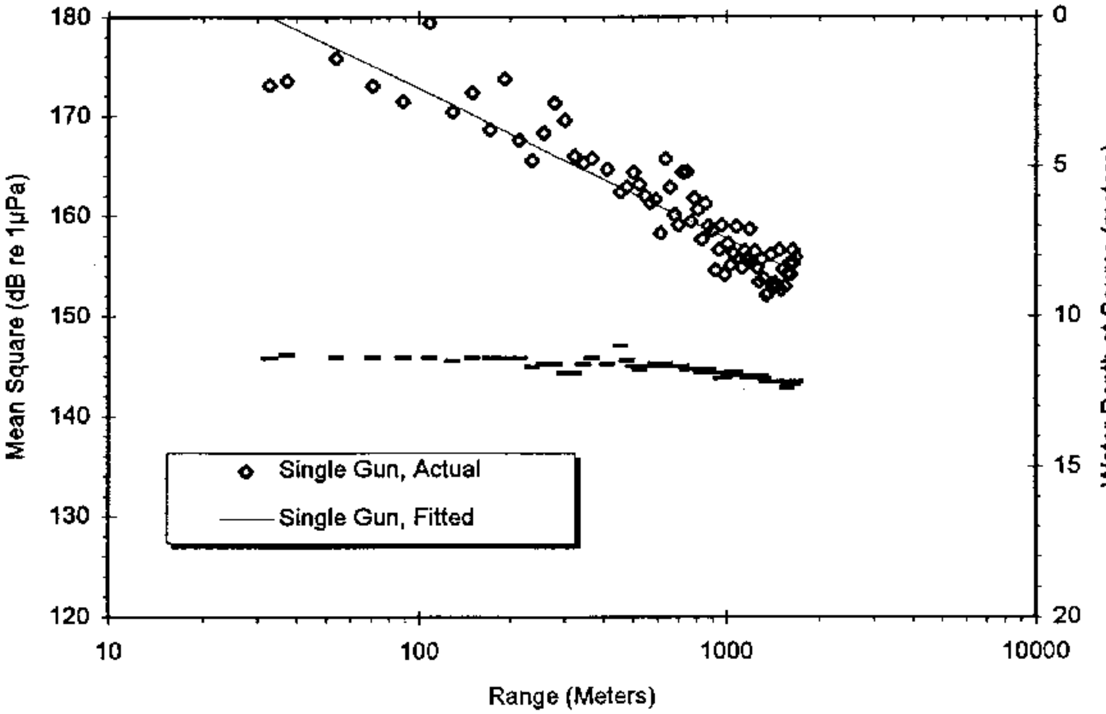

FIGURE 3.18. Rms pulse levels from a single airgun on 14 Aug. The line represents a least squares fit to the data. Water depth at the airgun is also plotted.

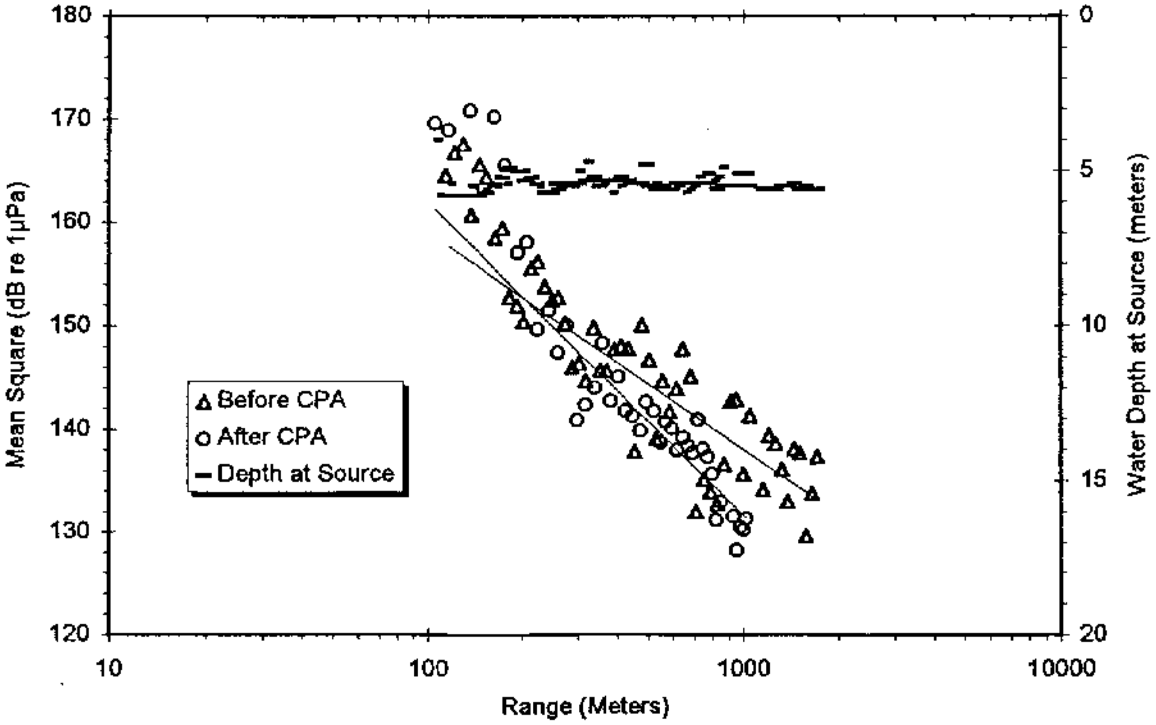

FIGURE 3.19. Rms pulse levels from a single airgun on 17 Aug. The lines are least squares regression fits based on the data from distances 200-600 m. Water depth at the airgun is also plotted.

cylindrical spreading mentioned in §3.3, which is expressed in decibels as -10*log(R), where R is the range from the source to the receiver. If the boundaries are not perfectly reflecting (which is the case for underwater channels), then other terms must be added that account for this loss. The following discussion explains how this modified transmission loss is expressed.

In the discussion above of the frequency spectrum of the airgun data, it was noted that shallow channels do not support the propagation of low frequency sound, and that the frequency below which the sound does not propagate depends on the water depth. Specifically, the shallower the channel, the higher this limiting frequency will be. There is a physical theory that explains this effect, and it depends upon a particular representation of sound propagation in such channels. This representation describes the sound as a function of frequency, range and depth, using mathematical quantities called normal modes (Brekhovskikh 1960; Frisk 1994; Richardson et al. 1995:60). In much the same way that a drum has preferred modes of vibration, so also does an acoustic channel. For a drum, these modes will depend upon the size and shape of the drum, as well as the tension in the drumhead. In the case of the acoustic channel, the modes depend upon the speed of sound in the channel, the channel depth, and the acoustic properties of the channel boundaries.

Assuming the simple model invoked to explain the low frequency cutoff in the pulse data (namely, a shallow water layer over a single bottom layer), the sound intensity of such a mode can be written as follows:

$$I=I_0F(f,z_S,z_R,d)\frac{e^{-\alpha r}}{r} \qquad \text{Equation 1}$$

This expression includes a factor that depends on the source intensity I_0, frequency f, source depth z_S, receiver depth z_R, and water depth d; and another factor that depends on range r and boundary losses represented by a mode attenuation α. Note that the inverse proportionality between I and r implies that the modal sound levels, in decibels, will vary as -10*log(r), or cylindrical spreading. In general, the sound field will include some number of these modes, and the function F and the constant α will be different for each mode.

For the interpretation of the Northstar data, the most important characteristic of the modes is their dependence on frequency. Using the analogy of a drum, there is a lowest frequency at which the drum will vibrate that, again, depends on its size and the tension in its drumhead. Similarly, for the sound channel, there is a lowest frequency at which it can propagate energy to long ranges (where long ranges are equivalent to many times the water depth). So, for a particular mode, the function F is essentially zero below its characteristic frequency. The so-called lowest order mode is the one that determined the sharp rolloff in the pulse spectra discussed above; for the data from 14 and 15 August, this occurred around 40 Hz. The theory of these modes shows that, if the lowest order mode has a characteristic frequency of f_0, then the higher order modes will have characteristic frequencies of $3f_0$, $5f_0$, $7f_0$, and so on. For the data from 14 and 15 August, these frequencies would be 120 Hz, 200 Hz, 350 Hz, and so on. Since most of the energy in the pulses is below 150 Hz, or less, it follows that most of its energy is represented by the lowest order mode.

Since the data for received levels are in decibels, the above expression for a single mode, in decibels, would be

$$10\log(I)=A-10\log(r)-Cr$$

where A depends on the source level, frequency, source and receiver depths, and water depth, but not on range; C is related to the mode attenuation α. This is the form that was fitted to the data in §3.3.

A consistency test for this representation of the sound field can be made using the data from Figure 3.17. The range-dependence of the pulse spectra can be used to estimate the parameter C in the above expression. To do this, an average level around the spectral peak was taken from the spectra in Figure 3.17 for the ranges out to 2 km; these levels are given in the second column of Table 3.1. (The levels at the two longer ranges in Fig. 3.17 will be considered below.) In the third column, these levels are adjusted for the expected dependence on the log of the range. These adjusted levels, which should have a linear dependence on range, are plotted in Figure 3.20. The straight line is a least squares fit to the adjusted levels; its slope, which is the constant C, is 4 dB/km.

TABLE 3.1. Peak spectrum levels from Figure 3.17.

Event Time	Level (dB re 1 μPa²/Hz)	Level + 10 log r	Range (m)
10:26:50	165	185.6	115
10:29:41	158	184.5	446
10:34:28	150	180.8	1193
10:40:01	145	178.2	2079

Using this value of C and the specific form of the function F which, for the lowest order mode, is

$$F=\left(\sin\left(\pi\frac{z_S}{d}\right)\sin\left(\pi\frac{z_R}{d}\right)\right)^2$$

the value of the peak in the spectrum at 115 m can be used to estimate the peak at 1 m. The appropriate values of source, receiver and water depths are 3.5, 9, and 11 m, respectively. This results in an estimated source level of 193 dB re 1 (μPa-m)²/Hz. The peak of the spectrum from Painter's model (Painter 1996) (Fig. 3.9B) is 198 dB re 1 (μPa-m)²/Hz. This value involves the coherent addition of the direct and surface-reflected energy, so the equivalent source spectrum level of the free-field source itself is 192 dB re 1 (μPa-m)²/Hz. Thus, the estimate from the Painter model is only 1 dB different from the estimate based on the received spectra at various ranges and the above propagation model. This is additional confirmation that the mode description, based on the simple model of a water channel over a single bottom layer, is usefully accurate for short-range propagation in the Northstar area.

This single-mode model was used to estimate received spectrum levels for the two longer-range situations illustrated in Figure 3.17. This involves using the water depth at the receiver and at the source in the expression for F. Using this approach, levels at 9 and 11.7

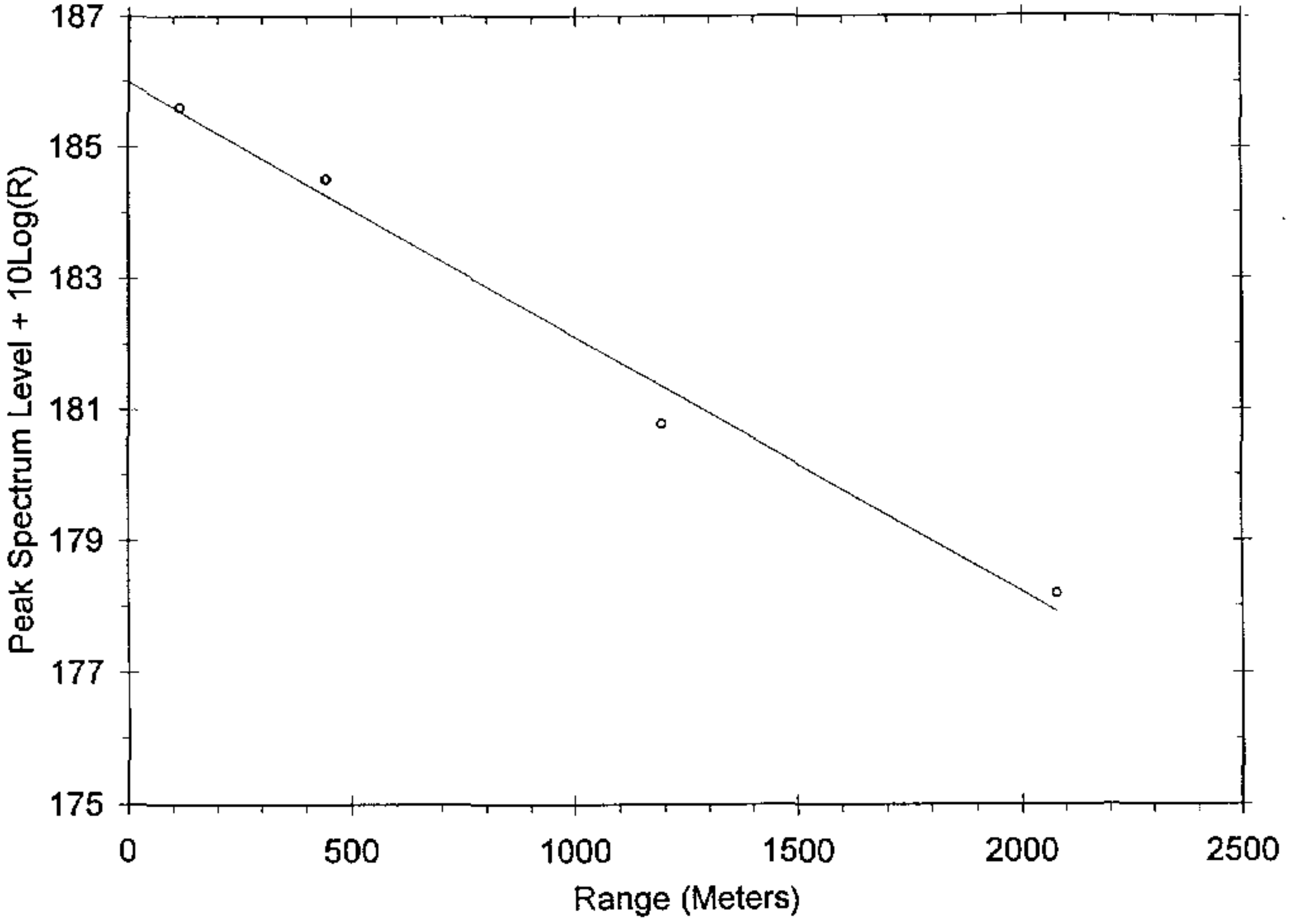

FIGURE 3.20. Least squares estimate of mode attenuation for 11-airgun array, 15 Aug 1996. The slope is -4 dB/km.

km are expected to be 116 and 104 dB re 1 $\mu Pa^2/Hz$, respectively. The observed levels (Fig. 3.17) are 10-15 dB lower than predicted, meaning that this simple model is not adequate to represent propagation out to ranges of 9-12 km. This could be because the mode attenuation, which is determined by the bottom properties, varies along the track into deeper water.

A possible explanation for variable bottom properties could be the sporadic presence of shallow relic permafrost, i.e. ice-bonded subsea permafrost. This appears as higher-velocity strata in seismic records. These higher-velocity regions would refract sound waves and would result in better horizontal sound propagation. They could have the effect of deepening the sound channel, enhancing low frequency propagation compared to a highly absorptive, low-velocity bottom material. Neave and Sellman (1984) chose velocities of 2.0 km/s and greater to be indicative of such subsea permafrost, as compared with 1.5 km/s for sea water. They found such strata as far as 60 km offshore from the barrier islands. Their Figure 1 is reproduced in this report as Figure 3.21. Additional information is presented in Morack and

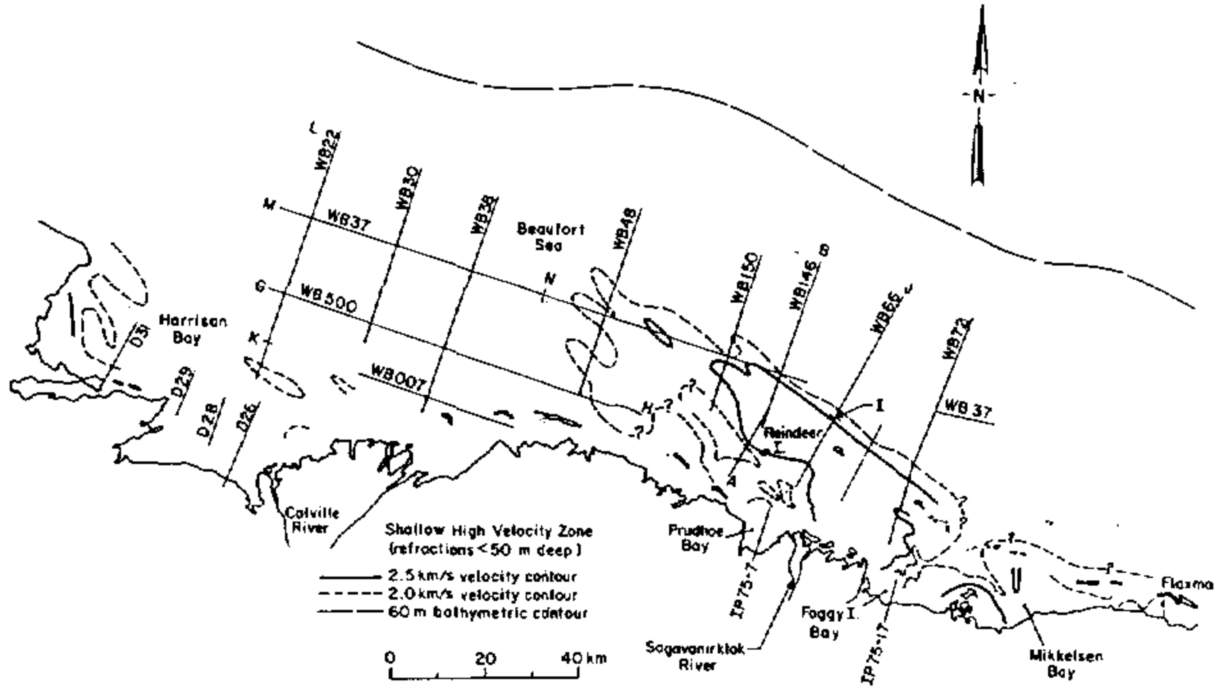

FIGURE 3.21. Distribution of known shallow high-velocity bottom material in the Beaufort Sea between Harrison Bay and Flaxman Island (from Neave and Sellman 1984).

Rogers (1984), and a more recent reference is Meyer (1996).

Summary.—Examination of the pulse levels and pulse spectra has quantified the importance of water depth in determining the frequencies that propagate to horizontal ranges that are many times the water depth. The observed behavior is consistent with a fairly simple representation of the propagation, given by the behavior of a single acoustic mode as shown in Equation 1 above. Using this equation, the attenuation of the single mode was estimated from data for the full 11-gun array as measured on 15 August 1996. With these data and the model, the source level at 1 m was estimated and compared to a theoretical calculation: the levels differed by only 1 dB, providing additional confidence in the use of the single-mode model as a representation of transmission loss over distances up to 2 km or perhaps slightly more.

The single-mode model and the attenuation rate deduced from measurements in shallow water (11 m) were used to estimate the expected received levels in deeper water (20 m) at ranges of 9-12 km. These model estimates were significantly higher than the measured levels, suggesting that the effective attenuation changed going into the deeper water. Thus, the single-mode model is not adequate for summarizing longer-range transmission. An alternative approach for the longer ranges is shown in a later subsection ("Long-Range Received Levels").

Direct examination of the single airgun data showed that the rate at which the levels decreased with range was a strong function of water depth. This implies that avoidance ranges for marine mammals probably vary with water depth, and that safety (shutdown) radii logically should be adjusted based on water depth.

Source Levels and Ranges for Specified Levels

Array Source Levels.—Effective horizontal source levels were estimated for bow and stern aspects based on short-range received level data recorded as the operating 11-airgun array was towed past *La Brisa* on 15 August (water depth 9-10 m). For the bow aspect, five measurements were taken from just before CPA, ranges 129-283 m, and a regression was computed with -10*log(R) (cylindrical spreading) forced:

$$\text{RL (dB re 1 µPa)} = 212.5 - 10*\log(R) + 0.0026*R, \text{ (R in m)}$$

The positive sign on the range coefficient is physically unrealistic but has a negligible effect for small values of R. The assumption of cylindrical spreading was based on the analyses described in previous subsections. From this equation, the level expected at distance 1 m if the array were a point source (the source level) is 213 dB re 1 µPa-m on an rms pressure level basis.

For the stern aspect, six measurements were taken just after CPA, ranges 150-321 m, and the regression line equation was

$$\text{RL (dB re 1 µPa)} = 222.4 - 10*\log(R) - 0.03*R, \text{ (R in m)}$$

From this equation, the source level is found to be 222 dB re 1 µPa-m on an rms basis.

Single Airgun Source Levels.—Using data and regression equations graphed in Figure 3.13, the difference in stern aspect received levels between the full 11-airgun array and the single airgun was found to be 23 dB. This 23 dB difference compares well with a predicted 20*log(11/1) = 21 dB difference assuming coherent addition of the 11 airgun pulses. Subtracting that 23 dB value from the 222 dB source level for the full array, the source level for a single 120 in^3 airgun was estimated to be 199 dB re 1 µPa-m on an rms basis. However, the short range single airgun measurements themselves do not predict an rms source level as high as 199 dB; a level closer to 192 dB re 1 µPa-m would be expected.

Peak Source Pressures.—The estimated effective source level of the full 11-airgun array is estimated above to be an rms pulse level of 222 dB re 1 µPa-m for propagation behind the vessel, and 213 dB re 1 µPa-m for propagation ahead of the source vessel. At the 6 closest measurement distances within 200 m, the peak pressures were about 8 dB higher than the rms pressures (e.g., Fig. 3.3). If this difference also applies at the source, then the source levels on a peak pressure basis would be 230 dB re 1 µPa-m for stern aspect and 221 dB re 1 µPa-m for bow aspect. In the units used by the geophysical industry (bar-meters, peak-to-peak), these peak pressures are approximately equivalent to 6.3 and 2.2 bar-meters. Levels expressed in bar-meters, peak to peak (P_a), can be converted approximately to peak levels in dB re 1 µPa with the following formula:

$$L_s \text{ (dB re 1 µPa-m)} = 20 \log (P_a) + 214$$

The equation is an approximation because it assumes that the positive and negative peaks in the pulse are of the same magnitude. In fact they are generally not the same, differing perhaps by as much as 50% and thereby leading to a possible error as large as 2.5 dB.

The above figures represent the effective source levels for long-distance horizontal propagation of sound from the full 11-gun array as used in the 1996 Northstar project, with airguns at depth 3½-4 m. As such, these figures can be expected to differ from the nominal source levels for downward propagation. When the application for an IHA (Incidental Harassment Authorization) for this project was submitted to the National Marine Fisheries Service, the source level for downward propagation was anticipated not to exceed 57.1 bar-meters peak-to-peak. This is approximately equivalent to a peak level of 249 dB re 1 µPa-m or an rms level of 241 dB. Thus, the measured effective source level for horizontal propagation was substantially less than the design limit for the nominal vertical source level. The difference was about 19 dB for stern aspect and 28 dB for bow aspect. After the IHA Application was submitted, Painter (1996) predicted a nominal vertical source level of 26.4 bar-m for the specific 11-airgun array to be used at Northstar, operating at depth 4 m. This is approximately equivalent to a peak level of 242 dB re 1 µPa, or 12 dB more than the "measured" peak source level for horizontal propagation of 230 dB at stern aspect.

Radii for Received Levels 200, 190, 180 and 160 dB.—The distances at which sounds from the full 11-airgun array diminish to 190, 180 and 160 dB re 1 µPa are of interest. The IHA issued to BPXA for this project required that airgun operations be temporarily suspended if seals were seen within the 190 dB radius, or if whales were seen within the 180 dB radius. Also, the IHA specified that the numbers of whales occurring within the 160 dB radius were to be estimated, on the assumption that they might have been disturbed by seismic pulses.

Prior to the field season, the 190, 180 and 160 dB radii were predicted to be 100 m, 650 m and 5 km, respectively. To be conservative, BPXA proposed to use a 150 m rather than 100 m shutdown radius for seals, and this proposal was adopted in the IHA. Based on preliminary analysis during August 1996 of some of the data quoted above, the estimated 190 dB and 180 dB radii were changed to 250 m and 750 m, and the shutdown distances were increased accordingly. Further analysis of the 1996 field measurements now allows a more definitive analysis. The 200 dB radius is also estimated for comparison.

The strongest source levels were found at stern aspect, i.e. behind the seismic source vessel: 222 dB re 1 µPa-m for stern aspect vs. 214 dB for bow aspect. These are the effective rms source levels for horizontal propagation. Also, the received levels were generally higher at any given distance at stern aspect than at bow aspect. In summary, for the stern aspect, the following radii were found for a time when sound propagated comparatively well:

RL (dB re 1 µPa)	Distance (m)
200	44
190	257
180	1020
160	4900

These values allow for variability and are thought to be the approximate maximum distances at which the specified rms sound levels might be received. If the regression equation for the stern aspect in Figure 3.10 is used to estimate typical radii, the results are

RL (dB re 1 µPa)	Distance (m)
200	31
190	240
180	960
160	3600

The measurements from which these estimates were derived were made with the receiving hydrophone at depth 8 m in water 9 m deep on 15 August 1996. The airgun array depth was 3½-4 m and the water depth at the source was 9-11 m (Fig. 3.10B). The measured received levels varied considerably from pulse to pulse and the tabulated received level vs. range tables were derived using curve-fitting to smooth the data.

Other sets of measurements obtained during full-array operations at Northstar gave distances significantly less than those tabulated above. The average distance for a received level of 160 dB re 1 µPa was approximately 3.7 km. This average comes from bow, beam and stern aspect data and includes measurements made with the full array on both the 15th and 16th of August.

Discussion.—The assumption that cylindrical spreading was occurring from the source to the short-range measurement locations is justified by the evidence for normal mode sound propagation previously presented. It is recognized that the source level estimates are strongly dependent on this assumption, and would be higher if propagation losses were higher than $-10*\log(R)$ along part of the propagation path. The calculated source levels are most useful as indicators of the relative levels of different sources operating in the same region, e.g. full 11-gun array vs. single airgun.

Long-Range Received Levels

Measurements of the survey pulses from the full array at ranges greater than 7 km were made in four ways: (1) by taking the receiving hydrophones on *La Brisa* to recording positions farther offshore than the source vessel either within the survey area or in the ice pack NNE of the survey area, roughly perpendicular to the coastline (030° T); (2) by taking the receiving hydrophones on *La Brisa* to recording positions WNW of the survey area, or roughly parallel to the coastline (300° T); (3) by dropping sonobuoys at greater ranges alongshore and offshore; and (4) by analyzing the sounds received and stored by the bottom recorder placed offshore from Northstar and, much farther east, offshore from Narwhal Island. These measurements aid in determining the long-range acoustic transmission loss for the relevant coastal areas of the Beaufort Sea (Fig. 3.22).

Boat-based Measurements Farther Offshore.—Measurements were made at ranges 1.0 to 2.1 km from *La Brisa* anchored in the survey area at 10:33-10:40 ADT on 15 August. Measurements at longer distances to the NNE (roughly perpendicular to the coast) were made on 15 August, 20:14-21:16 ADT (Fig. 3.22, circles). The *Point Barrow* presented a stern aspect during these recordings, including recording segments at ranges 9.4-9.9 km and 11.7-12.9 km. The water depths at the receiver varied from 23 m at the most distant (offshore) location to 9.4 m at the closest. The depths at the source were 11.7 to 13.6 m when the receiver was farthest away and 10.4-10.9 m when the receiver was closest.

Boat-based Measurements Alongshore.—Measurements at ranges 1.5 to 14.8 km to the WNW (roughly parallel to the coast) were made on 16 August, 09:34-11:47 ADT (Fig. 3.22, squares). The water depth at the receivers varied from 19 m at the most distant location to 15 m at the closer positions. The depths at the source varied from 6 to 14 m, but were mainly 13-14 m.

Sonobuoy Measurements.—Received levels were recorded from sonobuoys on 10 and 15 September (Fig. 3.22, diamonds). The levels plotted for distances 30 km and 41 km were recorded on 15 September when the airgun array was being operated with five airguns ("partial array"). For coherent combination of the sounds from the individual airguns, an increase from 5 to 11 airguns would be expected to increase the radiated sound by 20*log (11/5) or 7 dB (see §3.3). Therefore, in Figure 3.22, the measured received levels for 15 September were increased by 7 dB to approximate the levels that would have been received if a full 11-gun array had been in use.

Bottom-Recorder Measurements.—Received levels were recorded at the bottom recorders continuously beginning at midnight on 31 August. Airgun sounds were recorded frequently at the Northstar recorder but only twice at the Narwhal Island recorder. On 13 September the seismic vessel was operating in the patch labelled "E" on Figure 3.1. The water depths at the source varied from 12 to 20 m (according to fathometer records from the source boat) during the period of operation analyzed. Virtually all pulses from one seismic line were received at the Northstar bottom recorder, but only a few were recognized at the Narwhal Island bottom recorder 67 km away. The received rms pulse levels there were on

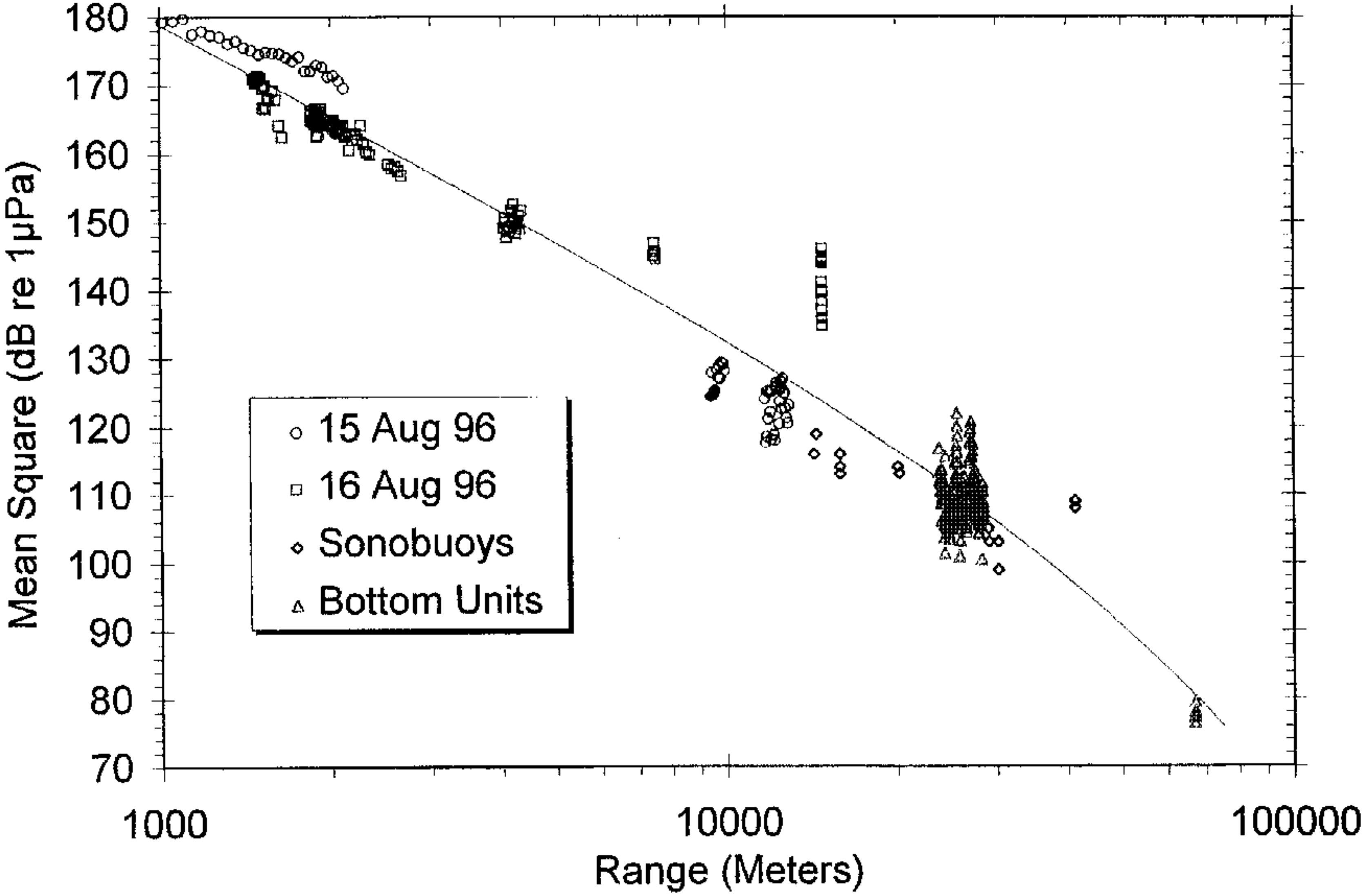

FIGURE 3.22. Summary of rms pulse levels vs. distance for distances >1 km, 15 Aug.-13 Sep. 1996. The line represents a least squares fit to all 372 data points:

$$\mathrm{RL} = 179.1 - 43.95*\log(R) - 0.28*R$$

for range R in kilometers and received level RL in dB re 1 µPa.

the order of 77 dB re 1 µPa (Fig. 3.22, triangles), compared to a minimum broadband background level of 75 dB observed at that site during 14 days of operation. The pulse frequencies (not shown) were observed to extend from about 200 to 400 Hz, signifying that most of the pulse energy had been stripped away by the shallow water propagation.

Listening to the airgun pulses received at the Northstar bottom unit provided a clear illustration of the effects of water depth at the source on the qualities of the received signal. The receiver depth was constant, of course, at 23 m (two meters above the bottom). The survey lines were along 030°-210° true course lines, roughly away from and back toward the Alaskan coast (see Fig. 2.1, 2.4 in Chapter 2). Depths at the source varied from as little as 5 m at the southern ends of the lines to 12 m or more at the north ends of each line. Listening at eight times real-time speed, the listeners could hear a 45-minute traverse along one source line in less than 6 min; the speed-up made the frequency and level changes easy to recognize as the source vessel moved from shallow to deep water (or the reverse).

Qualitatively, the listeners heard the sounds increase in level and decrease in pitch (frequency) as the airguns moved along the 030° course, from shallow into deeper water. That is, the sounds grew stronger and lower in tone. Then, as the airguns moved along the reciprocal course (210°) into shallower water, the received level decreased and the pitch increased. That is, the sounds grew weaker and higher in tone. Often the level decreased to less than the ambient noise and the airguns could not be heard. The shallowest water does not support low frequency sound transmission, so only the highest frequencies are heard when the source is in the shallowest water. Some of the reduction in received level when the source moved into shallow water was due to the slightly longer distance from the source to the Northstar recorder. However, because the source generates most of its energy at low frequencies, below 150 Hz, most of the level reduction when the source was near the southern (shallow) ends of the source lines resulted from the shallow water stripping away the low frequency components.

Summary.—All of the long-range data on received rms pulse levels are plotted together vs. distance from the source in Figure 3.22. As noted above, the levels received via sonobuoy on 15 September have been increased by 7 dB to adjust for the fact that the source array was being operated with only five airguns. The considerable variability observed is not surprising, given the influences of water depth and bottom characteristics and the variety of locations from which these data come. The levels summarized in Figure 3.22 represent the total sound level at all frequencies making up the received pulse.

A least squares fit of a simple equation to all 372 data points resulted in the following:

$$RL\ (\text{dB re } 1\ \mu\text{Pa}) = 179.1 - 43.95*\log(R) - 0.28*R \quad (R \text{ in km}).$$

The standard error of the fit was 8.8 dB; the coefficient of determination was 0.829. The equation estimates the received sound levels that might be expected at long ranges from the full array at stern aspect while it is operating in the Northstar area. In this case, no cylindrical spreading term was forced. As discussed earlier in this section, the single mode model (for which a cylindrical spreading term is appropriate) did not fit the long range data.

Based on the fitted curve in Figure 3.22, the received levels, on an rms pressure basis, are expected to be 160 dB re 1 μPa at distance 2.6 km from the source, 132 dB re 1 μPa at 10 km, 116 dB at 20 km, 106 dB at 30 km, and 97 dB at 40 km. Variability around these values may be ±10 dB or more, especially at distances greater than 5 km. To estimate received levels at long ranges from the Northstar survey area in a more precise manner, it would be necessary to develop a more complex model taking account of additional parameters.

3.5 Boat Sounds

Measurements

The radiated sounds of four primary boats used in the seismic survey were measured. The propulsion and other characteristics of these boats are described in Chapter 2 (§2.2). Measurements were made with the ITC 6050C hydrophone suspended from the sparbuoy deployed near *La Brisa*. Hydrophone depth was 9 m or, in shallower water, 1 m above the bottom. *Pt. Barrow*, the Crowley Marine tugboat used to tow the airgun array, was measured on 17 August at speed 5.6 knots with *La Brisa* anchored in water 5.3 m deep and the hydrophone at a depth of 4.3 m. *Peregrine Falcon*, used primarily for deploying and retrieving battery boxes, was measured on 13 August at speed 8.3 knots in water 11.7 m deep. *Sag River*, another Crowley tugboat used to push Barge 216 for ocean bottom cable deployment and retrieval, was measured on 19 August at speed 4.5 knots inbound and speed 5.8 knots outbound in water 10.7 m deep. *Faraday*, an LCM-type of boat used early in the season as a supplementary cable handling vessel, was measured on 14 August at a speed of 7.7 knots in water 11.7 m deep.

The received levels at various distances from each boat are shown in Figure 3.23 by ⅓-octave band and (at the right sides of the graphs) for three broader bands: 20-1000, 20-2000 and 20-5000 Hz. In general, the received levels increased as the boats approached and diminished as the boats moved away. However, there were some minor exceptions. This is to be expected given ▸ the usual variability in the sounds from a moving vessel and ▸ the complexities of sound propagation in shallow water. (Even with a steady source level, received level would not diminish smoothly with increasing range.)

The appearance of a bowl-shaped curve in the ⅓-octave data at the lowest frequencies is associated with the very shallow water of the measurements. As described in the previous section, low-frequency cutoff occurs at a frequency related to the water depth and to the density and speed of sound in the bottom. This cutoff frequency increases as water depth decreases. The received level curves for *Pt. Barrow* show the highest cutoff frequency (at about 100 Hz) and the most dramatic fall-off in level with increasing distance—as expected for the measurement location with the shallowest water, 5.3 m.

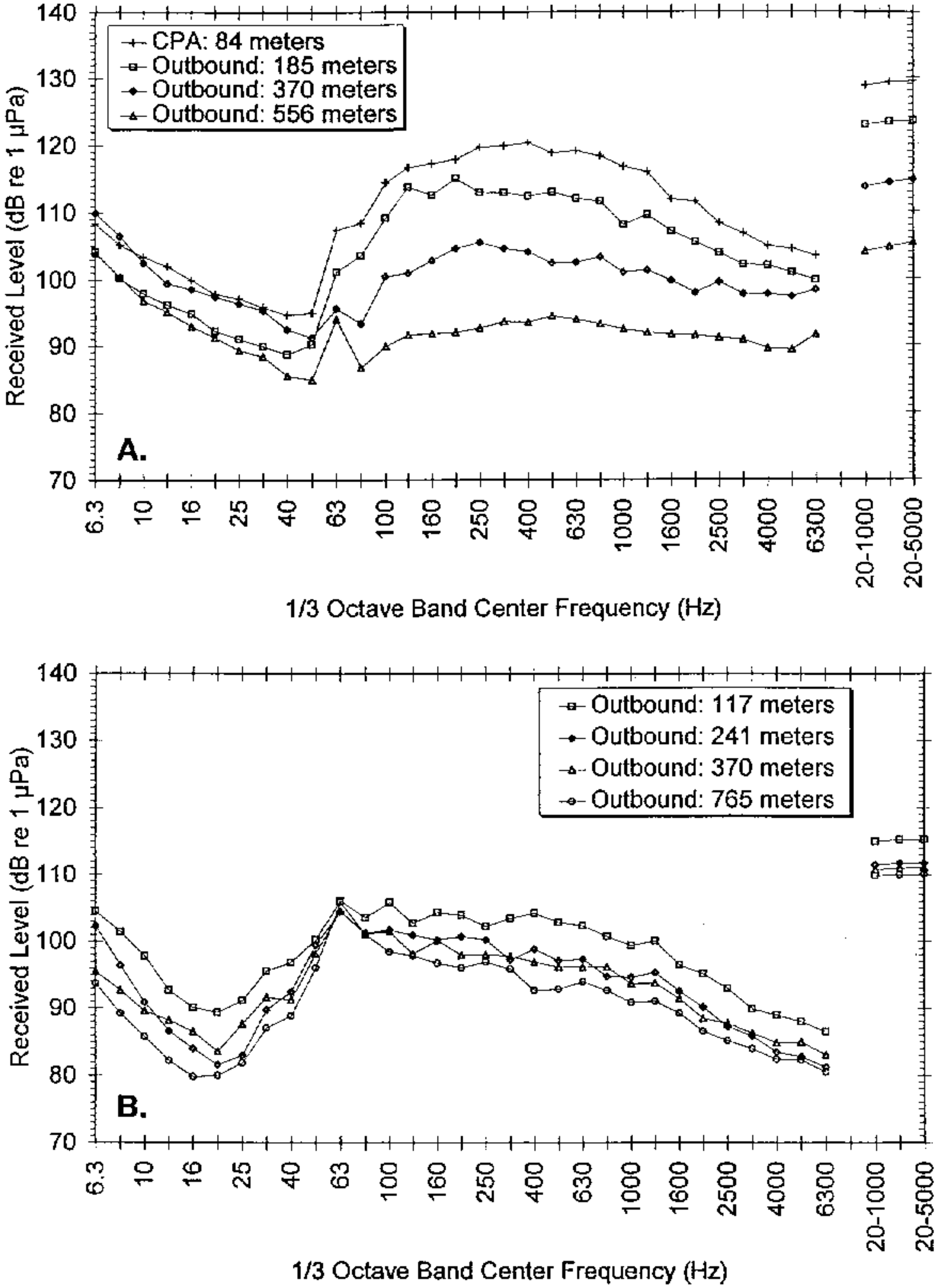

FIGURE 3.23. Boat noise at various ranges: radiated noise measurements in ⅓-octave bands for several vessels at various ranges from the receiver. ***(A)*** is *Pt. Barrow* outbound at 5.6 knots, water depth 5.3 m; ***(B)*** is *Peregrine Falcon* at 8.3 knots outbound, water depth 11.7 m; ***(C)*** is *Sag River* with *Barge 216* inbound at 4.5 knots, water depth 10.7 m; ***(D)*** is *Sag River* with *Barge 216* outbound at 5.8 knots; ***(E)*** is *Faraday* outbound at 7.7 knots, water depth 11.7 m. Levels at low frequencies show the effects of normal mode sound propagation in very shallow water.

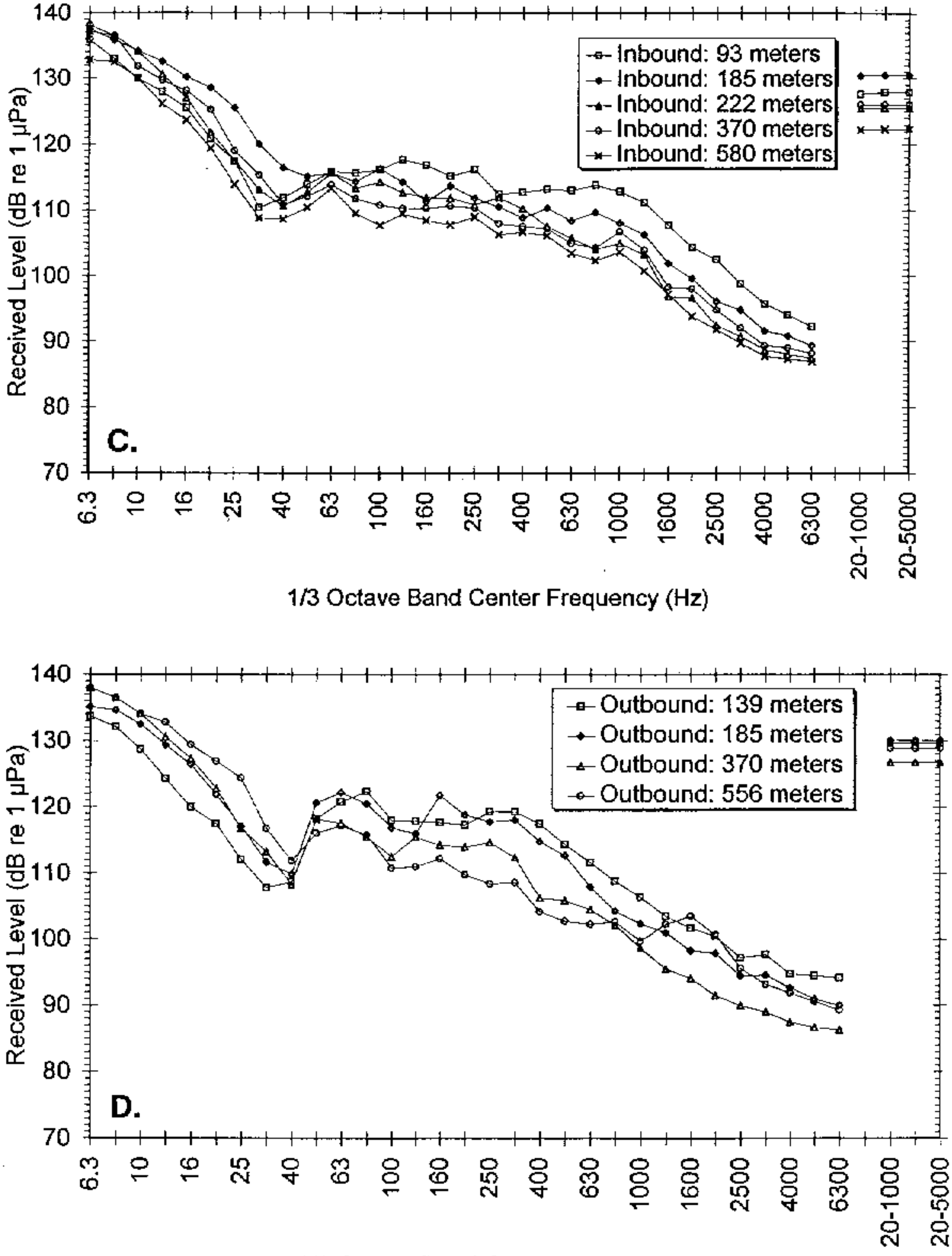

FIGURE 3.23. Continued.

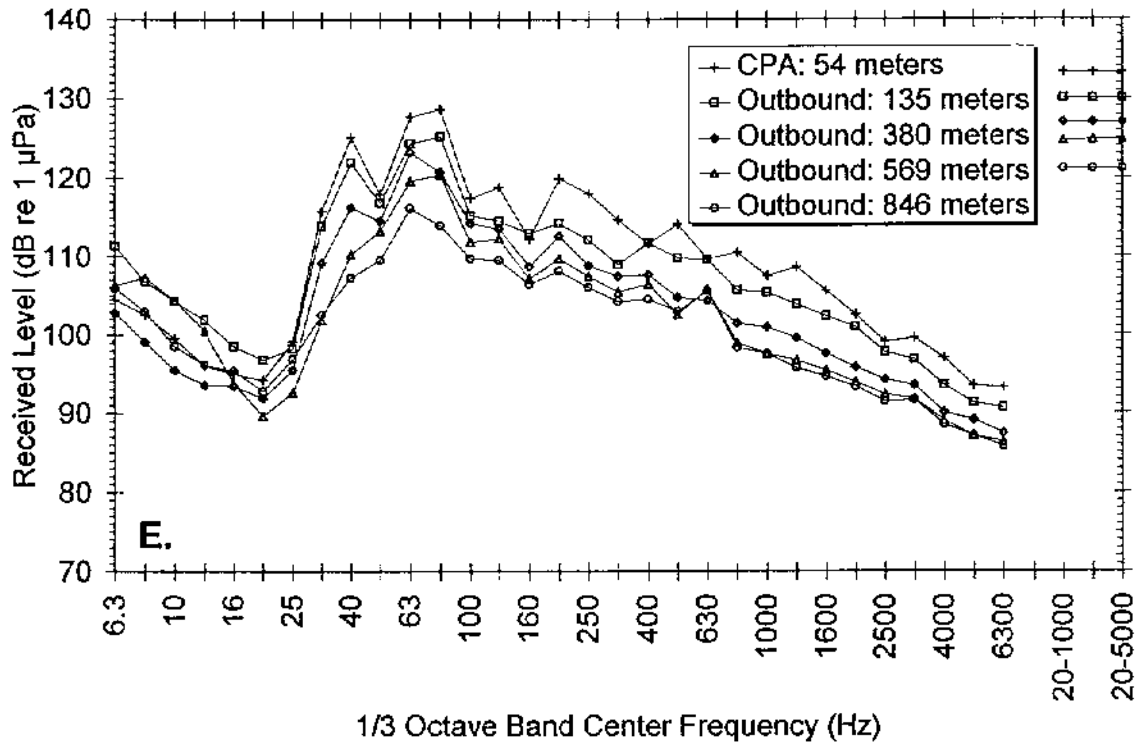

FIGURE 3.23. Continued.

Boat Source Levels

Figure 3.24 shows estimates of the effective source levels of these four boats in the ⅓-octave bands above the cutoff frequency. For *Sag River*, the data from the outbound run at 5.8 knots were used. Because of the modal sound propagation manifest in these shallow waters, the best range correction method is cylindrical spreading from CPA to one meter. Every mode propagates with cylindrical spreading.

The boat that emitted the strongest sounds overall (by 2 dB) was the *Sag River* pushing Barge 216 at 5.8 knots outbound; its estimated broadband source level (100-1000 Hz band) was 150 dB re 1 µPa-m. This result is not surprising considering that the *Sag River*'s three propellers are not shrouded. In contrast, the propellers on the *Pt. Barrow*, a more powerful vessel (2100 hp vs. 1095 hp) were in Kort nozzles. Nozzles are known to reduce the radiated underwater noise (Greene 1987; Richardson et al. 1995:114). Also, the *Sag River* was traveling slightly faster when measured. The source level of the *Pt. Barrow* was the second strongest, with an estimated source level of 148 dB re 1 µPa-m in the 100-1000 Hz band. The *Faraday* ranked third, with broadband source level 143 dB, and the *Peregrine* was "quietest", with broadband source level 139 dB. Vessels propelled by water jets, as used on *Peregrine* and *La Brisa*, may be inherently quieter than those with propellers.

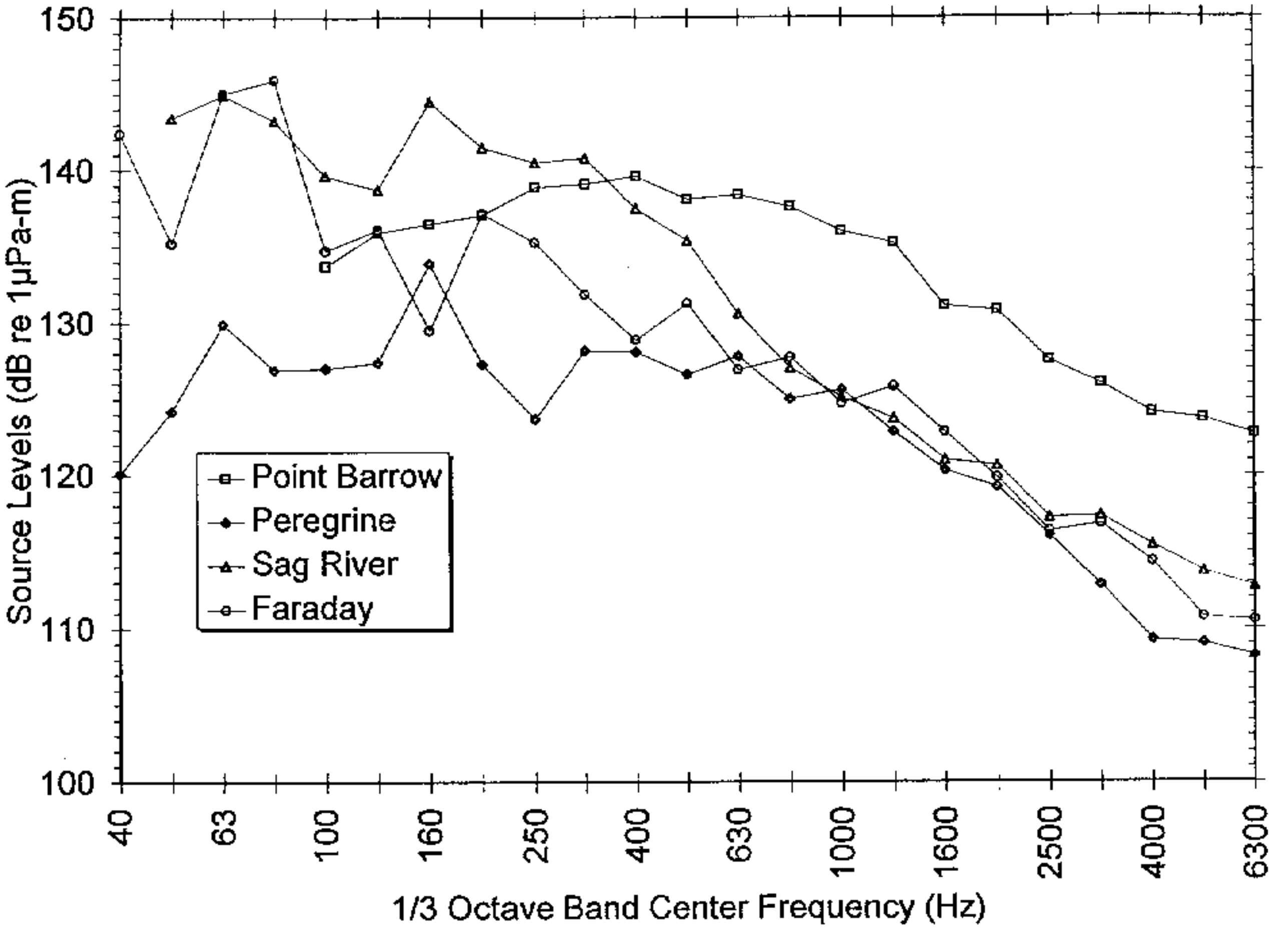

FIGURE 3.24. Source levels of boat noise: estimated effective source levels in ⅓-octave bands for the four boats whose measured sound levels are shown in Figure 3.23. For *Sag River*, the "5.8 knots outbound" condition was used (*cf.* Fig. 3.23D).

All quoted source levels are for the 100-1000 Hz band. Inclusion of the lower frequency bands would raise the overall source level of each boat. Boats such as these often emit strong sounds at low frequencies. However, judging from the ⅓-octave levels graphed in Richardson et al. (1995:112) for various boats, the 100-1000 Hz ⅓-octave source levels estimated for boats used at Northstar are consistent with previous estimates for similar-sized vessels.

Discussion

The estimates in Figure 3.24 are most useful in comparing the relative source levels of the various boats rather than their absolute source levels. The latter depend strongly on the accuracy of the assumed propagation loss between the source and the closest measurement distance. Also, *Pt. Barrow* was measured in such shallow water that reliable source level estimates were not feasible at frequencies below about 100 Hz. Therefore, the sounds of all four boats measured are compared based on the broadband sum of the 100-1000 Hz ⅓-octave band levels.

3.6 Aircraft Sounds

Sound transmission from air to water is restricted to a cone 26° wide under calm conditions. Sound outside the cone is totally reflected by the water surface (Richardson et al. 1995:80*ff*). Coupling is effective to somewhat wider angles if there are waves because they change the angle of the surface. However, the general effect of this restriction is to limit the duration of detectable sound at an underwater receiver from a passing airborne source.

The aircraft used during the whale surveys was N7UP, a modified Commander 680FL. It had been retrofitted with 400 hp Avco Lycoming IO-720 engines providing a total of 800 hp. The propellers had three blades. Normal speed during transect surveys and during measurements of aircraft sounds was 220 km/h (120 knots).

The sounds from the aircraft were recorded by means of a sequence of straight-line flights at altitudes 150 m, 310 m, 460 m and 760 m (500-2500 ft) over a sonobuoy. There were three flyovers at 460 m and two at each of the other altitudes. The sonobuoy was at 70°44'N, 149°10'W, in water about 20 m deep, and its hydrophone was suspended at 10 m. Beaufort Wind Force at the recording location was 0 (i.e. sea state 0), and ice cover was estimated to be 30%.

Propeller blade rate tones dominated the spectrum at all altitudes. The fundamental frequency was from 106 to 112 Hz. This range corresponds to a propeller shaft rate of 2120-2240 rpm and, with 3-bladed propellers, to a blade rate of 6360-6720/min (106-112/s). Some of the variation was presumably related to doppler shifts as the aircraft flew overhead. Numerous higher harmonics of the fundamental frequency also were evident in the spectrum (e.g., Fig. 3.25).

For three flyovers at altitude 1500 ft (460 m), the overall 20-1000 Hz band levels received at 10 m depth were 111, 103 and 115 dB re 1 μPa. These values are based on a 3.5 s averaging time. Sound levels received underwater increase and decrease rapidly as an aircraft flies overhead, particularly at the lowest altitudes. Thus, the received levels could be slightly higher with a shorter averaging time (especially for the lower-altitude passes), and would be lower if based on a longer averaging time. The spectrum for the pass when the 115 dB level was recorded is shown in Figure 3.25.

The ⅓-octave band levels and broadband (20-1000 Hz) levels of the sounds received during one flyover at each altitude are plotted in Figure 3.26. The data plotted for each altitude are those from the flyover that gave the strongest received sounds. In general, received sound levels diminished with increasing aircraft altitude, as expected. As expected from the narrowband spectrum (Fig. 3.25), ⅓-octave bands that contained one of the strong harmonic-

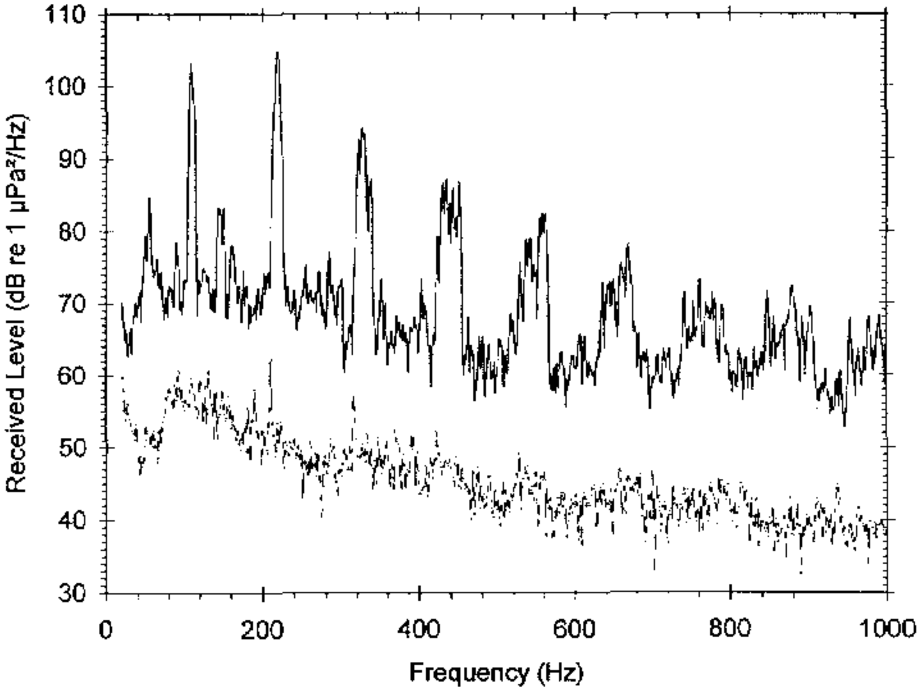

FIGURE 3.25. Underwater sound pressure spectral density for the whale survey aircraft, a modified Commander 680FL. Aircraft sound was recorded via a sonobuoy as the aircraft flew overhead at altitude 460 m (1500 ft) and speed 220 km/h (120 knots). Dashed (lower) curve is the ambient noise shortly before the aircraft flew overhead. Hydrophone depth was 10 m, spectrum analysis bandwidth was 1.7 Hz, and averaging time was 3.5 s.

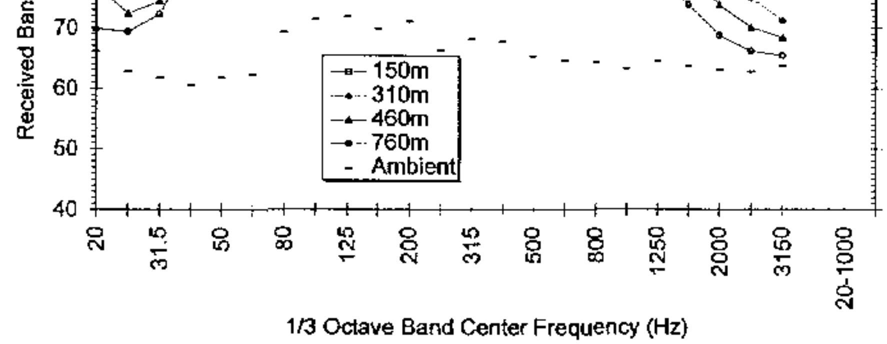

FIGURE 3.26. One-third octave band levels for modified Commander 680FL aircraft flying at altitudes 150, 310, 460 and 760 m over a sonobuoy with hydrophone depth 10 m. Averaging time was 3.5 s.

ally-related tones had higher levels than ⅓-octave bands not containing any of these tones.

As compared with the Twin Otter aircraft, which is also commonly used for surveys of marine mammals, the Commander 680 produced a tonal family with slightly higher fundamental frequency (~108 vs. ~83 Hz). For overflights at altitudes of 460 m and at normal aerial survey speeds, the received levels were several decibels higher for the Commander 680 than for Twin Otters on both an overall broadband basis and for the strongest tone (*cf.* Richardson et al. 1995:105*ff*; Patenaude et al. MS). Brewer et al. (1993) reported overflight sounds from the same aircraft. However, their sonobuoy hydrophone depth was 27 m, reducing the received levels compared to those at 10 m (this study) or at the 3-18 m depths where Twin Otter sounds have been measured in our previous studies. Comparisons among studies are also confounded by the different averaging times that have been used.

3.7 Ambient Noise

Ambient noise was measured underwater on an opportunistic basis with hydrophones and sonobuoys, and systematically via the two bottom recorders that were retrieved. From all four sources, ⅓-octave band levels were calculated from each observation to be included in statistical analyses. Wider band levels (20-1000 Hz) were also calculated to provide a single summary of the ambient noise at each measurement time.

Time Variation

Boat- and sonobuoy-based measurements of ambient noise were opportunistic, prohibiting a systematic examination of variability in ambient noise. The 20-1000 Hz band levels are plotted against time in Figure 3.27. This shows wide variation in the ambient noise levels, as would be expected with varying conditions of wind and waves. Times with noticeable man-made sounds such as airgun and boat sounds are excluded from these measurements.

The bottom recorders operated continuously. For one minute out of every 14 min 24 s (1/100th of the day), sampling occurred at 2000 times per second, twice the normal rate. This permitted an ambient noise spectrum including frequencies up to 1 kHz to be computed 100 times per day. The frequency resolution of these analyses was 1.7 s and the averaging time was 59.9 s. From these spectra the ⅓-octave and the 20-1000 Hz band levels were computed. Some of these observations will include bowhead calls, seismic pulses, and sounds from unknown sources because these results were computed for regular intervals (14 min 24 s) without editing. However, both the whale calls and the seismic pulses were brief and widely spaced. Also, the two bottom recorders were placed about 15 km and 48 km from the closest area where seismic exploration occurred during the recording period (Fig. 3.1). At the Narwhal Island recorder, seismic pulses were rarely detected and, even then, very weak.

Figure 3.28 shows the 20-1000 Hz band levels in relation to time for each of the two bottom units. It is evident that the ambient levels at a given site tended to wax and wane gradually over periods of hours or days. There were varying amounts of shorter-term fluctuation, including occasional high-level transient sounds for just a single sampling period. To

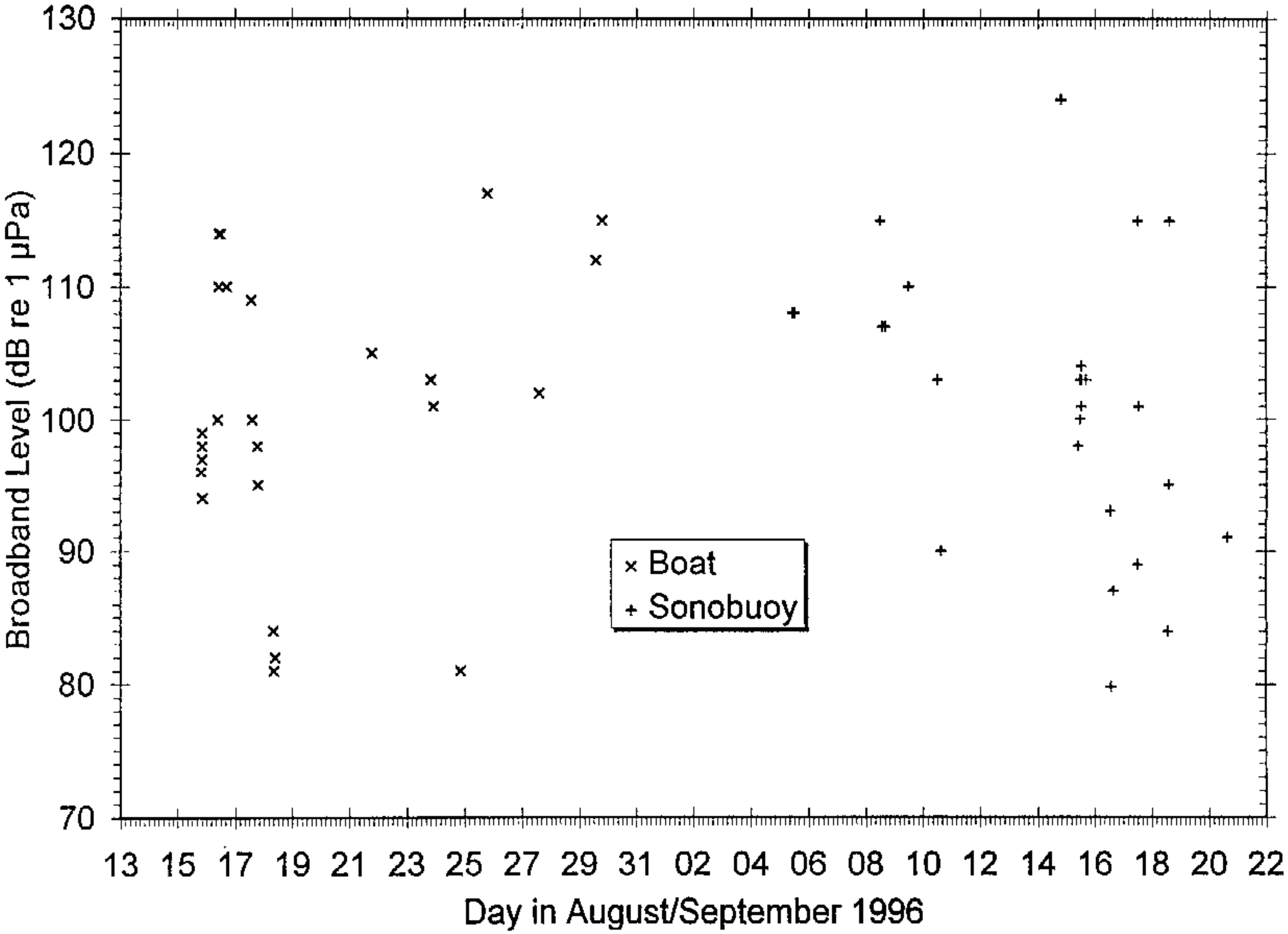

FIGURE 3.27. Hydrophone and sonobuoy measurements of broadband (20-1000 Hz) ambient noise levels, August-September 1996, central Alaskan Beaufort Sea. There were 25 boat-based samples and 27 sonobuoy samples of ambient noise.

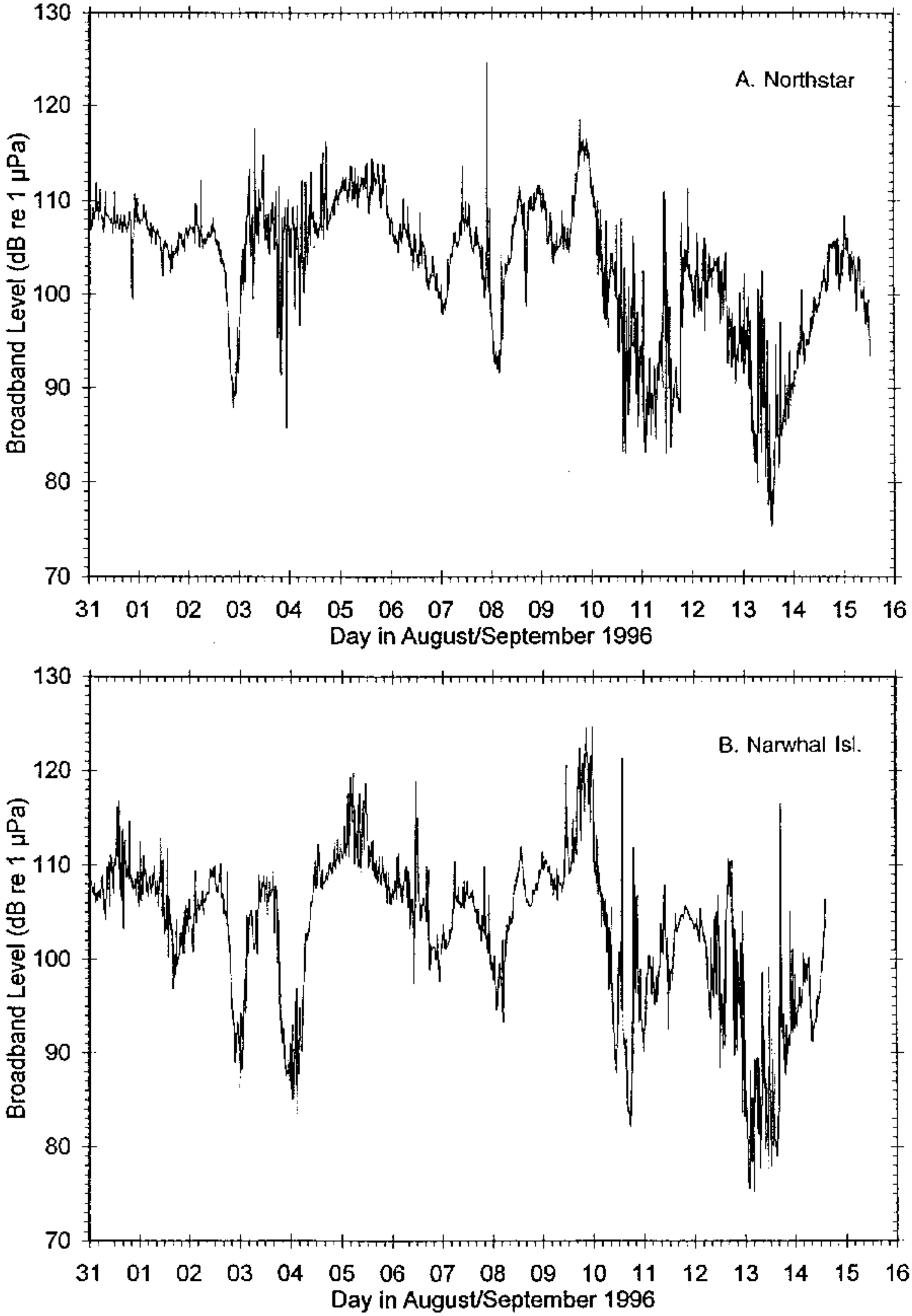

FIGURE 3.28. Bottom recorder measurements of broadband (20-1000 Hz) ambient noise levels, 31 Aug. to 14 or 15 Sep. 1996. ***(A)*** Northstar recorder. ***(B)*** Narwhal Island recorder. There are 100 measurements per day from each recorder.

the human listener, the sounds included occasional bumps, pops and even bangs of unknown origin.

Statistical Summary

Hydrophone Data.—There were 25 samples of ambient noise as measured with boat-based hydrophones. The resulting ⅓-octave band levels and 20-1000 Hz band levels were sorted to determine the percentile values for each band (Fig. 3.29). The median 20-1000 Hz band level was 100 dB re 1 µPa.

Sonobuoy Data.—There were 27 sonobuoy-based ambient noise analyses (Fig. 3.30). The median 20-1000 Hz band level was 103 dB re 1 µPa.

Bottom Recorder Data.—There were 100 ambient noise analyses per day for each bottom recorder. The Northstar unit collected 1552 samples while the Narwhal Island unit, which was retrieved one day earlier, collected 1460 samples (Fig. 3.31, 3.32). The respective median levels for the 20-1000 Hz band were 105 and 106 dB. The same data are presented on a narrowband (spectrum level) basis in Figures 3.33 and 3.34.

The most notable differences between the median spectra near Northstar and Narwhal Island were for frequencies below 30 Hz, where the Narwhal Island data showed higher apparent levels of ambient noise. This apparent difference may have been an artifact. Flow noise from water current around the hydrophone may have influenced the recorded sound below 30 Hz, especially off Narwhal Island. The median and 95th percentile spectra from the two sites were otherwise in general agreement. However, the 5th percentile spectrum levels differed markedly above 150 Hz. The 5th percentile levels (but not other percentiles) recorded off Northstar were higher at these higher frequencies.

Discussion

Ambient noise was measured with boat-based hydrophones from 15 to 29 August. The sonobuoy-based measurements were from 5 to 20 September. The bottom units began recording at midnight on 31 August and were retrieved on 14 September off Narwhal Island and on 15 September off Northstar. The boat-based hydrophone data had the lowest median broadband (20-1000 Hz) level, 100 dB, of the four data sets. Boat-based measurement times were probably biased toward better weather (lower wind and waves) and therefore to lower ambient levels generally. The sonobuoy data provided a median broadband level of 103 dB, which was 2-3 dB less than the median levels at the bottom recorders. Sonobuoys were dropped in a wide variety of sea conditions, including Beaufort Wind Forces ranging from 0 to 5. Also, most sonobuoys were dropped at places farther from shore and with deeper water as compared with the locations of boat-based measurements. The bottom recorders also operated at locations deeper than the sites sampled by hydrophone. The bottom recorders operated continuously without regard to weather or ice conditions.

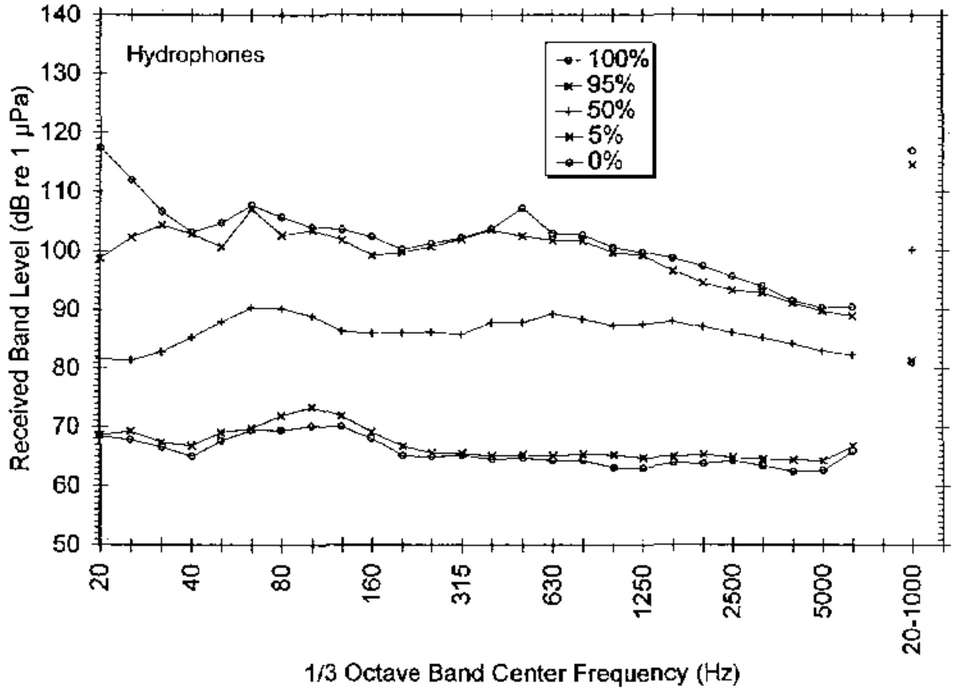

FIGURE 3.29. Percentile distribution of ambient noise measured by boat-based hydrophones, ⅓-octave bands (n=25 samples).

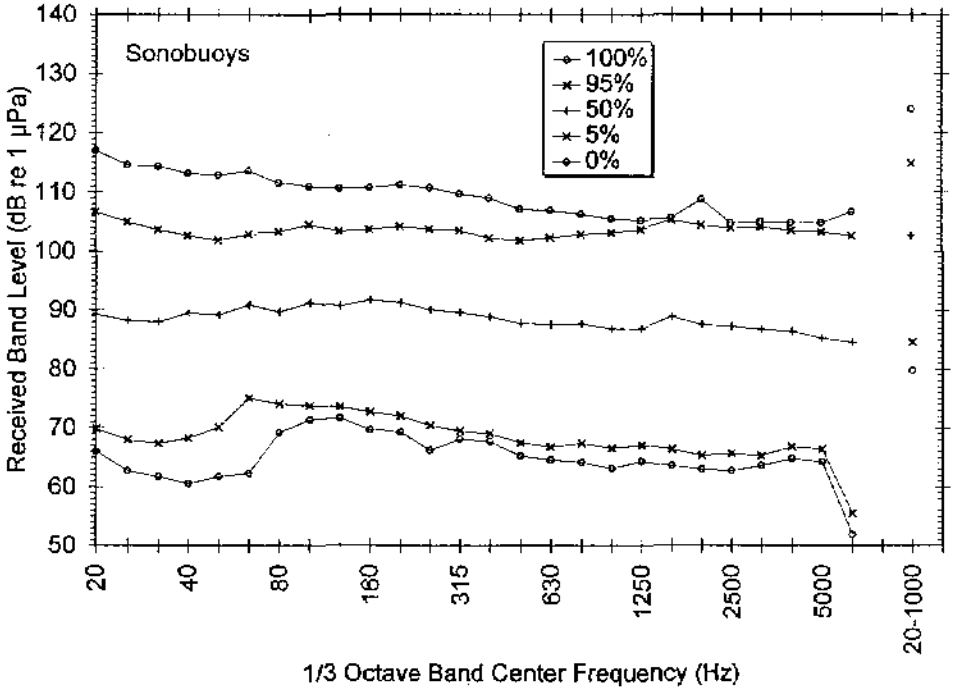

FIGURE 3.30. Percentile distribution of ambient noise measured by sonobuoys, ⅓-octave bands (n=27 samples).

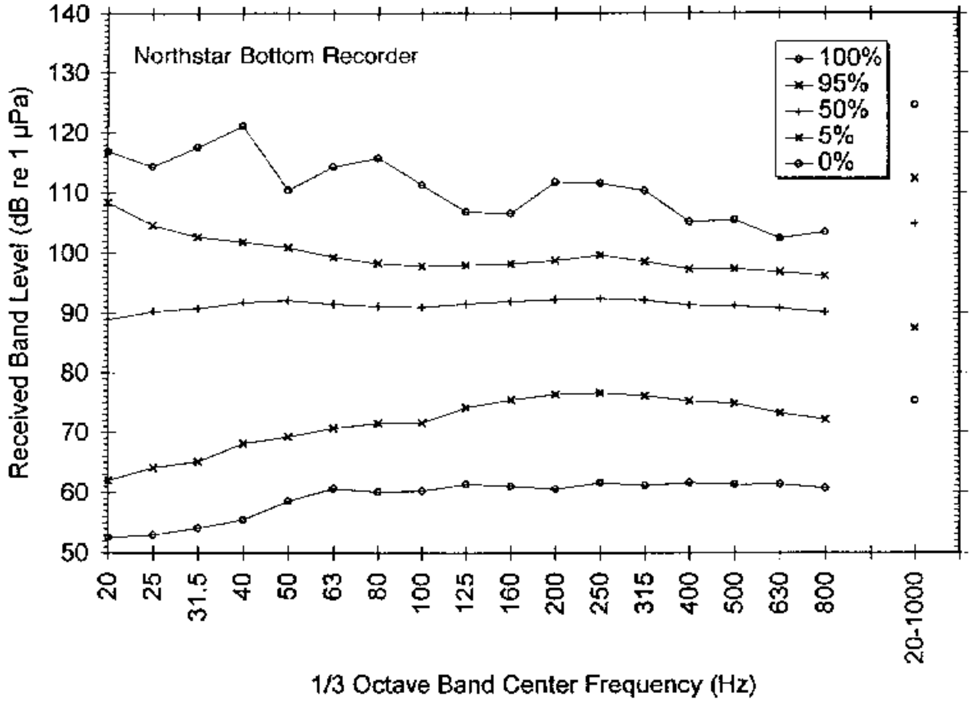

FIGURE 3.31. Percentile distribution of ambient noise measured by Northstar bottom recorder, ⅓-octave bands (n=1552 samples over 15.52 days).

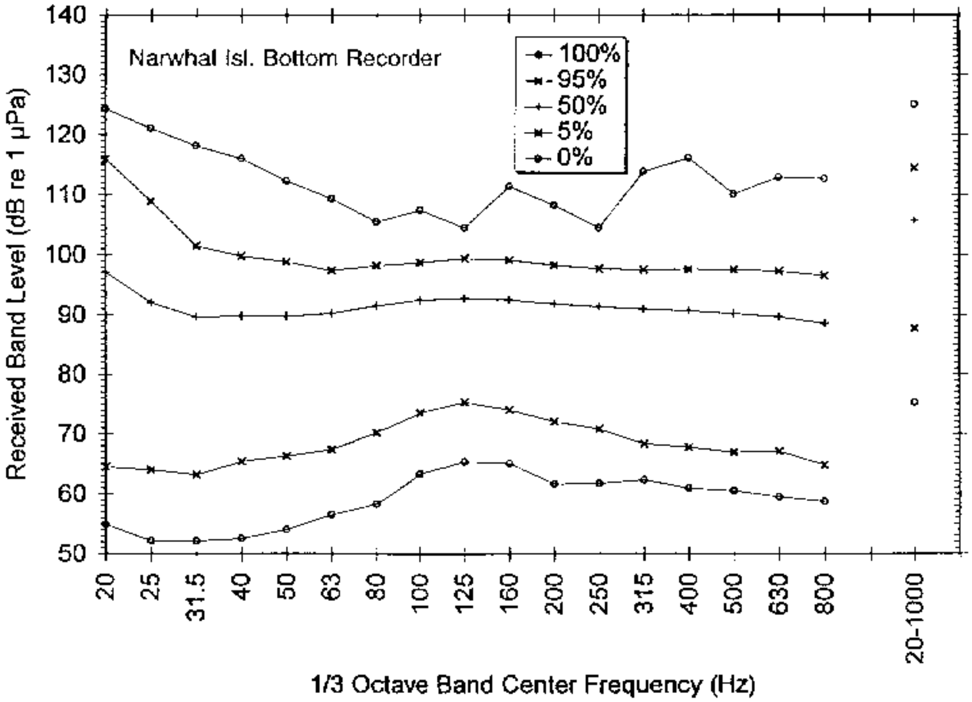

FIGURE 3.32. Percentile distribution of ambient noise measured by Narwhal Island bottom recorder, ⅓-octave bands (n=1460 samples over 14.60 days).

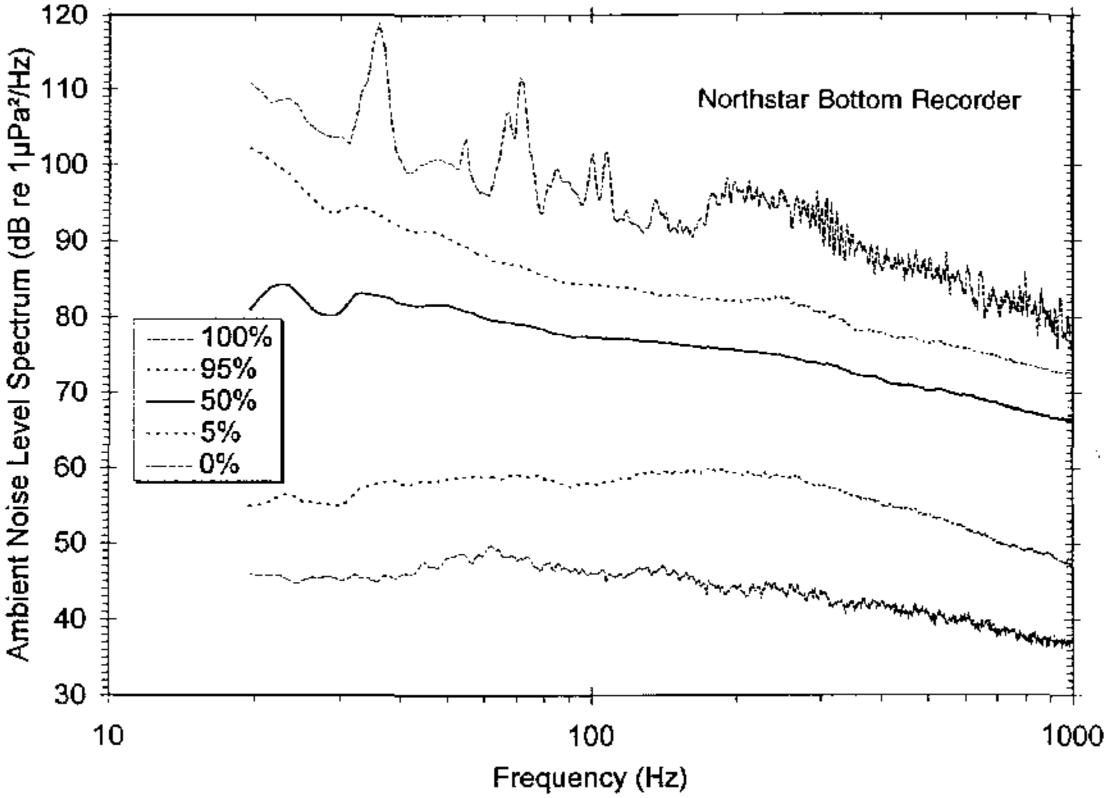

FIGURE 3.33. Percentile distribution of ambient noise spectrum levels measured by the Northstar bottom recorder. The analysis bandwidth was 1.7 Hz.

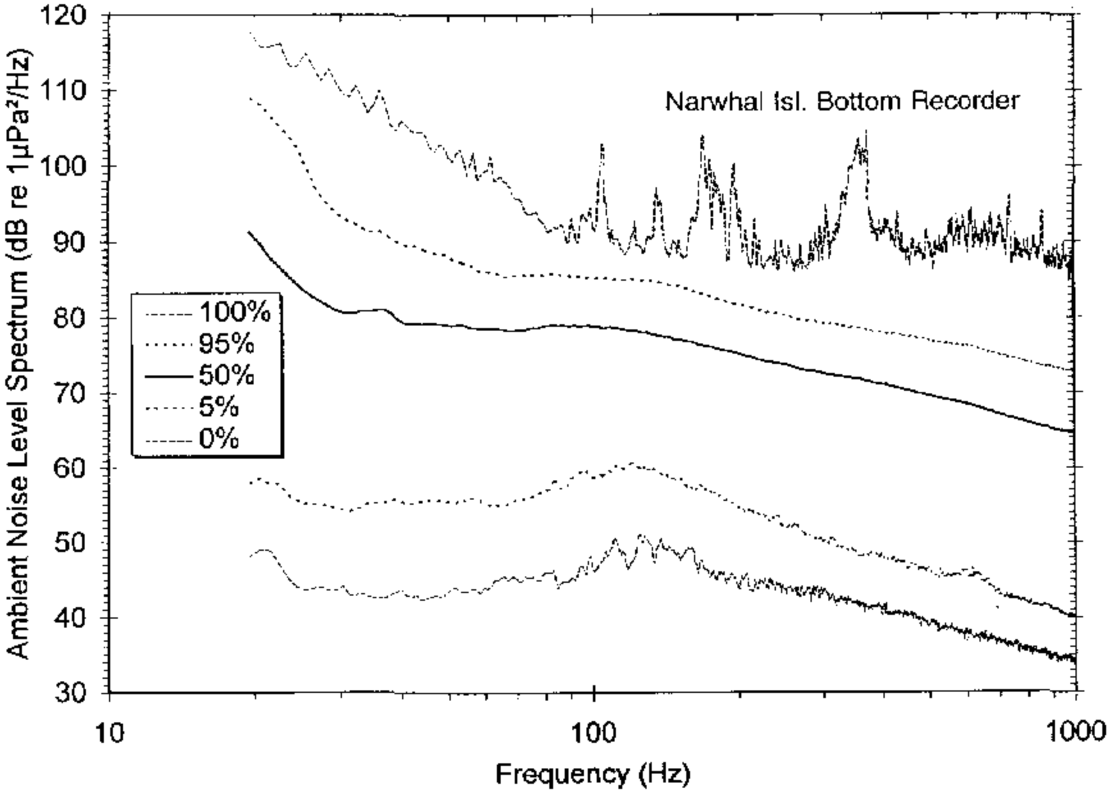

FIGURE 3.34. Percentile distribution of ambient noise spectrum levels measured by the Narwhal Island bottom recorder. The analysis bandwidth was 1.7 Hz.

How do these ambient noise measurements compare with others? A study of previous ambient noise measurements in the Northstar area was reported by Greene (1996). There were three sources of data: sonobuoys dropped on 24-30 August 1995, a bottom hydrophone cabled to Seal Island on 21-29 September 1984, and a hydrophone cabled to Sandpiper Island on 27 September-11 October 1985. Data from the two island hydrophones excluded times during drillrig operations on the respective artificial islands.

Ambient noise analyses from 40 segments of sonobuoy recordings offshore of Northstar from 24-30 August 1995 showed a median 20-1000 Hz band level of 95 dB re 1 µPa. The 1984 Seal Island hydrophone data also showed a median 20-1000 Hz band level of 95 dB, as did the 1985 Sandpiper Island hydrophone data. Thus, these earlier studies in the same general region revealed significantly lower median ambient noise levels than were observed in 1996 near Northstar.

The median levels documented with the bottom recorders were comparable to the wind and wave sounds expected from sea states 4-5 or Beaufort Wind Forces 5-6 (Wenz 1962). The presence of ice floes in the area most of the time generally prevented the build-up of large swells. However, smaller waves splashing against the floes may contribute considerable ambient noise.

Most of the energy in the seismic pulses, as received at long distances, was in the 50 to 400 Hz band. Therefore, the ambient noise in that band is relevant in determining how far away the seismic pulses would be detectable above natural background noise levels. The 5th, 50th and 95th percentile ambient noise levels in the 50-400 Hz band were 81, 101 and 108 dB re 1 µPa.

3.8 Whale Calls

Bowhead whale calls were recorded on the bottom recorders and noted during playback in the lab. Playback was usually at 8x actual speed. Call detection rates were calculated on a per hour basis for each recorder, and are graphed against time in Figures 3.35 and 3.36. The times when audible airgun pulses were received at each recorder are noted for reference.

The three bottom recorders that operated successfully during testing on 25-28 August 1996 provided useful data for about 80 hours. The positions are shown by in Figure 3.1 by ⊗ symbols. Figure 3.35 shows the 20-1000 Hz ambient noise levels, the number of bowhead calls detected per hour, and the presence of airgun sounds, plotted vs. time. It is noteworthy that bowhead calls were detected as early as 25 August, primarily at the northern and central locations (Fig. 3.35A,B vs. C). The total numbers of bowhead calls counted over the full deployment period were 930 at the southern unit, 1216 at the central unit, and 823 at the northern unit. This distribution of calls, although from only a limited time before the main migration is expected to begin, appears to support our selection of the central unit location at the core of the migration corridor. During this 3-day recording period, the airguns operated only on August 25th. Airgun sounds were received at the southern bottom recorder but not at either the center or the northern position.

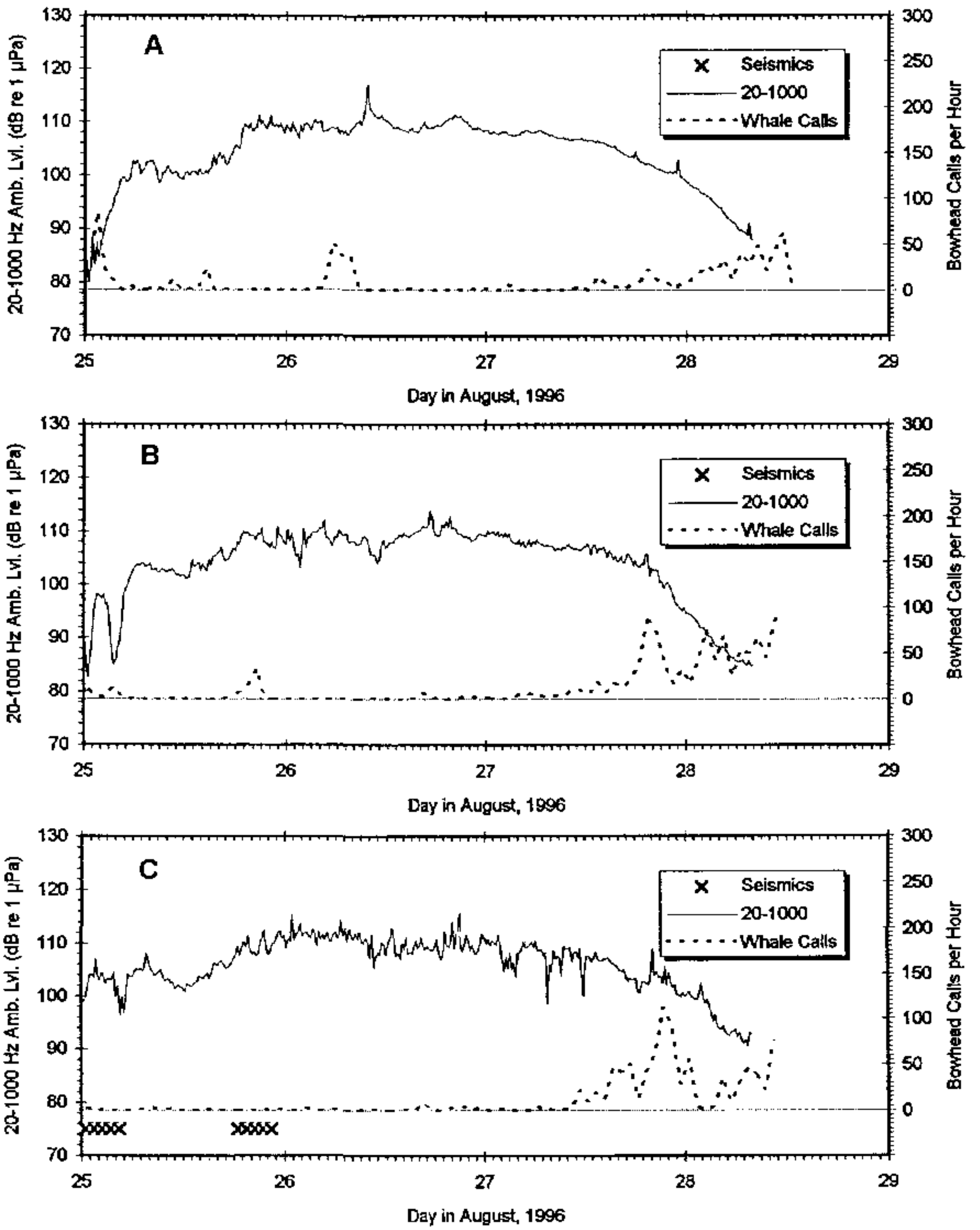

FIGURE 3.35. Ambient noise, bowhead call rates, and the presence of airgun sounds vs. time for three bottom recorders, 25-28 August 1996. *(A)* was 42 km (23 n.mi.) north of Northstar, depth 44 m. *(B)* was 30 km (16 n.mi.) north, depth 36 m. *(C)* was 24 km (13 n.mi.) north, depth 25 m. Figure 3.1 shows these locations.

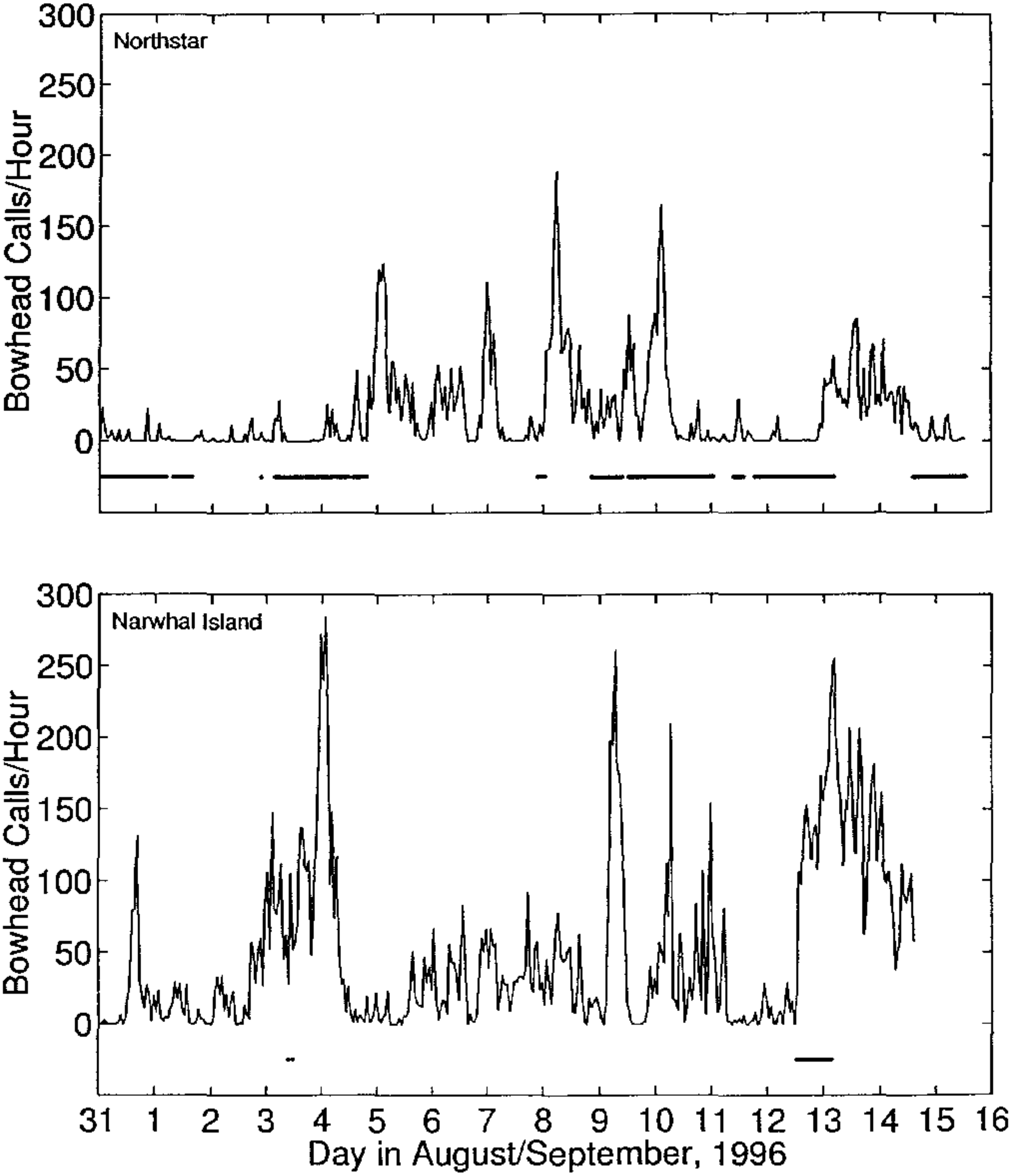

FIGURE 3.36. Bowhead whale call counts vs. time as detected via the bottom recorders north of Northstar and north of Narwhal Island. Also shown, by a line near the bottom of each panel, are the times when airgun sounds were heard at the two recorders. The tick marks on the date axis represent the start of the date in question (00:00 local time).

The total numbers of bowhead calls heard during the 351 hour period of simultaneous operation of the two long-term bottom recorders (31 August-14 September 1996) were 6920 calls off Northstar and 17,634 off Narwhal Island. Airgun pulses were heard during 49.6% of those 351 hours off Northstar and (faintly) during 5.1% of those hours off Narwhal Island. On a minute-by-minute basis, seismic pulses were detected 36.9% of the time at the Northstar recorder, and 2.1% of the time at the Narwhal Island recorder. Airgun pulses received at the Northstar recorder had low to moderate rms levels (on the order of 110 dB re 1 µPa); those received at the Narwhal Island recorder were very weak (≤79 dB re 1 µPa).

Additional analyses of bowhead call counts with and without the presence of audible airgun pulses are reported in Chapter 5, WHALES (§5.3.6).

3.9 Summary and Conclusions

This chapter describes measurements of the underwater sounds from geophysical survey operations ("seismic survey") in and near the Northstar Unit northwest of Prudhoe Bay during August and September 1996. Although boat, aircraft and ambient sounds were studied and are reported, the primary concern was with the sounds of the airgun pulses during the seismic survey itself.

The primary concerns are that the airgun sounds disturb bowheads or other marine mammals and that, as a result, the animals may be less accessible to subsistence hunters. Inupiat whalers believe that migrating bowhead whales can be displaced from their normal migratory path by as much as 30 miles (Kanayurak et al. 1997), reducing their accessibility to hunters. Also, the whalers report that bowheads are more difficult to approach when they are exposed to seismic (or other industrial) sounds. Their experience has been gained over decades of whaling along the northern coast of Alaska and is not based on the Northstar survey of 1996. As compared with the Northstar seismic survey, many of the surveys in the past have used larger arrays at greater depths and farther offshore. Thus, the characteristics and propagation of seismic pulses would not be expected to be the same during the 1996 Northstar seismic survey as during some previous surveys.

Source and received levels of seismic pulses quoted in this report and summary are, except where otherwise noted, rms pressure levels averaged over the duration of the pulse. Pulse duration is defined as the time including 90% of the pulse energy (i.e. from the time when the 5th to the time when the 95th percentile of the energy is received). Rms pulse levels averaged about 10 dB less than peak levels during this study.

The full array of airguns used for the 1996 Northstar program consisted of 11 airguns of volume 120 in^3 each (total airgun volume 1320 in^3) operating at 2000 psi (13.8 MPa). This is a medium-sized array. Its effective source level for horizontal propagation, computed from measurements within 200 m, is estimated to be 222 dB re 1 µPa-m for stern aspect and 213 dB re 1 µPa-m for bow aspect, with the difference perhaps due to screening by the source boat. These estimates are on an rms pressure basis. The corresponding peak source levels (horizontal plane) were about 230 and 221 dB re 1 µPa-m, or 6.3 and 2.2 bar-m peak-to-peak in the units often used by geophysicists. These peak levels are notably lower than the nominal vertical source level for the 11-airgun array, which was estimated by Painter (1996) to be 26.4 bar-m peak-to-peak or 242 dB re 1 µPa (peak). Large arrays may have peak source levels exceeding 255 dB re 1 µPa-m in the vertical and generating more than ten times the pulse pressure amplitude of the array used at Northstar.

The Northstar airguns were normally suspended at depths 3½-4 m below the surface, appropriate for very shallow water. During other surveys in deep water, the airguns are typically 6 m below the surface. Greater depth leads to more efficient sound transmission horizontally at the low frequencies associated with airguns.

The energy in the airgun pulses, as received at short horizontal distances, was mainly confined to frequencies in the 40-150 Hz band. The source array was close to omnidirectional in azimuth at 50 and 100 Hz but became increasingly directional at higher frequencies. The components of the seismic pulses below about 40-70 Hz tended to attenuate especially rapidly, with the cutoff frequency increasing with decreasing water depth near the source.

During operations with a single 120 in^3 airgun and with a partial array of six airguns, the source levels were about 23 dB and 4.5 dB lower, respectively, than that with the full 11-airgun array. These differences were consistent with the 21 and 5.3 dB differences expected on theoretical grounds when the energy from several airguns adds coherently.

The rms pressure levels from the full 11-airgun array diminished below 200, 190, 180 and 160 dB re 1 µPa at ranges not exceeding 44, 257, 1020 and 4900 m from the source, respectively. More typically, those levels were attained at respective ranges of 31, 240, 960 and 3600 m.

Because of the relatively shallow source and the shallow water in the survey area, energy at low frequencies was dissipated rapidly during propagation, leading to an unusually high apparent spreading loss rate of close to 40 dB/decade at long ranges. Based on the fitted curve in Figure 3.22, the received levels, on an rms pressure basis, are expected to be 160 dB re 1 µPa at distance 2.6 km, 132 dB re 1 µPa at 10 km, 116 dB at 20 km, 106 dB at 30 km, and 97 dB at 40 km. Variability around these values may be ±10 dB or more, especially at distances greater than 5 km. The longest distance where seismic pulses were received and measured during this study was 67 km (36 n.mi.). There, the received rms pulse level was only 77 dB re 1 µPa. That received level would be well below the natural background noise and undetectable during all but the quietest periods.

Ambient noise measurements near Northstar were made independently by three means: boat-based hydrophones, sonobuoys, and two widely-separated bottom-mounted autonomous recorders. The measurements were not all made at the same times. The measurements via hydrophones occurred during the last half of August, those via sonobuoys were made sporadically during the first half of September, and the bottom recorder measurements were continuous from 31 August until 14 or 15 September. The results were all comparable, however, with median broadband (20-1000 Hz) levels of 100 dB re 1 µPa from the hydrophones, 103 dB from the sonobuoys, and 105 and 106 dB from the two bottom recorders. These levels are similar to levels expected in the open ocean with sea states 4-5 (Beaufort force 5-6). These levels were higher than the median levels measured in the same general area in three prior years (95 dB re 1 µPa). The presence of a significant number of ice floes, with even moderate wave action, may account for the high levels.

Continuous recordings by the bottom recorders included sounds during all weather conditions. Ambient noise levels increase with higher winds and waves. The boat and sonobuoy data did not include severe weather cases and might be expected to have lower median levels. Another explanation for the differences in median level might be that ambient noise levels tended to increase during freeze-up.

Figure 3.37 shows the distances at which the received levels of the seismic pulses would be expected to diminish below the 50-400 Hz ambient noise levels (5th, 50th and 95th percentiles) at times with relatively good, typical and poor sound propagation. Chapter 5, WHALES, discusses this information in relation to the distribution of bowhead whales as observed during 1996 (see Fig. 5.47).

Sounds of boats operating as part of the survey were found to be moderate in level compared to vessel sounds generally. The strongest boat sounds measured at Northstar came from *Sag River* pushing barge 216 at speed 5.8 knots. *Sag River*'s propellers are not in Kort nozzles and would be expected to radiate more sound than a comparable vessel with shrouded propellers.

Sounds of overflights by the Twin Commander 680FL aerial survey aircraft were also measured 10 m below the water's surface as the aircraft flew over at various altitudes from 150-760 m (500-2500 ft). These sounds were several decibels stronger than previously-measured sounds from a Twin Otter performing similar overflights. The Commander's sounds were dominated by a harmonic family of tones related to the propeller blade rate; the fundamental frequency varied from 106 to 112 Hz.

Whale calls detectable in the signals recorded by the two widely-separated autonomous bottom recorders were counted for the 14.6-day period of simultaneous recordings (31 Aug.-1 Sep.) During that time, a total of 6920 calls were detectable via the recorder near Northstar, while 17,634 calls were detectable via the recorder 45 km to the ESE off Narwhal Island. Airgun pulses were received at the Northstar recorder 36.9% of the time at low to moderate mean-square levels (on the order of 110 dB re 1 µPa). Airgun pulses were received at the Narwhal Island recorder only 2.1% at the time, and those pulses were very weak (≤79 dB re 1 µPa). Further analysis of these data is given in Chapter 5, WHALES (§5.3.6).

Several conclusions may be drawn regarding the results of the acoustics studies at Northstar in 1996. From the perspective of whales migrating WNW parallel to the coast,

- the ambient noise levels were a few decibels higher than might have been expected. This would reduce the signal-to-noise ratios ("prominence") of the airgun pulse sounds by a few

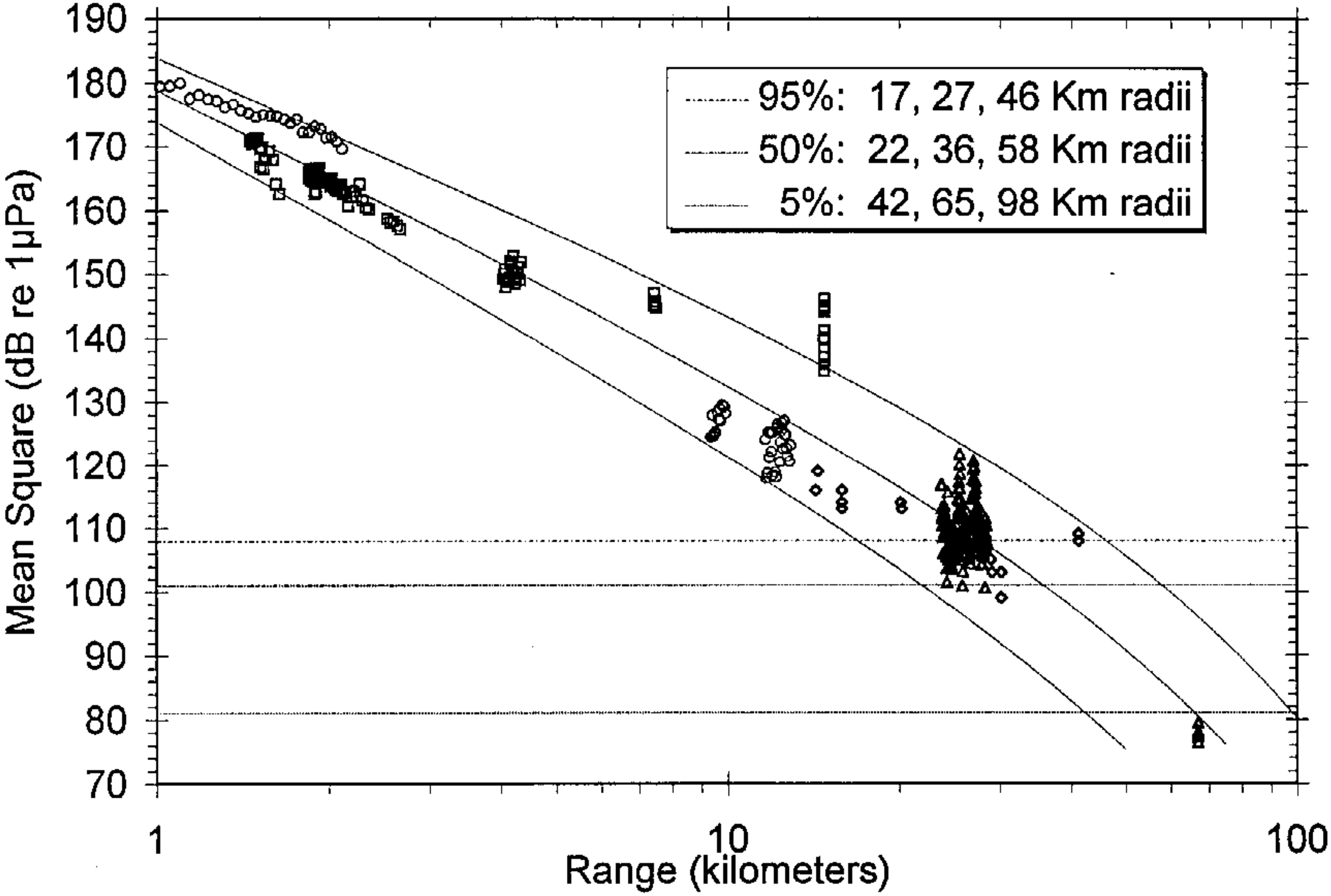

FIGURE 3.37. Rms pulse levels received at long range and fitted regression curve (from Fig. 3.22). Also shown are nominal curves for received levels with good propagation (upper curve) and poor propagation (lower curve). Horizontal lines show ambient noise levels (5th, 50th and 95th percentiles) for the 50-400 Hz band, which contains most of the pulse energy as received at long range. The intercepts of the "good, typical and poor" received level vs. range curves with the three ambient noise levels (shown in box) define radii from the source within which the received levels are expected to be heard by bowhead whales under those propagation and ambient noise conditions.

decibels, and would reduce the maximum detection distances somewhat. ▸ The airgun array being used was smaller than typically used during previous seismic surveys farther offshore in deeper water, thereby reducing the source level of the airgun sounds. ▸ The survey was being conducted in relatively shallow water, resulting in higher attenuation of the dominant low frequency sound in the pulses and correspondingly lower levels in the whale migration corridor offshore of the area of seismic exploration. ▸ The most distant airgun sounds detected had traveled 67 km (36 n.mi.) and were barely above the quietest background level observed during the field program; the maximum detection distance on a more typical day was about 36 km (19 n.mi.).

3.10 Acknowledgements

Everyone on the barge *Arctic Endeavor* helped with the acoustics field work. The crew of "sound boat" *La Brisa* was especially helpful: Pete Crosbie, Ted Whip, Rob Hulse, Bob Lockman and Alan Arrigoni. Jeff Hastings and Scott Nish, Northern Geophysical of America field operations directors, went out of their way to coordinate their activities with our data collection needs. Howard Claiborne helped with a variety of problem solutions. Juan Gardner, Pelagos Navigation, assisted immeasurably with position logging on the *La Brisa*. The LGL and Inupiat marine mammal observers on the *Point Barrow* were helpful. Tess Carr, BPX(A) environmental coordinator at Prudhoe Bay during our time on the barge, provided valuable support. The Crowley Marine crew on *Sag River* was indispensable during bottom-unit retrieval in mid-September. Dr. Bill St. Lawrence and Bob and Tena Lewellen provided weather and ice forecasts and data.

Dr. David Jacobs, Scripps Institute of Oceanography, provided the bottom recorder data storage electronics. Mark Chun provided the audio conditioning circuit boards. Mike Zika and Dave Christian at Greeneridge rigged electronics, batteries, and buoys for the field work. Dave Iddings engineered the bottom recorder unit pressure housings. Darcee Guttilla and Don Chalfant helped analyze tape recorded sounds. Debra Martinez, David Abrego, Kathy Stehno, Ashley Truitt, Jeff Ross and Kristin Otte listened to the bottom recorder sounds. Dr. John Richardson, LGL Limited, provided superior guidance and review as well as editorial direction. We thank them all.

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4. SEALS[1]

4.1 Introduction

This chapter reports primarily on the numbers, distances from the seismic boat, and behavior of seals that were observed during boat-based marine mammal monitoring from 24 July through 18 September 1996. Emphasis is given to the numbers and behavior of seals seen within 150 m of the seismic source vessel, 150-250 m away, and >250 m away. These distance criteria match the shutdown radii specified in the Incidental Harassment Authorization (IHA) issued to BPXA by the National Marine Fisheries Service (NMFS) for this project.

The focus here is on the differences in seal numbers, distances and behavior at times when the source vessel was underway but not shooting seismic versus times when the airguns were firing. The source vessel itself, even when not conducting seismic activities, may have had some effect on seals. However, in the absence of airgun operations, this potential boat effect would not differ from the effect of any similar tugboat.

Although a major aerial survey program for marine mammals was done in and around the Northstar area during September 1996, the aerial surveys were designed to detect whales. Survey altitudes were 900-1500 ft (275-460 m)—too high for reliable detection of pinnipeds at the surface. Seals were seen and recorded only opportunistically during the aerial surveys. These data are presented briefly in section 4.3, along with a general discussion of the status and annual cycle of each seal species. That general introductory material also summarizes seal sightings during aerial surveys of the central Alaskan Beaufort Sea done during the late summers and autumns of 1979 through 1995 by MMS and LGL.

4.2 Methods

Boat-Based Monitoring

Observation Procedures.—Three or four observers were assigned to the source vessel at all times during the 24 July through 18 September period of seismic operations. These included 2 or 3 biologists whose qualifications had been submitted in advance to NMFS, plus an Inupiat observer-communicator. Observation work was scheduled in 4-hour shifts, with each observer normally being responsible for two 4-hour shifts (separated by at least 4 hours) during a 24 hour period. Normally, one or two of the observers lived aboard the source vessel (*Point Barrow*) and the others commuted back and forth via crew boat to the camp barge (*Arctic Endeavor*) every 12 hours.

A fourth observer shared the observation duties during the period 31 August through 17 September. During that time, preparations were being made to deploy a second source

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[1] By Ross E. Harris, Gary W. Miller, Robert E. Elliott and W. John Richardson, LGL Ltd.

vessel (the *Hippo*). The additional observer, a biologist, was present to allow simultaneous observations from both source vessels if needed. In actuality, the *Hippo* was never used as an airgun source vessel. The presence of an additional biologist during the whale migration season also provided greater flexibility in personnel scheduling during times when the Inupiat observer-communicators had other communication responsibilities (as required by the Conflict Avoidance Agreement).

At all times while shooting was underway, or when it was expected to begin within the next 30 minutes, the on-duty observer watched continuously for mammals. Observations were made from the glass-enclosed wheelhouse of the *Point Barrow*, which was the highest vantagepoint on the vessel. Eye level was about 7.5 m above the water. The wheelhouse afforded a 360° view with only minor obstructions to vision toward the stern. During approximately 5-10% of the time while monitoring was underway, a second member of the monitoring crew was also on duty in the wheelhouse.

The observer scanned around the vessel using 7 x 50 Fujinon FMTRC-SX binoculars.[2] The binoculars included a reticle to measure depression angle relative to the horizon—an indicator of distance. The compass built into these binoculars was not useful on the steel vessel, but directional information was readily available in the wheelhouse.

Observers also used a Bushnell Lytespeed 400 laser rangefinder with 4x optics to test and improve the observers' abilities for visually estimating distances to objects in the water. This Class 1 eye-safe device was not able to measure distances to seals more than about 70 m away. However, it was very useful in improving the distance estimation abilities of the observers at distances up to about 600 m—the maximum range at which the device could measure distances to highly reflective objects such as other vessels.

During July and much of August there was no total darkness, and normal visual observations were possible during all hours when shooting was underway. Thereafter the nights rapidly became longer, such that by the end of operations on 18 September there were about 10.5 hours of total darkness each night. The IHA and other permits contained no requirement for seismic operations to be suspended at night or during periods of poor visibility, and seismic work continued at such times. At night, the observers used both the 7 x 50 binoculars and a Bushnell/ITT Night Ranger 250 binocular night vision device (NVD) equipped with up to 6-power lens adapters. A Bushnell/ITT Night Ranger 150 monocular NVD was also available for backup but was not used. Lights in the wheelhouse and on the outside of the vessel were usually on at night, and these reduced the effectiveness of the NVD. The IHA required nighttime observations by the monitoring personnel only at times while the array was being powered up. However, in practice, the monitoring personnel attempted to observe at all times, night or day, when the airguns were operating or were

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[2] The requirement in the original IHA for Big-Eye binoculars was deleted by a modification dated 28 July 1996.

expected to start operating within the next 30 minutes. Notwithstanding the use of the NVD, the observers' abilities to detect marine mammals were severely reduced at night.

Data Recorded.—While on watch, the marine mammal observer regularly recorded, on a data sheet, information regarding seismic status and environmental conditions. Additional data were recorded for marine mammal observations. For all records, the date, time, position (latitude, longitude), vessel heading, vessel speed and observer name were recorded. The latitude, longitude, heading and speed, along with information about seismic activity, were available from the computer monitor in the wheelhouse. Operational activities that were recorded were the "seismic state" (no airguns, single airgun, partial array [2-7 guns], full array [8-11 guns], ramp up, seismic testing) and/or the number of guns operating, and whether or not the shooting was on a source line or OBRL line. Only a single airgun was in use on OBRL lines (see §2.2, "Equipment and Operations"). Environmental conditions that were recorded included ice cover within about 1 km of the seismic source vessel (percent cover, primary ice type, secondary ice type), wind speed (from the boat's guage) and direction, sea state (Beaufort Scale), cloud cover and thickness, visibility, obstructions to visibility (e.g., fog, snow), and glare. Standardized codes were used for most of these records, but written descriptive comments were often added.

For each marine mammal sighting, the following information was recorded: species, number of individuals seen, sighting cue, age if evident, behavior, reaction, heading, bearing, distance, and seismic status. No cetaceans were seen from the seismic vessel, so the following description of the data recorded is limited to items relevant for seals. The sighting cue was the feature that initially drew the observer's attention to the seal. These cues included the head or body breaking the water surface, or a splash. For seals, no age determinations were possible and this category was never used.

Several standardized behavior and reaction categories were used. "Behavior" was the behavior of the seal when initially sighted. The "reaction" referred to behaviors observed subsequently. *Behavior categories* that applied to seals were dive, swim, mill, thrash, look, and unknown. Swimming involved directed movement, unlike milling. Thrashing was a particularly active swimming behavior at the surface. *Reaction categories* were none (i.e., no change in behavior), dive, swim away (=avoidance), swim toward (=approach), swim parallel, look, and other (with description). Two types of dives by seals were distinguished in the data from mid-August onward: "sink" and "front dive". Seals often floated in a vertical posture and then simply sank, tail first, straight back down into the water. Seals that "front dove" went below the surface head first. Seals that "looked" floated at the surface in a vertical posture and faced the source vessel. If it was possible to continue making observations of a seal after the initial sighting, this was done. To aid in subsequent analysis, a brief written description of seal behavior and sighting circumstances often was made, time permitting.

The seal's direction of movement (heading) and position relative to the boat (bearing) were recorded by reference to the boat's heading. Directions relative to the boat were estimated as hours on a clock face; "1 o'clock", for example, was 30 degrees off the boat's trackline to starboard. An estimate was made of the radial distance of the seal from the source vessel. Usually there was sufficient time to estimate the distance more accurately using the 7 x 50 reticle binoculars. Occasionally there was only enough time to estimate the distance by eye. The distance and bearing to the seal were measured from the wheelhouse, which was approximately 30 m ahead of the airgun array.

Shutdown Procedures.—The definitions of the safety zones for seals and cetaceans, and the procedures that were followed when a marine mammal was sighted within the safety zone, are described in §2.3, "Mitigation Measures". The IHA called for the airguns to be shut down when seals were within certain safety radii. These were defined based on the distances where received levels of seismic pulses were expected to be near 190 dB re 1 µPa, based on a "mean square" or rms basis over the effective duration of the pulse (see section 3.2).

Up to 30 August, the safety zone was defined as an area with radius 150 m. This was based on estimates of received level vs. distance from the airguns derived prior to the field season. Direct acoustic measurements of received levels vs. distance were obtained during mid-late August 1996 (see Chapter 3, PHYSICAL ACOUSTICS MEASUREMENTS).

On 30 August, based on those new measurements, the safety radius was changed to 250 m when an airgun array was in use, but remained as 150 m during single-airgun operations. Subsequent analysis of the physical acoustics data has confirmed that 250 m is a good estimate of the maximum radius within which the rms pulse level was 190 dB re 1 µPa or higher during airgun array operations. The actual 190 dB radius during single airgun operations was much less than 150 m (see Chapter 3).

When one or more airguns were operating, the observer determined from the distance estimate whether the seal was within, or about to come within, the safety zone (150 m radius up to 30 August; thereafter 150 m for single airgun and 250 m for airgun array, as described above). If the seal was within, or about to be within, the safety zone while airgun(s) were operating, the observer instituted the shutdown provisions described in §2.3. A total of 135 shutdowns were initiated during the 1996 seismic program because of seals sighted within, or about to enter, the safety zone.

Aerial Surveys

Seals were also recorded when seen during the aerial surveys conducted in the 1-21 September 1996 period. Because of weather limitations on some dates, there was aerial survey coverage on 14 days from 3 to 20 September. This included coverage of most or all of the pre-planned survey grid on 9 days and partial coverage on 5 additional days. The survey route and daily coverage are shown in Chapter 5, WHALES. The survey aircraft operated at altitudes of 900 to 1500 ft above sea level (275 to 460 m), as described in Chapter 5.

Ringed seals in the water are very difficult to see from those altitudes, and only a small and highly variable proportion of the numbers present are detectable. Sightability varies drastically depending on sea state, lighting, and ice conditions. Thus, no quantitative data on ringed seals were obtainable from the aerial surveys. However, the results do confirm the well-known common occurrence and widespread distribution of the species in the area. The aerial survey results are believed to be somewhat more meaningful for the larger and easier-to-sight bearded seals.

4.3 Status and Aerial Survey Results

LGL and Greeneridge (1996) include a summary of late summer and autumn sightings and distribution of seals in the Northstar region during the years 1979 to 1995, based on aerial surveys by the Minerals Management Service and its contractors (1979-1995) and by LGL Ltd (1982, 1984-85, 1995). This information is updated here with observations from the 1996 aerial surveys and the combined results are discussed.

Ringed Seal, *Phoca hispida*

Introduction.—Ringed seals are year-round residents in the Beaufort Sea and are the most consistently encountered of the seals in the project area. The estimated population of ringed seals in the Bering-Chukchi-Beaufort area is 1-1.5 million (Kelly 1988; Small and DeMaster 1995), with an estimated 80,000 seals found in the Beaufort Sea during summer and 40,000 during winter (Frost and Lowry 1981). The Alaska stock of ringed seals is not classified as a strategic stock. The worldwide population of ringed seals is estimated at 6-7 million (Stirling and Calvert 1979).

During winter months, the ringed seal occupies the land-fast ice and offshore pack ice of the Bering, Chukchi and Beaufort seas. In winter and spring, the highest densities of ringed seals are found on stable shore-ice. However in some areas where there is limited fast ice but wide expanses of pack ice, including the Beaufort Sea, Chukchi Sea and Baffin Bay, total numbers of ringed seals on pack ice exceed those on shore-fast ice (Burns 1970; Stirling et al. 1982; Finley et al. 1983). Ringed seals maintain breathing holes in the ice by using their claws and maintain lairs in accumulated snow (Smith and Stirling 1975). Ringed seals give birth in these lairs starting in early April and nurse their pups for 4-6 weeks. The highest densities of breeding ringed seals occur in areas of landfast ice. Mating occurs in late April and May.

During summer, ringed seals are found dispersed throughout open water areas, although in some regions they move into coastal areas. In the eastern Beaufort Sea and Amundsen Gulf, ringed seals concentrate in similar offshore areas from one year to the next and are often found in large groups in these areas (Harwood and Stirling 1992). It appears that these concentrations are found in areas of greater food abundance that may be related to oceanographic features. Similar summer concentrations have not been reported in the central and western Beaufort Sea. Ringed seals are significant predators of small fish and zooplankton. The ringed seal is also the principal food of polar bears (Stirling 1974; Kingsley 1990) and is important to other predators such as the arctic fox (Smith 1976).

In addition to local movements in response to seasonal changes in ice conditions, there may be large scale movements of ringed seals into and out of the Beaufort Sea. Smith and

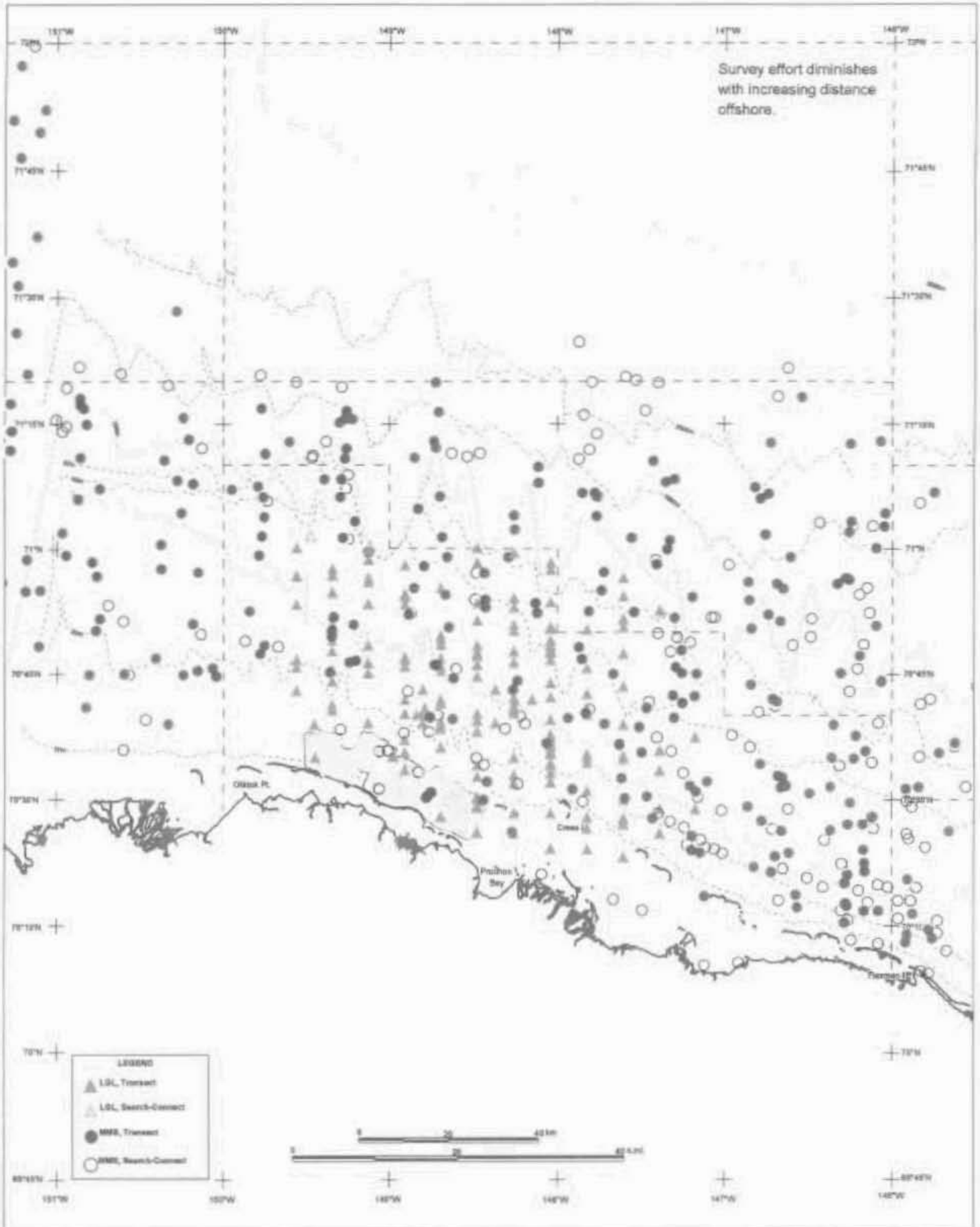

FIGURE 4.1. Ringed seal sightings in the central Alaskan Beaufort Sea during late summer and autumn of 1979-95 based on MMS and LGL aerial surveys. Shaded area is the Northstar area and nearby waters where seismic surveys were done during mid-August through mid-September 1996. See §5.2 for explanation of "Transect" vs. "Search-Connect" sightings. Faint dashed lines show boundaries of MMS survey blocks (see Fig. 5.2 for block numbers).

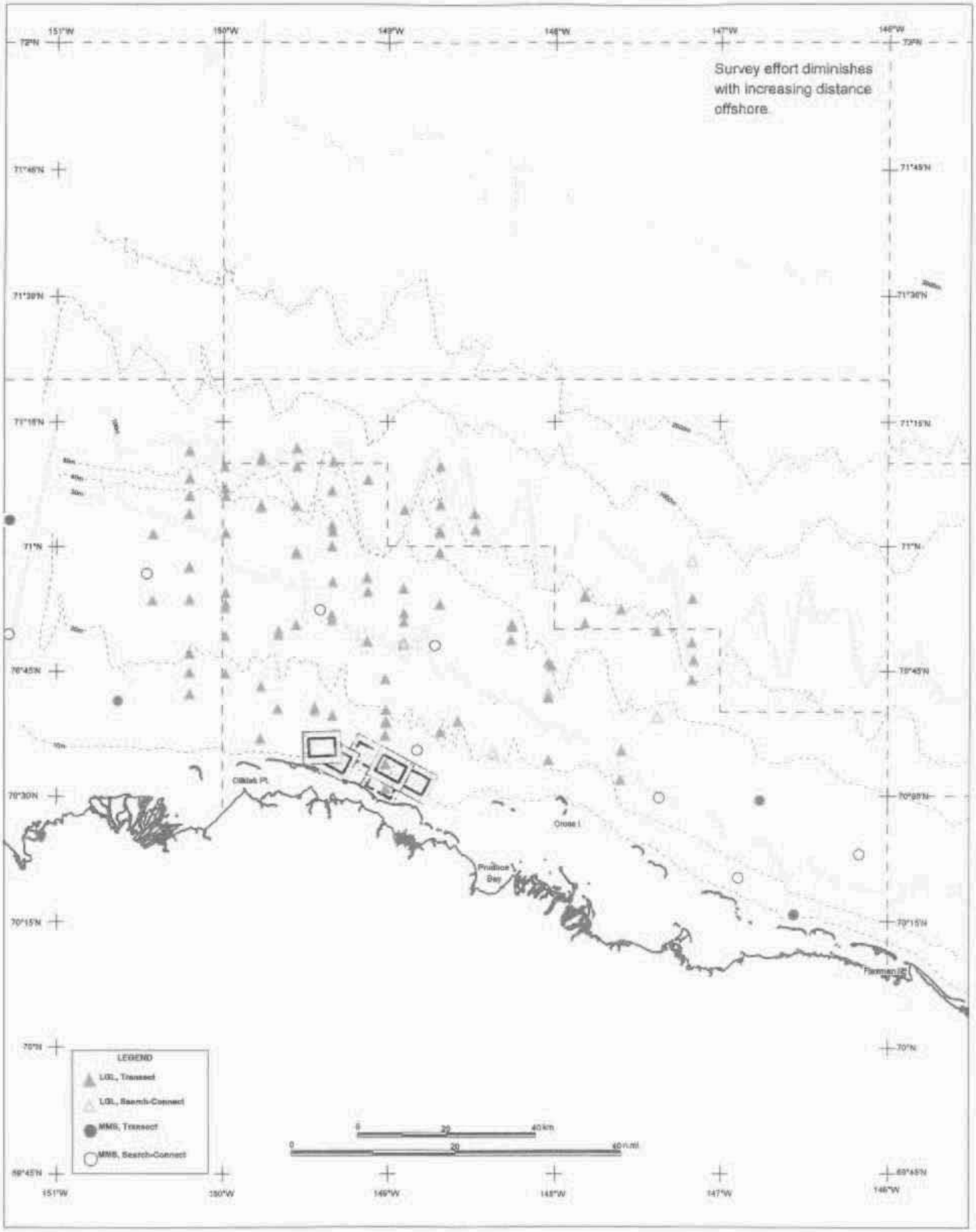

FIGURE 4.2. Ringed seal sightings in the central Alaskan Beaufort Sea during late summer and autumn of 1996 based on MMS and LGL aerial surveys. "Patches" where seismic work was done during the aerial survey period are shown. Otherwise plotted as in Fig. 4.1.

Stirling (1978) described a westward migration of subadult seals in the eastern Beaufort Sea prior to autumn freeze-up and a small number of long distance movements of marked individuals have been documented. However, the nature and extent of these movements are not well understood (Smith 1987; Kelly 1988).

Ringed seal surveys are conducted during late winter and spring; quantitative surveys have not been possible during late summer. Only a very small proportion of the ringed seals present in open water are seen during high-altitude aerial surveys designed to search for whales. Therefore, densities and numbers of this species in the project area during late summer and autumn cannot be estimated based on season-specific data. Densities of ringed seals on shore-fast ice between Lonely and Oliktok points averaged 0.54/km^2 in 1970 (Burns and Harbo 1972) and 0.17 to 0.61/km^2 from 1975 to 1977 in areas without on-ice seismic activity (Burns et al. 1981).

In general, ringed seals are common and widely dispersed within and near the project area at this season.

Aerial Survey Results.—Ringed seal sightings during the MMS and LGL aerial surveys are shown in Figure 4.1 (1979-95) and Figure 4.2 (1996). During late summer and autumn, ringed seals were observed to be widely distributed throughout the central Alaskan Beaufort Sea. However, relatively few were observed in the Northstar seismic area either in 1996 or in earlier years. In general, the aerial surveys suggest that ringed seals tended to prefer waters deeper than about 20 m, i.e. they may prefer waters farther offshore than the Northstar region.

Ringed seals in the water are difficult to detect from the altitudes at which most of the aerial surveys were flown. This is especially true when observers are searching primarily for whales. Ringed seals were undoubtedly much more abundant in the region than the late summer/autumn aerial survey data suggest. Detailed analyses and quantitative interpretations of the aerial survey data are not warranted because of the known serious biases of high-altitude surveys in detecting ringed seals in open water.

Bearded Seal, *Erignathus barbatus*

Introduction.—The Alaska stock of bearded seals, which occupies the Bering, Chukchi, and Beaufort seas off Alaska, may consist of about 300,000-450,000 individuals (MMS 1996). However, Small and DeMaster (1995) indicate that, "Until additional surveys are conducted, reliable estimates of abundance for the Alaska stock of bearded seals are considered unavailable." Nevertheless, the Alaska stock of bearded seals is not classified by NMFS as a strategic stock.

The bearded seal is the largest of the northern phocids. It is primarily a bottom feeder and its preferred habitat is, therefore, areas with water less than 200 m deep. However, bearded seals apparently also feed on ice-associated organisms when they are present; a few bearded seals have been found associated with ice in water depths much greater than 200 m.

Seasonal movements of bearded seals are directly related to the advance and retreat of sea ice and to water depth. During the winter, most bearded seals in Alaskan waters are found in the Bering Sea. In the Chukchi and Beaufort seas, favorable conditions are more limited and consequently bearded seals are less abundant there during the winter (Nelson et al., n.d.). In spring, between mid-April and June, as the ice recedes, seals overwintering in the Bering Sea migrate northward through the Bering Strait. During the summer most are found near the widely fragmented margin of multi-year ice covering the continental shelf of the Chukchi Sea and in nearshore areas of the central and western Beaufort Sea. In Alaska, bearded seals do not use coastal haul outs as bearded seals do in some other parts of their range.

In some areas, bearded seals are associated with the ice year-round; however, because bearded seals are primarily benthic feeders, they usually move into open water areas when the pack ice retreats to areas with water depths greater than 200 m. During the summer, when the Bering Sea is ice-free, the most favorable bearded seal habitat is found in the central or northern Chukchi Sea along the margin of the pack ice. Suitable habitat is limited in the Beaufort Sea, where the continental shelf is comparatively narrow and the pack-ice edge frequently occurs seaward of the shelf and over water too deep for feeding (Nelson et al., n.d.). The preferred habitat in the western and central Beaufort Sea during the open water period is the nearshore area seaward of the scour zone.

Aerial Survey Results.—Few bearded seals were observed in or adjacent to the Northstar seismic area during aerial surveys in late summer and autumn. Bearded seals were, however, widely distributed in the surrounding region (Fig. 4.3, 4.4). Bearded seals were sighted in waters ranging from <10 m (rarely) to >1000 m deep. Although bearded seals are known to prefer relatively shallow waters in which they can feed on benthic organisms, a few of the sightings recorded during the MMS surveys, which ranged farther north than the LGL surveys, were in waters north of the continental shelf. A few MMS sightings of bearded seals in prior years were in waters more than 3000 m deep and at latitudes north of 71°30'N (Fig. 4.3).

During 1996, 35 bearded seal sightings and 39 individuals were recorded during the Northstar aerial surveys done by LGL (Fig. 4.4). No bearded seals were reported during MMS surveys of the corresponding region (146°00'W-150°30'W longitudes) during 1996.

An analysis of 1979-95 bearded seal sighting data from the central Alaskan Beaufort Sea showed that sightings of bearded seals declined steadily as the late summer/autumn season progressed. The average sighting rate was 0.27 sightings per 100 km of survey in the 16-31 August period, 0.10 and 0.09 per 100 km during the first and last halves of September, and 0.05 and 0.04 per 100 km during the first and last halves of October (LGL and Greeneridge 1996). Some portion of the bearded seals that inhabit the Alaskan Beaufort Sea during the summer migrate into the Bering Sea to spend the winter months.

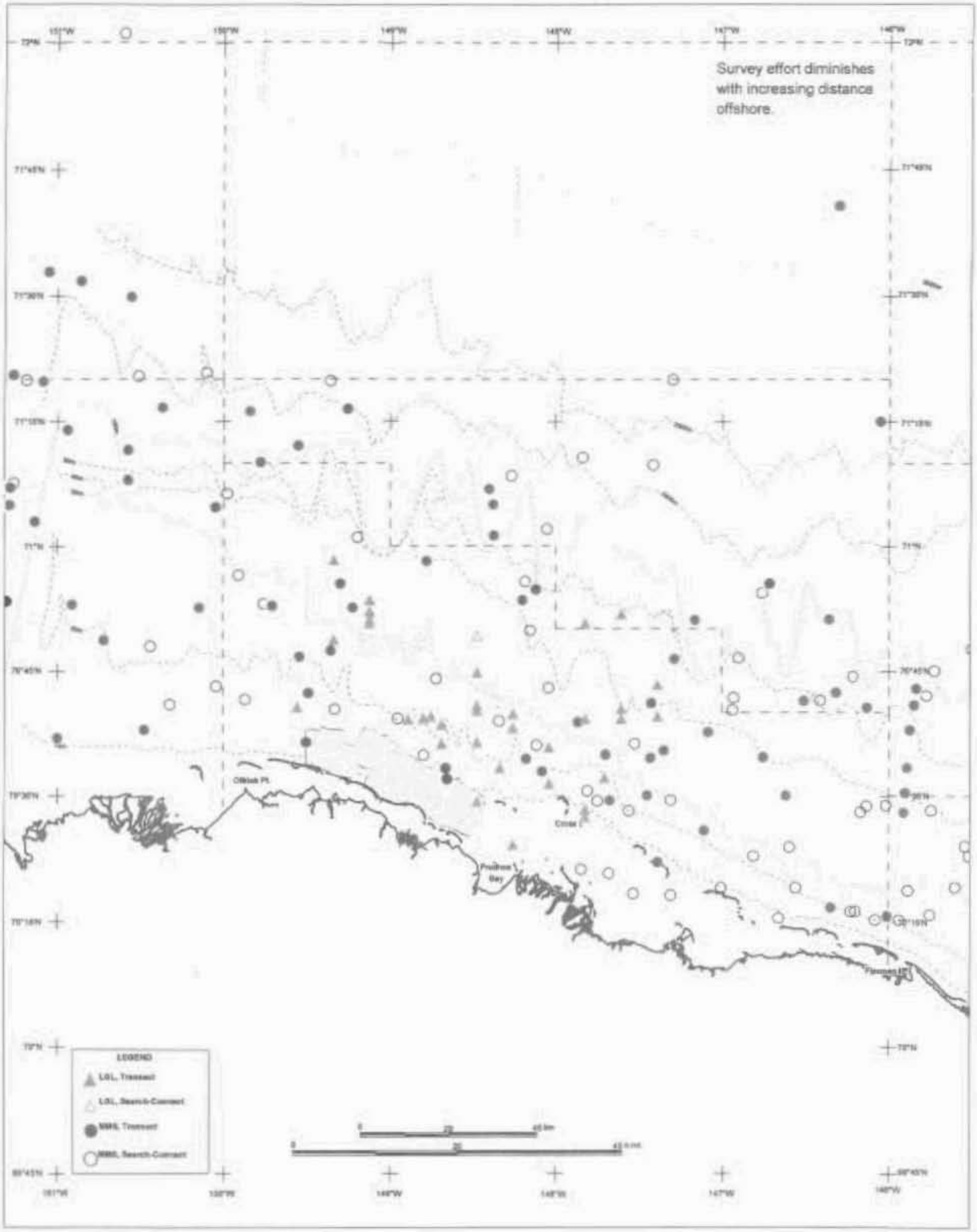

FIGURE 4.3. Bearded seal sightings in the central Alaskan Beaufort Sea during late summer and autumn of 1979-95 based on MMS and LGL aerial surveys. Plotted as in Fig. 4.1.

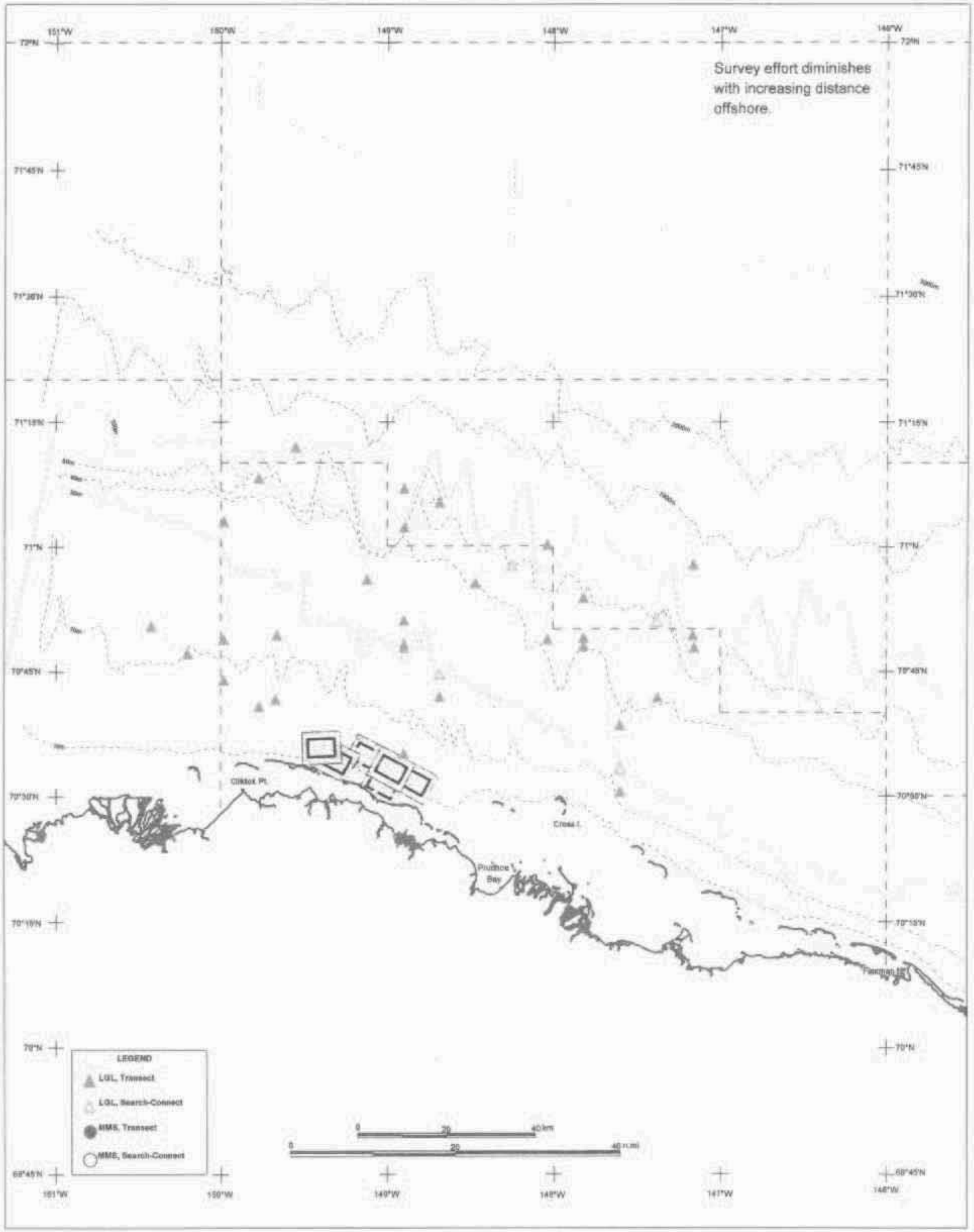

FIGURE 4.4. Bearded seal sightings in the central Alaskan Beaufort Sea during late summer and autumn of 1996 based on MMS and LGL aerial surveys. "Patches" where seismic work was done during the aerial survey period are shown. Otherwise plotted as in Fig. 4.1.

Spotted Seal, *Phoca largha*

Introduction.—An early estimate of the size of the world population of spotted seals was 370,000-420,000, and the size of the Bering Sea population, including animals in Russian waters, was estimated to be 200,000-250,000 animals (Bigg 1981). A reliable estimate of the size of the entire Alaska stock is currently not available because of incomplete sampling (Small and DeMaster 1995). Nevertheless, the Alaska stock of spotted seals is not classified as a strategic stock by NMFS (Small and DeMaster 1995).

During spring, when pupping, breeding, and molting occur, spotted seals are found along the southern edge of the sea ice in the Okhotsk and Bering seas. In late April and early May, adult spotted seals are often seen on the ice in female-pup or male-female pairs. Subadults may be seen in larger groups of up to two hundred animals. During the summer, spotted seals are found primarily in the Bering and Chukchi seas, but some range into the Beaufort and perhaps into the East Siberian seas (Lowry, n.d.). At this time of year, an unknown proportion haul out on mainland beaches and offshore islands and bars (Frost et al. 1993). Recent tagging studies during summer at Kasegaluk Lagoon, in the Chukchi Sea, indicate that spotted seals may travel long distances offshore to feed, and that a very small proportion (<10%) may be hauled out at any one time (Frost et al. 1993). In summer, they are rarely seen on the pack ice, except when the ice is very near to shore. The seals are commonly seen in bays, lagoons and estuaries. As the ice cover thickens with the onset of winter, spotted seals leave the northern portions of their range and move into the Bering Sea.

A few spotted seal haul-outs occur in the central Beaufort Sea in the deltas of the Colville and (at least formerly) the Sagavanirktok rivers. Historically these sites supported as many as 400-600 seals, but in recent times <10 seals have been seen at any one site (J.W. Helmericks, pers. comm.; S.R. Johnson, LGL Ltd., unpubl. data). In total, there are probably no more than a few tens of spotted seals along the coast of the central Beaufort Sea during summer and early fall.

Aerial Survey Results.—Spotted seals were not identified during MMS and LGL aerial surveys of the central Alaskan Beaufort Sea during the late summers and autumns of 1979-96. However, three spotted seals were identified during boat-based monitoring (see below).

4.4 Boat-Based Monitoring Results

Survey Effort

Marine mammal observers were on watch during all periods with airgun operations, and during many periods when the source vessel was underway but not shooting seismic. The numbers of hours of observation varied throughout the study period accordingly. Watches were conducted during daylight and, later in the season when there was overnight darkness, during the night as well. The hours of survey effort, categorized by week, seismic category, and darkness vs. daylight, are summarized in Table 4.1. The hours of survey effort shown

TABLE 4.1. Survey effort: the numbers of hours of observation from the source vessel by marine mammal observers. Effort is categorized by week, seismic category, and darkness vs. daylight periods. Hours of survey effort during seismic activity also are the total hours of all seismic activity as observers were on watch during all periods of seismic activity. "Partial Array" = 2-7 guns firing; "Full Array" = 8-11 guns firing.

	HOURS OF OBSERVATION									
SEISMIC STATE	Week 1 Jy 24 - Jy 27	Week 2 Jy 28 - Au 3	Week 3 Au 4 - Au 10	Week 4 Au 11 - Au 17	Week 5 Au 18 - Au 24	Week 6 Au 25 - Au 31	Week 7 Se 1 - Se 7	Week 8 Se 8 - Se 14	Week 9 Se 15 - Se 18	TOTAL
DARKNESS										
No Guns	0.0	0.0	0.0	4.2	11.2	4.5	8.1	7.4	2.3	37.8
Single Gun	0.0	0.0	0.0	1.4	2.2	0.7	0.6	5.1	0.0	9.9
Partial Array	0.0	0.0	0.0	0.7	1.6	1.6	1.2	3.7	5.7	14.4
Full Array	0.0	0.0	0.0	2.4	9.3	7.1	10.4	20.3	14.1	63.6
Ramp Up	0.0	0.0	0.0	0.0	0.5	0.7	0.5	1.7	1.4	4.8
Testing	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.9	0.1	3.2
Total	0.0	0.0	0.0	8.7	26.9	14.5	20.9	39.2	23.5	133.7
DAYLIGHT										
No Guns	27.5	38.9	26.0	56.4	48.2	14.0	13.8	29.0	8.6	262.3
Single Gun	2.6	27.9	30.8	17.6	7.1	0.1	4.8	4.3	0.0	95.3
Partial Array	0.4	15.5	24.4	11.6	4.3	2.6	2.8	2.0	8.4	72.0
Full Array	4.7	59.3	61.6	35.9	26.3	14.3	15.6	34.4	17.2	269.2
Ramp Up	0.0	1.9	3.5	5.1	4.4	1.7	1.4	5.2	3.5	26.7
Testing	4.8	7.9	3.6	3.7	3.5	1.2	0.2	1.1	0.3	26.3
Total	40.1	151.4	149.9	130.2	93.8	33.8	38.6	76.0	38.0	751.9
ALL										
No Guns	27.5	38.9	26.0	60.6	59.4	18.4	21.9	36.4	10.9	300.1
Single Gun	2.6	27.9	30.8	18.9	9.3	0.8	5.5	9.4	0.0	105.2
Partial Array	0.4	15.5	24.4	12.3	5.9	4.2	4.0	5.7	14.1	86.5
Full Array	4.7	59.3	61.6	38.3	35.6	21.4	26.0	54.7	31.3	332.8
Ramp Up	0.0	1.9	3.5	5.1	4.9	2.4	1.9	6.9	4.9	31.5
Testing	4.8	7.9	3.6	3.7	5.6	1.2	0.2	2.1	0.4	29.4
Grand Total	40.1	151.4	149.9	138.9	120.7	48.4	59.5	115.2	61.6	885.6

in Table 4.1 were used to calculate the numbers of seals observed per hour in the "Species and Numbers Observed" section that follows.

Total hours of observation were 885.6. Most watches were conducted during daylight (751.9 h daylight vs. 133.7 h darkness), and the majority of the watches were during periods of airgun operations (585.5 h with airgun(s) vs. 300.1 h without). Approximately 83% (738.1 h) of the survey effort occurred while the source vessel was firing either the full array (8-11 guns, 332.8 h, 37.6%), not firing any guns (300.1 h, 33.9%), or firing a single gun (105.2 h, 11.9%). In most cases, operation of the full array occurred while shooting production lines, and operation of a single gun occurred while conducting Ocean Bottom Receiver Localization (OBRL). OBRL was done to determine the precise locations of receiver cables (see §2.2). Relatively little time was spent firing a partial array (2-7 guns), ramping up, or testing the guns.

Survey effort varied markedly from week to week, depending primarily on the effect that sea state and ice conditions had on the seismic contractor's ability to conduct the seismic work. Weeks 2 through 5, and 8, were the busiest. Together they accounted for 676.1 of the 885.6 hours of observation, or 76.3%. During late August and early September, seismic activity was limited because of frequent high sea states and large broken floes of ice that were blown into the study area. No watches were done when the source vessel was not underway.

Detection of Seals

Seals were first seen at estimated radial distances from the vessel of 2 m to 1491 m. However, most seals were first sighted within a radial distance of 250 m of the source vessel (Fig. 4.5). Only 70 (18.4%) of the 381 sightings during daylight surveys were beyond 250 m. During airgun operations, seals were first seen as close as 12 m (ramp up), 16 m (full array), 20 m (single gun), and 30 m (partial array), as measured from the wheelhouse. Seals were often seen just ahead of or alongside the source vessel. However, when airguns were in operation, seals were not seen in the area ~30 m behind the wheelhouse, where the airgun(s) were located (see Fig. 4.7B,C, later).

The detectability of seals from the source vessel undoubtedly varied with several factors, including primarily glare, sea state, and ice cover. Observers also tended to concentrate on searching for seals within or near the limit of the safety zone (initially 150 m, then expanded to 250 m on 30 August). Nevertheless, it is apparent that observers did not detect seals as effectively beyond 250 m. Also, the observers apparently missed many seals within 250 m. One indication of this is that the numbers of initial sightings in the various 50-m annuli out to 250 m were generally similar even though the areas of those annuli increased with increasing radial distance (see Fig. 4.9, below, for additional information on sightability vs. distance).

Species and Numbers Observed

A total of 422 seals were seen by the marine mammal observers on board the source vessel during the 1996 field season. Of these seals, 421 were seen during daylight. Only one seal was seen during the 133.7 hours of nighttime observations.

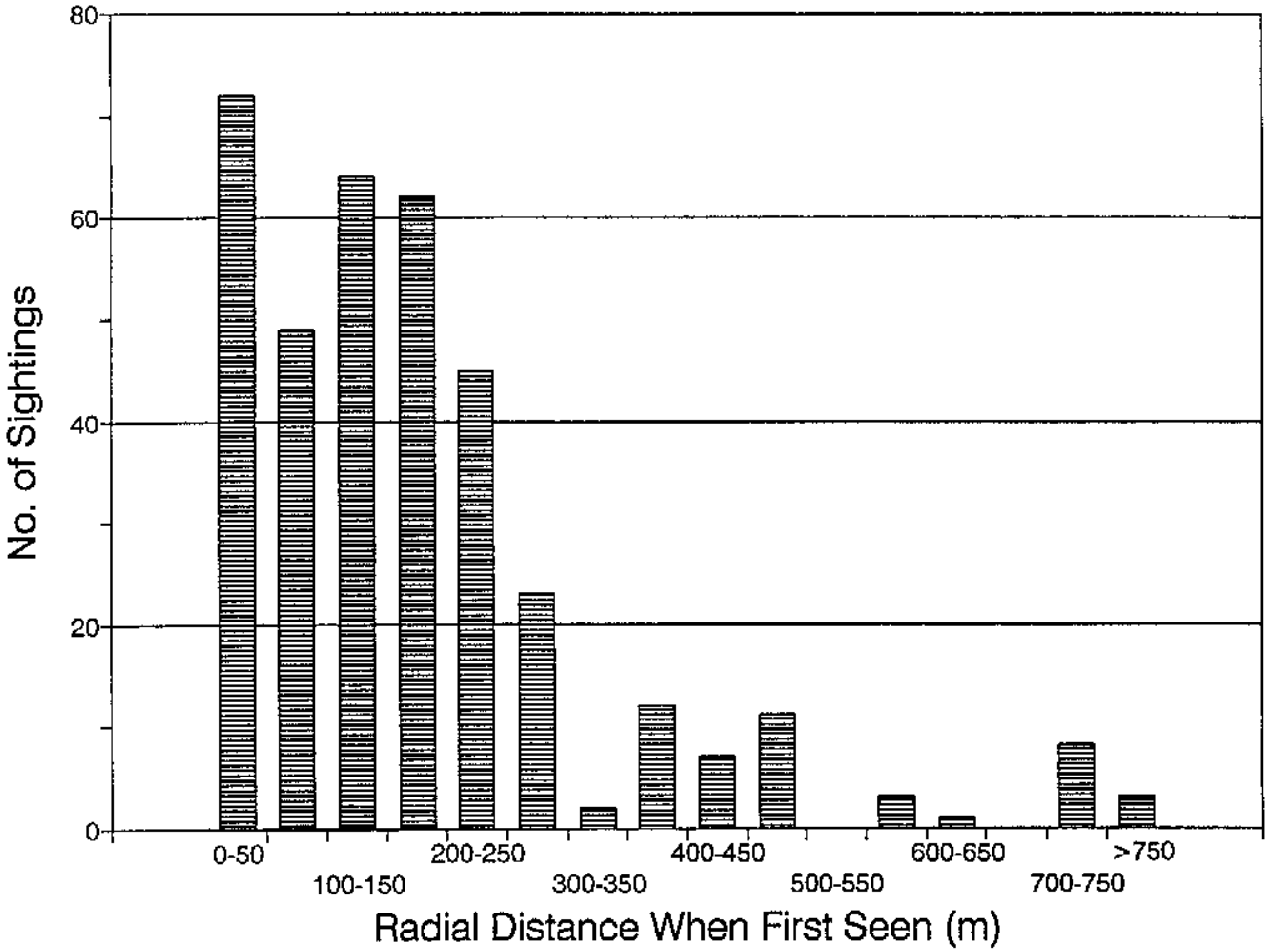

FIGURE 4.5. Numbers of seal sightings during daylight by 50 m radial distance intervals from the source vessel. Seals that were first seen in one distance interval were often seen subsequently at other distances, but only the first sighting is counted here.

The breakdown by species is presented in Table 4.2. That table also shows, for each category of seismic operations, the species breakdown as percentages of all identified seals seen. Of the 331 seals that were identified (78.4% of the total seals seen), almost 92% were ringed seals. Very few bearded seals (24; 7.3%) and even fewer spotted seals (3; 0.9%) were identified. One walrus and four polar bears also were seen (see Appendix 1). Observers on the source vessel did not see any whales.

Sighting Rates and Distances

Table 4.3 and Figure 4.6 summarize the data regarding the 421 seals that were observed in different seismic states and at different distances from the source vessel during daylight surveys. The six seismic states are no guns, single gun, partial array (2-7 guns), full array (8-11 guns), ramp-up, and seismic testing. Distances were categorized as <150 m, 150 to 250 m, and >250 m from the source vessel, corresponding to the safety zones identified in the IHA for seals. To compare appropriately the numbers of seals that were encountered during different seismic states, the data were standardized to numbers of seals observed per hour of daylight survey effort in each seismic state.

Distances from the source vessel were not determined for 20 seals. These seals are included in the "Total" bars on Figure 4.6. Consequently the "Total" bars sometimes show more seals than are represented in the three known distance categories. This is most evident with respect to the full array data (8-11 guns); distances were not determined for 17 seals in this seismic category (Table 4.3).

The largest numbers of seals were observed during full-array seismic, no-seismic, and single-gun seismic periods. Likewise, the largest numbers of hours of daylight observations were during those three seismic categories (Table 4.3). Consequently, the discussion that follows focuses on these categories. Less time was spent conducting partial-array and ramp-up seismic, and relatively few seals were observed during those conditions. No seals were observed during seismic testing—the least frequent category of operation (Table 4.3).

Numbers Seen With vs. Without Seismic.—The total numbers of seals seen during daylight periods were 164 under no-seismic conditions, 57 when a single airgun was in use, 17 when a partial array (2-7 airguns) was operating, 168 when the full array (8-11 airguns) was operating, and 15 during ramp-up. The breakdown by distance categories is given in Table 4.3 and is further described in §4.5, "Estimated Take". The one seal seen during periods of darkness was sighted within 150 m of the source vessel during full-array seismic. It is not included in the following discussion.

Overall, seals were observed at nearly identical rates during periods with no guns firing (0.63 seals/h), one gun firing (0.60/h), and a full array (0.63/h; Fig. 4.6). These were the three common seismic categories. Slightly more seals were seen per hour without seismic (0.63/h) than with all seismic categories combined (0.53/h). This difference was a result of the low sighting rate during the limited amount of seismic work with a partial array (Fig. 4.6).

TABLE 4.2. Numbers and species of seals observed from the source vessel in different seismic states, with percentages relative to the total of all identified seals in that seismic category. Only one of these seals, a ringed seal under full array, was observed during darkness. "Partial Array" = 2-7 guns; "Full Array" = 8-11 guns.

	NUMBERS OF SEALS									
		Identified		Ringed Seal		Bearded Seal		Spotted Seal		Unidentified Seal
SEISMIC STATE	Total	#	%	#	%	#	%	#	%	#
No Guns	164	136	82.9%	121	89.0%	15	11.0%	0	0.0%	28
Single Gun	57	47	82.5%	44	93.6%	3	6.4%	0	0.0%	10
Partial Array	17	12	70.6%	11	91.7%	0	0.0%	1	8.3%	5
Full Array	169	129	76.3%	121	93.8%	6	4.7%	2	1.6%	40
Ramp-Up	15	7	46.7%	7	100.0%	0	0.0%	0	0.0%	8
Seismic Testing	0									
TOTALS	422	331	78.4%	304	91.8%	24	7.3%	3	0.9%	91
Within safety radius*	160	133	83.1%	127	95.4%	5	3.8%	1	0.8%	27

* This includes all seals within 150 m of the source vessel during single gun seismic, and all seals within 250 m during partial- or full-array seismic (including ramp up). See Table 4.3 and Section 4.5 Estimated Take.

TABLE 4.3. Numbers of seals, and numbers of seals per hour of daylight observation, observed from the source vessel in different seismic states and at different distances. Only seals seen during daylight are included here.*
"Partial Array" = 2-7 guns; "Full Array" = 8-11 guns.

		NUMBERS OF SEALS								
	# Hours Daylight	Total*		<150 m		150-250 m		>250 m		Distance Not Determined
SEISMIC STATE	Observation	#	#/hr	#	#/hr	#	#/hr	#	#/hr	#
No Guns	262.3	164	0.63	97	0.37	40	0.15	25	0.10	2
Single Gun	95.3	57	0.60	32	0.34	18	0.19	7	0.07	0
Partial Array	72.1	17	0.24	7	0.10	4	0.06	6	0.08	0
Full Array	269.2	168	0.63	55	0.21	50	0.19	46	0.17	17
Ramp-Up	26.7	15	0.56	6	0.22	6	0.22	2	0.07	1
Seismic Testing	26.3	0	0.00							
TOTALS	751.9	421	0.56	197	0.26	118	0.16	86	0.11	20

* A total of 422 seals was seen; 421 during daylight plus one at night. The nighttime seal sighting is not included here.

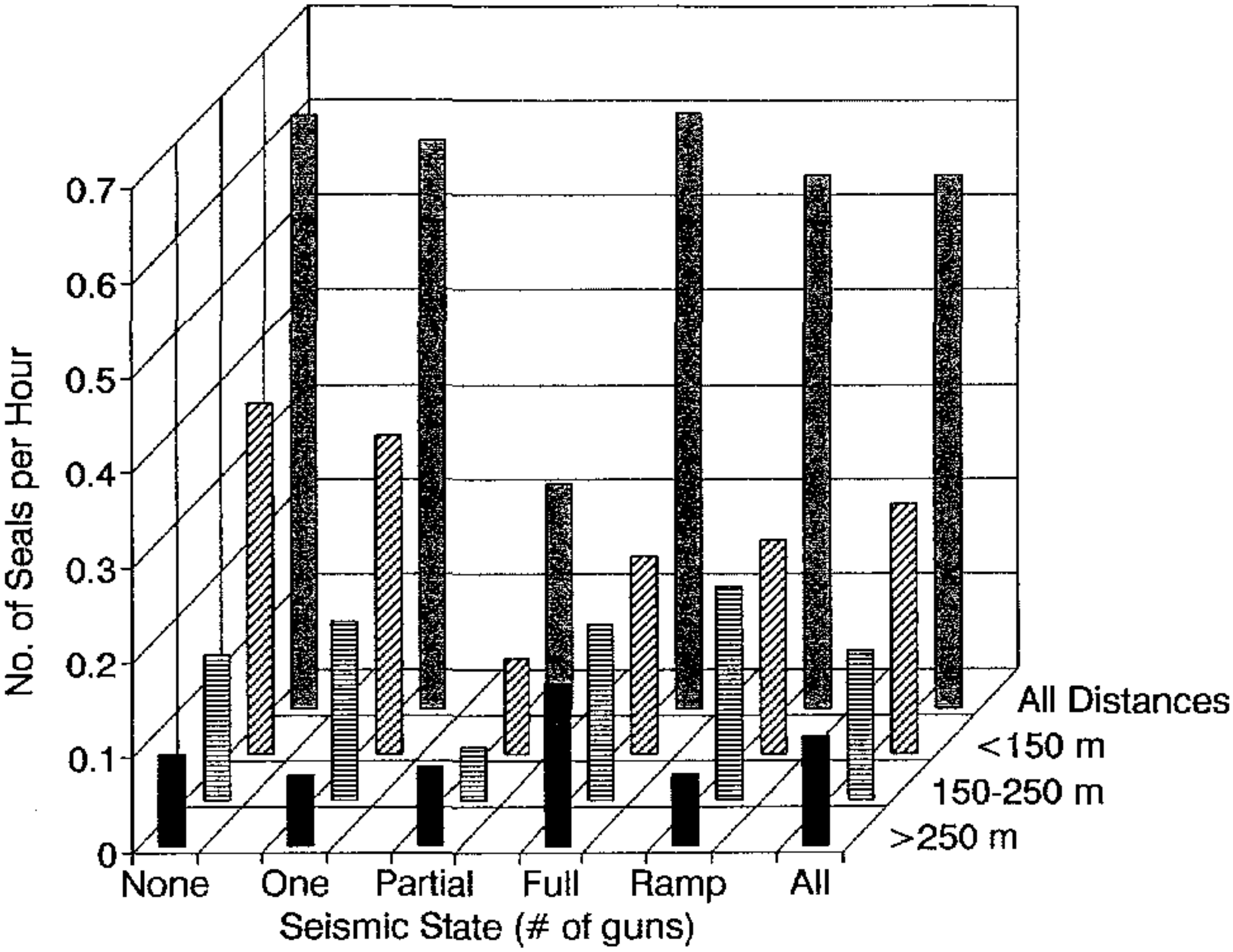

FIGURE 4.6 Numbers of seals observed from the source vessel, per hour of daylight observation, in different seismic states and at different distances from the source vessel. The "All Distances" category includes seals at known and undetermined distances; see Table 4.3 for details. None = no airguns; One = single airgun; Partial = 2-7 airguns; Full = 8-11 airguns; Ramp = ramp-up (increasing number of airguns over time).

Numbers vs. Distance, With vs. Without Seismic.—Did seismic state have any effect on the distances at which seals were first seen? If seals avoided the vessel during some or all types of airgun operations, the relative numbers seen in the various distance categories would be expected to differ among seismic states. Note that the areas under observation in the three distance categories are not equal, and that sightability decreases with increasing distance. Thus, comparisons of sighting rates in "seals per hour" must be done with caution, emphasizing relative sighting rates and distribution patterns rather than absolute numbers.

Within 150 m of the source vessel, where airgun noise was the strongest, seals were encountered most frequently during periods without seismic (0.37 seals/h). The number of seals seen per hour in the <150 m distance category was only slightly lower during single-gun seismic (0.34/h), but was notably lower during full-array seismic (0.21/h; Fig. 4.6). Conversely, the sighting rates in the >250 m category were lower with no seismic (0.10/h) or single-gun seismic (0.07/h) than with full array seismic (0.17/h; Fig. 4.6).

Although the overall sighting rate with full array seismic (0.63 seals/h) was similar to overall rates with no seismic (0.63/h) and single gun seismic (0.60), the pattern by distance category was not. With full (and partial) array seismic, sighting rates on a "seals per hour" basis were similar in the three distance categories. In contrast, with no seismic or single-gun seismic, sighting rates diminished with increasing distance (Fig. 4.6; Table 4.3). In other words, seals were encountered relatively more frequently at distances >250 m during full-array seismic.[3] Overall, the distance distributions of seals (Fig. 4.6; Table 4.3) and of seal sightings during single-gun seismic and no seismic were similar (Mann-Whitney U=4451, n= 56, 161 sightings, P>0.5). In contrast, the distribution of sighting distances during full-array seismic was very different than that for no seismic (U=8408, n=150, 161 sightings, P<0.001).

These results suggest that seals showed some tendency to avoid at least the zone closest to the boat (<150 m) during full-array seismic. The same was probably true during partial-array seismic, but the sample size was low. There was no such indication during single-gun seismic. The simplest explanation of the observations is that, as the seismic boat approached the seals while operating the full and probably the partial array, seals tended to move out of the <150 m distance zone and into the >250 m distance zone. However, they apparently did not move much beyond 250 m, as the observers rarely detected seals beyond 400-500 m, and the overall sighting rate was the same (0.63/h) with full-array seismic as with no seismic.

Overall, vessel-based observers saw seals at nearly identical rates regardless of whether no guns, a single gun, or 8-11 guns (full array) were firing. As would be expected, seals were seen most often close to the boat, and less often at greater distances. However, with full-array seismic, seals were encountered less frequently within 150 m of the source vessel and more frequently at distances between 250 m and the limits of vision, generally near 500 m for most seals. This suggests that, during operation of the full airgun array, some seals had

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[3] This would hold true even if all 17 seals seen at undetermined distances were actually in the <150 m category (55 + 17 = 72; 72/269.2 h = 0.27 seals/h; see Table 4.3).

a tendency to avoid the source vessel, possibly combined with a tendency to spend more time at the surface at the longer distances.

Distribution Around Source Boat, With vs. Without Seismic

The bearings of seal sightings around the source vessel under different seismic conditions, and overall, are shown in Table 4.4 and Figure 4.7. Positions were obtained for 238 of the 381 sightings made during daylight surveys. For the other 143 daylight sightings, bearing and/or radial distance were not recorded and thus locations could not be derived.

The recorded distributions in part reflect the data collection methods. Most sightings were recorded as being on lines radiating from the source vessel at 30-degree (occasionally 45°) intervals (Fig. 4.7). The bearing data were collected as "hours of the clock" relative to the vessel's bow. A seal seen 60° from the bow and to starboard was recorded as being at 2 o'clock. Seals on bearings from 45° to 75° to starboard were almost all recorded as being at 2 o'clock (i.e., most bearings were recorded by 30° category). Similarly (though less obviously in Figure 4.7), many radial distances, and especially the longer distances, also were grouped at the distances corresponding to the reticle markings on the binoculars. However, these measurements were made the same way for each seismic state and thus still allow meaningful comparisons.

Overall, the majority of initial sightings were made in front of, and to the sides of, the source vessel (Fig. 4.7D). Fewer initial sightings were made behind the bow of the source boat. This pattern reflects the fact that the marine mammal observers spent more time trying to detect seals that were ahead of the boat, as one of the observers' primary duties was to shut the airguns down when mammals about to enter the safety zone were sighted.

When no guns were firing, the sightings were distributed almost symmetrically around the source vessel, although the distance distributions on various bearings varied somewhat (Table 4.4, Fig. 4.7A). Overall, about 85% of the initial sightings when no guns were firing were to the front and sides of the source boat ("9 through 3 o'clock"). Nearly 14% were directly in front of the boat (12 o'clock); 26.5% were to the port front (10 to 11 o'clock); another 26.5% were to the starboard front (1 to 2 o'clock); and 9% and 10% were directly to the port and starboard sides respectively (9 and 3 o'clock). Fewer seals were sighted behind the source vessel (15% of sightings; Table 4.4).

The distribution of initial sightings under full-array seismic also was concentrated in front of and to the sides of the source vessel, and also was nearly symmetrical (Table 4.4, Fig. 4.7C). In comparison with the no-gun distribution, the percentage of the initial sightings made between 9 o'clock and 3 o'clock was only slightly greater with full-array seismic (89% vs. 85%; $\chi^2=0.38$, df=1, $P>0.5$). During full-array seismic, there were slightly more initial sightings to starboard (1- through 5 o'clock) than to port (7- through 11 o'clock; 43.5% vs. 36.5%), but again the difference was not statistically significant ($\chi^2=0.53$, df=1, $P>0.25$). The radial plots also show a greater dispersion in initial sighting distances during full-array periods than when no guns were firing (Fig. 4.7C vs. A), as shown previously.