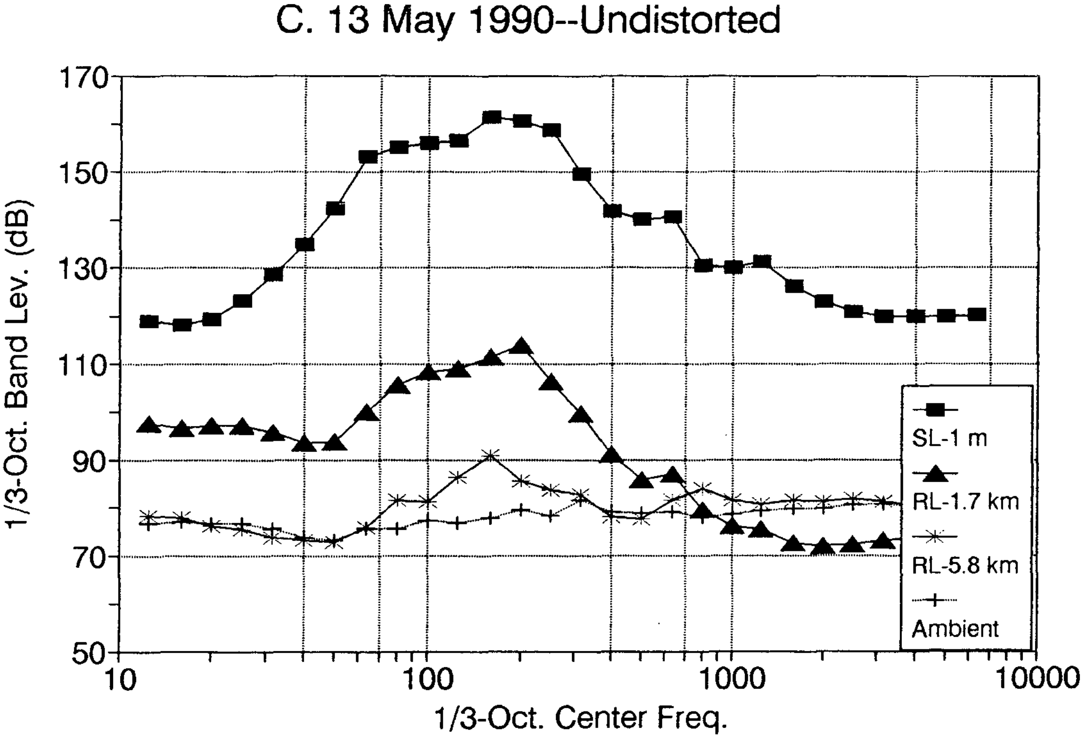


FIGURE 68. Third-octave source levels (squares) and received levels during distorted and undistorted playbacks on 13 May 1990 at times (A) 13:11, (B) 15:05, and (C) 16:14. Plus signs show ambient noise levels when the projector was not operating, times (A) 12:47 and (B,C) 15:32. Data are in dB re 1 μPa. For additional explanatory notes, see the caption to Figure 44.

During the undistorted playback, broadband received levels were 117-119 dB at range 1.7-2.4 km, and 94-101 dB at range 5.5-6.0 km (Fig. 66). The received 1/3-octave spectrum peaked in the usual frequency range near 200 Hz (Fig. 68C).

Estimated received levels: The results from the transmission loss tests, along with the direct measurements via sonobuoys, were used to develop equations suitable for predicting received level vs. distance from the projector on 13 May. For the undistorted playback, received levels at a given range can be predicted from the following equations:

$$RL_{20\text{-}1000\ Hz} = 129.0 - 4.08\ R - 10 \log (R)$$

$$RL_{200\ Hz} = 124.5 - 4.19\ R - 10 \log (R)$$

The 1/3-octave band centered at 1250 Hz was important during the latter part of the distorted playback but not during the undistorted playback, when the received level in the 1250 Hz band was low:

$$RL_{1250\ Hz} = 84.9 - 4.22\ R - 10 \log (R)$$

Appendix B describes how these equations were derived. Figure 69 shows the received levels predicted by the equations in relation to distance from the projector and ambient noise. Table

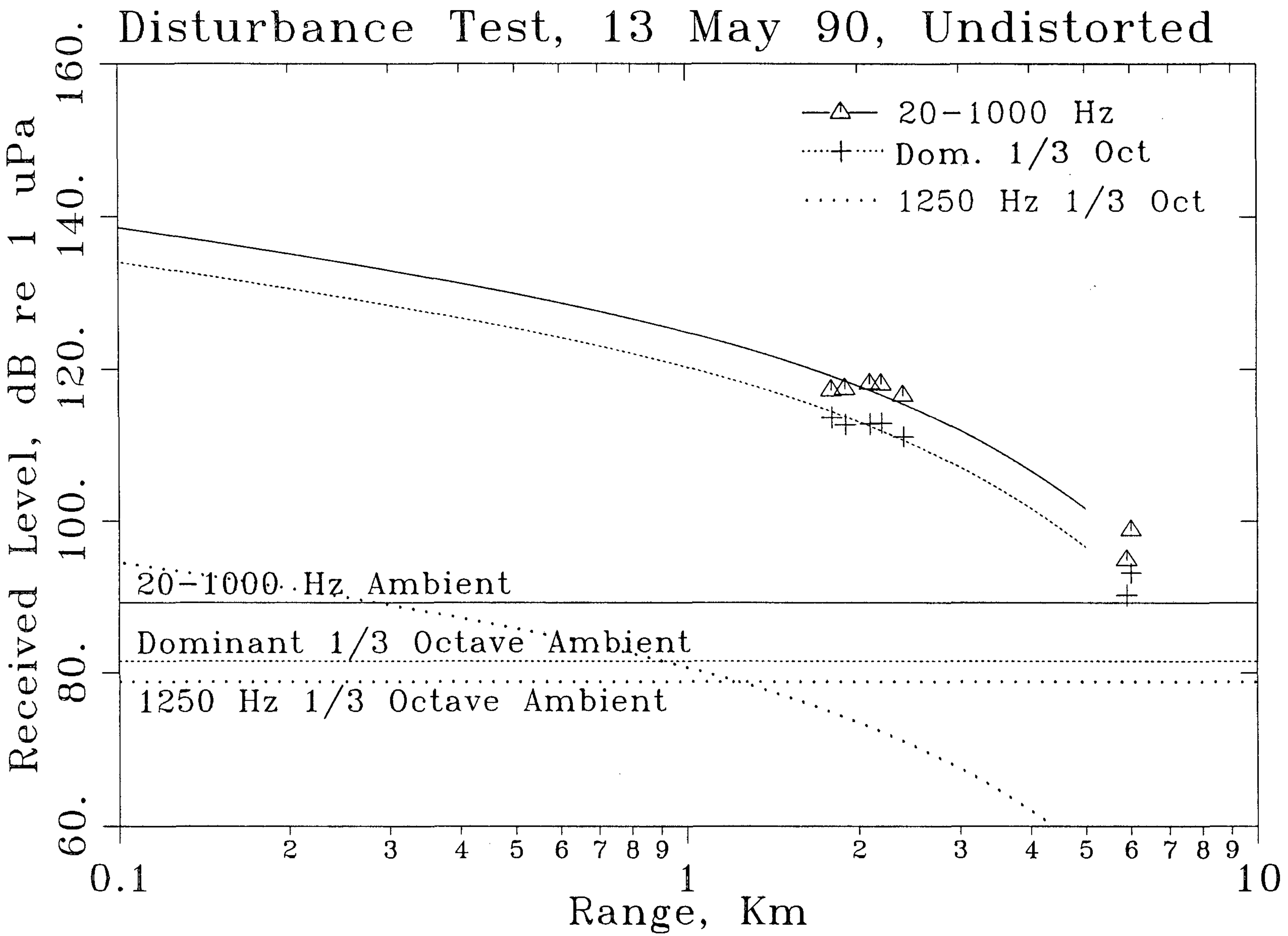
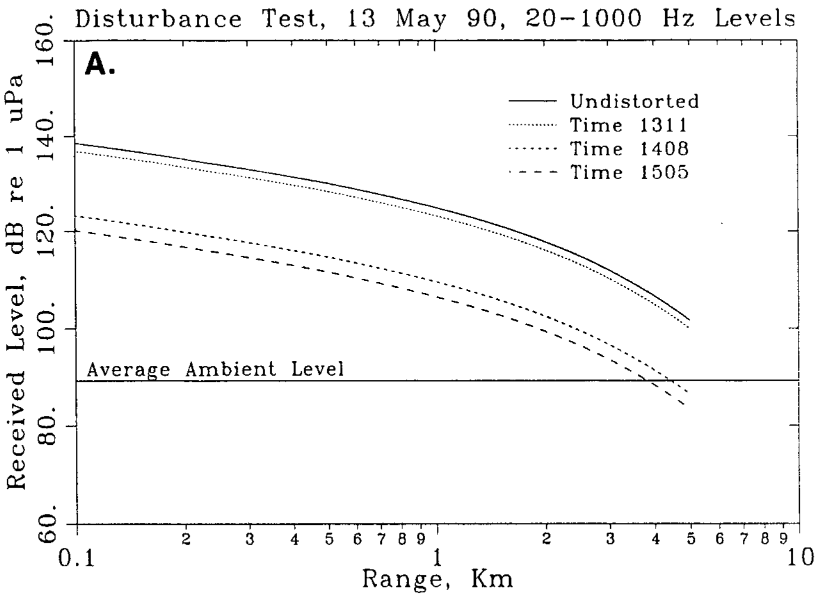
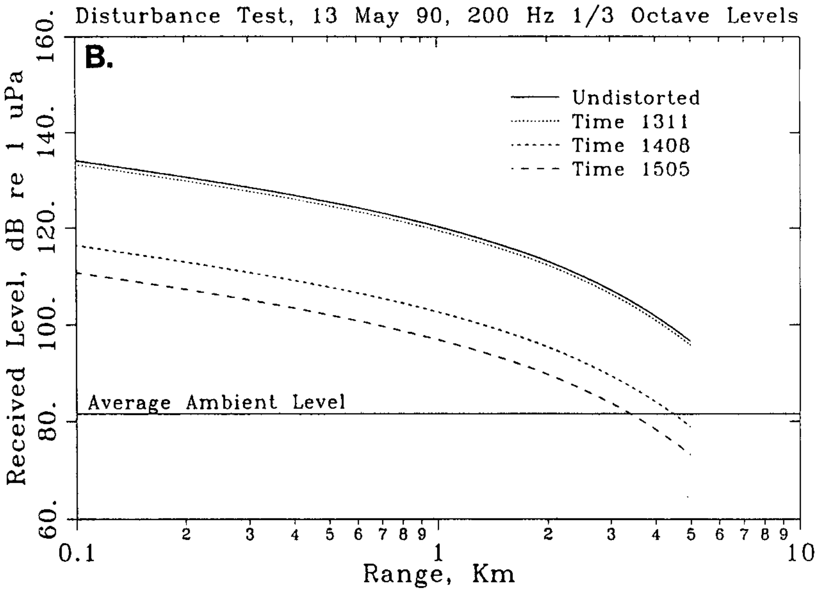


FIGURE 69. Measured and estimated received sound levels vs. range during the undistorted *Karluk* disturbance test on 13 May 1990. The triangles and pluses show measurements via two sonobuoys, one of which drifted from 1.7 to 2.4 km range during the playback. The three descending curves show the received levels estimated by the three equations given in the text. The average ambient noise levels for three bands are shown as the three horizontal lines.





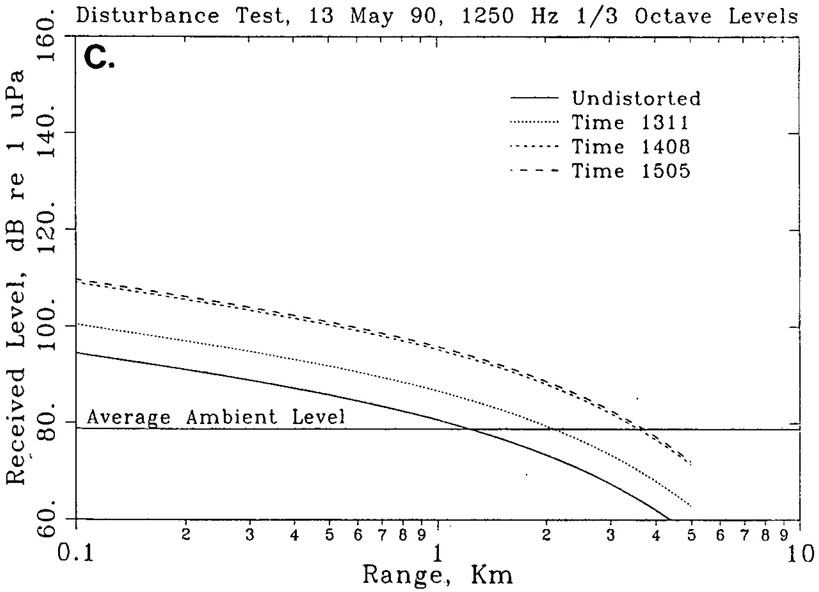


FIGURE 70. Estimated received sound levels vs. range at three times during the distorted playback vs. those during the undistorted *Karluk* playback, 13 May 1990: (A) 20-1000 Hz band; (B) 1/3-octave band centered at 200 Hz; (C) 1/3-octave band centered at 1250 Hz. The average ambient noise level in the corresponding band is shown as the horizontal line. See Appendix B for equations.

23E,F (p. 154-6) shows predicted received levels at the locations of specific whales observed during the undistorted playback.

Received levels during the distorted playback were a function of both distance and time, since the source level decreased and the spectrum shape changed during the distorted playback. Equations were developed for each of the three bands noted in the previous paragraph for each of three times during the distorted playback: 13:11 (start), 14:08 (middle), and 15:05 (end). The procedures and equations are given in Appendix B; the levels predicted by these equations are shown in Figure 70. The predicted levels for specific whale locations (Table 23C,D) are interpolations between the values estimated by the equations for the two closest times.

During the undistorted playback, the closest observed whale was 123 m from the projector at 18:35, and its CPA was ~110 m. However, most of the whales that were visible at or near the surface as they passed the projector were 160-195 m away, near the south edge of the lead (Table 23). Estimated broadband (20-1000 Hz) received levels at 195, 160 and 110 m were 135-138 dB re 1 µPa, or 46-49 dB above the day's average ambient level in that band (Table 34A). The corresponding received levels in the dominant 1/3-octave band, near 200 Hz, were 131-134 dB, or 50-53 dB above the day's average ambient level in that band (Table 34A). These values all refer to sounds at least a few meters below the surface. While whales were visible at the surface, they probably received sound levels a few decibels less than those quoted above.

Table 34. Estimated sound levels and signal-to-noise ratios at locations where selected bowheads were seen during undistorted and distorted playbacks, 13 May 1990.

		Type	20-1000 Hz			Dominant 1/3-Octave			
	Distance (km)	of Data	Drill. (dB)	Amb. (dB)	S:N (dB)	Freq. (Hz)	Drill. (dB)	Amb. (dB)	S:N (dB)
A. Undistorted Playback									
Closest whale seen	0.110	Est.	138	89	49	160/200	134	81	53
Corridor on S	0.160-	"	136	"	47	160/200	132	"	51
side of lead	0.195	"	135	"	46	"	131	"	50
Numerous other	<0.300-	"	>133	"	>44	"	>128	"	47
whales	<0.900	"	>126	"	>37	"	>121	"	40
B. Distorted Playback									
Corridor on S	0.155-	Est.	131	89	42	200	126	81	45
side of lead	0.190*	"	127	"	38	"	122	"	41
Numerous other	<0.270-	"	>132	"	>43	"	>128	"	47
whales	<1.000*	"	>111	"	>22	"	>104	"	23

* During the distorted playback, received levels and S:N depended on time as well as distance. Thus the received level when one whale was seen at 270 m exceeded the levels when some others were seen at 155-190 m.

Many other whales were sighted 300-900 m from the operating projector and heading toward it, but were below the surface at their closest points of approach. It is not known whether most of these whales passed along the south side of the lead 160-195 m from the projector and were exposed to sound levels comparable to those listed above. Some of these whales may have detoured under the ice, maintaining a greater minimum distance from the projector. However, even at 300-900 m, whales were exposed to significant sound levels: 126-133 dB on a broadband basis (S:N = 37-44 dB), and 121-128 dB in the dominant 1/3-octave band (S:N = 40-47 dB) (Table 34A). The projected sounds remained above the ambient level out to distances exceeding 6 km during the undistorted *Karluk* playback (Fig. 68C, 69).

Received levels and S:N ratios to which bowheads were exposed during the distorted playback were lower than those during the undistorted playback (Table 34B). Received levels in the migration corridor along the south side of the lead, about 155-190 m from the projector, were ~127-131 dB on a broadband basis and ~122-126 dB in the dominant 1/3-octave band. These levels were several dB less than those in the same corridor during the undistorted playback. However, the received levels of distorted sounds in the corridor south of the projector were far above the ambient levels in the corresponding bands. In fact, the projected sounds were above the ambient level out to a distance exceeding 5 km at the start of the distorted playback (Fig. 68A, 70), and out to at least 3-4 km throughout the distorted playback (Fig. 70).

In summary, the area ensonified by the projector during both playbacks on 13 May 1990 extended several kilometers from the projector. Behavioral reactions were obvious at distances up to 1 km, and there was evidence of more frequent turns as much as 1-2 km away during the normal *Karluk* playback or 2-4 km away during the distorted playback. However, during both playbacks, most if not all bowheads came within a few hundred meters of the operating projector. If they had not changed course, most would have passed within 50-100 m. Most of the visible whales diverted slightly so as to travel along a corridor whose closest point of approach to the projector was about 155-195 m. At those distances they were exposed to quite strong sounds: 38-47 dB above day's average ambient noise level. Some whales that were below the surface when within 300-900 m of the projector may have diverted somewhat farther to the side (under the ice), but even these whales approached well inside the ensonified zone and were exposed to strong *Karluk* sounds.

16 May 1990 Playback

The ice camp was set up on a triangular-shaped pan that projected northward from the south side of a secondary lead amidst the pack ice (Plate 5). The ice camp was 102 km from Barrow (Fig. 4, p. 41), far to the east of the main nearshore lead. Drilling sounds were projected from 14:10 to 17:50. The projected level increased from 14:10 to 14:16, and then was steady until 17:50. Late in the day the pan supporting the projector drifted NW across the lead to the north side. The projection period was terminated earlier than originally planned because of concern about the impending collision of the pan with adjacent ice.

Ice-based Observations.--About 36 bowheads (~20 groups) were observed from 13:09 to 14:10 when the projector was silent. During this period all bowheads sighted were moving eastward through the center of the lead 300-600 m north of the projector site (Fig. 71). When they arrived at the eastern edge of the lead, some whales turned to the NE and followed the ice edge NEward. The closest observed whale was 300 m from the silent projector at 13:54 (Table 35). However, prior to the arrival of the ice-based crew, the aerial observers had noticed two bowheads diving under the ice camp pan.

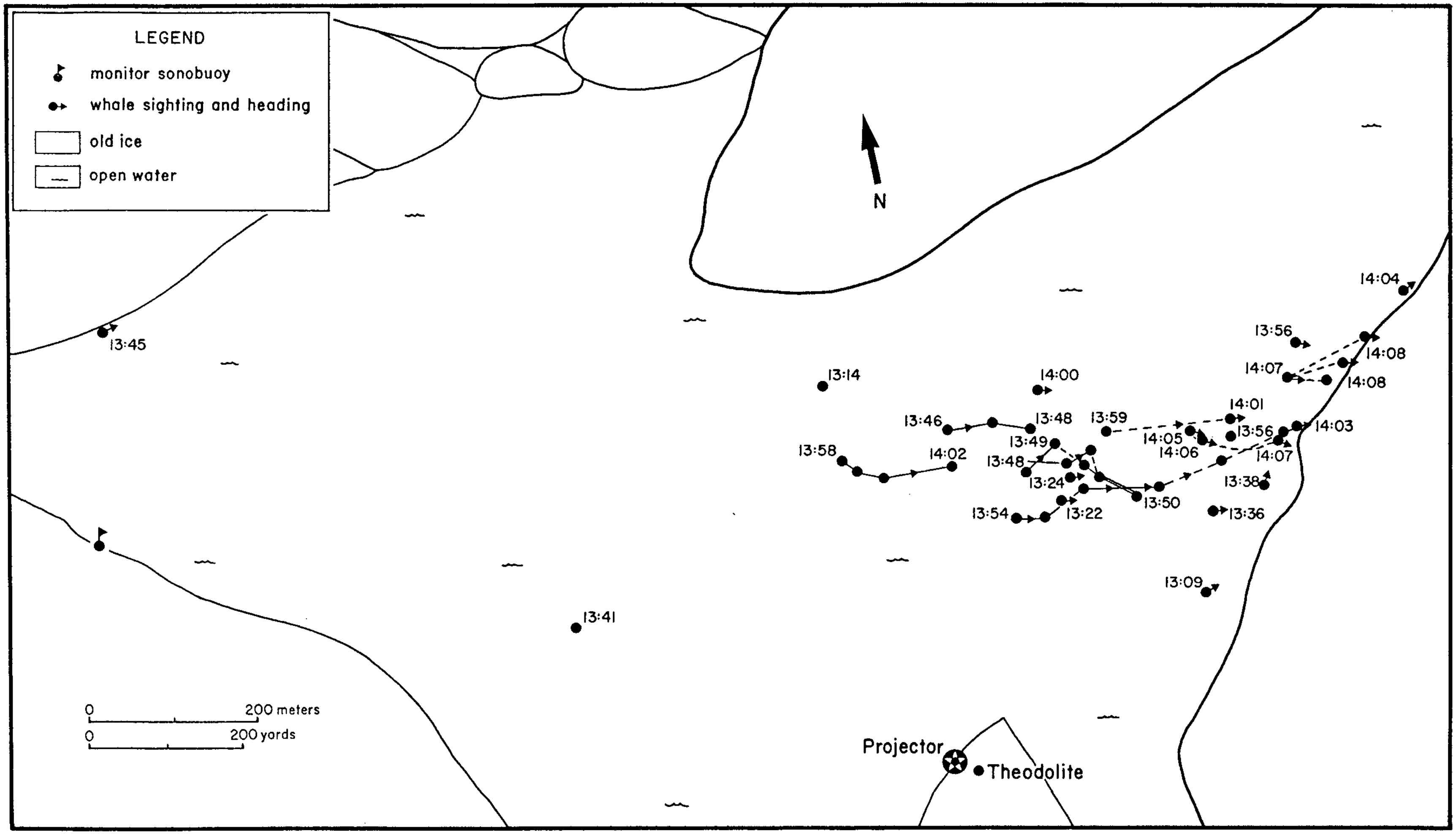
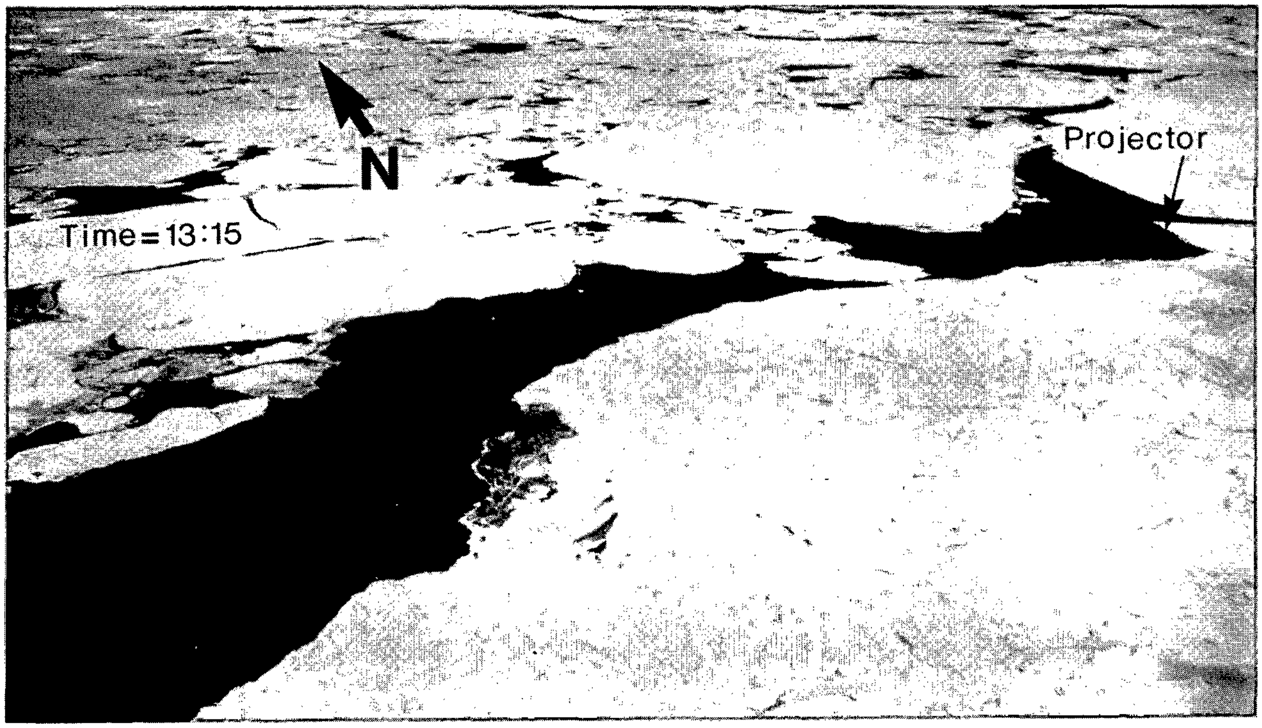


FIGURE 71. Ice-based observations of bowhead tracks relative to the silent projector amidst the pack ice NE of Barrow, Alaska, 16 May 1990. These observations were obtained prior to 14:10 when the playback began. Dashed lines represent presumed paths of whales while they were below the surface.



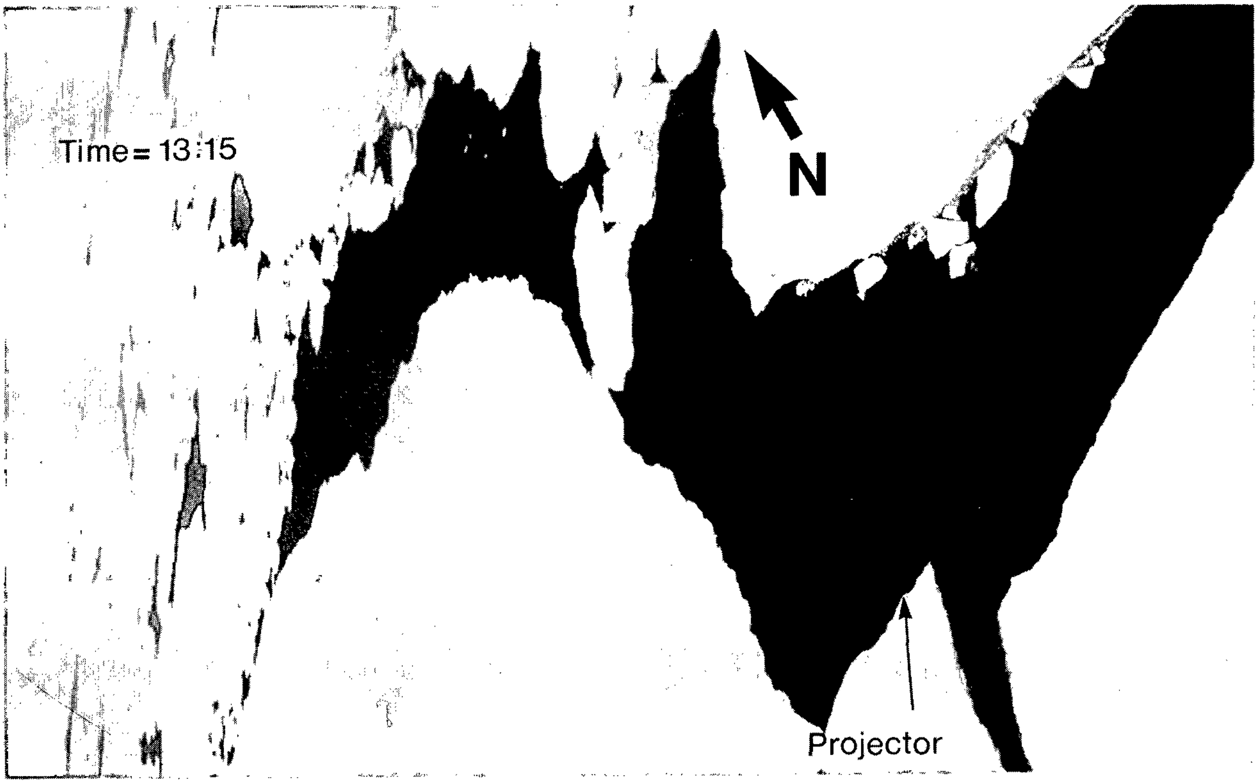


Plate 5. Ice conditions near the projector site on 16 May 1990, as viewed from two directions.

Table 35. Summary of sightings of bowhead whales passing close to the sound projector on 16 May 1990 when the projector was silent and when it was operating amidst the pack ice NE of Barrow. Only sightings with CPA within 1 km of the projector are included in this table.

Time	Radial Distance Followed From Projector (m)[a]	CPA (m)	Determination of CPA[b]	Sound Levels[c]	Nature of Track
Silent Projector--Ice-based observations					
13:09	single sighting	<360[d]	2	NA[e]	ENE of projector heading ENE
13:14	single sighting	475	2	NA	N of projector, heading unknown
13:22	single sighting	335	2	NA	NNE of projector heading E
13:24	single sighting	360	2	NA	NNE of projector heading E
13:36	single sighting	430	2	NA	NE of projector heading E, brief social activity
13:38	single sighting	500	2	NA	NE of projector heading NNE along ice edge, brief social activity
13:41	single sighting	475	2	NA	WNW of projector
13:46	+395 to +405	395	1	NA	N to NNE of projector heading E
13:48	+355 to +385	<355	1	NA	NNE of projector heading NE then SE
13:54	+300 to +560	300	1	NA	N and NE of projector heading generally E
13:56	single sighting	510	1	NA	NE of projector
13:56	single sighting	645	1	NA	NE of projector heading E
13:58	+378 to +350	350	1	NA	N of projector socializing and heading SE then E
13:59	+435 to +525	<435	1	NA	NNE of projector heading E
14:00	single sighting	455	1	NA	NNE of projector heading E
14:04	single sighting	<435	1	NA	NE of projector heading NE along ice edge
14:05	+485 to +700	485	1	NA	NE of projector heading E then NE along ice edge
Silent Projector--Aerial observations					
12:07	single sighting	<100	2	NA	Dives under pan near future projector site before ice-based crew arrived
Operating Projector--Ice-based observations					
14:11-12	+520 to +580	<520	1	Increasing	NNE of projector in mid lead heading E
14:14	single sighting	760	1	Increasing	NNE of projector near E ice edge

Continued...

Table 35. Concluded.

Time	Radial Distance Followed From Projector (m)[a]	CPA (m)	Determination of CPA[b]	Sound Levels[c]	Nature of Track
14:24	unknown to +505	<500	1	>123 / >117	NNE of projector heading ESE
14:31	single sighting	<970	1	>118 / >112	NE of projector heading NE along the ice edge
15:38	+670 to +810	<670	1	>121 / >115	NE of projector heading NE near E ice edge
15:43	single sighting	745	1	120 / 114	NNW of projector heading E
15:54	-370 to +490	200	1	128 / 122	NW to ENE of projector heading E; no apparent deviation from path
16:32	+640 to +735	640	1	121 / 115	NE of projector heading ESE
16:54	+690 to +715	<690	1	>121 / >115	NE of projector heading ESE under ice edge
17:15	single sighting	425	1	124 / 118	SSW of projector
17:16-18	-685 to -700	<685	1	>121 / >115	NNW of projector heading NNE to NE
17:52[f]	single sighting	<806	1	>120 / >114	ENE of projector following ice edge NE
Operating Projector--Aerial observations					
14:22[g] (5 whales)	-4600 to +3400	850-1100	1	117 / 111- 119 / 113	Traveling through mid lead, near projector moved to N side of lead and passed under large pan at CPA
17:41[g]	+455 to +850	455	1	124 / 118	Surfaced from under large pan NNE of projector heading E. Mud coming from their bodies.
17:46[g]	+455 to +2700	[455]	1	124 / 118	Surfaced with preceding group from under large pan NNE of projector heading E. Aerial activity observed 675-900 m NE of projector. travel NE
Later 17:48	+800 to +3200	800	1	120 / 114	Feeding 800 m ENE of projector for 30 min. Mud from mouth. Later travel NE
18:22	+650 to +750	650	2	121 / 115	SE of projector heading E then S along ice edge

---

[a] - indicates that whales are ≥180° from the projector (approaching); + indicates that whales are ≤180° from the projector (moving away).

[b] 1 = measured by theodolite or tape, 2 = visual estimate, 3 = estimate based on nearby surfacings, 4 = estimates based on distant surfacings (possibly unreliable).

[c] Estimated received level (dB re 1 μPa) of projected noise at CPA. Left: level in the 20-1000 Hz band. Right: level in the dominant 1/3-octave band.

[d] < indicates that whales were heading toward the projector when last seen.

[e] NA is not applicable.

[f] This whale was seen <2 min after the projector was turned off.

[g] These whales were also seen by the ice-based observers.

Twenty-one bowheads (12 groups) were observed from the ice camp while the projector was broadcasting drilling sounds (Fig. 72-74). The closest approach to the projector on this day was while drilling sounds were being projected: a single bowhead traveling rapidly eastward passed 200 m north of the projector without deviating from its straight-line course (Table 35; Fig. 73). As the ice pan supporting the projector drifted NW, the sightings of whales tended to become fewer and farther north or, in one case, SSW of the projector (Fig. 74). The latter sighting was the only sighting south of the projector site on this day. A single whale that was observed from 17:46 to 17:53 breached several times when it had moved >675 m NE of the ice camp; this whale was also observed by the aerial crew (see below).

Aerial Observations.--Three behavior observation sessions were conducted from the Twin Otter on 16 May 1990. During the first session a group of 6 traveling whales was followed from 5 km west to 4 km WNW of the projector. At this point the focal group joined a group of socializing whales and there was much confusion concerning the identities of individual whales. We ended the observation session before the whales approached the projector, and we moved to a smaller group of whales (see next paragraph).

During the second session, a group of 6-8 whales was followed from 4.6 km WNW to 3.4 km ENE of the projector. A playback of drilling sounds commenced at 14:10 when the whales were ~1.2 km NW of the projector. As they passed 850 m from the operating projector, the whales moved to the north side of the lead and dove under ice there (Table 35; Fig. 75A). During observations from the ice camp before the projector was on, whales traveled through the center of the lead rather than along the north side (Fig. 71). Thus it is possible, but unproven, that the operating projector caused the whales observed from the aircraft to divert slightly to the north. After passing the projector with CPA ~850 m, the whales crossed the lead to its eastern side and continued on to the ENE (Fig. 75B).

During the third behavior observation session, five bowheads were observed from 17:38 to 19:05. Despite considerable searching, no whales were found west of the projector, so these whales were followed from 450 m NE to 3.2 km ENE of the projector. Drilling sounds were projected until 17:50. When the bowheads were first seen, three whales apparently had been feeding at or near the bottom in water ~40 m deep. Mud was seen trailing from their bodies when they were 450 m from the projector. They slowly traveled to the NE. One whale breached 6 times after it had moved to >650 m from the projector. A fourth whale, a small subadult, apparently fed near the bottom 800 m NE of the projector for about 30 min both during and after projection of drilling sounds. After pausing briefly, the whales continued to travel NE, following a path similar to that of the whales followed during the previous session (Fig. 76; *cf.* Fig. 75B).

Noise Exposure.--On 16 May, a 41B monitor sonobuoy was deployed on the south side of the lead about 1 km west of the projector (Fig. 75A). The transit time of the projected sounds showed that this buoy was 1.1 km away at 14:17 but only 0.8 km away by 17:47 as the lead closed. In addition, a 53B DIFAR buoy was air-dropped into the lead 4.1 km west of the projector. It remained 3.8-4.2 km away throughout the day. The propagation path from the projector to the DIFAR buoy was partly under pack ice (Fig. 75A).

The source level of the projected drilling sounds was 167 dB on this date, and the received sounds were strong at the buoy ~1 km away. At that distance, the received levels were

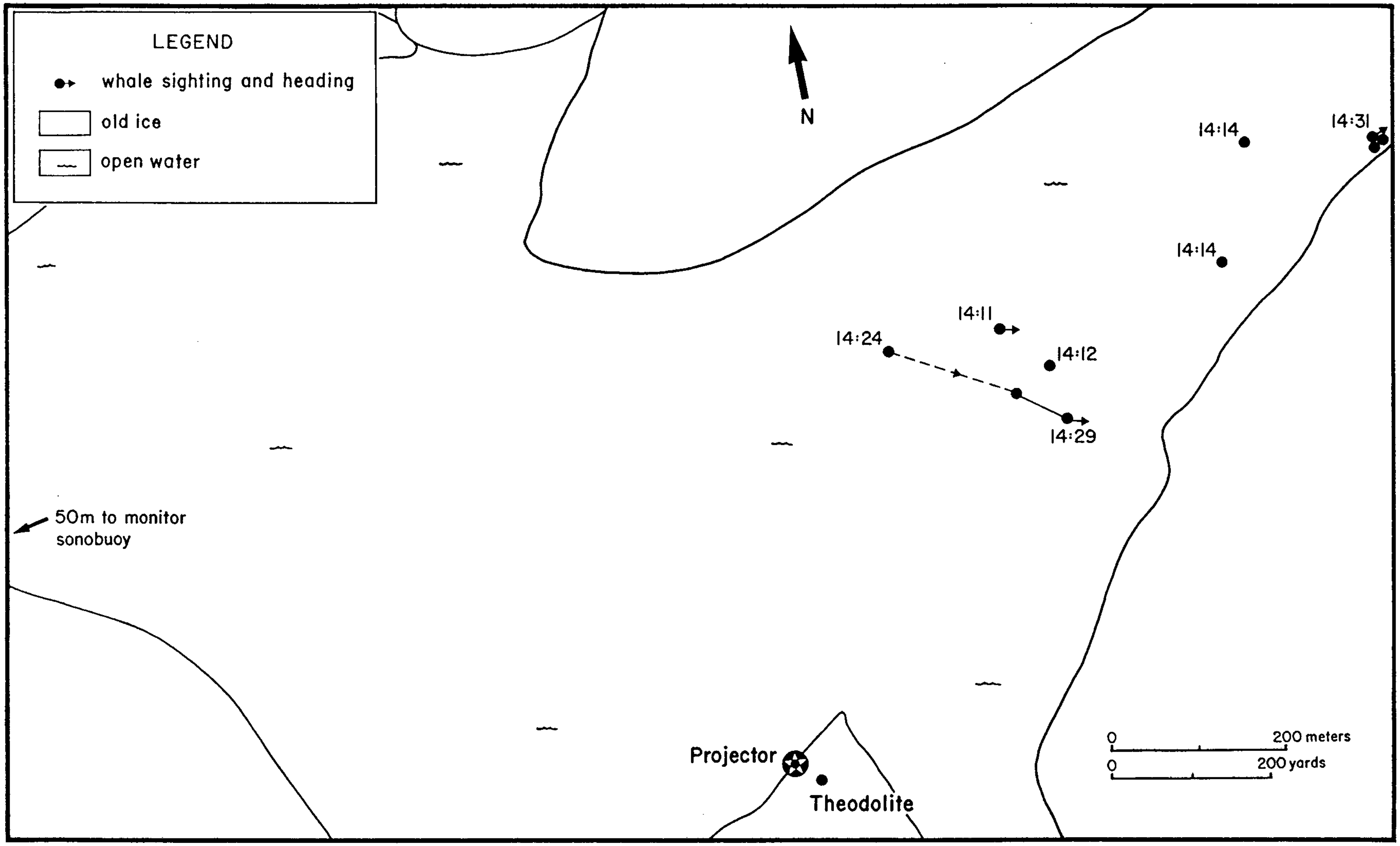


FIGURE 72. Ice-based observations of bowhead tracks relative to the sound projector broadcasting drilling platform sounds (0-30 min after startup) amidst the pack ice NE of Barrow, Alaska, 16 May 1990, times 14:10-14:40. Dashed line represents presumed path of whale while it was below the surface.

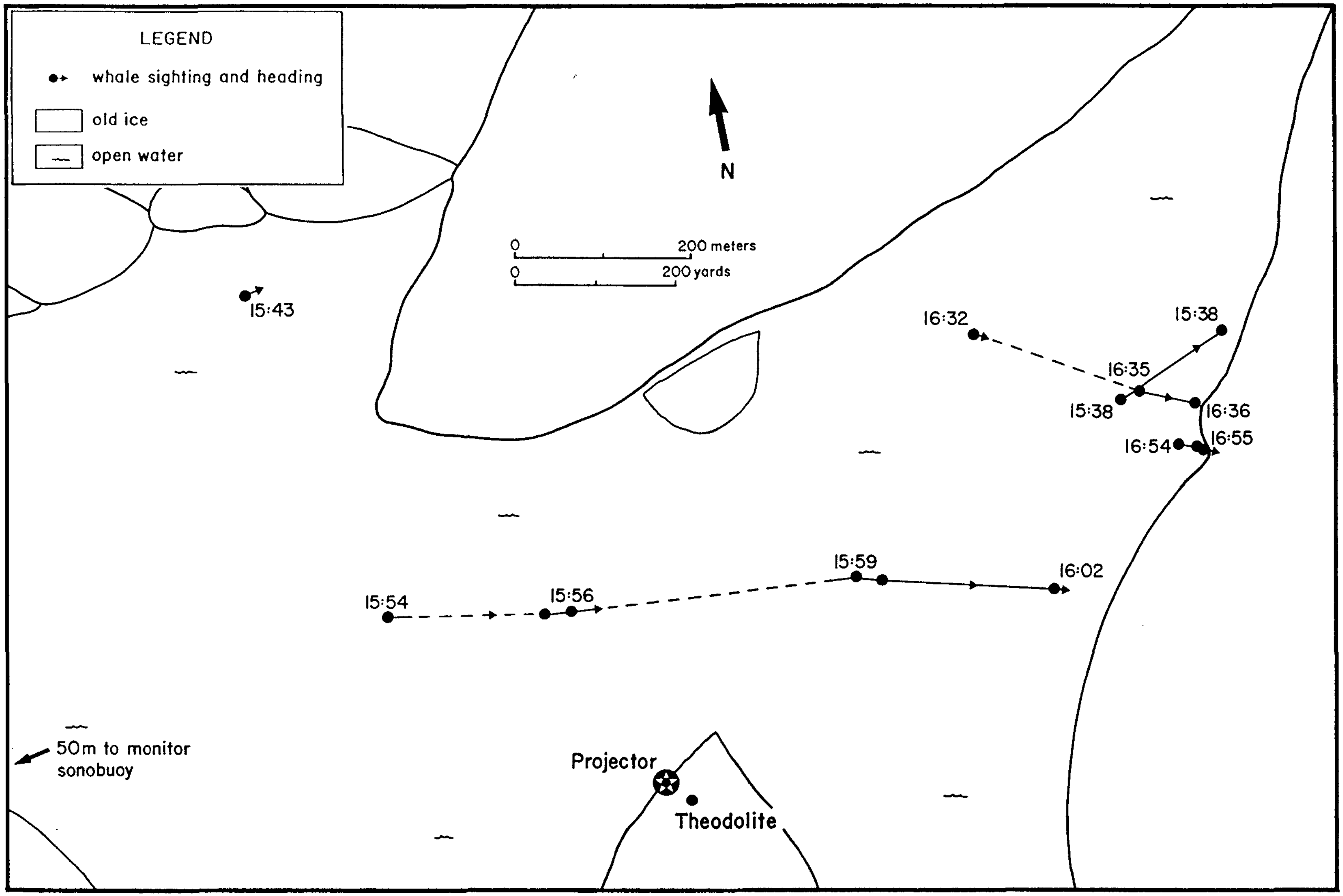


FIGURE 73. Ice-based observations of bowhead tracks relative to the sound projector broadcasting drilling platform sounds amidst the pack ice NE of Barrow, Alaska, 16 May 1990, times 14:40-17:00. Dashed lines represent presumed paths of whales while they were below the surface.

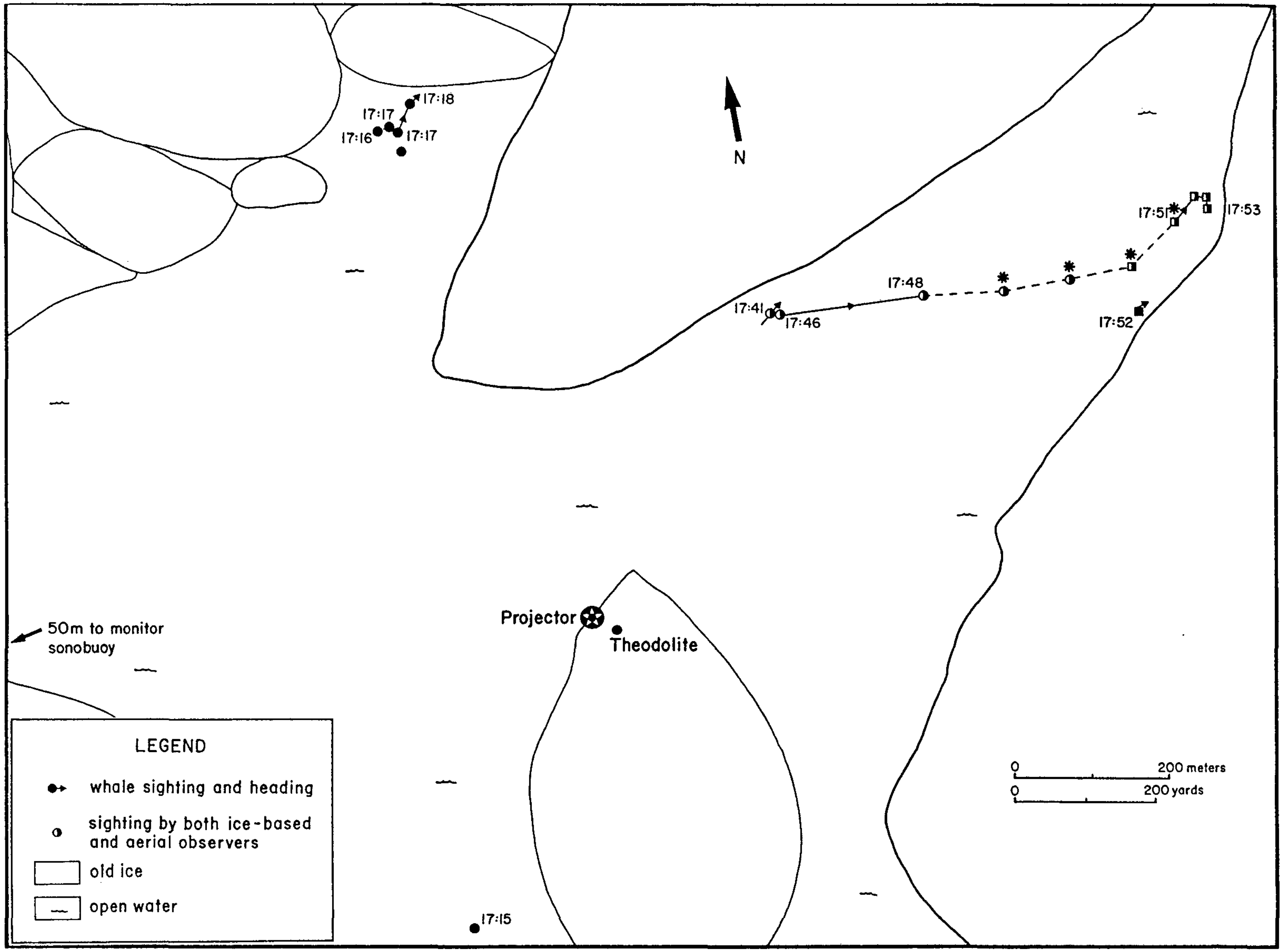


FIGURE 74. Ice-based observations of bowhead whale tracks relative to the sound projector broadcasting drilling platform sounds amidst the pack ice NE of Barrow, Alaska, 16 May 1990, times 17:00-17:53. Squares indicate sightings after 17:50, when the playback ended; these whales had been exposed to projected drilling sounds up to 17:50. Dashed line represents presumed path of breaching whale while it was below the surface; asterisks (*) indicate breaches.

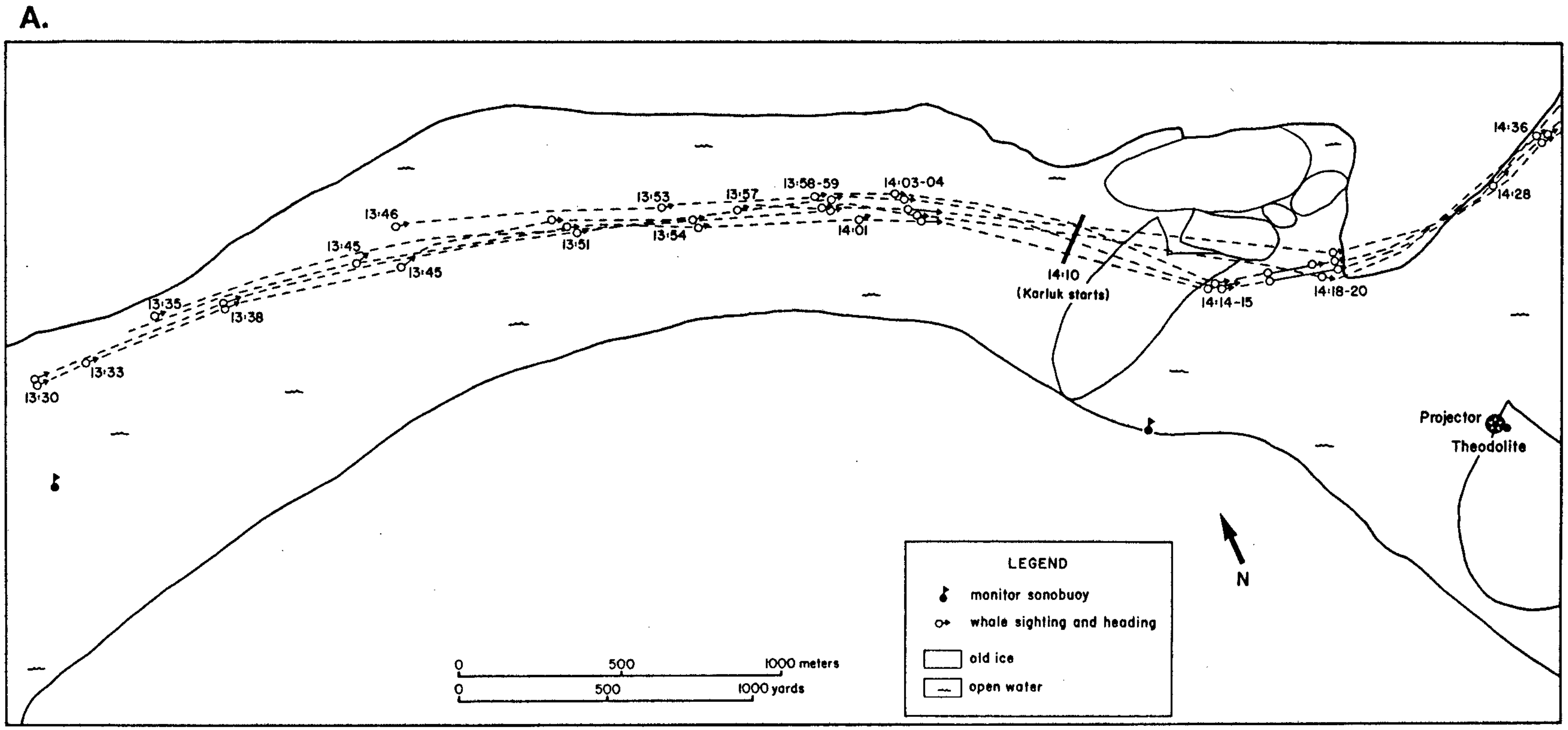


FIGURE 75A. Aerial observations of bowhead whale tracks relative to the sound projector amidst the pack ice NE of Barrow, Alaska, 16 May 1990. The projector was silent until 14:10 and projected drilling platform sounds after 14:10. Dashed lines represent presumed paths of whales while they were below the surface.

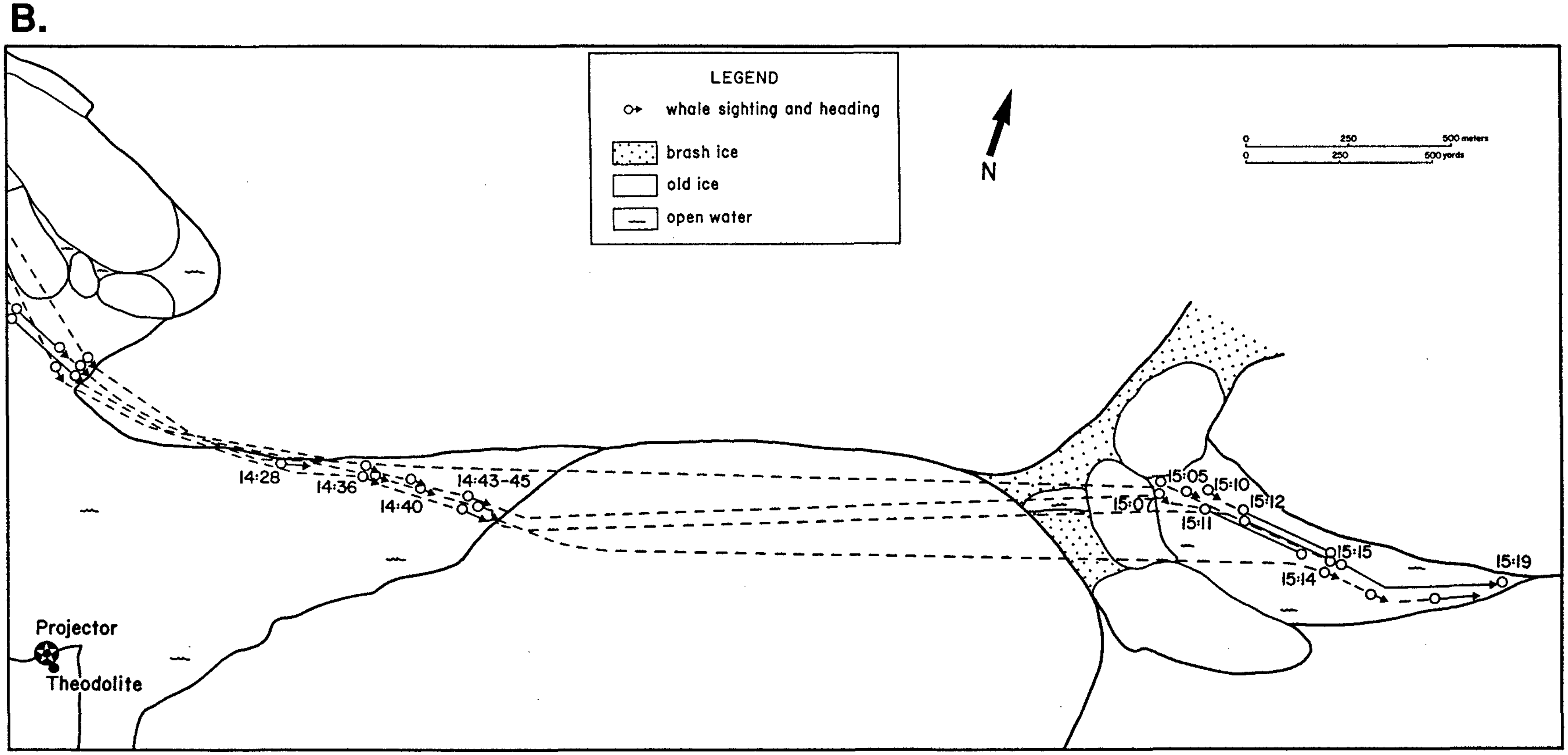


FIGURE 75B. Continuation of aerial observations of the bowhead whale tracks shown in Figure 75A, 16 May 1990. Drilling platform sounds were being projected.

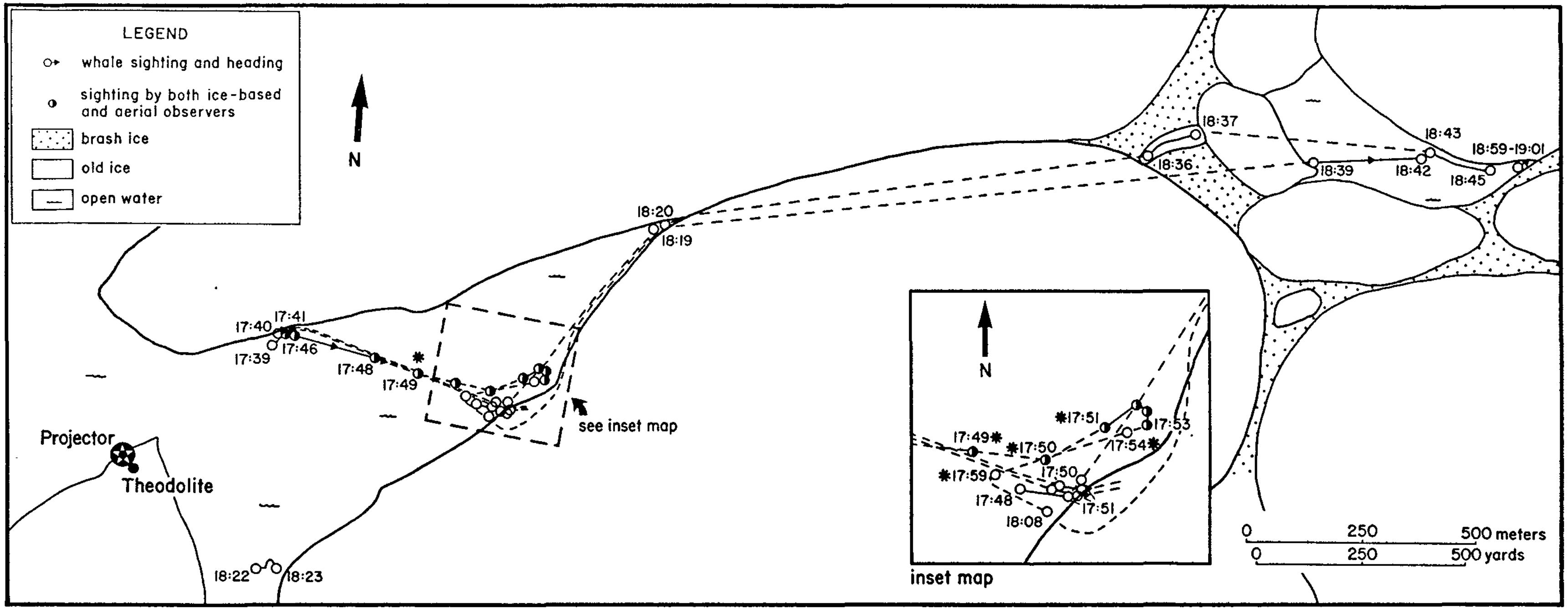


FIGURE 76. Aerial observations of bowhead whale tracks relative to the sound projector amidst the pack ice NE of Barrow, Alaska, 16 May 1990. The projector was broadcasting drilling platform sounds until 17:50; thereafter it was silent. Dashed lines represent presumed paths of whales while they were below the surface. Asterisks (*) indicate breaches.

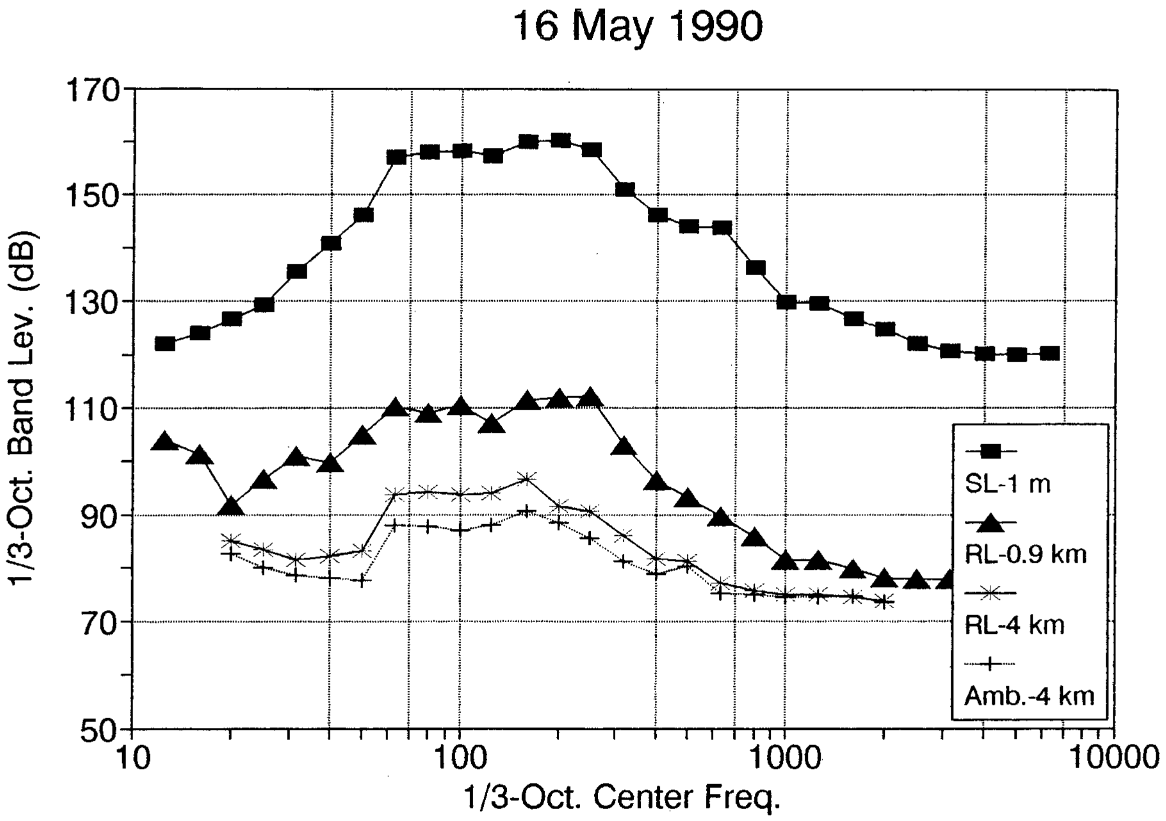


FIGURE 77. Third-octave levels of sounds 1 m from the projector (squares) and at sonobuoys 0.9 and 4 km from the projector during playback on 16 May 1990, time 17:01-17:45. Plus signs show ambient noise levels at the 4-km sonobuoy at 17:50 when the projector was not operating. Data are in dB re 1 µPa. For additional explanatory notes, see the caption to Figure 44.

well above ambient across a wide range of frequencies (Fig. 77). The drilling sounds were also faintly but distinctly audible (to the human ear) at a range of ~4 km. At 4 km, the received level was a few dB above the background ambient level at frequencies from about 40 to 500 Hz (Fig. 77). Thus, bowheads that approached the projector from ~15:00 to 17:50 (Fig. 73, 74, 76) had been exposed to measurable levels of *Karluk* drilling sound for at least 4 km before they reached their CPA positions relative to the projector..

The results from the transmission loss tests, along with the direct measurements at ~1 km and ~4 km range, were used to develop equations suitable for predicting received level vs. distance from the projector on 16 May:

$$RL_{20\text{-}1000\ \mathrm{Hz}} = 122.1 - 4.13\ R - 10 \log (R)$$

$$RL_{200\ \mathrm{Hz}} = 116.2 - 4.41\ R - 10 \log (R)$$

Appendix B describes how the equations were derived. Figure 78 shows the received levels predicted by these equations in relation to distance from the projector and ambient noise.

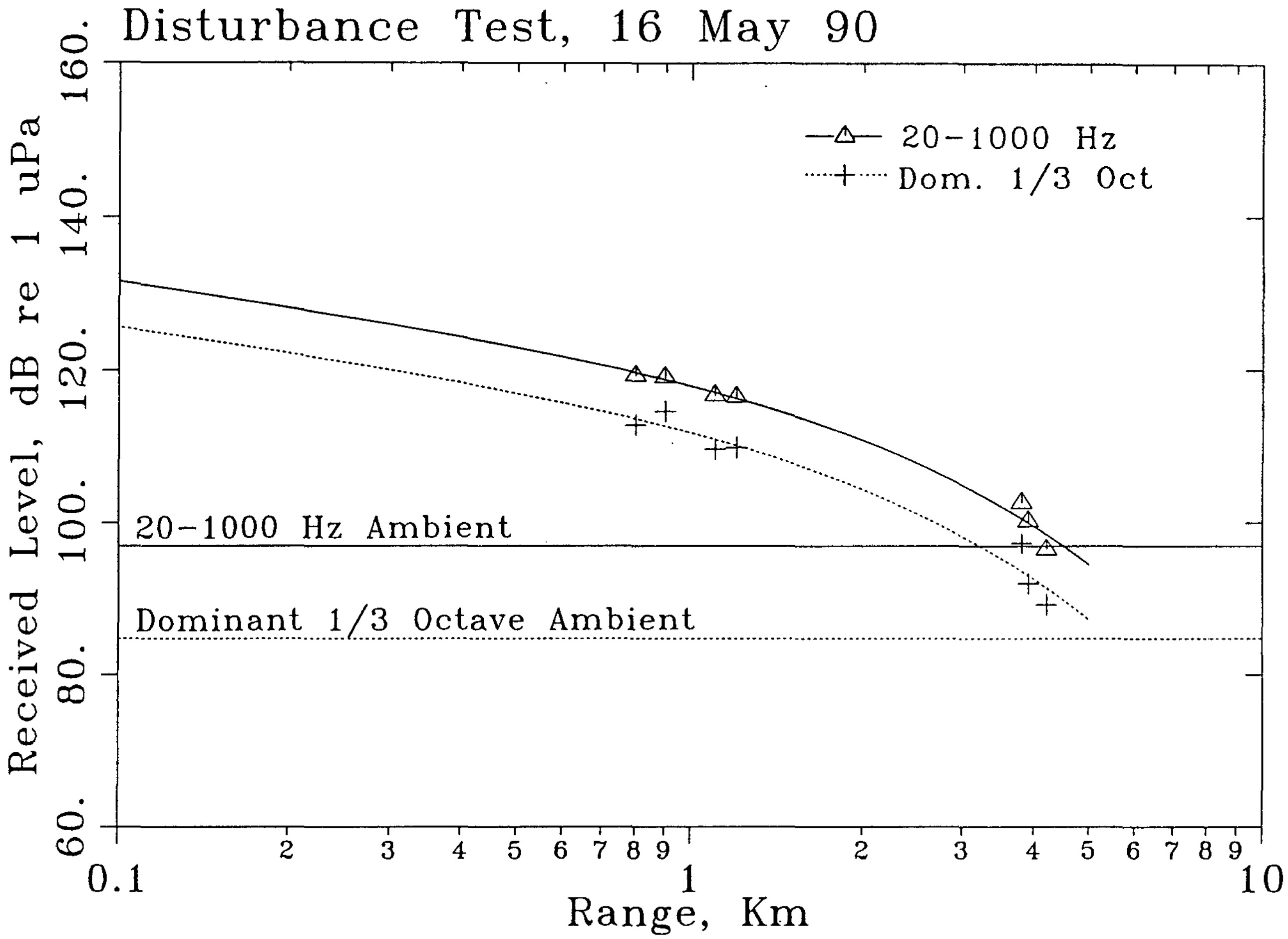


FIGURE 78. Measured and estimated received sound levels vs. range during the *Karluk* disturbance test on 16 May 1990. The triangles and pluses show the measurements via two sonobuoys. The descending curves show the values estimated by the equations given in the text. The average ambient noise levels for the 20-1000 Hz band and the dominant 1/3-octave band are shown as the two horizontal lines.

Estimated received levels for distances of specific interest, along with measured values at 1 m, ~1 km, and ~4 km, were as follows:

	Distance (km)	Type of Data	20-1000 Hz			Dominant 1/3-Octave			
			Drill. (dB)	Amb. (dB)	S:N (dB)	Freq. (Hz)	Drill. (dB)	Amb. (dB)	S:N (dB)
Source level	0.001	Meas.	167			200	161		
41B buoy-start PB	1.1	"	119	99	20	160	115	87	28
" " -end PB	0.8	"	120	103	17	250	112	96	16
53B buoy-start PB	4.2	"	100			160	93		
" " -end PB	3.8	"	103	97	6	160	97	91	6
Closest bowhead	0.2	Est.	128	97	31	200	122	85	37
Next " bowheads	~0.45	"	124	"	27	"	118	"	33
Group of "	0.85	"	119	"	22	"	113	"	28

One group of bowheads was approaching at distance 1.2 km from the projector when the projector was turned on, initially at low level (Fig. 75A). The received sound level increased rapidly, partly because the source level increased from zero at 14:10 to ~167 dB at 14:16, and partly because the whales were approaching the projector from 14:10 to ~14:25 (Fig. 75A). At their CPA distance of ~850 m, they received a broadband level of ~119 dB, or ~22 dB above the ambient level in the corresponding band.

Numerous bowheads swam past the projector at CPA distances of 425-850 m. They received broadband sound levels of ~119-124 dB, which were ~22-27 dB above the background ambient level in that band. The whale seen closest to the operating projector on 16 May (CPA = 200 m) received a broadband level of ~128 dB, or ~31 dB above the background ambient level. At 200 m from the projector, the level in the dominant 1/3-octave band was ~122 dB, or ~37 dB above the background level in the corresponding band.

19 May 1990 (Control Only)

The ice camp was set up on a secondary lead that was 600-700 m wide and oriented SW to NE. The projector was deployed but--for control purposes--was silent throughout. One bowhead whale was seen at 17:23 and 17:48 when it was, according to visual estimates, 700 m south and then 1000 m east of the projector (Fig. 79). There were no aerial observations because of a low cloud ceiling on this day.

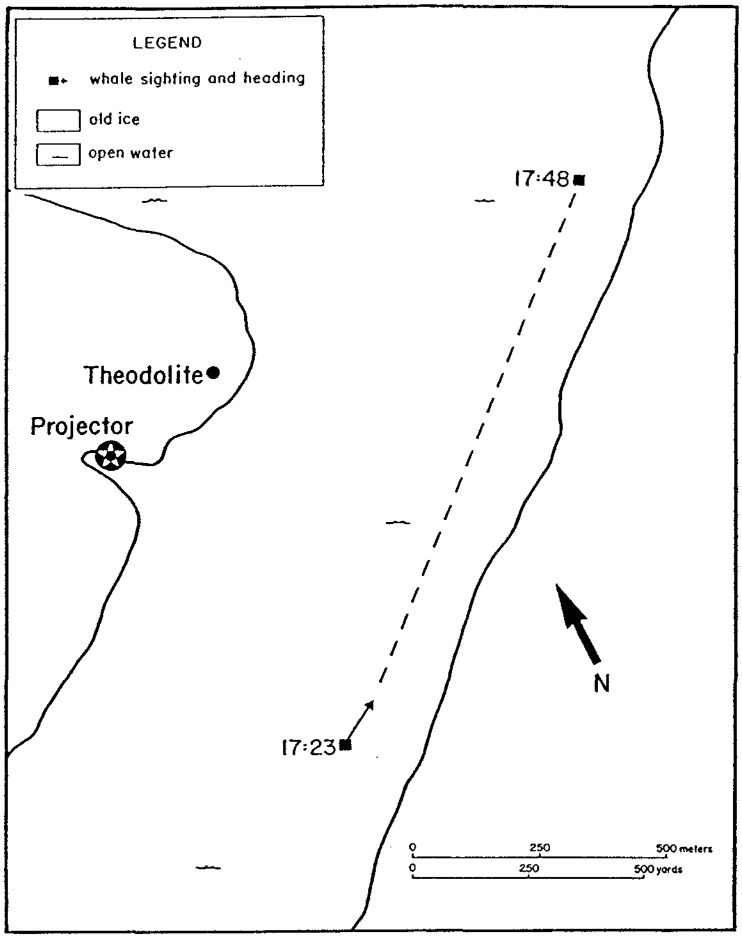


FIGURE 79. Ice-based observations of bowhead whale track relative to the silent projector amidst the pack ice NE of Barrow, Alaska, 19 May 1990. Whale positions were estimated visually, not by theodolite.

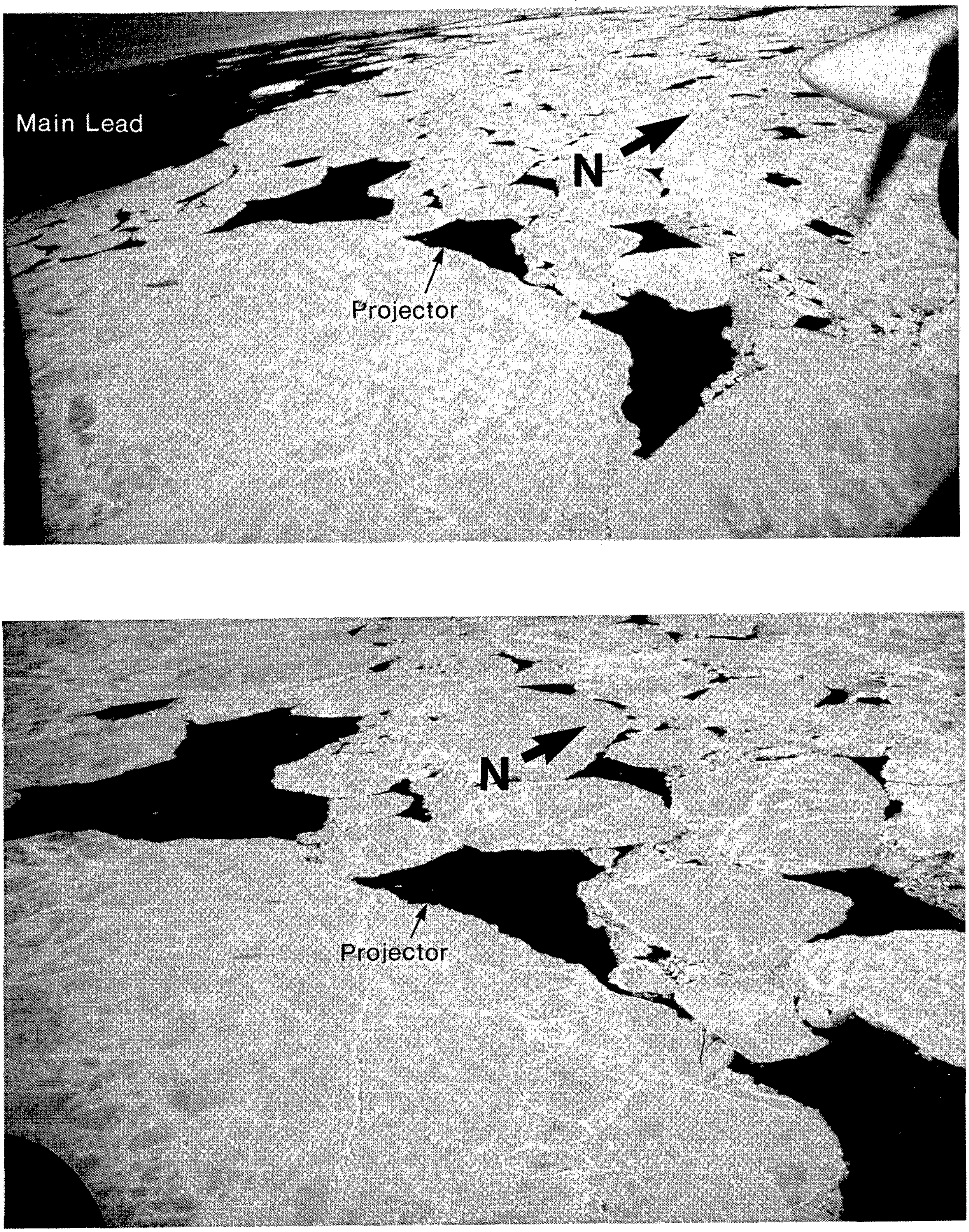


Plate 6. Ice conditions near the projector site on 21 May 1990. Note the main nearshore lead on the left of the top panel. Whales approached the projector site through the middle of the main lead, from which they traveled NE along the line of three major openings in the pack ice.

21 May 1990 Playback

The ice camp was set up on a large peninsula of pack ice that projected southward into the main nearshore lead from the north side. Near and to the west of the ice camp, the pack ice edge bordering the north side of the main lead was oriented NNW to SSE. The ice camp was situated on the southeast side of an opening that was ~400 m by ~1000 m and was 5 km into the pack ice from the main nearshore lead. It was along a series of openings that extended NE from the pack ice edge (Plate 6; Fig. 80).

The aircraft crew conducted observations of presumably undisturbed whales near the projector site before the ice-based crew arrived. Following arrival of the ice-based crew, bowheads were observed during both control and playback conditions. Drilling sounds were projected from 11:50 to 15:57, with gradually increasing source level from 11:50 to 11:55 and a steady level of 166-167 dB re 1 µPa-m after 11:55.

Ice-based Observations.--Only two bowheads were seen by ice-based observers on 21 May. A single subadult bowhead was sighted moving ENE 545 m (measured by theodolite) ENE of the silent projector at 10:33. A second whale, oriented northeast 350 m NW of the operating projector, was detected at 13:58. Both of these whales were also observed by the aerial crew.

Aerial Observations.--Three aerial observation sessions were conducted on 21 May. The first session consisted of discontinuous observations of ~15 bowheads traveling along the series of openings where the ice camp was subsequently set up (Fig. 80). At least two mother/calf pairs were present in the area. Observations of undisturbed behavior were conducted from 8:48 to 11:24; observations from 8:48 to 10:11 were conducted before the ice-based crew arrived at the camp site. At least four bowheads (3 sightings) were observed in the small opening where the ice camp was set up. The headings of the whales were predominantly ENE.

During the second behavior observation session, two single bowheads were followed from 1.5 and 2.9 km WSW to, respectively, 1.9 and 1.5 km ENE of the operating projector (Fig. 81). A third single bowhead recorded once at the beginning of the session probably had passed close to the projector, based on its position and orientation ENE of the projector at 13:03 (Fig. 81). The two bowheads that were followed during the session passed 300 m and 900 m to the side of the projector. Ice conditions were such that they could have traveled farther to the north through other openings in the pack ice, a route that would have kept the whales farther from the ice camp. On the other hand, all bowheads sighted during the pre-playback control period passed through the open water area where the projector was set up, whereas one of those observed during this playback period did not pass through that opening. The other bowhead, which did surface in the opening with the projector, turned ~30° to the left--away from the projector--as it entered the opening with the projector (range ~400 m; Fig. 81). It passed 300 m north of the projector on a NE heading, and returned to its ENE heading once it had passed the projector.

During the third observation session, two bowheads were followed from the main nearshore lead (6.3 km SW of the projector) until they were 5.6 km ENE of the projector (Fig. 82; Table 36). The whales did not appear to alter their headings or paths of travel near the operating projector. However, we were unable to determine their actual paths as they passed the projector because they did not surface near it. Their positions and headings when they dove WSW of

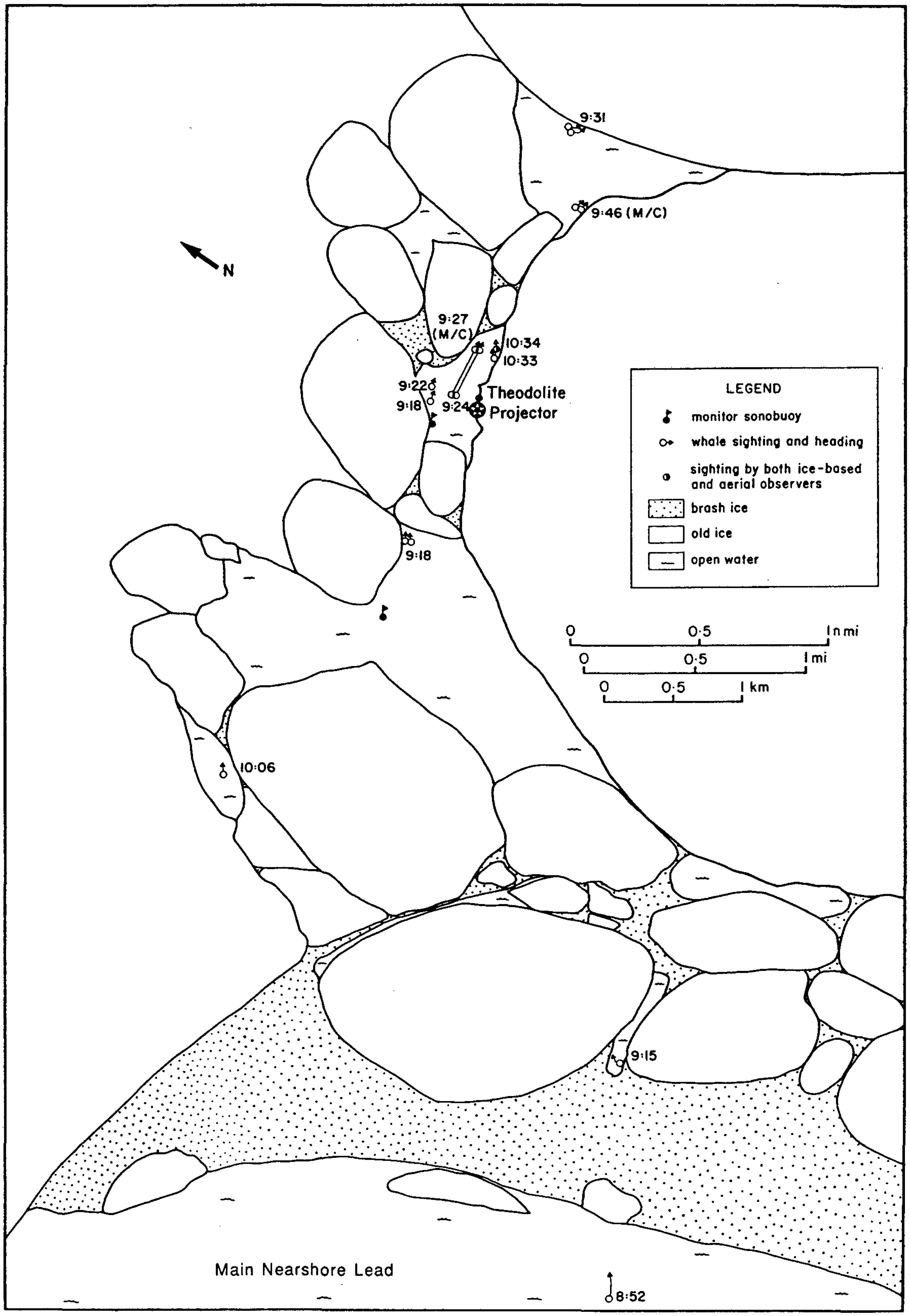


FIGURE 80. Aerial observations of bowhead whale tracks amidst the pack ice NE of Barrow, Alaska, from 8:47 to 11:24 on 21 May 1990. The ice-based crew arrived at the indicated projector site at 10:11 but the projector was silent during this period.

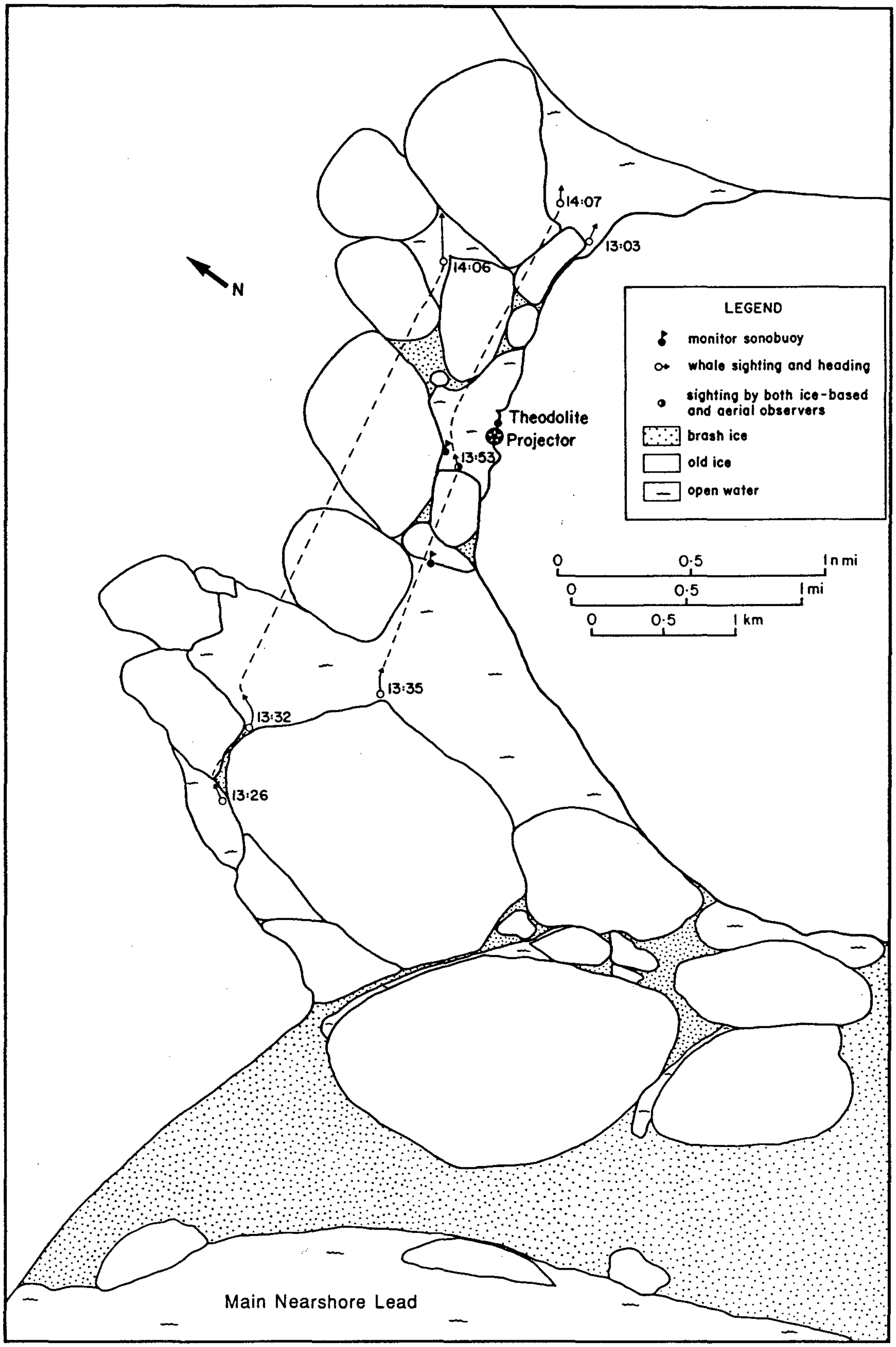


FIGURE 81. Aerial observations of bowhead whale tracks relative to the projector broadcasting drilling platform sounds amidst the pack ice NE of Barrow, Alaska, 21 May 1990, times 13:00-14:32. Dashed lines represent presumed paths of whales while they were below the surface.

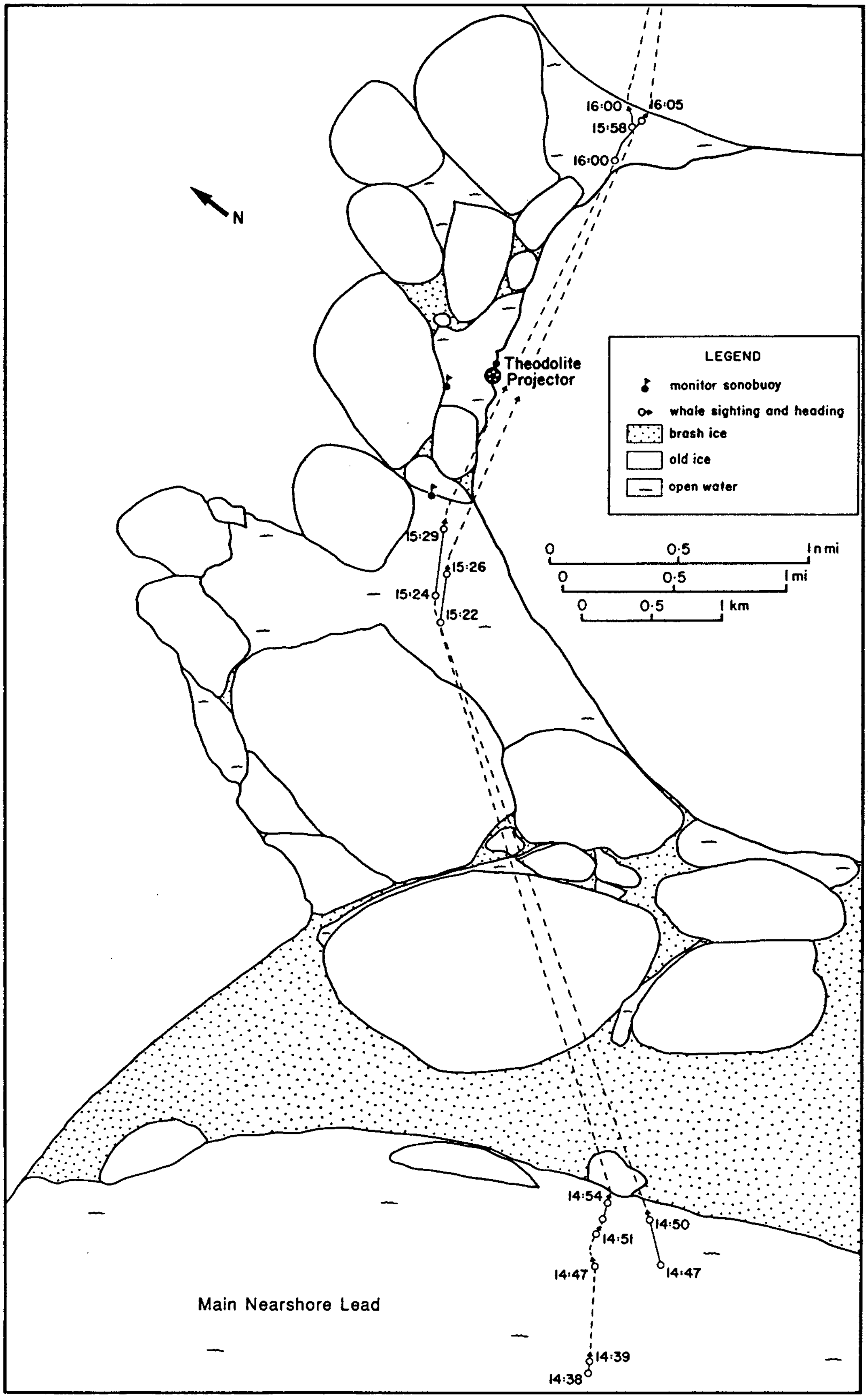


FIGURE 82A. Aerial observations of bowhead whale tracks relative to the projector amidst the pack ice NE of Barrow, Alaska, 21 May 1990. Drilling platform sounds were projected until 15:57 but not thereafter. Dashed lines represent presumed paths of whales while they were below the surface.

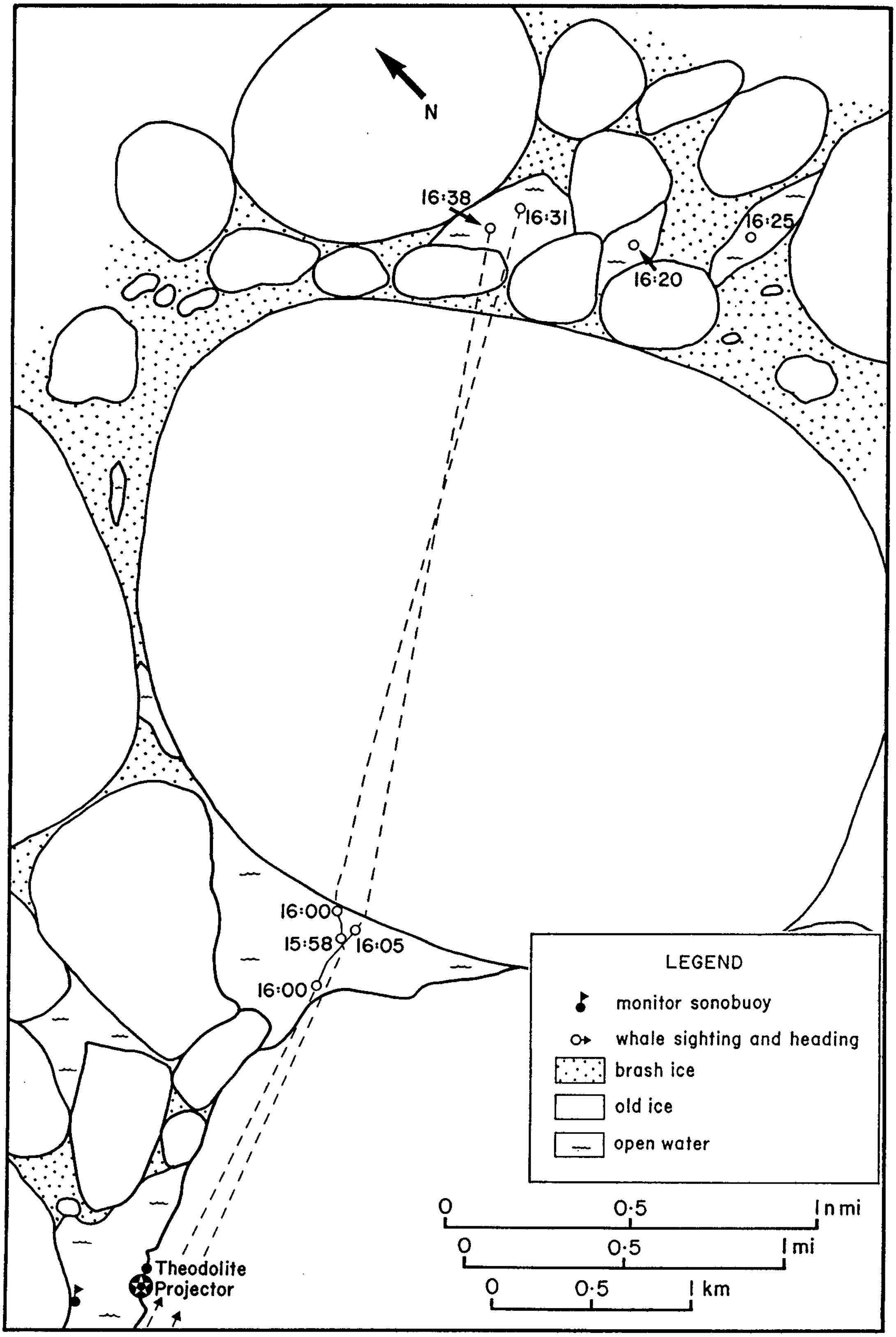


FIGURE 82B. Continuation of aerial observations of the bowhead whale tracks shown in Figure 82A, 21 May 1990. Drilling platform sounds were projected until 15:57 but not thereafter.

Table 36. Summary of sightings of bowhead whales passing close to the sound projector on 21 May 1990 before and after the ice-based crew arrived at the projector site amidst the pack ice NE of Barrow. Only sightings with known or probable CPA within 1 km are included in this table.

Time	Radial Distance Followed From Projector (m)[a]	CPA (m)	Determination of CPA[b]	Sound Levels[c]	Nature of Track
Projector Not Present--Aerial observations					
9:18	single sighting	450	2	NA[e]	N of future projector site heading ENE
9:22	single sighting	500	2	NA	N of future projector site heading ENE
9:24	+300 to +500	300	2	NA	Mother/calf; N and NE of future projector site heading E
Silent Projector--Aerial observations					
10:33[f]	+545 to +605	<545[d]	1	NA	E of projector heading ENE
Operating Projector--Aerial observations					
13:03	single sighting	<<1500	2	>>97 / >>92	Heading E directly away from projector.
13:50	-2900 to +1500	900	2	104 / 99	WNW of to NE of the projector heading E. Could have traveled farther north.
13:53	-1900 to +1700	300	2	116 / 112	W of to E of projector heading E. Turned slightly to follow far side of lead as it passed projector.
15:36	-6300 to +5600	~150	4	~123 / ~118	SW to E of projector heading NE then E Open water present N of projector and no hesitation or change of direction as it approached projector.
15:39	-7000 to +5500	~50	4	~133 / ~126	SW to E of projector heading NE then E. Open water present N of projector and no hesitation or change of direction as it approached projector.

[a] - indicates that whales are ≥180°T from the projector (approaching); + indicates that whales are ≤180° from the projector (moving away).

[b] 1 = measured by theodolite or tape, 2 = visual estimate, 3 = estimate based on nearby surfacings, 4 = estimates based on distant surfacings (possibly unreliable).

[c] Estimated received level (dB re 1 μPa) of projected noise at CPA. Left: level in the 20-1000 Hz band. Right: level in the dominant 1/3-octave band.

[d] < indicates that whales were heading toward the projector when last seen.

[e] NA is not applicable.

[f] The whales were also seen by the ice-based observers.

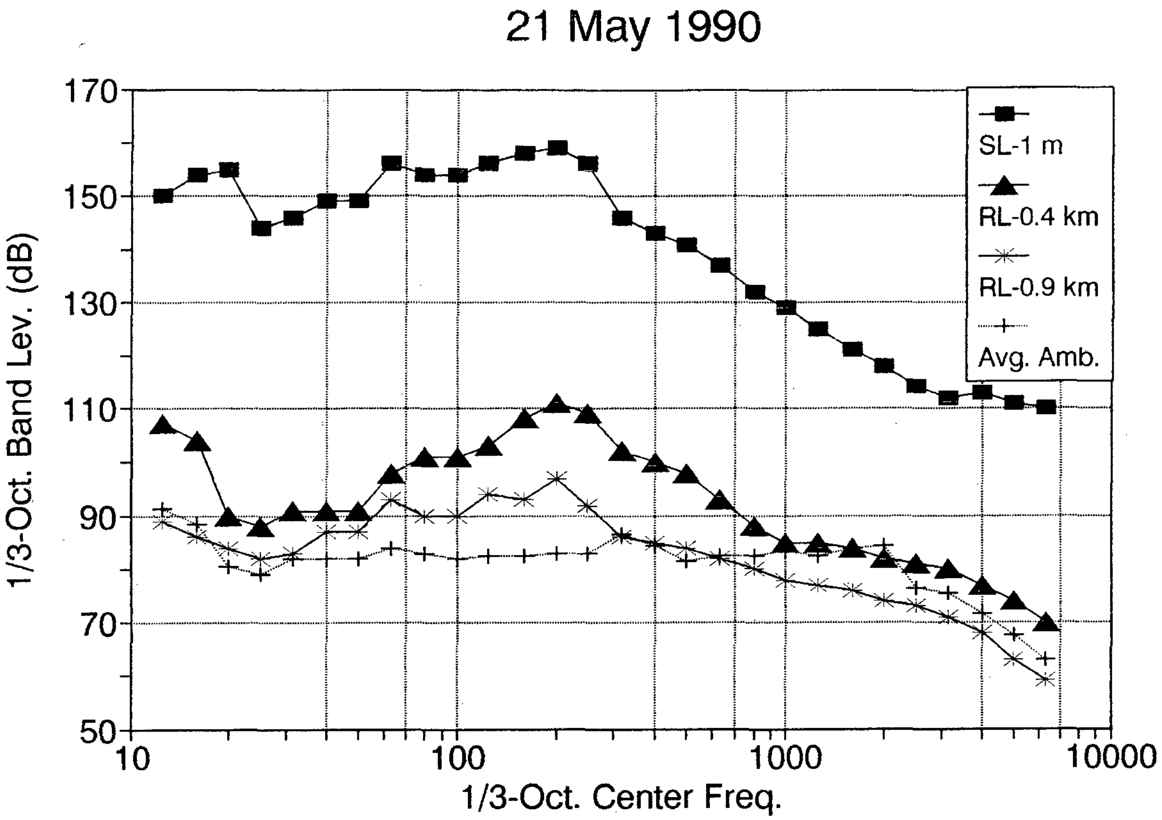


FIGURE 83. Third-octave levels of sounds 1 m from the projector (squares) and at sonobuoys 0.4 and 0.9 km from the projector during playback on 21 May 1990, times 14:39-14:43. Plus signs show average ambient noise levels received by the sonobuoys at 16:44-16:50 when the projector was not operating. Data are in dB re 1 μPa. For additional explanatory notes, see the caption to Figure 44.

the projector and when they resurfaced ENE of the projector suggest that they passed very close to the projector. Assuming a straight-line path during their dives, their CPAs would have been ~50 and ~150 m (Fig. 82; Table 36). Given the prevailing ice conditions, these whales also could have chosen a path farther to the north if they had "wanted" to avoid the operating projector; however, there was no evidence of any diversion or detour.

Noise Exposure.--On 21 May, a 41B monitor sonobuoy was manually deployed 400 m northwest of the projector, across the lead. Also, a 57A sonobuoy was air-dropped into an open-water area SW of the projector at time 11:27. This buoy was initially ~1.75 km from the ice camp (Fig. 80). However, it drifted and was 0.9 km from the projector at 13:32-15:54, based on transit-time measurements. The transmission path from the projector to the 400 m buoy was through open water, whereas that to the 900 m buoy was largely under pack ice. The broadband source level of the projected *Karluk* sounds on 21 May 1990 was 166-167 dB re 1 μPa-m, and the source level in the 1/3-octave band with the highest level was 160 dB in the band centered at 200 Hz (Fig. 83).

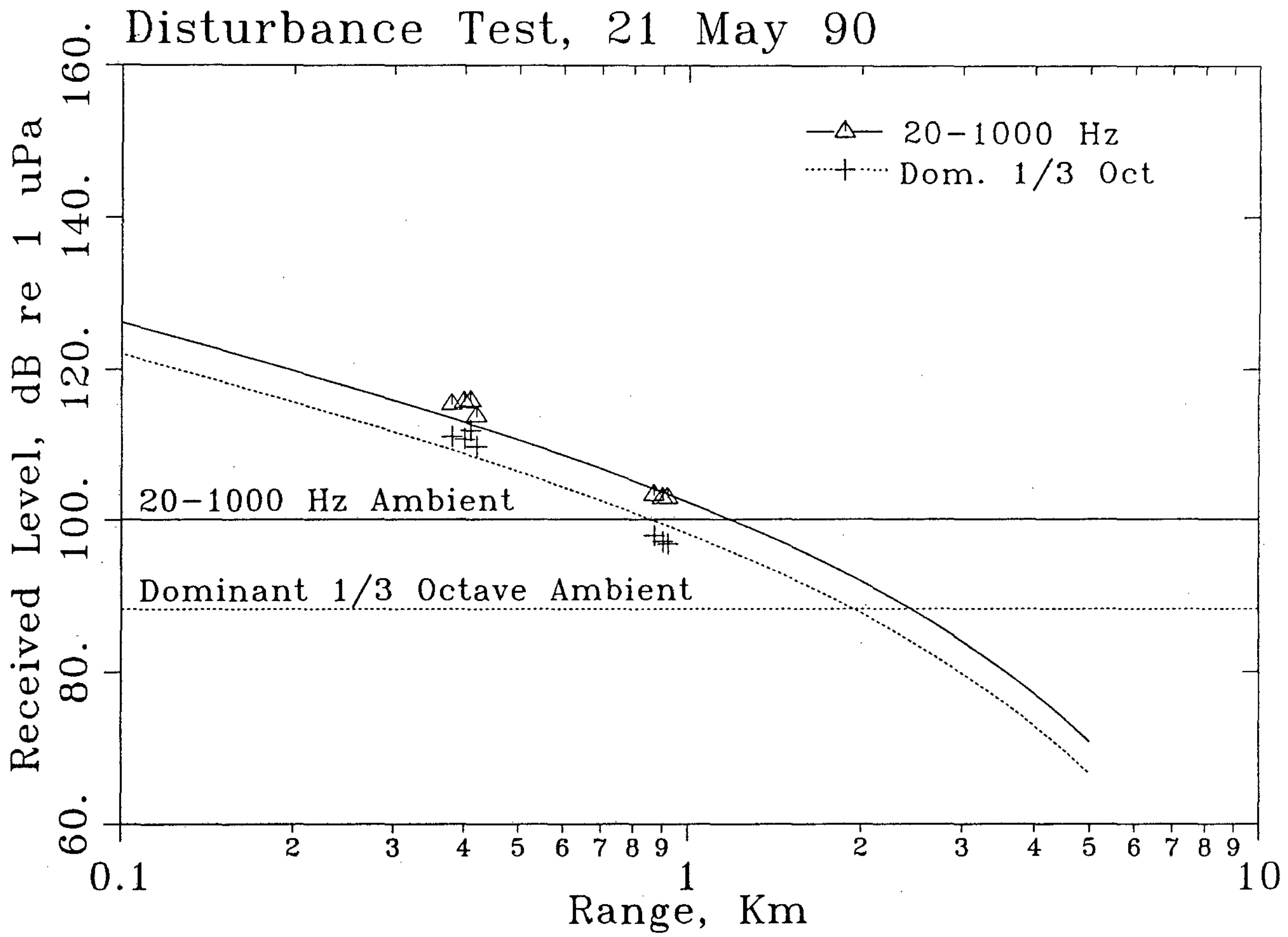


FIGURE 84. Measured and estimated received sound levels vs. range during the *Karluk* disturbance test on 21 May 1990. The triangles and pluses show the measurements via two sonobuoys. The descending curves show the values estimated by the equations given in the text. The average ambient noise levels for the 20-1000 Hz band and the dominant 1/3-octave band are shown as the two horizontal lines.

The broadband (20-1000 Hz) received levels of *Karluk* sounds were 116 dB at 400 m and 102 dB at 900 m at 14:39-14:43. The broadband (20-1000 Hz) ambient noise level after the end of the playback was 98 dB at the 400 m buoy and 92 dB at the 900 m buoy. If these ambient levels also applied during the playback, then the *Karluk* : ambient ratio during the playback was 18 dB at 400 m and 10 dB at 900 m. Given the same assumption, the *Karluk* : ambient ratio was higher in the dominant 1/3-octave band, which was centered at 200 Hz (Fig. 83): 25 dB at 400 m and 17 dB at 900 m.

The results from the transmission loss tests, along with the direct measurements at ~0.4 km and ~0.9 km range, were used to develop equations suitable for predicting received level vs. distance from the projector on 21 May:

$$RL_{20\text{-}1000\ Hz} = 106.7 - 4.40\ R - 20 \log (R)$$

$$RL_{200\ Hz} = 102.5 - 4.40\ R - 20 \log (R)$$

Appendix B describes how the equations were derived. Figure 84 shows the received levels predicted by these equations in relation to distance from the projector and ambient noise. Estimated received levels for distances of specific interest, along with measured values at 1 m, 0.4 km, and 0.9 km, were as follows:

		Type	20-1000 Hz			Dominant 1/3-Octave			
	Distance (km)	of Data	Drill. (dB)	Amb. (dB)	S:N (dB)	Freq. (Hz)	Drill. (dB)	Amb. (dB)	S:N (dB)
Source level	0.001	Meas.	166			200	160		
Buoy-41B	0.4	Meas.	116	98	18	200	111	86	25
" -57A	0.9	"	102	92	10	200	97	80	17
Bowhead @ CPA	0.9	Est.	104	100	4	200	99	88	11
" @ CPA	0.3	"	116	"	16	"	112	"	24
Possible CPA	0.15	"	123	"	23	"	118	"	30
" "	0.05	"	133	"	33	"	126	"	38

The CPA distances of two whales for which CPA was determined with good accuracy were 0.3 km and 0.9 km. The broadband levels received by these whales would have been ~116 and ~104 dB. These levels were about 16 and 4 dB above the relatively high and variable average ambient noise level on this date. As noted earlier, the whale with CPA 0.3 km turned away from the projector by ~30° when the whale came within ~400 m, possibly in response to the noise (Fig. 81).

Two whales may have passed within ~50 m and ~150 m of the operating projector if they traveled underwater on straight lines (Fig. 82A). If so, they would have received levels substantially higher than those at 300-400 m. At 50 and 150 m, the broadband (20-1000 Hz) levels would have been ~133 and ~123 dB (Fig. 84).

Distribution and Movements During All *Karluk* Playbacks

Results from 1989

In 1989, we observed bowheads within the areas ensonified by the sound projector on five dates: 30 April and 14, 19, 23 and 27 May. Whales were exposed to sounds from the transmission loss test tape on 30 April and on 27 May. That tape included various sounds at frequencies from 50 to 10,000 Hz, including swept tones, pure tones, and a sample of *Karluk* drilling platform sound. On 27 May, a mother/calf pair was exposed first to the test tape (at range 3.7 km) and then to continuous drilling noise. On 14, 19 and 23 May, bowheads were exposed to continuous drilling sounds but not to tones.

The number of bowheads seen near the sound projector in 1989 was too small to allow any statistical analysis of distribution or movements. However, a collation of the observations provides some information about the movements of bowheads toward and past the operating projector (Table 37). All whales listed in that table are known to have been in waters where the projected sounds were detectable above the natural ambient noise. The "Noise" column in Table 37 summarizes the maximum noise levels received by the whales. More detailed data about noise exposure were given in the daily accounts in Richardson et al. (1990a:174-196).

Table 37. Summary of sightings of bowheads passing near the operating sound projector during 1989.

Date	Whale	Distance	CPA	Noise*	Nature of Track
30 Apr	#1-#3	~1.1 - 2.2 km	60-75 m	≤115/≤20**	Continued toward projector after exposure to test tones at range ~ 1.1-2.2 km.
	#2	-	60 m	130 / 35**	Tones started while whale passing tangentially; no obvious change in behavior.
14 May	#8	4.7 → 0.9 km	0.9 km	102 / 8	Along ice edge almost directly toward projector and then tangentially past it.
	#9	4.7 → 0.5 km	0.5 km	107 / 13	Same.
	C	2.8 → 2.5 km	?		Aerial activity; subsequent movements unknown.
	#2,#3	0.5 km	0.5 km	104 / 10	Moving tangentially past during brief observation period.
19 May	#1	500 → ≤120 m	≤120 m	125 / 41	Curved from partially toward to almost directly toward projector; dove 100-120 m before reaching projector.
	#2	910 → 720 m	≤720 m	110 / 26	Heading partly toward projector; dove before reaching CPA position.
	#3,#4	1.8 → 1.0 km	1.0 km	107 / 23	Moved tangentially past projector on straight course.
23 May	Cow/Calf	1 → 5 km	<1 km	110 / 8	Headed NW and W away from projector.
	#5	5.2 → 2.4 km	~2 km	107 / 10	Headed partially toward projector and apparently passed tangentially with CPA ≈ 2 km.
	#6	2.3 km	~2 km?	107 / 10	Apparently on similar path as #5.
27 May	Cow/Calf	3.7 → 4.0 km	3.7 km	104/ 15**	Projector started broadcasting test tones while whales were moving tangentially at CPA (3.7 km). Continued SE on or near original course while exposed to drilling sounds.

* Received broadband level (dB re 1 μPa) and S:N ratio (dB) of drilling noise or tones at the closest distance where the whale was seen.

** Received levels for 30 April and 27 May refer to the strongest tone. Received levels of drilling noise were lower: 100-110 dB at 1.1-2.2 km on 30 April (S:N=6-19 dB), and 97 dB at 3.7 km on 27 May (S:N=11 dB).

Continuous Drilling Sounds.--Several whales were observed migrating northeast, east or southeast past the projector while it was broadcasting drilling sounds. On 19 May, one bowhead swam almost directly toward the projector until it was only 100-120 m away. It then dove, and its subsequent movements are unknown. On 14 May, at least three migrating bowheads passed 0.5 km to the side of the projector while it was broadcasting drilling sounds. Another bowhead seen on 19 May was heading almost directly toward the projector when it dove 720 m away; its subsequent movements are unknown. Bowhead #8 seen on 14 May passed tangentially at a CPA distance of ~0.9 km, and two additional bowheads seen on 19 May passed tangentially at CPA=1.0 km. On 23 May, at least one and probably two bowheads migrated eastward past the projector with CPA distances near 2 km.

Tonal Sounds.--On two dates, we observed whales migrating toward or past the projector while it was broadcasting a sequence of tonal sounds and a brief sample of the drilling noise. *(1)* On 30 April, one whale continued migrating east when the projector started to broadcast swept tones at 50-500 Hz while the whale was at the surface less than 100 m away. This whale and two others had been exposed to weaker tones several minutes earlier when the whales were approaching the projector. This previous exposure did not deter them from continuing on toward the projector. *(2)* On 27 May, a mother/calf pair was exposed to tones and the other sounds on the transmission loss test tape when they were 3.7 km from the projector and passing tangential to it. These whales were subsequently exposed to the continuous drilling sounds. They continued migrating along a path similar to that taken by two other mother/calf pairs earlier on that day in the absence of man-made noise.

Avoidance Reactions?--In 1989, we obtained only one observation suggestive of an avoidance reaction. On 23 May, a mother/calf pair was noticed swimming north ~1 km north of the projector (i.e. directly away). Continuous drilling noise had been projected for the 33 min preceding this sighting. The location of the whales when the playback period started is not known. The received broadband noise level 1 km from the projector was 110 dB (~8 dB above the natural ambient level). These whales initially could not be followed by the aerial observers because the cloud ceiling was below 460 m[14]. However, a mother and calf--probably the same animals--were seen 1 h later 4.2 km NW of the projector, traveling slowly but consistently west. The drilling sounds were faintly detectable in the water as much as 5 km west of the projector.

The westward direction of travel by this mother/calf pair was inconsistent with the normal NE, E or SE movements of migrating whales in spring, and suggestive of a disturbance reaction. However, observations of other whales in the absence of drilling sounds showed that mothers and calves were not as consistently engaged in eastward migration as were other bowheads (Richardson et al. 1990a:166-169). Ice conditions in late May 1989 were still quite heavy in many parts of the study area. It is possible that calves (and thus mother/calf pairs) are unable to travel through ice conditions as heavy as those negotiated by other whales. If so, this may induce mother/calf pairs to linger, awaiting improved ice conditions, or even to retreat westward temporarily. On 23 May, there was little open water east of the projector. Perhaps the mother, because of her young calf, was reluctant to enter the ice-filled lead that other large whales followed on this date.

---

[14] Previous studies have shown that bowheads are sometimes disturbed by an observation aircraft if it circles at an altitude <460 m (Richardson et al. 1985a,b).

It is impossible to determine whether the one mother/calf pair seen moving west away from the operating projector on 23 May 1989 did so because of the drilling noise or for some natural reason. There were no aerial observations of mother-calf pairs near the projector in 1990, so we have had no opportunity to replicate this 1989 observation.

Limitations of 1989 Observations.--The major limitations of the 1989 observations were (1) the low sample size, (2) the inability to follow many whales for long distances (several kilometers), (3) the lack of firm evidence of avoidance reactions at any distance, and (4) the limitations of the playback method in simulating an actual drilling operation. Of these four limitations, the first three were largely overcome in 1990. The fourth limitation, which pertains to 1990 as well as 1989, is discussed later (p. 261).

Results from 1990

The 1990 results provide a much improved understanding of the effects of the playbacks of *Karluk* drilling noise on the distribution and movements of bowheads. We observed bowheads within the areas ensonified by the sound projector on 6 days in 1990: on 9, 10, 11, 13, 16 and 21 May. During one of the two observation sessions on 13 May, the bowheads were exposed to distorted drilling sounds because the J-11 projector was failing. However, normal drilling sounds were projected for parts of all six dates. The total sample size in 1990 was many times higher than that in 1989, and some individual bowheads were observed as they swam for several kilometers toward, past, and away from the operating projector. Also, during 1990, unlike 1989, we observed some clear cases of bowheads changing course to divert around the ice camp. These observations provide the information needed to estimate the radius of influence of the projected noise from the *Karluk* drilling platform on distribution and movements, in terms of distance and received sound level.

Continuous Drilling Sounds.--In 1990, ice-based observers saw ~90 groups of bowheads (~132 individuals) when the projector was broadcasting normal, undistorted drilling sounds. Almost half of these sightings (40 groups) were recorded on 13 May. Even so, this is a substantial data base for evaluating the distribution of bowheads near the operating sound projector. In addition, aerial observers recorded substantial numbers of groups of whales while the sound projector was broadcasting drilling platform sounds. Tables 20-23, 35 and 36, included earlier under "Daily Playback Results", show the closest points of approach to the projector of each group of whales observed within 1000 m of the projector when it was silent and when it was broadcasting drilling sounds. These data provide a basis for assessing whether the distribution of bowheads near the projector was altered by the presence of *Karluk* drilling sounds.

Figure 85 shows the distribution of sightings of bowhead groups when the projector was silent and when it was broadcasting undistorted drilling sounds. Bowheads tended to be found slightly farther from the projector when the drilling sounds were being projected, but this difference was only marginally significant (chi^2=8.16, df=4, P<0.1).[15] The apparent absence of a statistically significant diversion effect is not surprising and not conclusive, given the inevitable variability in whale behavior and the pooling of data from different projector locations in

---

[15] Except where otherwise noted, chi^2 tests on CPA distributions were based on the five 200-m distance intervals between 0 and 1000 m from the ice camp.

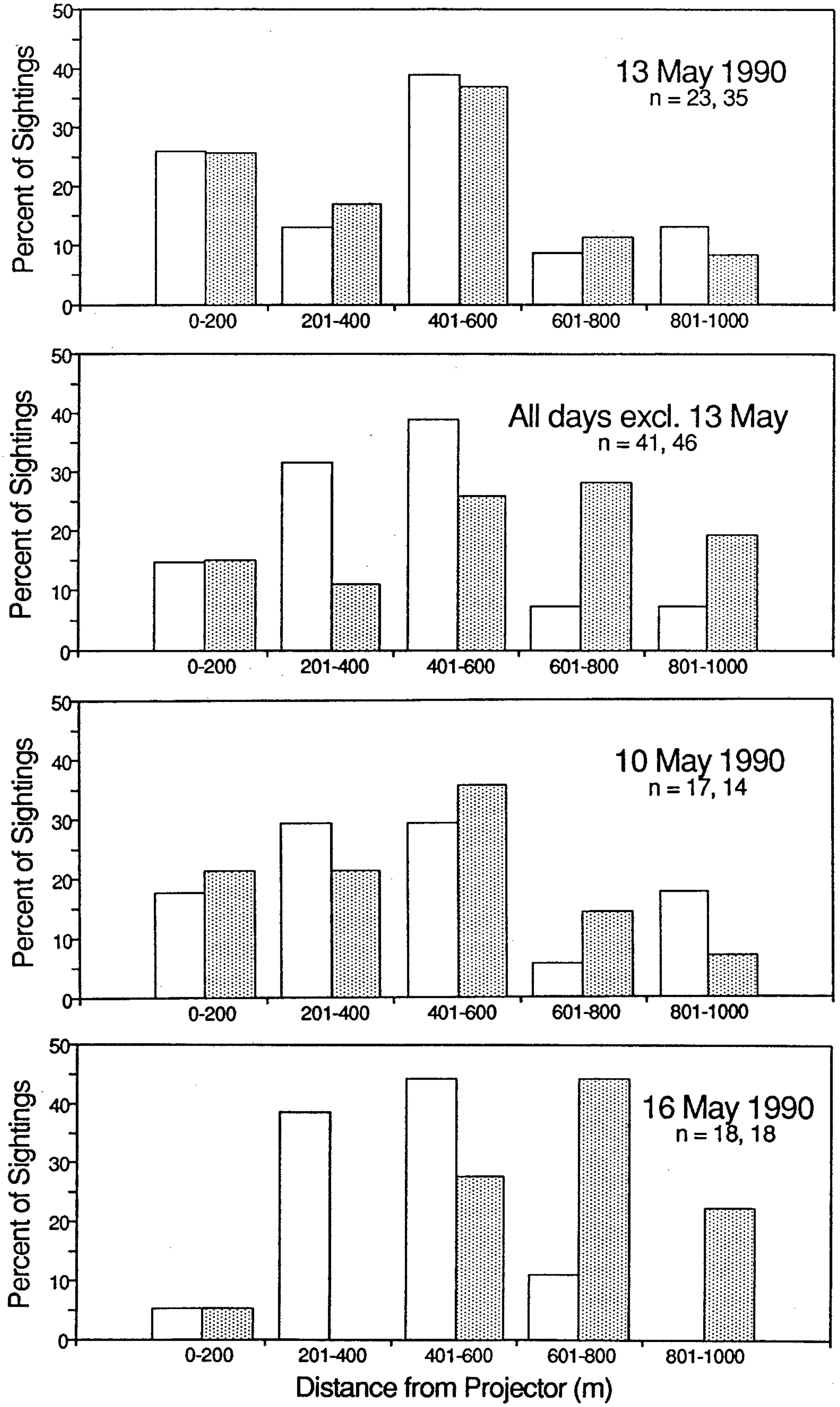


FIGURE 85. CPA distances of bowhead whales passing a quiet projector (open histograms) and operating projector (shaded histograms) on 10, 13 and 16 May 1990 and on all days in 1990 except 13 May. Playback data from 13 May include only the undistorted playback period. Some CPA distances are overestimated (see Table 38).

relation to ice. On 13 May, for example, any whale passing the projector at the surface had to be within ~200 m, whereas on other days in 1990 the area of open water near the projector was wider. The pooling of data from different observation platforms (aerial vs. ice-camp) is also a concern, given the greatly differing fields of view of aerial and ice-based observers. A more appropriate approach is to conduct a similar comparison for each day.

There were three days with sufficient sightings during both control and experimental periods to justify presentation by day (10, 13 and 16 May 1990; Table 38; Fig. 85). These three days all had slightly different ice conditions near the projector. On 13 May, the projector was set up along a long narrow lead only ~200 m wide. Migrating whales passing the projector were unable to divert more than 200 m from the projector without traveling under the ice. On 10 May, whales could remain in the open lead and pass 500 m north of the projector. On 16 May, whales could pass 500 to 1000 m north of the projector (depending on time of day) and still remain in the open lead.

The distributions of bowheads during playback periods on these days seemed to be related to the width of the lead at the projector site. When the lead was the widest (16 May), the CPA distributions of whales differed significantly between control and playback periods ($\text{chi}^2=13.74$, df=3,[16] $P<0.01$). Similarly on 9 May, when the corridor past the projector was also wide, most whales seemed to remain farther from the projector when it was operating than when it was silent. However, few whales were observed during the control period on 9 May, so statistical comparisons cannot be made for 9 May alone. On 13 May, when the lead was narrow, there was no difference in the CPA distributions between the control and "undistorted playback" periods when the data were categorized by 200 m intervals ($\text{chi}^2=0.53$, df=4, $P>0.1$). Considering all days except 13 May, the CPA distributions were significantly different during control vs. playback periods ($\text{chi}^2=13.21$, df=4, $P<0.025$).

Despite the lack of significance of the chi^2 test for 13 May, the distributional data from that date provide evidence of avoidance of the projector at very close range (Fig. 57-60; Table 38). Five sightings were within 100 m of the quiet projector on 13 May (50, 60, 60, 85 and 100 m) but the closest sighting to the operating projector was 110 m away. The projector was on the north side of the lead. A shelf of new ice extended ~40 m south of the projector, so the closest sightings during the control periods were only 10-20 m from the ice edge. In contrast, during the playback period, most whales that were at the surface as they passed the projector were near the south side of the lead. They moved as far as they could from the projector while still remaining in the open lead. In several cases, the whales were specifically seen to turn and move across the lead from the north to the south side. Nonetheless, there was no evidence of a blockage of migration, although some whales apparently slowed their eastward travel as they approached the projector (Tables 25, 29 on p. 166, 178).

Another trend is evident from inspection of the maps and tables summarizing sightings near the projector on 13 May. Aerial observers saw many surfacings by whales within 1.5 km west of the operating projector but did not see many whales within a comparable distance to the east (Fig. 59A,B). Observation effort over the two areas was similar. After passing the projector, whales frequently dove for 20 min or more and traveled 1.5 km or more before they surfaced.

---

[16] The 0-400 m interval was treated as one interval in this analysis, given the low expected values.

Table 38. CPA distances of bowhead whales passing the sound projector when it was silent and when it was broadcasting undistorted *Karluk* sounds. Whales for which CPA is listed as <*x* m in Tables 20-23, 35 and 36 are recorded as *x* m here, so many of the actual CPA distances were less than listed here. Groups of two or more whales are counted as one sighting if they remained together throughout the period of observation.

	CPA Distance from the Projector (m) was ≤						
	0-100	101-200	201-400	401-600	601-800	801-1000	0-1000 m
Silent Projector							
9 May	0	1	1	1	0	0	3
10 May	1	2	5	5	1	3	17
11 May	0	1	0	1	0	0	2
13 May	5	1	3	9	2	3	23
16 May	1	0	7	8	2	0	18
21 May	0	0	0	1	0	0	1
All 1990	7	5	16	25	5	6	64
All 1989	1	0	0	0	0	0	1
Karluk							
9 May	0	1	1	2	3	3	10
10 May	1	2	3	5	2	1	14
11 May	0	0	0	0	0	0	0
13 May (undistorted)	0	9	6	13	4	3	35
16 May	0	1	0	5	8	4	18
21 May	1	1	1	0	0	1	4
All 1990	2	14	11	25	17	12	81
All 1989	0	1	0	2	1	3	7

Small-scale Avoidance Reactions--The above data suggest that bowheads visible in leads often diverted their courses slightly in order to avoid coming as close to the operating projector as they would have come without a course change. The alterations in course appear to have been small: up to ~150 m on 13 May (i.e. from 50 m south to 200 m south of the projector), and up to a few hundreds of meters on some other days (9, 10, 16 May). Also, bowheads seldom surfaced near the projector after they had passed it. On 13 May, the operating projector did not deter whales from approaching within ~200 m when no alternative migration corridor was readily available. Whales that had been followed for several kilometers as they approached the projector moved to the far side of the lead from the projector and showed other behavioral changes, but they passed within 200 m of the projector with only minor hesitation. If the lead had been wider, many or all of these whale probably would have shown a larger diversion, based on the results from other dates.

Several bowheads that were followed for several kilometers as they approached the operating projector, or that were observed from the ice camp on 13 May 1990, continued toward the projector until they were 200-400 m from it (Fig. 57, 58). They then crossed from the north to the south side of the lead and passed <200 m from the projector. A single bowhead observed 300 m from the sound projector on 21 May also appeared to move slightly to the north to remain farther from the projector. This whale turned back slightly to the south when it had moved past the projector. The general tendency for proportionally fewer sightings within a few hundred meters during playbacks also suggests that some whales exhibit small-scale avoidance.

Different bowheads may react differently to the same potential source of disturbance. Although the 1990 (and 1989 data) have shown that some bowheads will pass within 200 m of a projector playing *Karluk* drilling platform sounds, other bowheads would likely avoid the same sound sources at distances greater than 200 m. The data from 1990 suggest that avoidance reactions to the projected *Karluk* sounds occurred only at close range and for brief periods. We observed no cases of whales fleeing from the projector in the manner commonly seen near rapidly-approaching boats or approaching seismic vessels.

Apart from the small-scale detours around the sound source at close distances, we saw few movement reactions that could be attributed to the projected sounds. One of these cases occurred on 10 May 1990 (Fig. 48 on p. 136). Unbeknownst to the projector operator, the biologists were observing a whale 225 m from the ice camp when the sound projector was started. The whale initially turned ~60° right, toward the projector. It then turned ~120° left so that it was heading almost directly away from the projector, whereupon it swam away from the projector while remaining on the surface. It dove ~2 min after the projector was turned on, and it was not recognized again. The turns may have been a type of startle response to the startup of the projector. However, the whale did not dive hastily as has been observed during startle responses elicited by sudden disturbances of other types, *viz* sonobuoy drops near whales or low-altitude overflights by aircraft.

A few observations were made of whales moving west or north when they approached within 500-600 m of the operating projector. At 17:12 and 17:47 on 13 May, whales 489 and 579 m west of the operating projector were observed heading west and NNE (Table 23E on p. 154). Another whale observed at 18:08 changed heading several times when it was ~750 m from the projector. A fourth whale that was followed by the aircraft-based crew temporarily turned north and west, away from the projector, after it had approached to within ~400 m of the projector (17:56, Table 23F). Similar westward movements were observed only once during control periods. In all cases the westward movements were brief and whales resumed their eastward movements within a few minutes.

Larger Scale Avoidance?--It is important to know whether most bowheads diverted by only the minor amounts discussed above, or whether some unseen bowheads may have diverted at greater distances. Only the aerial observations are relevant to this question. The ice-based observers have a limited field of view. They see few bowheads more than 1½ km away. The projected drilling sounds were sometimes measurable, and presumably audible to bowheads, as much as 5-10 km from the ice camp. If some bowheads responded to weak drilling noise, they might have diverted while still far enough away from the ice camp such that they would never be seen by the ice-based observers. Aerial observations are needed to resolve this question.

In 1990 and to a lesser degree in 1989, the aerial observers were able to follow several singletons or groups of bowheads as they approached from ~5 km away (13 and 21 May 1990; 14 and 23 May 1989). Data from bowheads followed for several kilometers on 11 and 16 May 1990 were also relevant to this point. There was no evidence of diversion more extensive than that described in previous paragraphs. If it were common for visible whales to initiate a detour around the projector at distances exceeding the several hundred meters described previously, we should have seen one or more examples of this during aerial observations. The lack of such observations indicates that few if any visible bowheads undertook medium-scale (approximately 1-5 km) displacements.

If some bowheads began a major diversion 5 km or more away from the operating projector, we might not have detected it. Given various logistical limitations, few whales were followed toward the projector from points more than 5 km west of the projector.

However, we consider it very unlikely that diversion occurred at distances beyond 5 km. It is unlikely that there would be a bimodal distribution of diversion distances, i.e. that some unobserved whales would divert at >5 km when others do not divert until they are within 1 km of the projector, if at all. Also, received levels of *Karluk* sound 5 km from the projector were usually low relative to (1) ambient sound levels and (2) the levels of continuous industrial sounds found to cause diversion or displacement during previous playback studies of gray and bowhead whales (*cf.* Malme et al. 1984; Richardson et al. 1990b).[17] There were only two playback days in 1990, 11 and 13 May, when the average *Karluk* : ambient ratios at 5 km (~13 dB, Fig. 56, 69 on p. 147, 192) approached the values known to cause reactions by some bowheads during previous studies. On 11 May, the one group of bowheads observed in detail while the projector was on were approaching at a distance of 5.2 km when the projector was turned on; there was no change in course. On 13 May the migration toward the projector continued unabated when the projector was on.

Hence, it is unlikely that any bowheads changed course in response to drilling noise from a projector 5 km or more ahead. If any bowheads did divert at such a long distance, it was only a small minority of those that approached the operating projector.

---

[17] On two playback days in 1990, received broadband levels at 5 km were below the broadband ambient level and presumably undetectable (16 and 21 May; Fig. 78, 84). On two additional days, received broadband levels at 5 km averaged only 3 and 8 dB above the broadband ambient levels (9 and 10 May; Fig. 45, 52).

Distorted Drilling Sounds.--Bowhead whales were observed on one occasion while distorted *Karluk* sounds were being projected (13 May 1990). Too few data are available to allow a statistical analysis of distribution or movements during the distorted playback vs. other occasions. However, the CPA distribution of bowheads observed by ice-based and aerial observers during the distorted playback appeared similar to that during projection of normal *Karluk* sounds later on the same day. Whales approaching the projector frequently dove under the ice on the north side of the lead as they approached from ~3 km distance (Fig. 59A). As they came within 200-400 m of the projector, they crossed to the south side of the lead and traveled by the projector (Fig. 57-60). As during projection of undistorted *Karluk* sounds, few bowheads were seen at the surface immediately east of the projector (Fig. 59A).

Evaluation of "Distribution & Movement Hypothesis"

The specific hypothesis concerning effects on distribution and movements of bowheads is as follows:

> "Playbacks of recorded noise from a bottom-founded platform will not (or alternatively will) significantly alter measures of migration routes and spatial distribution of whales in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska".

As stated, this hypotheses concerns reactions to *playbacks* of platform noise rather than to noise from the platform itself. Thus, questions about the fidelity of the playback noise to the noise from the original industrial site are not directly involved. (See later discussion of this issue, p. 261.)

The hypothesis refers to "a bottom-founded platform". To date, all experiments have dealt with continuous drilling noise from one specific platform--the *Karluk* drilling operation on a bottom-founded ice pad in shallow water. The results obtained to date should not be generalized to other types of noise, particularly to variable noises or to those with appreciably different frequency content.

It should be noted that the "distribution and movement" hypothesis and our experiments concern only the case of a single noise source.

The hypothesis uses the phrase, "*significantly* alter measures of...", but does not define whether the term "significantly" refers to statistical or biological significance. The data summarized in Table 38 show that, from a statistical perspective, there were at least marginally significant small-scale short-term diversions of the migration routes of many of the bowheads passing within a few hundred meters of the playback site. Data on headings and turns, which are related to this hypothesis as well as the hypothesis on behavior, revealed very clear statistical evidence of noise effects (see next section).

Although there was evidence of increased turning by bowheads at the surface up to 2 km from the operating projector, there was no direct evidence of diversion at distances beyond ~1 km, and there was no evidence of migration blockage. The latter was true even when bowheads were put to the severe test of placing the projector along a narrow (200 m wide) lead through an area of otherwise 100% ice cover. The whales continued to swim past the operating projector; many came within 200 m of it. At 200 m range on 13 May 1990, the broadband sound level was ~135 dB re 1 µPa, or ~46 dB above the then-prevailing ambient noise level in the corresponding band. ***Thus, while there was statistical evidence of small-scale diversion, the playback experiments--including the quite severe test on 13 May--showed no evidence of biologically significant diversion or blockage of migration.***

The hypothesis limits the question to "open water of nearshore lead systems during spring migration near Pt. Barrow, Alaska". The data collected in 1989 and especially 1990 dealt primarily with the general situation described in the hypothesis:

- During this study, bowheads usually can be detected only if they surface in open water. They can only be followed for significant distances if there is either much open water or a reasonably well defined corridor of open water (crack or lead) through the ice.
- Some 1989-90 data were collected near the north edge of the main nearshore lead. However, the majority of the data were collected in the pack ice a few kilometers north of the open or (in parts of 1989) closed nearshore lead. There has been no opportunity to collect data on the south side of the nearshore lead adjacent to the landfast ice. In the area 35 km or more NE or E of Pt. Barrow, where we have been constrained to work, bowheads rarely travel along the southern side of the nearshore lead close to the landfast ice. Thus, we have no specific evidence that bowheads traveling along the edge of the landfast ice would react in the same ways as documented in this study. In order to test that, we would need to conduct experiments farther west than was possible in 1989-90.[18]
- The 1989-90 data were collected during spring migration near Pt. Barrow, Alaska, as required by the hypothesis. All data were, in fact, collected in the western Beaufort Sea northeast and east of Pt. Barrow. There is no specific evidence that bowhead reactions would be the same in the Chukchi Sea. However, we have no reason to doubt that reactions under comparable conditions in the Chukchi Sea (i.e. well offshore in or near the pack ice) would differ from those documented in the western Beaufort Sea. Again, reactions along the edge of the landfast ice edge might or might not differ somewhat.

In conclusion, the available data allow evaluation of a modified null hypothesis concerning the effects of playbacks of platform noise on distribution and movements during spring:

> "Playbacks of recorded ***continuous*** noise from a bottom-founded platform ***like the Karluk drilling operation on a grounded ice pad*** will not significantly alter the migration routes or spatial distribution of bowhead whales ***visible*** in open water ***amidst the pack ice and in the seaward side of the nearshore lead system*** during spring migration ***east of*** Pt. Barrow, Alaska."

There were ***statistically significant small-scale (<1 km) alterations*** in migration routes and spatial distribution. There were also statistically significant alterations in some aspects of behavior related to distribution and movements (headings, turns, speed), as summarized in the next section. However, there was ***no evidence of biologically significant alterations*** in migra-

---

[18] During 1989-90 it was necessary to conduct all playback experiments in areas well to the NE or E of Pt. Barrow to avoid the possibility of interference with the spring bowhead hunt and the spring bowhead census.

tion routes or spatial distribution, or of migration blockage. We conclude that the available data are consistent with the modified null hypothesis insofar as biologically significant effects of the playbacks on migration routes and distribution are concerned.

Behavior During All *Karluk* Playbacks

Bowhead behavior on 13 May 1990, the day with the largest number of observations, was described in the section "13 May 1990 Playback" (p. 148*ff*). The present section describes similar data for all other playbacks in 1989-90, and for all playback periods (including 13 May 1990). Also included, for comparison, are corresponding 1989-90 results for bowheads observed in the absence of playbacks or any other form of disturbance.

All 1989-90 analyses in this section exclude data from mothers and calves, and consider only whales classified as "traveling", i.e. actively migrating. *(1)* There were no observations of mothers or calves in the presence of drilling noise playbacks during 1990, and only a limited number of such observations in 1989. Hence, to avoid confounding the data, the few observations of mothers and calves were excluded. *(2)* Most observations in 1990 and some of those from 1989 were of "traveling" bowheads. The behavior of traveling whales differs from that of whales engaged in other activities (see "Behavior of Undisturbed Bowheads", p. 111-115). Hence, only the traveling whales are considered here.

Surfacing, Respiration and Diving Behavior

All 1989-90 Playbacks Except 13 May 1990.--It is of interest to know whether the types of results obtained on 13 May 1990 were also found on other days with drilling noise playbacks. On 13 May, bowheads close to the projector exhibited short surfacings, few blows per surfacing, and long blow intervals (Fig. 61, p. 167).

Excluding the 13 May 1990 data, there were no statistically significant[19] correlations between any of these three surfacing/respiration variables and distance from the operating projector (Fig. 86A-C; Table 39). This was true regardless of the distance scale used: distance *per se* or logarithm of distance.

Excluding the 13 May 1990 data, durations of dives tended to be longer for whales close to the operating projector than for whales far from the projector (nominal $P<0.05$). This trend was weak (Fig. 86D) and in the opposite direction to the pattern often noted in previous bowhead disturbance studies. Previous studies in summer and autumn have found that dives by disturbed whales usually are short (Richardson and Malme in press). Also, the trend was evident only when distances from the projector were transformed logarithmically. No relationship between dive duration and distance from projector was evident on 13 May 1990.

These results provide no evidence that the playbacks of *Karluk* drilling noise on days other than 13 May 1990 affected the surfacing or respiration cycles of bowheads observed near the operating projector, and the evidence concerning effects on dive durations was weak. The lack of clear effects on days other than 13 May may have been attributable to the scarcity of

---

[19] References to significant differences refer to "nominally significant", ignoring potential problems associated with repeated observations of the same individual whales.

All 1989-90 Playbacks Except 13 May 1990

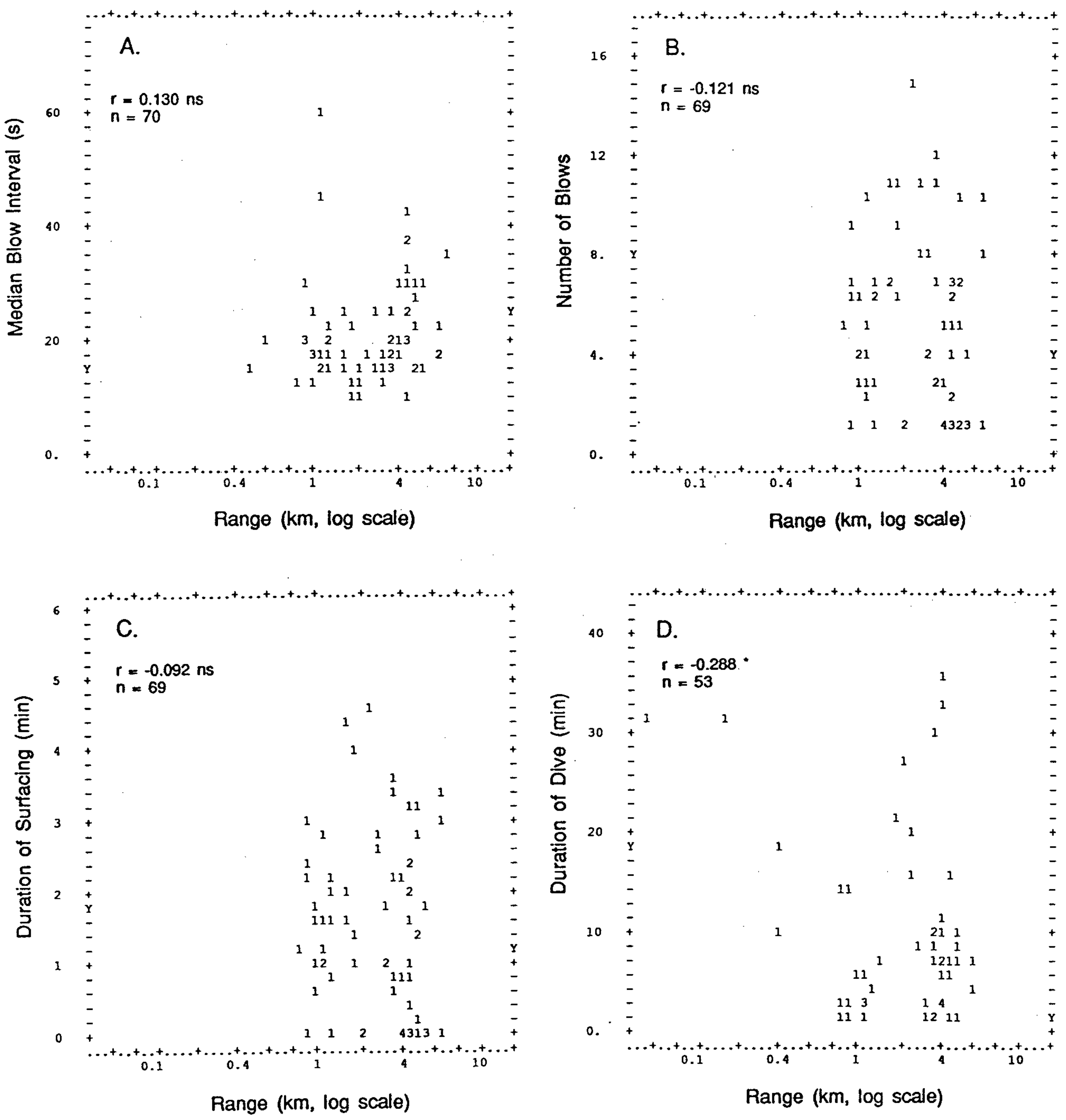


FIGURE 86. Surfacing, respiration and dive behavior in relation to distance from projector during all 1989-90 playbacks of *Karluk* sounds except on 13 May 1990. Both approaching and receding whales are included. Aerial observations only; only traveling whales included; mothers and calves excluded.

Table 39. Surfacing, respiration and dive behavior of traveling bowheads in relation to distance from projector (R), 1989 and 1990. Mothers and calves excluded. Correlations are shown for three categories of data: (a) with undistorted *Karluk* playback, including undistorted period on 13 May 1990, (b) same but excluding all 13 May 1990 data, and (c) "control" (ice camp present but no playback or other disturbance). Aerial observations only. P_n is nominal 2-tailed significance level of the correlation coefficient. See Table 26 for 13 May 1990 data.

			Approach			Recede			All Whales		
Behavior Variable		Situation	r	n	P_n	r	n	P_n	r	n	P_n
Median Blow Interval	vs. R	*Karluk* (undistort.)	-0.059	95	ns	-0.076	43	ns	-0.063	138	ns
		" (no 13 May)	0.225	47	ns	-0.159	23	ns	0.170	70	ns
		No playback	0.363	57	++	0.332	13	ns	0.373	70	+++
"	vs. log R	*Karluk* (undistort.)	-0.142	95	ns	-0.190	43	ns	-0.164	138	(-)
		" (no 13 May)	0.203	47	ns	-0.170	23	ns	0.130	70	ns
		No playback	0.274	57	+	0.357	13	ns	0.250	70	+
# Blows per Surfacing	vs. R	*Karluk* (undistort.)	0.048	92	ns	0.173	42	ns	0.078	134	ns
		" (no 13 May)	-0.216	43	ns	0.051	26	ns	-0.143	69	ns
		No playback	-0.036	60	ns	0.485	8	ns	-0.151	68	ns
"	vs. log R	*Karluk* (undistort.)	0.099	92	ns	0.222	42	ns	0.132	134	ns
		" (no 13 May)	-0.200	43	ns	0.069	26	ns	-0.121	69	ns
		No playback	-0.047	60	ns	0.590	8	ns	-0.152	68	ns
Duration of Surfacing	vs. R	*Karluk* (undistort.)	0.038	95	ns	0.228	44	ns	0.083	139	ns
		" (no 13 May)	-0.134	43	ns	-0.018	26	ns	-0.093	69	ns
		No playback	0.099	63	ns	0.537	8	ns	0.041	71	ns
"	vs. log R	*Karluk* (undistort.)	0.037	95	ns	0.254	44	(+)	0.089	139	ns
		" (no 13 May)	-0.132	43	ns	-0.008	26	ns	-0.092	69	ns
		No playback	0.078	63	ns	0.635	8	(+)	0.031	71	ns

Continued...

Table 39. Concluded.

Behavior Variable		Situation	Approach			Recede			All Whales		
			r	n	P_n	r	n	P_n	r	n	P_n
Duration of Dive	vs R	*Karluk* (undistort.)	-0.072	65	ns	-0.109	17	ns	-0.060	82	ns
		" (no 13 May)	-0.190	38	ns	-0.210	15	ns	-0.140	53	ns
		No playback	-0.123	55	ns	-0.541	4	ns	-0.201	59	ns
"	vs. log R	*Karluk* (undistort.)	-0.162	65	ns	-0.033	17	ns	-0.150	82	ns
		" (no 13 May)	-0.333	38	-	-0.131	15	ns	-0.288	53	-
		No playback	-0.177	55	ns	-0.555	4	ns	-0.263	59	-
Degree of Turn	vs. R	*Karluk* (undistort.)	-0.369	99	---	-0.116	42	ns	-0.314	141	---
		" (no 13 May)	-0.279	47	(-)	-0.130	26	ns	-0.229	73	(-)
		No playback	0.023	62	ns	0.330	9	ns	0.011	71	ns
	vs. log R	*Karluk* (undistort.)	-0.522	99	---	-0.125	42	ns	-0.440	141	---
		" (no 13 May)	-0.311	47	-	-0.120	26	ns	-0.249	73	-
		No playback	0.029	62	ns	0.269	9	ns	0.015	71	ns

observations at distances ≤ 1 km from the operating projector, especially at distances <0.7 km (Fig. 86). In contrast, on 13 May there were meaningful samples at 0-½ km as well as ½-1 km (Fig. 61). On 13 May, strong effects were evident only within 1 km (Fig. 62).

All 1989-90 Playbacks.--When all undistorted playbacks of *Karluk* drilling platform sound were pooled, there was little evidence that surfacing or respiration behavior was related to distance from the projector (Table 39, Fig. 87):

- For approaching whales and all whales, number of blows per surfacing and duration of surfacing were not significantly correlated with distance from projector or with logarithm of distance (Fig. 87B,C; $P_n>0.1$ in each case).
- There was a weak tendency for longer blow intervals among whales close to the operating projector than for those a few kilometers away (Fig. 87A; $r_{\log R} = -0.164$, $n=138$, $P_n<0.1$). This weak trend was consistent in direction with that seen for blow intervals during some previous summer/autumn studies of disturbance reactions. This trend was attributable to the 13 May 1990 data (compare Fig. 61A, 86A and 87A).
- There was a weak tendency for whales moving away from the projector to have longer surfacings when they were several kilometers away than when they were closer (Table 39; $r_{\log R}=0.254$, $n=44$, $P_n<0.1$). This weak trend was consistent in direction with that seen for duration of surfacing on 13 May 1990 (Fig. 61C) and during previous summer/autumn studies of disturbance reactions.

All 1989-90 Control Data.--During periods when the ice camp was present but there was no playback or other human disturbance, duration of surfacing and number of blows per surfacing were not significantly correlated with distance or logarithm of distance (Table 39). However, there were no data for distances much less than 2 km (Fig. 88B,C), so the lack of correlation is not very meaningful. There was a weak tendency for longer dive durations close to the ice camp (Fig. 88D). There was also a tendency for short blow intervals close to the ice camp ($r_R=0.373$, $P_n<0.001$; $r_{\log R}=0.250$, $P_n<0.05$; Fig. 88A). These two trends are in the opposite direction to those often seen in the presence of disturbance during summer or autumn, and to the trend in blow intervals seen on 13 May 1990 (Fig. 61A).

Turns

Degrees of Turn during Surfacings.--On 13 May 1990, there was a significant tendency for more turning during surfacings when whales were close to the operating projector (Fig. 89A). This was true during both the distorted and the undistorted playback (Table 28).

A similar but weaker trend was evident for all playbacks excluding those on 13 May 1990 ($P_n<0.05$). The trend was strongest for approaching whales (Fig. 89B), but was also evident for all whales--approaching plus receding (Table 39).

When all days with playbacks (including 13 May) were pooled, the tendency for more turning close to the projector was highly significant for approaching whales (Fig. 89C) and all whales (Table 39) but not so for receding whales.

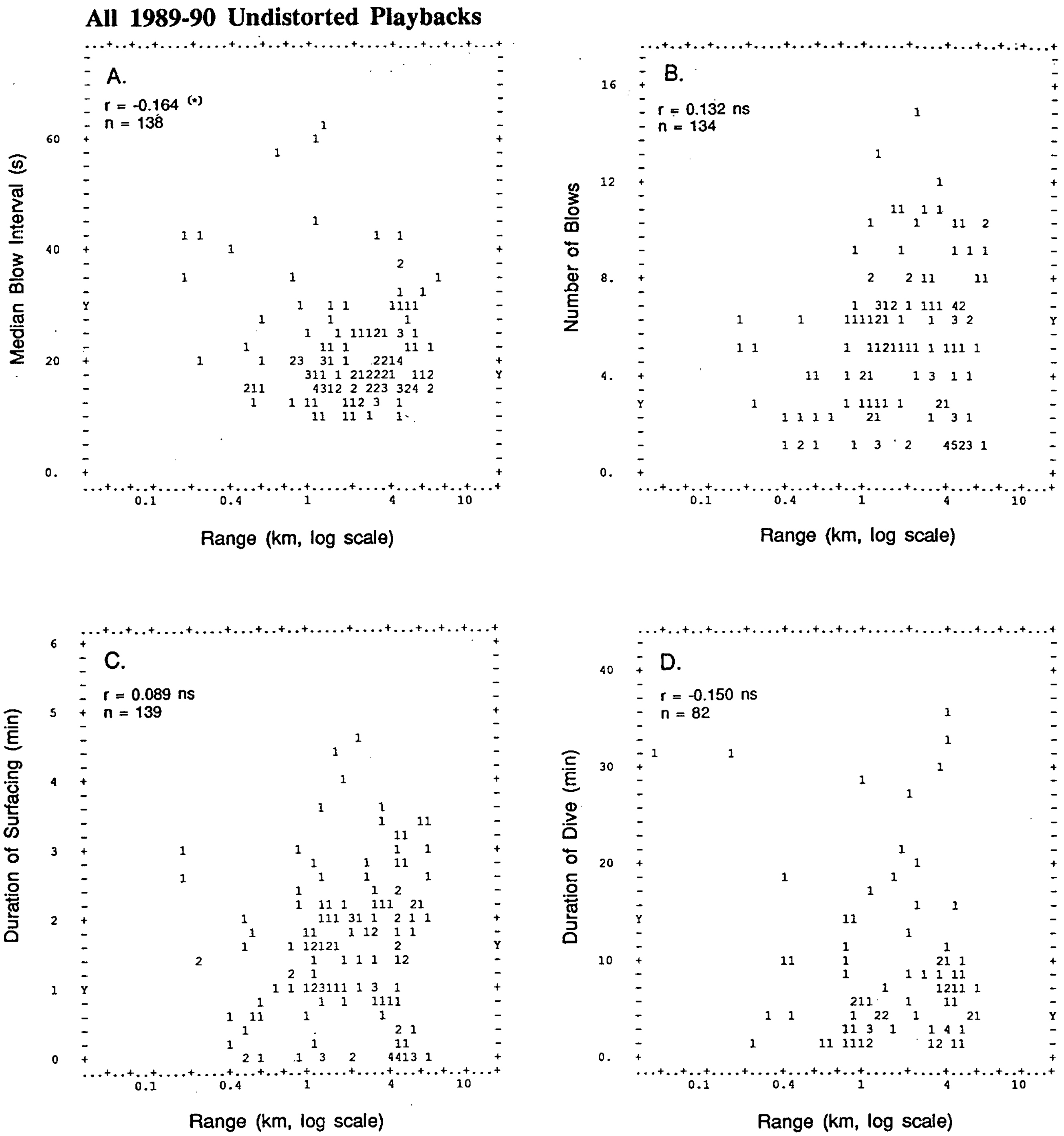


FIGURE 87. Surfacing, respiration and dive behavior in relation to distance from projector during all undistorted 1989-90 playbacks of *Karluk* sounds. Both approaching and receding whales are included. Aerial observations only; only traveling whales included; mothers and calves excluded.

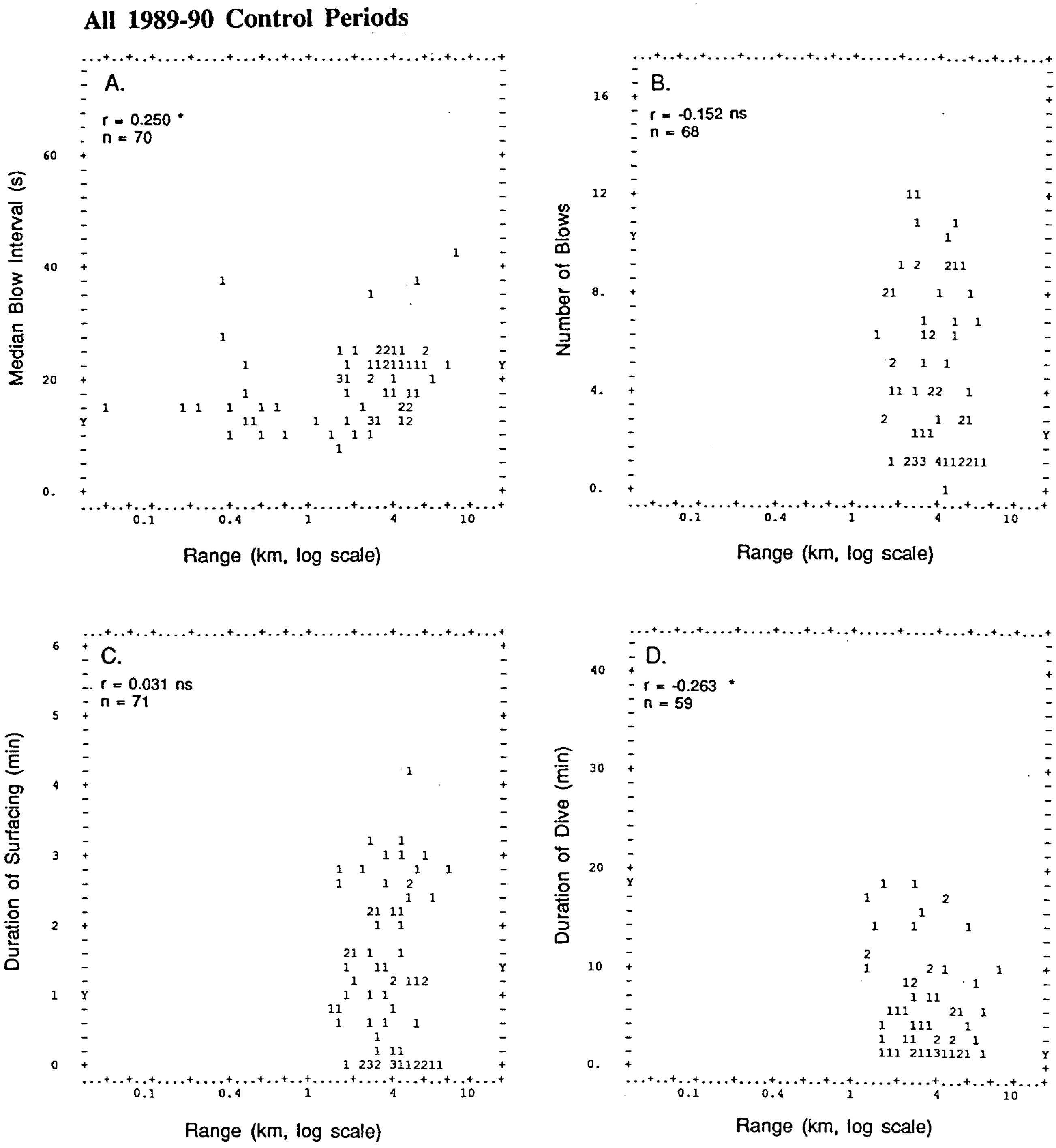


FIGURE 88. Surfacing, respiration and dive behavior in relation to distance from projector during all 1989-90 control periods (ice camp present but projector off). Both approaching and receding whales are included. Aerial observations only; only traveling whales included, mothers and calves excluded.

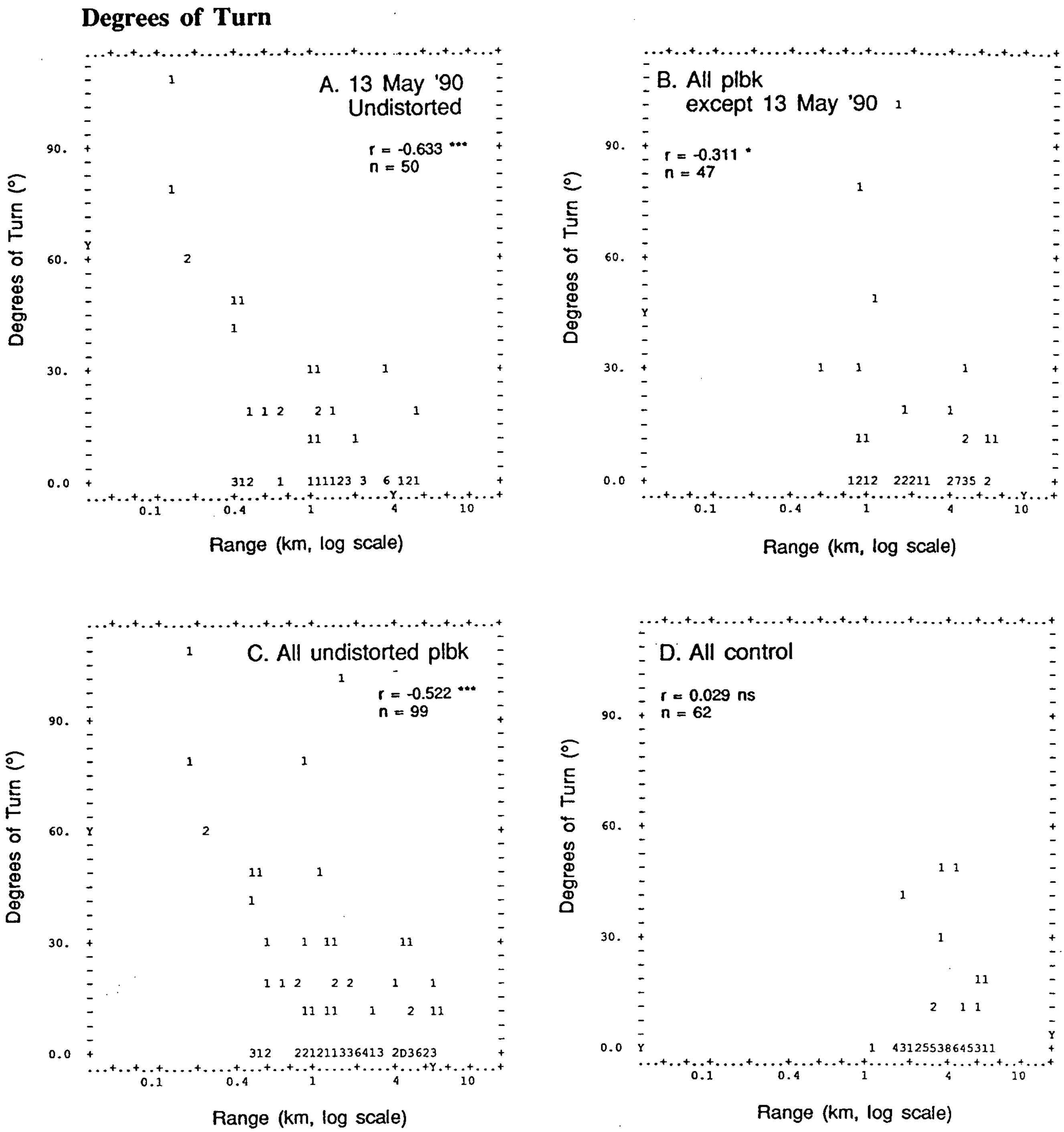


FIGURE 89. Degrees of turn during surfacings in relation to distance from projector during (A) 13 May undistorted playbacks, (B) all 1989-90 playbacks except on 13 May 1990, (C) all undistorted playbacks in 1989-90, and (D) all control periods in 1989-90. Only approaching whales are included. Aerial observations only; only traveling whales included; mothers and calves excluded.

There was no significant correlation between degrees of turn and distance from the ice camp during control periods. However, there were no control data from distances ≤1 km (Fig. 89D), so the lack of correlation was not very meaningful.

Frequency of Turns during Surfacings.--During undistorted playbacks, turns occurred more frequently when approaching whales were within 2 km of the projector than when they were farther away. This was true both on 13 May 1990 and on all other days with playbacks (Table 40; Fig. 90). For all undistorted *Karluk* playbacks, turns occurred during 24% of surfacings >4 km from the operating projector, 15% of those 2-4 km away, 46% of those 1-2 km away, and 62% of those ≤1 km away. The differences were statistically significant (chi^2=13.83, df=3, P_n<0.01).

Table 40. Proportion of surfacings with turns vs. distance from ice camp, considering traveling bowhead whales approaching the ice camp during *Karluk* playbacks and control periods, 1989-90. Aerial observations only, excluding mothers and calves. Control data are for camp present but projector not operating. See Figure 90 for graphical depiction.

Distance (km)	13 May '90 Undistorted[a]	Playbacks, Other Days[b]	All Undist. Playbacks[b]	Control, All Days[b]	13 May '90 Distorted[a]
>4	2 of 12 17%	5 of 17 29%	7 of 29 24%	5 of 31 16%	0 of 7 0%
2-4	1 of 7 14	2 of 11 18	3 of 20 15	6 of 25 24	7 of 9 78
1-2	7 of 13 54	6 of 15 40	13 of 28 46	0 of 4 0	7 of 7 100
1	11 of 18 61	5 of 8 63	16 of 26 62	8 of 8 100	4 of 7 57

[a] From Table 29 [b] From Table 41

However, during control periods, there was also a trend for more frequent turning ≤1 km from the projector (chi^2=20.8, df=1, P_n<0.001). Hence, it is necessary to consider whether the increased frequency of turning near the ice camp during playbacks was attributable to (1) the projected drilling noise, (2) some general effect of the ice camp independent of the presence or absence of drilling noise, or (3) a combination of the two. Possibility (2) cannot be the sole explanation. In the absence of playbacks there was no increase in turn frequency until the approaching whales were in the ½-1 km category, whereas the effect began 1-2 km away during undistorted playbacks and 2-4 km away during the distorted *Karluk* test on 13 May (Table 40; Fig. 90).

The interpretation most consistent with the turn data is that playbacks of undistorted drilling noise resulted in increased turning when whales came within 2 km, but that--in the absence of playbacks--other aspects of the camp were sufficient to cause increased turning when whales came within 1 km. The non-playback effects within 1 km might be attributable to visual detection of the camp or, perhaps more likely, acoustic detection of generator noise during control periods (see "Generator Noise", p. 98, and "Non-Playback Effects of Ice Camp", p. 245). However, these effects accounted for few if any of the behavior vs. distance trends found during playbacks. The "Non-Playback Effects" section also discusses some changes in field procedures planned for 1991 that will reduce the likelihood of such undesired camp effects in future work.

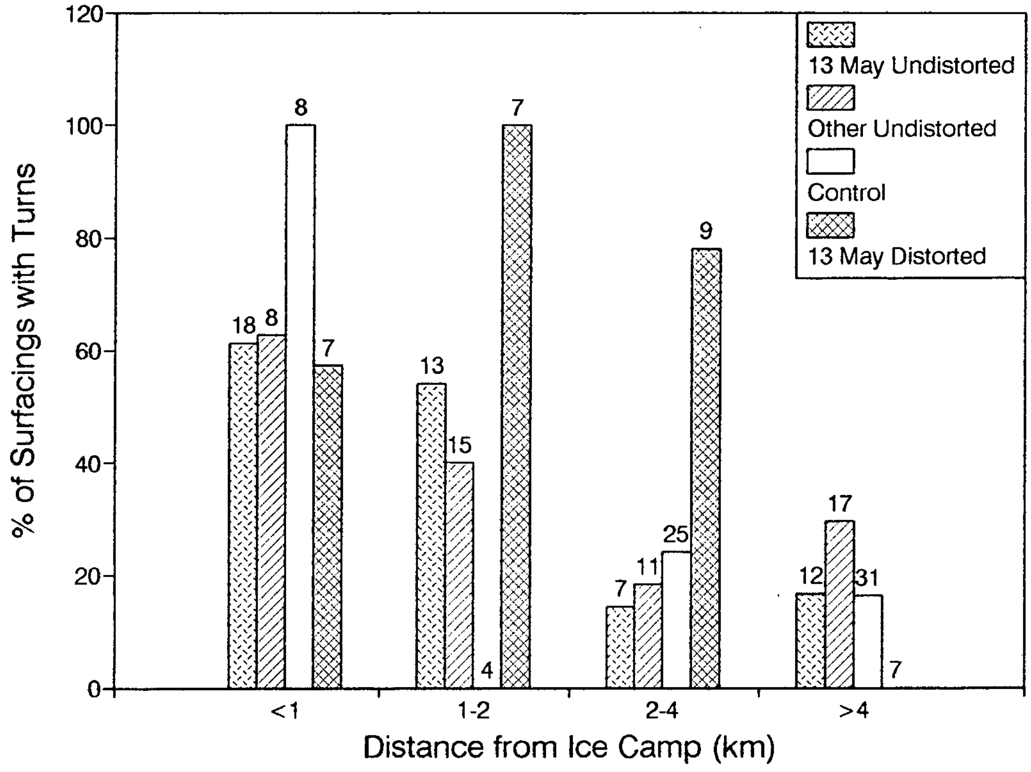


FIGURE 90. Percent of surfacings with turns vs. distance from ice camp, 1989-90. Data from Tables 29 and 40. Aerial observations only, excluding mothers and calves. Numbers of surfacings involved in obtaining each percentage are shown.

Other Behavioral Variables

Swimming speeds during the undistorted drilling noise playback on 13 May 1990 tended to be lower when approaching whales came within 1 km of the sound projector (see Table 29 and associated text). Also, based on a very small sample, whales that had passed the projector during that playback seemed to speed up relative to those that were approaching (Table 25). However, there was no evidence of similar effects during playbacks on other days (Table 41A).

Pre-dive flexes were rarely seen at any time in 1989-90, playback or otherwise (Table 42; see also Table 15, p. 113). ***Aerial behaviors*** were also seen too rarely to be useful in evaluating playback effects (Table 30, 42).

Fluke-out dives were almost absent during the undistorted playback on 13 May 1990, and were infrequent during other playbacks as well (Table 30, 42). During all undistorted playback experiments in 1989-90, the flukes were raised above the water at the start of 10 of 142 dives by bowheads >1 km from the projector, and 2 of 29 dives by bowheads ≤1 km from the projector (7% in each case; Table 42B). Thus, there was no evidence that proximity to the playback site affected the frequency of fluke-out dives.

Table 41. Frequency of turns and various swimming speeds during surfacings by traveling bowheads, excluding mothers and calves, as observed from a Twin Otter aircraft, spring 1989-90. Distances from ice camp in left column are in parentheses for approaching whales and not in parentheses for whales moving away. "Control" data are for camp present but projector not operating. The units of observation are surfacings by an individual whale.

Situation & Distance in km	Turns					Estimated Speed at Surface							
	None	Right	Left	Multiple	Total	None	Slow	Medium	Fast	Moving Unkn Speed	Mill	Change Speed	Total
A. 1989-90 Except 13 May 1990													
Karluk Playback													
(>4)	12	0	5	0	17	0	0	23	0	4	0	1	28
(2-4)	9	1	1	0	11	0	1	14	0	3	0	0	18
(1-2)	9	2	2	2	15	0	0	18	0	1	0	0	19
(.5-1)	3	1	0	3	7	0	1	3	0	2	0	2	8
(0-.5)	0	0	0	1	1	0	0	3	0	1	0	0	4
0-.5	0	0	0	0	0	0	0	0	0	0	0	0	0
.5-1	1	1	0	0	2	0	0	3	0	0	0	0	3
1-2	6	0	0	1	7	0	0	5	0	0	0	2	7
2-4	12	0	4	1	17	0	0	15	0	3	0	0	18
>4	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	52	5	12	8	77	0	2	84	0	14	0	5	105
Control													
(>4)	26	2	2	1	31	0	0	29	0	4	0	2	35
(2-4)	19	0	3	3	25	1	0	22	0	2	0	0	25
(1-2)	4	0	0	0	4	0	3	1	0	1	0	1	6
(.5-1)	0	3	1	0	4	0	0	2	0	4	0	1	7
(0-.5)	0	2	2	0	4	0	1	2	0	11	0	1	15
0-.5	0	0	0	0	0	0	0	0	0	0	0	0	0
.5-1	0	0	0	1	1	0	0	1	0	1	0	0	2
1-2	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	3	2	1	0	6	0	0	2	1	0	0	3	6
>4	1	0	0	1	2	0	0	0	0	0	0	2	2
Total	53	9	9	6	77	1	4	59	1	23	0	10	98
B. All Days 1989-90													
Karluk Playback (excl. 13 May distorted)													
(>4)	22	1	6	0	29	0	0	35	0	6	0	1	42
(2-4)	17	1	2	0	20	0	1	25	0	3	0	2	31
(1-2)	15	5	4	4	28	0	0	29	0	1	0	2	32
(.5-1)	6	3	2	3	14	0	6	5	0	2	0	2	15
(0-.5)	4	1	3	4	12	0	3	9	0	2	0	1	15
0-.5	1	0	1	0	2	0	0	2	0	0	0	0	2
.5-1	1	1	0	0	2	0	0	3	0	0	0	0	3
1-2	10	1	3	1	15	0	0	10	0	0	0	5	15
2-4	14	0	5	2	21	0	4	18	0	3	0	1	26
>4	0	0	3	1	4	0	0	5	0	0	0	2	7
Total	90	13	29	15	147	0	14	141	0	17	0	16	188
Control													
(>4)	26	2	2	1	31	0	0	29	0	4	0	2	35
(2-4)	19	0	3	3	25	1	0	22	0	2	0	0	25
(1-2)	4	0	0	0	4	0	3	1	0	1	0	1	6
(.5-1)	0	3	1	0	4	0	0	2	0	4	0	1	7
(0-.5)	0	2	2	0	4	0	1	2	0	11	0	1	15
0-.5	0	0	0	0	0	0	0	0	0	0	0	0	0
.5-1	0	0	0	1	1	0	0	1	0	1	0	0	2
1-2	0	0	1	0	1	0	0	1	0	0	0	0	1
2-4	3	2	1	0	6	0	0	4	1	0	0	3	8
>4	1	0	0	1	2	0	0	0	0	0	0	2	2
Total	53	9	10	6	78	1	4	62	1	23	0	10	101
C. All Days, 1989-90, including "No camp" & "Distance Unknown" cases													
Karluk Playback (excl. 13 May distorted)	90	13	29	15	147	0	14	141	0	17	0	16	188
All Undisturbed	168	22	18	15	223	1	18	215	3	33	0	19	289

Table 42. Frequency of pre-dive flexes, fluke-out dives and aerial behaviors during surfacings by traveling bowheads, excluding mothers and calves, as observed from a Twin Otter aircraft, spring 1989-90. Distances from ice camp in left column are in parentheses for approaching whales and not in parentheses for whales moving away. "Control" data are for camp present but projector not operating. The units of observation are surfacings by an individual whale.

Situation & Distance in km	Pre-dive Flex			Flukes Out as Diving			Aerial Behaviors						
	No	Yes	Total	No	Yes	Total	None	Roll	Flip-Slap	Tail Slap	Breach	2 or 3 Types	Total
A. 1989-90 Except 13 May 1990													
Undistorted Karluk													
(>4)	21	0	21	24	0	24	24	0	0	0	0	0	24
(2-4)	13	0	13	14	1	15	15	0	0	0	0	0	15
(1-2)	16	0	16	16	1	17	15	0	0	0	0	0	15
(.5-1)	7	0	7	6	1	7	8	0	0	0	0	0	8
(0-.5)	0	0	0	0	0	0	1	0	0	0	0	0	1
0-.5	0	0	0	0	0	0	0	0	0	0	0	0	0
.5-1	2	0	2	1	1	2	2	0	0	0	0	0	2
1-2	7	0	7	5	2	7	7	0	0	0	0	0	7
2-4	18	0	18	16	2	18	18	0	0	0	0	0	18
>4	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	84	0	84	82	8	90	90	0	0	0	0	0	90
Control													
(>4)	33	0	33	31	3	34	32	1	0	0	0	0	33
(2-4)	24	0	24	24	1	25	25	0	0	0	1	0	26
(1-2)	5	0	5	5	0	5	5	0	0	0	0	0	5
(.5-1)	2	0	2	1	1	2	1	0	0	0	0	0	1
(0-.5)	4	0	4	4	0	4	6	0	0	1	0	0	7
0-.5	0	0	0	0	0	0	0	0	0	0	0	0	0
.5-1	2	0	2	2	0	2	2	0	0	0	0	0	2
1-2	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	4	2	6	3	3	6	6	0	0	0	0	0	6
>4	2	0	2	2	0	2	2	0	0	0	0	0	2
Total	76	2	78	72	8	80	79	1	0	1	1	0	82
B. All Days 1989-90													
Karluk Playback (excl. 13 May distorted)													
(>4)	32	0	32	36	0	36	38	0	0	0	0	0	38
(2-4)	26	0	26	24	4	28	28	0	0	0	0	0	28
(1-2)	29	0	29	29	1	30	28	0	0	0	0	0	28
(.5-1)	14	0	14	13	1	14	15	0	0	0	0	0	15
(0-.5)	11	0	11	11	0	11	12	0	0	0	0	0	12
0-.5	2	0	2	2	0	2	2	0	0	0	0	0	2
.5-1	2	0	2	1	1	2	2	0	0	0	0	0	2
1-2	15	0	15	13	2	15	15	0	0	0	0	0	15
2-4	25	0	25	24	2	26	26	0	0	0	0	0	26
>4	7	0	7	6	1	7	7	0	0	0	0	0	7
Total	163	0	163	159	12	171	173	0	0	0	0	0	173
Control													
(>4)	33	0	33	31	3	34	32	1	0	0	0	0	33
(2-4)	24	0	24	24	1	25	25	0	0	0	1	0	26
(1-2)	5	0	5	5	0	5	5	0	0	0	0	0	5
(.5-1)	2	0	2	1	1	2	1	0	0	0	0	0	1
(0-.5)	4	0	4	4	0	4	6	0	0	1	0	0	7
0-.5	0	0	0	0	0	0	0	0	0	0	0	0	0
.5-1	2	0	2	2	0	2	2	0	0	0	0	0	2
1-2	1	0	1	1	0	1	1	0	0	0	0	0	1
2-4	4	2	6	4	3	7	8	0	0	0	0	0	8
>4	2	0	2	2	0	2	2	0	0	0	0	0	2
Total	77	2	79	74	8	82	82	1	0	1	1	0	85
C. All Days, 1989-90, including "No camp" & "Distance Unknown" cases													
Karluk Playback (excl. 13 May distorted)	163	0	163	159	12	171	173	0	0	0	0	0	173
All Undisturbed	236	3	239	229	22	251	260	1	0	4	1	0	266

All Behavioral Variables Combined

As noted earlier for 13 May 1990 (p. 181), it is often difficult to evaluate changes in behavior when many different intercorrelated measures of behavior are recorded. Factor analysis can be used to reduce the original behavioral variables to a smaller number of uncorrelated indices of behavior. Then one can more easily evaluate the relationships of these few indices to environmental circumstances--in this case playbacks of drilling noise. In this study, six indices of behavior (factors) were derived from 14 intercorrelated behavioral variables (see Table 31 and associated text).

During the undistorted playback on 13 May 1990, there were significant relationships between several factors and log-transformed distance from the operating projector (see Table 32, Fig. 64, 65, and associated text). The results were clearest for Factors 1 and 2, for which there were no parallel trends in the pooled 1989-90 control data. Factors 1 and 2 represented the occurrence and magnitude of turns, and the duration and number of blows per surfacing (Table 31). Values of these original variables were also correlated with distance from the operating projector on 13 May.

The factor analysis approach provided almost no evidence that behavior was related to distance from the operating projector during playbacks on days other than 13 May 1990. There was no significant relationship between Factors 1-4 or 6 and the log-transformed distance from the projector (Table 43). Factor 5 also was unrelated to log (distance) when either approaching or all whales were considered. However, for the few observations of bowheads moving away from the projector (n=17), there was a positive association of unknown biological significance between Factor 5 and log (distance).[20]

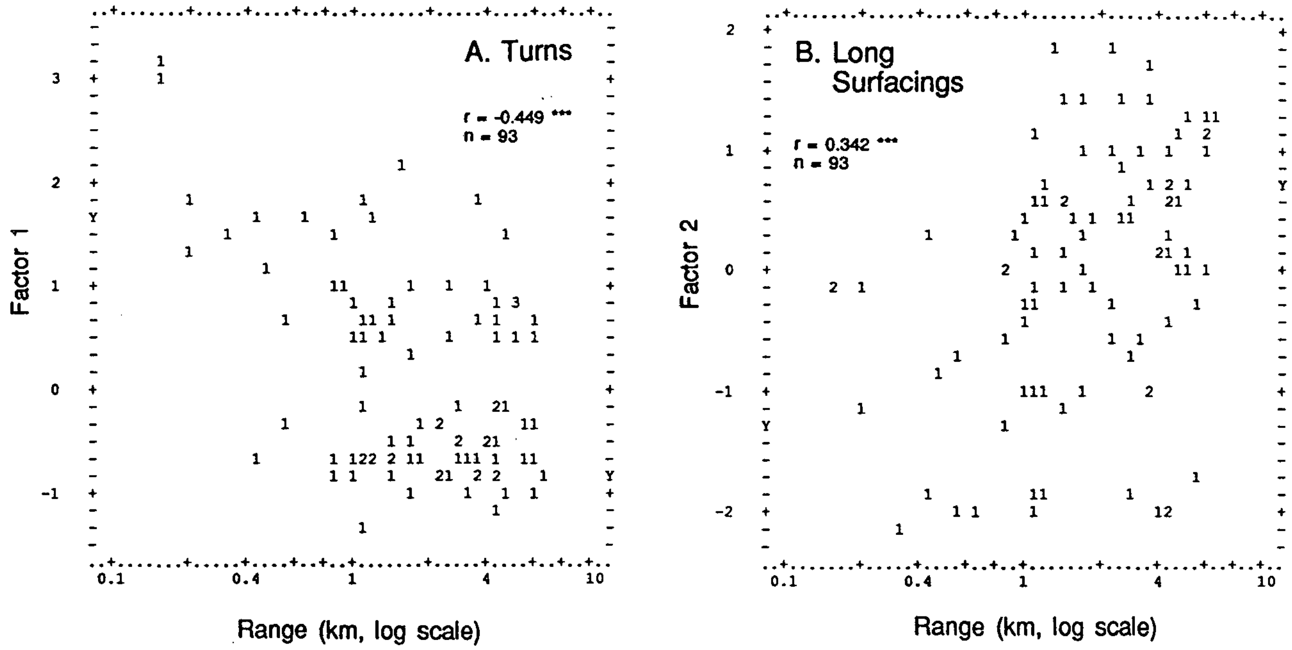
When results from all undistorted playbacks (including 13 May 1990) were pooled, three behavior factors were found to be strongly related to distance from the operating projector (Table 43; Fig. 91). The occurrence and magnitude of turns tended to increase close to the projector ($P_n<0.001$, Factor 1). The duration and number of blows per surfacing tended to decrease close to the projector ($P_n<0.001$ for "All Whales", Factor 2). Slow travel with underwater blows tended to be most common near the projector ($P_n<0.001$, Factor 6). These were the same three factors that were most closely related to distance during the undistorted playback on 13 May 1990. As on that day, the association with Factor 6 is confounded by the fact that a similar (but weaker) trend was evident in the pooled 1989-90 control data (Table 43).

The three most meaningful behavioral indices for all undistorted 1989-90 data were summarized according to the standard distance categories (Fig. 92). The orthogonal contrast and multiple comparison methods described on p. 170 were used to identify the distance categories where behavior was distinguishable. Values of Factor 1 at 0-½ km from the operating projector were distinct from those in distance categories beyond ½ km, which were indistinguishable from one another (Table 44). Values of Factors 2 and 6 at 0-½ km and ½-1 km were distinct from values in categories beyond 1 km (Table 44). This analysis is generally consistent with that for 13 May 1990 (Fig. 65; Table 27B). Both analyses show that playback effects extended out at least to the ½-1 km distance category.

---

[20] Factor 5 was an index of a previously-unrecognized association between travel parallel to ice edges and short blow intervals.

Behavior Indices (Factor Scores)



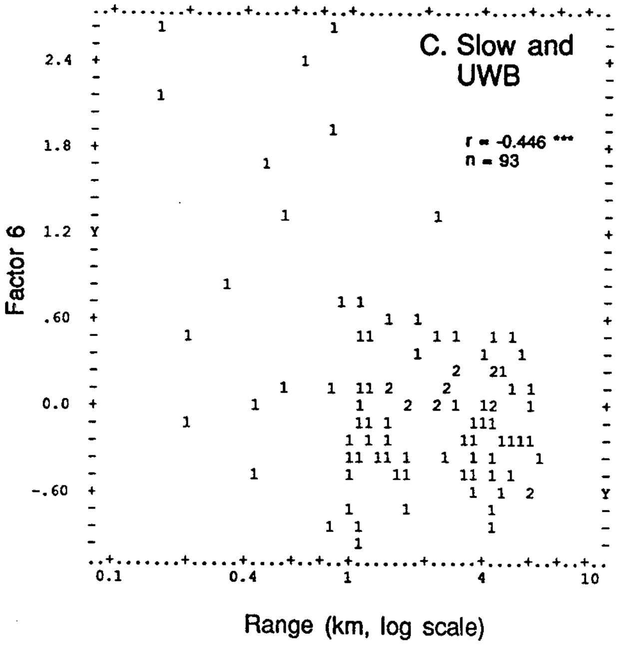


FIGURE 91. Factor scores for behavior indices 1, 2 and 6 in relation to distance from projector during all playbacks of undistorted *Karluk* sounds, 1989-90. Approaching and receding whales are both included. Aerial observations only; mothers and calves excluded.

Table 43. Behavior factors of traveling bowheads in relation to distance from projector (R), 1989 and 1990. Mothers and calves excluded. Correlations are shown for three categories of data: (a) with undistorted *Karluk* playback, including undistorted period on 13 May 1990, (b) same but excluding all 13 May 1990 data, and (c) "control" (ice camp present but no playback or other disturbance). P_n is nominal 2-tailed significance level of the correlation coefficient. Aerial observations only.

Behavior Factor		Situation	Approach			Recede			All Whales		
			r	n	P_n	r	n	P_n	r	n	P_n
Factor 1	vs. log R	*Karluk* (undistort.)	-0.551	68	---	-0.025	25	ns	-0.449	93	---
Turn (+) or		" (no 13 May)	-0.061	29	ns	0.190	17	ns	0.026	46	ns
not (-)		No playback	0.127	32	ns	-0.326	4	ns	0.098	36	ns
Factor 2	vs. log R	*Karluk* (undistort.)	0.303	68	+	0.484	25	+	0.342	93	+++
Surfacing long (+)		" (no 13 May)	0.069	29	ns	0.374	17	ns	0.163	46	ns
or short (-)		No playback	0.149	32	ns	0.833	4	ns	0.057	36	ns
Factor 3	vs. log R	*Karluk* (undistort.)	0.093	68	ns	0.128	25	ns	0.109	93	ns
Group (1)		" (no 13 May)	0.193	29	ns	0.092	17	ns	0.132	46	ns
or alone (-)		No playback	-0.706	32	---	0.117	4	ns	-0.485	36	--
Factor 4	vs. log R	*Karluk* (undistort.)	0.181	68	ns	0.037	25	ns	0.145	93	ns
Flukes (1)		" (no 13 May)	-0.288	29	ns	-0.161	17	ns	-0.243	46	ns
or not (0)		No playback	0.605	32	+++	0.187	4	ns	0.478	36	++
Factor 5	vs. log R	*Karluk* (undistort.)	-0.031	68	ns	-0.005	25	ns	-0.021	93	ns
Paralleling ice/		" (no 13 May)	-0.240	29	ns	0.604	17	++	0.003	46	ns
Short BI (+)		No playback	0.211	32	ns	-0.452	4	ns	-0.125	36	ns
or not (-)											
Factor 6	vs. log R	*Karluk* (undistort.)	-0.488	68	---	-0.183	25	ns	-0.446	93	---
Slow & UWB		" (no 13 May)	0.110	29	ns	-0.051	17	ns	0.080	46	ns
(+) or Faster		No playback	-0.472	32	--	-0.597	4	ns	-0.292	36	(-)
& no UWB (-)											

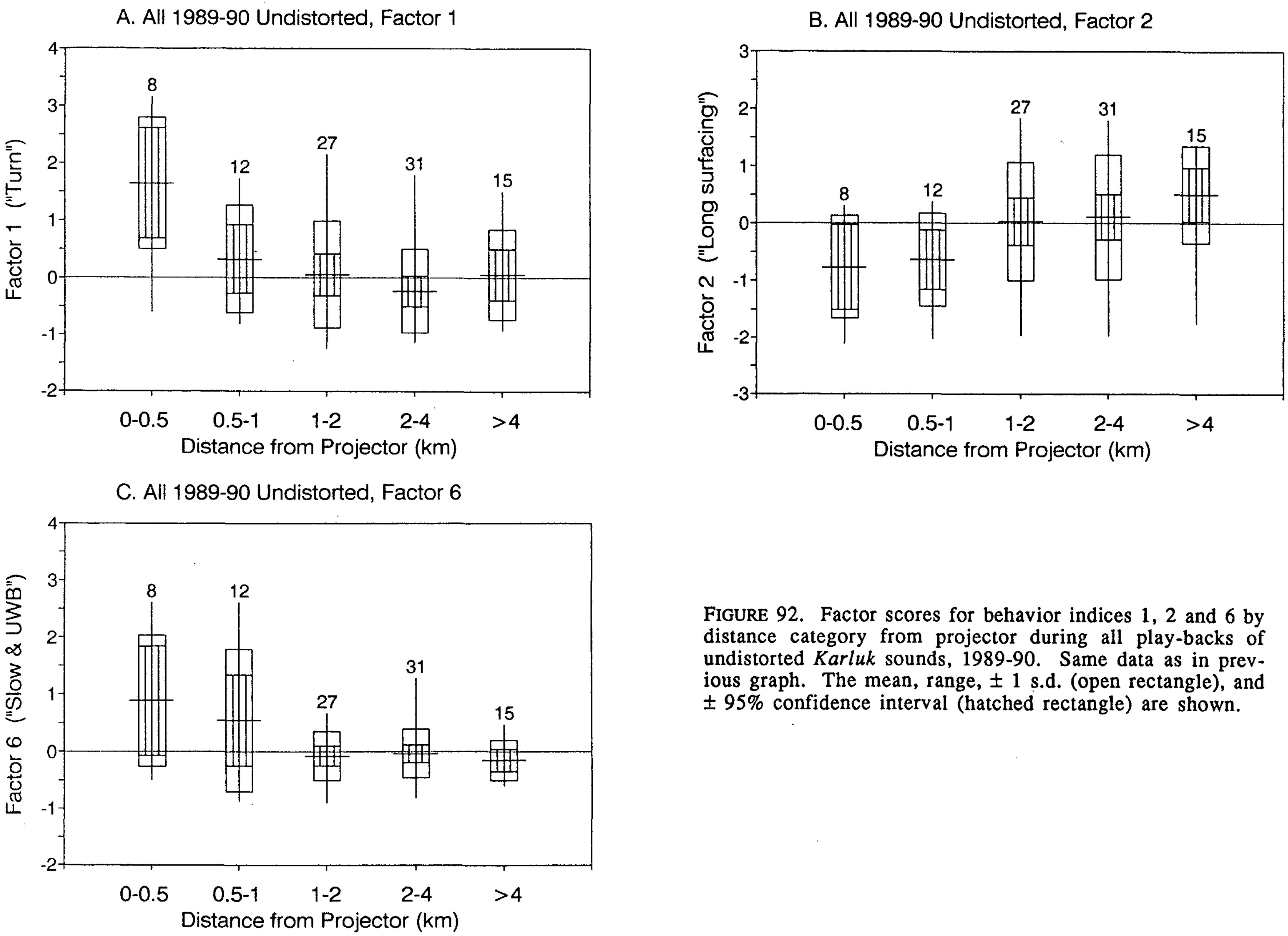


FIGURE 92. Factor scores for behavior indices 1, 2 and 6 by distance category from projector during all play-backs of undistorted *Karluk* sounds, 1989-90. Same data as in previous graph. The mean, range, ± 1 s.d. (open rectangle), and ± 95% confidence interval (hatched rectangle) are shown.

Table 44. ANOVA and related analyses of distance from operating projector vs. behavioral factors, all 1989-90 undistorted playbacks. Same data as in Figures 91 and 92. See text for details.

	1-way ANOVA on 5 distance categories	Orthogonal Contrasts, various distances (km) vs. all greater distances (km)		Bonferroni Tests[1], various distances (km) vs. >4 km	
Factor One	***	2-4 vs. >4	ns	2-4 vs. >4	ns
		1-2 vs. >2	ns	1-2 vs. >4	ns
	var =	½-1 vs. >1	ns	½-1 vs. >4	ns
		<½ vs. >½	***	<½ vs. >4	***
Factor Two	**	2-4 vs. >4	ns	2-4 vs. >4	ns
		1-2 vs. >2	ns	1-2 vs. >4	ns
	var =	½-1 vs. >1	**	½-1 vs. >4	*
		<½ vs. >½	*[4]	<½ vs. >4	*
Factor Six	***[2]	2-4 vs. >4	ns	2-4 vs. >4	ns[3]
		1-2 vs. >2	ns	1-2 vs. >4	ns
	var ≠	½-1 vs. >1	**	½-1 vs. >4	ns
		<½ vs. >½	**[4]	<½ vs. >4	ns

ns P>0.1; (*) 0.1≥P>0.05; * 0.05≥P>0.01; ** 0.01≥P>0.001; *** P≤0.001.

[1] Alpha adjusted to allow for conducting 4 comparisons.
[2] Brown-Forsythe method for unequal variances (Dixon 1990:193) gives P<0.05.
[3] Bonferroni tests for this variable are computed not assuming equal variances.
[4] This contrast may not be meaningful because behavior varied significantly with distance at distances beyond the cutpoint.

As discussed in the 13 May 1990 section, the factor data do not rule out the possibility of a weak noise effect at a distance somewhat greater than 1 km. The turn data (see earlier) suggested that the noise effect extended out to the 1-2 km distance category during undistorted playbacks, and even farther during the playback of distorted *Karluk* sounds.

Non-Playback Effects of Ice Camp

It has always been a concern that whales might react to attributes of the ice camp other than the projected industrial sounds. The projected underwater sounds are undoubtedly detectable much farther away than any other sounds emitted during playback periods. Also, the projected sounds are detectable much farther away than the maximum possible visual detection distance for a whale. Thus, it is unlikely that reactions seen during playback periods would be attributable to cues other than the playback noise. However, during control periods (no playback), the much weaker underwater sounds originating from the generator or from human movements on the ice are potentially detectable within a few hundred meters. Also, whales within a few hundred meters might sometimes be able to see the camp, or perhaps to smell it. Thus, there is the possibility that whales might react to camp noise or to non-acoustic cues during control periods. There is also the possibility that whales might react to non-acoustic cues during playback periods if the whales are not affected by the projected sounds that are detectable much farther away than other camp stimuli.

A few of the results from control periods in 1989-90 increase our concern about non-playback effects of the ice camp:

- during control periods, turns were more frequent when bowheads were within 1 km of the camp than when they were farther away (Fig. 90; Table 40),
- whales approaching the camp on 13 May 1990 may have slowed down under "control" as well as playback conditions (Table 29 on p. 178; n very low),
- blow intervals tended to be short near the camp during control periods (Fig. 88A; Table 39 on p. 230), and
- dive durations tended to be long near the camp during control periods (Fig. 88D; Table 39).

None of these effects fully paralleled the trends during playback periods; the increased frequency of turns began farther away during playback periods, and the distance vs. blow interval and distance vs. dive duration trends were not in the directions expected for disturbed bowheads. Also, various other variables that were related to distance from camp during playbacks were not related to distance during control periods. Hence, there is no reason to believe that the trends observed during drilling noise playbacks were artifacts of non-playback effects. However, it is a concern that the presence of the camp seems to have weak effects, acoustic or otherwise, on whale behavior. Any such effects reduce our ability to recognize and characterize the reactions to simulated industrial noise.

Generator noise is one camp sound that has been of concern to us from the start of planning for this project. During previous summer playback tests with bowheads, we operated the sound projector for 30-40 min at a time from a bank of car batteries (Richardson et al. 1985b, 1990b). The batteries were used to avoid the complication of generator noise. However, this was not possible in the present project, given the need to operate the projector continuously for several hours and the requirement for a lightweight, helicopter-portable power supply.

In 1990, the generator was operated consistently during control periods to ensure that the only difference between control and playback periods was the presence of drilling noise. In retrospect, this premeditated "precaution" may not have been necessary or optimal. During playbacks, underwater noise from the generator was completely masked at all frequencies by the stronger sounds emitted by the projector (Richardson et al. 1990a:97-99). Thus, underwater noise from the generator was undetectable to whales during playbacks. Consequently, it is arguable whether operation of the generator during control periods was necessary for a valid experiment. Although desirable from a standard experimental design viewpoint, it may have been counterproductive in that it caused--during control periods--weak underwater sounds that were not detectable during playback periods.

During control periods, it is possible that generator noise might have been responsible for some or all relationships between behavior and distance from the ice camp. During control periods in 1990, generator noise was detectable at least 0.9-1.1 km away when there was little ambient noise, and possibly out to ~1.5 km. In contrast, at times with higher ambient noise levels, generator sounds became inaudible at closer distances--less than 100 m on one occasion (see "Generator Noise", p. 98).

Non-acoustic cues from the ice camp (sight, odor) also may have had some short-range effects on behavior during control periods. The olfactory sensitivity of bowhead and other baleen whales is poorly known (Lowell and Flanigan 1980). However, baleen whales have the necessary anatomical apparatus (Cave 1988).

During playbacks, the various behavioral effects noted within 1-2 km could not be attributed to generator noise or non-acoustic cues. The projected drilling sounds completely masked the much weaker underwater noise of the generator during playbacks. The possibility that visual cues or odor were responsible for behavior vs. distance trends during playbacks can also be ruled out based on the lack of parallelism between those trends under playback and control conditions.

During the 1991 fieldwork, we will reduce the likelihood of whale reactions to aspects of the ice camp other than the playbacks. The ice-based crew will wear white outer shells over their clothing to make themselves visually less conspicuous. The generator will be better isolated from the ice to reduce transmission of generator noise into the water.

Evaluation of "Behavior Hypothesis"

The specific hypothesis concerning playback effects on behavior of bowheads is as follows:

> "Playbacks of recorded noise from a bottom-founded platform will not (or alternatively will) significantly alter subtle aspects of individual behavior in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska".

The hypothesis deals specifically with playbacks of recorded sounds. Hence, questions about the fidelity of playback sounds to sounds near the actual industrial site are not directly relevant.

The earlier discussion of the wording of the "distribution and movements" hypothesis also applies to this behavior hypothesis. The available data allow evaluation of a modified null hypotheses:

> "Playbacks of recorded ***continuous*** noise from a bottom-founded platform ***like the Karluk drilling operation on a grounded ice pad*** will not significantly alter subtle aspects of individual behavior of bowhead whales ***visible*** in open water ***amidst the pack ice and in the seaward side of the nearshore lead system*** during spring migration ***east of*** Pt. Barrow, Alaska."

The 1989-90 data show that--***from a statistical viewpoint***--this null hypothesis must be rejected. There were statistically significant changes in individual behavior among bowhead whales approaching the sound projector. Although there were many indications of this, the most all-encompassing evidence is that summarized in Figures 91 and 92. Those diagrams show that at least three of six multivariate indices of behavior were related to distance from the sound projector. These relationships were monotonic and statistically significant.

The ***biological significance*** of these changes in behavior is less obvious. The altered behavior was not statistically significant until the whales had approached within 1-2 km of the projector, and did not persist in a significant way after they had moved 1-2 km beyond the projector. Thus, for whales migrating at 4 km/h or more, the significantly altered behavior persisted for about ½-1 hour. Certain behavioral effects may have lasted somewhat longer. The mean duration of surfacing and mean number of blows per surfacing may have been slightly altered at distances up to 2-4 km during the undistorted *Karluk* playback on 13 May 1990 (Table 27, p. 172). However, there was no evidence of blockage or major diversion of migration.

Sounds from the projector diminished below the ambient noise level at distances ranging from ~2 km under high ambient noise conditions to ~10 km with low ambient noise (Fig. 84 vs. Fig. 52, 56). Traveling bowheads would move from 10 km west to 10 km east of the projector--the approximate radius of audibility of the projected *Karluk* sounds on a quiet day--in about 4-5 h. In the absence of blockage or hesitation, this 4-5 h time period would be the maximum period of exposure to industrial noise. On a day with high ambient noise level (projected sounds detectable only to 2 km), the period of noise exposure would be ~1 h.

Reaction Thresholds during Playbacks

Results from *Karluk* Playbacks

In this section we use the results from the playbacks in 1989 and 1990 to estimate the levels of *Karluk* sound that elicited various degrees of response from bowhead whales migrating through the study area in spring. These responses are discussed in terms of

- distance from the projector,
- absolute level of *Karluk* sound, and
- *Karluk* noise : ambient noise ratio (i.e. signal-to-noise ratio).

Distance Thresholds.--In an earlier section, the closest points of approach (CPAs) of bowheads to the operating projector were documented (p. 218*ff*). Many bowheads were seen within 1 km of the projector. There was no evidence that the playbacks caused diversion by more than a few hundred meters. Figure 93 summarizes the 1989-90 sightings of bowheads within 1 km of the projector when it was broadcasting undistorted *Karluk* sounds and when it was silent (control periods). For 1990, the graph distinguishes bowheads that did and did not show evidence of diversion--a course change to avoid close approach to the projector. Figure 93 shows the closest *documented* points of approach of bowheads to the projector; the actual CPA distances of whales that were below the surface at CPA could not be determined. Hence, CPA distances for many sightings were undoubtedly closer than shown in Figure 93.

Closest sightings to the projector: Many bowheads came well within 500 m of the operating projector. On 10 May 1990, one bowhead approached within 35 m, and there were three sightings at 115-132 m on 19 May 1989 and 9-10 May 1990. On 13 May 1990, one bowhead was seen within 110 m, and several were seen migrating at CPA distances of 160-200 m.

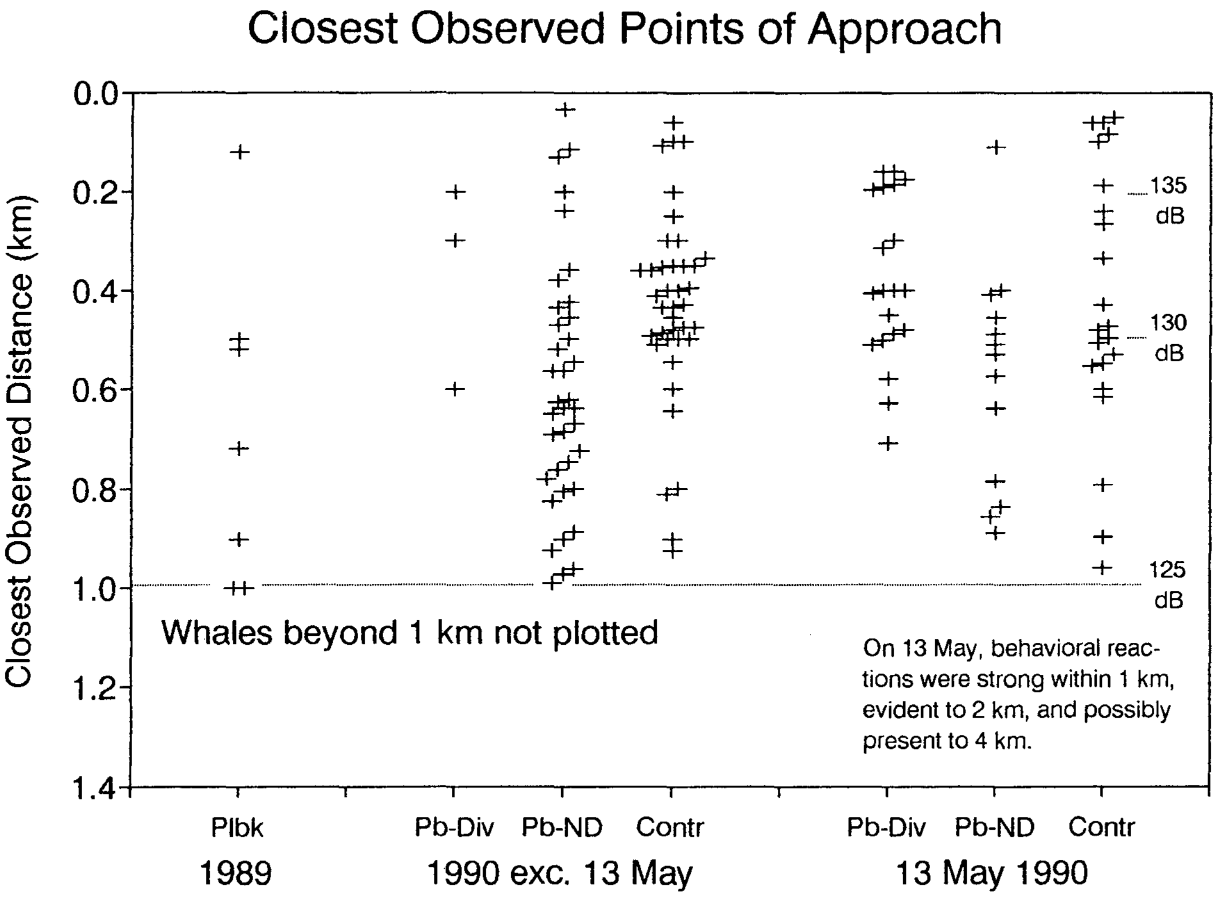


FIGURE 93. Closest observed points of approach of bowheads sighted within 1 km of the ice camps during undistorted playbacks and corresponding control periods, 1989-90. Results are shown for (left) all dates in 1989, (middle) all dates in 1990 excluding 13 May, and (right) 13 May 1990. In 1990, playback cases are separated into two groups: Pb-Diverted, including whales that apparently changed course to maintain a greater distance from the projector, and Pb-NoDiversion. Each "+" symbol represents a different singleton whale or group of whales. The dB values at right apply to 13 May 1990 only, and show the received levels in the 20-1000 Hz band at distances 0.2, 0.5 and 1.0 km; levels at corresponding distances on other dates were lower (Table 45).

Notes: *(1)* The 1990 CPA data are from Tables 20-23, 35 and 36, excluding cases listed in those Tables as being estimated by "Method 4". The 1989 CPA data are from Richardson et al. (1990a, p. 178-190). *(2)* Many whales were below the surface and invisible at CPA. When the closest observed point of approach was near the actual CPA and the heading was steady, the actual CPA distance was estimated. In other cases the value plotted is the closest observed distance, which was usually an overestimate of the actual CPA. *(3)* No symbols are plotted for whales whose CPA distances, estimated as described in note (2), were >1.0 km from the ice camp. *(4)* The Received Level (RL) and Signal-to-Noise ratio (S:N) data shown in Figures 94 and 96 are the values estimated for these "CPA distances", based on the equations and ambient noise values summarized in Table 45.

Diversion distances: Most of the bowheads that exhibited obvious diversion were seen *13 May 1990*. On that date, bowheads that were not exposed to strong *Karluk* sounds traveled ESE along the middle or north side of the narrow WNW-ESE lead. They were counted as diverting if, as they neared CPA, their headings were less than 90° or more than 135°, or if they moved to the south side of the lead. On 13 May, diverting whales were common at distances of 160-500 m from the operating projector, and a few were diverting as much as 700 m away (Fig. 93). *On other dates* in 1990, the three recognized cases of diversion were at distances of 200 m (10 May, projector startup), 300 m (21 May), and 600 m (9 May); for details, see pages 131, 209 and 125.

The closest point to which a typical bowhead approached the projector seemed to differ between 13 May 1990 and other dates. *On 13 May 1990*, the typical CPA distances of bowheads that were visible as they passed the projector were 160-200 m. However, the behavior of these whales was clearly altered, and they maintained about the maximum possible distance from the projector without leaving the lead. Many bowheads dove when they were a few hundred meters west of the projector, and were not seen again until they were >1 km east of the projector. They may have diverted under the ice, remaining >200 m north or south of the projector. Hence, we assume that the typical CPA distance on 13 May was about 200 m.

On other dates with successful playbacks, ice conditions were not as confining as on 13 May 1990. On those other dates, bowhead sightings within ~400 m of the projector were proportionally less common during playbacks than during control periods (Fig. 93; see also p. 220*ff*). Hence, we assume that a typical bowhead maintained a distance of about 400 m from the operating projector on dates other than 13 May 1990. Both on 13 May 1990 and on other dates, some whales approached closer than these "typical" distances while other whales changed course at greater distances from the projector.

Behavioral reaction distances: Behavioral reactions to the projected *Karluk* sounds extended considerably farther than the diversion distances and distances of closest approach summarized above. *On 13 May 1990*, there were strong behavioral reactions of several types at distances out to 1 km. Significant increases in turning frequency extended out to 2 km. There may have been subtle changes in two behavioral attributes (duration of surfacing and number of blows per surfacing) at distances as great as 2-4 km (p. 172).

On other dates, turning frequency was increased at distances up to 1-2 km (p. 236). However, there was little evidence of other behavioral changes at any distance (p. 228). The lack of strong effects on most aspects of behavior was probably attributable to the scarcity of behavioral data on whales within 1 km of the projector on dates other than 13 May 1990.

Summary of distance thresholds: The reaction distances discussed above can be summarized on the basis of five different distance criteria:

	13 May 1990	Other Dates
1. closest CPA distance	110 m	35 m
2. typical CPA distance	200 m	400 m
3. strong behavioral reactions out to	1 km	-
4. frequent turns out to	2 km	2 km
5. possible behavioral reactions out to	4 km	2 km

For 13 May 1990, all five distance criteria have been estimated from the playback experiment with undistorted *Karluk* sounds. For other dates, it was not possible to identify the distance out to which strong behavioral reactions occurred, as noted above. On other dates, the increased frequency of turns at 1-2 km was the most distant behavioral reaction noticed. Hence, for other dates, 2 km is shown as the distance threshold for the fifth criterion as well as the fourth.

Acoustic Thresholds.--Acoustic response thresholds can be reported in terms of either absolute received level (RL) or signal-to-noise ratio (S:N). In this context, the signal is the received level of the simulated industrial sound (*Karluk* playback). The noise is the background ambient noise. Because decibel scales are logarithmic, S:N (in decibels) is obtained by subtracting the ambient noise level from the received level of the projected *Karluk* sound. Both absolute RL and S:N ratio can be reported for any frequency band. We present the acoustic thresholds based on two bands: the broad 20-1000 Hz band, and the 1/3-octave band with the strongest sound (which was centered at or near 200 Hz). Table 45 summarizes relevant data concerning sound levels in relation to distance from the projector during the 1990 playbacks.

Absolute received level*:** Figure 94 shows the estimated sound levels at the CPA locations of the bowheads sighted within 1 km of the projector. These are the same sightings as those whose CPA distances are shown in Figure 93. For playback periods, Figure 94 shows the estimated sound levels to which bowheads were exposed when the whales were at their documented CPA locations. ***For control periods, the sound levels shown are those that would have occurred at the CPA locations earlier or later in the day when the playback was underway; the control whales were not exposed to these sound levels. For each day, there is an inverse relationship between received level and distance from the projector. For 13 May 1990 only, the distances corresponding to various RL values are shown near the right side of the graph.

The highest sound levels received by the observed bowheads were about 138 dB re 1 µPa on a broadband basis (20-1000 Hz band; Fig. 94A), and 133-134 dB in the strongest 1/3-octave band (Fig. 94B). These were the estimated levels of *Karluk* sound received by the bowheads 110 m from the projector on 13 May 1990 and 35 m from the projector on 10 May 1990. These values may be slightly overestimated (by as much as a few decibels)[21], but in any case these closest whales were receiving quite high sound levels. These specific whales showed no evidence of diversion of their migration paths.

Many bowheads approached close enough to the projector to be exposed to broadband levels over 130 dB, mostly on 13 May 1990. However, a substantial proportion of the whales exposed to sounds this strong exhibited evidence of diversion.

Table 46B summarizes the estimated sound levels at the various distance thresholds identified in the previous subsection. At the "typical CPA" distances, the received broadband levels were about 135 dB on 13 May 1990 (distance = 200 m) and 120 dB on other dates (distance = 400 m). Strong behavioral reactions occurred on 13 May when broadband RL

---

[21] These received level estimates for the closest whales are subject to greater uncertainty than are most others quoted in this section. (1) They refer to specific whales rather than averages for many whales. (2) They refer to distances near the projector, where the applicability of the equations listed in Table 45 is uncertain. Actual received levels at the locations of the closest whales may have been as much as a few dB less than the quoted values if spherical spreading applied out to distances greater than those assumed here.

Table 45. Summary of equations for estimating received level vs. range during 1990 playbacks. For each date, there is one equation for the 20-1000 Hz band and another for the dominant 1/3 octave, which was usually centered at or near 200 Hz. Each equation is of the form

$$\text{Received Level (dB re 1 }\mu\text{Pa, R in km)} = A - B*R - C*\log(R)$$

See "Noise Exposure" subsections in "Bowheads/Playbacks/Daily Accounts" (p. 125, 139, 146, 187, 199, 215) and Appendix B for details.

	Levels in 20-1000 Hz Band							Levels in Dominant 1/3 Octave						
Date Water Depth (m)	9 May 137	10 May 66-72	11 May 117-140	13 May 27	16 May 41	21 May 204-219	Average exclud. 13 May	9 May 137	10 May 66-72	11 May 117-140	13 May 27	16 May 41	21 May 204-219	Average exclud. 13 May
Coeff. of Eq'n														
A	107.9	116.4	121.4	129.0	122.1	106.7	-	100.0	111.0	117.2	124.5	116.2	102.5	-
B	0.88	0.81	1.24	4.08	4.13	4.40	-	0.88	0.81	1.37	4.19	4.41	4.40	-
C	15	15	15	10	10	20	-	15	15	15	10	10	20	-
Source Level (1 m)	165	165	166	166	167	166	-	159	160	159	160	161	160	-
Est. RL at Range														
0.2 km	118	127	132	135	128	120	125	110	121	127	131	122	116	119
0.5 km	112	121	125	130	123	111	118	104	115	121	125	117	106	113
1.0 km	107	116	120	125	118	102	113	99	110	116	120	112	98	107
2.0 km	102	110	114	118	111	92	106	94	105	110	113	104	88	100
4.0 km	95	104	107	107	100	77	97	87	99	103	102	93	73	91
Average Ambient	90	94	91	89	97	100	94	76	88	78	81	85	88	83

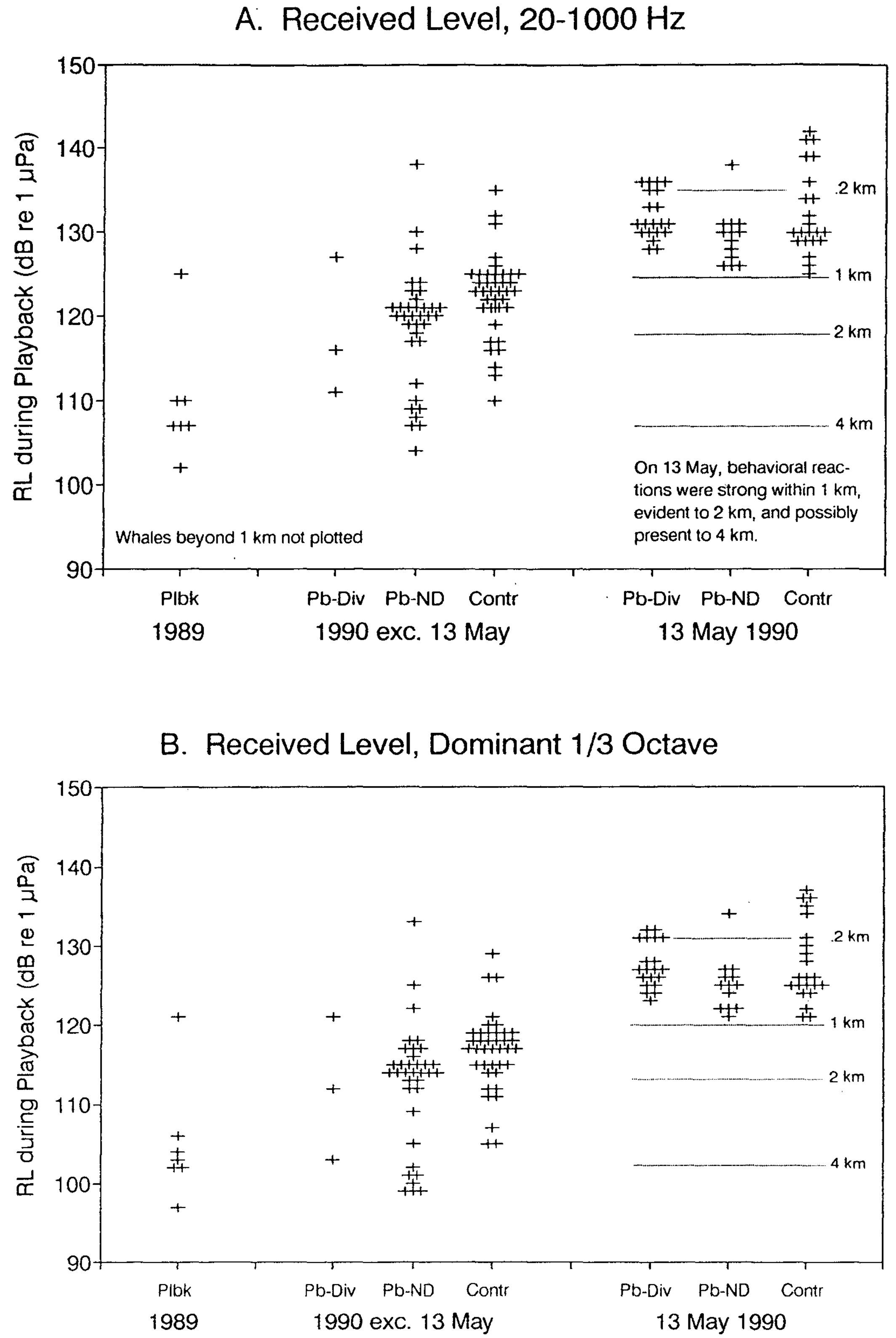


FIGURE 94. Estimated received levels (RLs) of *Karluk* drilling sound at the "CPA distances" of bowheads seen within 1 km of the ice camps during undistorted playbacks and corresponding control periods, 1989-90. RL for each whale sighting during a control period is the RL expected at its CPA distance during the playback period on the corresponding day. Many CPA distances are overestimated, so RL values are underestimated (see "*Notes*" below Fig. 93).

values were above 125 dB. There were frequent turns when broadband RL was above 118 dB on 13 May 1990 and above 106 dB on other dates. There was evidence of some behavioral reaction at broadband levels above 107 dB on 13 May 1990 and 106 dB on other dates.

Reaction thresholds based on sound levels in the dominant 1/3-octave band were 4-6 dB *lower* than those based on the 20-1000 Hz band (Table 46B). This occurred because received levels in the dominant 1/3-octave band (centered near 200 Hz) were several decibels lower, at corresponding distances, than levels in the broader 20-1000 Hz band.

The received levels at the closest CPA distances were virtually identical on 13 May 1990 to those on all other dates combined (Table 46B). Likewise, the received levels at the maximum distances with weak behavioral reactions were about the same for the two sets of data. However, at typical CPA distances, the received level was much higher on 13 May than on other dates: 135 vs. 120 dB in the 20-1000 Hz band; 131 vs. 115 dB in the dominant 1/3 octave. This difference was probably caused, at least in part, by the constraining influence of the ice on 13 May 1990. In order to pass the projector while at the surface, whales had to approach within 200 m of the projector on 13 May. On other dates, when the ice imposed fewer constraints on migration paths, most bowheads apparently chose to remain slightly farther from the projector.

Table 46. Reaction thresholds for bowheads exposed to playbacks of *Karluk* drilling sounds, 1989-90. See text for explanation.

		Closest CPA *	Typical CPA	Strong Behav. Reaction Out to	Frequent Turns Out to	Possible Behav. Reaction Out to
A. Distance						
	13 May	110 m	200 m	1 km	2 km	4 km
	Other	35 m	400 m	-	2 km	-
B. Received Level						
20-1000 Hz	13 May	138 dB*	135 dB	125 dB	118 dB	107 dB
	Other	138 *	120	-	106	106
Dominant 1/3 Oct.	13 May	134 *	131	120	113	102
	Other	133 *	115	-	100	100
C. Signal-to-Noise Ratio						
20-1000 Hz	13 May	49 *	46	36	29	18
	Other	44 *	26	-	12	12
Dominant 1/3 Oct.	13 May	53 *	50	39	32	21
	Other	49 *	32	-	17	17

* These values may be overestimated by as much as a few decibels, as explained in footnote 21 on page 250.

For 13 May 1990, Figure 95 shows the same information in the form of "zone of influence" graphs. Figure 95 is in the same format as the conceptual zone of influence model illustrated in Figure 1 (p. 4). However, the broadband and 1/3-octave zone of influence models in Figure 95 are quantified based on the specific physical acoustic and biological results from

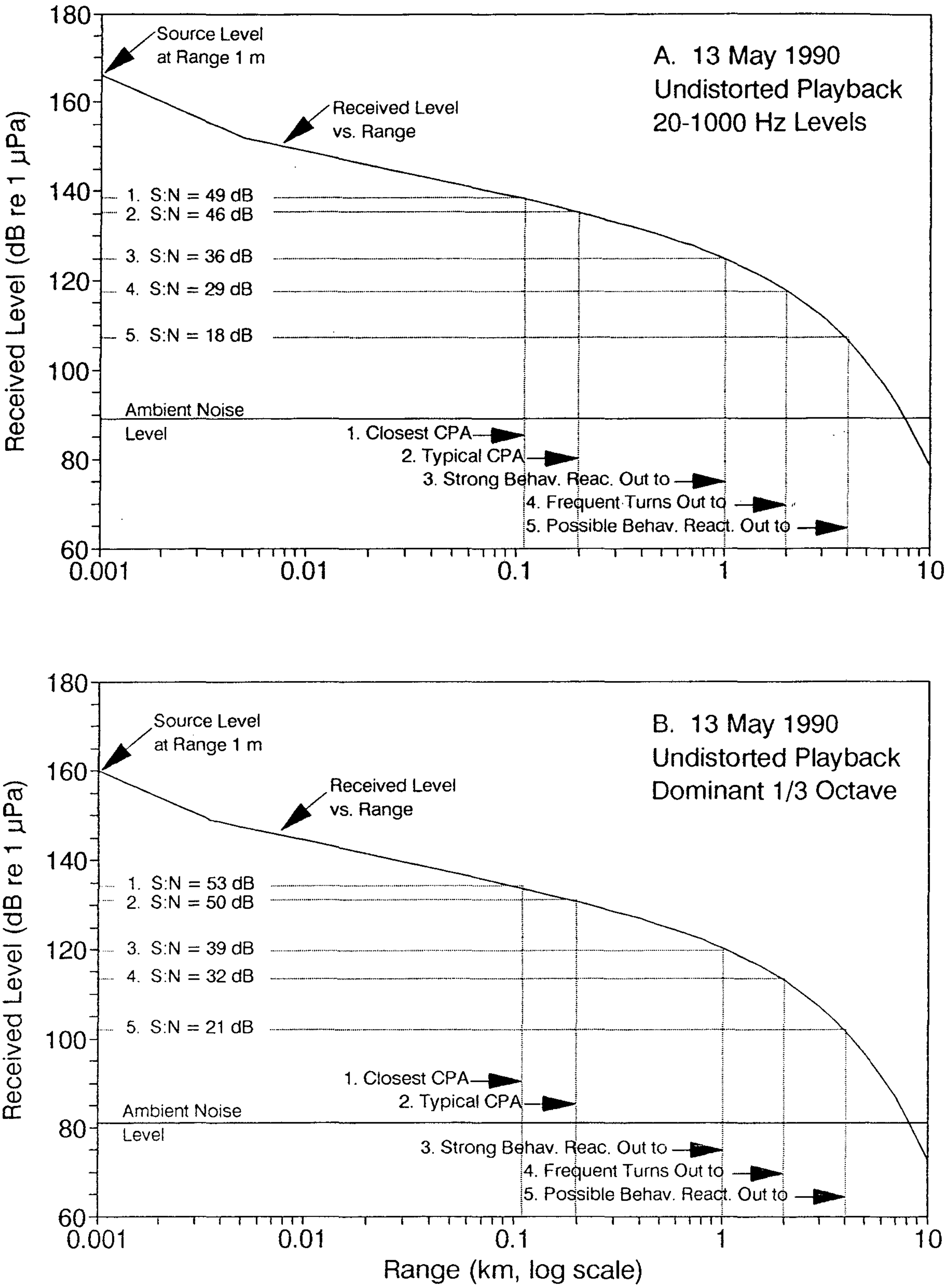


FIGURE 95. Zone of acoustic influence models for the undistorted *Karluk* noise playback on 13 May 1990, based on (A) broadband 20-1000 Hz sound levels, and (B) sounds in the dominant 1/3 octave band, which was centered near 200 Hz. See text for explanation.

the 13 May 1990 playback. The physical acoustic data used here are the source levels of the projected sounds, the equations relating received level to range, and the ambient noise levels (Table 45). The biological data used in the models are the five reaction criteria discussed above. Pages 3-5, in the Introduction, provide further explanation of the layout and components of a zone of influence model like Figure 95.

Signal-to-Noise ratio: The bowhead sightings can also be plotted on the basis of signal-to-noise (S:N) ratios at the apparent CPA distances (Fig. 96). Here the received level of *Karluk* sound is the signal, the ambient noise level is the noise, and the difference is the S:N ratio.

The highest S:N ratios received by the observed bowheads were about 44-49 dB re 1 µPa on a broadband basis (20-1000 Hz band; Fig. 96A), and 49-53 dB in the strongest 1/3-octave band (Fig. 96B). Again, these values may be slightly overestimated (see footnote 21 on p. 250). These particular whales showed no evidence of diversion of their migration paths.

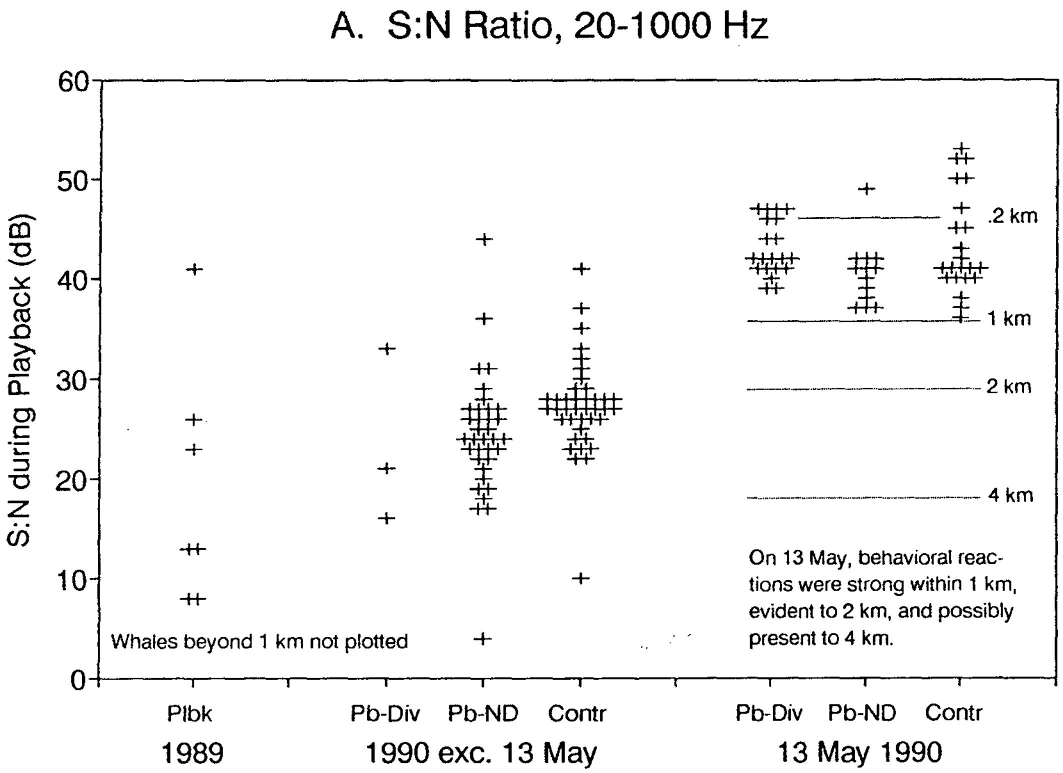
Many bowheads approached close enough to the projector to be exposed to broadband S:N ratios above 40 dB and 1/3-octave S:N ratios above 45 dB, mostly on 13 May 1990 (Fig. 96). However, a substantial proportion of the whales exposed to sounds this strong exhibited evidence of diversion.

Table 46C summarizes the estimated S:N ratios at the various distance thresholds identified previously. For 13 May 1990, Figure 95 shows the same S:N information in the form of "zone of influence" graphs. At the "typical CPA" distances, the broadband S:N ratios were about 46 dB on 13 May 1990 (distance = 200 m) and 26 dB on other dates (distance = 400 m). Strong behavioral reactions occurred on 13 May when broadband S:N ratios were above 36 dB. There were frequent turns with broadband S:N above 29 dB on 13 May 1990 and above 12 dB on other dates. There was evidence of some behavioral reaction at broadband S:N ratios above 18 dB on 13 May 1990 and 12 dB on other dates.

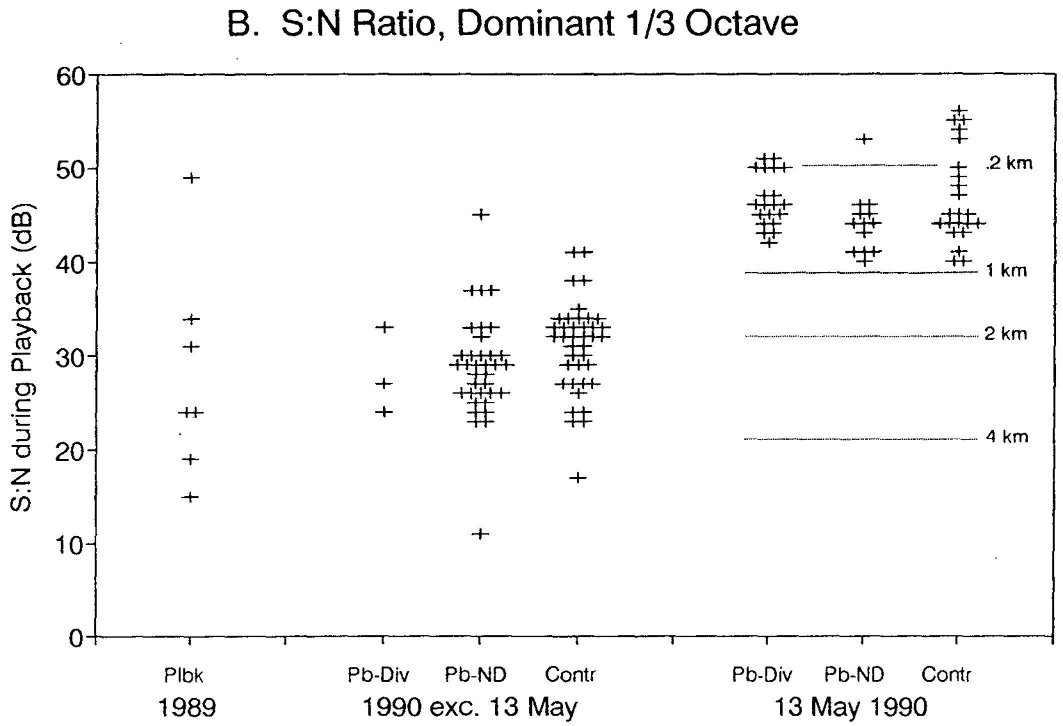
Reaction thresholds based on S:N ratios in the dominant 1/3-octave band were 3-6 dB *higher* than those based on the 20-1000 Hz band (Table 46C). This occurred because S:N ratios in the dominant 1/3-octave band (centered near 200 Hz) were generally several decibels higher, at corresponding distances, than S:N ratios in the broader 20-1000 Hz band.

The S:N ratios at the closest CPA distances were only slightly higher on 13 May 1990 than those on all other dates combined (Table 46C). Likewise, the S:N ratios at the maximum distances with weak behavioral reactions were only a few decibels different. However, at typical CPA distances, the S:N ratios were much higher on 13 May than on other dates: 46 vs. 26 dB in the 20-1000 Hz band; 50 vs. 32 dB in the dominant 1/3 octave. These differences were probably caused, at least in part, by the constraining influence of ice on 13 May 1990.

We emphasize that all of these distance, RL and S:N thresholds are approximations because of sample size limitations, natural variability, and the limitations of the playback methodology. Also, these estimated thresholds refer to one particular type of continuous, low-frequency sound. ***It is uncertain whether the same estimated thresholds would apply to other similar types of sounds. These estimated thresholds probably do not apply to sounds that are variable.*** For bowheads and other baleen whales, reaction thresholds tend to be lower for



A. S:N Ratio, 20-1000 Hz



B. S:N Ratio, Dominant 1/3 Octave

FIGURE 96. Estimated signal-to-noise ratios (S:N) for *Karluk* noise vs. ambient noise at the "CPA distances" of bowheads seen within 1 km of the ice camps during undistorted playbacks and corresponding control periods, 1989-90. S:N for each whale sighting during a control period is the S:N expected at its CPA distance during the playback period on the corresponding day. Many CPA distances are overestimated, so S:N values are underestimated (see "*Notes*" below Fig. 93).

varying sounds, and especially for sounds with increasing levels, than for steady sounds (Miles et al. 1987; Richardson et al. 1991).

Comparisons with Other Studies

Bowhead Whales in Summer and Autumn.--We have estimated previously that a typical bowhead in the open waters of the eastern Beaufort Sea in late summer did not react overtly to a short (30-40 min) playback of steady drilling or dredge sounds unless the 20-1000 Hz received sound level was at least ~115 dB, or ~20 dB above ambient. Corresponding figures for the dominant 1/3-octave band were ~110 dB and S:N ≈ 30 dB (Miles et al. 1987; Richardson et al. 1990b).

The criteria for recognizing reactions in summer, when the whales were not traveling, were necessarily different than those applied to migrating whales in spring. The reactions of the summering whales involved changes in several behavioral variables and, in most cases, displacement away from the initial location. Hence, the summer criteria are most closely comparable to the "typical CPA" and "strong behavioral reaction" criteria used in this spring study. The reaction thresholds in summer appeared to be slightly lower than those for spring-migrating whales that were not constrained by ice, and substantially lower than those for spring-migrating whales in a narrow lead:

	Summer	Spring Typical CPA*	Spring, Strong Behav. Reac.**
RL, 20-1000 Hz	115	120-135	125
RL, dominant 1/3 octave	110	115-131	120
S:N, 20-1000 Hz	20	26-46	36
S:N, dominant 1/3 octave	30	32-50	39

* Higher value refers to whales constrained by ice. ** Whales constrained by ice.

Thus, bowheads migrating in relatively open conditions during spring seemed slightly less responsive than those studied in summer. This difference was small enough (2-6 dB, depending on which of the four criteria is considered) that it may not be replicable or biologically meaningful. However, bowheads migrating through a narrow lead in spring tolerated considerably higher sound levels than did most of the bowheads studied in summer.

These apparent seasonal differences may relate to differences in circumstances and playback procedures rather than to a real difference in responsiveness. The specific sounds projected in the two seasons were different, although in each case whales were exposed to repeated presentations of a short loop-tape containing continuous sounds, predominantly at low frequency. A J-11 projector was used in both studies. In summer, whales that were more or less stationary were exposed to drilling or dredge sounds whose level increased rather rapidly (over 10 min), then remained steady for 10-20 min, and then decreased for 10 min. This pattern of change is not characteristic of an actual drilling or dredging operation. In contrast, during spring, migrating bowheads approached and passed the projector site, and most exposed themselves to slowly increasing and decreasing levels of sound.[22] In spring, unlike summer, the rate of change in the sound level received by most whales was similar to what would be experienced by a whale passing an actual industrial site.

In autumn, bowheads migrating west past an active drillship (*Explorer II*) and its support vessels apparently avoided the area within 10 km of the drillship (LGL and Greeneridge 1987). Some bowheads apparently began to divert around the drillsite when still 20 km or more away. At a radius of 10 km, the underwater sound field was dominated by industrial noise. Noise at that radius averaged 114 dB on a broadband basis and 104 dB in the two 1/3-octave bands with strongest noise (Greene 1987a). Thus, most if not all autumn-migrating bowheads apparently reacted to those noise levels. In contrast, during the playback study in summer, roughly 50% of the bowheads tolerated broadband levels as high as ~115 dB, or 1/3-octave levels as high as ~110 dB. During the present playback study in spring, thresholds seemed to be even higher than those in summer.

The seemingly greater responsiveness in autumn needs to be corroborated by additional study, given the substantial differences between the spring, summer and autumn studies. These differences included varying whale activities, study locations and ice conditions as well as major differences in study techniques.

Although there may be a real seasonal difference in sensitivity, we suspect that bowheads are more sensitive to an actual drillsite (as studied in autumn) than to a drillsite simulated by playback methods (as studied in spring and summer). The playback technique cannot fully duplicate the sounds emitted by an actual drillsite. Playbacks do not reproduce the very low frequency components of the industrial sound. Also, in the playback studies conducted to date, the projected sound has been quite steady in level. In contrast, during the autumn study near an actual drillsite, industrial noise levels were quite variable; bowheads and other whales often react to sudden increases in sound level. Furthermore, the playback method does not attempt to simulate visual cues, odors, or other non-acoustic stimuli from a drillsite. These limitations are discussed further on p. 11*ff* and 88*ff*.

In summary, the apparent sensitivity of bowhead whales to industrial sounds differs among seasons. Bowheads constrained to a narrow migration corridor by heavy ice during spring tolerated the highest sound levels. Bowheads migrating in open water in autumn seemed to react to the lowest levels. However, it is not yet known how much of the seasonal difference is real, and how much is attributable to study-to-study differences in noise characteristics, study procedures, study locations, and whale activities.

Migrating Gray Whales.--It is also useful to compare the spring (and summer) results for bowheads with results for gray whales migrating along the California coast (Malme et al. 1983, 1984). Gray whales were studied when exposed to underwater playbacks of noise from a drillship, semi-submersible, drilling platform, and production platform. The recorded drillship

---

[22] In a few cases, the received level of *Karluk* sound increased rapidly. This occurred when whales were near the projector when it was turned on. This happened on 10 May 1990 (R=225 m; p. 131) and on 16 May 1990 (R≈1.2 km; p. 199). There were three additional cases with a sudden onset of test tones as well as *Karluk* sounds--on 30 April and on 23 and 27 May 1989 (R≈60 m, <1 km and 3.7 km, respectively; Richardson et al. 1990a:174, 188, 192).

sounds were the same as those used during our summer playback tests near bowheads (Richardson et al. 1985b, 1990b). Migrating gray whales showed statistically significant responses to all four sources. The usual reactions included reduced swimming speeds and slight seaward or shoreward deflections of tracks so as to avoid the immediate vicinity of the sound projectors.

The received broadband noise levels at which gray whales reacted were reasonably consistent among the four sources of continuous noise (Table 47). They were also generally consistent with the received broadband levels of drilling platform sound at the typical CPA distances of spring-migrating bowhead whales that were not constrained by ice.

Table 47. Received broadband sound levels (dB re 1 µPa) at which various percentages of migrating gray whales reacted to simulated sources of industrial noise (from Malme et al. 1984, p. 9-6).

	Levels for Various Percent Avoidance		
	10%	50%	90%
Drillship (*Explorer II*)	110 dB	117 dB	122 dB
Semisubmersible (*Ocean Victory*)	115	120	>128
Drilling Platform (*Holly*)	114	117	>128
Prod'n Platform (*Spark*)	120	123	>129

Reaction Threshold vs. Hearing Threshold

Previous work has shown that baleen whales respond to steady man-made noises only when the received level is well above the background noise level in the corresponding band (Richardson et al. 1991). The same effect was evident in this study. The projected *Karluk* sounds were measurable and above the natural ambient noise level at distances as great as 5-10 km from the projector. However, bowheads did not show overt reactions to the sounds until they were much closer to the projector than 5-10 km. Hence, it is important to evaluate the maximum distance at which the sounds might have been detectable to bowheads, as compared with the maximum distance where it was measurable by instruments.

The intensity of sound that is barely audible in the absence of significant ambient noise is the absolute hearing threshold, which varies with frequency. From anatomical evidence, Fleischer (1976) suggested that baleen whales are adapted to hear low frequencies. Norris and Leatherwood (1981) examined the hearing apparatus of bowheads and concluded that they likely hear sounds ranging from "high infrasonic [or] low sonic to high sonic or low ultrasonic frequencies". Watkins (1986) reports that other baleen whales often react to sounds with frequencies from 15 Hz to 28 kHz, but not to pingers and sonars at 36 kHz and above. Many authors have suggested that marine mammals probably hear best in the frequency range of their calls. Although some bowhead calls include components up to 4-5 kHz, most are at 50-400 Hz

(Ljungblad et al. 1982; Clark and Johnson 1984; Cummings and Holliday 1987). Thus, bowheads probably are well adapted to receive frequencies below 1 kHz plus those in the low kilohertz range.

The effective filter (i.e. critical) bandwidth of the bowhead auditory system is unknown. However, for mammals in general, it is typically 1/3-octave or less within the range of best hearing (Fay 1988; Richardson et al. 1991). Thus, the bowhead's effective filter bandwidth for low frequency sounds is probably 1/3-octave or less. Given this assumption, signal to noise ratios in 1/3-octave bands are probably useful as rough measures of the prominence of a sound to a bowhead. As a first approximation, a sound signal like drilling noise is expected to be detectable by a bowhead if its received level exceeds that of the background noise within at least one 1/3-octave band, i.e. if S:N > 0 dB in at least one such band.

It is apparent that some bowheads continued migrating past the operating sound projector when the received level of drilling noise was far above the natural background noise level not only in the strongest 1/3-octave band, but also on a broadband basis (Fig. 95, 96; Table 46). This result for spring-migrating bowheads is consistent with previous observations of reactions of summering bowheads to drilling and dredging sounds. Thus, bowheads migrating east of Pt. Barrow in spring, like bowheads and other baleen whales studied in other circumstances, often tolerate exposure to man-made sounds that they presumably can hear. However, if the level of man-made sound is high enough, avoidance reactions and other behavioral changes occur. The maximum reaction distance is considerably less than the assumed maximum detection distance.

Levels Received by Whales near the Surface

All noise data quoted above were measured 9-18 m deep in the water column. Close to the surface of open water, the pressure release or "Lloyd mirror" effect can result in somewhat lower received levels (Urick 1983). This phenomenon becomes evident within ¼ wavelength of an open-water surface. At 200 Hz and 80 Hz, two of the dominant frequencies in the drilling platform sound, the wavelengths are 7 and 18 m, respectively. Thus, whales more than about 2 and 5 m below the surface would be exposed to the full level of 200 Hz and 80 Hz sounds, respectively. The water near Barrow is usually very clear in spring. When the aerial observers look down into the water at a steep angle, they can see whales several meters below the surface. In that situation, any bowhead that is deep enough to be invisible to aerial observers is deep enough for the pressure release effect to be negligible for sounds at ≥200 Hz, and probably for those at 80 Hz as well. However, this effect will cause reduced received levels in the cases of whales that are visible at the surface.

The reduced levels near the surface may be important in interpreting reactions to sounds that start while the whales are at the surface. On 30 April 1989, for example, a whale exposed to the onset of tonal sounds when it was within 100 m of the projector probably did not receive intense low-frequency sounds until it dove out of sight. Likewise, the reduced levels near the surface are important in interpreting cases where a whale is at the surface continuously while near its point of closest approach to the sound source.

The Infrasound Problem and Related Study Limitations

The main limitations of this study are enumerated and discussed in the Introduction to this report (p. 10-13).

The 1989 phase of the study suffered from several major limitations resulting from the difficult weather and ice conditions in that spring season. The sample size for whales studied during playback experiments in 1989 was low. Because of the prevailing heavy ice conditions in 1989, most whales could not be followed for long distances as they approached the projector. There were no unequivocal cases of bowheads reacting to the projected sounds in 1989, so reaction thresholds could not be estimated. During the 1990 work, all three of those 1989 problems were largely overcome.

One potentially serious limitation in both 1989 and 1990 was the inability of the J-11 projector, or any other projector usable in the circumstances of this study, to reproduce the lowest frequency components of the *Karluk* sounds. The J-11 is rated as being effective from 20 Hz to 12,000 Hz. In practice, however, its output began to diminish below ~80 Hz and was strongly reduced below ~63 Hz (see "Fidelity of Playbacks", p. 88*ff*).

Even if the projector could emit strong low-frequency sounds, it would not fully mimic the acoustic characteristics of a bottom-founded drilling platform. Much of the low frequency energy emanating from a drilling platform sitting on the bottom probably enters the bottom by direct conduction. Some of this energy will travel through the bottom and may re-enter the water some distance away. In contrast, low frequency sounds emitted by a suspended projector would have to travel through the water and then through the water-bottom interface before reaching this conduction path. Thus, low frequency sounds from a suspended projector might not propagate as well as those from a bottom-founded platform.

Several unknowns prevent an assessment of the importance of the very low frequency components of the sound from *Karluk* itself:

1. It is unproven whether bowheads can sense sounds below 50 Hz, although this is likely.
2. The acoustic output of the *Karluk* drilling operation below 10 Hz is unknown.
3. The attenuation rate of infrasonic components from a bottom-founded platform in shallow waters of the western Beaufort Sea is unknown. The attenuation rate is probably high, but there is a possibility that this might not be the case.
4. Few data on the ambient noise levels at infrasonic frequencies have been reported for the study area.

The following subsections discuss these points in more detail.

Low-frequency Hearing

There are no specific data on the lower limit of hearing sensitivity of any baleen whale. Given the anatomical evidence mentioned on p. 259, plus the fact that many bowhead calls include energy at frequencies as low as 50 Hz, bowheads probably have good sensitivity at frequencies as low as 50 Hz.

One indirect way to help determine whether bowheads may be sensitive to very low frequencies is to determine whether any of their calls contain energy at frequencies below 50 Hz. Previous studies of bowhead calls generally have not examined very low frequencies. We have begun such an analysis, examining frequencies down to 5 Hz (p. 91*ff*). Thus far, the data show that bowhead calls rarely if ever contain energy below ~30 Hz; few contain energy below 50 Hz. However, one of the 45 calls examined in this study may have contained weak components at 15-32 Hz as well as much stronger components at higher frequencies. A similar analysis by C.W. Clark has, thus far, found no evidence of components below ~30 Hz (C.W. Clark, pers. comm., 7 March 1991). Thus, calls of the "usual" types are rarely if ever accompanied by components at 5-30 Hz. However, to date there has been no attempt to determine whether bowheads emit purely infrasonic (<20 Hz) calls that would not be directly detectable to the human ear.

In other mammals, the low frequency portion of the audiogram slopes upward gradually as frequency decreases. Inspection of the mammalian audiograms in Fay (1988) indicates that, at low frequencies, sensitivity typically deteriorates by 20-40 dB with a 10-fold reduction in frequency. If this applies to bowheads, and if their sensitivity is good at frequencies as low as 50 Hz, then they may be able hear strong sounds at 5 Hz or below.

The hearing abilities of bowheads at low frequencies will be difficult to resolve without an underwater projector able to reproduce very low frequency sounds. However, it would be helpful to conduct further work to determine more conclusively whether bowhead calls include any infrasonic components. If they do, bowheads probably can hear those frequencies.

Infrasounds from Oil Industry Platforms

Infrasounds from oil industry platforms are amenable to study, but data on the levels and attenuation of *Karluk* sound components below 10 Hz are lacking. *Karluk* was a temporary ice platform. It no longer exists, so its sound characteristics cannot be studied further. However, some other types of offshore oil platforms are known to emit strong infrasound (Gales 1982; Hall and Francine 1991). *Karluk* probably did so as well.

Low-frequency long-wavelength sounds usually attenuate rapidly in shallow water. However, with certain bottom conditions, infrasound can propagate through the bottom and re-enter shallow water some distance away (Richardson and Malme in press). This sound might be detectable to whales.

We had hoped to measure the sounds (including infrasounds) at various distances from the SSDC caisson while it drilled in the Beaufort Sea during the winter of 1990-91. This would have provided data on infrasonic output from that drilling caisson and data on the attenuation rate of those infrasounds. The SSDC's drilling program stopped too early in the winter of 1990-91 to allow such measurements. We will again try to obtain these data during in the winter of 1991-92.

Infrasonic Ambient Noise

The infrasonic ambient noise levels in the study area appear to be high, at least in the 10-20 Hz range (Fig. 7-12 and p. 62). This means that infrasonic components of industrial noise may diminish below the ambient level, at the corresponding frequency, relatively close to the industrial source. Data on ambient noise at frequencies below 10 Hz would be useful in interpreting the potential detection radius of infrasonic components of industrial noise. However, it is very difficult to avoid measurement artifacts when determining ambient noise at such low frequencies. Wave- and current-induced motion of the sensor and its supporting cable are difficult to avoid. These motions cause low-frequency acoustic signals that are difficult to separate from real ambient noise.

Interpretation of Playback Results

We cannot be sure that bowheads reacted in the same way to the playbacks of *Karluk* sound as they would have to the actual *Karluk* sounds. The actual *Karluk* sounds included low-frequency components that were unduly weak or totally lacking in the projected sound (p. 88*ff*). If bowheads are sensitive to those low frequency components, the playback results may underestimate the potential radius of influence of the actual *Karluk* sounds.

However, at distances beyond 100-200 m from the projector, the overall level of *Karluk* sound in the 20-1000 Hz band was at least as high as that at corresponding distances from *Karluk* itself (Fig. 30, p. 90). At these distances, received levels above 80 Hz were high enough to compensate, at least in part, for the inability of the projector to fully reproduce the components below 80 Hz. The projector adequately reproduced the overall 20-1000 Hz level at distances beyond 100-200 m, even though components below 80 Hz were underrepresented. If bowheads are no more responsive to sound components at 20-80 Hz than to those above 80 Hz, then the playbacks provided a reasonable test of bowhead responsiveness to components of *Karluk* sound above 20 Hz.

Hence, the main potential limitation of the playback tests was probably the lack of *Karluk* sound components below 20 Hz, not the underrepresentation of components at 20-80 Hz. *Karluk* did emit strong sounds at 10-20 Hz (Fig. 31A), and probably did so at frequencies below 10 Hz. If bowheads can hear frequencies below 20 Hz, as suspected, then they might react farther from *Karluk* itself than is predicted based on the results of the playback tests.

One piece of evidence suggests that the inability of a practical projector to reproduce the low-frequency components of industrial sounds does not seriously affect the results of the experiments. In summer, bowhead whales seemed to be at least as sensitive to playbacks of drilling and dredge noise as to actual drillships and dredges (Richardson et al. 1990b). Those playback experiments were done with the same types of playback equipment as used in the present study. These results suggest that playbacks are a useful method for evaluating the probable reactions of baleen whales to noise from stationary industrial sources.

The playback technique provides the only way to address this issue in the absence of actual industrial operations in the area and season of interest. However, playback experiments cannot reproduce all attributes (acoustic and otherwise) of an actual industrial operation. Hence, it is possible that whales would react to the actual operation at somewhat longer distances than predicted based on playback results. This may account, at least in part, for the seemingly greater sensitivity of bowheads to an actual drilling operation in autumn than to playbacks of drilling noise in spring or summer (p. 257).

Bowhead Reactions to Aircraft

A secondary objective of this study is to determine the short-term behavioral reactions of whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to actual helicopter overflights (specific objective 5, p. 6). In addition, reactions of bowheads to the fixed-wing observation aircraft are of interest: (1) data on those reactions could help clarify the responsiveness of bowheads to aircraft in general, and (2) reactions to that aircraft could confound the behavioral data if reactions occurred during routine behavioral observations.

Tests of bowhead reactions to aircraft were a lower priority than sound playback experiments. Hence, little effort could be devoted to this question in either 1989 or 1990. Some limited opportunistic observations concerning responses to the project's Twin Otter and Bell 212 helicopter were obtained in both years. We conducted no systematic experiments on reactions to the Twin Otter, but there was one planned overflight of bowheads by the Bell 212 in 1990. Sounds of these two aircraft types were measured in 1989 (Richardson et al. 1990a:81*ff*).

Reactions to Twin Otter

During the spring of 1990, weather conditions were better than in spring 1989, and the Twin Otter observation aircraft was able to circle at the relatively high altitude of 460 m (1500 ft) during all behavioral observation sessions. No apparent bowhead reactions to the Twin Otter aircraft were noticed in 1990. The lack of 1990 data for periods of circling at lower altitudes prevented any analysis of behavior when the aircraft was at high vs. lower altitude.

On two occasions in 1989, observers in the Twin Otter survey aircraft noticed behaviors that they attributed to aircraft disturbance. *(1)* On 26 May 1989, a mother and calf exhibited unusually brief surfacings when the Twin Otter circled to pass over them at an altitude of 145 m during a photography session. *(2)* On 14 May 1989, a bowhead dove hastily as the aircraft flew almost directly overhead, but slightly behind the whale, at 460 m altitude. (Note: we rarely fly directly over whales that are under observation during behavioral observation sessions; those "focal" whales are at the center of the circular path of the aircraft.) No other observations of apparent reactions to the aircraft were noticed while it was flying at ≥460 m ASL in 1989.

On a few occasions in 1989 when low cloud ceilings prevented behavioral observations from ≥460 m altitude, we observed at least briefly from lower altitudes. During these periods, the aircraft flew in circles with the usual radius of about 1 km, centered on the whale(s). Almost all bowheads observed while the aircraft circled at <460 m altitude were classified as traveling. No obvious behavioral reactions were noticed. Too few quantitative data on surfacing, respiration and diving behavior were obtained during this low-altitude circling to merit interpretation. Likewise, there were few observations concerning the occurrence of discrete behaviors like turns, pre-dive flexes, fluke-out dives, and aerial activities while the aircraft circled at low altitude. However, cross-tabulations of these variables vs. whale status (calf, mother, other) revealed no evidence that, in 1989, any of these discrete behaviors was noticeably different during circling at <460 m than at ≥460 m altitude.

During previous studies in late summer and autumn, we have found that reactions of bowheads to a circling observation aircraft are common when it is at ≤305 m altitude, rare when it is at 460 m, and virtually absent when it is above 460 m (e.g. Richardson et al. 1985a,b). Few data have been reported concerning reactions of bowheads to aircraft in spring (reviewed by Richardson et al. 1991). We need additional spring data before drawing firm conclusions about relative sensitivity to fixed-wing aircraft in spring vs. late summer. However, preliminary indications from 1989 and 1990 are that bowheads seem no more sensitive to a fixed-wing observation aircraft during spring migration through leads and pack ice conditions than they are in late summer in largely open waters.

Reactions to Bell 212 Helicopter

Whenever bowheads were accessible during May 1990, helicopter-supported work was devoted to noise playback experiments. Hence, little effort could be devoted to tests of reactions to the helicopter. However, such observations were obtained as opportunities allowed.

Controlled Overflight, 11 May 1990.--On 11 May 1990 at 18:56, the project's Bell 212 helicopter was directed to fly at altitude 150 m ASL directly over a group of two bowheads. Observers in the Twin Otter aircraft circling at 460 m ASL observed the behavior of these whales before, during and after the helicopter overflight.

These two whales had been under observation for 1.0 h as they migrated NE at medium speed in the main nearshore lead (water depth ~22 m). Their surfacing durations had averaged 1.02 ± s.d. 1.21 min (n=15) with 3.6 ± 3.33 (n=15) blows per surfacing. Median blow intervals had averaged 19.5 ± 8.0 s (n=8). Dive durations had averaged 3.93 ± 3.22 min (range 1.00-9.67; n=13). There had been almost no socializing. During most dives, these whales had remained close enough to the surface to be visible from above.

The two whales were at the surface as the helicopter approached at 150 m ASL. They began mild social interactions ~20 s before the helicopter passed overhead, and whale #1 dove 15 s before the overflight. It dove deep enough to be out of sight, contrary to its earlier pattern, and remained down for 5.3 min. This dive duration was well within the range exhibited prior to the overflight. Whale #2 stayed near the surface during the overflight and until 1.0 min thereafter (total duration 1.78 min; 3 blows). It then dove for 1.8 min, remaining in sight just below the surface. Whale #2 resurfaced first, 2.8 min after the overflight; #1 surfaced 2.2 min later. Both whales were still traveling NE at medium speed. They resumed mild social interactions at the surface before diving again, oriented NE.

The overflight had no clear effect on the northeastward migration of these whales. Mild social interaction, consisting of brief orientation toward one another and brief body contact, began as the helicopter approached and continued during the surfacing after it departed. Whether this interaction was related to the helicopter overflight is unknown.

Incidental Observations, 1990.--The behavior of bowhead whales exposed to close approaches by the helicopter was observed briefly on eight additional occasions in 1990:

- On 1 May, a bowhead immediately dove when the helicopter flew at 150 m ASL directly over the whale as it surfaced in a short, narrow crack.

- On 10 May at 21:05, a bowhead traveling NE toward the ice camp at medium speed dove as the helicopter approached to within 500 m of the whale. This whale had respired 4 or 5 times before it dove, and it is uncertain whether the dive occurred earlier than would have occurred in the absence of the helicopter.
- Another bowhead sighted on 10 May, at 21:14, continued traveling at the surface and respiring with no indication of disturbance as the helicopter approached and flew directly overhead at 30 m ASL. The bowhead continued to respire and maintain its E heading up the lead after the helicopter had landed at the ice camp, ~275 m N of the whale.
- On 11 May three bowheads were engaged in surface activity, including tailslaps, as the helicopter flew at 150 m ASL approximately 500 m W of the whales at 10:07 before landing at the ice camp at 10:09.
- On 13 May a bowhead at the surface swam ESE along a lead while the helicopter, with rotors turning, idled on the ice along the lead edge about 500 m SE of the whale (i.e. whale heading almost toward helicopter).
- Also on 13 May, a group of two bowheads continued its ESE course and respirations as the helicopter lifted off the ice and flew, at altitude ~60 m, within 200 m of the whales (time 11:56). The helicopter had been operating in the area for 13 minutes while deploying a sonobuoy.
- On 16 May three groups of bowheads continued engaging in apparent social activity, including rolling at the surface and pectoral fin extensions, while moving slowly E or NNE along the lead while the helicopter operated within 1 km between 13:35 and 13:41.
- On 24 May four bowheads surfaced twice with no overt signs of disturbance while the helicopter operated within 200 m at 100 m ASL.

Summary.--The observations on bowhead reactions to a Bell 212 helicopter in 1990 are limited; the sample size was small and most observations were unsystematic. However, most of the bowheads did not appear to respond overtly to the presence of the helicopter. Most whales maintained their headings and continued respiring at the surface as the helicopter operated nearby. On only two occasions did a bowhead dive when the helicopter was overhead. On one of these occasions (10 May, 21:05) it was unclear whether the dive was a disturbance response. On the other occasion (1 May) the dive was probably in response to the helicopter.

In 1989, we observed a mother/calf pair exposed to four low-altitude passes by a Bell 212 (Richardson et al. 1990a:211). The mother was at the surface during two passes, and dove on each occasion. The calf was at the surface during all four passes, and dove only once. In each case, the low flying helicopter flew within 200 m of the whales, and once was <50 m from the mother. These bowheads showed no obvious signs of disturbance other than the dives, which may or may not have been attributable to the overflights. The mother and calf remained near the path of the helicopter for ~25 min after the mother was overflown at close range.

Evaluation of Helicopter Overflight Hypotheses.--Overall, the limited 1989-90 observations suggest that spring-migrating bowheads sometimes dive in response to a close approach by a turbine-powered helicopter. However, other bowheads show no obvious reaction to single passes--even at altitudes of 150 m or below. There is no evidence that single helicopter overflights at altitudes of 150 m (or below) disrupt spring migration of bowheads in any biologically significant way.

Two of the hypotheses to be evaluated during this study concerned the effects of helicopter overflights on whales (p. 7). Those hypotheses were as follows:

- Helicopter overflights will not (or alternatively will) significantly alter measures of migration routes and spatial distribution of whales in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.
- Helicopter overflights will not (or alternatively will) significantly alter subtle aspects of individual whale behavior in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.

Because the evidence available to date is mostly opportunistic, and additional relevant data will be collected during subsequent years of this study, it is premature to draw conclusions about these hypotheses. However, the evidence available to date indicates that the first null hypothesis--concerning migration routes and distribution--is likely to be accepted, with some qualifications in wording. If future data are consistent with those from 1989-90, we would conclude that ***single*** overflights by a ***Bell 212*** helicopter ***at altitudes 150 m or below*** do not have ***biologically*** significant effects on the migration routes and distribution of migrating bowheads ***visible*** in ***areas of pack ice or on the seaward side*** of the main nearshore lead near Pt. Barrow. There have been no studies of the effects of other types of helicopters on the migration route and distribution in spring. However, it is worth noting that the Bell 212 used in this project is one of the noisier types of helicopters used by the offshore oil industry.

The second hypothesis, concerning helicopter effects on subtle aspects of individual behavior, will be evaluated when additional data from subsequent years of this project are available. Most aspects of behavior are difficult or impossible to study during brief, opportunistic observations of the types that have contributed most available data concerning spring-migrating bowheads and helicopters.

WHITE WHALE RESULTS

Distribution and Movements of White Whales

Specific objective 6 required us to document, as opportunities allowed, the movements, behavior and basic biology of white whales along their spring migration route.

In May 1989, we saw more white whales than bowheads. Although there was broad overlap in their distributions, the main migration route of white whales extended farther offshore into the pack ice than did the main route of bowheads. (Details are given in Richardson et al. 1990a:217-222). During the latter part of May 1989, when a broad nearshore lead developed along the edge of the landfast ice, the two species migrated both along the lead and amidst the pack just north of the lead. White whales seen in May 1989 were most often traveling or resting; there was seldom any indication of feeding and never any active socializing.

In 1989, most white whales were either migrating in a generally NE direction or resting on the surface. Migrating white whales tended to follow leads or cracks, changing heading as necessary to remain within the crack. Several groups of white whales were seen resting quiescent beneath the thin ice covering recently-refrozen cracks amidst heavy pack ice. In one case, a group of ~25 white whales vigorously swam back and forth between two holes ~15 m apart, apparently trying to keep the holes from freezing over.

In late April and May of 1990, white whales were seen much less regularly than in 1989. When seen, they were migrating steadily northeast and east through the pack ice or along the north side of the main nearshore lead. In 1990, unlike 1989, we did not see white whales whose migration was blocked by heavy ice conditions. The only day in 1990 when white whales passed the ice camp while a playback experiment was in progress was 21 May 1990. On that occasion, the white whales were moving northeast and east through pack ice a few kilometers north of the pack ice edge bordering the north side of the main nearshore lead.

White Whale Reactions to Playbacks of Drilling Platform Sound

Specific objective 3 required us to study, when possible, the short-term behavioral responses of white whales visible in open water areas along their spring migration corridor to underwater playbacks of continuous drilling platform sound (see p. 6). Work on white whales was secondary to that on bowheads. A significant number of data were collected in 1989, when white whales were seen commonly, but few data were collected in 1990 when they were seen near the projector site on only one day.

White Whales, 21 May 1990

On 21 May 1990, the ice camp was set up on the SE side of a small closed-in lead approximately 400 m wide and 1 km long (Fig. 97). A total of 14 white whale groups consisting of an estimated 65 individuals were observed on this day. Most of these groups (12 of 14) maintained a general NE heading through the lead.

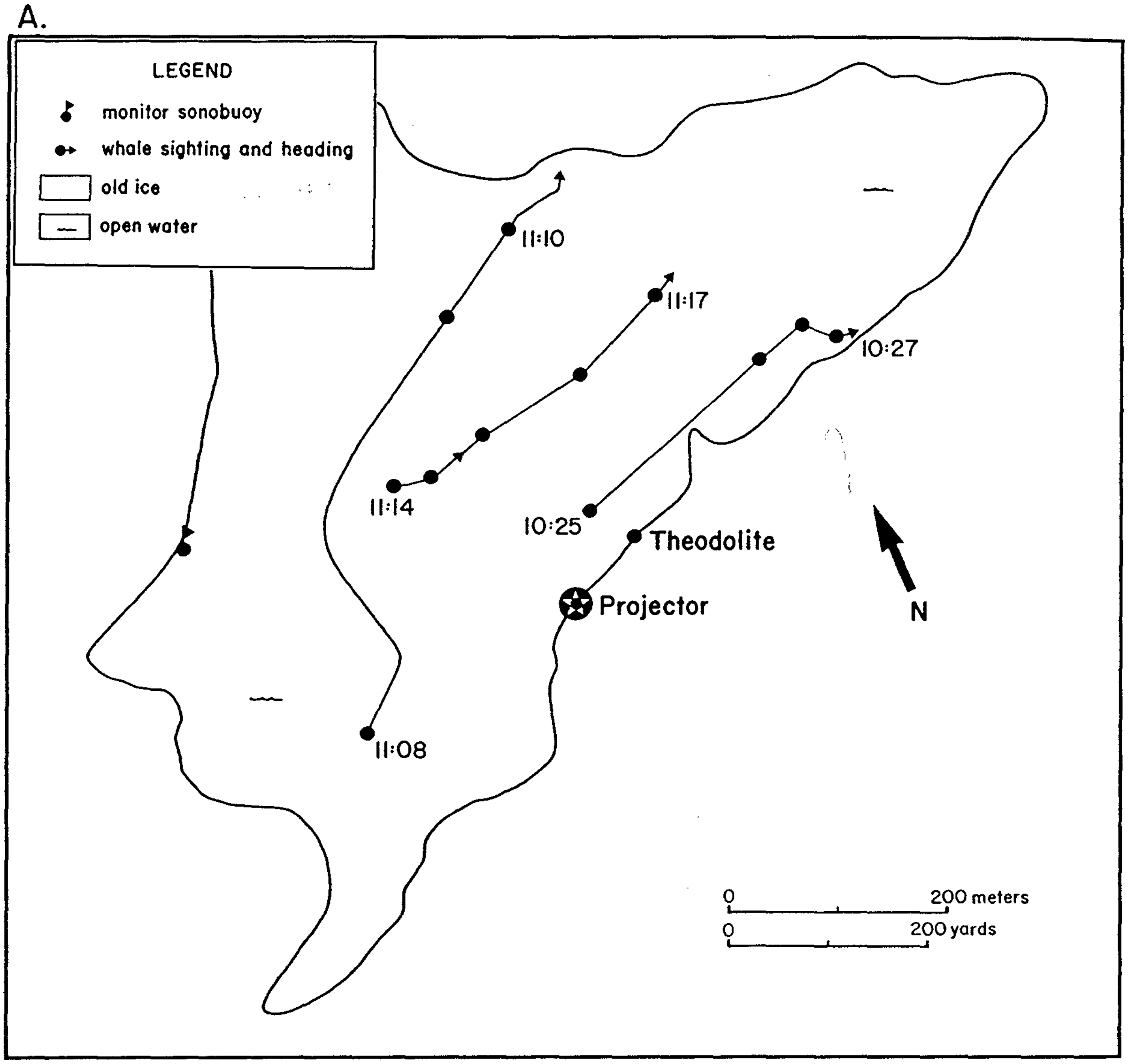


FIGURE 97. Ice-based and aerial observations of white whale tracks through a lead amidst the pack ice NE of Barrow, Alaska, 21 May 1990. (A) Pre-playback. (B) Drilling platform sounds projected. (C) Post-playback.

During the ***pre-playback control period*** between 10:10 and 11:49:44, three groups of white whales (#1,2,3) consisting of 8, 8 and 13 whales, respectively, were tracked by theodolite as they traversed NE across the lead. Each group was sighted initially in the E half of the lead--the side closest to the silent projector (Fig. 97A). Group #1, including two calves, traveled ENE along the ice edge, passing approximately 25-30 m in front of the ice camp. Group #2 moved NNE across the middle of the lead at medium-fast speed, initially 220 m SW and finally 345 m N of the silent projector site. The Twin Otter crew also observed these whales. Group #3 traveled ENE through the middle of the lead.

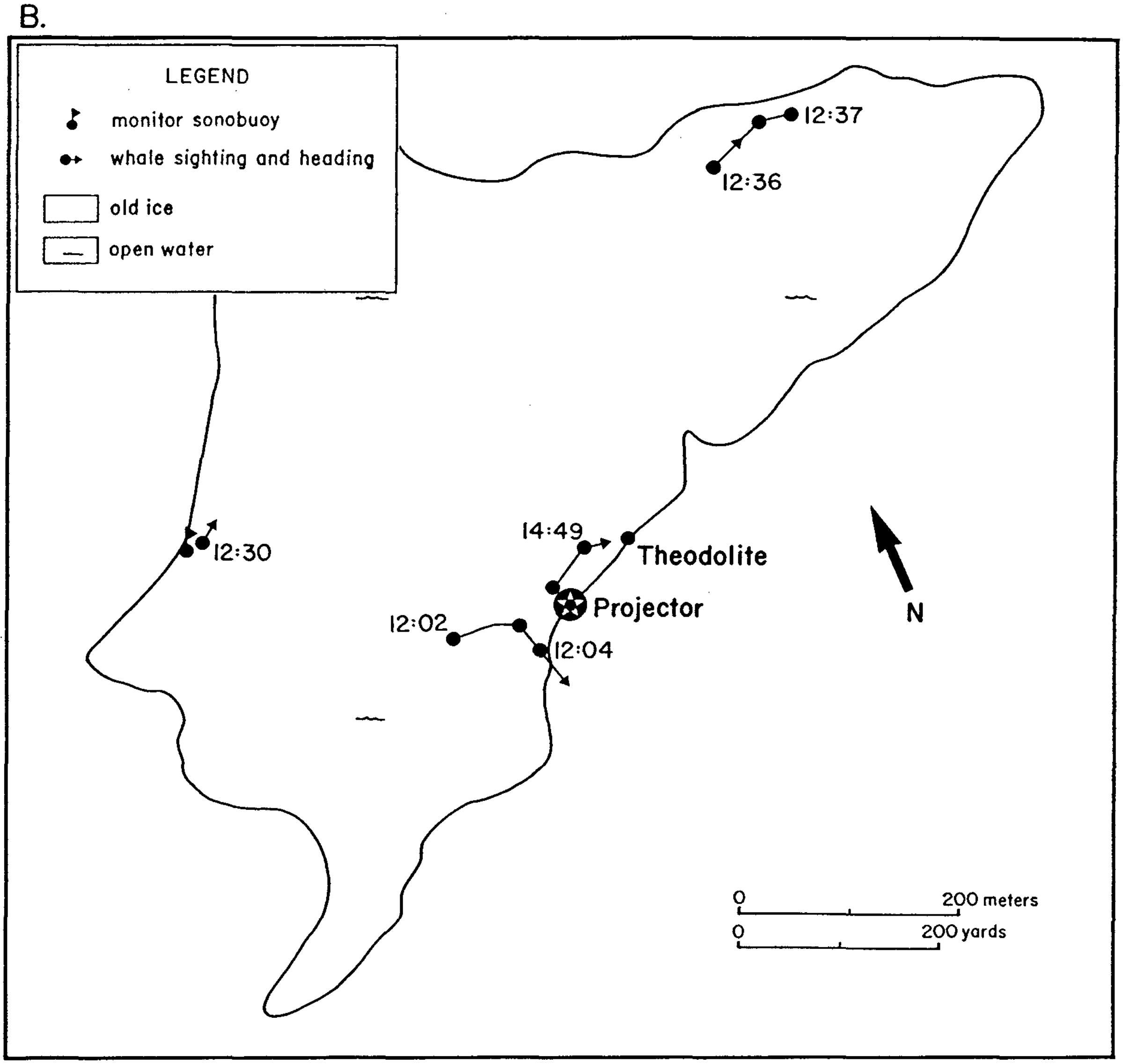


FIGURE 97. Continued (Part B--Drilling platform sounds projected).

During the ***playback period***, a total of 16 white whales in five groups were observed between 11:49:45 and 15:57:22. The only white whales that deviated from course, possibly in response to the projected drilling sound, were two adults (group #4) sighted at 12:02. The whales initially moved slowly E toward the projector, and then turned right approximately 110° toward the ice edge; they headed slowly S when approximately 40 m WNW of the operating projector (Fig. 97B). The whales then increased speed to medium speed and dove S under the ice edge ~40 m SW of the projector. The overall closest observed approach to the projector was made by a group of four white whales (group #7) at 14:49. The whales were initially sighted approximately 15 m in front of the projector while traveling ENE and following the ice edge; they dove under the edge 64 m ENE of the projector. The remaining groups (#5,6) traveled NE closely following the NW (far) edge of the lead.

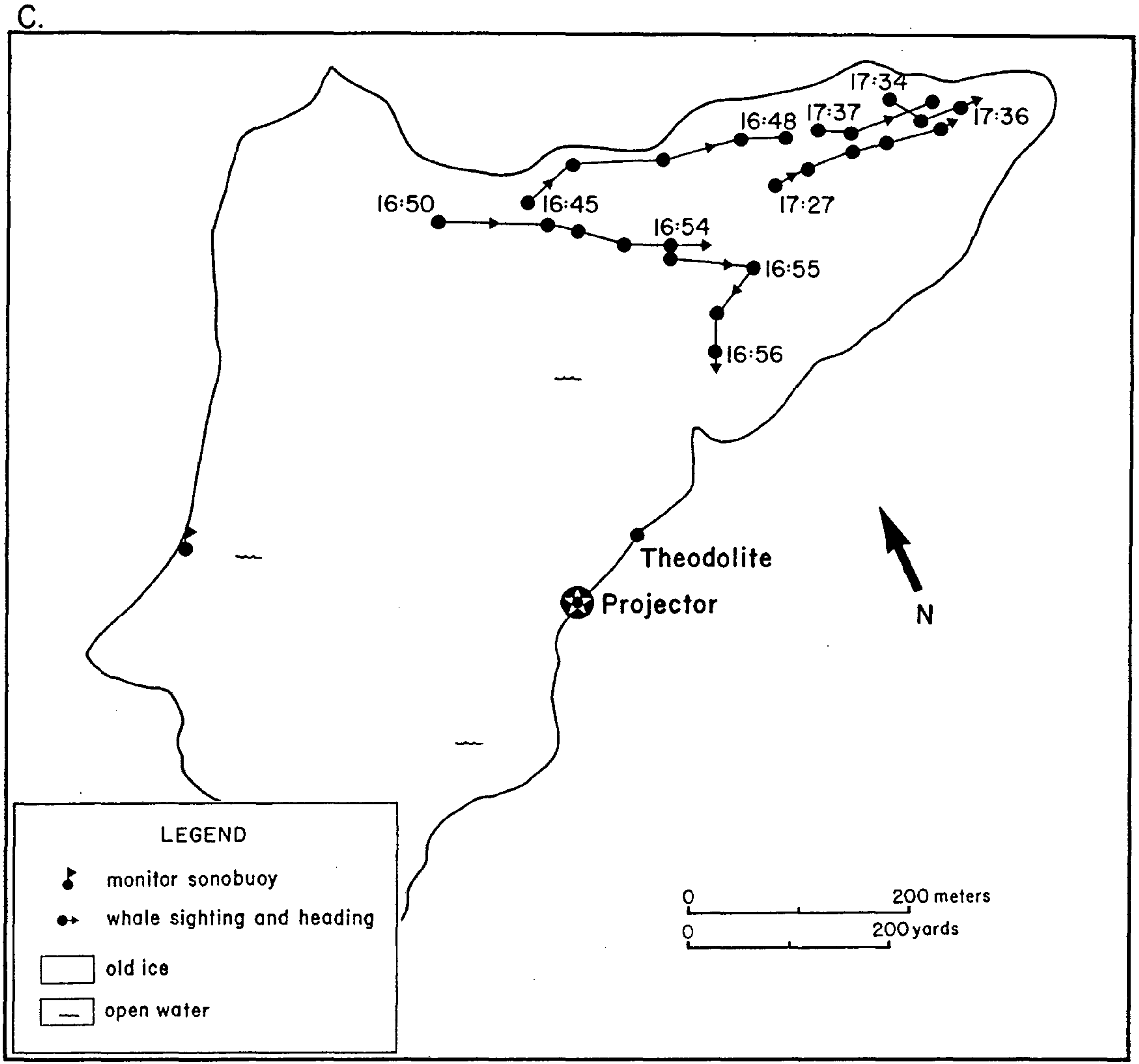


FIGURE 97. Concluded (Part C--Post-playback).

During the ***post-playback period*** between 15:57 and 17:45, 20 white whales were observed in six groups (#9-#14). All groups were first sighted in the northern third of the lead N to NE of the projector location (Fig. 97C). These whales tended to follow the ice edge at the far side of the lead from the projector. Most groups maintained a general E or ESE heading. The exception was group #11, consisting of an adult and subadult, which were first observed affiliating briefly with a single subadult (#10) when 345 m NE of the projector site at 16:54. The affiliated groups continued ESE until 16:56 when #10 continued ESE and #11 turned SW toward the observers and then SSW. Group #11 was last observed 197 m NE of the projector site, still heading SSW.

On 21 May, received sound levels were measured via two sonobuoys, one deployed 400 m across the lead from the projector (Fig. 97) and another in an adjacent lead 0.9 km WSW of the projector. The source level was measured at the projector. Ambient noise was measured at each buoy after the end of the playback. The measurements can be summarized as follows:

			20-1000 Hz			Dominant 1/3-Octave*			
	Distance (km)	Type of Data	Drill. (dB)	Amb. (dB)	S:N (dB)	Freq. (Hz)	Drill. (dB)	Amb. (dB)	S:N (dB)
Source	0.001	Meas.	166			200	160		
Buoy	0.4	Meas.	116	98	18	200	111	86	25
"	0.9	"	102	92	10	200	97	80	17

All white whales seen between the projector and the 400 m sonobuoy during the playback period would be, during dives, exposed to sounds levels at least as high as those noted above for the 400 m buoy. These whales had approached the projector despite being exposed to weaker but above-ambient sounds as they approached from more than 0.9 km away.

The white whales that seemed to divert at a distance of 40 m from the projector would have been exposed, during dives, to a broadband level of ~134 dB re 1 µPa (S:N ≈ 36 dB), and ~128 dB in the strongest 1/3-octave band (S:N ≈ 42 dB). These estimates assume spherical spreading (20 log R) from the source to a distance of 40 m. (The water depth was over 200 m, so the spherical spreading assumption is reasonable.) These high levels would only have been received when the whales dove; received levels while the whales were at or near the surface and under observation from the ice camp would have been lower because of pressure release effects at the surface. The white whales seen 15 m from the projector would have received even higher levels and S:N ratios if they had been below the surface at that distance from the projector. However, they did not dive until they were 64 m away, where the received levels would have been ~4 dB lower than those at 40 m.

Figure 98 shows that the received 1/3-octave levels of *Karluk* sounds 400 m from the projector on 21 May barely reached the known auditory threshold curve of the white whale. Thus, white whales may not have been able to hear the projected sounds until the whales came within a few hundred meters of the projector, even though the sounds were detectable by instruments considerably farther away.

Summary of 1989 Results

We observed migrating white whales close to the source of drilling noise on four dates in 1989: 14, 19, 23 and 27 May. On three of these dates, at least a few whales came within 175-225 m of the projector. On one of these three days (14 May), a few white whales came even closer--within 50-75 m of the projector. On the fourth day, several white whales migrated past the projector at CPA distances near 1 km. Detailed results from each day are given in Richardson et al. (1990a:222-236). In general, white whales that were migrating toward the projector appeared to travel unhesitatingly toward it until they came within a few hundred meters. Some of those whose paths came within a few hundred meters continued past the projector without apparent hesitation or turning. However, others definitely did react temporarily at distances on the order of 200-400 m.

There was clear evidence of short-term behavioral reactions on one day in 1989--14 May. On that occasion, an unknown but substantial proportion of the white whales that came within

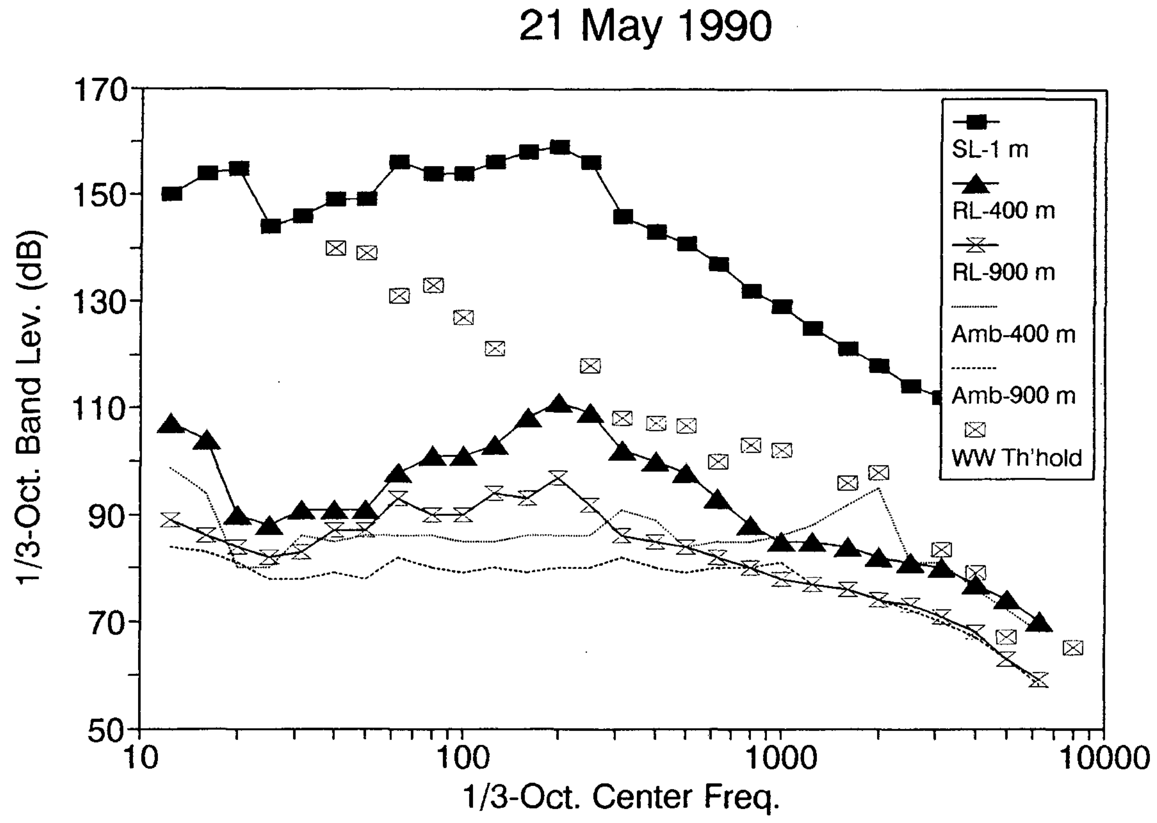


FIGURE 98. Third-octave levels of sounds 1 m from the projector (filled squares) and as received at sonobuoys 400 m and 900 m from the projector during playback on 21 May 1990, times 14:39-14:43. Data are in dB re 1 μPa and are plotted in relation to the background ambient noise levels (lines without symbols) and the hearing threshold of the white whale (open squares, from Fig. 100). For additional explanatory notes, see the caption to Figure 44 (p. 129).

200-400 m of the operating projector slowed down, milled, and in some cases reversed course temporarily. This interruption of migration was brief in the few cases that we could observe in detail. (We were observing bowheads at the same time.) After several minutes of interrupted migration, the whales continued past the projector, in some cases passing within 50-100 m of it. On all three of the days in 1989 when white whales were seen passing within ~225 m of the projector, there was enough open water such that they could have given the projector a wider berth while remaining within the same lead.

In 1989, the broadband (20-1000 Hz) received sound levels averaged 118 dB re 1 μPa at 200 m from the projector, and 112 dB at 400 m (Fig. 99).[23] Levels in the strongest 1/3-octave bands (near 200 Hz) averaged about 112 dB at 200 m and 106 dB at 400 m.

---

[23] Based on data from four transmission loss tests in 1989; data are in Richardson et al. (1990a, their Tables 6, 8, 10, 13 and their Fig. 34).

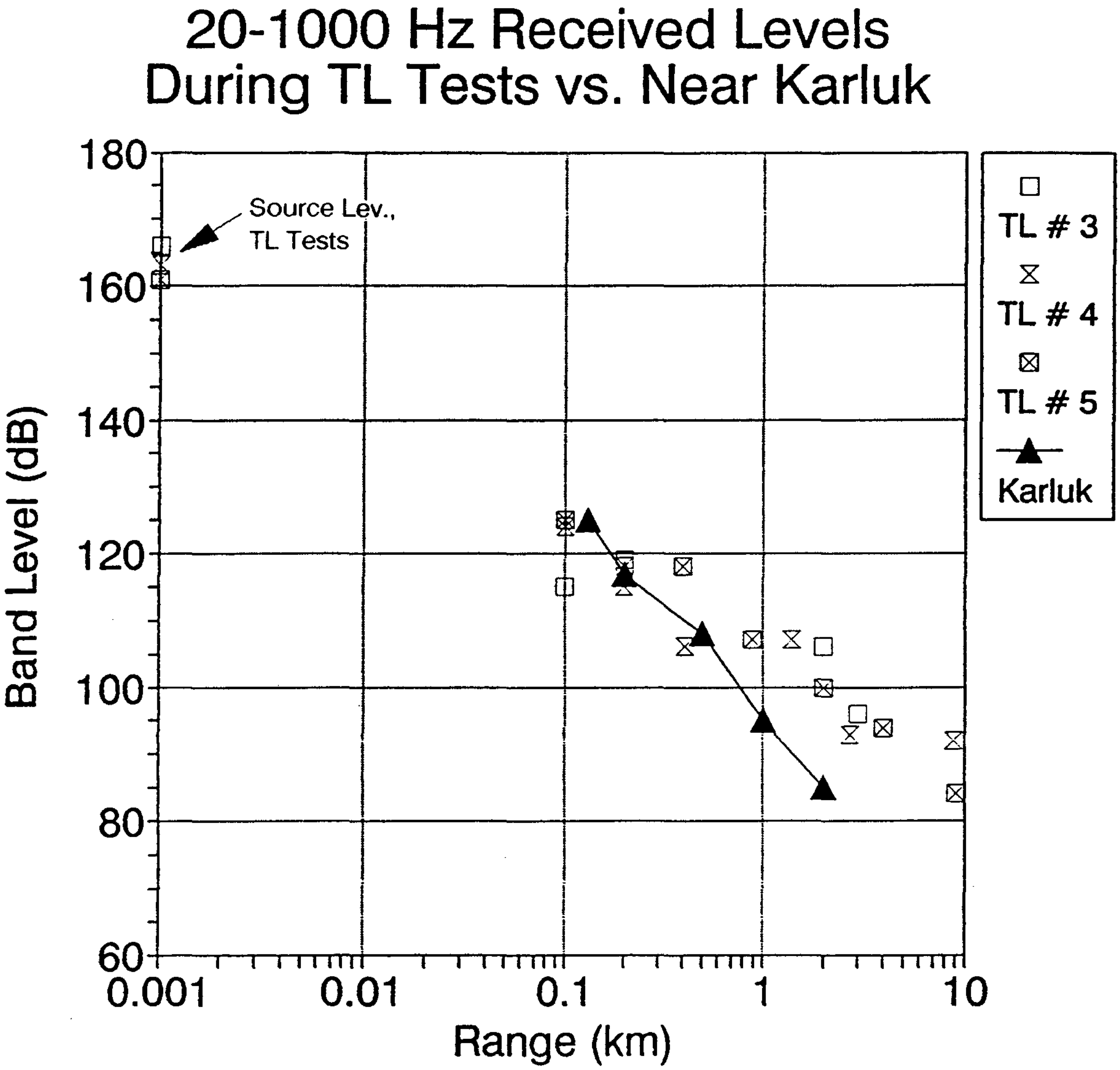


FIGURE 99. Received levels of *Karluk* drilling sounds, 20-1000 Hz band, as a function of distance from the actual drillsite in March 1989 (black triangles) and the sound projector during three transmission loss tests in 1989 (open symbols). From Richardson et al. (1990a:103). See Figure 30 (p. 90) for corresponding 1990 data.

Discussion of 1989-90 Results

White whales migrating toward the operating projector were observed on five days in 1989-90. They appeared to travel unhesitatingly toward it until they came within a few hundred meters. Some of those whose paths came within a few hundred meters continued past the projector without apparent hesitation or turning. The closest approach to the operating projector was on 21 May 1990, when a group of four white whales approached to within 15 m. However, they did not dive (and thus expose themselves to strong low frequency noise) until they were 64 m past the projector. Another group seen on that day turned away when they came within 40 m, and dove at that distance. Other white whales seen on 14 May 1989 definitely reacted temporarily at distances as great as 200-400 m.

We suspect that the apparent lack of reactions of white whales to the drilling sounds at distances greater than 200-400 m was related to the poor hearing sensitivity of this species at the low frequencies where the drilling sounds were concentrated. White whales have very good hearing sensitivity at frequencies above about 5 kHz, but their sensitivity deteriorates rapidly with diminishing frequency below 5 kHz (Fig. 100). The received 1/3-octave levels of the low-frequency drilling sounds were less than the measured hearing sensitivity of white whales at distances beyond ~200 m (Fig. 98, 101; see Richardson et al. 1990a:228-229 for 1989 data).

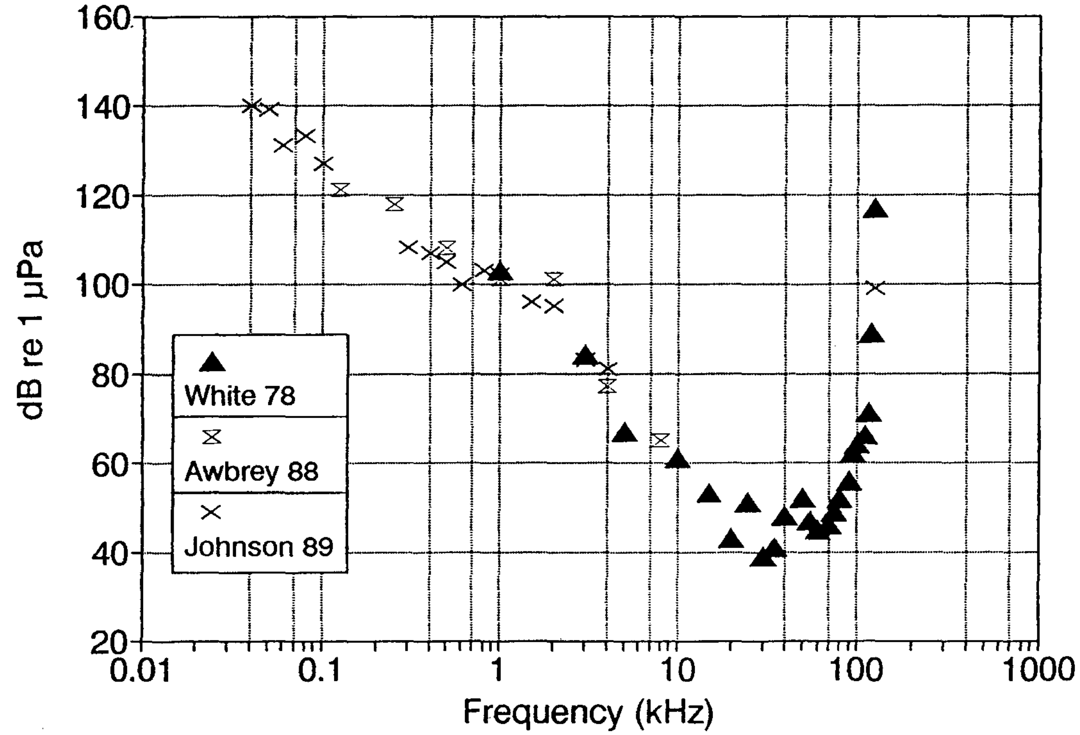
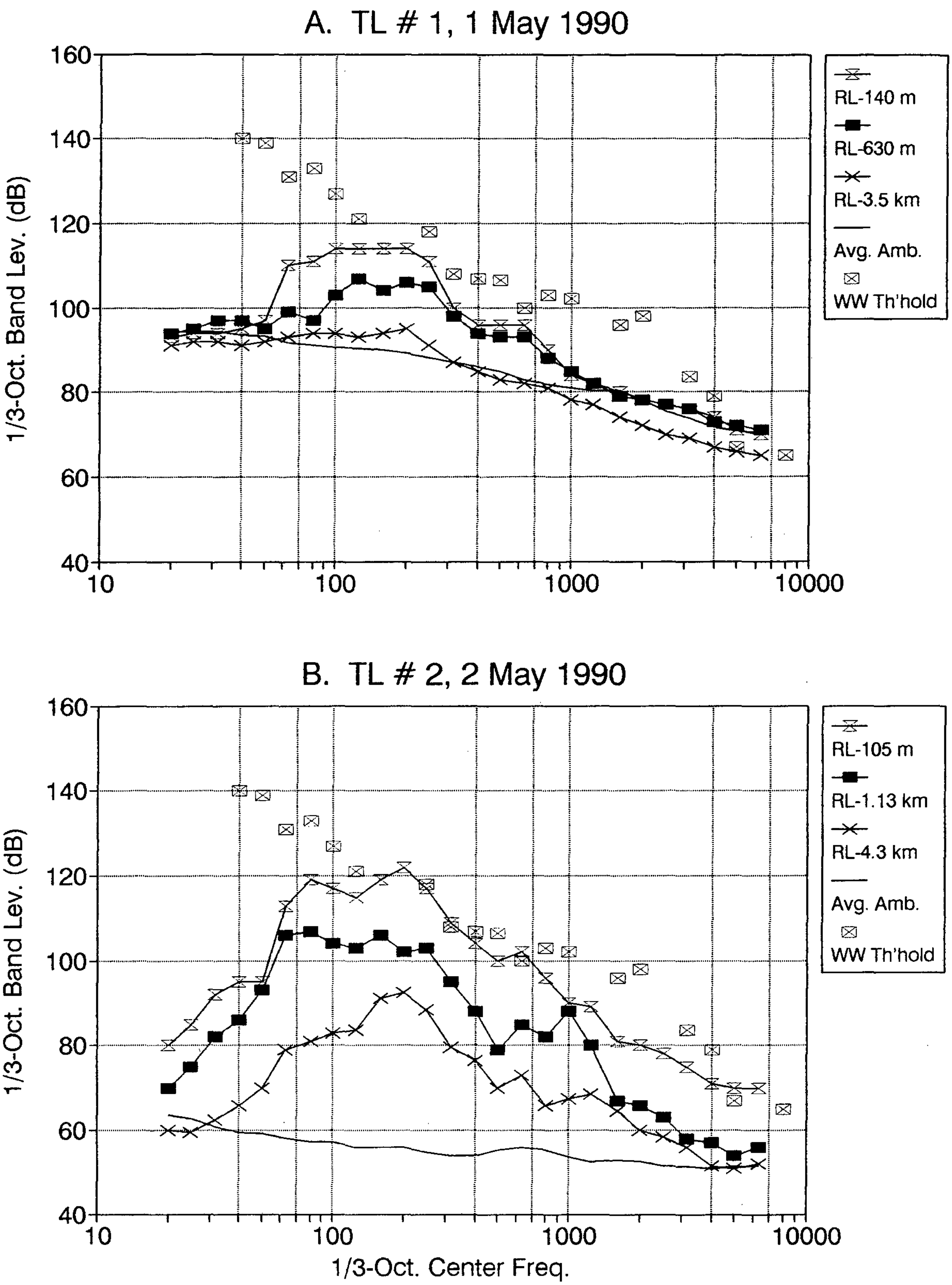


FIGURE 100. Absolute hearing sensitivity of white whales listening underwater, plotted in relation to frequency. Data are from White et al. (1978, average of two animals), Awbrey et al. (1988, n = 3), and Johnson et al. (1989, n = 1).



A. TL # 1, 1 May 1990

B. TL # 2, 2 May 1990

FIGURE 101. Third-octave received levels of drilling sound at various ranges during sound transmission loss (TL) experiments in 1990. Lowest curve (without symbols) shows average ambient noise levels during that TL test. Open squares show hearing threshold of the white whale (from Fig. 100). See Richardson et al. (1990a:228-229) for 1989 TL data.

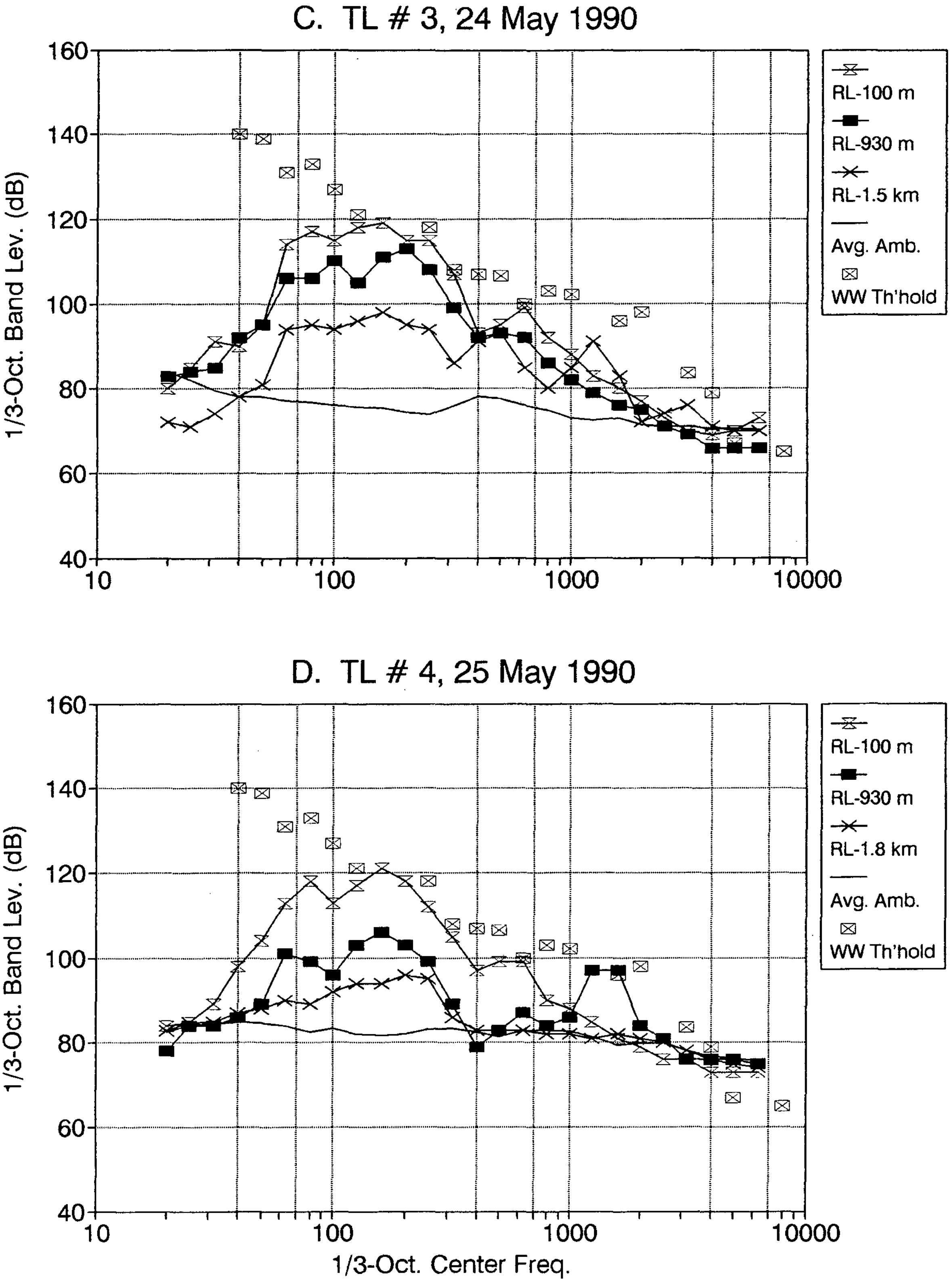


FIGURE 101 (Concluded).

The projected sounds during playbacks in 1989-90 included low-intensity components at frequencies above 2-3 kHz, the apparent upper limit of the sounds emitted by the actual *Karluk* drillsite (*cf.* Richardson et al. 1990a:100). This low-intensity high-frequency sound originated from electronic system noise (Richardson et al. 1990a:99). This artifactual noise was not strong enough to raise the third-octave levels as received about 1 km from the projector above the corresponding ambient levels during playback experiments in either 1990 (Fig. 98) or 1989 (Richardson et al. 1990a:226,234). However, at distances within a few hundred meters, the projected high-frequency system noise sometimes did exceed the ambient level in corresponding frequency bands. This may have been true at 400 m range on 21 May 1990, although interpretation of those data is confounded by variability in ambient noise levels (Fig. 98). It was especially obvious during the transmission loss test on 2 May 1990, when the ambient noise level was extremely low (Fig. 101B).

Given the known sensitivity of the white whale hearing system to high-frequency noise (Fig. 100), the weak artifactual high-frequency noise probably was detectable by white whales within a few hundred meters of the projector. Thus, we do not know whether the white whales that reacted when within a few hundred meters of the projector were reacting to low-frequency drilling noise, to the much weaker high-frequency noise that was projected, or to visual cues. In any case, they apparently did not react until they were quite close to the projector.

These results provide evidence about the seemingly low sensitivity of white whales to the one type of drilling sound used in the 1989-90 experiments. It is of interest to assess how white whales might have reacted to an actual drillsite emitting noise like the *Karluk* noise.

- Considering the 20-1000 Hz band, sound levels received near the projector were similar to those a few hundred meters from the actual *Karluk* drillsite (200-500 m in 1989--Fig. 99; 100-200 m in 1990--Fig. 30 on p. 90). At distances less than these, the received levels during playbacks were lower than those at corresponding distances from the actual *Karluk* site. At distances greater than these, the received levels during playbacks were higher than those at corresponding distances from *Karluk* itself (Fig. 30, 99).

- In 1989, some white whales reacted temporarily to the projected sounds at distances as much as a few hundred meters from the projector. Received levels (20-1000 Hz band) at those distances were similar to those at corresponding distances from the actual drillsite (Fig. 99).

- The projector did not adequately reproduce the low frequency components of the actual *Karluk* sounds (Fig. 31 on p. 92). Thus, levels of low frequency noise near the projector were less than those near the actual drillsite. This was true for all components below ~80 Hz, and especially for those below ~63 Hz. Note, however, that the J-11 projector did emit strong signals (1/3-octave source level >150 dB re 1 μPa-m) at frequencies down to 63 Hz (Fig. 31B). Also, contrary to the situation for bowheads, the underrepresentation of low-frequency components was probably not a significant limitation of the white whale experiments, given the poor sensitivity of the white whale auditory system to low frequency sounds (Fig. 100).

The above results and discussion concern reactions of white whales to one particular type of drilling noise that was continuous and concentrated at low frequencies. Sensitivity to other types of sounds associated with oil exploration or production may differ. Some sources, e.g. a bottom-founded caisson, may emit less noise than the *Karluk* drillsite or our projector at the frequencies important to white whales (Hall and Francine 1990, 1991). The acoustic zone of influence around such a "quiet" source would be expected to be smaller than that around a drillsite like *Karluk.*

Noise from some other sources, e.g. an icebreaker working on ice, is stronger and more variable, with more energy at moderately high frequencies. There are many reports that cetaceans react more strongly to variable than to continuous noises (Richardson et al. 1991). Also, the hearing sensitivity of white whales improves greatly with increasing frequency (Fig. 100). Thus, reaction distances are likely greater for industry noises containing higher frequency components. In the Canadian high arctic during spring, migrating white whales react strongly to noise from ships and icebreakers at extraordinarily long distances--tens of kilometers away (LGL and Greeneridge 1986; Cosens and Dueck 1988; Finley et al. 1990). To understand the effects of industrial noise on spring-migrating white whales in the Beaufort Sea, we need to test their reactions to additional types of noise whose characteristics differ from those studied in 1989-90. We hope to do so during subsequent years of this study.

A further reason for caution in interpreting the 1989-90 results is that we tested the reactions of white whales to drilling platform noise, but not to any other stimuli associated with it. Non-acoustic stimuli are unlikely to be important if whales react to noise at long distances from the source, but may be important in the absence of long-distance acoustic effects. The available data suggest that, in the case of white whales and *Karluk* sounds, long-distance acoustic reactions are lacking. Hence, other stimuli may be significant.

If white whales within a few hundred meters of an industrial site are sensitive to visual stimuli or perhaps odor, they might react differently to the actual site than to a playback (however realistic) of its noise. Also, white whales--unlike bowheads--have good high-frequency echolocation abilities (Au et al. 1985, 1987; Turl et al. 1987; Turl and Penner 1989). The echo characteristics of an actual industrial source would be very different than those of our projector. This echolocation ability probably would exist even in the presence of strong low frequency industrial sounds, given what is known about the critical bandwidths for masking in white whales (Johnson et al. 1989). For these reasons, white whales close to an actual industrial site might react differently than they do to its noise alone.

However, we doubt that echolocation or non-acoustic effects would be important at distances exceeding a few hundred meters--the maximum distances where we would expect an actual drilling platform like *Karluk* to have acoustic effects on white whales. Thus, we would not expect that white whales would react to non-acoustic cues from an actual industrial site like *Karluk* at distances much beyond the 200-400 m ranges where some white whales reacted during the playback experiments.

Conclusions

Although the sound projector had reduced output below 80 Hz and especially below 63 Hz, the 1989-90 playback experiments included strong signals down to ~63 Hz and good reproduction of the components of *Karluk* sound above 80 Hz--the frequencies to which white whales are most sensitive. The acoustic simulation was best at distances 200-500 m from the projector in 1989, and 100-200 m away in 1990. At these distances, broadband received levels were comparable to those at similar distances from the actual *Karluk* drillsite (Fig. 30, 99).

Reaction Distances and Acoustic Thresholds.--Some white whales reacted to the projected sounds at distances as great as 200-400 m, but other individuals approached considerably closer. The minimum confirmed distances from the operating projector were 15 m for white whales at the surface and 40 m during a dive. Estimated received sound levels several meters or more below the surface at these distances were as follows:

Range (m)	Broadband (dB re 1 µPa)	Max. 1/3-Octave (dB re 1 µPa)
400	112	106
200	118	112
40	134[a]	128[b]

[a] S:N≈36 dB

[b] S:N≈42 dB

The above values provide estimates of the minimum and maximum reaction distances during playbacks.

The 1/3-octave levels of drilling sound noted above for the observed minimum and maximum reaction distances quite likely do not represent the actual acoustic reaction thresholds. Although maximum projected and received levels occurred in 1/3-octave bands near 200 Hz, the levels received 200-400 m from the projector in that frequency band appear to be too low to have been heard. Acoustic reactions are more likely to depend on reception of lower level sounds at higher frequencies where the white whale hearing apparatus is more sensitive.

The white whales that reacted to the *Karluk* playback at 200-400 m in 1989 may have begun to react at about the distance where they could first hear the projected drilling sounds (Richardson et al. 1990a:228-229). The maximum reaction distance noted during playbacks (200-400 m) may also apply, as a first approximation, to an actual drilling operation like *Karluk* itself. This speculation is based on the similar broadband sound levels 200-500 m from the projector (in 1989) relative to levels from the actual *Karluk* site (Fig. 99).

The projected sounds included weak high frequency (above 2-3 kHz) components not in the original *Karluk* sounds. Hence, the reaction distance relative to the projector may exceed that relative to the actual drillrig.

We doubt that the other differences between our simulation and the actual *Karluk* site (characteristics of platform as an echolocation target, visual cues and/or odor of platform) would be significant to white whales more than a few hundred meters away. We based this suggestion, in part, on the observed occurrence of white whales near oil platforms in Cook Inlet (Gales 1982) and artificial islands in the Beaufort Sea (Fraker 1977a,b). Thus, it is unlikely that white whales would react to an actual drillsite like *Karluk* much beyond the 200-400 m ranges where some white whales reacted during the 1989 playbacks.

The minimum reaction distance for the drilling operation *per se* would be expected to be higher than the minimum during playbacks: *(1)* Noise levels very close to the actual *Karluk* site were higher than at comparable distances from the projector (Fig. 30, 99). *(2)* Non-acoustic and echolocation-related effects that do not apply in the playback situation might occur close to an actual drillsite.

Evaluation of Hypotheses.--The two hypotheses with respect to effects of drilling platform noise on white whales were as follows:

- Playbacks of recorded noise from a bottom-founded platform will not (or alternatively will) significantly alter measures of migration routes and spatial distribution of whales in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.

- Playbacks of recorded noise from a bottom-founded platform will not (or alternatively will) significantly alter subtle aspects of individual whale behavior in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.

The wording of these hypotheses is somewhat broader than the available data. We can only draw conclusions about the effects of playbacks of ***continuous noise from drilling on a bottom-founded ice platform like Karluk.*** Also, the data apply to white whales migrating through ***pack ice and along the seaward side of the nearshore lead east of Pt. Barrow.***

With these restrictions and amendments to the wording, the data show that playbacks of sounds from drilling on a bottom-founded ice platform like *Karluk* have no ***biologically significant*** effects on migration routes and spatial distribution of white whales visible while migrating through pack ice and along the seaward side of the nearshore lead east of Point Barrow in spring. Furthermore, as discussed above, we expect that maximum reaction distances of white whales to an actual drillsite like *Karluk* (a few hundred meters) would be similar to those observed during the playback experiments. In drawing these conclusions, we consider that the observed temporary hesitation and minor changes in migration paths exhibited by some white whales within 200-400 m of the noise source were not biologically significant. Our acceptance of the amended null hypothesis is based on a "weight of evidence" approach; the available data are not suitable for a statistical test of the hypothesis.

We emphasize strongly that our conclusions relating to the "distribution and movements" hypothesis pertain only to continuous low-frequency drilling noise from a bottom-founded ice platform like Karluk. Reaction distances to some other sources of industrial noise may be very different. This is evident from the reactions of spring-migrating white whales in the Canadian high arctic to ships and icebreakers at very long distances (LGL and Greeneridge 1986; Cosens and Dueck 1988; Finley et al. 1990).

The available data are not adequate for a test, statistical or otherwise, of the second hypothesis, concerning effects of *Karluk* drilling noise on subtle aspects of the individual behavior of white whales. It is obvious that the temporary hesitation and small-scale diversion of migration paths sometimes noted within 200-400 m of the sound projector involved short-term changes in the behavior of white whales. However, the available data do not allow quantification of white whale behavior as a function of proximity to the projector, nor do they allow evaluation of the possibility that drilling noise evokes longer-term changes in the behavior of white whales. In order to address hypothesis #2 in detail for white whales, it would be necessary either *(1)* to re-direct project priorities from bowheads to white whales, or *(2)* to encounter situations when large numbers of white whales pass the projector site at times when bowheads are not passing.

White Whale Reactions to Aircraft

Specific objective 5 (p. 6) requires us to determine the reactions of white whales to helicopter overflights. Specific objective 6 includes a requirement to determine reactions to other sources of disturbance. During 1989-90, we noticed several occasions when white whales may have been reacting to the Twin Otter observation aircraft or to the Bell 212 helicopter. The following subsections describe occasions when overt reactions were noted or when aircraft altitude was low and reactions might have been expected. We do not describe the many occasions when, while at altitudes ≥460 m ASL, we flew over white whales and saw no reactions.

Reactions to Twin Otter

In 1990, there were only two observations of possible responses of white whales to the Twin Otter observation aircraft. Both cases were on 21 May. *(1)* The Twin Otter, initially at altitude 150 m (500 ft), was heading ~WSW about 300 m to the south of a narrow lead through pack ice. As the aircraft approached, a white whale in the lead was heading SSE, ~300 m to the side of (and toward) the aircraft's track. As the aircraft reached its closest point of approach, high power was applied to the aircraft engines in order to begin a climb from 150 m ASL to higher altitude. The whale abruptly turned 90° onto a ENE heading (opposite to that of the aircraft). *(2)* Later that day, a group of seven white whales turned 60°, sharply away from the Twin Otter, as it circled over them at altitude 460 m (1500 ft). This group was only about 200 m from the ice camp at the time, and the turn was away from the camp as well as the aircraft. No sounds were being projected at the time. We cannot determine whether these whales reacted to the aircraft, ice camp, or both.

We observed responses of white whales to overflights of the Twin Otter on three occasions in May 1989. *(1)* On 14 May, an adult white whale accompanied by a subadult rolled slightly and looked up at the aircraft as it flew over at 260 m (860 ft) ASL. *(2)* On 24 May, a group of seven white whales dove abruptly and steeply when the aircraft flew almost directly over them at 200 m (650 ft) while circling bowheads. *(3)* On 29 May, one white whale among a group of 13 adults looked up at the aircraft as it passed over at 460 m ASL; again, the aircraft was circling bowheads at the time.

Reactions to Bell 212 Helicopter

1990 Results.--The behavior of white whales exposed to close approaches by the helicopter was observed on two days in 1990.

On 10 May, two white whales dove as the helicopter flew overhead at 13:48. Between 14:04 and 14:06 another group of two subadult white whales continued swimming at the surface along the closest ice edge, ~200 m from a stationary helicopter with its engines running. When the helicopter's engine speed decreased at 14:06, the whales dove. At 14:09 a group of four white whales swam at the surface up the lead past the helicopter which was still stationary on the ice with its engines running. At 14:10 the whales began milling and then dove as the helicopter taxied across the ice, moving away from the whales. At 14:29 a group of white whales approached the helicopter/ice camp and began milling as the stationary helicopter's engines were restarted ~120 m from the whales. (These whales may have been the same whales sighted earlier at 14:10.) One subadult was observed to spyhop as the engines started. The helicopter lifted off the ice at 14:31:10 and the whales dove 20 s later. At 14:33, white whales approached the ice camp to within 45 m as the helicopter was airborne. (These whales may have been the same whales sighted earlier at 14:31.)

On 21 May, the helicopter landed ~20 m from the S edge of an estimated 100-m-wide lead running WNW to ESE while four white whales were traveling E up the lead. (This was a temporary landing site and the theodolite could not be used; hence all distance estimates are visual estimates.) Between 09:15 and 10:06, an estimated 48 white whales in strung-out subgroups traveled ESE through the narrow lead. All three subgroups sighted while the helicopter was stationary on the ice with its engines running (09:16 and 09:20) maintained a SSE or ESE heading while traveling in the half of the lead farthest from the helicopter (Table 48). After the helicopter's engines were turned off, most white whales (5 of 6 subgroups) were observed in the closest third of the lead. All of these subgroups except an adult/yearling pair (group #7) maintained their headings. The exceptional pair turned from ESE to SSE, directly toward an observer standing at the S ice edge. Three other subgroups (#8-#10) also appeared to be obliquely crossing the lead toward the landing site. As the helicopter was lifting off the ice at 10:05, two white whale groups remained at the surface, maintaining their SSE heading up the lead, apparently undisturbed by the helicopter.

Table 48. Behavior of white whales on 21 May 1990 in relation to helicopter engine status.

Helicopter Engines	Group ID #	Time	Group Size	Direction of Travel	Distance Across Lead From Helicopter	Comments
ON	1	09:15	4	SSE	?	
ON	2	09:19	3	ESE	3/4	traveling at surface
ON	3	09:19	7	SSE	1/2	
ON	4	09:20	2	ESE	3/4	
OFF	5	09:25	5	ESE	1/3	
OFF	6	09:29	4	ESE	3/4	
OFF	7	09:31	2	ESE, SSE	1/2	turned from ESE to SSE approaching observer standing at edge of lead
OFF	8	09:38	4	WSW	1/4	
OFF	9	09:39	1	SSW	1/4	traveling toward ice camp
OFF	10	09:47	2	SSW	1/4	traveling toward ice camp
ON	11	10:05	4	SSE	?	traveling at surface as helicopter lifts off
ON	12	10:06	10	SSE	?	traveling at surface as helicopter lifts of

Although these few observations are anecdotal, overall behavior of white whales in the presence of the helicopter at low altitude or on the ice appeared to be variable. Some white whales dove, apparently in response to disturbance by the helicopter at ranges up to ~200 m. Other whales at similar distances exhibited no obvious reactions. Observations on 21 May suggest that white whales may have attempted to avoid close exposure to the operating helicopter by swimming along the far side of a 100-m-wide lead when the helicopter was operating, as opposed to swimming along the closer side of the lead while the helicopter was silent. Varied reactions of white whales to helicopters are consistent with previous observations of white whales exposed to aircraft overflights (Richardson et al. 1991).

1989 Results.--In 1989, white whales exposed to close approaches by the Bell 212 helicopter were observed on three days (Richardson et al. 1990a:239-240):

- On 16 May 1989, the ice-based observers watched a group of three white whales as the helicopter passed within 500 m laterally at 15-30 m ASL. The whales remained at the surface and continued on their original NNE heading. No overt reaction was noticed.

- On 17 May 1989, the ice-based crew observed six groups of white whales. Two groups were overflown by the Bell 212 while it flew back and forth over a pair of hydrophones. The helicopter was at 150 m and 460 m ASL when it flew over these groups; both dove immediately. These groups dove 20-50 m before reaching the end of the lead in which they were swimming, whereas other groups that were not disturbed did not dive until they were within a few meters of the ice. Thus, the two groups overflown by the Bell 212 very likely dove in response to the helicopter.

- On 26 May 1989, a single white whale dove rapidly and steeply when the Bell 212 flew 50 m to the side at 120 m ASL and at cruise speed.

Summary of White Whale Reactions to Aircraft

The largely-anecdotal observations of movements and behavior in the presence of a Bell 212 or Twin Otter are generally consistent with previous observations of white whales exposed to aircraft overflights (Richardson et al. 1991). Reactions to turbine-powered aircraft during the spring migration near Pt. Barrow are variable. Some individuals show no overt response to a fixed-wing aircraft or helicopter flying at low level or to a helicopter standing on the ice edge (with engines running) within 100-200 m of the whales. Others look upward or dive abruptly when an aircraft passes over at altitudes at least as high as 460 m (1500 ft). Based on the results from 21 May 1991, some white whales whose paths come within 100 m of a helicopter on the ice with its engines running may divert as much as 100 m away from the helicopter. It is not known whether these small-scale and apparently brief reactions are to the noise from the aircraft, visual cues, or both.

Evaluation of Hypotheses

The two hypotheses relating to reactions of white whales to helicopter overflights were as follows:

- Helicopter overflights will not (or alternatively will) significantly alter measures of migration routes and spatial distribution of whales in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.
- Helicopter overflights will not (or alternatively will) significantly alter subtle aspects of individual whale behavior in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.

As discussed under reactions of bowheads to helicopter overflights, the available data apply only to the ***Bell 212*** helicopter, and to white whales migrating through ***pack ice and along the seaward side of the nearshore lead east of Pt. Barrow.***

The available results from 1989-90 suggest that single overflights by a helicopter of the Bell 212 class do not cause blockage or ***biologically significant*** diversion of the spring migration of white whales traveling in pack ice or along the seaward side of the nearshore lead. We consider that diversion of migration routes by 100 m (as may have occurred on 21 May 1990) is not biologically significant.

Thus, the available data are consistent with the view that the null hypothesis about helicopter effects on migration routes and spatial distribution (amended as described above) should be accepted. This preliminary assessment is based on the "weight of evidence"; the available data are not amenable to a statistical test. It should be noted that the available data are limited and non-systematic, and additional related data are likely to be obtained during subsequent years of this project. Hence, a final determination as to the validity of the "distribution and movement" null hypothesis for white whales is postponed until later in the project.

The available data are not adequate for a test, statistical or otherwise, of the hypothesis concerning helicopter effects on subtle aspects of the individual behavior of white whales. It is obvious that short-term effects on their behavior do occasionally occur (hasty dives, looking at the passing helicopter). However, the available data do not allow quantification of the probability of these reactions as a function of proximity to the helicopter, nor do they allow evaluation of the possibility that helicopter overflights evoke longer-term changes in the behavior of white whales.

REACTIONS OF SEALS TO PLAYBACKS

When they were not observing bowhead and white whales, the ice-based observers also recorded the distribution and behavior of ringed and bearded seals near the sound projector. Sightings near the ice camp and sound projector in 1989 were described by Richardson et al. (1990a:241-243). This section describes the results from 1990.

A total of 69 seals were observed in 1990; 41 were seen while the projector was broadcasting drilling platform sounds or test tones, and 28 were recorded when the projector was not operating (Table 49). Most (53) of the seals were ringed seals; 14 were bearded seals. The majority (63) of seals were alone; three groups consisting of two seals were seen.

Table 49. Closest observed point of approach of seals to **(A)** a sound projector broadcasting drilling platform sounds or test tones, and **(B)** a quiet projector. Sightings were made by the ice-based crew and include distances estimated visually and those measured via theodolite. RS = Ringed seal, BS = Bearded seal, US = Unidentified seal.

Closest Point	A. Projector Operating				B. Projector Off			
of Approach (m)	RS	BS	US	Total	RS	BS	US	Total
< 50	4	0	0	4	1	1	0	2
50-99	3	0	0	3	4	1	0	5
100-149	5	1	0	6	7	0	0	7
150-199	3	2	1	6	5	0	0	5
200	15	5	1	21	5	3	0	8
Unknown	0	1	0	1	1	0	0	1
Total	30	9	2	41	23	5	0	28

Fewer seals (28) were noticed when the projector was not operating, probably because the observers were usually busy setting up or dismantling equipment at those times. During quiet periods, a subadult bearded seal was seen to approach as close as 10 m from the projector.

While the projector was broadcasting drilling platform sounds, three lone ringed seals approached within 30 m of the projector; two lone ringed seals approached within 20 m while test tones were being projected. Slightly over half (22 of 40) of the seals observed at known distances while the projector was broadcasting were ≥200 m away. In comparison, about a third of the seals seen while the projector was silent were ≥200 m away. Only 17% (7 of 40) of the seals observed were within 100 m of the broadcasting projector, as opposed to 26% (7 of 27) while the projector was silent (Table 49).

Of the 13 seals whose headings were noted, two initially approached to within 55 m (Fig. 102) and 73 m of the broadcasting projector and then swam away. Four others swam away (3 ringed, 1 bearded); one seal approached (bearded); and the remaining six seals (ringed) exhibited no remarkable behavior or heading relative to the operating projector.

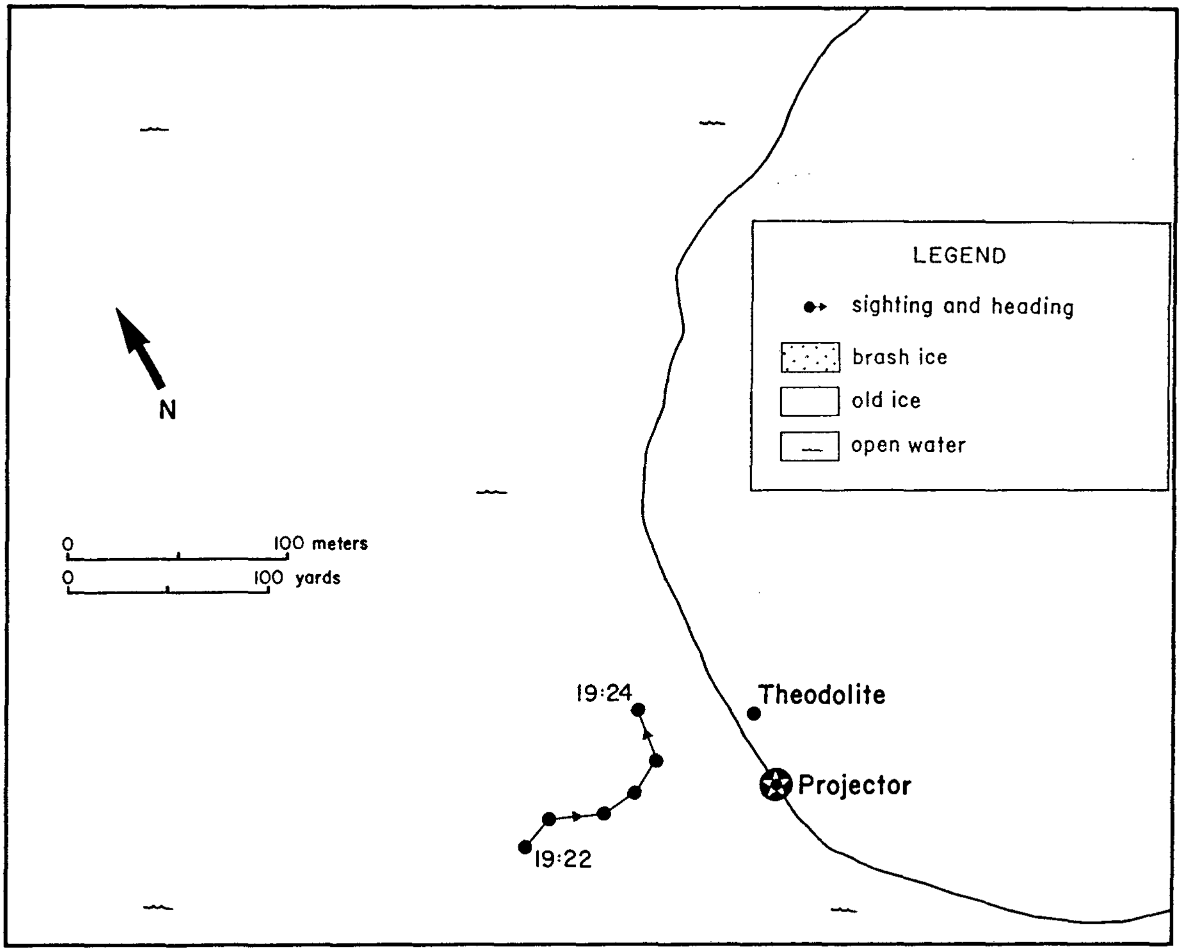


FIGURE 102. Track of a ringed seal observed by ice-based observers during a playback of drilling platform sounds amidst pack ice NE of Barrow, Alaska, 10 May 1990. Seal positions relative to the projector are plotted from theodolite readings.

Reactions of ringed and bearded seals to the projected sounds and camp may have differed. Of the seals sighted while the projector was operating in 1990, 12 ringed seals were seen <150 m from the projector; only one bearded seal was observed within 150 m (at a visually estimated distance of 130 m). However, this difference was not significant ($chi^2 = 1.08$, df = 1). It is possible that ringed seals were attracted to the operating projector, or perhaps to the appearance of the ice camp. On 21 May, a subadult bearded seal was observed to swim directly toward and past the silent projector/ice camp (CPA < 10 m). It subsequently turned 180° and swam away.

Most seals observed in 1990 were seen only once (56 of 66 groups), indicating that they did not remain long in the study area. The most extensive track of a ringed seal was obtained on 10 May between 19:22 and 19:24 while the projector was broadcasting drilling platform sounds (see p. 139*ff* for noise exposure data). Locations were measured on six occasions when the seal surfaced (Fig. 102). The seal was first sighted 121 m W of the projector. It moved ENE and then E toward the projector, coming within 75 m. Then the seal veered NE, partly away from the projector. It finally turned NNE and angled away from the projector when at its CPA distance of 55 m (Fig. 102).

On 1 May a bearded seal remained hauled-out on the ice, ~600 m from the projector, while test tones were projected. The seal also remained stationary on the ice during overflights by the helicopter and Twin Otter aircraft.

Although all observations were necessarily of seals at the surface of the water, the seals also dived out of sight. During their dives they were exposed to high levels of drilling sounds. If seals dove down to depths of ~15 m or more, they would have been exposed to broadband received levels of about 140 dB re 1 µPa at a distance of 20 m from the projector, and 132 dB at 50 m. These estimates are based on the average source level in 1990 of ~166 dB re 1 µPa-m and an assumption of spherical spreading over the short distances relevant here.

The hearing sensitivity of the ringed seal has been measured at 1 kHz and above (Terhune and Ronald 1975), but there are no data on the underwater hearing sensitivity of any hair seal at frequencies below 760 Hz (reviewed in Richardson et al. 1991). The absolute hearing threshold of the ringed seal at 1 kHz is ~75 dB re 1 µPa. The received level of the projected sounds in the 1/3-octave band centered at 1 kHz was above 75 dB out to distances beyond 1 km (Fig. 101). Sound components near 1 kHz would have been strong at all depths greater than ~1 m. Hence, regardless of their hearing sensitivity below 1 kHz, ringed seals within a few hundred meters of the operating projector probably could hear the projected sounds.

In summary, half of the seals seen from the ice camp in 1990 were <200 m from the sound projector. Only ringed seals were sighted <100 m from the operating projector, suggesting that ringed seals, in particular, may have been attracted by the projected sounds or by other stimuli--visual or acoustic. When they dove, seals were exposed to strong drilling sounds. We surmise that ringed seals would have been able to hear these sounds at distances as great as a few hundred meters. Despite this, some seals approached the ice camp and operating projector to much closer distances. Seals may have avoided very close approaches to the projector for the most part, but if so the zone of exclusion appeared to be very small (radius ≤30 m for drilling platform sounds; ≤20 m for test tones). Similar results were obtained in 1989 (Richardson et al. 1990a: 241-243).

SUMMARY AND CONCLUSIONS

To avoid repetition, the summary and conclusions sections are presented as the major components of the Executive Summary at the front of the volume.

LITERATURE CITED

Au, W.W.L., D.A. Carder, R.H. Penner and B.L. Scronce. 1985. Demonstration of adaptation in beluga whale echolocation signals. **J. Acoust. Soc. Am.** 77(2):726-730.

Au, W.W.L., R.H. Penner and C.W. Turl. 1987. Propagation of beluga echolocation signals. **J. Acoust. Soc. Am.** 82(3):807-813.

Awbrey, F.T., J.A. Thomas and R.A. Kastelein. 1988. Low-frequency underwater hearing sensitivity in belugas, *Delphinapterus leucas*. **J. Acoust. Soc. Am.** 84(6):2273-2275.

Brennan, J.W. 1988. Letter of 23 November 1988 from Nat. Mar. Fish. Serv. to Robert Callman, Director, Minerals Manage. Serv., including "Endangered Species Act-Section 7 Consultation/ Biological Opinion/Oil and Gas Leasing and Exploration-Arctic Region".

Buck, B.M. and C.R. Greene. 1980. A two-hydrophone method of eliminating the effects of nonacoustic noise interference in measurements of infrasonic ambient noise levels. **J. Acoust. Soc. Am.** 68(5):1306-1308.

Buckingham, M.J. 1990. Infrasonic ambient noise in the ocean due to atmospheric pressure fluctuations on the surface. **J. Acoust. Soc. Am.** 88(2):984-994.

Carroll, G.M. and J.R. Smithhisler. 1980. Observations of bowhead whales during spring migration. **Mar. Fish. Rev.** 42(9-10):80-85.

Cave, A.J.E. 1988. Note on olfactory activity in mysticetes. **J. Zool., Lond.** 214(2):307-311.

Clark, C.W. and J.H. Johnson. 1984. The sounds of the bowhead whale, *Balaena mysticetus*, during the spring migrations of 1979 and 1980. **Can. J. Zool.** 62(7):1436-1441.

Cosens, S.E. and L.P. Dueck. 1988. Responses of migrating narwhal and beluga to icebreaker traffic at the Admiralty Inlet ice-edge, N.W.T. in 1986. p. 39-54 *In*: W.M. Sackinger *et al.* (eds.), Port and Ocean Engineering under Arctic Conditions, Vol. II. Geophysical Inst., Univ. of Alaska, Fairbanks, AK. 111 p.

Cummings, W.C. and D.V. Holliday. 1987. Sounds and source levels from bowhead whales off Pt. Barrow, Alaska. **J. Acoust. Soc. Am.** 82(3):814-821.

Cummings, W.C. and P.O. Thompson. 1971. Underwater sounds from the blue whale, *Balaenoptera musculus*. **J. Acoust. Soc. Am.** 50(4, Pt. 2):1193-1198.

Davis, R.A., C.R. Greene 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. Rep. from LGL Ltd., King City, Ont., for Shell Western E & P Inc., Anchorage, AK. 70 p.

Dixon, W.J. (ed.) 1990. BMDP statistical software manual, Vol. 1. Univ. Calif. Press, Berkeley, CA. 629 p.

Dorsey, E.M., W.J. Richardson and B. Würsig. 1989. Factors affecting surfacing, respiration, and dive behaviour of bowhead whales, *Balaena mysticetus*, summering in the Beaufort Sea. **Can. J. Zool.** 67:1801-1815.

D'Spain, G.L., W.S. Hodgkiss and G.L.O. Edmonds. 1991. Energetics of the deep ocean's infrasonic sound field. **J. Acoust. Soc. Am.** 89(3):1134-1158.

Edds, P.L. 1982. Vocalizations of the blue whale, *Balaenoptera musculus*, in the St. Lawrence River. **J. Mammal.** 63(2):345-347.

Edds, P.L. 1988. Characteristics of finback *Balaenoptera physalus* vocalizations in the St. Lawrence estuary. **Bioacoustics** 1:131-149.

Evans, W.E. 1987. Letter of 1 September 1987 from Nat. Mar. Fish. Serv. to William D. Bettenberg, Director, Minerals Manage. Serv., including "Endangered Species Act Section 7 Consultation/ Biological Opinion/Oil and Gas Leasing and Exploration-Chukchi Sea Lease Sale 109".

Fay, R.R. 1988. Hearing in vertebrates: a psychophysics databook. Hill-Fay Associates, Winnetka, IL. 621 p.

Finley, K.J., G.W. Miller, R.A. Davis and C.R. Greene. 1990. Reactions of belugas, *Delphinapterus leucas*, and narwhals, *Monodon monoceros*, to ice-breaking ships in the Canadian high arctic. **Can. Bull. Fish. Aquatic Sci.** 224:97-117.

Fleischer, G. 1976. Hearing in extinct cetaceans as determined by cochlear structure. **J. Paleontol.** 50(1):133-152.

Fox, W.W., Jr. 1990. Letter of 28 August 1990 from Nat. Mar. Fish. Serv. to Ed. Cassidy, Deputy Director, Minerals Manage. Serv.

Fraker, M.A. 1977a. The 1976 white whale monitoring program, Mackenzie Estuary, N.W.T. Rep. by F.F. Slaney & Co. Ltd., Vancouver, for Imperial Oil Ltd., Calgary. 76 p. plus maps, tables and appendices.

Fraker, M.A. 1977b. The 1977 white whale monitoring program, Mackenzie Estuary, N.W.T. Rep. by F.F. Slaney & Co. Ltd., Vancouver, for Imperial Oil Ltd., Calgary. 53 p. plus maps.

Gales, R.S. 1982. Effects of noise of offshore oil and gas operations on marine mammals--an introductory assessment. NOSC TR844, 2 vol. Naval Ocean Systems Center, San Diego, CA. 79 p. and 300 p.

George, J.C., L.M. Philo, R. Suydam, R. Tarpley and T.F. Albert. 1991. Summary of the 1989 and 1990 subsistence harvests of bowhead whales (*Balaena mysticetus*) by Alaskan Eskimos. SC/43/PS18. Int. Whal. Comm., Cambridge, UK. 15 p.

Greene, C.R. 1981. Underwater acoustic transmission loss and ambient noise in arctic regions. p. 234-258 *In*: N.M. Peterson (ed.), The question of sound from icebreaker operations: the proceedings of a workshop. Arctic Pilot Project, Petro-Canada, Calgary, Alberta. 350 p.

Greene, C.R. 1985. Characteristics of waterborne industrial noise, 1980-84. p. 197-253 *In*: W.J. Richardson (ed.), Behavior, disturbance responses and distribution of bowhead whales *Balaena mysticetus* in the eastern Beaufort Sea, 1980-84. OCS Study MMS 85-0034. Rep. from LGL Ecol. Res. Assoc., Bryan, TX, for U.S. Minerals Manage. Serv., Reston, VA. 306 p. NTIS PB87-124376.

Greene, C.R. 1987a. Acoustic studies of underwater noise and localization of whale calls. Sect. 2 *In*: Responses of bowhead whales to an offshore drilling operation in the Alaskan Beaufort Sea, autumn 1986. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for Shell Western E & P Inc., Anchorage, AK. 128 p.

Greene, C.R., Jr. 1987b. Characteristics of oil industry dredge and drilling sounds in the Beaufort Sea. **J. Acoust. Soc. Am.** 82(4):1315-1324.

Hall, J.D. and J. Francine. 1990. Report on sound monitoring and bowhead whale calls [*sic*] localization efforts associated with the Concrete Island Drilling Structure (CIDS) off Camden Bay, Alaska. HMRC Tech. Rep. 89-219. Rep. from Hubbs Mar. Res. Cent., San Diego, CA, for ARCO Alaska Inc., Anchorage, AK. 22 p.

Hall, J.D. and J. Francine. 1991. Measurements of underwater sounds from a concrete island drilling structure located in the Alaskan sector of the Beaufort Sea. **J. Acoust. Soc. Am.** 90(3):1665-1667.

Hall, J.D., M.L. Gallagher, K.D. Brewer and D.K. Ljungblad. 1991. Passive acoustic monitoring program at the ARCO Alaska, Inc. "Fireweed" prospect September - October 1990. Rep. from Coastal & Offshore Pacific Corp., Walnut Creek, CA, [for ARCO Alaska Inc., Anchorage, AK]. 41 p.

Hanna, J.S. 1976. Reflection loss for long-range transmission loss estimates: what matters and how it may be measured. Rep. SAI-76-688-WA. Rep. from Science Applications Inc. for Office of Naval Res., Arlington, VA. 22 p.

Hoekstra, J.A. and J. Jansen. 1986. Statistical significance in comparative ethological experiments. **Appl. Anim. Behav. Sci.** 16:303-308.

Johnson, C.W., M.W. McManus and D. Skaar. 1989. Masked tonal hearing thresholds in the beluga whale. **J. Acoust. Soc. Am.** 85(6):2651-2654.

Johnson, S.R., C.R. Greene, R.A. Davis and W.J. Richardson. 1986. Bowhead whales and underwater noise near the Sandpiper Island drillsite, Alaskan Beaufort Sea, autumn 1985. Rep. from LGL Ltd., King City, Ont., for Shell Western E & P Inc., Anchorage, AK. 130 p.

Knudsen, V.O., R.S. Alford and J.W. Emling. 1948. Underwater ambient noise. **J. Mar. Res.** 3:410-429.

Koski, W.R. and S.R. Johnson. 1987. Behavioral studies and aerial photogrammetry. Sect. 4. *In*: Responses of bowhead whales to an offshore drilling operation in the Alaskan Beaufort Sea, autumn 1986. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for Shell Western E & P Inc., Anchorage, AK. 371 p.

Koski, W.R., R.A. Davis, G.W. Miller and D. Withrow. in press. Reproduction. *In*: J.J. Montague and J. Burns (eds.), The bowhead whale. Soc. Mar. Mamm. Spec. Publ.

LGL and Greeneridge. 1986. Reactions of beluga whales and narwhals to ship traffic and ice-breaking along ice edges in the eastern Canadian high arctic: 1982-1984. Envir. Stud. No. 37, Dep. Indian Affairs & North. Devel., Ottawa. 301 p.

LGL and Greeneridge. 1987. Responses of bowhead whales to an offshore drilling operation in the Alaskan Beaufort Sea, autumn 1986. Rep. from LGL Ltd., King City, Ont., and Greeneridge Sciences Inc., Santa Barbara, CA, for Shell Western E & P Inc., Anchorage, AK. 371 p.

Ljungblad, D.K., P.O. Thompson and S.E. Moore. 1982. Underwater sounds recorded from migrating bowhead whales, *Balaena mysticetus*, in 1979. **J. Acoust. Soc. Am.** 71:477-482.

Ljungblad, D.K., B. Würsig, S.L. Swartz and J.M. Keene. 1988. Observations on the behavioral responses of bowhead whales (*Balaena mysticetus*) to active geophysical vessels in the Alaskan Beaufort Sea. **Arctic** 41(3):183-194.

Lowell, W.R. and W.F. Flanigan Jr. 1980. Marine mammal chemoreception. **Mamm. Rev.** 10(1):53-59.

Machlis, L., P.W.D. Dodd and J.C. Fentress. 1985. The pooling fallacy: problems arising when individuals contribute more than one observation to the data set. **Z. Tierpsychol.** 68:201-214.

Malme, C.I., P.R. Miles, C.W. Clark, P. Tyack and J.E. Bird. 1983. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior. BBN Rep. 5366. Rep. from Bolt Beranek & Newman Inc., Cambridge, MA, for U.S. Minerals Manage. Serv., Anchorage, AK. Var. pag. NTIS PB86-174174.

Malme, C.I., P.R. Miles, C.W. Clark, P. Tyack and J.E. Bird. 1984. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior/Phase II: January 1984 migration. BBN Rep. No. 5586. Rep. from Bolt Beranek and Newman, Inc., Cambridge, MA, for U.S. Minerals Manage. Serv., Anchorage, AK. Variously paginated. NTIS PB86-218377.

Malme, C.I., J. Webb, G. Duckworth and P.R. Miles. 1989/1990. Prediction of spring acoustic environmental conditions near Point Barrow. BBN Tech. Memo. 1026. Rep. from BBN Systems & Technol. Corp., Cambridge, MA, for LGL Ltd., King City, Ont. 23 p. Appears as Appendix 1 in Richardson et al. (1990a).

Mead, R. 1988. The design of experiments. Cambridge Univ. Press, Cambridge, U.K. 620 p.

Miles, P.R., C.I. Malme and W.J. Richardson. 1987. Prediction of drilling site-specific interaction of industrial acoustic stimuli and endangered whales in the Alaskan Beaufort Sea. BBN Rep. 6509; OCS Study MMS 87-0084. Rep. from BBN Labs Inc., Cambridge, MA, and LGL Ltd., King City, Ont., for U.S. Minerals Manage. Serv., Anchorage, AK. 341 p. NTIS PB88-158498.

Miller, G.W. 1989. Site selection and timing of the 1989 spring bowhead disturbance study: a background report. Rep. from LGL Ltd., King City, Ont., for U.S. Minerals Manage. Serv., Anchorage, AK. 23 p.

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. Rep. from SEACO Inc., San Diego, CA, for U.S. Minerals Manage. Serv., Anchorage, AK. 111 p. NTIS PB86-168887.

Nerini, M.K., H.W. Braham, W.M. Marquette and D.J. Rugh. 1984. Life history of the bowhead whale, *Balaena mysticetus* (Mammalia: Cetacea). **J. Zool. (Lond.)** 204(4):443-468.

Norris, J.C. and S. Leatherwood. 1981. Hearing in bowhead whale, *Balaena mysticetus*, as estimated by cochlear morphology. p. 745-787 *In*: T.F. Albert (ed.), Tissue structural studies and other investigations on the biology of endangered whales in the Beaufort Sea. Vol. II. Rep. from Dept. Vet. Sci., Univ. Maryland, College Park, MD, for U.S. Bur. Land Manage., Anchorage, AK. NTIS PB86-153566.

Norton, D. and G. Weller. 1984. The Beaufort Sea: background, history, and perspective. p. 3-19 *In*: P.W. Barnes, D.M. Schell and E. Reimnitz (eds.), The Alaskan Beaufort Sea ecosystems and environments. Academic Press, Orlando, FL. 466 p.

Richardson, W.J. 1989. Theoretical detection and reaction distances of bowhead and white whales migrating near Barrow, AK, in spring when exposed to noise from an underwater sound projector. Rep. from LGL Ltd., King City, Ont., for U.S. Minerals Manage. Serv., Anchorage, AK. 22 p.

Richardson, W.J. and K.J. Finley. 1989. Comparison of behavior of bowhead whales of the Davis Strait and Bering/Beaufort stocks. OCS Study MMS 88-0056. Rep. from LGL Ltd., King City, Ont., for U.S. Minerals Manage. Serv., Herndon, VA. 131 p. NTIS PB89-195556.

Richardson, W.J. and C.I. Malme. in press. Man-made noise and behavioral responses. *In*: J.J. Montague and J. Burns (eds.), The bowhead whale. Soc. Mar. Mamm. Spec. Publ.

Richardson, W.J., M.A. Fraker, B. Würsig and R.S. Wells. 1985a. Behaviour of bowhead whales *Balaena mysticetus* summering in the Beaufort Sea: reactions to industrial activities. **Biol. Conserv.** 32(3):195-230.

Richardson, W.J., R.S. Wells and B. Würsig. 1985b. Disturbance responses of bowheads, 1980-84. p. 89-196 *In*: W.J. Richardson (ed.), Behavior, disturbance responses and distribution of bowhead whales *Balaena mysticetus* in the eastern Beaufort Sea, 1980-84. OCS Study MMS 85-0034. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Manage. Serv., Reston, VA. 306 p. NTIS PB87-124376.

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. **J. Acoust. Soc. Am.** 79(4):1117-1128.

Richardson, W.J., B. Würsig and G.W. Miller. 1987. Bowhead distribution, numbers and activities. p. 257-368 *In*: W.J. Richardson (ed.), Importance of the eastern Alaskan Beaufort Sea to feeding bowhead whales, 1985-86. OCS Study MMS 87-0037. Rep. from LGL Ecol. Res. Assoc. Inc., Bryan, TX, for U.S. Minerals Manage. Serv., Reston, VA. 547 p. NTIS PB88-150271.

Richardson, W.J., C.R. Greene, J.P. Hickie and R.A. Davis and D.H. Thomson. 1989. Effects of offshore petroleum operations on cold water marine mammals. a literature review. 2nd edition. API Rep. 4485. Am. Petrol. Inst., Washington, DC. 385 p.

Richardson, W.J., C.R. Greene, Jr., W.R. Koski, C.I. Malme, G.W. Miller, M.A. Smultea and B. Würsig. 1990a. Acoustic effects of oil production activities on bowhead and white whales during spring migration near Pt. Barrow, Alaska--1989 phase. OCS Study MMS 90-0017. Rep. from LGL Ltd., King City, Ont., for U.S. Minerals Manage. Serv., Herndon, VA. 284 p. NTIS PB91-105486.

Richardson, W.J., B. Würsig and C.R. Greene, Jr. 1990b. Reactions of bowhead whales, *Balaena mysticetus*, to drilling and dredging noise in the Canadian Beaufort Sea. **Mar. Envir. Res.** 29(2):135-160.

Richardson, W.J., C.R. Greene Jr., C.I. Malme and D.H. Thomson. 1991. Effects of noise on marine mammals. OCS Study MMS 90-0093. Rep. from LGL Ecol. Res. Assoc. Inc., Bryan, TX, for U.S. Minerals Manage. Serv., Atlantic OCS Region, Herndon, VA. 462 p. NTIS PB91-168914.

Rihaczek, A.W. 1986. Doppler-tolerant signal waveforms. IEEE Proc. 54 (June 1986).

Ross, D. 1976. Mechanics of underwater noise. Pergamon, New York, NY. 375 p.

Sonntag, R.M. and W.T. Ellison. 1987. Refraction effects in the arctic environment applied to the visual censusing of bowhead whales, *Balaena mysticetus*. Sci. Doc. SC/39/PS9. Int. Whal. Comm., Cambridge, UK. 31 p.

Steel, R.G.D. and J.H. Torrie. 1960. Principles and procedures of statistics with special reference to the biological sciences. McGraw-Hill, New York, NY. 481 p.

Terhune, J.M. and K. Ronald. 1975. Underwater hearing sensitivity of two ringed seals (*Pusa hispida*). **Can. J. Zool.** 53:227-231.

Thomas, J.A., R.A. Kastelein and F.T. Awbrey. 1990. Behavior and blood catecholamines of captive belugas during playbacks of noise from an oil drilling platform. **Zoo Biol.** 9(5):393-402.

Thorp, W.H. 1967. Analytic description of the low-frequency attenuation coefficient. **J. Acoust. Soc. Am.** 42(1):270

Turl, C.W. and R.H. Penner. 1989. Differences in echolocation click patterns of the beluga (*Delphinapterus leucas*) and the bottlenose dolphin (*Tursiops truncatus*). **J. Acoust. Soc. Am.** 86(2):497-502.

Turl, C.W., R.H. Penner and W.W.L. Au. 1987. Comparison of target detection capabilities of the beluga and bottlenose dolphin. **J. Acoust. Soc. Am.** 82(5):1487-1491.

Urick, R.J. 1983. Principles of underwater sound, 3rd ed. McGraw-Hill, New York, NY. 423 p.

USRD. 1982. Underwater electroacoustic standard transducers catalogue. Standards Sect., Transducer Branch, Underwater Sound Reference Detachment, Naval Res. Lab., Orlando, FL. 175 p.

Watkins, W.A. 1986. Whale reactions to human activities in Cape Cod waters. **Mar. Mamm. Sci.** 2(4):251-262.

Watkins, W.A., P. Tyack and K.E. Moore. 1987. The 20-Hz signals of finback whales (*Balaenoptera physalus*). **J. Acoust. Soc. Am.** 82(6):1901-1912.

Wenz, G.M. 1962. Acoustic ambient noise in the ocean: spectra and sources. **J. Acoust. Soc. Am.** 34(12):1936-1956.

White, M.J., Jr., J. Norris, D. Ljungblad, K. Baron and G. di Sciara. 1978. Auditory thresholds of two beluga whales (*Delphinapterus leucas*). HSWRI Tech. Rep. 78-109. Rep. from Hubbs/Sea World Res. Inst., San Diego, CA, for Naval Ocean Systems Center, San Diego, CA. 35 p.

Würsig, B. 1978. On the behavior and ecology of bottlenose and dusky porpoises in the South Atlantic. PhD dissertation, State Univ. of New York at Stony Brook, Stony Brook, NY. 335 p.

Würsig, B., E.M. Dorsey, M.A. Fraker, R.S. Payne, W.J. Richardson and R.S. Wells. 1984. Behavior of bowhead whales, *Balaena mysticetus*, summering in the Beaufort Sea: surfacing, respiration, and dive characteristics. **Can. J. Zool.** 62(10):1910-1921.

Würsig, B., E.M. Dorsey, M.A. Fraker, R.S. Payne and W.J. Richardson. 1985. Behavior of bowhead whales, *Balaena mysticetus*, summering in the Beaufort Sea: a description. **Fish. Bull. U.S.** 83(3):357-377.

Würsig, B., E.M. Dorsey, W.J. Richardson and R.S. Wells. 1989. Feeding, aerial and play behaviour of the bowhead whale, *Balaena mysticetus*, summering in the Beaufort Sea. **Aquat. Mammals** 15:27-37.

Würsig, B., J. Guerrero, D. Wartzok, W. Watkins, G. Silber and B. Kelly. 1990. Social and sexual behavior of bowhead whales in fall: a re-evaluation of seasonal trends. p. 213-217 *In*: 5th Conf. on the Biology of the Bowhead Whale *Balaena mysticetus*/Extended Abstracts and Panel Discussions. North Slope Borough, Barrow, AK. 244 p.

Zar, J.H. 1984. Biostatistical analysis, 2nd ed. Prentice-Hall, Englewood Cliffs, NJ. 718 p.

APPENDIX A:

SOME ANALYSIS OF THE 1990 PROPAGATION DATA FROM BARROW

JOHN S. HANNA

Introduction

In this note, the 1/3 octave sweep data collected by Greeneridge Sciences Inc., in 1990 off Pt. Barrow are analyzed to establish approximate forms of the propagation loss as a function of range and frequency. The method used involves comparison of the data with a simple model for an isovelocity waveguide that has both volume and boundary losses. Under the assumption that data are measured along tracks of approximately constant depth in a region with homogeneous bottom properties, the model allows scaling the data from tracks with differing depths to a common set of coordinates. With the data coalesced this way, it is possible to fit model curves to the data. The boundary losses are parameters in the equations for these model curves.

Model

An analytical model has been developed for sound propagation in a homogeneous waveguide with a lossy boundary (Hanna 1976). The approach uses ray theory and a particular relationship between reflection loss and angle. The intensity form of the propagation loss is

$$I=4\frac{e^{-\frac{\gamma_0 R\theta_{\min}}{2D}}}{\gamma R^2}\left[1-e^{-\frac{\gamma R\Delta\theta}{2D}}\right] \tag{1}$$

where R is range (in meters or yards, depending on the convention for a reference range), D is depth of the waveguide, γ_0 and γ are parameters related to the boundary loss, $\theta_{\min}$ corresponds to the ray with the longest allowable ray-cycle distance, and $\Delta\theta$ is the aperture of propagating energy. Equation 1 is valid for R>D, that is, beyond the initial spherical spreading range from the source. The details of the relationships of these parameters to physical bottom properties are not important for this discussion. At this point, it is enough to note that γ_0 is related to the loss at grazing incidence and γ is related to the loss at higher angles. The functional dependence of Equation 1 on range, depth, and the environmental parameters γ_0 and γ is the primary interest. This emphasis suggests rewriting the equation in the following way:

$$I=\frac{\Delta\theta}{D^2}\frac{e^{-\alpha\rho}}{\beta\rho^2}\left[1-e^{-\beta\rho}\right] \tag{2}$$

where

$$\alpha \equiv \gamma_0 \theta_{min}$$
$$\beta \equiv \gamma \Delta\theta$$
$$\rho \equiv \frac{R}{2D}$$

If there is volume attenuation, then Equation 2 will be modified by an additional exponential factor, $e^{-\delta R}$.

The form of Equation 2 suggests that, if data are available from waveguides of differing depths but the same bottom properties, then plotting the quantity

$$\bar{I} = e^{\delta R} D^2 I \tag{3}$$

as a function of R/2D, where δ is the volume attenuation constant, will produce a single curve. In the analysis below, the hypothesis is adopted that, for the region where the 1990 data were collected, the bottom properties were constant. Furthermore, it is assumed that a representative depth can be assigned to each propagation test. This is arguable, but does differentiate the significant difference in depth for the three shallow-depth tests and one deep test.

Before turning to the data, it is instructive to examine the implications of Equation 2. First, if α and β are zero, the equation becomes

$$I = \frac{\Delta\theta}{D^2} \frac{1}{\rho}$$

which is the familiar cylindrical spreading result for a waveguide without boundary losses. For finite β and $\beta\rho \gg 1$, Equation 2 approaches

$$I = \frac{\Delta\theta}{D^2} \frac{e^{-\alpha\rho}}{\beta\rho^2}$$

which corresponds to a single path at the shallowest grazing angle, suffering a loss at the boundary expressed by the exponential attenuation term. Although β is related to loss properties of the waveguide, it is useful to interpret its reciprocal as the transition range between cylindrical and spherical spreading determined by the factor

$$\frac{1-e^{-\beta\rho}}{\beta\rho^2}$$

since for $\beta\rho \ll 1$ this factor behaves like cylindrical spreading, and for $\beta\rho \gg 1$ it behaves like spherical spreading. As an illustrative example, Figure 103 shows the model version of Equation 3 for cylindrical and spherical spreading. Figure 104A shows a case for which β=0.07, implying that the transition range is about 14. Figure 104B illustrates the case from Figure 104A with some damping from α=0.01. At this value of α, the loss at a range of 100 is 10 log(e)=4.34 dB greater than it would otherwise be; this can be confirmed by comparison of Figures 104A and B. The parameter I0 accounts for the factor $\Delta\theta$, when necessary.

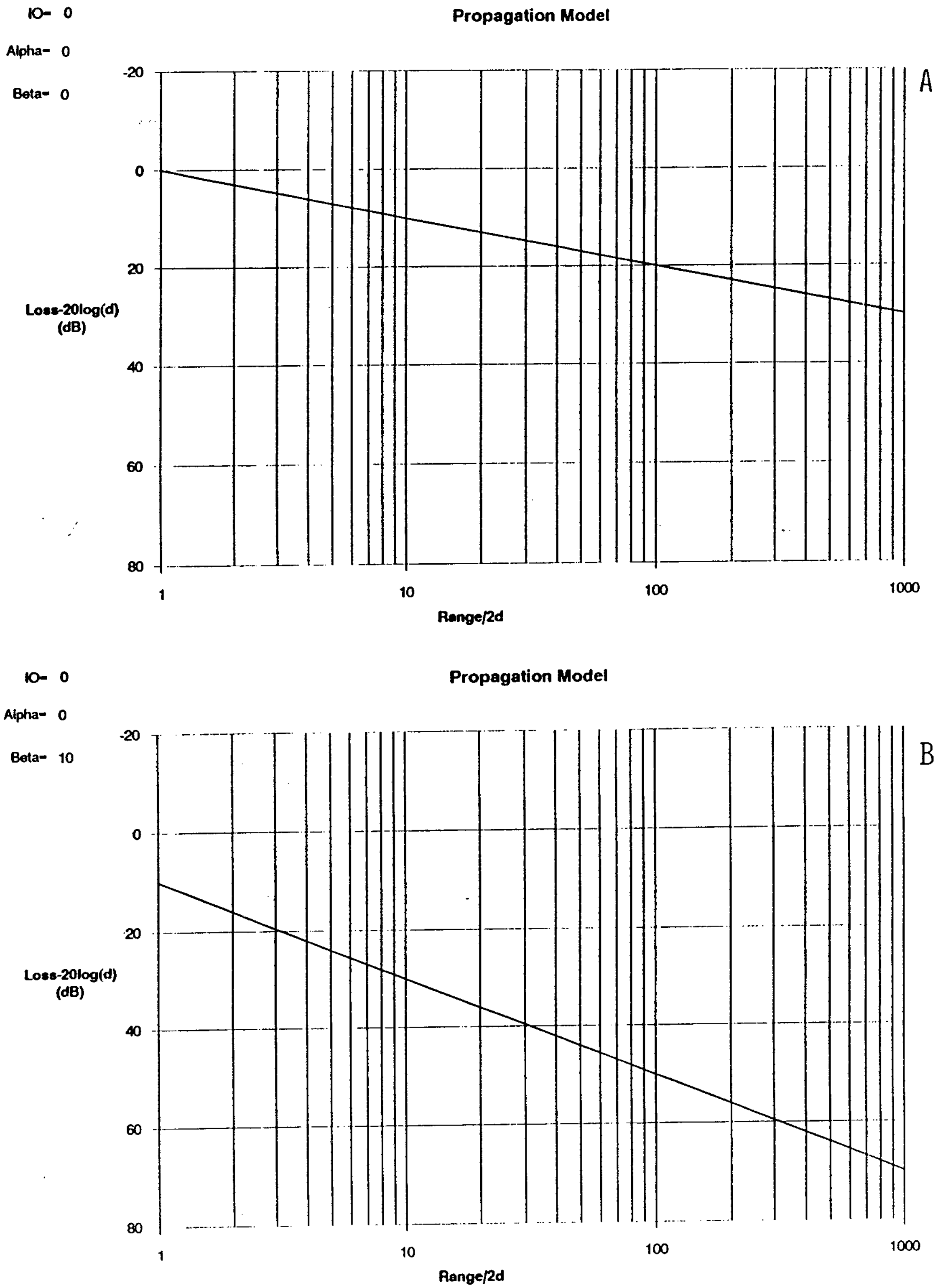

IO= 0
Alpha= 0
Beta= 0
Propagation Model
A
-20
0
20
40
60
80
Loss-20log(d)
(dB)
1
10
100
1000
Range/2d
IO= 0
Alpha= 0
Beta= 10
Propagation Model
B
-20
0
20
40
60
80
Loss-20log(d)
(dB)
1
10
100
1000
Range/2d

FIGURE 103.

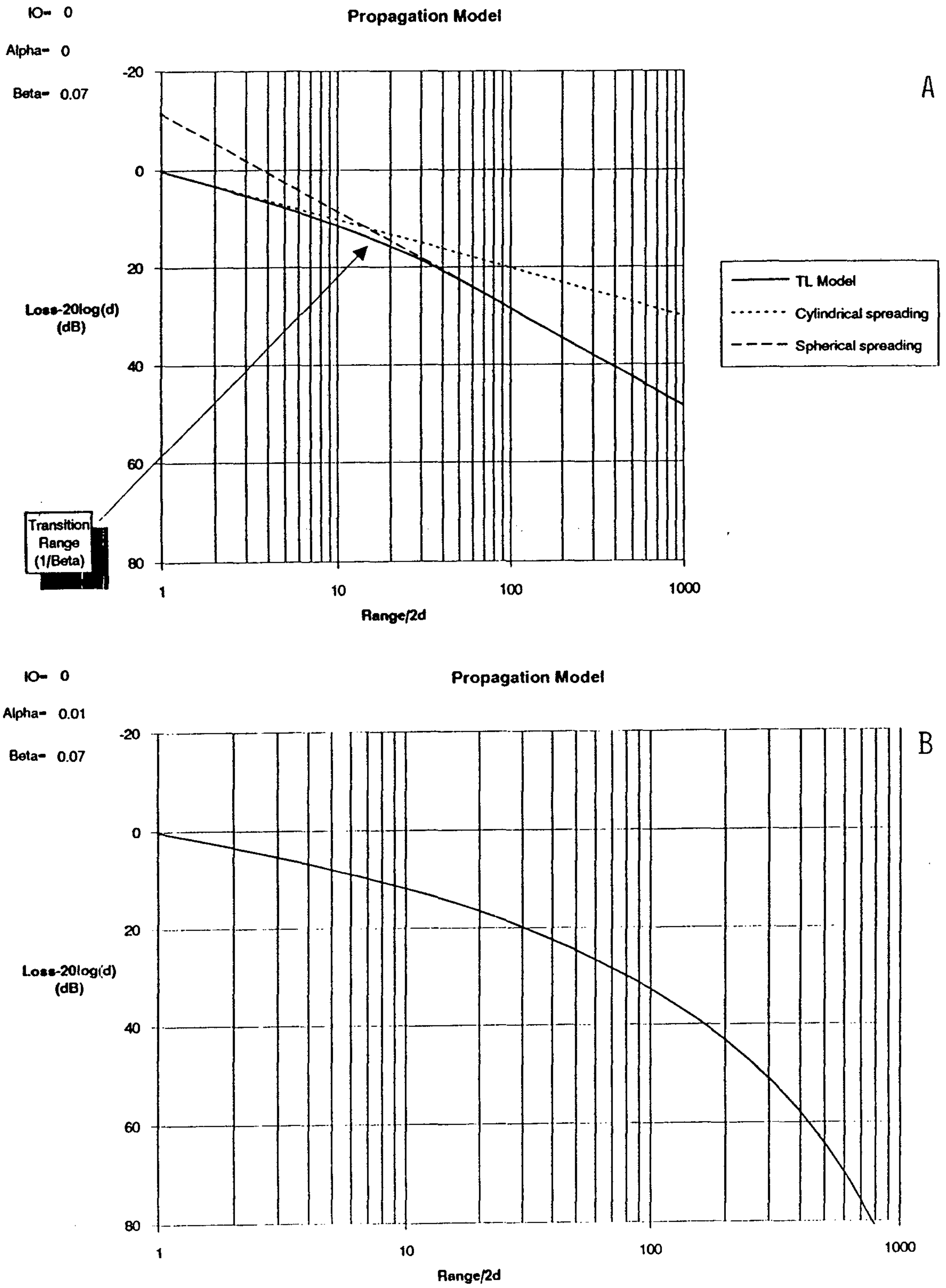

IO= 0
Alpha= 0
Beta= 0.07
Propagation Model
A
-20
0
20
40
60
80
Loss-20log(d) (dB)
1
10
100
1000
Range/2d
TL Model
Cylindrical spreading
Spherical spreading
Transition Range (1/Beta)
IO= 0
Alpha= 0.01
Beta= 0.07
Propagation Model
B
-20
0
20
40
60
80
Loss-20log(d) (dB)
1
10
100
1000
Range/2d

FIGURE 104.

Data

With the perspective contained in the model described above, it is possible to plot the 1990 data from all four tests on a single graph for each frequency. This requires assigning a depth for each test, which was done from visual examination of the geographic plot of the measurement points and their depths for each test. The choices made are in Table 50. The procedure in scaling the data consisted of removing the volume attenuation using Thorp's expression (Thorp 1967):

$$-10\log(e^{-\delta}) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} \quad dB/km$$

where f is in kHz. The loss was then scaled for the appropriate depth and plotted as a function of the scaled range. The results of this operation for frequencies from 50 to 5000 Hz are shown in Figures 105 and 106.

Table 50

Test Number	Depth (m)
1	180
2	40
3	50
4	60

The first point to note is that the general behavior of all the data, out to a scaled range of 100, is quite similar at all frequencies. Recalling that spherical spreading in these coordinates is a straight line with a slope of 20 dB per decade of range, it can be seen that such a line is a reasonable first approximation at all frequencies except 50 Hz. At 50 Hz the data exhibit some noticeable curvature for ranges less than 100. Only the data points beyond this range (at 500, 1000 and 2000 Hz) suggest a significantly more rapid increase in loss with range. Also, at 50 Hz the variability at short ranges is probably the result of individual path behavior not captured in the simple model. However, the consistency of the data plotted in this scaled fashion is gratifying and lends some support to the hypothesis that the bottom conditions are homogeneous across the sampled area.

Model/Data Comparison

The model described above was used to obtain some fits to the data shown in Figures 105 through 106. The methodology involved fixing a value of α and searching for a value of β that produced the most appealing visual fit to the data. There was no attempt at something quantitatively objective, such as minimizing mean squared errors. Also, the assumption was made that the effective loss should be non-decreasing with frequency, which leads to the constraint that α and β must behave similarly. The choice of parameters was significantly influenced by the few data points beyond a range of 100 at the frequencies of 500, 1000, and 100 Hz. The resulting parameter choices are listed in Table 51 and the model/data comparisons are shown in Figures 107 through 110. The parameter I0 was not used in adjusting the curves. As mentioned in the model section, it corresponds to the factor $\Delta\theta$ in Equation 2; this effective aperture of propagating energy, as determined by the critical angle of reflection, might be expected to change with

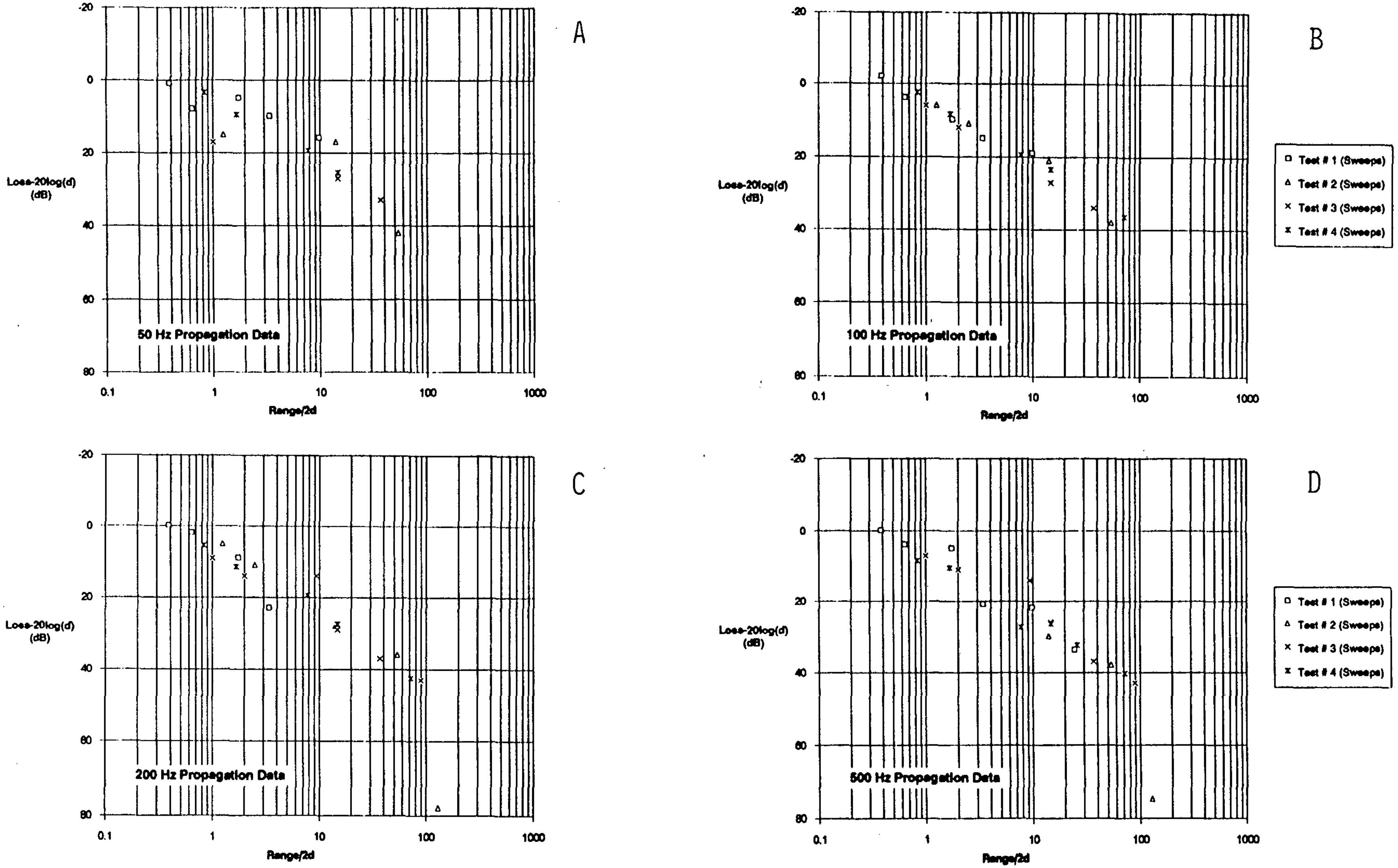

A
B
C
D
-20
0
20
40
60
80
Loss-20log(d) (dB)
0.1
1
10
100
1000
Range/2d
50 Hz Propagation Data
100 Hz Propagation Data
200 Hz Propagation Data
500 Hz Propagation Data
□ Test # 1 (Sweeps)
△ Test # 2 (Sweeps)
× Test # 3 (Sweeps)
ж Test # 4 (Sweeps)

FIGURE 105.

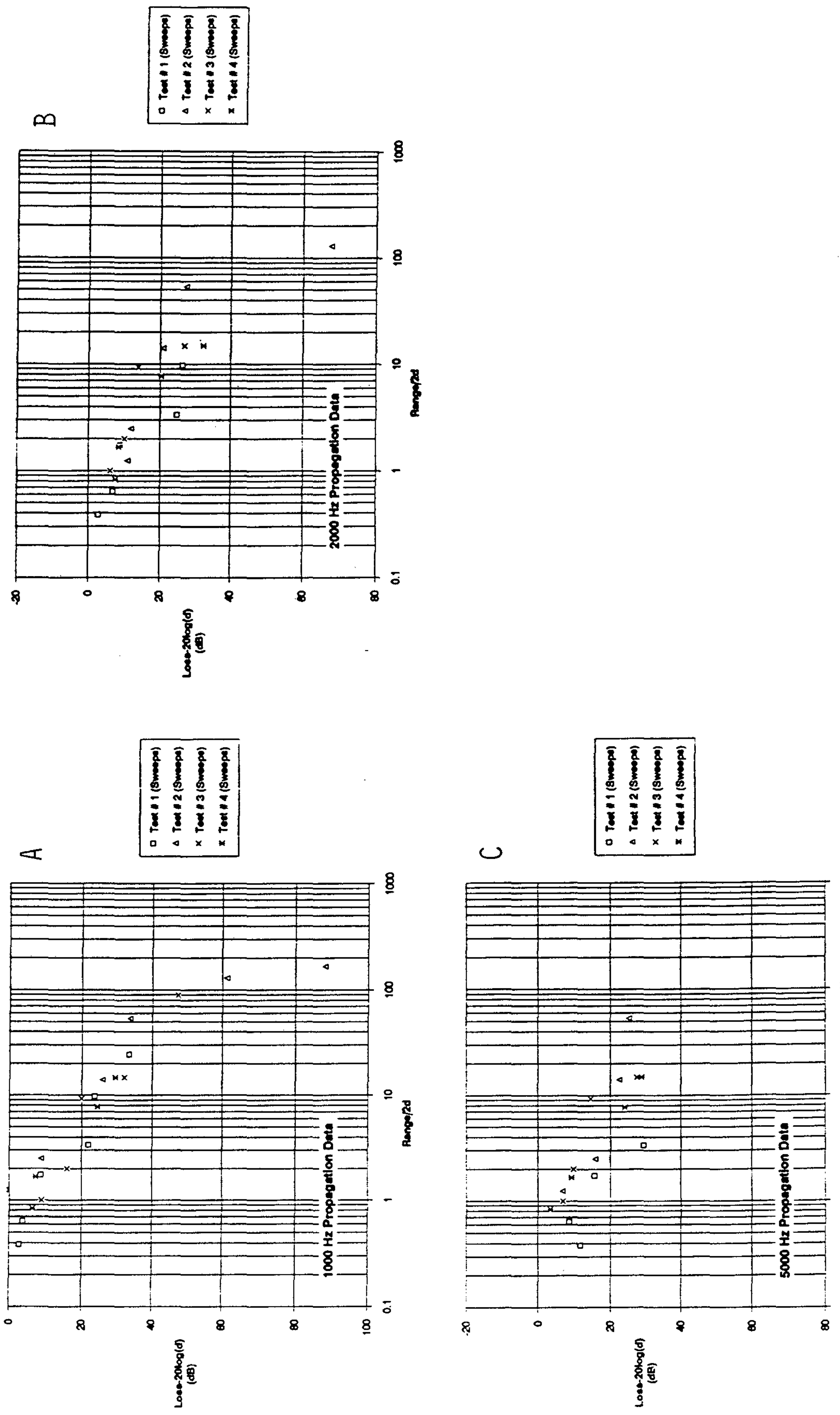

B
2000 Hz Propagation Data
Loss-20log(d) (dB)
Range/2d
-20
0
20
40
60
80
0.1
1
10
100
1000
Test # 1 (Sweeps)
Test # 2 (Sweeps)
Test # 3 (Sweeps)
Test # 4 (Sweeps)
A
1000 Hz Propagation Data
Loss-20log(d) (dB)
Range/2d
0
20
40
60
80
100
0.1
1
10
100
1000
Test # 1 (Sweeps)
Test # 2 (Sweeps)
Test # 3 (Sweeps)
Test # 4 (Sweeps)
C
5000 Hz Propagation Data
Loss-20log(d) (dB)
Range/2d
-20
0
20
40
60
80
0.1
1
10
100
1000
Test # 1 (Sweeps)
Test # 2 (Sweeps)
Test # 3 (Sweeps)
Test # 4 (Sweeps)

FIGURE 106.

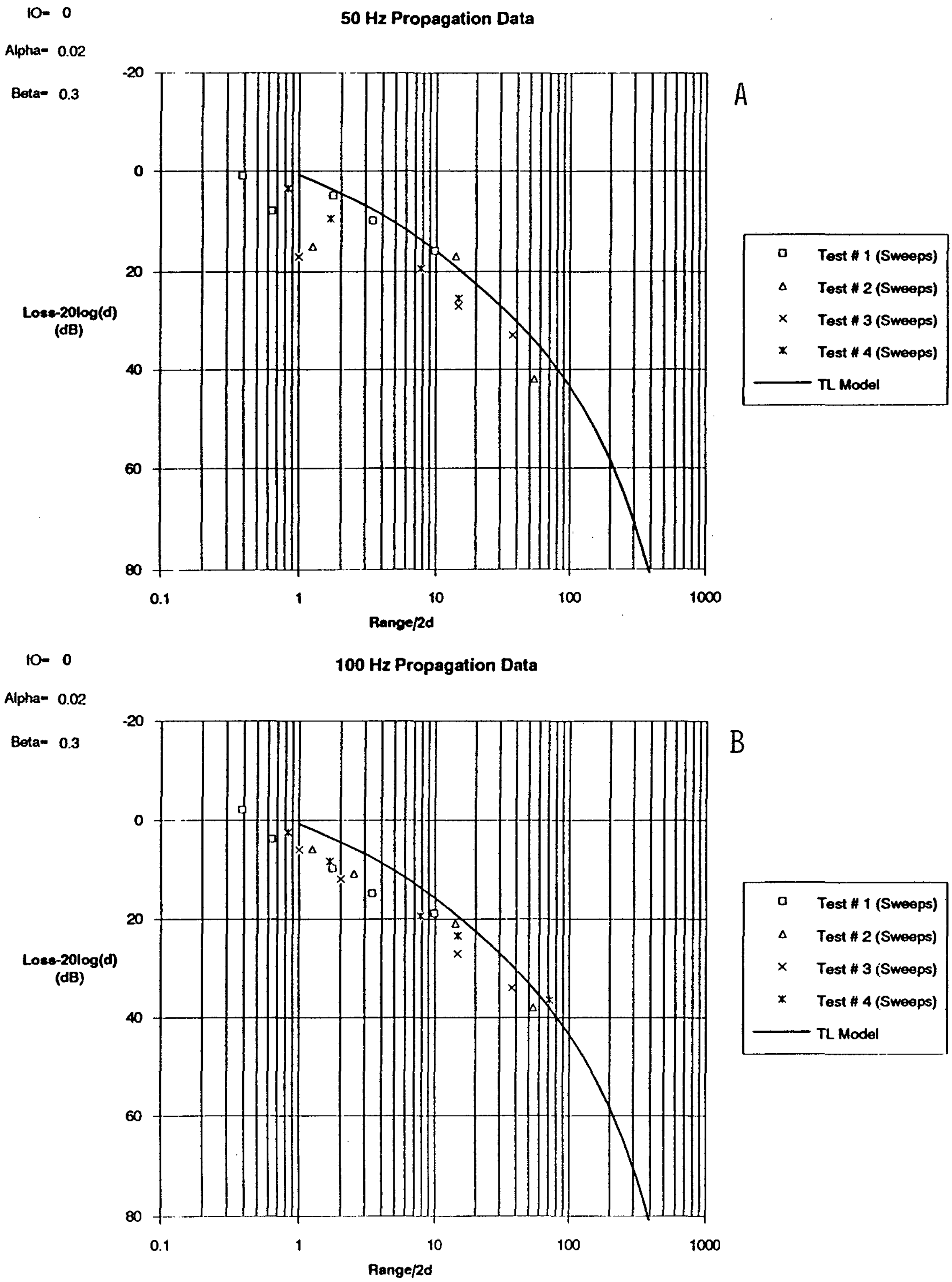

fO= 0
Alpha= 0.02
Beta= 0.3
50 Hz Propagation Data
A
-20
0
20
40
60
80
Loss-20log(d) (dB)
0.1
1
10
100
1000
Range/2d
Test # 1 (Sweeps)
Test # 2 (Sweeps)
Test # 3 (Sweeps)
Test # 4 (Sweeps)
TL Model
fO= 0
Alpha= 0.02
Beta= 0.3
100 Hz Propagation Data
B
-20
0
20
40
60
80
Loss-20log(d) (dB)
0.1
1
10
100
1000
Range/2d
Test # 1 (Sweeps)
Test # 2 (Sweeps)
Test # 3 (Sweeps)
Test # 4 (Sweeps)
TL Model

FIGURE 107.

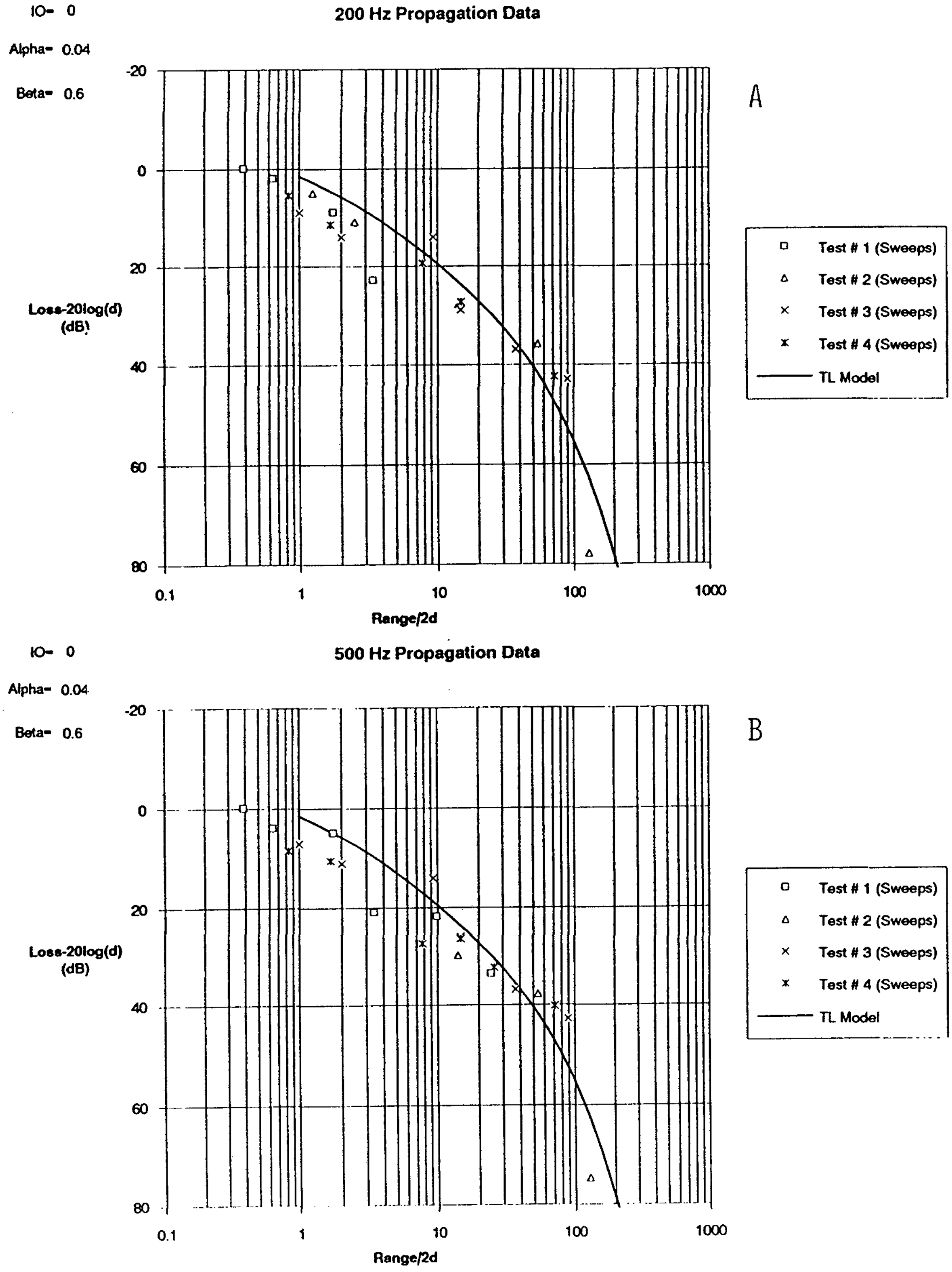

IO= 0
Alpha= 0.04
Beta= 0.6
200 Hz Propagation Data
A
-20
0
20
40
60
80
Loss-20log(d) (dB)
0.1
1
10
100
1000
Range/2d
Test # 1 (Sweeps)
Test # 2 (Sweeps)
Test # 3 (Sweeps)
Test # 4 (Sweeps)
TL Model
IO= 0
Alpha= 0.04
Beta= 0.6
500 Hz Propagation Data
B
-20
0
20
40
60
80
Loss-20log(d) (dB)
0.1
1
10
100
1000
Range/2d
Test # 1 (Sweeps)
Test # 2 (Sweeps)
Test # 3 (Sweeps)
Test # 4 (Sweeps)
TL Model

FIGURE 108.

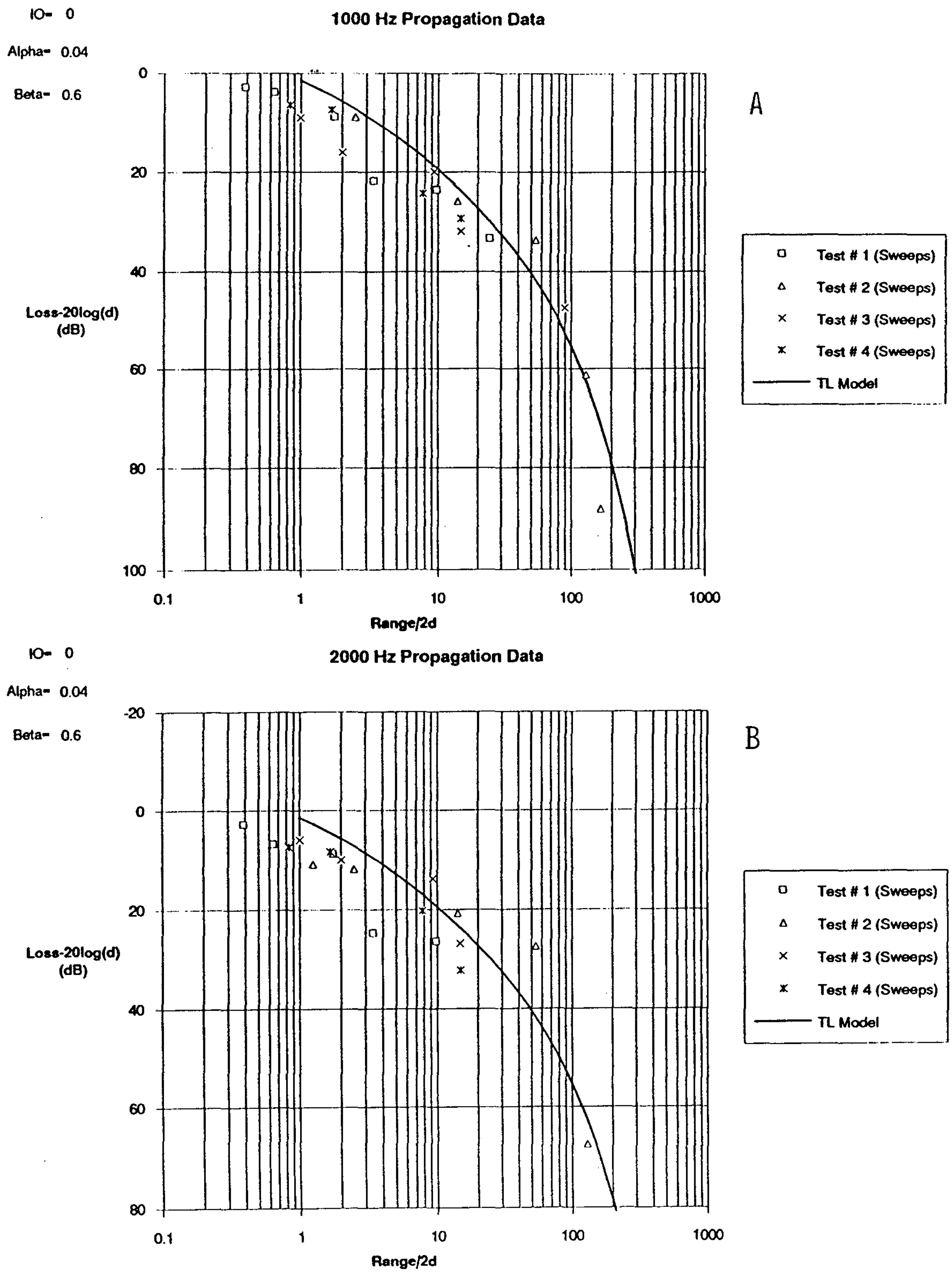

IO= 0
Alpha= 0.04
Beta= 0.6
1000 Hz Propagation Data
A
0
20
40
60
80
100
Loss-20log(d) (dB)
0.1
1
10
100
1000
Range/2d
Test # 1 (Sweeps)
Test # 2 (Sweeps)
Test # 3 (Sweeps)
Test # 4 (Sweeps)
TL Model
IO= 0
Alpha= 0.04
Beta= 0.6
2000 Hz Propagation Data
B
-20
0
20
40
60
80
Loss-20log(d) (dB)
0.1
1
10
100
1000
Range/2d
Test # 1 (Sweeps)
Test # 2 (Sweeps)
Test # 3 (Sweeps)
Test # 4 (Sweeps)
TL Model

FIGURE 109.

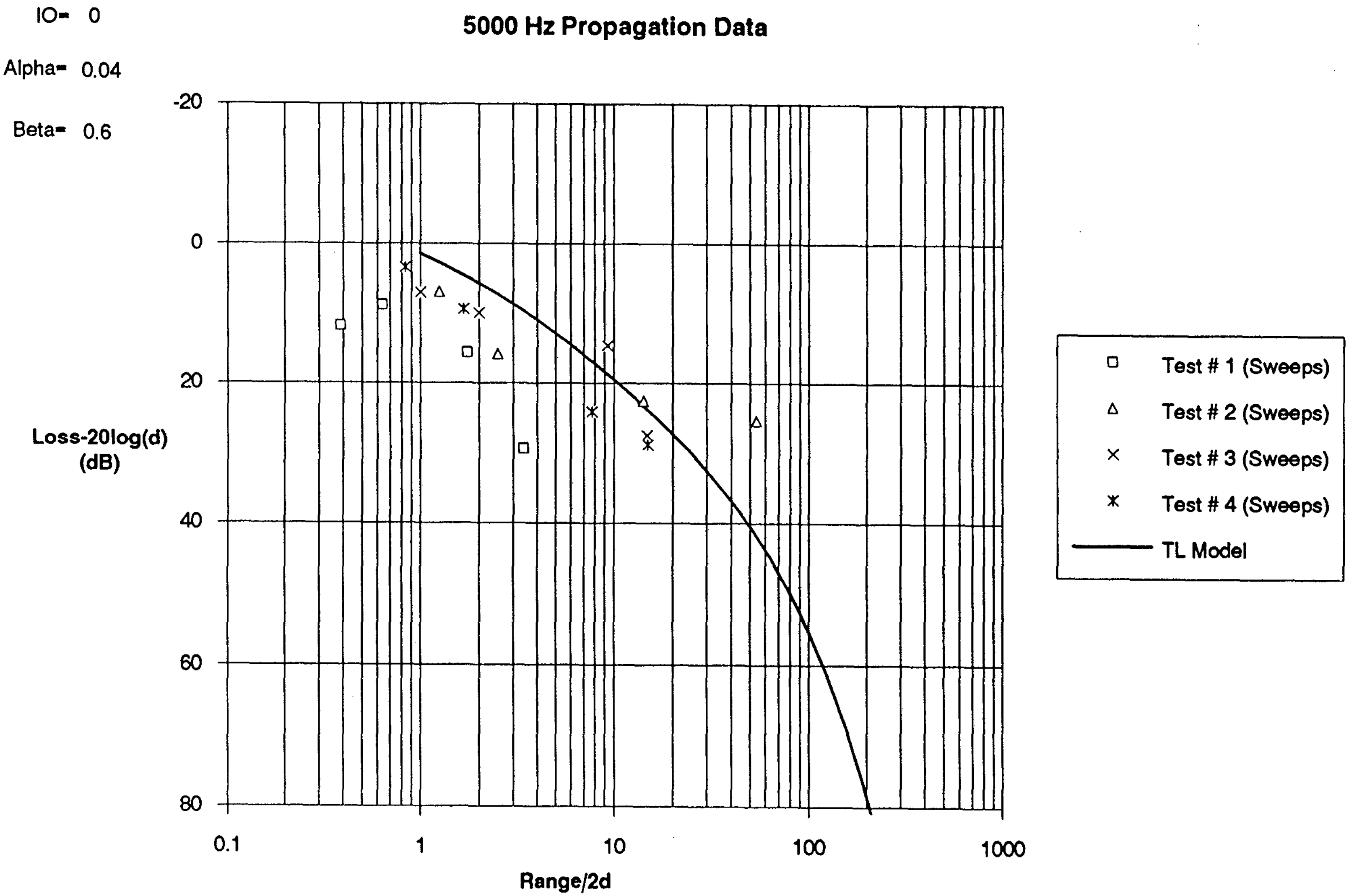

IO= 0
Alpha= 0.04
Beta= 0.6
5000 Hz Propagation Data
-20
0
20
40
60
80
Loss-20log(d)
(dB)
0.1
1
10
100
1000
Range/2d
□ Test # 1 (Sweeps)
△ Test # 2 (Sweeps)
× Test # 3 (Sweeps)
ж Test # 4 (Sweeps)
TL Model

FIGURE 110.

frequency; however, the level of fit permitted by the data did not seem to warrant small adjustments using this parameter.

The modeled representations of the data seem encouraging, given the model's lack of sophistication and detail. The fact that the environmental parameters are not very sensitive to frequency could be consistent with a sandy bottom that has a significant sound speed contrast. Such bottoms are common in shallow water near land. A more detailed test of this speculation is most appropriately made using a normal mode or PE model with a geoacoustic bottom. However, the parameterization of the data given here could be useful in estimating the approximate levels of ensonification during disturbance tests.

Table 51

f (Hz)	α	β
50	.02	.3
100	.02	.3
200	.04	.6
500	.04	.6
1000	.04	.6
2000	.04	.6
5000	.04	.6

References

Hanna, J.S. 1976. Reflection loss for long-range transmission loss estimates: what matters and how it may be measured. Rep. SAI-76-688-WA. Rep. from Science Applications Inc. for Office of Naval Res., Arlington, VA. 22 p.

Thorp, W.H. 1967. Analytic description of the low-frequency attenuation coefficient. **J. Acoust. Soc. Am.** 42(1):270.

APPENDIX B:

WHALE SOUND EXPOSURE

Whales were exposed to varying levels of *Karluk* sounds during the playback tests on six days in 1990: 9, 10, 13, 16 and 21 May. The projected sound levels were monitored at the sound projector to permit determination of the source level at 1 m distance. Received levels were monitored at sonobuoys at varying distances from the projector. The measured levels during playbacks, and the sound transmission loss models derived from transmission loss experiments on other days, were used to develop equations for received levels vs. distance during each playback test in 1990.

This Appendix describes the methods used to derive those equations. The resulting equations have been given earlier in the report, in the daily "Noise Exposure" sections (p. 125, 139, 146, 187, 199 and 215). Those sections include graphs showing the received levels measured by sonobuoys and predicted by the equations as a function of range. The results for all six days of interest are summarized in Table 45 on page 251.

General Procedures

Measured water depths at the playback sites influenced the choice of equation. In the shallowest water, i.e. depth <50 m, a spreading loss term of 10 log (R) corresponding to cylindrical spreading was appropriate. For depths 50 to 200 m, an intermediate spreading loss term of 15 log (R) was appropriate. For depths >200 m, spherical spreading--represented by 20 log (R)--was assumed to apply. These depth zones were selected after examining the measured received levels vs. range during disturbance and transmission loss tests.

Two or three frequency bands were considered when describing sound exposure: *(1)* The 20-1000 Hz band, which included all significant energy from the *Karluk* playback. *(2)* The one-third octave band centered at 200 Hz, which was generally the strongest one-third octave band in the *Karluk* spectrum. Occasionally, due to frequency-dependent propagation effects, the level in the one-third octave band centered at 160 or 250 Hz was slightly stronger than that near 200 Hz. In these cases, the band around 160 or 250 Hz was considered. *(3)* For the first disturbance test on 13 May, the one-third octave band centered at 1250 Hz was also considered. The first J-11 projector used on the 13th had developed a slow leak. Its output level gradually decreased and signal distortion increased. For part of this period the one-third octave band near 1250 Hz contained the strongest projected sounds. The adjacent one-third octave bands, centered at 1000 and 1600 Hz, were also considered in determining the strongest received levels during the first test on the 13th.

The specific procedures used to develop suitable transmission loss models for each playback day differed among days, depending on circumstances and the available data. During the analyses and computations, all sound levels were specified to the nearest 0.1 dB re 1 µPa. For presentation in tables, the results are rounded to the nearest integer dB.

For each playback test, the sound levels in the above-described frequency bands were calculated as functions of range. Estimated sound levels based on transmission loss models were graphed in relation to distance from the projector. These estimates were tabulated for standard distances of 0.2, 0.5, 1.0, 2.0, and 4.0 km (see Table 45 on p. 251). The equations were also used to estimate the received sound levels at the distances of closest approach by bowheads (see Tables 20-23, 35, 36 and Fig. 94).

The estimated levels received by bowheads were converted into signal-to-noise (S:N) ratios by taking into account the average measured ambient noise level on each playback day. These S:N estimates (Fig. 96) are the estimated received level of *Karluk* sound minus the ambient noise level in the corresponding frequency band. It should be noted that the ambient levels varied by as much as 20 dB during measurements on any given day, so specific S:N estimates are approximations.

9 May 1990

Received levels were measured at only one range (0.6 km) on 9 May 1990. Hence, it was not possible to derive an equation for received level vs. range solely from the 9 May measurements. The water depth at the 9 May playback site (139 m) was more similar to that during TL Test #1 (166-212 m) than to the shallower depths during the other three TL tests in 1990.

During TL Test #1 on 1 May 1990, received levels of *Karluk* sounds in the 20-1000 Hz band were determined at ranges 0.14-3.54 km (see Table 13 on p. 79 and Fig. 23D on p. 81). For TL Test #1, the received level at range R (in km) is given by the source level minus the transmission loss:

$$RL = SL - TL = 164.9 - 57.0 - 0.88\ R - 15 \log (R)$$

Thus, for TL Test #1,

$$RL_{20\text{-}1000\ Hz} = 107.9 - 0.88\ R - 15 \log (R)$$

If this equation from TL Test #1 is used to predict the received level at range 0.6 km, the result is 110.7 dB, as compared to the measured level of 110.2 dB on 9 May (Fig. 45 on p. 130). We would not generally expect such a close match, as TL Test #1 was actually conducted in a different area with different water depths and perhaps different geoacoustic bottom conditions.

During TL Test #1, received levels in the one-third octave band centered at 200 Hz were measurable only at distances 0.14-1.22 km. The resulting TL equation, while appropriate for the limited TL data, may not be appropriate for the 9 May disturbance test. As a first approximation, the equation used for 20-1000 Hz was adopted for the third-octave centered near 200 Hz, but with the constant term reduced so that the predicted value matches the measured level at range 0.6 km (Fig. 45). The resulting equation was

$$RL_{200\ Hz} = 100.0 - 0.88\ R - 15 \log (R)$$

10 May 1990

On 10 May, *Karluk* sounds were projected for 5.3 h beginning at 15:32. Water depths at the 10 May projector site varied from 66 to 72 m, compared to depths of 44-110 m for TL Test #3 and 50-105 m for TL Test #4. Received signal levels were recorded from a sonobuoy that drifted from range 1.6 to range 1.4 km while being recorded. This was an insufficient variety of ranges from which to derive equations for received levels out to 4 km, so results from relevant TL tests were also considered.

The results of TL Test #4 on 25 May 1990 seemed most applicable to the disturbance test conditions on 10 May. Of the frequency-specific equations derived for TL Test #4, the one for 200 Hz seemed appropriate. The measurement ranges spanned 0.1-12.74 km, compared to only 0.1-1.78 km for the 20-1000 Hz band (Table 13, Fig. 28-29). The equation was $TL_{200} = 56.2 + 0.81\ R + 15\ \log\ (R)$. The coefficients of the linear and log(R) terms were retained for the disturbance test equations. The constant terms for the disturbance test equations were derived by forcing the estimated values at range 1.6 km to match the measured values (see Fig. 52 on p. 141). The resulting equations were

$$RL_{20\text{-}1000\ Hz} = 116.4 - 0.81\ R - 15\ \log\ (R)$$

$$RL_{200\ Hz} = 111.0 - 0.81\ R - 15\ \log\ (R)$$

11 May 1990

The playback on 11 May began at 16:28 and ended at 17:48. Received levels were recorded from one sonobuoy while it drifted from range 3.2 to range 3.6 km, and from another sonobuoy while it drifted from 9.6 to 9.9 km. Water depths were 117-140 m. These depths were comparable to those during TL Test #1 on 1 May (166-212 m), when the spreading loss term was 15 log (R) (see Table 13 and Fig. 22-23 on p. 79-81). Hence, we fitted equations that included 15 log (R) terms to the received sound levels as measured via sonobuoys on 11 May (Fig. 56 on p. 147). Equations were derived for the 20-1000 Hz band and for the one-third octave band centered at 200 Hz:

$$RL_{20\text{-}1000\ Hz} = 121.4 - 1.24\ R - 15\ \log\ (R)$$

$$RL_{200\ Hz} = 117.2 - 1.37\ R - 15\ \log\ (R)$$

13 May 1990

On 13 May, there were two prolonged playback periods. *(1)* At 13:01 the projector was started at a low power level, and the power was gradually increased until full power was reached at 13:05. Noise spikes were received at the monitor hydrophone near the projector. The power was reduced slightly at 13:13, and again at 13:14. Operation continued with slowly increasing sound distortion, and decreasing overall level, until the projector was turned off at 15:06. Upon retrieval, the projector was found to be damaged. The rubber seal over the diaphragm was torn and sea water had flooded the projector. *(2)* The helicopter brought a backup J-11 from Barrow. It was turned on at 16:10, and reached full, undistorted power by 16:11. The second playback ended at 18:46.

Analyses of the transmitted and received sound levels were performed for several times during each of the two playbacks. During the undistorted period, the source level varied only slightly, within a range of 1.7 dB. However, the analyses for the distorted playback documented the declining source level and the increasing distortion (see Fig. 66-68 on p. 188-191). The increasing distortion was accompanied by increases in sound level in the third octave bands centered at and near 1250 Hz. By the middle and end of the distorted playback, these high-frequency bands contained the highest sound levels (Fig. 67, 68B)

On this date there were measurements of received levels at "near" sonobuoys 1.3-3.5 km west of the projector, and at a far sonobuoy 5.5-6.0 km west of the projector. The source level was determined throughout the playbacks by a monitor hydrophone near the projector.

Equations for received level vs. range were obtained taking account of transmission loss data for the shallowest TL test (#2), when the appropriate spreading loss term was 10 log (R), i.e. cylindrical spreading. The shallow depth during the 13 May playback, 27 m, strongly suggested that cylindrical spreading would apply then as well. Equations including a 10 log (R) spreading loss term were fitted to the 20-1000 Hz and 200 Hz measurements obtained during the undistorted playback on 13 May.

These fitted equations had linear loss terms of 4.08 dB/km for the 20-1000 Hz band and 4.19 dB/km for the one-third octave band centered at 200 Hz. Received levels in the one-third octave band centered at 1250 Hz were not measurable during the undistorted test on 13 May. However, the linear loss term for 1000 Hz from TL Test #2 (water depths 38-54 m) was 4.22 dB/km, and it was assumed to apply on 13 May. These three linear loss terms are mutually consistent. They also are reasonable when compared with the loss terms derived from summer and fall measurements without ice in other Beaufort Sea waters of comparable depth (Greene 1985, 1987a). In those measurements, loss terms of 1-2 dB/km were derived. Given the presence of much ice during this spring study, the surface roughness is greater and the scattering losses, in terms of dB per kilometer, are expected to be greater.

The constant terms for the 20-1000 Hz band and the one-third octave band centered at 200 Hz were selected so as to match estimated to measured levels (Fig. 69 on p. 192). For the 1250 Hz band, no measurements of received levels were available. In that case the constant was derived by applying the TL equation for 1000 Hz from TL Test #2 to the measured source level in the 1250 Hz band on 13 May (RL = SL - TL).

Figure 69 (p. 192) shows the estimated and measured levels vs. range during the undistorted playback on 13 May. Results are shown for the one-third octave band centered at 1250 Hz as well as for the usual 20-1000 Hz and 200 Hz bands. The equations for the undistorted playback were as follows:

$$RL_{20\text{-}1000\ \mathrm{Hz}} = 129.0 - 4.08\ R - 10 \log (R)$$

$$RL_{200\ \mathrm{Hz}} = 124.5 - 4.19\ R - 10 \log (R)$$

$$RL_{1250\ \mathrm{Hz}} = 84.9 - 4.22\ R - 10 \log (R)$$

Figure 70 shows estimated levels vs. range at three times during the distorted playback as well as for the undistorted period. The constant terms in the equations for the distorted playback period differed from those given immediately above for the undistorted playback; the linear (db/km) and 10 log (R) terms were unchanged. Because the source levels in the 20-1000 Hz band and the one-third octave band near 200 Hz diminished over the course of the distorted playback, the constant terms diminished correspondingly. However, the level in the one-third octave band near 1250 Hz increased as the distorted playback progressed; this is reflected in an increasing constant term over time for that band:

	Constant Term					
	Undistorted	at 13:11	at 14:08	at 15:05	Linear Term	Spreading Loss Term
20-1000 Hz	129.0	127.3	113.7	110.6	- 4.08 R	- 10 log (R)
200 Hz	124.5	123.7	106.8	101.1	- 4.19 R	- 10 log (R)
1250 Hz	84.9	90.9	99.5	100.1	- 4.22 R	- 10 log (R)

16 May 1990

The disturbance test on 16 May was conducted in shallow water, depth 41 m. Hence, it was assumed that cylindrical spreading would apply (10 log R) The *Karluk* sound projection began at a low level at 14:10, increased gradually, and reached full power at 14:16. Projection ended at 17:50. Measured source levels varied from 169.1 to 167.6 dB re 1 μPa-m in the 20-1000 Hz band. Sonobuoy measurements were available from a buoy that drifted over ranges 0.8-1.2 km and from a second buoy that drifted over ranges 3.8-4.2 km. The received levels at range 4.2 km were close to the ambient noise levels (Fig. 78 on p. 207). However, when the close and distant measurements were used to derive equations for received level vs. range, reasonable equations resulted. The resulting equations were as follows:

$$RL_{20\text{-}1000\ Hz} = 122.1 - 4.13\ R - 10 \log (R)$$

$$RL_{200\ Hz} = 116.2 - 4.41\ R - 10 \log (R)$$

21 May 1990

The water depths in this playback area were the deepest of any measured during the 1990 field season, 204-219 m. The *Karluk* playback began at 11:50 at low power. The level increased gradually from then until 11:55, when the "full-power" level was reached. The projector ceased operating at 15:57. Measured source levels during the period of full power operation varied from 165.5 to 166.9 dB re 1 μPa-m. Sonobuoy measurements of received level were available only from buoys at 0.4 and 0.9 km--too narrow a range of distances to provide good empirical data concerning the linear loss rate (dB/km).

The deep water implied that spherical spreading (20 log R) would occur out to a considerable distance from the projector. When equations with spherical spreading terms were fitted to the measurements, the linear loss terms were unreasonably high (10.26 and 13.26 dB/km for the 20-1000 Hz band and 200 Hz third-octave band, respectively). For better consistency with results from other days, the linear loss terms were forced to be 4.4 dB/km and the constants were adjusted so the curves would fall between the measured levels at 0.4 and 0.9 km (Fig. 84 on p. 216). The resulting equations were as follows:

$$RL_{20\text{-}1000\ Hz} = 106.7 - 4.40\ R - 20 \log (R)$$

$$RL_{200\ Hz} = 102.5 - 4.40\ R - 20 \log (R)$$