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MMS 95-0051

ACOUSTIC EFFECTS OF OIL PRODUCTION ACTIVITIES ON BOWHEAD AND WHITE WHALES VISIBLE DURING SPRING MIGRATION NEAR PT. BARROW, ALASKA—1991 AND 1994 PHASES:

SOUND PROPAGATION AND WHALE RESPONSES TO PLAYBACKS OF ICEBREAKER NOISE

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PROJECT ORGANIZATION

The 1991 and 1994 phases of this contract were 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, now of Foster Wheeler Environmental Corp., 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. **BBN Systems & Technologies Corp.** assisted with physical acoustics modeling in 1989. The affiliations of the senior authors (in boldface) and co-authors are as follows:

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Another major contributor to the fieldwork in 1989-91 and 1994 was Kenneth Toovak Sr. of Barrow.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Previous studies of the reactions of bowhead whales to noise from oil industry operations have been conducted during late summer or early autumn, in open water or at most light ice conditions. Concern has arisen about potential effects of man-made noise in the leads through which bowheads migrate in spring.

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 were

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 1991/94 Objectives

The present report deals primarily with data collected in the springs of 1991 and 1994, the third and fourth years of the project. However, many parts of the report also take account of data collected in 1989 and 1990. In 1989-90, data were obtained on ambient noise, acoustic transmission loss, activities of undisturbed bowhead and white whales during spring migration, reactions of both species to playbacks of recorded continuous low-frequency sound from a drilling operation on the *Karluk* grounded ice pad, and reactions of both species to aircraft overflights. The 1989-90 results were reported in two previous LGL reports to MMS, OCS Studies MMS 90-0017 and 91-0037 (Richardson et al. 1990a, 1991a).

The specific objectives of the 1991 and 1994 phases of this project were similar to those in 1989-90, with the main exception being that the top priority work involved playbacks of variable icebreaker sounds to bowheads. When possible, reactions of white whales as well as bowheads were to be determined. Because of poor weather and ice conditions in 1991, and the low number of whales observable during playbacks in that year, few data on reactions to playbacks of icebreaker sounds were acquired in 1991. Hence, the highest priority for subsequent fieldwork was to continue studying reactions of bowheads to icebreaker noise playbacks. Fieldwork was not possible in 1992 or 1993 because of concern about potential interference with the ice-based bowhead census at Barrow in 1992 and 1993. Fieldwork resumed in 1994.

Because of the possible effects of low-frequency industrial sound components on bowheads, and the inability of a practical sound projector to reproduce those components adequately, indirect methods of addressing the importance of low-frequency components were again identified as one of the specific objectives in 1991/94 (see item 5, below).

The specific objectives for 1991/94 were as follows:

1. To record sounds from the SSDC caisson while it was drilling during winter conditions, including infrasonic components, and to analyze those sounds to determine their levels, spectral characteristics, and attenuation properties.
2. 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.
3. 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, and *(b)* continuous industrial sounds. Infrasonic components cannot be projected.
4. 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 variable icebreaker sounds. Infrasonic components cannot be projected.
5. To collect some of the data needed to assess the importance of the infrasonic components of industrial noise. Specifically, *(a)* to measure ambient noise at infrasonic frequencies, and *(b)* to determine whether bowhead calls contain infrasonic components (supplementing limited data from 1990). Also, based on the winter recordings of SSDC sounds (specific objective 1), we were *(c)* to determine the frequencies, levels and attenuation of the infrasonic components of drilling caisson sound.
6. To measure, on an opportunistic basis, 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 (supplementing limited data from 1989-90).
7. To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses and acoustic environment of bowhead and white whales along their spring migration corridor in the western Beaufort Sea.
8. 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.
9. To analyze the data to test hypotheses concerning the effects of the icebreaker sounds and helicopter overflights mentioned in (4) and (6) 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.

Significant progress has been made toward meeting all nine objectives during the four spring seasons. Several objectives—2, 3, 5a, 7 and 8—can be considered "achieved". Some data on the responsiveness of spring-migrating bowheads and white whales to playbacks of steady drilling noise and variable icebreaker noise were obtained, along with some data on responsiveness to actual aircraft overflights (objectives 4, 6 and 9). However, better quantification of whale responses to these activities than achieved in this study would be desirable. Similarly, objectives 1 and 5b,c were partially met, but additional data would be helpful.

Approach and Procedures

No oil production facilities have yet been constructed in or near the spring lead systems off northern Alaska, so a study of the effects of such facilities on whales must be done by simulation methods. The underwater sound playback method was used. Two types of playbacks were conducted: ▸ In 1989-90, playbacks of steady low-frequency noise recorded near the *Karluk* drilling operation on a grounded ice pad. ▸ In 1991/94, playbacks of variable and broader-bandwidth sound from the icebreaking supply ship *Robert Lemeur* recorded while it was managing ice.

The study had to be conducted such 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 with spring whaling, and the bowhead census is also done just north of Barrow. After consultation with the Barrow Whaling Captains' Association, Alaska Eskimo Whaling Commission, and North Slope Borough Dept of Wildlife Management, it was agreed that the most suitable location for playbacks in 1989 was about 60+ km (32+ n.mi.) NE or ENE of Pt. Barrow. In 1990-91 and 1994, 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 one or two underwater sound projectors from ice pans or, on some dates in 1991/94, the landfast ice edge. They projected recorded drilling platform sound or icebreaker 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(s). In addition, this crew measured the rate of attenuation of projected underwater sounds with increasing distance from the projector(s). *(2)* A second crew, in a Twin Otter aircraft, located whales and suitable projector sites, documented behavior of whales as they swam toward and past the projector(s), and (in 1989, 1991 and 1994) obtained known-scale vertical photos of bowheads to identify and measure them. The aircraft crew also used naval sonobuoys to monitor underwater sounds near whales.

Whale observations obtained by the two crews were complementary. Ice-based observers obtained detailed data on the paths and speeds of some whales that passed within 1-1½ km (0.54-0.8 n.mi.) of the projector, and observed whales even when there were low clouds. Aerial observers could observe whales at any distance from the projector site, could follow them for longer distances, and had a much better vantagepoint for viewing details of behavior. However, aerial observations were only useful when the cloud ceiling was at least 460 m (1500 ft) above sea level, as bowheads sometimes react to an observation aircraft circling at lower altitudes. Low cloud frequently interfered with behavioral observations in 1989 and especially 1991, but did so less commonly in 1990 or 1994. In 1994, strong winds often hindered behavioral observations from both the ice and the aircraft.

Sample Sizes

The ice-based crew worked from the ice on 33 days from 27 April to 30 May in 1989-90, and on 26 days from 28 April to 26 May in 1991/94. They conducted successful transmission loss tests on eight days in 1989-90 and five days in 1991/94. They projected industrial sounds into the water for several hours on each of 19 days in 1989-90 (drilling noise) and 13 days in 1991/94 (icebreaker noise).

The aircraft-based crew conducted reconnaissance surveys on 46 dates from 29 April to 30 May in 1989-90, and on 45 dates from 27 April to 26 May in 1991/94. The aerial crew conducted 46 behavior observation sessions on 22 days in 1989-90, and 30 sessions on 15 days in 1991/94. Behavioral observations totaled 72.4 h in 1989-90, 4.1 h in 1991 (limited by prevailing low cloud), and 36.2 h in 1991. Of these 112.7 h of systematic aerial observations over four spring seasons, 72.1 h involved presumably undisturbed bowheads (control data) and 40.6 h involved potentially disturbed bowheads.

Bowheads were observed in waters ensonified by the projected industrial sounds on 10 days with *Karluk* drilling noise in 1989-90 and on 7 days with icebreaker noise in 1991/94. **Total numbers of bowheads observed near the operating projector(s) during playbacks were ~221 in 1989-90 and 93 in 1991/94.** Bowheads were also observed near the ice camp under quiet "control" conditions at other times during most playback dates, and on a few additional days as well, in 1989-90 (~204 bowheads) and 1991/94 (~229 bowheads). White whales were seen near the operating projector(s) on five days in 1989-90 (~219 exposed to playbacks of *Karluk* drilling sounds) and on three days in 1991/94 (~46 exposed to playbacks of *Robert Lemeur* icebreaker sounds). In 1989-90, observation time near the ice camps totalled 74 h during drilling noise playbacks, plus 119 h of "control" observations near the ice camps. In 1991/94, observation time there totalled 40 h during the icebreaker playbacks, plus 101 h of "control" observations.

Physical Acoustics

Ambient Noise

Ambient noise levels measured in 1991 were similar to those during 1989-90, with median levels in the 20-1000 Hz band being 89-92 dB re 1 µPa, just above the 87 dB level computed for Knudsen's sea state zero extrapolated down to 20 Hz. In 1994, the corresponding measured median level was notably higher, 97 dB. This is ~2 dB less than the computed level for Knudsen's sea state two. The 1994 measurements were made in higher average wind speeds than prevailed in 1989-91. Wind speed has a dominant influence on underwater noise levels. Compared to the Wenz spectrum level ranges at 32 and 1000 Hz, the 1991/94 levels during this project were about mid-range. Compared to Chukchi shallow water measurements at those frequencies from May 1977, the 1991/94 levels were 7 dB re 1 $\mu Pa^2/Hz$ higher at 32 Hz and 18 dB higher at 1000 Hz.

Overall, the measurements from the western Beaufort Sea in spring fit well into the range of ambient noise measurements taken around the world.

Transmission Loss Tests

Transmission loss measurements were conducted 14 times during the four field seasons. The best results came from 1/3-octave hyperbolic frequency modulated "sweeps" and from samples of broadband *Karluk* drilling sounds. Tests with tones and clusters of tones gave more variable results. Icebreaker sounds, although broadband, varied too much in level over the duration of transmission to give consistent results. Assuming that bottom acoustic properties did not vary significantly over the region where the transmission loss tests were conducted, a basic model for sound transmission loss was developed. The validity of the assumption was ascertained by plotting, for each test frequency, transmission loss minus 20log(water depth) vs. range, normalized by twice the depth. Agreement among tests was generally within about ±4 dB (s.e.) for frequencies 50-1000 Hz and within about ±6 dB for higher frequencies to 5000 Hz. The model is thus frequency and depth dependent. All sources and receivers were at depth 18 m, and a frequency-dependent Lloyd's Mirror component is included in the model for frequencies <50 Hz. For example, the transmission loss at 10 Hz will be 28 dB greater than at 50 Hz due to the Lloyd's Mirror effect.

Comparison of received levels at sonobuoys during playbacks with model predictions for those ranges and water depths showed that the broadband measured levels generally agreed with the predicted broadband levels within the ±4 dB spread expected. As expected, exceptions occurred when the distance was so great that the predicted levels were less than the measured ambient noise. Model estimates of received level in the strongest 1/3-octave band may be underestimated by a few decibels.

Transmission loss at the 13 May 1990 playback site was less than that expected based on the transmission loss tests. The 13 May 1990 site was in water shallower (27 m) than that where any transmission loss test was done. The observed results from 13 May 1990 can be accounted for if there was subsea permafrost close to that playback site. Received levels of man-made noise from a source in such an area would be higher than levels predicted by the propagation model developed from the 14 transmission loss tests.

Comparison of transmission loss in the western Beaufort Sea (this project) with U.S. Navy-sponsored measurements in the Chukchi Sea (Greene 1981) suggests that the two areas are similar.

Playback Tests

In 1991/94, recorded underwater noise from an actual icebreaker (*Robert Lemeur*) operating in heavy ice was transmitted repetitively to simulate an icebreaker operating at the playback test sites. How did the playbacks compare with the original icebreaker?

Over the 40-6300 Hz range, the median source levels of the icebreaker playbacks on various days were 20-44 dB lower than the median source level of the actual icebreaker. Thus, at any distance from the source, the median level of the simulated icebreaker sound was 20-44 dB lower than would be expected if the actual icebreaker were operating there. A given received level would be found much farther from the actual icebreaker than from the projectors.

The overall median playback source level in the frequency range 40-6300 Hz was 34 dB less than the actual icebreaker source level (0.04% of the acoustic power). The median deviation from a flat frequency response across the 40-6300 Hz range was ±10 dB. The differences in source level at frequencies below 40 Hz increased with decreasing frequency to a median difference of 63 dB at 20 Hz. Considering the 1/3-octave bands centered at 20-6300 Hz (i.e. the 18-7100 Hz band), 45% of the acoustic power emitted by the icebreaker was below 45 Hz. Because of the more rapid attenuation of the lowest sound frequencies with increasing distance, the percentage of power below 45 Hz is estimated to diminish to 18% at range 50-100 m from the icebreaker, 17% at 1000 m, and 6.5% at 10,000 m. In comparison, <1% of the acoustic power emitted by the projectors during icebreaker playbacks was below 45 Hz.

Because of the differences between the actual icebreaker sound and the projected sound, and because of the variable levels at different times during playbacks, it was necessary to examine whale behavior in relation to the sound level being received at the whales' locations. A sound exposure model was developed to estimate received levels at whale locations, based on projected level and spectral composition and on the transmission loss model.

Infrasounds

Characteristics of the infrasonic components of ambient noise and drilling caisson noise were studied, along with the possibility that bowhead calls include infrasonic components. This work was done to help assess whether oil-industry sources emit strong infrasounds, how far away these infrasounds might be detectable, and whether bowheads are likely to hear infrasounds.

Infrasonic (<20 Hz) ambient noise was measured in the 1/3-octave bands centered at 10, 12.5 and 16 Hz. Compared to median levels at higher frequencies, the levels in infrasonic bands increased slightly with decreasing frequency in 1991 but decreased markedly with decreasing frequency in 1994. The median and range of 10 Hz spectral density levels agree well with measurements made in the deep Beaufort Sea and shallow Chukchi Sea during May 1977 (Greene 1981) and fit into the range of levels at 10 Hz reported by Wenz (1962). If bowhead calls include infrasonic components at levels comparable to those of the known call components, the expected high rate of attenuation in shallow water would result in masking by the observed levels of ambient infrasonic noise at relatively short ranges. Similarly, industrial noise components at infrasonic frequencies, unless much stronger than industrial noises at sonic frequencies, would be masked by the infrasonic ambient noise at short ranges.

There was no evidence of infrasonic tones (at frequencies <20 Hz) in a brief recording of noise from the SSDC drilling caisson engaged in drilling east of Barrow during winter.

If bowhead calls contain infrasonic components, bowheads probably can hear infrasounds. Infrasonic sound coincident with bowhead calls was studied in 1990 and 1991. In 1990, of 45 calls analyzed, one showed coincidence with an infrasonic transient. In 1991, of 73 calls analyzed, 11 occurred coincidently with infrasonic transients. An array of acoustic sensors would be needed to determine if the source locations of infrasonic and sonic components are coincident, thereby providing stronger evidence of infrasonic calls by bowheads.

Bowhead Whales

Movements and General Behavior

Bowheads migrated northeast and east through the study area during late April and May of 1989-91 and 1994. In 1989, the migration was often through heavy pack ice conditions. In other years, the ice was less compacted. In 1989-91, even when a broad nearshore lead extended east along the landfast ice edge through the study area, the migration corridor 35+ km (19+ n.mi.) ENE of Pt. Barrow was mainly along the offshore side of the lead or through the pack ice north of the lead. However, up to 15 May in 1994, the landfast ice edge that far east of Pt. Barrow was farther offshore than normal, and at times bowheads traveled near the landfast ice edge as far as 70 km (38 n.mi.) east of Pt. Barrow. This allowed much of the 1994 playback work to be done from the landfast ice edge 40-70 km east of Pt. Barrow.

Bowheads visible under undisturbed conditions in 1989-94, mainly amidst pack ice and in the main nearshore lead, were engaged predominantly in traveling (migration), sometimes intermixed with socializing. In 1989, when ice conditions were heavy, some resting bowheads were seen in small areas of open water amidst heavy ice. In subsequent years when heavy ice cover was less common, a higher proportion of the whales observed were actively migrating northeast or east. No surface feeding was seen, and apparent water-column or under-ice feeding was rare. A few bowheads were seen surfacing with mud streaming from their bodies and (rarely) from their mouths. Pre-dive flexes and fluke-out dives were seen less commonly in spring than in previous summer/autumn studies. A few bouts of sexual activity were observed during early May. Most mating apparently occurs earlier in the spring.

Bowhead calves and their mothers were seen only in the latter half of May in 1989, 1990 and 1991; only one calf was seen in 1994. In late May, mothers and calves often constituted the majority of the bowheads present in the study area. They did not migrate as strongly or consistently eastward as did other bowheads, especially in 1989 when the ice was heavy. Direct observations and photographic resightings showed that a few mother-calf pairs traveled *west* for at least a few kilometers. 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. Dives by calves tended to be short. Heavy ice conditions pose a greater impediment to spring migration of mother-calf pairs than of other bowheads.

Drilling Noise Playbacks

Results of the drilling noise playbacks in 1989-90 were described and summarized in OCS Study MMS 91-0037. Migrating bowheads tolerated exposure to high levels of continuous drilling noise if this was necessary to continue their migration. Bowhead migration was not blocked by projected drilling sounds, and there was no evidence that bowheads avoided the projector by distances exceeding 1 km (0.54 n.mi.). However, local movement patterns and various aspects of the behavior of these whales were affected by the noise exposure, sometimes at distances considerably exceeding the closest points of approach of bowheads to the operating projector. When ice was loose, some migrating bowheads diverted their courses enough to remain a few hundred meters to the side of the projector. Surfacing and respiration behavior, and the occurrence of turns during surfacings, were strongly affected out to 1 km. Turns were unusually frequent out to 2 km (1.1 n.mi), and there was evidence of subtle behavioral effects at distances up to 2-4 km (1.1-2.2 n.mi.).

From a statistical viewpoint, the null hypotheses of no playback effects on migration route and behavior were rejected. However, the demonstrated effects were localized and temporary. We concluded that the effects of the *Karluk* playbacks on distribution and movements were not biologically significant, and that playback effects on behavior probably were not biologically significant either. At distances beyond 100 m (109 yd), the projector used in 1989-90 adequately reproduced the overall 20-1000 Hz level even though sound 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 the actual *Karluk* sound above 20 Hz.

Icebreaker Noise Playbacks

Bowheads migrating in the nearshore lead often tolerated exposure to projected icebreaker sounds at received levels up to 20 dB or more above the natural ambient noise levels at corresponding frequencies. Bowheads are believed to be able to hear sounds of this type at levels near ambient. Thus, most of them apparently did not react in a manner that we could detect when they received weak icebreaker sounds.

However, some bowheads that would have come within a few hundred meters of the projectors if they had not turned apparently diverted so as to remain farther away. Diversion was apparently common when bowheads were exposed to levels of projected icebreaker sound more than 20 dB above the natural ambient noise level in the 1/3-octave band of strongest icebreaker noise. However, not all bowheads diverted at that signal-to-noise ratio (S:N), and a minority of them apparently diverted at lower S:N.

Bowhead behavior was significantly correlated with S:N and with received level (RL) of icebreaker sound in the 1/3-octave of strongest icebreaker sound, but not with distance from the projectors. The lack of correlation with distance was no doubt related to the highly variable levels of icebreaker sound at different times. Various measures of behavior were significantly different when S:N (the icebreaker-to-ambient ratio) exceeded 20 dB or, in the case of frequency of turning during surfacings, exceeded 10 dB. Measures of behavior that were significantly correlated with S:N were turning, duration of surfacing, number of blows per surfacing, and two multivariate indices of behavior. With icebreaker noise, turns during surfacings tended to be more common and larger, durations of surfacing longer, and blows per surfacing more numerous.

In general, movements and behavior of migrating bowheads exposed to playbacks of variable icebreaker noise were altered subtly but statistically significantly when S:N (as defined above) exceeded 20 dB, and when RL of icebreaker sound exceeded 100 dB re 1 μPa. Statistical power analyses showed that the possibility of behavioral effects at lower S:N and RL values cannot be excluded. One measure of behavior (frequency of turning) was apparently affected at S:N as low as 10-20 dB, and another measure (duration of surfacings) was apparently affected at RL as low as 90-100 dB re 1 μPa (1/3-octave basis).

The source level of an actual icebreaker is much higher than that of the projectors used in this study (median difference 34 dB over the frequency range 40-6300 Hz). If bowheads react to an actual icebreaker at S:N and RL values similar to those found during this study, they might commonly react at distances up to 10-50 km (5.4-27 n.mi.) from the actual icebreaker, depending on many variables. Predicted reaction distances around an actual icebreaker far exceed those around an actual drillsite like *Karluk* because of (a) the high source levels of icebreakers and (b) the better propagation of sound from an icebreaker operating in water depths 40+ m than from a bottom-founded platform in shallower water.

This study is consistent with previous analyses that predicted highly variable reaction distances even for a single source of man-made noise. Predicted reaction distances depend on

- temporal variations in its source level;
- temporal and geographic variations in propagation loss between source and receiver;
- temporal and geographic variations in ambient noise (and thus signal-to-ambient ratio);
- variations in the response thresholds of individual whales.

Given these factors and the observed reactions to playbacks of icebreaker sound, predicted reaction distances for bowheads around an icebreaker like *Robert Lemeur* vary from as little as ~2 km to as much as 95 km.

One of the main limitations of the study (during all four years) was the inability of a practical sound projector to reproduce the low-frequency components of recorded industrial sounds (see "Playback Tests", p. xvii). Both the *Karluk* rig and the icebreaker *Robert Lemeur* emitted strong sounds down to ~10-20 Hz, and quite likely at even lower frequencies. It is not known whether the underrepresentation of low-frequency (<45 Hz) components during icebreaker playbacks had significant effects on the responses by bowheads. Bowheads presumably can hear sounds extending well below 45 Hz. It is suspected but not confirmed that their hearing extends into the infrasonic range below 20 Hz.

Also, this study was not designed to test the potential reactions of whales to non-acoustic stimuli detected via sight, olfaction, etc. At least in summer/autumn, responses of bowheads to actual dredges and drillships seem consistent with 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 playbacks provide meaningful results.

Additional limitations of the playbacks included low sample sizes (especially for the 1991/94 icebreaker tests, see p. xvi) and the fact that responses were only evident if they could be seen or inferred based on surface observations. The numbers of bowhead and white whales observed during both playback and control conditions were low percentages of the total Beaufort Sea populations. These samples may or may not have been representative of the overall populations. Also, differences between whale activities and behavior during playback vs. "control" periods represent the incremental reactions when playbacks are added to a background of other activities associated with the research. Thus, the playback results may somewhat understate the differences between truly undisturbed whales vs. those exposed to playbacks.

Nonetheless, the data allow us to conclude that exposure to a single ***playback*** of variable icebreaker sounds can cause statistically but probably not biologically significant effects on the movements and behavior of migrating bowheads visible in the open water of nearshore lead systems during spring migration east of Pt. Barrow. Reaction distances around an ***actual icebreaker*** like *Robert Lemeur* are predicted to be much greater, commonly on the order of 10-50 km. Effects of an actual icebreaker on migrating bowheads, especially mothers and calves, could be biologically significant.

Aircraft Disturbance

The 1989-94 observations show that a minority of spring-migrating bowheads dive or exhibit other short-term behavioral changes 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, and lateral distances ≤250 m (820 ft).

We conclude that, although some bowheads exhibit short-term behavioral reactions, single helicopter overflights at altitudes of 150 m (or below) do not appear to disrupt the distribution, movements or behavior of bowheads visible during spring migration in pack ice or nearshore leads in a biologically significant way. This assessment concerns potential effects of single, straight-line overflights. Repeated passes, circling, or prolonged hovering at low altitude would be more likely than single, straight-line overflights to cause significant disturbance effects.

Spring-migrating bowheads occasionally dive, turn or otherwise react in an obvious manner to low-altitude overflights (altitude ≤182 m or ≤600 ft) by a Twin Otter fixed wing aircraft. A very small percentage (~1.3%) react similarly to overflights at altitude 460 m (1500 ft) if the lateral distance is ≤300 m (≤1000 ft). In spring, migrating bowheads do not react in an obvious manner to a Twin Otter aircraft circling at altitude 460 m and radius 1-1½ km, nor is there any clear evidence of subtle alterations in their behavior within 15 min after circling begins as compared with later observations.

White Whales

Sightings of white whales were more numerous than those of bowheads, and white whales tended to be more widely scattered and slightly farther offshore than bowheads. However, their migration corridors overlapped broadly.

Drilling Noise Playbacks

Results of the drilling noise playbacks in 1989-90 were described and summarized in OCS Study MMS 91-0037. In brief, we observed migrating white whales close to the operating projector on five dates. On four of these dates, at least a few white whales came within ~200 m (655 ft) of the operating projector, including a few within 50-100 m (165-330 ft). White whales 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 continued past without apparent hesitation or turning. Others reacted temporarily to the noise, or perhaps to visual cues, at distances on the order of 200-400 m (655-1310 ft). Some white whales slowed down, milled, or reversed course for several minutes. Then they continued past the projector, in some cases passing within 50-100 m of it.

We saw no evidence that white whales reacted at distances greater than 200-400 m even though projected drilling noise was measurable up to several kilometers away. This was probably related to the poor hearing sensitivity of white whales at low frequencies where the *Karluk* drilling sounds were concentrated. At distances beyond ~200 m, received levels of 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 stronger *Karluk* components at ~63-300 Hz. Although weak, the high-frequency components were potentially audible to white whales at somewhat greater ranges, given the much better hearing of white whales at higher frequencies.

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 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. However, 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.

We conclude, based on a small sample size, 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; available data are not suitable for a statistical test of the hypothesis. Also, 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.

Icebreaker Noise Playbacks

We observed migrating white whales close to the operating projector(s) on three dates in 1991/94. Interpretable data were collected on 17 groups of white whales observed during playbacks on two of these dates. At least six groups appeared to alter their paths in response to playbacks. As in the drilling noise playbacks, however, white whales approached within a few hundreds (and sometimes tens) of meters before showing any response. At these distances received levels at frequencies below 1000 Hz were high, but below the hearing threshold at corresponding frequencies. However, white whales within a few hundred meters of the projectors probably could hear, at least faintly, higher frequency components of the projected sounds, around

5000 Hz. Icebreaker sounds received by six groups of white whales that reacted were estimated as 78-84 dB re 1 μPa in the 1/3-octave band centered at 5000 Hz, or 8-14 dB above ambient in that band. Corresponding levels for 11 groups showing no obvious diversion were generally similar.

If some white whales react to an actual icebreaker at RL near 80 dB re 1 μPa or S:N near 10 dB (both in the 1/3-octave band near 5000 Hz), reactions would be expected to occur at distances on the order of 10 km from an icebreaker like *Robert Lemeur* operating in the present study area in spring.

Because we saw few groups of white whales near the projector(s) during icebreaker playbacks, additional field tests would be needed before formally evaluating their effects on movements of migrating white whales. However, small-scale diversions such as those sometimes seen in 1991/94 are unlikely to be biologically significant. Given the much larger anticipated radius of influence around an actual icebreaker and our small sample size, any conclusions about the effects of icebreaker playbacks on white whales cannot be applied directly to actual icebreaker effects.

Aircraft Disturbance

Opportunistic observations in 1989-94 showed that spring-migrating white whales appeared more responsive to aircraft overflights than were bowheads, often responding to a close approach by a turbine-powered helicopter. Apparent reactions were observed during 31% of overflights. Whales reacted by diving, veering away, or showing other changes in behavior. During overflights, reactions occurred exclusively when the helicopter passed at ≤250 m (820 ft) lateral distance from the white whales, and at altitudes up to 460 m ASL (1500 ft). However, most white whales showed no obvious reaction to single passes at altitudes >150 m ASL. These white whales maintained their headings and continued respiring at the surface when the helicopter operated nearby. Reactions were also noted among half of the 14 groups observed from the ice camp when the helicopter was stationary on the ice with its engines running.

Operations by a Bell 212 helicopter can locally alter the movements of white whales visible in the open water of nearshore lead systems and amidst the pack ice during spring migration near Pt. Barrow. However, these local effects do not cause migration blockage or biologically significant diversion from migration routes in the circumstances studied. Likewise, single overflights at lateral distances <250 m, especially at altitudes ≤150 m ASL, often affect the behavior of the white whales. There is no objective way to assess the biological significance of these behavioral reactions, but they appear brief and probably are not of lasting significance. This assessment concerns potential effects of single, straight-line overflights.

White whale groups were sometimes observed reacting overtly to Twin Otter overflights. Most reactions occurred when the aircraft was at altitudes ≤182 m (600 ft) and lateral distances ≤250 m (820 ft). Direct overflights generated the most pronounced reactions, such as vigorous swimming, abrupt dives, or tail thrashing. In a few cases, white whale responses involved turning directly away from the aircraft. In other cases, white whales responded to overflights by looking up at the aircraft. The number of white whales observed reacting overtly to Twin Otter overflights represented a very small fraction of the total number of white whales observed from the aircraft: 24 of ~760 groups.

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Dr. Thomas Albert	North Slope Borough Dep. Wildl. Manage. (1989-95),
Mr. Mark Fraker	BP Exploration (Alaska) (1989-91),
Ms. Michelle Gilders	BP Exploration (Alaska) (1994-95),
Dr. Roger Green	University of Western Ontario (1990-95),
Mr. Edward Itta	Barrow Whaling Captains Assoc. (1994-95),
Mr. Charles Malme	Hingham, MA (1994-95),
Mr. Allen Milne	Sci. Rev. Board Chairman (1989-91),
Mr. Ron Morris	Nat. Mar. Fish. Serv. (1990-95),
Mr. Thomas Napageak	Alaska Eskimo Whaling Commission (1989-91),
Mr. Burton Rexford	Barrow Whaling Captains' Assoc. (1989-91) and Alaska Eskimo Whaling Commission (1994-95),
Dr. Steven Swartz	Nat. Mar. Fish. Serv. (1989-95; SRB Chairman in 1994-95).

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GLOSSARY

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

acoustic impulse. Integral over time of the initial positive acoustic pressure pulse, measured in pascal-seconds (Pa·s); used in describing sound pulses.

acoustic intensity. Acoustic power crossing a unit area; pressure squared divided by acoustic impedance (ρc, where ρ represents the density of the medium and c the sound speed).

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.

Argotec 220. A particular type of underwater sound transducer that can project low-frequency sounds. Used in 1994.

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 of 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.

Bell 212. Medium-size helicopter (4500-5100 kg gross weight) with 2-bladed main and tail rotors producing families of tones with fundamental frequencies ~11 and 55 Hz, respectively. Powered by paired turboshaft engines (PT6T), together producing 1100 shp for cruise and a maximum of 1800 shp. Civil equivalent of military Twin Huey UH-1N.

biologically significant. Likely to affect the long-term well-being or reproductive productivity of individuals or of the population.

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

CEPA. Closest Estimated Point of Approach. A term used in this study to represent the closest known distance of a whale from the ice camp. It is (a) the interpolated Closest Point of Approach for whales observed both before and after passing the ice camp; and (b) the closest observed distance for whales seen either approaching or moving away from the ice camp, but not both.

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.

crosscorrelation. A measure of the similarity of two waveforms. As a function of time displacement or delay between the two waveforms, useful for determining the travel time difference of a signal received at two spatially separated sensors. Computed for each value of displacement by averaging the product of the two waveforms.

cylindrical spreading. Sound spreading as cylindrical waves. The transmission loss for cylindrical spreading is given by

$$10*\log_{10}(\mathrm{Range}/R_0),$$

where R_0 is a 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 with cylindrical fronts. For a point source in shallow water, a cylindrical wave forms at distances that are large compared to the water depth because of the way sound reflected 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) with the ability to determine the direction of arrival of a sound. Effective at 10-2400 Hz.

DSP. Digital Signal Processor. A microprocessor whose internal design is optimized for the types of repetitive mathematical calculations required during signal analysis.

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

F-40. A particular type of U.S. Navy underwater sound transducer that can project high-frequency sounds, e.g. 1-10 kHz. Used in 1991 with J-13.

faired cable. A cable with many ribbon- or hair-like attachments to reduce strumming in currents.

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 sec.).

GPS. Global Positioning System. A system for determining position (latitude, longitude, altitude) based on reception of signals from several of the GPS satellites that orbit the earth; horizontal accuracy 100 m or better.

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

high-pass filter. A filter passing only sounds above a specified frequency, to eliminate lower-frequency sounds.

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

impulse. see "acoustic impulse.

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

intensity. See "acoustic intensity".

J-11; J-13. Particular types of U.S. Navy underwater sound projectors. The J-11 is a broadband projector (used in 1994 with or without Argotec 220); the J-13 is a low-frequency projector (used in 1991 with F-40).

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 drill-site during that winter. The underwater sounds projected during playback experiments in the 1989-90 phases of this study were recorded 130 m from *Karluk* while it was drilling during March 1989.

Lemeur. See *Robert Lemeur*.

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

Lloyd's 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 ⅓-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 ⅓-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. See "acoustic power".

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 signal component. 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 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 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.

projector. An underwater transducer used to transmit sounds; an underwater loudspeaker.

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).

Robert Lemeur. An Arctic Class 3 icebreaking supply ship whose underwater sounds, recorded during icebreaking, were projected during playback tests in 1991 and 1994. The ship has 83 m length overall, 3184 tons gross displacement, with two turbocharged diesel engines of combined power 9600 bhp (7.2 MW). The two four-bladed controllable-pitch propellers are in Kort nozzles.

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* or icebreaker 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 (µPa).

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 a 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 surface 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 or ⅓ 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 includes spreading, absorption and scattering losses.

Twin Otter (de Havilland). A relatively small (≤5670 kg gross weight) fixed-wing utility aircraft commonly used for offshore aerial surveys. Two PT6A gas turbine engines totalling ~1200 shp turn 3-bladed propellers, producing a family of tones with fundamental frequency about 83 Hz.

VLF Navigation (Very Low Frequency). VLF/Omega navigation systems, based on very long-wavelength radio transmissions, have been widely used for aircraft navigation, especially in remote areas where LORAN was not usable. Accuracy variable, often deteriorating during a flight. Now being replaced by GPS in most applications.

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 may indicate only relative powers.

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

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

1. INTRODUCTION[1]

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 monitoring studies of the reactions of bowhead whales to oil industry operations in the Alaskan Beaufort Sea (e.g. LGL and Greeneridge 1987; Hall et al. 1994). These and other similar studies have been reviewed by Richardson and Malme (1993) for bowheads, and by Richardson et al. (in press) for marine mammals in general.

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: aircraft and boat traffic, marine seismic exploration, drillships, and offshore construction. Previous to this project, only a very limited effort had been devoted to the reactions of bowheads to icebreaking, which is a particularly noisy activity (e.g. Greene 1987a; Thiele 1988; reviewed in Greene and Moore in press:117*ff*). Reactions of bowheads to sounds from an oil production platform had 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 Biological Opinions on lease sales in the Beaufort and Chukchi seas. NMFS believed 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

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[1] By W.J. Richardson

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 had not been studied previous to this project.

Bowhead and white whales are both important to subsistence hunters in Alaska. An assessment of the potential effects of industrial activities on subsistence hunting is beyond the scope of this project. However, if industrial sounds affect the availability of these species to subsistence hunters, there could be economic, social, cultural, and political implications.

To answer some of these questions, MMS funded this study. The main objectives were 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 was 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 were also to be determined when possible.

This report describes results from 1991 and 1994, the third and fourth years of the study. In 1989-1990, we obtained

- considerable information on physical acoustic phenomena (ambient noise and sound propagation) in spring lead systems,
- considerable data on reactions of bowhead and white whales to playbacks into spring lead systems of continuous sounds from one drilling platform—a rig on a bottom-founded ice pad, and
- limited data on reactions of bowhead and white whales to the Twin Otter fixed wing aircraft and the Bell 212 helicopter (Richardson et al. 1990a, 1991a).

In 1991 and 1994, our highest priority objective was to determine the reactions of bowhead and white whales to a second type of industrial noise, the variable noise from an icebreaker that was actively breaking ice. There were several additional related objectives (see below).

Weather and ice conditions were generally unfavorable for this type of work near Barrow, Alaska, during the spring of 1991. In 1991, we obtained additional information about physical acoustic phenomena and whale movement patterns past Barrow, but results from the playback experiments with icebreaker noise were very limited. Consequently, the Minerals Management Service decided to continue the project for another spring season, and to cancel the requirement for a detailed report on the 1991 data. The additional fieldwork was not possible in 1992 or 1993 because of concern about the potential for interference with bowhead censusing efforts underway in those years. Consequently, the fourth field season was delayed until 1994.

This report was planned and funded to describe results from 1991 and 1994, years 3 and 4 of the study, not as an integrated account of results from all four years of the study. Results from 1989 and 1990 were described in Richardson et al. (1990a, 1991a). However, some sections of the present report do incorporate data from 1989-90 as well as 1991 and 1994. These include the sections on acoustic transmission loss (§4.3), the activities of undisturbed bowheads in the study area during spring (§5.1-5.4), the migration of white whales during spring (§7.1), and the reactions of both species to aircraft (§6.7 and §7.4). These comprise most of the sections for which data were collected in comparable ways during 1989-90 and 1991/94. The top-priority acoustic playback work in 1989-90 involved playback tests of whale reactions to steady low-frequency drilling sounds, whereas the corresponding work in 1991 and 1994 tested reactions to more variable and wider-bandwidth icebreaker sounds. Thus, the 1989-90 and 1991/94 playback data cannot be combined, although the two sets of results can be compared. Sections 6.1-6.6 and 7.2 of this report present the 1991/94 icebreaker playback results, and compare them with the previously-reported 1989-90 drilling noise playbacks.

1.1 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 1.1.

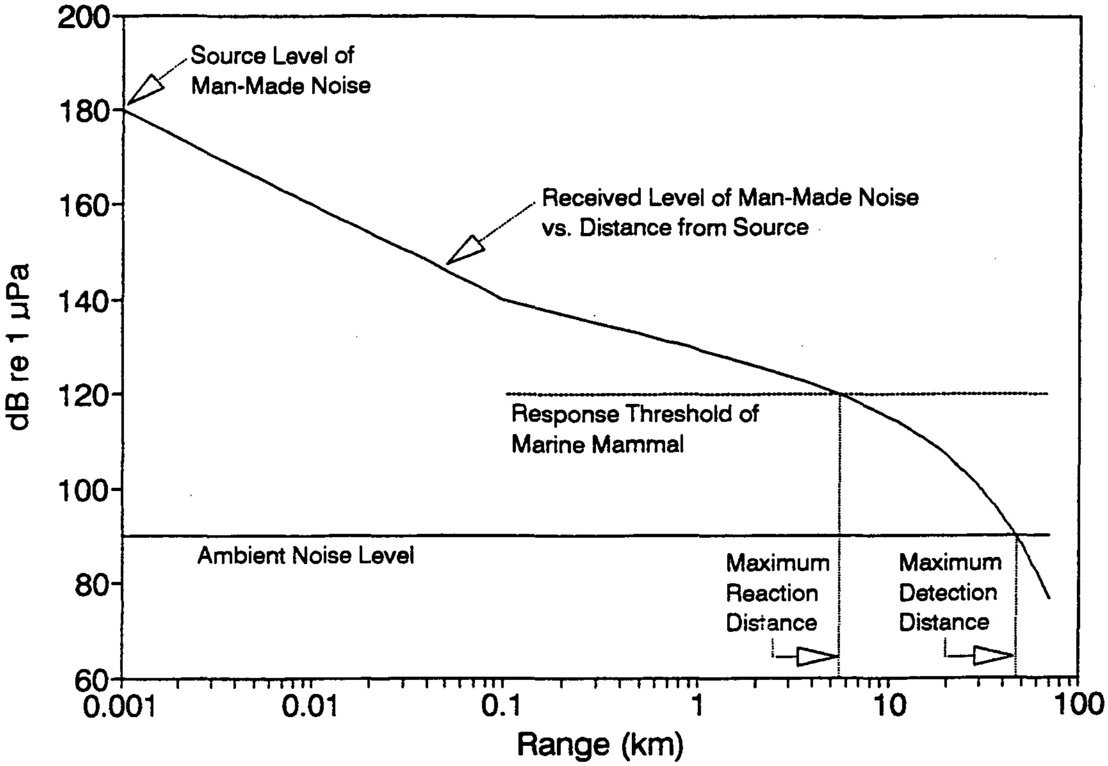

FIGURE 1.1. Components of a simple zone of acoustic influence model. See text for explanation.

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 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. 1.1). 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 been 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. 1.1). 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. 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 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 is 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. 1.1), 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. This assumes that a given received level of sound from the projector causes the same reaction as the same received level of sound from the actual industrial source. This assumption is discussed as item (3) in §1.3, Assumptions and Limitations.

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, given various assumptions. This study aims to collect the types of data needed to quantify, for particular situations, the conceptual model illustrated in Figure 1.1. Section 6.4 of this report develops a preliminary model of this type for reactions of spring-migrating bowheads to playbacks of icebreaker sound (Fig. 6.26, p. 314). Section 6.5 compares it to a similar preliminary model concerning their reactions to steady drilling sound. The model for drilling is based mainly on our 1989-90 work (Richardson et al. 1991a).

Specific 1991 and 1994 Objectives

The specific objectives of the 1989-90 and the 1991/94 phases of this project were similar, except that a different type of industrial sound was to be used during sound playback experiments in 1991/94. Specific objectives in 1989-90 were listed by Richardson et al. (1990a:17, 1991a:5). As in 1989-90, physical acoustic measurements—including data on received sound levels near whales, sound propagation loss, and ambient noise—were necessary to interpret the 1991/94 playback results. 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, indirect methods of addressing the importance of low-frequency components were again identified as objectives in 1991/94 (see specific objective 5, below). As a lower priority, the reactions of bowhead and white whales to actual helicopter overflights again were to be determined if opportunities allowed.

The first of the specific objectives for the third and fourth years of the project involved work during the winter, not the spring:

1. To record sounds from the SSDC caisson while it was drilling during winter conditions, including infrasonic components, and to analyze those sounds to determine their levels, spectral characteristics, and attenuation properties.

It had originally been thought that this effort might provide a suitable sound stimulus for use during playbacks in years three and/or four of the study. However, it was later decided that a recording of underwater sounds from the Canmar icebreaker *Robert Lemeur* while it was actively breaking ice would be more appropriate for playbacks in 1991 and subsequently in 1994.[2] The icebreaker sounds used for the 1991/94 playbacks vary widely during the duration of the recording. It was agreed that reactions of whales to these variable sounds, relative to their reactions to the steady *Karluk* drilling platform sounds tested in the 1989-90 playbacks, would be of much interest. Tests of the reactions of whales to icebreaker sounds had been identified by MMS as one of the top priority objectives since the beginning of the project.

Only a few data on reactions of bowheads and white whales to icebreaker sounds were obtained in 1991 (year 3) because of difficult weather and ice conditions. Therefore, specific objectives for the spring work in 1994 (year 4) were essentially unchanged from those in the spring of 1991:

2. 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.
3. 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, and *(b)* continuous industrial sounds. Infrasonic components cannot be projected, as discussed on page 10, item (3).

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[2] Winter drilling from the icebound SSDC (Steel-Sided Drilling Caisson), which operated in the Alaskan Beaufort Sea during the winters of 1990-91 and 1991-92, was considered a potentially suitable source of sounds for playbacks. Drilling by the SSDC ceased early in December 1990, before the caisson operator considered it practical for us to make the desired field measurements. Hence, this objective was not met in 1990-91. In the absence of a suitable recording of drilling noise from an icebound caisson, it was decided to use icebreaker sounds as the playback stimulus during the spring of 1991. The SSDC drilled again at another site east of Barrow during the winter of 1991-92, and SSDC sounds were recorded in January 1992. Thereafter, discussions were held with the project's Scientific Review Board, the Barrow Whaling Captains' Association, and the Minerals Management Service to determine whether to use the icebreaker or the SSDC sounds during the fourth spring season of playback work in 1994. It was agreed to continue using the icebreaker sound.

4. 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 variable icebreaker sounds. Infrasonic components cannot be projected.

5. To collect some of the data needed to assess the importance of the infrasonic components of industrial noise. Specifically, *(a)* to measure ambient noise at infrasonic frequencies, and *(b)* to determine whether bowhead calls contain infrasonic components (supplementing limited data from 1990). Also, based on the winter recordings of SSDC sounds (specific objective 1), we were *(c)* to determine the frequencies, levels and attenuation of the infrasonic components of drilling caisson sound.

6. To measure, on an opportunistic basis, 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 (supplementing limited data from 1989-90).

7. To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses and acoustic environment of bowhead and white whales along their spring migration corridor in the western Beaufort Sea.

8. 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.

9. To analyze the data to test hypotheses concerning the effects of the icebreaker sounds and helicopter overflights mentioned in (4) and (6) 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.

Significant progress has been made toward meeting all nine objectives during the four spring seasons. Several objectives—2, 3, 5a, 7 and 8—can be considered "achieved". Some data on the responsiveness of spring-migrating bowheads and white whales to playbacks of steady drilling noise and variable icebreaker noise were obtained, along with some data on responsiveness to actual aircraft overflights (objectives 4, 6 and 9). However, better quantification of whale responses to these activities than achieved in this study would be desirable. Similarly, objectives 1 and 5b,c were partially met, but additional data would be helpful.

1.2 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 by adding more specific wording about four topics: (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 some production activities. Four null hypotheses of a more specific nature were developed for each of the two whale species:

1. Playbacks of recorded noise from a bottom-founded platform (1989-90) or an icebreaker working on ice (1991/94) 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 (1989-90) or an icebreaker working on ice (1991/94) 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, we 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.

Hypotheses 1 and 2 have already been addressed with respect to the effects on ***bowheads*** of playbacks of recorded continuous noise from a bottom-founded platform like *Karluk* (Richardson et al. 1991a:226*ff*, 246*ff*). We concluded that, at least in the circumstances studied,[3] *Karluk* playbacks resulted in statistically significant small-scale changes in migration routes, spatial distribution, and individual behavior. However, there was no evidence of migration blockage, and we concluded that the observed effects were likely to be biologically non-significant. (By biologically non-significant, we mean "Would be unlikely to affect the long-term well-being or reproductive productivity of individuals or of the population.") We have discussed elsewhere the

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[3] For 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.

numerous complications and limitations in applying these 1989-90 results from playback tests with one type of industrial sound to the situation of an actual drilling platform operating in or near a spring lead system (Richardson et al. 1991a:10*ff*, 261*ff*). One purpose of the 1991/94 tests with a second and more variable type of industrial sound was to evaluate the generality of the 1989-90 results. Section 6.6 of this report addresses hypotheses 1 and 2 as regards reactions of spring-migrating bowheads to playbacks of icebreaker noise.

Hypothesis 1 has also already been addressed with respect to the effects on ***white whales*** of playbacks of the *Karluk* sounds (Richardson et al. 1991a:281). We concluded that, in the circumstances studied (see footnote [2]), playbacks of *Karluk* sounds had detectable but biologically non-significant effects on migration routes and spatial distribution of white whales. Again, various complications and limitations apply. Hypothesis 2, concerning effects on individual behavior, could not be tested for *Karluk* drilling sounds vs. white whales. Section 7.3 of this report addresses hypothesis 1 as regards reactions of spring-migrating white whales to playbacks of icebreaker noise.

Hypotheses 3 and 4, relating to effects of helicopter overflights on bowheads and white whales, were not formally tested during the 1989 or 1990 phases of the work. Relevant data were obtained in 1989-90, but this work was given a low priority; the 1989-90 data were opportunistic. Further relevant data of the same types were obtained in 1991 and 1994, and hypotheses 3 and 4 are evaluated in §6.7 and §7.4 of this report for bowheads and white whales, respectively.

1.3 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 1989-94 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)* The applicability of the 1989-94 results to the Chukchi Sea is not verified. 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) are similar to those in the Chukchi Sea during late winter-early spring (Greene 1981)—see §4.3 (p. 115).
>
> *(b)* Water depths at many 1989-94 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 1989-94 data on reactions to noise were from whales migrating through open pack ice or along 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. This "observability bias" was a problem in 1989, when heavy ice hindered observations, and 1991, when aerial observations were not possible during playbacks, but it was less of a problem in 1990 and 1994.
>
> *(c)* Because of masking problems, acoustic monitoring and localization methods are not as useful in a noise playback study as in a study of undisturbed whales.
>
> *(d)* Relatively low numbers of whales were observable during playbacks in the area where this study had to be conducted (§1.4, Study Area). Sample sizes during playbacks are shown later in this report, in Tables 2.2, 6.1 and 6.2 (see §2.2 and §6.1).

(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.

> ***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. ▸ It is uncertain how closely the *Karluk* drilling sound and the *Robert Lemeur* icebreaker sound resemble sounds that would emanate from future oil industry activities in or near spring lead systems. To date, neither drilling nor production have been done in or near spring lead systems off northern Alaska, so it has been impossible to record or study the sounds emitted by such an operation. ▸ Also, icebreaker sound is unlikely to be commonly associated with future oil

production activities in or near leads used by migrating whales in spring. ▸ However, the steady, low-frequency drilling sounds and the variable, broader-bandwidth icebreaker sounds used during the playbacks represent a wide range of noise characteristics. 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. 1991b, in press). Nonetheless, any extrapolation of the 1989-94 playback results to situations involving other types of industrial sounds would be 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. In 1991/94, we repeatedly projected a 14.3-min segment of sounds emitted by one icebreaker operating in a particular type of ice conditions at one site. Icebreaker noise varies somewhat depending on the vessel and the circumstances of operation.

(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. Procedures used during most playbacks in 1991/94 provided a reasonable simulation of the components of icebreaker sound within the 40 to 6300 Hz bands, and probably up to 12,000 Hz. To the human ear, the projected *Karluk* and icebreaker sounds, as received by hydrophone or sonobuoy 100 m to 1+ km from the projector(s), strongly resembled the original recordings of *Karluk* and icebreaker sounds. ▸ However, the playback systems used in 1989-90 and 1991/94 underrepresented the components at frequencies below, respectively, 80 Hz and 40 Hz, and especially the components below, respectively, 63 Hz and 32 Hz (see Richardson et al. 1991a:88 for 1989-90, and §4.4 for 1991/94). ▸ White whales are not sensitive to these low frequency components unless their levels are very high (§7.2). Hence, the inability to project them was not a problem during playback tests on white whales. However, bowhead whales are expected to be sensitive to these low frequency components. ▸ In summer, bowheads seem at least as sensitive to playbacks of drillship and dredge sounds as to actual drillships and dredges (Richardson et al. 1990b), suggesting that playbacks can provide relevant data.

(e) The rate of change of received sound level with increasing distance (sound gradient) may be steep near a playback site, potentially causing stronger reactions than with shallower gradients (Ellison and Weixel 1994a,b). When the playback source level is less than that of the human activity being simulated, a given received sound level will occur closer to the playback site than to the actual source. The gradient usually diminishes with increasing range. Whales approaching through a steep gradient close to a playback site would be exposed to a more rapidly increasing sound level than would those swimming at the same speed through an equally strong but shallower gradient farther from the actual source. Whales often seem to be more responsive to rapidly changing sound (Richardson et al. in press). If so, a given sound level may have more effect on traveling whales when it comes from a "weak" source nearby (e.g. playback) as compared with a strong source farther away (e.g. icebreaker). If

so, the reaction threshold to the full-scale noise source would be less than that estimated by playbacks simulating that source. Differences in the vertical position of the playback vs. actual sources, and in their acoustic coupling into the bottom, may also affect the propagation and received level of the sound.

(4) It is assumed that the presence of the observers did not bias the results significantly. Three potential problems existed (see below). However, the potential for bias was limited, and comparison of playback vs. control data provided meaningful data.

> ***Limitations***: *(a)* Whales are known to react to aircraft overflights in some situations; many of the 1989-90 and 1994 observations were obtained from an aircraft circling above the whales. However, studies in summer and autumn, corroborated in this spring study (§6.7), indicate that an observation aircraft circling over bowheads very rarely causes any overt 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 and Malme 1993). Opportunistic observations suggest that white whales also tolerate aircraft at that height (reviewed by Richardson et al. 1991b, in press; this study, §7.4). Given this, and the fact that we excluded behavioral 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. In 1991/94, personnel at the ice camp wore long, white snow-shirts to reduce their visual conspicuousness. 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.
>
> *(c)* It was necessary to use a small gasoline-powered generator at the ice camp during playbacks. For consistency, the generator was also operated during most control periods, whether or not it was needed as a power source. The generator emitted underwater noise, which was detectable underwater within a few hundred meters of the campsite during control (quiet) periods in 1989-90. There may have been some short-range responses to acoustic (or non-acoustic) cues from the camp itself during 1989-90. However, these cannot explain the more pronounced responses observed during projection of drilling noise than when the projector was off. In 1991 and 1994, underwater noise from the generator was greatly reduced through use of a suspension system (§4.6).

(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 aerial observers can see them 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 or 1994 (see limitation 2b, above).

(e) This study concerns the short-term reactions of migrating whales, mainly to two sources of man-made noise. The long-term consequences with respect to the well-being of individuals and the population are not addressed directly.

(6) To perform meaningful tests of hypotheses about disturbance effects on bowheads and belugas, it is necessary to have adequate data. The lack of a statistically significant disturbance effect does not prove the absence of a disturbance effect. A statistical power analysis will indicate how large a disturbance effect might have occurred without being detectable statistically.

Limitations: Because of logistical constraints, sample sizes for most types of disturbance observations in this study are small. Nonetheless, playbacks of both drilling and icebreaker sound were shown to cause statistically significant effects on bowhead behavior. Thus, the limited sample sizes and limited power are not central issues in determining whether the null hypotheses of "no disturbance effect from playbacks" can be rejected. The limited sample sizes and limited power are, however, an issue in evaluating the threshold distances and threshold sound levels at which disturbance become detectable. Section 6.3 (p. 290-295) includes analyses of the power of this study to detect whether disturbance effects from icebreaker playbacks occurred at various received sound levels and icebreaker-to-ambient ratios.

(7) Evaluations of potential disturbance radius often assume that ambient noise levels and propagation loss rates are average, or are equal to those at a particular date and time. Also, it is often assumed that a given human activity is representative of other activities of the same general type, e.g., that icebreaking by the specific icebreaker whose sounds were used in the 1991 and 1994 playbacks is representative of icebreakers in general.

> ***Limitations***: (a) There is much variability in ambient noise levels and propagation loss rates in leads and below pack ice during spring. Therefore, a given received sound level or signal-to-ambient ratio may occur at widely differing distances from a particular noise source, depending on physical factors such as ice cover, water depth, wind speed, bottom conditions, etc. If marine mammals begin to react at a given received sound level or a given signal-to-ambient ratio, reaction radii are expected to vary drastically depending on these physical factors. This variability is added to the variability in expected reaction radii caused by differences in the responsiveness of different animals. This topic is discussed in §6.4.
>
> (b) There can be differences in the levels and spectral characteristics of the sounds emitted by different human activities of a given class, e.g., different icebreakers. *Robert Lemeur*, the icebreaking supply ship whose sounds were used in the 1991 and 1994 playbacks, is a relatively low-powered icebreaker (9600 bhp or 7.2 MW).

1.4 Study Area

In choosing a study area, it was necessary to compromise between choosing *(a)* an area where many whales would be encountered in situations where playbacks and observations were practical, 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 (NSB), the Alaska Eskimo Whaling Commission (AEWC), or the Barrow Whaling Captains' Association (BWCA). 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 almost two decades there has been a spring bowhead census near Pt. Barrow in certain years. 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 or 1991. A full-scale census was attempted in 1992 (unsuccessful due to ice conditions) and again in 1993 (successful). 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 and data analysis procedures depend on the consistent migratory behavior of the whales. Disturbance-related changes in swimming speeds, average distance from the ice edge, or whale headings could affect the census results. Also, if background noise levels at acoustic monitoring sites 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 was 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 Locations

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 that, in most years, few whales are found along the landfast ice edge more than about 35 km east of Barrow. This was confirmed by our 1989-91 studies, although 1994 was an exception (§5.1). Farther east, most whales in most years move offshore into the seaward side of the nearshore lead or into the pack ice beyond the nearshore lead.

Thus, during most if not all 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 more difficult with increasing distance to the east. Dedicated helicopter support was essential for work on the pack ice.

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. 1989; included as 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 specific locations of the main ice-based and aerial work in 1989 and subsequent years of the study are mapped later, in §3.2 (Fig. 3.2-3.9) and §5.2 (Fig. 5.19, 5.21).

The 1989 study showed that we could conduct the work without interfering with whaling. Therefore, in ***1990*** and ***1991***, after consultation with the BWCA, AEWC and NSB, 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 1990-91 proved to be very helpful in providing more flexibility in choice of projector sites.

In 1991, spring whaling at Barrow ended in mid-May, and there was no ice-based whale census. During consultations in mid-May, representatives of the BWCA, AEWC and NSB agreed that we could work close to Barrow, where the whale migration corridor seems to be more concentrated and consistent. Starting on 17 May 1991, we began to conduct aerial surveys west and north of Barrow as well as in our usual study area farther to the northeast. On 17 and 18 May, the sound projector was set up on the landfast ice closer to Pt. Barrow than we had worked before. The sound playback results from 17 May were the most valuable playback results obtained in 1991. On other dates in mid- and late May 1991, experimental opportunities were better on the pack ice, and we worked there rather than on the landfast ice. However, we continued to work closer to Barrow than had been possible previously.

In ***1992*** and ***1993***, the Barrow Whaling Captains' Association requested that LGL and MMS not undertake this study in the usual area northeast of Barrow because of the possibility that it might interfere with the full-scale bowhead census efforts planned for those years. In the absence of any logistically-practical alternative study area, this study was deferred from 1992 to 1993 and then again from 1993 to 1994.

In ***1994***, when no census work was planned, the BWCA indicated that it had no objection to resumption of the study in the usual area northeast of Barrow. The agreed-upon guidelines were the same as for 1990 and 1991: projector 15 n.mi. beyond northeasternmost whaling camp; no flying within 5 n.mi. of whaling camps.

In 1994, bowheads migrating through the area up to 15 May often traveled close to the landfast ice edge even in areas as much as 70 km east of Pt. Barrow where, in 1989-91, they tended to be at least a few kilometers north of the landfast ice edge. This difference was related to the fact that, until 15 May in 1994, the landfast ice in the eastern part of the study area extended unusually far offshore (§3.1, Ice and Weather Conditions). This situation allowed us to conduct playback work from the landfast ice edge 40-70 km ENE of Pt. Barrow during the 7-14 May 1994 period. However, because of the precarious nature of the ice there, it was again necessary to go to that area on a daily basis by helicopter rather than to establish a longer-term camp on the landfast ice edge. The landfast ice in that area began to break up on 15 May 1994. Thereafter, the main bowhead migration corridor was far enough north of the new landfast ice edge to require that ice-based work be done from the pack ice, as in previous years.

1.5 Decibel Scales

Sound levels are expressed in decibels in this report. Decibels are logarithmic units. Decibel scales cause considerable confusion and misunderstanding among acousticians and non-acousticians alike, but serve a useful purpose. The range of sound levels perceived by human beings extends from the molecular noise of air molecules colliding on the low side to the roar of jet engines at close range. The ratio of sound pressures thus spanned is about 1,000,000:1. A linear pressure scale to portray such a range of sound pressures would be cumbersome, and sounds at low and intermediate levels (e.g., molecular noise and typewriter noise) would seem very similar on this scale. A logarithmic scale for pressures solves this problem.

Human beings respond to sound pressures on a logarithmic basis as well. The minimum change in sound level perceived by humans is on the order of 1 dB. In the middle of the frequency and intensity ranges for human hearing, a sound pressure increase of 10 dB is perceived by humans as an apparent doubling of loudness. Thus, there is more than one reason for using a logarithmic scale.

A logarithmic scale has to be "anchored" by some reference unit of pressure. The reference unit now used to describe underwater sounds is the micropascal. Thus, decibels on a sound pressure level scale are said to be referred to 1 micropascal, or "dB re 1 μPa". Other reference units are sometimes used, including 20 μPa (=0.0002 μbar) for airborne sounds, and 1 μbar (0.1 Pa) in much of the older underwater acoustics literature. Table 1.1 summarizes the interrelationships of various scales for acoustic measurements, and shows the levels of some airborne and underwater sounds on these measurement scales. More details, including information about decibel scales as used to describe sound pressure spectral density and sound energy, are given in Greene (in press).

TABLE 1.1. Interrelationships of various scales for acoustic measurements; standard reference units are underlined[a]

Pascals	Dynes/ cm^2	Bars	dB re 1 μPa	dB re 1 μbar	dB re 0.0002 μbar	Typical airborne sounds and human thresholds	Typical underwater sounds and marine mammal thresholds
1,000,000	10^7	10	240	140	214		
							2 kg high explosive, 100 m
100,000	1,000,000	1	220	120	194		Beluga echolocation call, 1 m
10,000	100,000	.1	200	100	174		Airgun array, 100 m
						Some military guns	
1,000	10,000	.01	180	80	154		
						Sonic booms	
100	1,000	.001	160	60	134		Large ship, 100 m
10	100	100 μ	140	40	114	Discomfort threshold, 1 kHz	Fin whale call, 100 m
						500 m from jet airliner	
1	10	10 μ	120	20	94		
.1	1	**1 μ**	100	**0**	74	15 m from auto, 55 km/h	Beluga threshold, 1 kHz
						Speech in noise, 1 m	Ambient, SS4, ⅓-OB @ 1 kHz[b]
.01	.1	.1 μ	80	-20	54	Speech in quiet, 1 m	Seal threshold, 1 kHz
.001	.01	.01 μ	60	-40	34		Ambient, SS0, ⅓-OB @ 1 kHz
.0001	.001	.001 μ	40	-60	14		Beluga threshold, 30 kHz
20 μ	200 μ	**.0002 μ**	26	-74	**0**	Open ear threshold, 1 kHz	
10 μ	100 μ	.0001 μ	20	-80	-6	Open ear threshold, 4 kHz	
1 μ	10 μ	.00001 μ	**0**	-100	-26		

[a] From Greene (in press); airborne portions adapted from Kryter (1985:8).

[b] Ambient noise in ⅓-octave band centered at 1 kHz under sea state 4 conditions.

2. METHODS[4]

2.1 Physical Acoustics Methods

The specific 1991 and 1994 field objectives that concerned physical acoustics, in whole or in part, 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 underwater sound transmission loss along the study portion of the spring migration corridor, based on transmissions of (a) test tones at selected frequencies between 20 Hz and 10 kHz, and (b) steady drilling platform sounds (*Karluk*) and variable icebreaking sounds (*Robert Lemeur*).
3. ***Playback Experiments***: To measure the short-term behavioral responses of bowheads and 6(as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of variable icebreaking (*Robert Lemeur*) sounds.
4. ***Infrasonic Sounds***: To collect some of the data needed to assess the importance of the infrasonic components of industrial noise. Specifically, (a) to measure ambient noise at infrasonic frequencies (less than 20 Hz), and (b) to determine whether bowhead calls contain infrasonic components (supplementing limited data from 1990).

An additional objective associated with the 1991 effort was to obtain and analyze recordings of the SSDC during winter drilling operations east of Pt. Barrow (Appendix H). The sounds associated with the SSDC were considered for use during playback experiments.

This section begins with a general description of the approach and equipment used in the acoustic work. Then there are sections describing specific methods applicable to each of the above objectives. Emphasis is given to acoustical methods applied in 1991 and 1994, but significantly-different procedures used in 1989-90 are mentioned as well. Methods applied in 1989 and 1990 were described in more detail by Richardson et al. (1990a, 1991a).

General Approach and Equipment

Acoustical work in 1991 and 1994 generally followed the methods of 1989-90. The work occurred at two types of places: (1) ice camps located along the edges of ice pans or (less often) the landfast ice edge, and (2) aboard the project's chartered Twin Otter fixed-wing aircraft:

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[4] By W.J. Richardson, C.R. Greene Jr., and W.R. Koski

- The ice-based personnel were transported by helicopter to a suitable place on the ice on a daily basis. Weather and ice conditions permitting, personnel typically remained on the ice for 8 to 12 hours. On most days, the ice-based crew attempted to perform either a transmission loss test or a playback experiment, as well as measuring ambient noise and observing whales.
- The aircraft-based crew dropped sonobuoys to measure sounds received near whales, as well as observing and photographing whales (§2.2, Whale Surveys and Observations).

At a minimum, the ice camps were occupied by an acoustician, two field biologists, and an Eskimo guide from Barrow. A second acoustician was present occasionally in 1991 and frequently in 1994. The biologists observed marine mammals and operated a theodolite to measure azimuth and depression angles to whales and seals. Distances were computed from depression angles and the measured height of the theodolite above the sea. Ice camps were established by flights from Barrow, AK, in a NOAA Bell 212 helicopter dedicated to support the field work.

The major types of equipment used at and near the ice camp for acoustical aspects of the work were as follows:

- sound projector(s) for use in both playbacks and transmission loss tests, with tape recorder and amplifier(s) to play the recorded sounds;
- generator to power this and other equipment;
- hydrophone(s) deployed near the projector(s) to monitor the projected or ambient sounds, and tape recorder to record these sounds;
- monitor sonobuoy deployed ~1 km from the ice camp to monitor sounds received at that distance.

Also, sonobuoys were air-dropped from the project's Twin Otter aircraft to record projected and ambient sounds received near whales. During transmission loss experiments, a hydrophone and tape recorder were taken to various receiving stations to record the sounds received at different distances from the sound projectors. The specific equipment varied from year to year, as summarized in Table 2.1.

Sound Projectors and Signal Source.—To project sounds for transmission loss and playback experiments, a davit installed in the ice about 1 m from the edge of the ice floe supported various sound projectors and one or more monitor hydrophones lowered over the edge. The sound projectors were at depth 18 m (60 ft) except during a transmission loss test on 30 April 1989, when projector depth was 9 m.

In 1989 and 1990, a U.S. Navy model J-11 wideband electrodynamic acoustic transducer served as the sound projector. The J-11 is limited to a maximum sound pressure source level of about 166 dB re 1 μPa-m. It is rated as effective at 20-12,000 Hz, but its output diminishes at frequencies below about 100 Hz, becoming negligible at frequencies below 50 Hz. The J-11 was powered by a Bogen model MT250 amplifier rated at 250 W. The signal source in 1989-90 was an audio cassette recorder (Table 2.1A) with servo-controlled capstan for accurate speed control. Playback frequency response was flat ±5 dB from 20 to 10,000 Hz. Further details are given in Richardson et al. (1990a, 1991a).

TABLE 2.1. Equipment used for acoustic work in each year of the project.

	1989	1990	1991	1994
A. Projectors and Signal Source				
Projector(s)	J-11	J-11	J-13 & F-40	Argotec 220 & J-11
Amplifier(s)	Bogen MT250	Bogen MT250	Bogen MT250	Techron 7560 & Techron 7550
Source tape recorder	Marantz PMD-430 cas.	Sony TC-D5M cas.	Sony TCD-D3 DAT	Sony TCD-D3 DAT
Generator	Honda 2.2 kW	Homelite 2.2 kW EH2500HD	Homelite 2.2 kW EH2500HD	Kubota 5 kW (most days)
B. Sound Monitoring on Ice				
Monitor hydrophone near proj.	ITC 1042	ITC 1042	ITC 1042	ITC 1042
Ambient & TL signals @ depth	ITC 6050C @ 18 m	ITC 6050C @ 18 m	ITC 6050C @ 18 m	ITC 6050C @ 18 m
Infrasonic ambient @ depth		ITC 1032 @ 18 m	ITC 1032 @ 18 m	
Monitor sonobuoy at approx. 1 km range from camp	AN/SSQ-41B @ 9 m or -57A @ 12 m	-41B @ 9 m or -57A @ 14 m	-57A @ 18 m (usually)	-57A @ 18 m
Sonobuoy receiver	L-tronics LS44	Kenwood RZ-1 (mod.)	Kenwood RZ-1 (mod.)	L-tronics LS44
Tape recorders				
Playback monitor @ camp	* & Sony TC-D5M cas.	* & Marantz PMD-430 cas.	* & TEAC RD-101T DAT	* & TEAC RD-101T DAT
Ambient @ camp	Sony TC-D5M cas.	TEAC RD-101T DAT	TEAC RD-101T DAT	TEAC RD-101T DAT
TL monitor @ camp	*	* & Marantz PMD-430 cas.	* & Sony TC-D5M cas.	* & Sony TCD-D7 DAT
TL & Amb. @ TL receive sites	Sony TC-D5M cas.	TEAC RD-101T DAT	TEAC RD-101T DAT	TEAC RD-101T DAT
C. Sound Monitoring from Twin Otter				
Sonobuoys	AN/SSQ-57A @ 12 m	-57A @ 14 or 18 m or -41B @ 18 m	-57A @ 14 or 18 m or -53B @ 27 m	-57A @ 14 or 18 m or -53B @ 27 m
Sonobuoy receivers	2xRegency MX5000 (modified)	2xRegency MX5000 (modified)	2x Kenwood RZ-1 (mod.)	3x Kenwood RZ-1 (mod.) & 1 ICOM R100 (mod.)
Tape recorder	Marantz PMD-430 cas.	TEAC RD-101T DAT	TEAC RD-101T DAT	TEAC RD-101T DAT
D. Position Finding				
Ice camp	Si-Tex A-310 SatNav	Si-Tex A-310 SatNav	Magellan OEM GPS	Magellan OEM GPS
Bell 212 helicopter	GNS-500 VLF	GNS-500 VLF	GPS & VLF	GPS & VLF
Twin Otter aircraft	GNS-500A VLF	GNS-500A VLF	Wulfsburg GPS/VLF	2xGPS & VLF

* An oscilloscope and voltmeter were used to monitor projector output during each year.

In 1991 a U.S. Navy model J-13 electrodynamic sound projector served to project the low frequency sounds and a model F-40 ceramic spherical transducer was used for frequencies above about 1000 Hz. A crossover network set for 1 kHz was used to divide the sound between low and high frequencies. Each projector was driven separately with signals from one 250-W Bogen model MT250 power amplifier. In use, the J-13/F-40 combination was disappointing, providing source levels on the order of 164-167 dB re 1 μPa-m, about the same as obtained with the J-11 during 1989-90. The signal source in 1991 was a Sony TCD-D3 DAT Walkman, with frequency response flat ±3 dB from 6 Hz to 23 kHz.

In 1994 an Argotec model 220 low frequency projector was obtained, along with two model 219 transducers for mid-range frequencies, and an F-56 for high frequencies. Separate power amplifiers were used for each of the three frequency ranges, and frequency equalizers were used to divide the DAT recorder output signal into three bands for driving the power amplifiers. The model 220, having pistons at each end, required two amplifiers, although their inputs were the same. There were thus four power amplifiers: two 1600-W Techron model 7560 amplifiers for the Argotec 220, and two 350-W Techron model 7550 amplifiers, one for the mid- and one for the high frequencies. The system was designed to provide sound pressure source levels up to 180 dB at the low frequencies and to 170 dB at the higher frequencies. This frequency-related difference in maximum potential source level was acceptable because the playback stimulus sounds were at least 10 dB lower at the mid- and high frequencies than at the lower frequencies.

The 1994 projector system was tested at Argotec and at the Navy's Underwater Sound Reference Detachment, Orlando, FL, before our 1994 field season. However, operational problems with the projectors at the ice camps led to use of only one end of the model 220 for low frequencies (up to 500 Hz) and a J-11 for frequencies from 500 Hz upward. These were powered by two of the Techron amplifiers, one model 7560 and one model 7550. Furthermore, during three playback days in 1994 (3, 9 and 17 May), only the J-11 was operational. Source levels varied from day to day, and typically were comparable to those obtained in previous years (§4.4, Playback Fidelity). The signal source in 1994 was a Sony TCD-D3 DAT Walkman.

Generator.—The sound projectors and other equipment were powered by a small gasoline-engine generator (Table 2.1A). In 1989-90 the generator was placed directly on the ice. In 1991 and 1994, it was suspended by bungee cords from a frame constructed of PVC pipe. The frame stood on the ice, but the bungee cords isolated the generator from the frame and ice. In all years, the generator was placed about 20 m back from the ice edge where the projector was suspended.

Sound Monitoring at Ice Camp.—Whenever the projectors were deployed during any of the four years, an International Transducer Corporation (ITC) model 1042 spherical hydrophone was used to monitor the projected signals. This was secured to the lowering line at a measured position 1.6-3 m above the projector face (1990-94) or was positioned 0.8 m in front of the projector (1989). An ITC model 6050C wideband low-noise hydrophone was also lowered to depth 18 m over the edge of the floe, usually 3-5 m from the sound projector. The hydrophone cable was faired with 15-cm long nylon fibers to minimize cable strum. This hydrophone was used to record ambient noise when the projectors were silent, and during projector operations in 1994 it served as a second monitor of the projected sounds.

During almost all days of ice-based work, a sonobuoy was deployed ~1 km from the ice camp to serve as a far-field monitor of projected sounds (Table 2.1B). This buoy was attached to an ice edge to minimize its drift relative to the ice camp, with the exception of 17 May 1994 when the sonobuoy drifted freely. In 1991 and 1994, sonobuoy position at installation time was determined by the helicopter's GPS navigation system. The buoy radio signal was received at the ice camp with a sonobuoy receiver (Table 2.1B). When the sonobuoy and ice camp were on different ice pans, the distance from ice camp to sonobuoy was, when possible, determined periodically through the day by theodolite readings taken from the ice camp and/or by crosscorrelation of the sounds recorded near the projector and at the sonobuoy. This monitor sonobuoy, along with a hydrophone at the ice camp, provided ambient noise data at times when there was no playback.

To document the sounds being projected during playbacks and transmission loss tests, a tape recorder was used to record the signals from the ITC 1042 monitor hydrophone and, during playbacks, the monitor sonobuoy. During playbacks in 1991 and 1994, we also recorded, on the same recorder, the signals being fed to the projector amplifier(s) and the signals received at the ITC 6050C hydrophone a few meters from the projector(s). Equipment and procedures varied somewhat, depending on the year and whether a playback or a TL test was in progress (Table 2.1B). This acoustic monitoring is described further in later subsections on methods for "Transmission Loss" and "Playback Experiments".

Sound Monitoring Aboard Aircraft.—Acoustics work from the Twin Otter was based on airdropping sonobuoys at locations near whales or where whales were likely to pass. The aircraft had an antenna, preamplifier, two or four calibrated sonobuoy radio receivers (depending on year), and a TEAC four-channel DAT recorder (1990-94) or a calibrated cassette recorder (1989; Table 2.1C). The sonobuoys were mainly of two types: Sparton AN/SSQ-57A omnidirectional, calibrated wideband (10-20,000 Hz) sonobuoys, and AN/SSQ-53B DIFAR (DIrectional low Frequency and Recording) 10-2400 Hz sonobuoys. Calibrations were extrapolated down to 8 Hz to permit measuring the sound level in 1/3-octave bands centered down to 10 Hz. Hydrophone depth was 18 m for most -57A buoys (a few had been customized for 14-m or, in 1989, 12-m depth for use in shallow areas) and 27 m for the -53B buoys.

Sonobuoy position was determined from the aircraft navigation system (GPS in 1991/94; VLF in 1989-90; Table 2.1D) at launch and impact time, and (when the sonobuoy was visible from the air) by flyovers at later times. Also, we sometimes flew directly from the ice camp to a sonobuoy (or the reverse) to take GPS or VLF readings in quick succession at the two locations. Generally, the signal from the ice camp's monitor sonobuoy located ~1 km from the projector(s) was recorded on one channel of the same recorder that was recording the signals from aircraft-deployed sonobuoys. This allowed us to use crosscorrelation methods to determine relative distances of two sonobuoys from the projector based on differences in arrival times of projected sounds.

The following sections describing specific acoustic tasks include more information about specific equipment and procedures applied during those types of work.

Ambient Noise

Field Procedures.—Ambient noise was recorded from the 6050C hydrophone at the ice camps and, during transmission loss (TL) tests, at TL receiving sites. Standard practice was to record ambient noise before and after projector operation at each ice camp. During TL tests, ambient noise was recorded at the various receiving stations prior to transmission of the test signals. Hydrophone depth was 18 m in all of these cases. Ambient noise was also recorded from the monitor sonobuoy near the ice camp and from sonobuoys deployed and recorded by the aircraft-based crew. Sonobuoy frequency range was 10-2400 Hz for the AN/SSQ-53B DIFAR sonobuoys and 10-20,000 Hz for the AN/SSQ-57A sonobuoys. Sonobuoy hydrophones were at depths ranging from 9 to 27 m (Table 2.1B,C). An ITC model 1032 spherical hydrophone was used in 1990 and 1991 to record infrasonic sounds.

Ambient noise was recorded on a TEAC DAT recorder in 1990-94 and a calibrated cassette recorder in 1989 (Table 2.1B). At the ice camp, the TEAC DAT recorder was sometimes operated as a four-channel recorder in 1990-91, and always in 1994. In 4-channel mode, the frequency range on each channel was 0-10,000 Hz. Analyses were restricted to frequencies up to 8000 Hz (see "Analysis", below). This 8000 Hz upper limit was reasonable because the man-made sounds used in playbacks during 1989-94 diminished severely in level with increasing frequency, and because bowhead calls rarely contained components approaching 8 kHz.

A major component of arctic springtime ambient noise is bearded seal calls. When measuring ambient noise, we avoided sampling the taped data at times when there were prominent bearded seal calls. At times such sounds had to be included; these were times for which an ambient analysis was needed but there was no 8.5-s segment lacking bearded seal sound. At these times the spectrum had higher than usual levels at high frequencies, anywhere from 400 Hz up. Thus, the resulting ambient noise data represent noise levels in the quieter periods between bearded seal calls or, when bearded seal calls were nearly continuous, at times with such calls. When the 1/3-octave ambient noise data were summarized on a percentile basis, the shape of the 100th percentile (maximum) 1/3-octave spectrum may be influenced by the presence of a bearded seal call. However, the 95th percentile spectrum usually does not manifest such calls.

Analysis Procedures.—Segments of ambient recordings were analyzed to characterize the noise on each day of ice camp operation and during TL tests. Analysis methods in 1991 and 1994 were generally the same as in 1989 and 1990. Recorded sounds were analyzed with a computer workstation that included a two-channel 12-bit analog-to-digital converter in 1989-90, and a two-channel 16-bit analog-to-digital converter and digital signal processor (DSP) in 1991/94. The sample frequency was generally $2^{14} = 16{,}384$ samples/second, permitting useful analyses of sounds up to 8 kHz and determination of levels in 1/3-octave bands centered up to 6300 Hz. System calibrations (hydrophones, amplifiers, sonobuoys, sonobuoy receivers, tape recorders, A/D converter, and processing software) permitted results to be computed in units of pressure (micropascals) and pressure spectral density ($\mu Pa^2/Hz$) at frequencies from 8 to 8000 Hz.

A standard ambient noise analysis was based on an 8.5-s segment of sound (139,264 samples). These data were processed by Fourier transforming 0.5-s blocks (8192 samples/block) to which a Blackman-Harris window had been applied, overlapping blocks by 50%, and averaging the results from the 0.5-s blocks. The resulting spectrum elements were spaced by 2 Hz and the effective bandwidth of each element was 3.4 Hz.

From these narrowband results, we summed the powers to determine the levels in 1/3-octave bands centered at frequencies 10 to 6300 Hz. The 1/3-octave bands centered at 10, 12.5 and 16 Hz constituted the infrasonic components. Levels in several broader bands were also computed from the narrowband spectra or from the 1/3-octave band levels. In the latter case, half of the power in each of the relevant 1/3-octave end-bands was assumed to be within the broadband frequency range. The resulting 1/3-octave and broadband levels were saved in a spreadsheet.

After the 1989 field season, the project's Scientific review Board (SRB) recommended investigating the shorter-term variability of the ambient noise. This would show whether there were short periods of time (briefer than the standard 8.5 s analysis interval) 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 longer-term 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 computations: 512 and 17,408 samples (0.25 and 8.5 s).

The work was part of the 1990 effort and the results are reported in Richardson et al. (1991a).

Transmission Loss

Field Procedures.—Transmission loss (TL) tests were completed on 13 dates over the four years: on four dates in each of 1989, 1990 and 1991, and on one date in 1994. An additional partial test was done in 1994. Figure 2.1 shows the projector locations and, for each of these, the line along which the receive stations were located.

The bathymetric contours on this and subsequent maps were developed by Paul Dysart, SAIC Applied Ocean Sciences, McLean, VA, based on soundings on National Ocean Service chart 16004, the NOAA bathymetric databases, and soundings taken by us in 1989-94 at our ice camp locations and at many TL receive sites.

During TL measurements, the sound projector system described above and in Table 2.1A projected a sequence of sounds that had been recorded at carefully-chosen levels on a test tape:

- discrete tones (1989-90) or combined tones (1991 and 1994),
- 1/3-octave band tonal sweeps (1989-90) or tone clusters (1991 and 1994),
- steady drilling sounds from *Karluk* (1989-90 and 1994), and
- varying icebreaking sounds from *Robert Lemeur* (1991 and 1994).

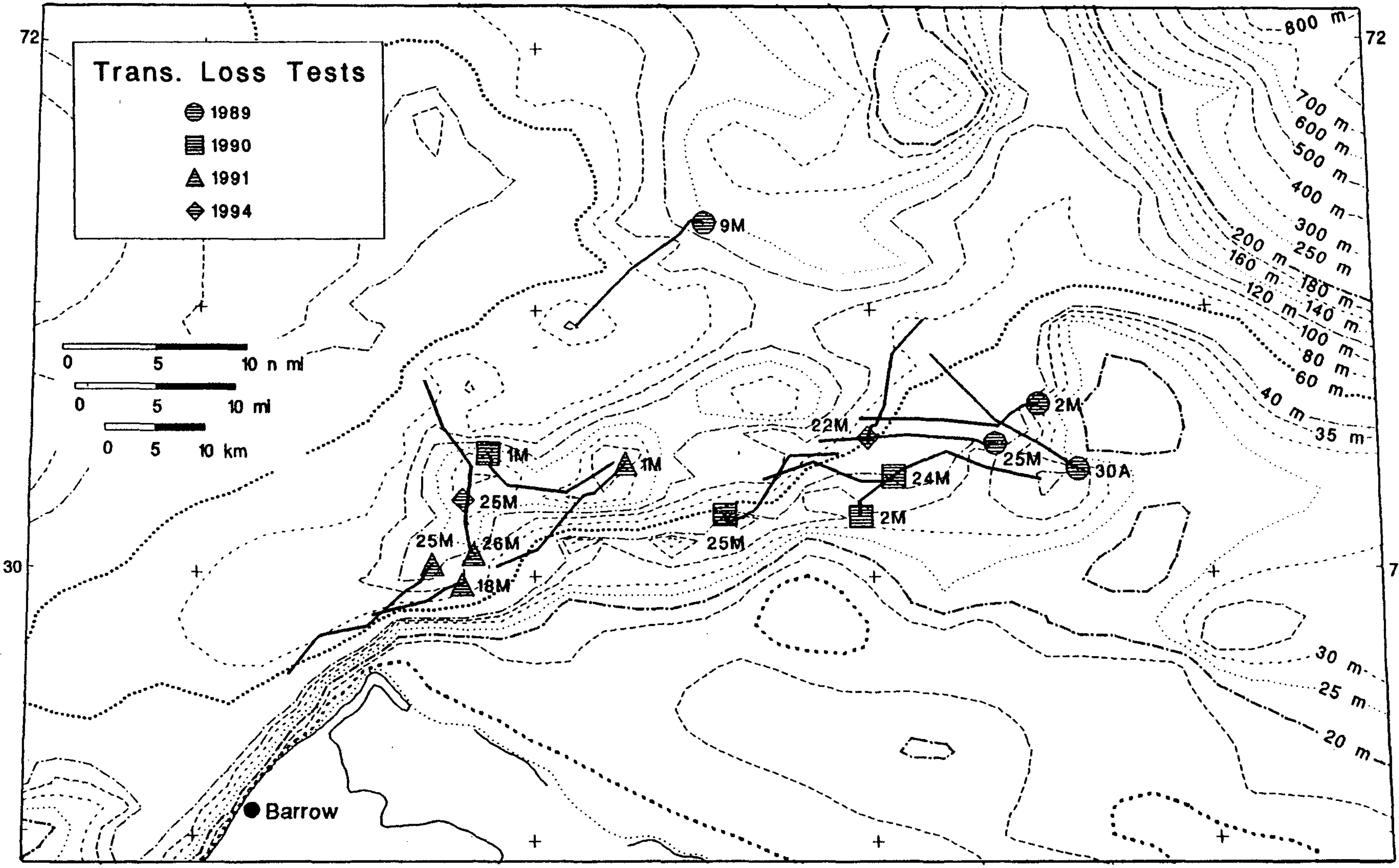

FIGURE 2.1. Projector locations during transmission loss tests and, for each test, the line along which the receive stations were located.

These signals were as follows:

- The discrete tones used in 1989-90 consisted of 10- or 20-s segments of pure tone at the following frequencies: 50, 100, 200, 500, 1000, 2000, 5000 and 10,000 Hz.
- The combined tones used in 1991 and 1994 were combinations of continuous wave (CW) tones at different frequencies, phased to assure that peak levels were not too high. There were three waveforms of this type, containing tones at (a) 20 and 40 Hz, (b) at 50, 100, 200 and 500 Hz, and (c) at 1000, 2000, 5000, and 10,000 Hz. These three waveforms were each transmitted for 30 s.
- The tonal sweeps used in 1989-90 were hyperbolic frequency modulation (HFM) signals synthesized by BBN Systems & Technologies Corp. following Rihaczek (1986). Each 5-s sweep spanned 1/3-octave at a center frequency of 100, 200, 500, 1000, 2000 or 5000 Hz. Each sweep was projected two or four times.
- The tone clusters used in 1991 and 1994 were clusters of narrowly-spaced tones spanning 20 Hz. There were two waveforms of this type: (a) with clusters centered at 150 and 300 Hz, and (b) with clusters centered at 500 and 1000 Hz. Each was transmitted for 30 s.
- The sample of *Karluk* drilling sound used in 1989-90 and 1994 was a 35-s (or longer) segment of the rather steady, low-frequency (mainly 50-350 Hz) drilling sound used during playback experiments in 1989-90. It was recorded in shallow water under ice 130 m from a drillrig on an ice pad east of Prudhoe Bay on 30-31 March 1989, as described in Richardson et al. (1990a:80).
- The sample of icebreaker sounds used in 1991 and 1994 was a 60-s (1991) or 20-s (1994) segment of the icebreaking sounds used during playback experiments in those years. This sound had been recorded 460 m from the icebreaking supply ship *Robert Lemeur* while it was breaking ice in water 35 m deep, as described in Greene (1987a).

At the projector site (base camp), TL test signals were played back with the DAT (1991 and 1994) or cassette (1989-90) recorders listed in Table 2.1A. In 1990-94, another DAT or cassette tape recorder was used to record the monitor hydrophone signal and, in 1994, the projector amplifier input signal. These recordings provided the basis for measuring the projector source levels. During each TL test, the sequence of test sounds was projected several times, twice during the period of recording at each receiving station. The location of the ice camp, which was on drifting pack ice during all but one TL test, was recorded periodically via GPS (1991 and 1994) or a Si-Tex model A-310 satellite navigation receiver (1989-90).

During each TL test, ambient noise and the transmitted sounds were received successively at various distances from 100 m to 18.5 km along or near a single azimuth. Receiving stations were along the edges of ice pans or, during one TL test (18 May 1991), on the landfast ice edge and on drifting floes in the lead. To obtain data at distances 100 m, 200 m and (rarely) 400 m from the projectors, a sled was used to haul the equipment along the ice edge from the base camp. Distance to these sites was determined with a Rolotape distance measuring wheel rolled along the ice. The helicopter provided transportation to the more distant sites at nominal distances 0.5, 1, 2, 5, 7.5 and 10 n.mi. (0.93, 1.85, 3.7, 9.3, 13.9 and 18.5 km). The 10 n.mi. station was skipped if no projected sounds were heard at 7.5 n.mi. Positions of these sites were determined via the helicopter's navigation system (GPS in 1991 and 1994; GNS-500 VLF in 1989-90). In 1989-90, when the less-precise VLF navigation system was used, the helicopter often flew back over the ice camp and noted its apparent VLF position before moving to a new receiving station and noting its VLF position. About 4 h were required to measure the received signals at ~8 ranges, exclusive of the time (4-5 h) needed to set up and remove the projection equipment.

At each receiving station, the transmitted test signals were recorded with an ITC model 6050C hydrophone suspended via faired cable at 18 m depth. Also, ambient noise was recorded at each receiving station before and after the period with test signals. During some tests in 1989-91, ambient noise was recorded at the closer ranges with the generator at the base camp turned off as well as operating. This was done to determine the characteristics and range of detectability of the generator sounds. The received sounds were tape recorded with a battery-powered portable TEAC DAT recorder in two-channel mode (bandwidth 0-20,000 Hz) during 1990-94, and with a calibrated cassette recorder in 1989 (Table 2.1B). Water depths at the ice camp and at most of the more distant receiving stations were measured with an echosounder. An ITC 1032 hydrophone was used to record infrasound at TL receive stations in 1990-91.

Analysis Procedures.—Signal analysis was generally the same as was used for ambient noise analysis (see above). Signal segments 8.5-s long were sampled at 16,384 samples/s. For each receive station, we measured the received level of each projected signal and of the ambient noise level. These signals were analyzed by Fourier transformation of windowed, overlapped blocks 0.5 s long (8192 samples), and the results were averaged. The spectrum resolution was 3.4 Hz on 2-Hz centers. The powers (pressures squared) in the analysis cells spanning each 1/3-octave band were summed to derive the 1/3-octave band levels for the drilling, icebreaker, and ambient sounds received at each station. The tone levels were measured from the appropriate narrowband frequency element, and the sweeps were analyzed by taking the appropriate 1/3-octave band level.

Results were kept separate by type of signal: tones, HFM sweeps, clusters, *Karluk* drilling, and *Robert Lemeur* icebreaking. The variable qualities of the icebreaking sounds, even over the relatively short period of 20 s, and the fact that the received and transmitted signals were not recorded on the same tape recorder, made it impossible to analyze exactly the same transmitted and received segments. Thus, the TL measurements based on the samples of variable icebreaker sounds were less accurate than the measurements based on the steady *Karluk* drilling sounds and the HFM sweeps.

Transmission loss was computed by subtracting the measured received levels from the measured source levels. The resulting data were used directly when the signal + noise level exceeded the ambient noise level in the corresponding frequency band by at least 10 dB. When the signal + noise level exceeded the noise level by 3-10 dB, the combined level was corrected for the noise to calculate the signal level alone. The TL modeling effort based on the resulting data is described in §4.3. This effort resulted in a model that, for the conditions prevailing in our study area in late April and May, predicts transmission loss in relation to frequency, water depth, and distance from source.

Playback Experiments

The acoustical methods used during playback experiments are best described in conjunction with methods for biological observations during playbacks. This material appears in §2.3.

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 projectors of practical size, 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 this study. 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.

Infrasonic Ambient Noise.—The standard methods for determining ambient noise also provided data on infrasonic ambient noise. The hydrophone, preamplifier and DAT recorder used for hydrophone-based ambient noise recordings in 1990-94 were calibrated at frequencies from 5 to 20,000 Hz; the response was suitable for recording the infrasonic sounds from 8 to 18 Hz. The sonobuoys, radio receivers and DAT recorders used at the ice camp and on the aircraft in 1990-94 were sufficiently calibrated to be useful at infrasonic frequencies as well. Both the -57A and -53B sonobuoys are sensitive from 10 Hz upward. All ambient noise recordings from 1991 and 1994 that were suitable for measurements at higher frequencies were also suitable for infrasonic noise measurements at 8-18 Hz. The 1/3-octave band levels centered at 10, 12.5 and 16 Hz were determined along with the levels in higher-frequency bands. Those infrasonic band levels were saved in the same spreadsheet with the higher frequency 1/3-octave band levels.

A special hydrophone (ITC model 1032 sphere) was used in 1990-91 to sense infrasonic ambient noises and bowhead calls that might contain infrasonic sounds. The 1032 with a high-impedance preamplifier was essentially flat down to a frequency of 1 or 2 Hz.

Infrasonic Components of Bowhead Calls.—The 1990 results on the question of infrasonic components in bowhead calls were presented in Richardson et al. (1991a:91*ff*). In 1991, narrow-band spectral density analyses were performed on all bowhead calls received on the 6050C hydrophone or sonobuoys and recorded on the TEAC DAT recorder during five dates: 1, 11, 18, 25 and 26 May 1991. Waterfall spectrograms were plotted for the frequency range 6-250 Hz to support a search for call energy at frequencies below 20 Hz. A minority of the calls analyzed in this way included infrasonic energy that may have been associated with the call (§4.5).

Waterfall spectrum analysis was useful in determining whether, at the times when bowheads emitted their known types of calls, there also were 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 s of data analyzed and displayed per spectrum displayed.
- Typically, 9.45 s of data were displayed in a waterfall plot showing frequencies 5 to 250 Hz.

2.2 Whale Surveys and Observations

Aerial Reconnaissance and Surveys

General Approach.—Aerial reconnaissance and surveys were necessary to meet specific objective 4, "To measure the short-term behavioral responses of ... whales ... to underwater playbacks of variable icebreaker sounds ...". Aircraft-based work was also important in addressing specific objective 7, "To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses and acoustic environment ...".

Aerial reconnaissance of the study area was done daily to locate whale migration corridors, which often changed from day to day. This information was used in selecting the location where the sound projectors were set up each day. Aerial reconnaissance was also a necessary first step in locating and selecting the specific whales to be observed and photographed from the air.

The flight route depended upon ice conditions, and was non-systematic. On most days, the survey route initially followed the south side of the nearshore lead along the landfast ice edge. We generally began surveying about 15 km northeast of Pt. Barrow and flew east along the ice edge for as much as ~75 km. (We did not search that far east on days ▸ when the nearshore lead did not extend that far east, or ▸ when it was apparent that the main bowhead migration corridor was farther offshore, or ▸ when weather deteriorated to the east.) If a suitable projection site was not identified along the landfast ice edge, the north side of the lead was then surveyed. Finally, if a suitable projection site was not found in or adjacent to the nearshore lead, or if the nearshore lead was congested with pack ice, a series of widely-spaced transects was usually flown over the pack ice farther offshore to determine ice conditions there, the locations and orientations of leads and cracks, and the locations of any bowhead or white whale concentrations. When searching for whales in the pack ice, we often followed leads and cracks that seemed likely to provide migration routes for migrating bowheads and white whales.

After a location for the sound projectors had been selected, additional surveys were usually conducted as far as ~20 km west and southwest of the projector site. At the point when it became apparent that further reconnaissance surveys were unnecessary in meeting that day's objectives, the aerial crew

- began to conduct systematic aerial observations of whale behavior if bowheads were found and if clouds either were absent or were above 460 m Above Sea Level (1500 ft ASL); or
- began to photograph bowheads if bowheads were present but low cloud prevented behavioral observations from 460 m ASL; or
- returned to Barrow if no bowheads could be found or if the weather was too marginal for productive or safe flying.

In 1989-91, insofar as possible, we avoided flying low (at <460 m) over the main nearshore lead during midday. At midday, a National Marine Mammal Laboratory (NMML) crew was usually flying low over the leads within the study area, searching for bowheads to photograph. In 1994, the NMML crew was not present so low-level flights were possible at any time.

We avoided flying within 5 n.mi. (9 km) of active whaling camps except when this was unavoidable because of the presence of camps within 5 n.mi. of the approach to Barrow's airport. In 1991, whaling at Barrow ended in mid May. From 17 May onward, we conducted reconnaissance surveys along the landfast ice edge and nearshore lead west and northwest of Barrow as well as in the usual study area farther northeast of Pt. Barrow. In 1994, whaling continued until the end of the our field season, and surveys were restricted to the normal study area east and northeast of Pt. Barrow.

Survey Methods and Data Recording.—We conducted aerial surveys from 28 April through 26 May 1991 and from 27 April through 25 May 1994 in a DHC-6-300 Twin Otter aircraft. (Table 3.2, on p. 62, summarizes aerial efforts in all four years of the project.) In addition to the standard belly fuel tanks, the aircraft had wingtip tanks (1991 only) and an additional tank in the cabin; total aircraft endurance under our typical operating conditions was 9+ or 8+ hours in 1991 and 1994, respectively. Other special equipment included marine VHF radios, VLF/GPS navigation system, radar altimeter with digital display, invertors for 120 V/60 Hz AC power, three bubble windows (right center, left center, left rear), intercom system with voice activated microphones, and ventral camera port.

In 1991, the aircraft was equipped with a Wulfsburg combined VLF/GPS navigation system that operated in GPS mode normally and reverted to the less-precise GNS-VLF mode during the small percentage of the time when GPS was unusable. (The GPS satellite constellation was not yet complete during the 1991 work.) When GPS became usable again after a period of VLF navigation, the GPS automatically updated the VLF system to correct for accumulated errors. When the GPS was usable, position readouts were usually accurate within 0.2 n.mi., based on the readout upon return to a known location at Barrow. As usual, position errors as large as 1 km were common when operating in VLF mode. A microcomputer interfaced to the VLF/GPS system and the radar altimeter automatically recorded aircraft position and altitude at intervals of 10 s or less.

In 1994, the aircraft was equipped with two independent GPS systems in addition to a VLF system. One GPS was part of the aircraft navigation equipment. The second GPS system, a Trimble Pathfinder, was part of a GeoLink data acquisition and mapping system that provided a real-time map display on a portable computer (Dell 25 MHz 386/387), and stored GPS positions at 1-s intervals.

There were a total of 30 offshore flights on 23 different dates from 28 April to 26 May during 1991 (Table 3.2, p. 62). On five of these days, the single flight was terminated within 0.3-1.0 hours because of poor weather offshore. The remaining 25 flights ranged from 1.6 to 5.2 h in duration. Longer flights were not warranted during 1991 because of the low clouds that almost always prevented observations from altitude 460 m. Total flight time during the 30 offshore flights was 75.4 h, of which 55.8 h was spent on reconnaissance.

In 1994, there were 35 flights on 22 dates from 27 April to 25 May. Poor visibility or high winds prevented any useful work during flights conducted on the afternoons of 2 and 18 May. The remaining 33 flights ranged from 1.0 to 7.3 h in duration. Total flight time during the 35 offshore flights was 119.0 h, of which 66.0 h was spent on reconnaissance.

Flight and observation procedures were consistent with those during the 1989-90 phases of this project. During reconnaissance work, the aircraft was flown at ~185-200 km/h groundspeed and, when possible, at 460 m ASL. When the cloud ceiling was lower than 460 m, as it almost always was in 1991 and frequently was in 1994, the maximum possible altitude below the cloud layer was maintained.

Four observers were present during almost all surveys in 1990-94 (three in 1989). 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 seats behind the pilot's seat, and the fourth was at a rear-left bubble window. When a whale was sighted, the observer(s) notified other members of the crew via the intercom. Most bowheads 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 were usually not circled, but large groups were sometimes circled to obtain more accurate counts and heading information. For each whale sighting, we recorded on paper and/or a tape recorder the time, location, species, number, general activity, orientation, and percent ice cover. Ice conditions were recorded throughout the survey, particularly whenever a change in ice type or percent cover occurred. Aircraft position and altitude were recorded manually from the GPS or VLF system whenever sightings were made and whenever the aircraft changed course. Position and altitude were also logged automatically throughout each flight, as noted earlier.

All sightings of bowheads and white whales from all years of the project (1989-90 as well as 1991 and 1994) have been transcribed into a standard numerical format, computerized, and mapped in this report.

Aerial Photography of Bowheads

Field Procedures.—Aerial photography of bowheads was one of the lower priorities during this project. However, it was often possible at times when higher priority work was prevented by the low clouds that prevailed during the spring of 1991 and that occurred commonly during other years. Vertical photos of bowheads were obtained in 1991 during 11 flights on 10 dates ranging from 29 April through 26 May, and in 1994 during 12 flights on 10 dates ranging from 30 April to 25 May. Similar work was done during the 1989 phase of this project, when vertical photos were obtained during 9 flights on 8 days (Richardson et al. 1990a). Vertical photography was not possible in 1990.

We used the calibrated vertical photography technique developed by LGL and described by Davis et al. (1983) and Koski et al. (1992). The resulting photos provided data on the individual identities and sizes of many of the whales photographed. These data are relevant to specific objective 7 concerning the movements, behavior and basic biology of bowheads (p. 7). The data are also at least indirectly relevant in certain aspects of the evaluation of playback effects (specific objective 4).

Field procedures were as described by Davis et al. (1983), Richardson et al. (1990a:60*ff*), and Koski et al. (1992). Briefly, the aircraft, flying at an airspeed of ~160 km/h and—cloud ceiling permitting—an altitude of ~137 m (450 ft), passed directly over bowheads. Because of the prevailing low clouds in 1991, some 1991 photographs were taken from lower altitudes. Photographs were taken through the aircraft's ventral camera port with one of two hand-held Pentax medium-format cameras (6x7 cm film size), each with a 105 mm *f*2.4 lens, pointed directly downward. Ektachrome 200 and Fujichrome 400 color positive film were used. Aircraft altitude was recorded from the radar altimeter at the moment the camera shutter fired. In 1989 and 1994, radar altitude was manually recorded by the observers in the rear of the aircraft from a digital display and, independently, in the front of the aircraft from an analog display on the instrument panel. In 1991, the radar altitude was recorded both manually and via the computerized data logger.

On one date in each year, a calibration target of known dimensions was spread out on a flat surface (airport runway in 1989; lagoon ice in 1991 and 1994) and photographed with each of the two cameras from the same altitudes used to photograph whales. Both whale and calibration photographs were most commonly taken from ~137 m, but in 1991 a few photographs were taken from altitudes as low as ~76 m.

When behavioral observations of whales were possible either from the aircraft or by ice-based observers, low-altitude photographic work was avoided until the behavioral observations were completed. In 1989 and 1991, we also did not purposefully photograph bowheads at locations where the NMFS/NMML crew had photographed bowheads on the same date. We supplied NMML with copies of our 1989, 1991 and 1994 photos of identifiable bowheads, and they reciprocated with copies of their relevant 1989 and 1991 photos (NMML did not conduct photography in 1994).

Analysis Procedures.—The procedures used to identify individual whales and to determine their sizes are summarized by Richardson et al. (1990a:62-63); Koski et al. (1992), and Rugh et al. (1992a).

Measurements of the 1991 LGL calibration target as photographed from ~76 m ASL were more variable than those from higher altitudes. Hence, we considered whale lengths determined from photographs taken at <91 m (<300 ft) to be approximate. Such lengths are included in histograms when no "better" measurement was available for the whale in question. However, these approximate lengths will be excluded from analyses that require precise length measurements, e.g. analyses of growth rate.

All LGL and NMML whale images obtained were classified as Grade A (recognizable between years if compared to a photo of similar or better quality), Grade B (recognizable on a different day within the same season if compared to a photo of similar or better quality), or Grade C (not recognizable). The reader is referred to Davis et al. (1983) for a more detailed description of grading of photos for reidentification purposes.

To check for whales photographed more than once within a given year, each LGL image from 1989 was compared to all others acquired by LGL in 1989, and to all images acquired by NMML in 1989 after 11 May. For 1991, each LGL and NMML Grade A and B whale image was compared with all other Grade A and B images acquired within 7 days of that image. The procedure used in 1994 was the same as that in 1991, except that in 1994 there were no NMML photos. The procedure used in 1991 and 1994 assumes that no whale would linger in the Barrow area for more than 7 days during spring migration.

To identify between-year resightings, we also compared all LGL and NMML Grade A images from 1989, 1991 and 1994 with the complete 1981-94 LGL and 1984-91 NMML collection of Grade A photos. (NMML's 1992 photos were not considered.) In these inter-year comparisons, the new Grade A whale images were compared with images in the same file and in "adjacent" files. The adjacent files are those containing whale images with similar characteristics (Rugh et al. 1992a).

Aerial Observations of Behavior

Our standard procedures for aerial observations of focal groups of bowheads (e.g. Richardson et al. 1991a:27*ff*) were applied whenever observations were possible from an altitude of 460 m. Previous studies have indicated that bowheads observed from an aircraft circling at 460 m ASL and at reduced power (~165 km/h) are usually not disturbed by the aircraft (Richardson et al. 1985a,b, 1991; Richardson and Malme 1993). Results from the present study verified this (§6.7).

In 1991, the prevailing low cloud usually prevented useful behavioral observations from the aircraft. We obtained only 4.1 h of systematic behavioral observations; these came from 7 observation sessions on 5 dates (29 April, 4, 6, 20 and 25 May). In 1991, we were never able to obtain aerial observations of bowheads near the operating sound projectors. The few times when the aircraft crew could observe from 460 m ASL near the ice camp were times ▸ when no bowheads were present, or ▸ when the sound projection equipment was still being set up, or ▸ when dangerous ice conditions or encroaching fog forced termination of ice camp and/or aircraft operations before useful data could be obtained.

In 1994, we were able to observe the behavior of bowheads or (rarely) white whales from the Twin Otter circling at 460 m ASL for a total of 36.2 hours during 23 observation sessions on ten different days (Table 3.2, p. 62). Twelve of these sessions on four days (7, 9, 16 and 17 May) were done near the ice camp either during a playback of icebreaker sounds or during the preceding or following control period; five of these 12 sessions were at times while icebreaker sounds were being projected. Numerous bowheads were observed during most playback sessions (see Table 3.8, p. 80-81). However, the high sea states encountered commonly during 1994 resulted in discontinuous and fragmentary observations on most days. When the sea state is high, it is often impossible to detect bowheads when they first surface. This prevents determination of the duration of surfacing, number of blows per surfacing, amount of turning during surfacing, and other variables that require observation of the complete surfacing. Also, with high sea states it is frequently impossible to be sure whether any surfacings have been missed, or to see the distinctive markings that show whether a given whale is the same one observed during a previous surfacing. These problems were unusually common during the 1994 behavioral observation work.

Observation Procedures.—Throughout each observation session, two full-time observers plus (in 1990-94) one part-time observer on the right side of the aircraft dictated standardized behavioral observations and whale position data via the intercom into a single audio recorder and also into the audio channel of a video recorder. The two full-time observers were seated in the co-pilot's seat and the seat two rows behind it. The part-time observer occupied a seat 2-3 rows behind the primary observers. During each surface/dive sequence by bowheads, they described the same behavioral attributes as recorded in our previous studies of bowhead behavior and disturbance reactions (e.g., Würsig et al. 1984, 1985, 1989; Richardson et al. 1985a, 1986, 1990b, 1991a, 1995; Koski and Johnson 1987; Dorsey et al. 1989). These data included times when each focal whale surfaced, blew and dove; its headings and turns; occurrence of pre-dive flexes, fluke-out dives and aerial activities (breaches, tail and flipper slaps, etc.); and occurrence of numerous other behaviors as listed in §5.3, Behavior of Undisturbed Bowheads.

Another observer, also on the right side during behavioral observations, operated a high-resolution 8-mm video camera whenever whales were at the surface. In 1991, this was usually a Sony CCD-V99 with 11-88 mm zoom lens, x1.4 teleconverter, and monochrome viewfinder. In 1994, we usually used a Sony CCD-TR500 with 5.4 to 54 mm lens, x2 teleconverter (on some days), and color LCD viewfinder. Videotaping was through a side window at the rear of the aircraft. In 1991/94, the standard plexiglass window there had been replaced by flat glass. The video camera was usually operated with manual focusing and with high shutter speed (e.g. 1/1000 s) to provide sharp images when viewed in stop-frame mode. Automatic exposure was used when practical, but manual exposure adjustment was necessary when there was much ice within the field of view. The date and time (to the second, synchronized with observers' digital watches) were recorded on each video frame to facilitate analyses. The audio signal recorded on the videotape was taken from the aircraft intercom, and thus included the behavioral, positional, and other data dictated by all personnel on the aircraft. While the focal whale or group of whales was at the surface, the video camera was normally kept tightly framed on those whales. After they dove, a wide-angle view of the area was normally recorded to assist in determining whale position relative to ice features and the ice camp.

Behavioral data were transcribed from audiotape between flights or, in some cases, after the field season. The videotape was then examined 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 (BMDP/ Dynamic, release 7.0 for MS-DOS computers—Dixon 1992).

Behavioral Definitions and Criteria.—Most definitions and criteria were the same as in our previous related studies (e.g. Dorsey et al. 1989; Richardson et al. 1995). In particular, a surfacing is again defined as the interval from the first arrival of a whale at the surface after a long ("sounding") 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. Some studies define the surface time as the interval from the first blow to the last blow of a surfacing sequence. In contrast, we define it as the interval from first arrival of the whale at the surface to the final submergence of the sequence. Bowheads are often visible at the surface for a few seconds after the last blow, and occasionally for a few seconds before the first blow. Therefore, surface times defined on the basis of the first and last blows presumably would average a few seconds shorter than those obtained with our procedure.

There were two changes in procedures in this study (1989-94) relative to our previous projects concerning bowhead behavior in summer and autumn:

- 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 spring than in summer or autumn. 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 study is the "median blow interval for a surfacing". In some previous summer/autumn analyses we used mean, not median, blow intervals. The median is less affected by occasional extreme values, or by missed blows.

There can be some doubt as to whether certain brief (<1 min) submergences should be counted as dives or as intervals between two blows within a surfacing sequence. The procedure for handling these cases is important because it has major effects on variables such as duration of surfacing and number of blows per surfacing. One approach is to use "log survivorship analysis" (Fagen and Young 1978) to identify a specific time interval to be used to separate long blow intervals from short dives. We did not use that approach, as no one simple arithmetic criterion is appropriate. Certain blow intervals, e.g. by some whales resting at the surface, are quite long but nonetheless clearly blow intervals and not dives. Conversely, certain dives, e.g. when bowheads are being actively pursued, are quite short but nonetheless clearly dives and not blow intervals. Thus, the longest blow intervals are longer than the shortest dives and no single "duration" criterion is appropriate for all cases.

When viewed from an aircraft, the behavior of bowheads at the start of a sounding dive is usually distinct from that at the start of a submergence between blows. When sounding, a bowhead usually arches its back as it submerges, the flukes are sometimes raised, and the whale typically appears to be diving deeper and/or more steeply. However, bowheads occasionally surface again within ½-1 min after such an apparent sounding dive. In this study, we classified these short submergences as dives if one or more of the usual indicators of a dive were seen: an arch, fluke-out, or steep submergence. If the whale sank out of sight without any of these indicators of a dive, and surfaced again within 1 min, the submergence was classified as a blow interval within a surfacing sequence. Shallow dives during which whales swam close enough to the surface to be visible from above were counted as dives only if they were >1 min in length (>½ min for calves).

Number of Observations.—In this report, when analyzing the behavior of undisturbed bowheads (§5.3, §5.4), we combined results from 1991 and 1994 with those from the 1989-90 phase of the project. Observation procedures in 1989-90 were very similar to those described above for 1991 and 1994 (see Richardson et al. 1990a, 1991a for details). Results from all four years are directly comparable. Over the four years of the study, the numbers of bowhead surfacings and dives for which we have at least partial behavioral data are shown in Table 2.2.

TABLE 2.2. Number of bowhead surfacings and dives for which behavioral data (complete or partial) were obtained via the aerial observation technique.

	1989	1990	1991	1994	Total
Surfacings					
Presumably undisturbed whales	258	558	57	496	1369
Potentially disturbed whales[a]					
Drilling noise playbacks	128	261	-	-	389
Icebreaker noise playbacks	-	-	0	149	149
<30 min after playback	0	27	0	26	53
Aircraft at <460 m ASL	58	2	0	0	60
Other or combination	39	12	0	26	77
Total, undisturbed + disturbed	483	860	57	697	2097
Dives					
Presumably undisturbed whales	157	377	40	325	899
Potentially disturbed whales[a]					
Drilling noise playbacks	105	136	-	-	241
Icebreaker noise playbacks	-	-	0	83	83
<30 min after playback	0	15	0	20	35
Aircraft at <460 m ASL	35	2	0	1	38
Other or combination	36	4	0	22	62
Total, undisturbed + disturbed	333	534	40	451	1358

[a] Includes observations during 30-min or (for aircraft) 15-min post-disturbance periods.

Ice-based Observations

Ice-based observations of bowheads and white whales were obtained to help meet specific objectives 4, 6 and 7 (p. 7). A watch for whales was maintained by 1-4 people (most often 2 or

3) starting within a few minutes of arrival on the ice and continuing until about ½ h before departure. At least one person watched throughout this period, but the number of additional people who were watching for whales tended to be lower early and late in each day's observation period, when equipment was being set up or packed, than during the middle hours. When no whales were present, ringed and bearded seals were observed opportunistically, or the day's plan was changed to conduct a transmission loss test.

Field procedures in 1991 and 1994, primarily involving use of a surveyor's theodolite to observe and locate whales, were very similar to those during 1990 (see Richardson et al. 1991a:29*ff*). In 1991, we used a Lietz/Sokkisha model DT5 digital theodolite with 10 second precision. In 1994, we used a Lietz/Sokkisha model DT5A with 5 second precision. The height of the theodolite was determined each day by taking a gravity-referenced reading from a vertical stadia rod at the projector location. Theodolite readings in degrees, minutes and seconds were referenced to magnetic north and to gravity. Ice ridges on which the theodolite was placed ranged in height from 2.8 to 6.0 m ASL, but were less stable than desired. To control for errors caused by movement of the theodolite base, the horizontal and vertical zeroes were checked every 15-30 min and after tracking episodes, and were reset if off by >1 minute of arc in 1991 or >40 seconds of arc in 1994.

One difference from 1989-90 was that, on most dates, the digital theodolite was interfaced by way of an RS-232 serial interface to a Hewlett Packard 71B "palmtop" computer (1991) or a Tandy 102 "laptop" computer (1994). This allowed direct logging of bearings and depression angles in relation to time. The program also permitted entry of notes about whale behavior and identification. Distances were computed using an iterative equation that included correction for curvature of the earth.[5] Data were stored on diskette and, for backup, printed in real time via a portable ink jet printer. A heating pad designed for a car battery and powered by the generator at the ice camp kept the computer batteries and ink jet printer warm enough to work on the ice. This data logging system allowed for automated and hence quicker collection of theodolite readings, resulting in more detailed tracks of successive animal positions.

Because of the low vantage point from the ice, ice-based observers could not see whales unless they were within ½-2 km, depending on ice conditions, visibility, and perch height. Also, because of the near-horizontal observation angle, whales could not be seen when slightly below the surface, and many aspects of behavior were difficult to observe. The most valuable data obtained from the ice-based observations were data on the closest point of approach (CPA) of whales to the ice camp, and on the paths of the whales passing close to the camp. For whales passing within about 1 km, ice-based observers aided by the theodolite could obtain more precise data on whale CPAs and tracks than could aerial observers. Also, ice-based observers maintained a continuous watch on the area near the ice camp throughout each playback and its associated pre- and post-playback control periods. During much of this time, aerial observations were not possible

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[5] The computer program that acquired and processed the theodolite data in 1991 was prepared by F. Cipriano, Dept of Ecology and Evolutionary Biology, University of Arizona. A similar program prepared by A. Frankel, Dept of Oceanography, University of Hawaii, was used in 1994.

near the ice camp because the aerial crew was observing other whales farther away, or was away refueling, or was unable to observe because of low clouds. Thus, the ice-based and aerial observations were complementary to one another.

During each day of ice-based work, ice conditions near the ice camp were documented by taking theodolite readings of ice edges and other prominent ice features visible from camp. These readings were taken about once per hour, and/or immediately after whales were observed. The theodolite-to-projectors distance was also measured each day using a Rolotape measuring wheel.

During 1991 and 1994 all personnel at the ice camp wore long white snow-shirts over their parkas to minimize their visual conspicuousness.

2.3 Playback Experiments

General Playback Approach

The general approach was very similar to that in preceding years of this project, as described by Richardson et al. (1991a:30*ff*). Icebreaker sounds were projected from a mobile ice-based camp established on the landfast or pack ice each day when weather or ice conditions were suitable. The reactions of whales to these sounds were determined by systematic observations of whales approaching, passing, and moving away from the ice camp. Such observations were obtained both when the projectors were operating ("playbacks") and when they were silent ("control"). These types of observations were obtained by observers at the ice camp and, when the cloud ceiling exceeded 460 m, by observers in an observation aircraft, as described in §2.2.

Playback experiments had higher priority than any other project task during all four years of fieldwork. This was particularly so on days when whales were observed migrating through the study area and when weather conditions were suitable for behavioral observations of whales from the circling fixed-wing aircraft. On these occasions, personnel at the ice camp projected sounds, and personnel on the ice and in the aircraft observed whale behavior. On many days, the cloud was too low for aerial observations from 460 m altitude, but horizontal visibility was good. If whales were migrating in the area on these "low-cloud" days, playback experiments were usually attempted, with all observations then being from the ice camp. In either case, the Twin Otter aircraft generally departed Barrow first, conducted a survey for whales and ice conditions, and selected a possible site for the ice camp before the helicopter arrived.

Cloud permitting, the Twin Otter crew then conducted "control" observations of the behavior of undisturbed whales within a few kilometers of the ice camp while the ice-based crew set up the projection equipment and, simultaneously, began ice-based control observations of whales. Weather permitting, both aerial and ice-based observations of whales continued during the subsequent playback period and during a following post-playback "control" period. Often weather conditions changed during the day. Sometimes this forced cancelation of aerial observations but allowed continuation of ice-based work. Occasionally clouds were too low for aerial observation during the pre-playback control period early in the day, but aerial observations became possible later, during and after the playback period.

Playbacks were done with the equipment listed in Table 2.1A (p. 21). The time required to set up the equipment at an ice camp was 1-2 h in 1989-90, 2-3 h in 1991, and 3-4 h in 1994. These are the approximate intervals from first arrival on the ice until everything was ready to project underwater sound. Setup time became longer after 1990 because of the increasingly heavy and elaborate sound projector systems and associated electronics in 1991 and especially 1994. Control observations were collected during the setup process but, especially in 1991 and 1994, conditions on the ice sometimes became untenable before the equipment was ready for a playback or shortly after the playback began.

Meaning of the Term "Control"

Insofar as possible, we obtained control observations near the ice camp under conditions that differed from those during playbacks only by the emission of sound from the projectors. This is the usual definition of "control". This approach is appropriate for determining whether playbacks *per se* had any discernible effects. However, concern has been expressed that this approach might underestimate the actual effects of playbacks if whales observed under control conditions were already somewhat disturbed.

Some whales that approached the ice camp during control conditions probably could hear man-made sounds associated with operation of the generator, intermittent helicopter operations, and the circling Twin Otter observation aircraft. We attempted to minimize exposure of whales to noise from these sources, but it was not possible to eliminate all exposure. Section 4.6 describes the generator noise, and §6.7 and §7.4 describe reactions of spring-migrating bowhead and white whales to aircraft. The few cases of bowheads and belugas reacting to helicopter operations near the ice camp are excluded from our "control" datasets. There was little indication of reactions to our other activities during control periods. However, we cannot exclude the possibility that these activities had subtle effects on some whales observed near the ice camp during control periods.

Strictly speaking, therefore, the differences between whale activities and behavior during playback vs. control periods represent the incremental reactions to playbacks when playbacks are added to a background of other human activities associated with the research. If the whales observed under control conditions were somewhat disturbed, then the differences in whale activities between control and playback conditions might understate the differences between activities of truly undisturbed whales vs. those exposed to playbacks. However, almost all bowhead and white whales observed during control conditions during this study behaved in a manner indistinguishable from that seen, during this and other studies, by ice- or shore-based personnel observing in the absence of any known disturbance. Of the few exceptions, most involved helicopter disturbance, and these cases have been excluded. Therefore, we believe that the playback vs. control comparisons in this study provide a good indication of the differences in whale activities that would occur between playback conditions and otherwise-similar situations with no human activities.

Acoustical Aspects of Playbacks

Playback Stimuli.—During 1989 and 1990, the steady underwater sounds of drilling on an ice pad, as recorded at the *Karluk* site, were projected as the playback stimulus. The collection and characteristics of these sounds were described in Richardson et al. (1990a, p. 44 and 80*ff*).

During 1991 and 1994, the varying sounds of an icebreaker operating in heavy ice were used, as recommended by project personnel and agreed by the Minerals Management Service and the project's Scientific Review Board. In contrast to the steady, low-frequency drilling sound used in the 1989-90 tests, icebreaker sound has significant energy at frequencies up to a few kilohertz, and the source level is quite variable over time. After data on whale reactions to the drilling sound were collected in 1989-90, it was considered important to test the reactions to a more variable sound with broader frequency composition.

The icebreaking sounds used for playback stimulus were recorded on 2 September 1986 from a drifting boat 0.25 n.mi. (460 m) from the icebreaking supply ship *Robert Lemeur* operating in heavy ice near the Corona drillsite ~40 km north of Camden Bay (Greene 1987a). This ship is an Arctic Class 3 icebreaker of 83 m length overall and 3184 tons gross displacement. It has two turbocharged diesel engines of combined power 9600 bhp (7.2 MW). The two four-bladed controllable-pitch propellers are in Kort nozzles. Sounds were recorded continuously for over 14 minutes. The characteristics of these received icebreaker sounds were reported by Greene (1987a) and are further summarized in §4.4 of this report (p. 115*ff*).

Prior to the field season, the taped icebreaker sounds were played back several times to record a 2-h DAT tape of icebreaking sounds, which was itself copied to provide a second 2-h DAT tape. The end time of the 14-min segment was selected such that the levels at the start and end of the segment were closely matched. Thus, there was no sharp change in the sound at 14-min intervals when the segment began to repeat. During playback experiments on the ice, the two tapes were played sequentially, replacing the played-out tape with the alternate quickly to minimize the break in transmission (about 30 s), and then rewinding the first tape while the second one played.

Projector Operations.—Playbacks were done with the equipment listed in Table 2.1A and described in §2.1 under "General Approach and Equipment". Briefly, during 1991 and 1994, a Sony DAT recorder was used to play back the icebreaker sounds. This resulted in accurate speed and frequency reproduction for the playbacks. These sounds were projected into the water by a J-13/F-40 system (1991) or an Argotec 220/J-11 system (1994) suspended at a depth of 18 m. In 1991, we used a 250-W amplifier powered by a 2.2 kW gasoline generator. In 1994, we used a 1600-W amplifier to drive the Argotec 220, only one side of which was operational, and a 350-W amplifier to drive the J-11; these were powered by a 5 kW gasoline generator. In 1991 and 1994, the generators were suspended from a frame via bungee cords to minimize transmission of generator noise and vibration into the water. In both years, the projectors were turned on at a time when no whales were known to be within ½ km of the ice camp, as required by Scientific Research Permit 670/Modification 2, issued by the National Marine Fisheries Service. At the start of most playbacks, the sound level was increased gradually over 1-5 minutes ("ramped up").

In 1991 and 1994, icebreaker playbacks were done for a total of ~40 h distributed over 13 d. This included 7 d when bowheads were seen near the ice camp during the playback, and 3 d when white whales were seen there during the playback (see Table 6.1 in §6.1).

Playback operations in 1989-90 were described by Richardson et al. (1990a, 1991a). Drilling sounds were projected for prolonged periods on 19 d, including 10 d when bowheads were seen near the ice camp during the playback, and 6 d when white whales were seen there during the playback (Table 6.2 in §6.1). Equipment used for playbacks in 1989-90 is summarized in Table 2.1.

Acoustic Monitoring.—During all playback experiments in 1994, a four-channel TEAC DAT recorder was operated continuously to record the following signals: (1) the tape player output signal (the signal being amplified for projection); (2) an ITC 1042 monitor hydrophone within 3 m of the projectors; (3) an ITC 6050C hydrophone about 3-5 m from the projectors; and (4) when available, a sonobuoy installed manually about 1 km from the projector site. Date and time were recorded continuously and automatically, and periodic voice announcements by the operator were recorded on a special fifth memo channel. Amplifier and tape recorder gain settings were noted, along with the exact times of any changes. In 1991, procedures were similar, except that usually only the monitor hydrophone and sonobuoy signals were recorded on the DAT recorder, and these recordings were intermittent during the playback. In 1989-90, the signal from the ITC 1042 monitor hydrophone and the monitor sonobuoy ~1 km away were recorded intermittently on a calibrated audio cassette recorder (Table 2.1B).

When the cloud ceiling was high enough to allow the aerial observation crew to observe from 460 m ASL, personnel on the aircraft dropped sonobuoys (AN/SSQ-57A or AN/SSQ-53B DIFAR) near bowheads to monitor and record the sounds received near the whales. This was done in 1989-90 and 1994. In 1991 the prevailing low cloud made it impractical to conduct aircraft operations near the projector site during playback experiments. The procedures followed when using both manually-deployed and air-dropped sonobuoys are described in §2.1. Because the positions of many buoys relative to the ice camp changed over time, especially when the ice camp was on landfast ice, sonobuoy data were used to determine received levels of projected sounds only when the distance from the ice camp was known through one or more of the following procedures:

- the buoy had just been deployed at a known distance, or
- the buoy's location relative to the camp was more-or-less fixed by ice and was determined when it was first deployed, or
- the buoy's location was variable but known and periodically measurable from the ice camp by theodolite or from the observation aircraft by direct overflight and GPS readout, or
- the buoy's location was variable but measurable by crosscorrelating the sounds received near the projector and at the sonobuoy.

Acoustic Analysis.—In all years, the taped acoustic data, along with notations about gain settings and associated calibration data, allowed us to measure the source level of the projected sounds on an overall and a 1/3-octave basis. These source level analyses were done after each field season for various representative times during each playback test.

To determine the source level of the projected sounds at a given time, an 8.5-s segment of the sound recorded from the ITC 1042 monitor hydrophone was sampled at 16,384 samples/s and analyzed by Fourier transforming windowed, overlapped blocks of 8192 samples, followed by averaging of the various ½-s blocks and application of calibration data. This was the same process that was applied in analyzing ambient noise, signals received during transmission loss tests, and signals received at sonobuoys. From the resulting narrowband spectrum, we determined the levels received at the monitor hydrophone in 1/3-octave bands from 10 to 6300 Hz, and in various broad bands. These data were converted to source levels based on the measured distance of the monitor hydrophone from the projectors, assuming spherical spreading over this distance. Because the icebreaker sounds were variable, repeating after 14 minutes, it was important to determine the time of each source level measurement within the 14.3-min sequence. For each source level measurement, the offset time from the start of the sequence was determined by crosscorrelating the sample segment against the entire 859-s sequence length.

Levels of icebreaker sound received at sonobuoys that had been deployed near the ice camp manually or from the aircraft were determined in a similar manner, taking account of the strongly sloped frequency response of sonobuoys.

The crosscorrelation method could be used to determine the distance between the projector and any hydrophone, including a sonobuoy, when sounds at the two sites were recorded on the same tape recorder. By crosscorrelating the projector input signal or the monitor hydrophone signal with the signal from the monitor sonobuoy, the delay time between the two signals could be determined to an accuracy of about 5 ms. Distance was determined by multiplying the time delay by the speed of sound (about 1435 m/s near the surface under our field conditions). Crosscorrelation was also used occasionally to determine the difference in distances of two sonobuoys from the projector based on differences in arrival times of projected sounds.

Ambient noise levels just before and after the playback period were determined from hydrophone and sonobuoy signals recorded at the ice camp and from sonobuoy signals recorded aboard the project aircraft, as described in §2.1, Physical Acoustics Methods. These data were later used to estimate the signal-to-noise ratio at locations of observed whales, i.e. the difference (in decibels) between the levels of the icebreaker signal and the ambient noise in a corresponding band (§6.1-6.3).

Whale Movements and Behavior During Playbacks

Observation Procedures.—To maximize the power of the observations in assessing the hypotheses, we planned to use whales approaching the sound projectors as their own controls insofar as possible. Our intent was to compare the movement patterns and behavior of the same whales when they were at various distances from the projectors. 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 system that they could not hear it or, at the least, were not likely to react to it.[6] This required aerial observations, as ice-based observers stationed near the projectors would be unable to see whales more than ½-2 km away, depending on ice conditions and visibility. We then intended to observe whale movements and behavior as they approached and passed the projectors. This would involve both aerial and ice-based observations.

Specific procedures for aerial and ice-based observations of whale movements and behavior are described in §2.2. Near the ice camp, the same ice-based and aerial observation procedures were used during playback and non-playback periods. Also, the aerial observation procedures used for whale observations in the absence of an ice camp were the same as those near the ice camp, with the exception that bearings and distances of whales from the ice camp were not relevant in the latter case.

Because the ice camp and projector system had to be reestablished on the ice each day, the projectors often began operating while whales were already under observation from the aircraft. To minimize observer expectancy biases, during 1991/94 we prevented the two primary behavioral observers in the aircraft from knowing whether the sound projector was operating. A third part-time observer on the aircraft was, unavoidably, often aware of projector status because she was monitoring the signals received by sonobuoys, which detected the projected sound when it was present. The fourth biologist on the aircraft (project director) was in radio communication with the acoustician on the ice, and was aware of projector status. The 3rd and 4th observers did not discuss projector status on the aircraft intercom, and behavioral data were transcribed from audiotape and videotape onto dataforms without knowledge of projector status.

The ice-based observers, because of their proximity to the projector site and their involvement in its deployment and retrieval, occasionally were aware of projector status (on or off). However, most of their data were theodolite readouts, which do not involve subjective judgments. Thus, observer expectancy 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 icebreaker (1991/94) or drilling (1989-90) sounds was operated, and those 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 sounds were being projected into the water.

Distances and Bearings of Whales from Ice Camp.—When whales were seen by observers at the ice camp, the distances and bearings were determined using a theodolite (§2.2). This was done whether or not the projectors were operating at the time.

When aerial observations were obtained within 10 km of the ice camp, bearings and distances of whales from the camp were determined for each surfacing. Again, this was done whether or not man-made sounds were being projected from the ice camp. (As described above, the primary

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[6] 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 and Malme 1993; Richardson et al. in press).

aerial observers did not know when sounds were being projected.) Several types of data were used to determine whale position relative to the ice camp; not all of these were relevant or available at any one time. Types of data used included the following:

- Whale-to-projector bearings were estimated by eye to the nearest 10° by reference to the aircraft's gyrocompass and, on some occasions in 1994, real-time GPS readouts of aircraft-to-camp bearing. These estimates were usually accurate within 10°, and should always be accurate within 20°.
- The distance from the whale to the projector was estimated visually during most whale surfacings. When distance between two points could be determined by some independent means, we compared our visual estimates with the independent determination. For distances of 0.5 to 5 km, visual estimates were usually within 25% of the correct value. In most cases, one or more of the following types of data were available to replace or refine the visual estimate.
- Whales within ½-2 km of the ice camp were often under observation from the ice camp as well as the aircraft. When accurate theodolite data on bearing and distance from the ice camp were available, these data were used in preference to visual estimates by aerial observers.
- In all years, aerial observers frequently dictated onto audiotape the position of the aircraft according to the aircraft's GPS (1991/94) or VLF (1989-90) navigation system as we reached a consistent point on the observation circle (e.g., north of the whale position). Although the focal whale(s) usually were ~1 km from this location, the offset from aircraft to whale was similar from one surfacing to the next, as we attempted to fly circles of consistent radius.
- In 1994, the aircraft's GPS position was logged by computer about once per second. A program was written to compute the centroid positions of successive observation circles and, from those plus ice camp position, the distance and bearing from ice camp to centroid. The focal whales were usually near the centroid.
- When the focal whale(s) were not at the center of the observation circle, whale position relative to the center was often dictated onto audiotape (e.g., "whale is about 400 m north of the center").
- Whale position relative to any nearby distinctive ice features was usually dictated onto audiotape and/or visible on videotape. Locations of ice features relative to the ice camp were determined by vertical photography from high altitude on days when cloud ceiling permitted (see below).
- Whale positions were estimated by eye relative to locations of other whales and locations of the same whale during preceding surfacing(s).
- The aircraft was occasionally (1991/94) or often (1989-90) flown from the location where whales had just dived to the ice camp. By flying directly over these two positions within a short interval, even the less-accurate VLF navigation system used on the aircraft in 1989-90 provided accurate (±0.3 km) data on the whale-to-projector distance and bearing.
- The absolute location of the ice camp was determined using the GPS (1991/94) or VLF (1989-90) navigation systems on the Twin Otter and helicopter, and a separate GPS (1991/94) or Si-Tex model A-310 SatNav receiver (1989-90) at the ice camp. When the ice camp was on pack ice, its position often changed substantially during an experiment due to wind- and current-induced drift of the ice. To account for this, all whale sightings and movements were plotted relative to the sound projector location at the sighting time.

By considering all of these types of data, positions of most whales relative to the ice camp were determined within ±20% distance and ±20° bearing. In the few cases where the uncertainty appeared to be greater, the distance and/or bearing were recorded as unknown. A high proportion of the distance and bearing records are accurate within ±20% and ±20°, and we believe that many are accurate within ±10% and ±10°. Also, relative distances and bearings of the same whale during successive surfacings were determined with greater accuracy than were the absolute distances and bearings. Distance uncertainties of ±10% and ±20% translate into received level uncertainties of only 1 or 2 dB, respectively, if spherical spreading is occurring, and less with cylindrical spreading. Even a 40% error in a distance estimate, which would be rare, translates into no more than a 4 dB error in estimated received level.

Ice Conditions Near Playback Sites

On playback days when clouds were absent or high, we obtained vertical photographs of the area near the ice camp in order to "map" the ice in the area. Whale locations were often identified, in part, relative to ice features described or videotaped by the aerial observers. Thus, vertical photos of the ice were extremely valuable in mapping positions and movements of whales relative to the ice camp.

In 1994, once or twice during each day with coordinated aerial and ice-based work, the project aircraft climbed to an altitude as high as 9000 ft or 2750 m (cloud ceiling permitting). A sequence of vertical photographs was taken through the aircraft's ventral camera port using a 35-mm camera with 17-mm very wide angle lens and/or a video camera with wide angle lens. One photo-mosaic prepared from these vertical photos appears as Plate 6.1 on p. 258. In addition, oblique photos of the ice and leads were sometimes taken with a Polaroid camera; these provided prints onto which notes could be made immediately. In 1991, ice photos were not available at playback sites because low clouds prevented aircraft operations near the ice camp.

During each day of ice-based work, ice conditions near the ice camp were documented by taking theodolite readings for ice edges and other prominent ice features visible from the camp. From these theodolite readings, distances were later calculated.

Sound Levels Received by Whales During Playbacks

Unlike the steady drillrig sounds from *Karluk*, the icebreaker sounds played back in 1991 and 1994 varied considerably with time, corresponding to the phases of heavy icebreaking: ramming ahead, stopping but maintaining full-ahead power, and backing down. Accordingly, the received signal levels near the actual icebreaker and near our projectors varied with time as well as with distance from the projector. Figure 2.2 shows the distribution of 1/3-octave received levels as recorded at distance 460 m from the actual icebreaker at the Corona site. These levels represent the range of recorded levels provided to the projector amplifiers during the playback experiments reported here.

The effective source levels for the actual icebreaker were estimated by using the acoustic transmission loss model developed in the present project for the western Beaufort Sea (see §4.3, Transmission Loss, p. 96*ff*), the water depth at the icebreaker recording site (35 m), and the measured received levels near the Corona site off Camden Bay. We estimated the source level in various broad bands (e.g., 20-1000 Hz; 20-5000 Hz) and in each 1/3-octave band from 20 to 6300 Hz. The underlying assumption for this derivation is that the bottom properties at the Corona drillsite are similar to those in the present study area.

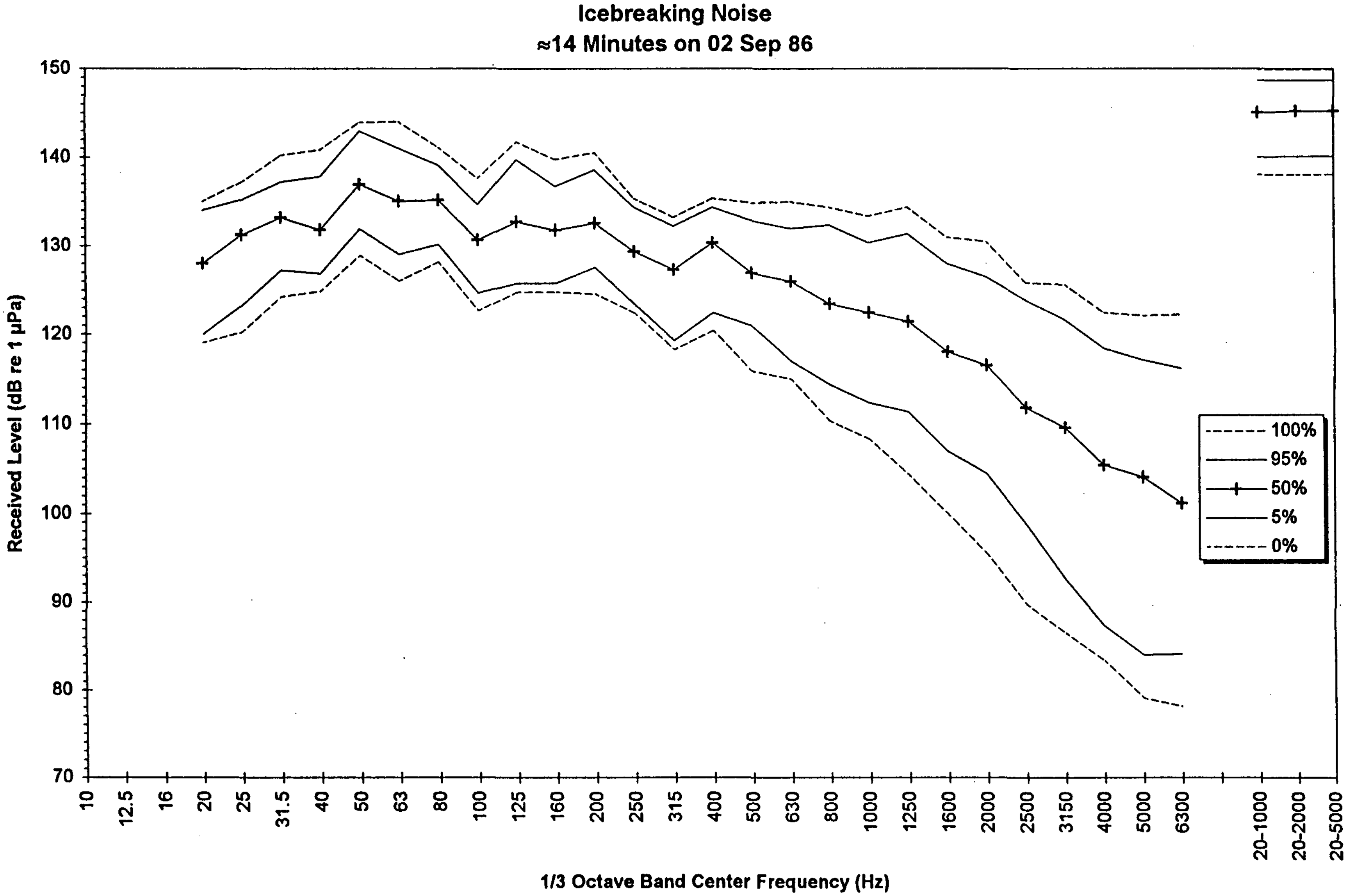

FIGURE 2.2. The distribution of received levels from the icebreaker *Robert Lemeur* operating at range 460 m, by 1/3-octave band center frequency. This distribution was computed from the 14+ minute recording of Greene (1987a:48*ff*).

Figure 4.25 in §4.4 shows the resulting estimates of 1/3-octave effective source levels during the 14-min recording. Figure 4.26 shows the time-variability of the resulting estimated source levels in four bands in relation to changes in ship activity. The results shown in these Figures are important in the discussion of playback fidelity (§4.4).

To interpret our observations of whale behavior, it was necessary to estimate the sound levels to which the observed whales were exposed. Whales under observation at a given distance from the projectors at various times in 1991 and 1994 were subjected to widely varying sound levels because of

- moment-to-moment variability in received levels of the original icebreaker sound at the recording site 460 m from the icebreaker,
- day-to-day variability in projector capabilities, and
- site-to-site variability in sound propagation conditions at different projector locations.

Thus, sound levels received at any specified distance on a given date and time had to be estimated on a statistical basis. We chose to estimate the minimum, median and maximum levels expected for each band within the 64-s period preceding the observation time, and the minimum, median and maximum plus 5th and 95th percentiles expected for each band during the entire 14-min segment of recorded icebreaker sound. Because the 14-minute segment was repeated over and over during prolonged playbacks, the distribution of sound levels at a given distance from the projectors would be the same for one 14-min period as for the next if the projection equipment was not adjusted in the meantime and if the playback did not start or stop within the 14-min period.

Some sonobuoy measurements were available for directly measuring the received levels at specific sites, times and distances from the projector. However, given the variability in the sounds, it was usually essential to rely on a complex source level/transmission loss database and prediction program (which we call the "sound exposure model") to estimate the received level statistics for a given projector location, time, and projector-to-whale distance.

The basic elements of the resulting sound exposure model are as follows:

a. Measurements of the 1/3-octave spectrum of the recorded icebreaker sounds at 8-s intervals throughout the 14+ minute sequence used in the playbacks. This database consists of a series of 109 1/3-octave spectra, each of which represents the average signal characteristics over an 8.5-s interval. This series characterizes the playback levels vs. time. Although not calibrated absolutely, the series spectra are comparable to one another. Given calibrated acoustic pressure source levels for one spectrum in the series (see [c], below), all other series spectra can be adjusted to be calibrated source spectra, thereby characterizing the source levels of the projected icebreaking sounds for any time during the playback until the playback conditions changed.

b. A histogram arrangement of the 109 series spectral elements in "a" above, where the levels for each frequency band are ordered and the corresponding minimum, 5th, 50th, 95th percentiles, and maximum values are identified. Once calibrated for a given playback condition, these values characterize the distribution of playback levels during any 14-min interval until the playback conditions changed.

c. A database of measured projector source levels from selected times during every icebreaker playback experiment when whales were observed, keyed by date, time, and offset time from the beginning of the 14+ minute icebreaking sequence. As a minimum, a new source level measurement was taken whenever there was a change in amplifier setting or other playback conditions. Each of the several measured source level spectra in the database for each day was calculated from an 8.5-s segment of recorded sound, and the offset time of each such segment relative to the start of the 14-min icebreaker sequence was determined (see p. 43 in "Acoustic Analysis"). Knowing the offset time, one can match the source levels with specific elements in the 109 series analyses. Thus, each source level measurement can be used to calibrate all 109 members of the series database. In other words, having measured the projected source level in one 8.5-s segment of the playback, and knowing when during the 14-min sequence this segment occurred, one can determine the projected source level during any 8.5-s segment until the playback conditions changed. The water depth associated with each source level measurement, for use in the transmission loss model, is also stored in this database.

d. A depth-dependent transmission loss model with parameters for the 1/3-octave bands centered at 20-6300 Hz. This model was developed based on the transmission loss data collected during all four years of the present project, as described in §4.3, Transmission Loss. This TL model is specific to the present study area northeast and east of Pt. Barrow under spring (late April and May) conditions.

To use the sound exposure model to estimate the levels of projected icebreaker sound that will reach a given distance from a particular playback site, the user has only to specify one of the playback dates, a time during that playback, and the distance. The program follows a sequence of steps:

1. It searches the source level database ("c" above) to find the closest measurement time preceding the specified time of interest.
2. From the offset time associated with the source level measurement in "1", the program selects the two series spectra in "a" that bracket that time. Interpolating between the two, the program computes a 1/3-octave spectrum corresponding to the exact time of the source level measurement.
3. The program calculates the differences between the measured source level spectrum and the interpolated series spectrum. These differences may be added to any series spectrum, and to the histogram spectra, to derive corresponding calibrated source level spectra.
4. The program selects the eight consecutive spectra from "a" that characterize the 64-s period up to the time of interest specified in "1" above.
5. From these eight spectra, the program calculates the minimum, median and maximum levels in each 1/3-octave spectral band for the 64-s period up to the time of interest.

6. Applying the differences from "3" to the minimum, median and maximum values in "5", the program calculates the range of source levels for each 1/3 octave band for the 64-s period immediately preceding the specified time of interest.
7. Applying the differences from "3" to the 14-min minimum, 5%, 50%, 95% and maximum 1/3-octave band levels in "b" above, the program calculates the calibrated source level distribution, by 1/3-octave band, for the full 14-min playback cycle and for all following times, including the specified time of interest, up to the time of some change in projector operation.
8. The program applies the transmission loss model mentioned in "d" to the source levels computed in "6" and "7" above to obtain the expected ranges of received levels at the specified distance for both the 64-s period preceding the time of interest and the entire 14-minute playback duration.
9. The program also calculates the expected received broadband levels for the 20-1000 Hz, 20-2000 Hz, and 20-5000 Hz bands.

The 1/3 octave band spectra from "8" and the broadband received levels from "9" constitute the output of the sound exposure model program. If the specified time of interest occurred within 64 s after some change in projector operation, such as turning it on or adjusting the transmitted power, the 64-s results are reported as "discontinuity". Similarly, if the specified time of interest occurred sooner than 14 min after a change in projector operation, the 14-minute results are reported as "discontinuity".

To validate the sound exposure model, we used it to estimate the expected received levels of projected icebreaker sounds at times and distances where sonobuoy measurements of actual received levels were obtained during 1991 and 1994. The sonobuoy measurements were not used in developing either the transmission loss model or the sound exposure model. Thus, the sonobuoy measurements provided an independent source of data useful in checking the models. Results of this comparison are described in §4.3 (Fig. 4.21, 4.22). As described there, the sound exposure model provides reasonable estimates of actual received levels.

The sound exposure model has been implemented as a series of 14 interlinked spreadsheets in a MicroSoft Excel version 5 notebook. It can be used either to process single date/time/distance requests entered from the keyboard or, in batch mode, to process a file containing any number of such requests, saving the results to output files for subsequent use in other analyses. The latter capability was used to estimate the received sound levels at times and distances when whales were observed. The resulting estimates of received sound level were subsequently used in analyses of whale movements and behavior relative to received sound levels and relative to the ratio of icebreaker sound to ambient noise (§6.1-6.3).