NORTHSTAR MARINE MAMMAL MONITORING PROGRAM, 1996:

Marine Mammal and Acoustical Monitoring of a Seismic Program in the Alaskan Beaufort Sea

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National Marine Fisheries Service
Anchorage, AK, and Silver Spring, MD

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1. INTRODUCTION[1]

BP Exploration (Alaska) Inc. (BPXA) conducted an open-water seismic program in shallow waters of the central Alaskan Beaufort Sea during the 24 July through 19 September period of 1996. This region is occupied by ringed and bearded seals throughout the open water period, and small numbers of spotted seals also occur in the area. Bowhead and beluga whales migrate westward through the region in late summer and autumn, although their main migration corridors are offshore of the area of seismic exploration. Gray whales occur in the area only on rare occasions (LGL and Greeneridge 1996a).

Marine mammals might be disturbed by underwater sounds from the seismic exploration program. Bowhead whales usually show avoidance reactions to seismic vessels operating within several kilometers (Richardson et al. 1986; Ljungblad et al. 1988). Reaction distances may (or may not) be different for whales migrating past a relatively localized seismic operation like Northstar than in the circumstances previously studied. Previous monitoring studies have provided inconclusive results concerning avoidance at longer distances. However, there have been indications that some bowheads may show avoidance at distances as great as 24 km (Koski and Johnson 1987). Subtle behavioral reactions are suspected to extend to even longer ranges (Richardson et al. 1986; Richardson and Malme 1993). Reactions of gray whales to seismic exploration are similar (Malme et al. 1984, 1988). There are few published data on the reactions of either toothed whales or pinnipeds to open-water seismic exploration. However, given what is known about the hearing abilities of belugas and seals, they are expected to be able to hear seismic sounds, and may react to them (Richardson et al. 1995; Richardson and Würsig in press).

Inupiat whalers are especially concerned that seismic programs may displace some bowhead whales farther offshore, making them less accessible to hunters (Jolles [ed.] 1995; Rexford 1996). Based on their accumulated observations and experience, the Inupiat whalers also believe that whales exposed to seismic and other industrial noises are more "skittish" and difficult to hunt. These concerns were emphasized at a workshop entitled "Arctic Seismic Synthesis and Mitigating Measures Workshop", held in Barrow, AK, on 5-6 March 1997. Inupiat whalers believe that, during autumn migration, bowhead whales migrating west though the Alaskan Beaufort Sea can be displaced northward by as much as 30 miles from their normal migration corridor (Kanayurak et al. 1997).

One of the dominant considerations during the design of this monitoring project was the need to determine, insofar as possible, whether displacement of the bowhead migration corridor occurred during the Northstar seismic program. This study was designed to take into account both the results of previous scientific studies and the accumulated experience of the Inupiat whalers, both of which are useful in formulating hypotheses and study designs.

Whether seismic exploration sounds are strong enough to cause temporary or permanent hearing impairment in any marine mammals that might occur very close to the seismic source is unknown (Richardson et al. 1995:366). In part to avoid any such possibility, the

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National Marine Fisheries Service (NMFS) has concluded that baleen whales should not be exposed to seismic pulses with received levels above 180 dB re 1 μPa, and that pinnipeds and odontocetes should not be exposed to levels above 190 dB re 1 μPa (NMFS 1995).

1.1 Incidental Harassment Authorization

Behavioral disturbance to marine mammals is considered to be "take by harassment" under the provisions of the Marine Mammal Protection Act (MMPA). Such disturbance falls within the MMPA definition of Level B harassment, which entails "disruption of behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering". "Taking" of marine mammals without special authorization is prohibited. However, under the 1994 amendments to the MMPA and regulations finalized in 1996, "citizens of the United States can apply for an authorization to take incidentally, but not intentionally, small numbers of marine mammals by harassment" (NMFS 1996). Incidental Harassment Authorizations (IHAs) can be issued if the "taking will have a negligible impact on the species or stock(s) of marine mammals and will not have an unmitigable adverse impact on the availability of the species or stock(s) for subsistence uses". IHAs can authorize Level B harassment (disturbance). Because of the possibility that the planned Northstar seismic program might disturb marine mammals, BPXA applied in March 1996 for an Incidental Harassment Authorization to cover the 1996 Northstar seismic project.

The IHA process does not authorize injurious or lethal takes of marine mammals. To minimize the possibility that marine mammals close to the seismic source might be exposed to levels of sound high enough to cause hearing damage or other injuries, the IHA application included proposals for a marine mammal monitoring program and for shutdown of the seismic source when mammals were seen within designated "safety radii". BPXA's application for an IHA proposed to shut down the airguns if seals were detected within 150 m, or if cetaceans were detected within 650 m. The rationale is described under "Shutdown Criteria" on page 2-14. The IHA application also included provision to measure actual sound levels vs. distance prior to the start of the whale migration season. This would allow the "shutdown radii" to be adjusted, if appropriate.

A draft monitoring plan prepared by LGL Ltd. and Greeneridge Sciences Inc. for BPXA was submitted to NMFS in March 1996 with the IHA application. The proposed monitoring program was reviewed by NMFS, by representatives of the subsistence hunters in northern Alaska, and by outside experts during the spring of 1996. An amended monitoring plan was prepared in June 1996 taking these comments into account. In addition, a "Conflict Avoidance Agreement" was negotiated between BPXA, the Alaska Eskimo Whaling Commission, and the Whaling Captains' Associations of the villages of Nuiqsut and Kaktovik. On 18 July 1996, NMFS issued an Incidental Harassment Authorization to BPXA for the 1996 Northstar open-water seismic program.

The IHA (as amended) required submission of a preliminary report on sound measurements prior to 1 September 1996, a report on the results of the monitoring work within 90 days after the end of the field program, and a draft final report by 1 April 1997. The preliminary sound measurement report was submitted to NMFS on 30 August. Based on those measurements, it was agreed by BPXA and NMFS that the pinniped and cetacean "safety radii" applicable to the array of airguns should be increased from 150 and 650 m, respectively, to 250 and 750 m. This change was implemented on 30 August.

1.2 Objectives

Three different but related sets of objectives have been specified for this monitoring project. (1) The monitoring plan identified a set of field tasks that needed to be met. (2) A meeting of a peer review group in Seattle on 21 May 1996 identified eight analytical objectives that should be addressed. (3) The Incidental Harassment Authorization issued by NMFS identified various reporting requirements.

Field Tasks Identified in Monitoring Plan

The tasks to be addressed by the 1996 Northstar marine mammal monitoring program, as listed in the final monitoring plan dated 11 June 1996, were as follows:

- provide qualified marine mammal observers for the seismic source boat(s) throughout the seismic exploration period in 1996, to monitor the occurrence and behavior of marine mammals near the seismic source during daytime and nighttime periods when it is and is not operating, fulfilling the monitoring and mitigation conditions of the IHA and other permits; night vision devices would be used at night;
- conduct an aerial monitoring program from 1 September 1996 until seismic work ends to monitor the distribution, movements and general activities of bowheads and other marine mammals in and near the Northstar Unit;
- exchange 1996 aerial survey data with MMS, as agreed between BPXA and MMS;
- conduct a vessel-based acoustics program for ~10 days in late August 1996 to obtain systematic measurements of seismic sounds, propagation loss, and ambient noise;
- drop sonobuoys during the aerial survey program after 1 September to collect data on (a) ambient noise and (b) seismic exploration noise. Sonobuoys would provide noise data at more places and times, and under more environmental conditions, than possible from the vessel, including ambient and seismic data from bowhead locations;
- deploy bottom-mounted acoustic recording devices at several locations east of and offshore of the Northstar region to obtain near-continuous records of underwater noise and whale calls in those areas from 1 September to the end of the seismic program (or until ice precludes data retrieval);
- update the 1995 evaluation of marine mammal use of the area [LGL and Greeneridge 1996a] to take account of the BPXA/LGL and MMS visual and acoustic results from 1996, and evaluate the effects of the 1996 seismic program on the distribution and movements of bowhead whales;
- prepare the "90 day report" on the monitoring and estimated "take by harassment", and a subsequent comprehensive report on all aspects of the 1996 work.

All of the general field objectives were met in whole or in part.

Analysis Objectives Identified by Peer Review Group

Eight analysis objectives were identified at a meeting held in Seattle on 21 May 1996 to review the draft monitoring plan:

a. "Estimate the proportion of the bowhead whales (and other marine mammals) that migrate past the Northstar study site within 20 nm of the northern edge of the site when the air guns are in operation." [Results are in section 5.3.8, "Estimated Bowhead Take by Harassment".]

b. "Estimate the number of other marine mammals within 20 nm of the northern edge of the study site when the air guns are in operation." [For belugas, see §5.5.]

c. "Estimate the number of baleen whales within 2130 ft of the sound source when the air guns are in operation." [See §5.3.8.]

d. "Estimate the number of other marine mammals within 500 ft of the sound source during seismic operations." [For seals, see §4.5.]

e. "Estimate the distribution of observed distances between the (closest) active seismic vessel and bowhead whales seen on effort during the aerial survey." [See §5.3.2, "Distribution" and Table 5.3.]

f. "Test the hypothesis that the distribution of bowhead whales (and other marine mammals) is independent of the estimated received sound level produced by all of the vessels associated with the Northstar study." [See §5.3.3, "Distance from Shore".]

g. "Test the hypothesis that the swimming direction of bowhead whales is independent of the estimated received sound level produced by all of the vessels associated with the Northstar study." [See §5.3.4, "Behavior and Headings".]

h. "Test the hypothesis that vocalization rates of bowhead whales are independent of the estimated received sound level produced by all vessels associated with the Northstar study (using some type of remote data collection system)." [See §3.8, "Whale Calls" and §5.3.6, "Bowhead Call Counts".]

Reporting Requirements Specified in the IHA

The Incidental Harassment Authorization issued by NMFS on 18 July 1996 included the following requirements for the "90 day report" and final report:

1. Dates of the seismic survey from start to termination. [See Chapter 2.]
2. Specifications of the survey including, but not limited to, a description of the seismic array, total power output, number and length of seismic track lines, number of seismic vessels (if more than one at one time), etc. [See Chapter 2.]
3. Results of the vessel monitoring program, including: (a) Information on the numbers (by species) of marine mammals observed during the survey; (b) the estimated number of marine mammals (by species) that may have been harassed as a result of the seismic array either through noted behavioral change or because the animal was within its designated zone of potential harassment (bowhead, gray and beluga

whales—160 dB isopleth; seals—190 dB); (c) marine mammal behavior patterns observed within the 160 dB isopleth whenever the seismic source is off (speed, direction, submergence time, respiration, etc.); and (d) any behavioral responses or modifications of these behavioral indicators due either to the seismic array's or vessel's noise. [See Chapters 4 and 5.]

4. Aerial survey data from the BPXA and MMS surveys in and near the Northstar Unit must be analyzed and summarized for bowhead distribution, movement patterns (spatial and temporal), abundance indices and estimated numbers in the area during 1996. [These data are] to be compared with data collected previously. [See §5.3.2, "Bowhead Whale/Distribution".]
5. Results of any research conducted on the effects of seismic airgun noise on marine mammals, including any measurements made of attenuation rates. [Acoustic data are in Chapter 3.]

1.3 Report Organization

The present document constitutes the final technical report on the monitoring work. It is an expanded version of the "90 day report" submitted to NMFS, the Alaska Eskimo Whaling Commission (AEWC) and the North Slope Borough (NSB) in December 1996 (LGL and Greeneridge 1996b). This final report contains additional data and updated analyses. It takes account of comments from the AEWC and the NSB concerning the "90 day report". It also takes account of comments received from NMFS, AEWC, NSB and MMS at a review meeting held in Seattle on 16-17 July 1997. This final report supersedes the "90 day report".

The present report includes four main chapters describing the following:

- the 1996 Northstar open-water seismic program (Chapter 2);
- the physical acoustics measurement program (Chapter 3);
- the results of monitoring for seals, and the estimated numbers of seals "taken by harassment" (Chapter 4); and
- the results of monitoring for whales, and the estimated numbers of whales "taken by harassment" (Chapter 5).

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2. SEISMIC PROGRAM DESCRIBED[1]

2.1 Introduction

The Northstar seismic program in 1996 consisted of an Ocean Bottom Cable (OBC) seismic survey in nearshore waters of the central Alaskan Beaufort Sea. This work was conducted from 24 July through 19 September 1996 with an airgun array consisting of eleven 120 in^3 Bolt airguns totalling 1320 in^3 when all guns were used. Testing of the airgun array began on 24 July; production operations began on 27 July and continued until deteriorating ice and weather conditions forced an end to airgun operations on 18 September. Most work was conducted in and near the Northstar region, including waters from Prudhoe Bay West Dock out to about 45 km northwest of West Dock, and from the barrier islands out to as much as 13 km offshore of the barrier islands (depths up to about 55 ft or 17 m; see Fig. 2.2-2.5, later). However, initial work from 24 July until 8 August 1996 was east of Prudhoe Bay in waters east of the Endicott Development (depths 10-25 ft or 3-8 m).

This project was different from previous open-water seismic programs in the Beaufort Sea in that the Ocean Bottom Cable (OBC) method was employed. The area to be surveyed was divided into patches, each approximately 5.9 km by 4.0 km in size. Within each patch, six receiving cables were placed on the bottom parallel to one another. Seismic data for each patch were acquired by towing the airgun array along a series of 27 source lines, each 7.3 km long, oriented perpendicular to the receiving cables. While seismic data acquisition was underway on one patch, the cable deployment vessels normally were laying cables in the patch that was to be surveyed next, and/or in retrieving cables from the patch where surveys had just been completed. During the 1996 program, seismic data were acquired from all or parts of 16 patches: four patches east of Endicott and 12 patches in or near Northstar.

Overall, a total of about 2946 km of production seismic survey was shot. Of this, 1135 km was shot during the period 1-18 September when it was likely that bowhead whales would be in the area. This production shooting occupied an estimated total of 355 hours, of which 126 h were in September. Also, a single 120 in^3 airgun was used for an additional 98 h and 834 km, of which only 9 h and 77 km were in September; this single-gun work was done to calibrate the locations of receiving cables. Finally, one or more airguns were operated during many line changes. Line changes occupied 164 h, of which 42 h were in September.

Marine mammal monitoring personnel were aboard the source vessel throughout the period of operations. They watched for marine mammals at all times (day and night) while airguns were operated, and helped implement the provisions of the Incidental Harassment Authorization (IHA) that had been issued to BPXA by the National Marine Fisheries Service (NMFS). They also conducted watches during selected periods when the airguns were not firing. A large number of seals, but no whales, were seen from the source vessel. When seals

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were seen within the "safety radius" specified in the IHA, the airguns were immediately shut down. As described on page 1-2, the designated safety radius for seals was 150 m up to 30 August. Based on sound propagation measurements done at Northstar during August (see Chapter 3) and on discussions with NMFS, the safety radius for seals was increased—effective on 30 August—to 250 m for times when >1 airgun was in use. The safety radius remained 150 m during single-airgun operations.

The following subsection provides additional details about the equipment used for the seismic program and its mode of operation, insofar as these are relevant to marine mammal monitoring and mitigation. A subsequent subsection summarizes the marine mammal monitoring and mitigation procedures. Measurements of the underwater sounds propagating horizontally from the seismic operation are given in Chapter 3 on PHYSICAL ACOUSTICS MEASUREMENTS. Results of marine mammal monitoring and estimates of numbers of marine mammals "taken by harassment" are given in Chapters 4 and 5 on SEALS and WHALES, respectively.

A variety of metric and non-metric measurement units are used in this Chapter. Metric units are usually used for distances, but maps also show a nautical mile scale. Non-metric units are used if they were referenced in the associated study objective. Non-metric units are also used when they are the units usually used in describing equipment or procedures.

2.2 Equipment and Operations

Vessels Used

The vessels used for the 1996 Northstar OBC program were the following:

Source vessel	*Point Barrow* 32 x 90 ft Point Class tugboat, used to tow airgun array; also the platform from which vessel-based marine mammal observers watched for marine mammals. *Point Barrow* had 8-10 ft draft and two Caterpillar 3512 diesel engines totaling 2100 hp, each engine driving a 4-bladed stainless steel propeller in a Kort nozzle. Three 8000 lb compressors provided compressed air for the airgun array.
Telemetry/Camp Barge	R/V *Arctic Endeavor* 90 x 210 ft ice-resistant barge with 78-person camp; data from the OBCs were received and recorded here. Anchored in or near patches where work was underway; periodically moved to new work area by tug. Had four generators with Caterpillar D-353 engines rated at 350 kW each; two generators were normally in operation.

Cable barge	Barge 216 60 x 200 ft deck cargo barge; primary platform for cable deployment and retrieval; carried spill response trailer, 25 kW generator; pushed by tug *Sag River.*
Support tug	*Sag River* 27 x 64 ft Lighter Class tug, used to move the cable barge (Barge 216). Powered by three D-343 Caterpillar diesels totaling 1095 hp, with each engine driving a four-bladed stainless steel propeller; no nozzles. Draft 3-5 ft.
Cable tug	*Toolik River* 27 x 64 ft Lighter Class Tug, used from 6 September onward for cable deployment and retrieval. Specifications same as for *Sag River*.
Crane barge	Barge 215 60 x 200 ft deck cargo barge; Manitowoc 4600 S-4 350 ton crane.
Battery/cable handling	*Peregrine Falcon* 17 x 72 ft jet-driven aluminum landing craft; used to deploy, retrieve and charge 250-lb batteries; assisted in cable deployment and interconnection. Powered by three Cummings diesels, 300 hp each, driving Kodiak model 403 jets. Draft 28 inches.
Sea taxi/Acoustic research	*La Brisa* 14 x 59.5 ft jet-driven charter vessel; used for crew changes, support of boat-based acoustic measurements, and (in September) deployment of Digicourse system to determine locations of OBCs. Powered by three Volvo Pinta diesels of 380 hp each, driving Doran 13 inch jets. Draft 3 ft; 5000 lb crane; 12 kW diesel electric generator.
Cable LCM-6	*Faraday* 14 x 56 ft landing craft; supplementary cable deployment/ retrieval vessel; used early in the season.
Source LCM-6	*Hippo* 14 x 56 ft landing craft; intended as supplementary source vessel, but not used.

Ocean Bottom Cables

For each patch, the cable layout consisted of six 5.9-km cables laid parallel to one another with spacing of 660 m. In most patches the cables were oriented 300°-120° True (Fig. 2.1). Receiving hydrophones were attached at frequent intervals along the cables. Cables were deployed or retrieved by Barge 216, LCM *Faraday*, or tug *Toolik River* as the vessel moved along the desired line. *Peregrine Falcon* was used to deploy and retrieve the required

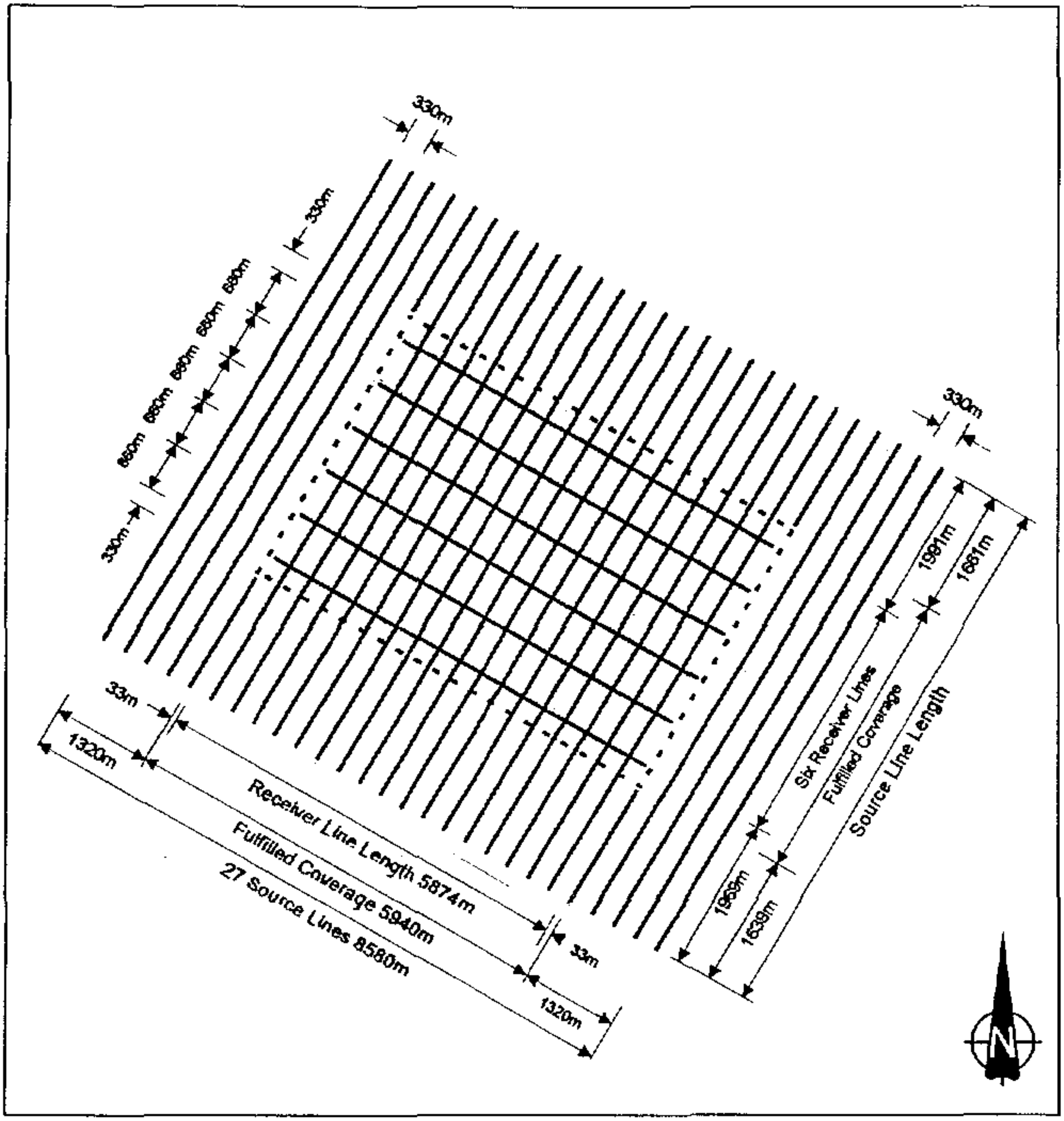

FIGURE 2.1. Configuration of the 27 source lines and 6 receiver cables for a standard patch during the 1996 Northstar OBC seismic survey. The dashed rectangle shows the outline of one patch (5.9 x 4.0 km). The 27 source lines cover an area of 8.6 x 7.3 km. Source lines for each patch extend into adjoining patches. The source lines are oriented 030°-210° True; the receiver cables are oriented 300°-120° True.

batteries, and to establish necessary electrical connections. Data received by the hydrophones were transferred to the telemetry barge (*Arctic Endeavor*) for recording.

Source Vessel

The tug *Point Barrow* was used as the source vessel throughout the program. For each patch, it operated along a series of 27 source lines oriented perpendicular to the OBC receiving cables. As the cables were usually oriented 300°-120° True, most source lines were oriented 210°-030° True. The standard length of each source line was 7.3 km, and the lines were spaced 330 m apart to cover a total area of 7.3 km by 8.6 km approximately centered on the grid of receiving cables (Fig. 2.1).

The *Point Barrow* towed an airgun array system consisting of 11 Bolt 1900LX airguns, each of 120 in^3, usually firing every 44 meters (166 shots per 7.3 km source line). All of the active guns were fired simultaneously. The *Point Barrow* typically travelled at about 4 to 5 knots, covering a 7.3-km source line in just under one hour with the interval between shots usually being 15-18 seconds. During the initial several days of the program, shots were fired every 22 m (331 shots per 7.3 km source line), but the speed of the vessel was generally lower.

Production operations between 27 July and 18 September 1996 totalled 2946 km and 355 hours, of which 1135 km and 126 hours were during September. These figures do not include line changes.

Line changes required widely varying amounts of time, depending on whether lines were shot in order, and whether pauses for maintenance, crew changes, or other activities were necessary. A subset of the airguns, usually 4 to 6, sometimes continued to fire during line changes in order to avoid the need for gradual "ramping up" to full power at the start of the next line (see Mitigation, below) and/or for operational purposes. Line change operations totalled 164 hours (42 h in September); this includes the extended periods when other activities were done during line changes. At those times, shooting was often interrupted.

The characteristics of the airgun array are described in more detail in Chapter 3 on PHYSICAL ACOUSTICS MEASUREMENTS (§3.3).

Ocean Bottom Receiver Localization (OBRL)

One of the methods used to verify the exact positions of the receiver cables on the ocean bottom entailed the use of a single airgun for Ocean Bottom Receiver Localization (OBRL). OBRL was done by traveling along each side of each receiver line at an offset distance of about 150 m while firing one airgun, normally at intervals of 22 m (about one shot every 8 s). Up to 12 OBRL lines (two per cable) were run per patch, generally while the patch was being laid out and before the start of production shooting with the full airgun array. Later in the season, there was increasing reliance on alternative methods of position-finding. OBRL was done on 17 dates in late July and August, but on only two dates in September (1 and 9 September). OBRL shooting totalled 834 km and 98 hours (not counting line changes), of which 77 km and 9 hours were in September.

Interruptions by Ice and Weather

Drifting ice caused considerable complications in deploying and retrieving cables, and sometimes damaged cables that were on the bottom. Late in the season, newly-forming ice caused further difficulties. The presence of ice strongly affected where operations were possible on any given date, and sometimes interrupted the program. There were four periods when heavy seas or ice (sometimes combined with other problems) resulted in suspension of airgun operations for extended periods:

- from 19 August (afternoon) to 22 August (early morning);
- from 25 August (evening) to 30 August (evening), except for some test shooting the afternoon of 29 August;
- from 1 September (mid-day) to 3 September (early morning); and
- from 4 September (late afternoon) to 9 September (early morning).

Cable laying and/or cable retrieval continued during some of these times. There were many shorter periods when airgun operations were interrupted because of weather, ice, or operational considerations.

Navigation and Vessel Movements

Locations of all primary vessels were determined within an accuracy of a few meters by Differential GPS receivers. These locations were transmitted by telemetry to the telemetry barge (*Arctic Endeavor*). A real-time map display of vessel locations and other relevant data was used to assist in managing the operations. Positions of the source vessel and airgun array were logged for every airgun shot, along with water depth and other information about the shot. In addition, at most times during the season, positions of all vessels were logged in digital files every 5 minutes to allow retrospective mapping of vessel movements.

Prior to 8 August, operations were centered east of Prudhoe Bay. From 8 August onward, operations were northwest of Prudhoe Bay. Within the latter period and area, operations moved generally westward as the season progressed. Figures 2.2 and 2.3 show the movements of the airgun source vessel and other project vessels during the middle part of the seismic program, from 15 to 31 August. Within this period, movements during different weeks are shown with different colors. Figures 2.4 and 2.5 show similar data for September. The maps of source vessel movements show all positions logged for *Pt. Barrow*, including times when the airguns were and were not operating. For example, the airguns were not operating when *Pt. Barrow* was used for an ice reconnaissance to the northeast on 7 September (Fig. 2.4). In general, the airgun array was in use whenever *Pt. Barrow* was traveling NNE-SSW or N-S along grid lines. A single airgun was in use for OBRL when *Pt. Barrow* was traveling WNW-ESE along grid lines.

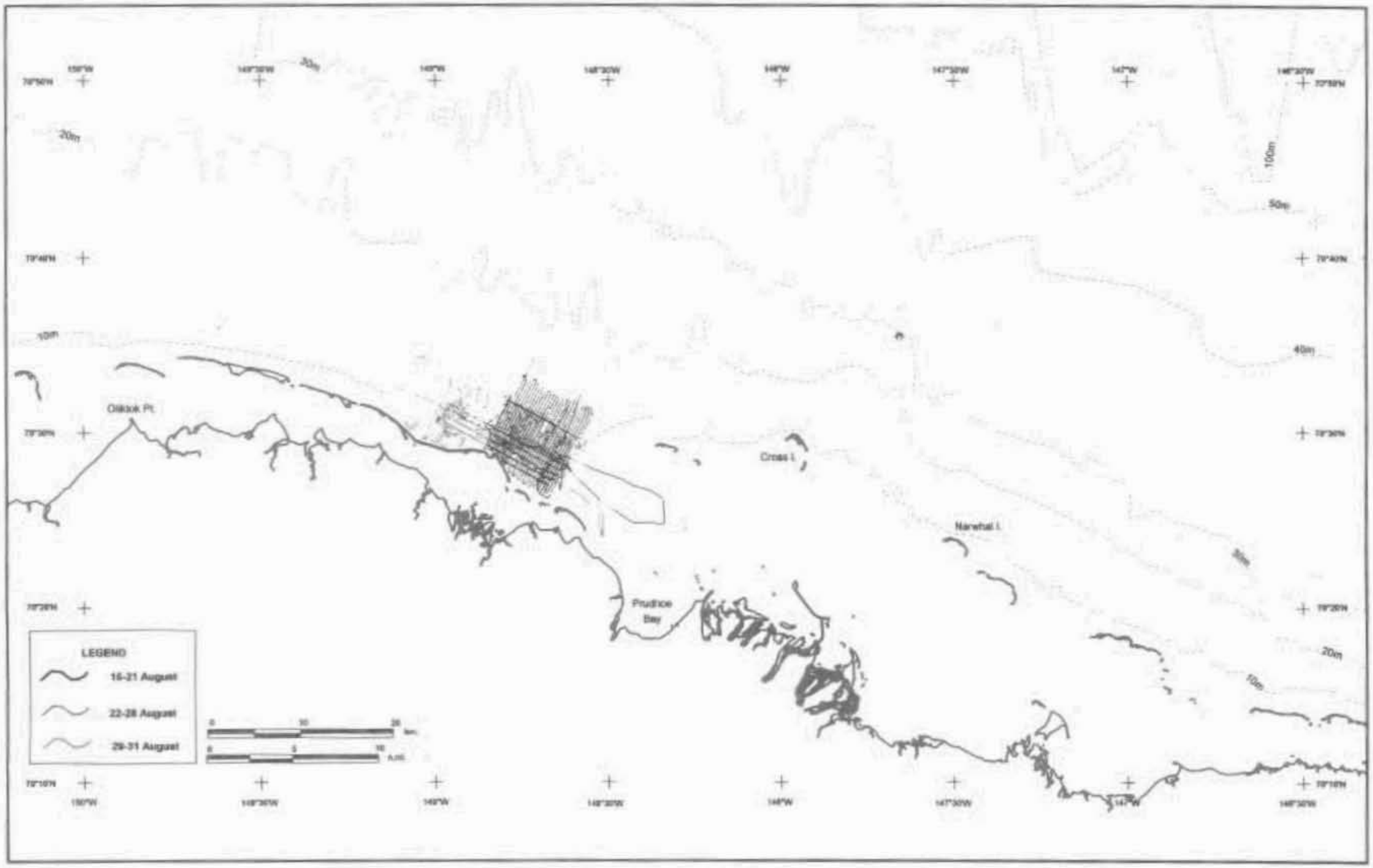

FIGURE 2.2. Movements of the seismic source vessel *Point Barrow* during the period 15-31 August 1996. Colors distinguish different weeks. See Figure 2.3 for movements of other vessels involved in the seismic operation during this period.

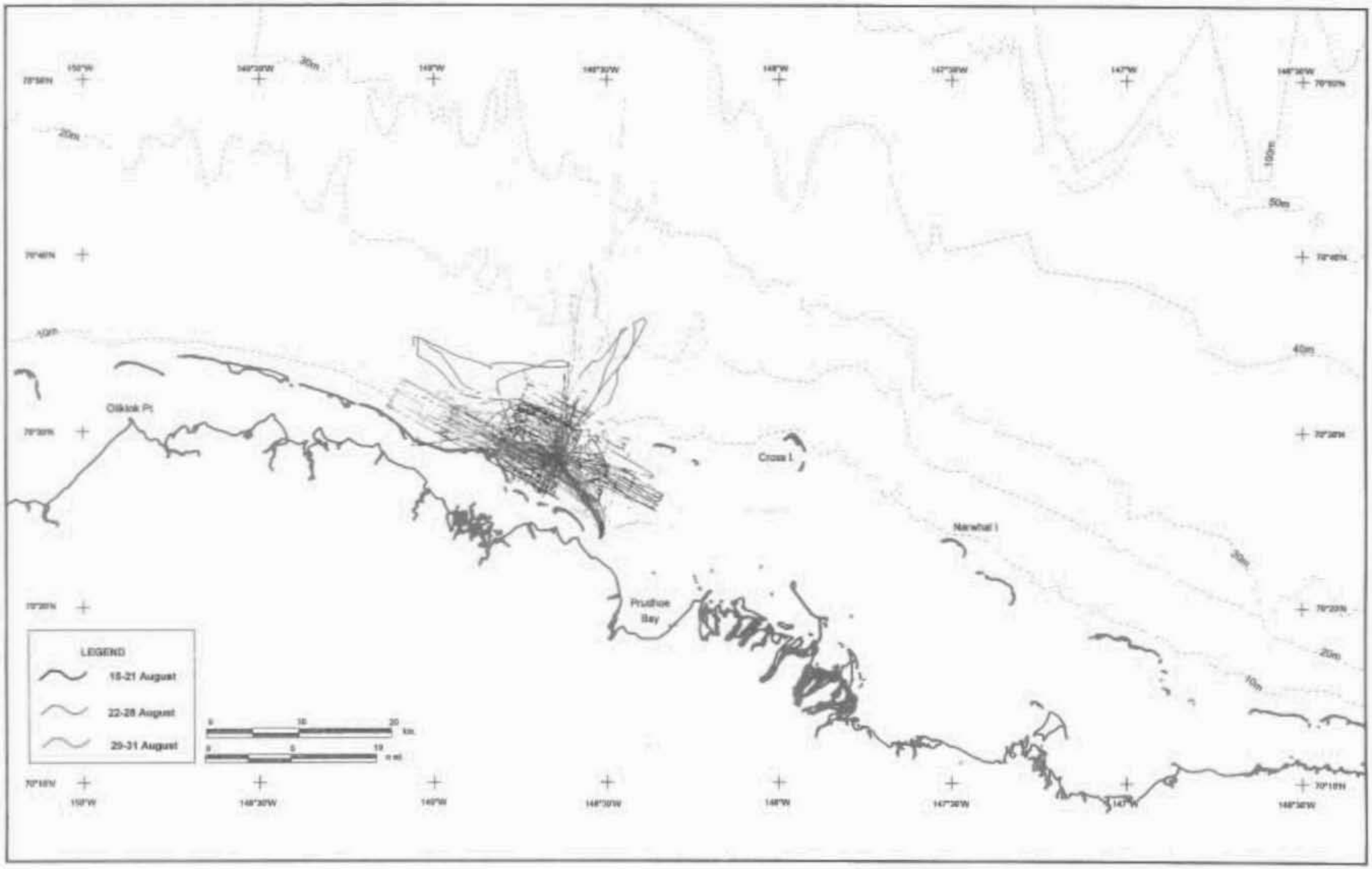

FIGURE 2.3. Movements of vessels involved in the Northstar OBC seismic operation, excluding the source vessel *Point Barrow*, during the period 15-31 August 1996. Colors distinguish different weeks. See Figure 2.2 for movements of the source vessel during this period.

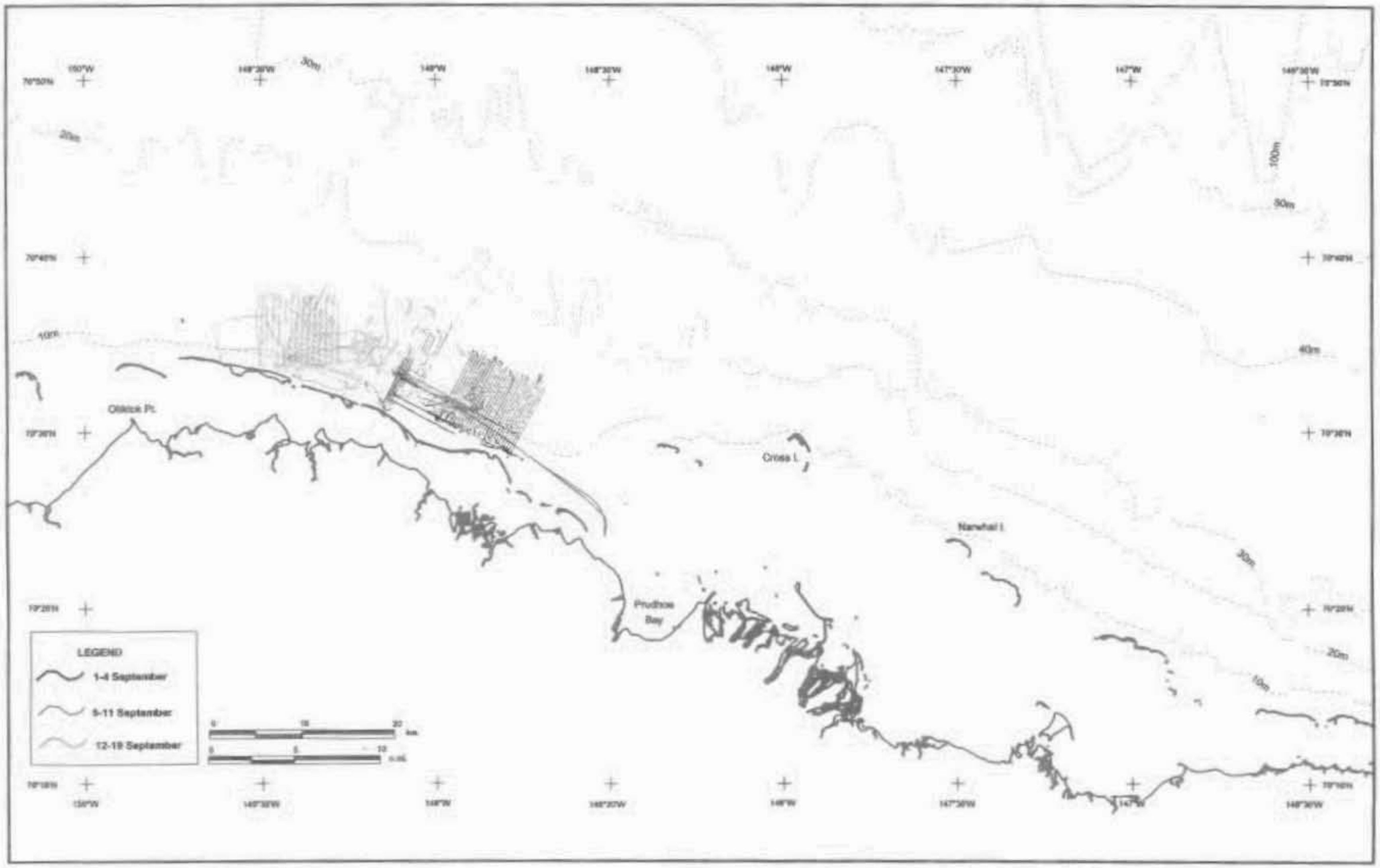

FIGURE 2.4. Movements of the seismic source vessel *Point Barrow* during the period 1-19 September 1996. Colors distinguish different weeks. See Figure 2.5 for movements of other vessels involved in the seismic operation during this period.

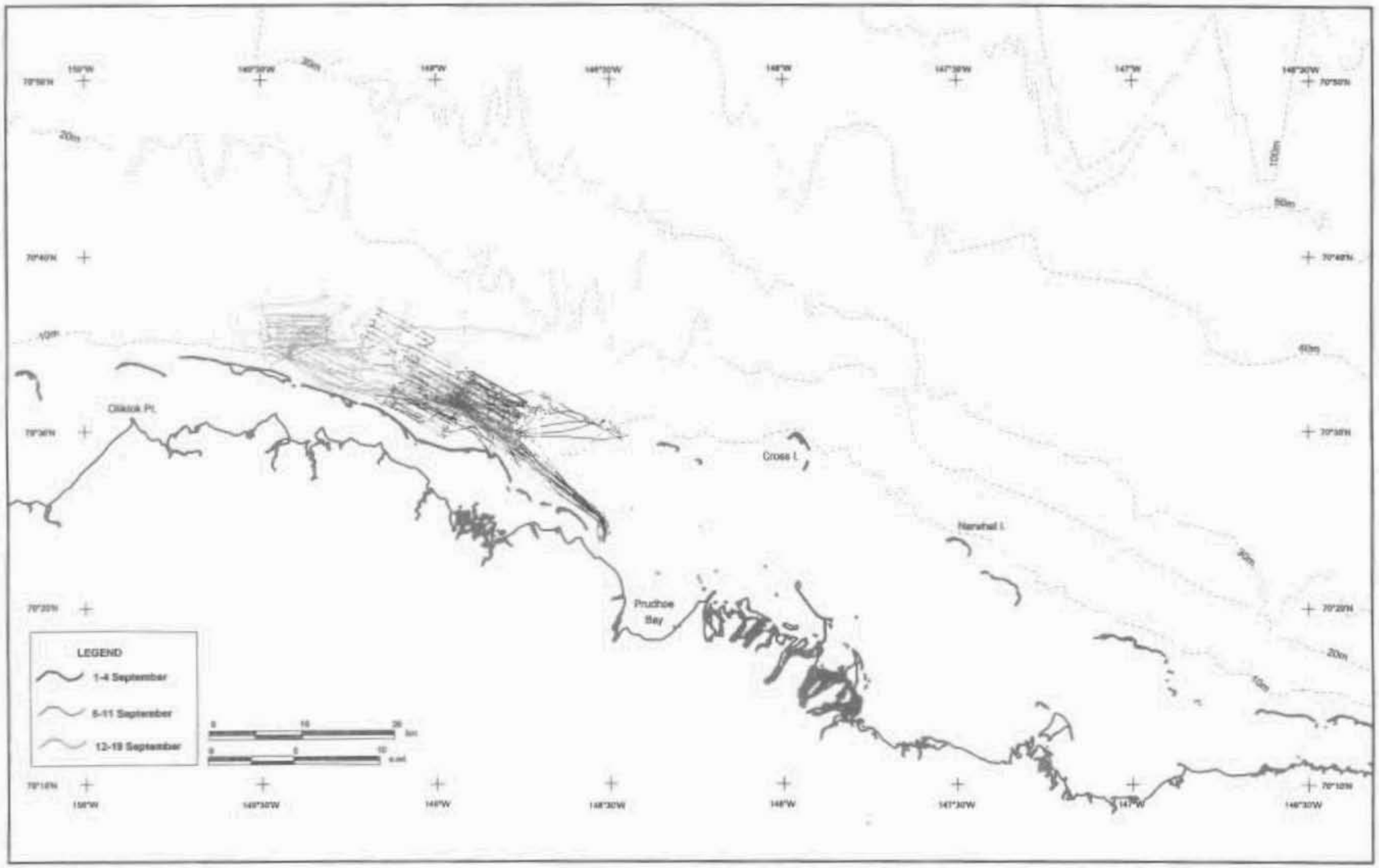

FIGURE 2.5. Movements of vessels involved in the Northstar OBC seismic operation, excluding the source vessel *Point Barrow*, during the period 1-19 September 1996. Colors distinguish different weeks. See Figure 2.4 for movements of the source vessel during this period.

There are some gaps in the automatically-logged files of vessel locations. For example, positions of the *La Brisa* were not logged on 27 August while it was deploying bottom-mounted acoustical recorders northeast of Cross Island. Positions of *Sag River* were not logged on 14-15 September while it was retrieving bottom recorders northeast of Cross Island (14th) and north of Northstar (15th). Before the *Sag River* traveled east of Cross Island on 14 September, the crew contacted the whaler coordination center. They confirmed that whaling was not in progress because of poor weather, and that the whalers had no objection to the *Sag River* traveling east of Cross Island on that date to retrieve the bottom recorders.

2.3 Marine Mammal Monitoring and Mitigation

Boat-Based Monitoring

The Incidental Harassment Authorization (IHA) issued by NMFS required that a minimum of two biologically-trained observers be present on the source vessel. Their duties included watching for and identifying marine mammals; recording their numbers, distances and reactions to the seismic operations; calling for mitigation measures when appropriate; and reporting the results. There was no requirement for suspension of seismic operations during times with poor visibility or at night, and in fact seismic work continued during such periods. Details of the boat-based monitoring effort are given in Chapter 4 on SEALS. (No whales were sighted from the source vessel.) This section includes only a brief introduction to the monitoring procedures, followed by a description of the mitigation measures that were implemented when marine mammals were seen close to the source vessel.

Two or three biologist observers plus one Inupiat observer/communicator were assigned to the source vessel at all times. Whenever shooting was underway, or when it was expected to begin within the next 30 minutes, the on-duty observer watched continuously for mammals. The observer scanned around the vessel using 7 x 50 Fujinon binoculars with a reticle to measure depression angle relative to the horizon (an indicator of distance). During July and much of August there was no total darkness. Thereafter the nights rapidly became longer. At night, the observers used both the 7 x 50 binoculars and a Bushnell/ITT Night Ranger 250 binocular night vision device (NVD). The IHA required nighttime monitoring only while the array was being powered up. However, in practice, monitoring personnel attempted to observe at all times, night or day, when the airguns were operating or were 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.

Aerial Monitoring

Aerial monitoring of a much larger region surrounding the area of seismic exploration was conducted on a daily basis, weather permitting, from 1 to 21 September. Aerial surveys after 18 September, when seismic work ended, were "post-seismic control" surveys. Poor weather prevented effective surveys on ⅓ of the days; surveys were done on 14 dates from 3 to 20 September. If any whales had been seen close to the source vessel during this work, this information would have been relayed by radio to the seismic source vessel and used in determining whether shutdown of the airguns was required in accordance with the 750 m criterion applicable for whales seen during September. However, the closest sightings of whales by the aircraft-based observers were much more than 750 m from the source vessel. The aerial monitoring procedures and results are described in Chapter 5 on WHALES.

Mitigation Measures

Ramp-up.—The IHA called for the airguns to be "ramped-up slowly over a period of several minutes" any time after the guns had been shut down "by firing the smallest gun first and then adding additional guns in sequence until the full array is firing".

Because all guns were the same size (120 in^3), the actual procedure applied during this project was to begin with one gun and to add additional guns in sequence over a period of 3-4 minutes. The specific ramp up sequence varied during the season. Sometimes one additional gun began firing every 20 seconds until all guns were firing. At other times, one gun was fired for the first minute, 2 guns for the second minute, 4 guns for the third minute, 8 guns for the fourth minute, and then all guns (normally 11 guns). The latter procedure resulted in close to a 6 dB increase in source level and (for distances within 500 m) in received level for every doubling of the number of airguns.[2] There were occasional variances from these nominal ramp-up sequences, but at all times efforts were made to ramp-up gradually rather than to suddenly begin firing with the full array.

The guns fired intermittently during normal operations—typically about once every 15-18 seconds, with the exact time interval depending on vessel speed. Thus, it was necessary to define how long a gap between shots could occur without it being necessary to ramp up before again firing the full array. Initially it was decided that ramp up would be required if there had been an interval of 1 minute or longer when no gun had fired. Late in the season, ice sometimes forced the vessel to slow down to the extent that it took more than 1 minute for the vessel to travel the 44 m between shotpoints. It was decided on 16 September that, under those conditions, ramp up would be required if there had been an interval of 2 min or longer since the previous shot.

Line Changes.—Procedures during line changes varied. A common practice was to continue firing some of the airguns during line changes to avoid the need to go through a full ramp-up sequence at the start of each line. The specific number of guns firing during line changes varied, but the intention was to keep at least 4 guns firing.

Shutdown Criteria.—The IHA required that the permittee "Power down the array whenever any seal enters, or is about to enter, the 500-ft (150 m) safety zone around the

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[2] At frequencies below 100 Hz, the individual airgun sounds added coherently (6 dB per two-fold change), and the array was essentially omnidirectional in azimuth. The airguns emitted significant sound energy at 150 Hz as well. The array was only slightly directional at 150 Hz, and the addition of components from the different airguns was only slightly incoherent at that frequency (see Chapter 3, PHYSICAL ACOUSTICS MEASUREMENTS, §3.3).

seismic source or whenever a whale enters, or is about to enter, the 2,130 ft (650 m) safety zone established around the source for these species."

The 150 m and 650 m radii for seals and whales, respectively, were based on an assumption that seismic pulses at received average pulse levels below 190 or 180 dB re 1 µPa (respectively) are unlikely to affect the hearing abilities of seals and whales, but that higher received levels might have some such effects. It is not known whether exposure to pulses of low-frequency underwater noise from marine seismic exploration can cause hearing damage in marine mammals (Richardson et al. 1995:372*ff*). However, there has been considerable speculation about this, based mainly on what is known about hearing damage to humans and other terrestrial mammals exposed to impulsive low-frequency airborne sounds (e.g. artillery noise). The 180 dB criterion for baleen whales was established by NMFS (1995) based on those considerations. NMFS concluded that there would be no hearing damage to baleen whales exposed to received levels of seismic pulses as high as 180 dB re 1 µPa. Because odontocetes like belugas are known to be less sensitive to low-frequency sounds than are baleen whales, NMFS (1995) concluded that the hearing apparatus of odontocetes would not be harmed by seismic pulses with received levels as high as 190 dB re 1 µPa. However, for this project BPXA proposed to apply the stricter 180 dB criterion to belugas as well as bowhead whales. Likewise, NMFS (1995) concluded that the hearing systems of pinnipeds would be less susceptible than those of baleen whales to seismic pulses. BPXA proposed and NMFS adopted a safety criterion of 190 dB re 1 µPa for seals.

Calculations done before the field season indicated that the average pulse levels would diminish below 190 dB at a distance less than 150 m and below 180 dB at about 650 m. These calculations were based on the expected characteristics of the seismic array and on previously-existing data on underwater sound propagation in the Sandpiper Island area, near Northstar (Miles et al. 1987:301).

The IHA also required that the permittee "Conduct, and provide a report on, an acoustic transmission loss test of the seismic source, within the Northstar Unit, prior to September 1, 1996. Based upon the results of this test, the safety zone described [above] may be modified accordingly." These measurements were done as part of the work described in Chapter 3 on PHYSICAL ACOUSTICS MEASUREMENTS. Based on this work, it was concluded that the received average pulse level could be as high as 190 and 180 dB re 1 µPa at distances as great as 250 m and 750 m, respectively. Therefore, on 30 August 1996, the safety radii for seals and whales were increased to 250 m and 750 m, respectively, for times when more than one airgun was in use. A modification of the IHA, dated 6 September 1996, formalized this change. The safety radii remained 150 m and 650 m when a single gun was being fired. Subsequent analyses of the sounds from a single airgun showed that the received sound levels diminished below 190 dB and 180 dB re 1 µPa at distances considerably less than 150 and 650 m, respectively (see Chapter 3).

It should be noted that the intention of the shutdown criteria was to minimize any possibility of hearing damage to marine mammals. Hearing damage, if it occurred, might be considered to be "Level A Harassment" (injury) under the provisions of the Marine Mammal

Protection Act. It is recognized that, at least among bowhead whales, disturbance reactions or "Level B Harassment" can occur at received sound levels lower than the shutdown criteria (see p. 1-1 *in* Chapter 1, INTRODUCTION). Thus, disturbance can occur at distances exceeding the shutdown radii. Disturbance to small numbers of marine mammals was authorized under the provisions of the IHA issued to BPXA for this seismic project, provided that it

- has a negligible impact on the species or stock(s) of marine mammals, and
- does not have an unmitigable adverse impact on their availability for subsistence.

Numbers of marine mammals that may have been disturbed by the seismic program, and the nature of this disturbance, are discussed in Chapter 4, SEALS, and Chapter 5, WHALES.

Shutdown Implementation.—No whales were seen from the source vessel, so only the seal criterion was relevant. Whenever the marine mammal monitor(s) or other personnel in the wheelhouse sighted a seal within the 150 m or 250 m shutdown radius, the navigator was notified immediately and the airguns were shut off. In the event that the navigator was not immediately available, the marine mammal observer activated a switch on the bridge to shut off the array. The airguns normally were shut off within 3 to 5 seconds after a seal was sighted inside the safety zone. Given the normal shot interval of about 15-18 s, there typically was either no shot or no more than one shot between the time the seal was seen and the time when the shutdown took effect. In total, there were 135 shutdowns for seals during the 24 July through 18 September 1996 period.

The procedure after shutdown varied. Sometimes the source vessel turned away from the seal and initiated a circle of about 300-400 m diameter. About half way around the circle, a ramp-up of the airguns was begun. This timing was selected so that, with a normal ramp-up schedule and with no further seal sightings, the full array would be shooting by the time the vessel returned to the point on the source line where the shutdown had occurred. At that point, the vessel resumed the original course along the source-line.

On other occasions, the vessel continued along the source-line after shutting down the airguns, and resumed firing when more than 150 m or 250 m (depending on date) beyond the seal's location. This necessitated not firing the airguns at several of the pre-planned shot-points, which were at 44 m intervals. "Missed" points were sometimes shot at a later time.

When another seal sighting occurred within the safety zone during a shutdown, the shutdown continued until no seals were known to be within the safety zone.

Field Reports

Throughout the seismic program, the boat-based marine mammal monitoring team prepared weekly reports summarizing the numbers of seals sighted with and without seismic shooting, the distances of these seals from the airguns, and the apparent reactions (if any) to the boat and/or airguns. These reports were faxed to the National Marine Fisheries Service, Western Alaska Field Office, with follow-up telephone contact to discuss any questions or concerns.

During periods when physical acoustic measurements were being taken (primarily during the latter half of August), weekly reports summarizing the acoustic work accomplished were also faxed to the NMFS Western Alaska Field Office, Anchorage. In addition, on 30 August 1996 the required report on the sound propagation tests was provided to that office and to the NMFS Office of Protected Resources, Silver Spring, MD.

During the 1-21 September period while daily aerial surveys were being conducted, daily reports were faxed to the NMFS Western Alaska Field Office. These summarized the survey coverage and bowhead whale sightings each day.

2.4 Literature Cited

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NMFS. 1995. Small takes of marine mammals incidental to specified activities; offshore seismic activities in southern California. **Fed. Regist.** 60(200, 17 Oct.):53753-53760.

Richardson, W.J., C.R. Greene Jr., C.I. Malme, D.H. Thomson. 1995. Marine mammals and noise. Academic Press, San Diego, CA. 576 p.

3. PHYSICAL ACOUSTICS MEASUREMENTS[1]

3.1 Introduction

The 1996 Northstar seismic program was conducted under the provisions of an Incidental Harassment Authorization (IHA) issued by the National Marine Fisheries Service (NMFS) to BP Exploration (Alaska) Inc. (BPXA). The IHA required that a marine mammal and acoustical monitoring program be conducted.

An array of airguns is the most common energy source used during modern open-water seismic exploration programs. An airgun array emits strong, low-frequency sound pulses into the water at intervals of several seconds. Geophysical survey contractors design their airgun arrays to focus the sounds downward insofar as possible. Even so, strong pulses of low-frequency sound propagate horizontally through the water. Their received levels tend to diminish with increasing distance. However, even in the horizontal plane, the source levels of the pulses are strong enough that the pulses are often detectable many tens of kilometers away (Greene and Richardson 1988; Richardson et al. 1995:136*ff*).

The size, number and positioning of the airguns comprising an array are customized for different applications. For example, arrays for shallow water surveys generally will not be as large as arrays for deep water surveys. Larger arrays generally emit significantly more sound than a middle- or small-sized array. In addition, sounds from an airgun array in deep water generally will transmit farther at higher levels than the sounds from a similar array in shallow water. Thus, a shallow water survey may create less sound at a given distance than a deep water survey for two reasons: a smaller source and poorer sound transmission.

Airgun sound pulses are undoubtedly audible to at least some marine mammals, including baleen whales, at long distances from the airgun array (Richardson and Würsig in press). Bowhead and other baleen whales often are disturbed when exposed to strong seismic sounds. They sometimes may react at least subtly to weaker seismic sounds as well (see §1.1). However, they probably are not always disturbed when they detect weak sounds from a distant airgun array. The circumstances when they are or are not disturbed are not adequately documented. As part of any attempt to monitor or study the reactions of marine mammals to seismic exploration, it is important to understand the characteristics and levels of the seismic sounds in the situations where the mammals were studied.

Tasks and Objectives

The final Technical Plan for this monitoring program included three acoustical measurement tasks:

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[1] By Charles R. Greene Jr., Greeneridge Sciences Inc., assisted by John S. Hanna and Robert W. Blaylock.

- "conduct a vessel-based acoustics program for ~10 days in late August 1996 to obtain systematic measurements of seismic sounds, propagation loss, and ambient noise;"
- "drop sonobuoys during the aerial survey program beginning 1 September to collect data on (a) ambient noise and (b) seismic exploration noise. Sonobuoys would provide noise data at more places and times, and under more environmental conditions, than possible from the vessel, including ambient and seismic data from bowhead locations;"
- "deploy bottom-mounted acoustic recording devices at several locations east of and offshore of the Northstar region to obtain near-continuous records of underwater noise and whale calls in those areas from 1 September to the end of the seismic program (or until ice precludes data retrieval)".

The resulting acoustical measurement program documented the major types of underwater sounds associated with the seismic program. The main sources included the airgun array, a single airgun, various project vessels, and the aircraft used for aerial surveys of whales. In addition, sound propagation conditions within the Northstar area and from there northward toward the main whale migration corridor were studied. During the bowhead whale migration period, continuous acoustical monitoring was conducted to listen for whale calls and seismic pulses at two locations, one offshore from Northstar and one much farther to the east. Ambient noise was also recorded and analyzed at many locations in and near the Northstar area.

As called for by the three tasks listed above, three general approaches were used to achieve the acoustic measurement objectives: (1) one or two hydrophones were deployed from a boat, the *La Brisa*, while at anchor in the Northstar survey area or drifting several kilometers offshore; (2) sonobuoys were deployed from the aircraft that was conducting aerial surveys of marine mammals during the 1-21 September period, as described in Chapter 5, WHALES; and (3) seven autonomous bottom recorders were installed to collect acoustic data at various distances offshore in areas north and east of Northstar during the first three weeks of September. Also, four bottom recorders were installed north of Northstar on 24 August for three days in a test deployment. Figure 3.1 shows the areas where seismic exploration occurred during the period of acoustical measurements, and the locations where the bottom recorders were installed. The two long-term bottom recorders whose data are available for use in this report were located at two sites: (1) 15 km (8 n.mi., 9 st.mi.) offshore of the northern edge of the seismic exploration area; and (2) 20 km (11 n.mi., 12 st.mi.) ENE of Cross Island and 14 km (7.5 n.mi., 8.7 st.mi.) north of Narwhal Island. The latter location is 45 km (24 n.mi., 28 st.mi.) to the ESE of the other recorder.

Subsequent to the August-September field season, a major acoustical analysis effort was conducted to extract the needed data from the field recordings and other records of field activities.

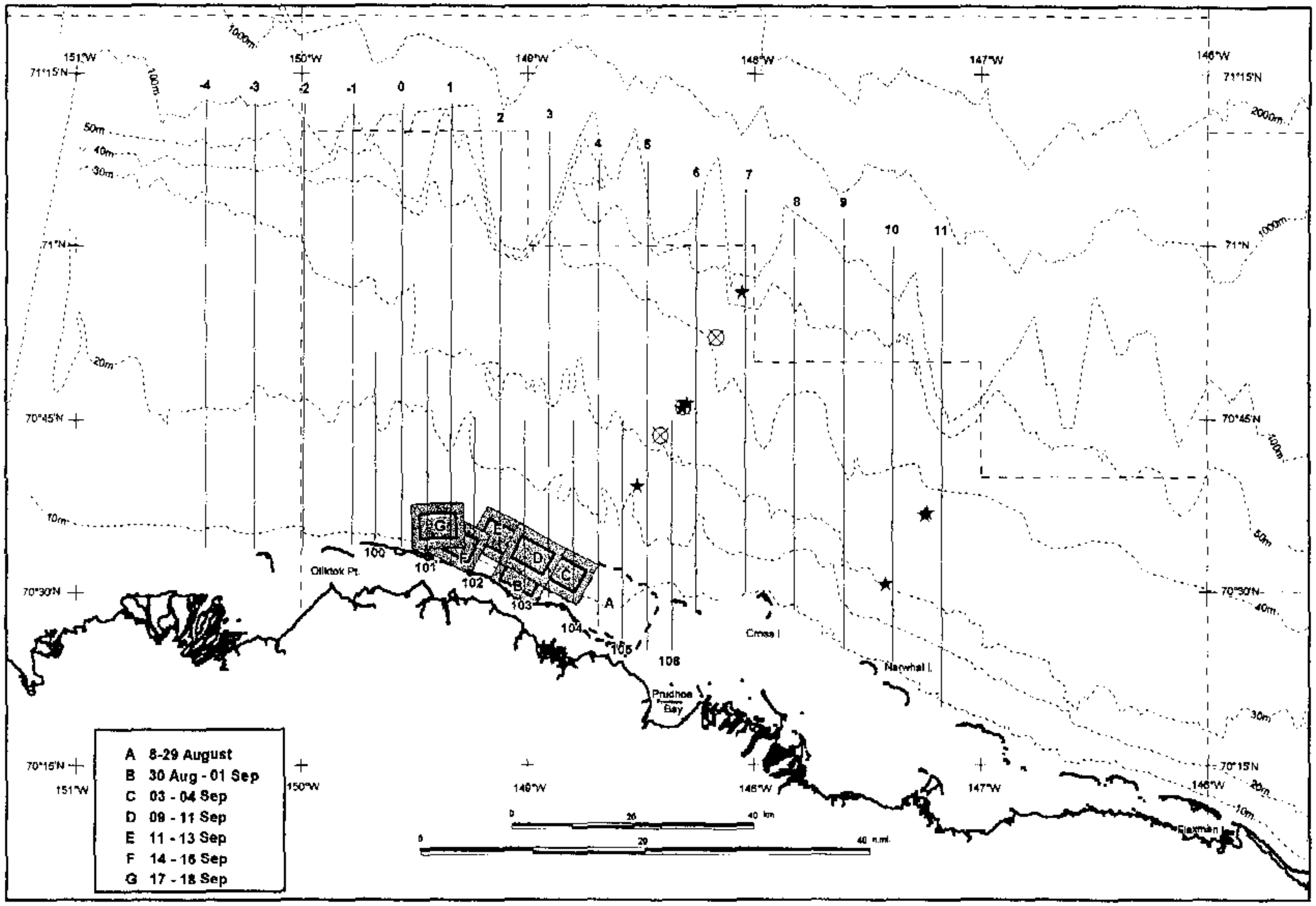

FIGURE 3.1. Central Alaskan Beaufort Sea showing the Northstar area where seismic operations occurred from 8 August through 18 September 1996, and the locations of bottom recorders (⊗ for the 3-day test in late August; stars for the long-term deployment commencing 31 Aug.) B to F are the six "patches" where seismic surveys were done during the long-term deployment, starting at 00:00 ADT on 31 August. The southernmost recorders off Narwhal Island and Northstar were retrieved on 14 and 15 September, respectively. The north-south lines are aerial survey transects (see Chapter 5).

Concepts and Terminology

Acoustic concepts and terminology are generally confusing to non-acousticians, and often to acousticians as well. An attempt to summarize the concepts and terms relevant in assessing noise effects on marine mammals was given in Chapter 2 (and the associated Glossary) of Richardson et al. (1995). A few remarks about terms used in this report are included here.

The word "level" is used to denote a sound measurement in decibels. A one decibel (dB) change in sound level is considered to be the smallest change in sound level perceptible to a human listener. A change of +10 dB or -10 dB is perceived by a human listener to be, respectively, about a doubling or a halving of the sound level (i.e. a two-fold change). However, in physical units, a 10 dB change in sound level actually corresponds to a ten-fold change in sound power (commonly measured in watts) and a three-fold change in sound pressure (commonly measured in micropascals).

A doubling of the sound pressure corresponds to a 6 dB increase in sound pressure level. A doubling of the sound power corresponds to a 3 dB increase in sound pressure level. The decibel value of a sound level is the same whether one uses a power reference or a pressure reference; the equation to compute the sound level in decibels allows for the fact that sound power is proportional to the square of the sound pressure.

Unrelated sound sources add incoherently, meaning that the sound waveforms are not correlated and that the sound powers in each add to result in the sound power of the sum. Related sound sources, i.e. sound sources with the same waveforms, may add coherently, meaning that the sound pressures add to result in the sound pressure of the sum. For coherent waveforms, the sum of two equal sources is twice the sound pressure and four times the sound power of either source (i.e., a 6-dB higher sound level). Closely spaced airguns firing at the same time have related waveforms that add coherently.

In calculating average sound levels over specified lengths of time, the common practice is to square the pressures and average them, obtaining a mean square pressure, and then compute 10*log(mean square) to obtain the sound pressure level. An alternative procedure is to compute the square root of the mean square to obtain the "root-mean-square" or rms sound pressure, and then compute 20*log(rms) to obtain the sound pressure level. The results are the same, and it is convenient to refer to the value derived by either procedure as an rms pressure level.

"Peak" and "rms" pulse levels for received airgun signals are described and compared in sections 3.2 and 3.3, below. In general, the peak level is the instantaneous maximum or minimum value whereas the rms level is an average over the pulse duration. Another term used to emphasize this distinction is the "crest factor" of a waveform, which is the ratio of the peak level to the rms level. The crest factor of a sinusoidal waveform is 1.4, or 3 dB.

Regarding distance measures other than the MKS standard kilometer, the usual practice is to use statute miles (st.mi.) on land and nautical miles (n.mi.) at sea. One nautical mile is equal to 1.15 st.mi. and to 1.85 km.

3.2 Methods

Boat-Based Measurements

Two hydrophones were deployed from the stern of *La Brisa*. An International Transducer Corporation (ITC) model 6050C hydrophone with built-in low-noise preamplifier was suspended from a sparbuoy drifting near the vessel. An ITC 1103 hydrophone without built-in preamplifier was suspended directly from the stern. Both hydrophones were deployed at depth 9 m, except that, where the water was shallower, the hydrophones were raised to be about one meter above the bottom. The 1103 hydrophone was capable of receiving very strong signals, up to 220 dB re 1 µPa peak pressure, without distortion. This hydrophone was useful at the shortest distances from the airguns. The 6050C hydrophone was useful at long distances from the airguns and for measuring the ambient noise. It would distort when the received signals exceeded 179 dB re 1 µPa. In those cases, data from the ITC 1103 were used.

The 1103 hydrophone cable was attached to a preamplifier in the boat's cabin. The preamplifier gain could be selected in 10 dB steps from 0 to 60 dB. The 6050C hydrophone cable was connected to a postamplifier in the boat's cabin. The postamplifier gain could be selected in 10 dB steps from 0 to 60 dB. The two amplifier outputs were connected to the inputs of a TEAC model RD-101T digital audio tape (DAT) recorder. This recorder permits recording with a dynamic range of about 80 dB, meaning that there is a large range of amplitudes between self-noise and distortion. In addition, the speed accuracy and stability of the recording permits reproducing signal frequencies very accurately and without the flutter and wow associated with non-digital recorders. A memo channel permitted recording annotation by voice without disrupting the data recording.

The boat-based measurement system was used in two ways. In one, *La Brisa* anchored in the survey patch at a point selected because the operating airguns would be passing within about 100 m. This approach provided data on the received levels of airgun pulses at varying distances during the approach and subsequent departure of the source vessel. Both hydrophone signals were always recorded during such runs because the 6050C preamplifier overloaded at the closest distances and the relatively insensitive 1103 hydrophone was required. In the other application, *La Brisa* motored to a distant position either NNE or WNW of the survey patch and drifted while recording the airgun sounds. The 1103 hydrophone was not always used at these long distances, where received levels were lower, because the 6050C provided high-quality signals.

In addition, sounds from four vessels involved in the Ocean Bottom Cable seismic operation were also recorded. All vessels involved in the operation are listed and described in §2.2, "Equipment and Operations".

La Brisa had a 3 kw inverter for converting battery power to 120 V ac power during quiet recording operations. This inverter powered heaters, ventilators, pumps and electronics like the fathometer, radio and GPS computers on the vessel, some of which created hum in the acoustic signals. Generally we were able to find and turn off such troublesome auxiliary equipment, but there were instances when low-level residual hum appeared in our data at 60 Hz or in the ⅓-octave band centered at 63 Hz.

Distances between recording vessel *La Brisa* and the various vessels whose sounds were measured were determined by radar and by Differential GPS (DGPS). Positions of all major vessels involved in the seismic operation were determined continuously by DGPS (accuracy within ~1 m), and were logged into computer files every 5 min. Also, the position and heading of the airgun array were determined by DGPS and logged for every airgun pulse during production surveys. The water depth at the airgun array location, as determined by fathometer, was also logged for every such pulse.

Sonobuoy Measurements

Sonobuoys were procured from the Sparton Corporation for use from the survey aircraft. They were model AN/SSQ-57A omnidirectional, wide-range sonobuoys calibrated (±2 dB) over the frequency range 10-20,000 Hz. These buoys employ a wideband FM radio transmitter to achieve low instrument background noise. However, their radio power is only one watt and sonobuoy signals received aboard the aircraft became contaminated by radio static as the aircraft departed the vicinity of the buoy, especially at low altitudes. On the aircraft, a four-channel sonobuoy receiver was connected to an antenna through a low-noise RF preamplifier to minimize noise induced by the antenna cable. The signals were recorded on a TEAC model RD-135T DAT recorder effective (in four channel mode) at frequencies up to 10 kHz. The operator monitored the audio quality with a headset and made voice announcements on the recorder's memo channel.

All sonobuoys obtained for the survey were modified during manufacture to deploy the hydrophone to a depth of 10 m instead of the standard 18 m hydrophone depth. This change was made to permit deployment of some sonobuoys in the shallow waters around Northstar. In addition, some of the sonobuoys had sensitivities that were reduced by 20, 30 or 40 dB compared to standard AN/SSQ-57A sonobuoys. This was to permit recording the expected higher levels of airgun sounds without distortion. Standard sonobuoys are designed to detect and monitor low-level sounds. The standard AN/SSQ-57A can begin to distort on sounds with received levels on the order of 127 dB re 1 µPa, depending on frequency. Sonobuoys desensitized by 20, 30 or 40 dB would not distort unless the received signals exceeded about 147, 157 or 167 dB re 1 µPa, respectively.

At least one sonobuoy was dropped offshore of the Northstar area during most aerial surveys in order to monitor ambient noise and seismic sounds. On days when seismic exploration was underway and bowhead whales were seen, sonobuoys usually were dropped near one or more of the bowheads. To avoid overloading the sonobuoys, reduced-sensitivity buoys were used when the seismic vessel was operating nearby.

Bottom Recorder Measurements

The third approach to acoustic data collection involved the use of autonomous devices installed on the ocean bottom remotely from the survey area. These were designed to provide continuous acoustic data over extended periods, including information about seismic pulses, ambient noise, and bowhead whale calls. The objective was to obtain acoustical data from three pairs of locations east of and offshore of Northstar—one pair of locations near the southern edge of the bowhead migration corridor, one pair near its center, and one pair farther offshore. In practice, recording units were deployed at five of the six planned locations (Fig. 3.1). To date, data have been recovered successfully from the southernmost two locations, and it is hoped that the remaining recorders can be recovered during the 1997 open water season.

Batteries and electronics were housed in a 6" PVC pipe, 52" long, with machined aluminum end caps and double O-ring seals. The inside ends of the PVC pipe were machined to match the O-rings on the end caps. The sole penetration was for a hydrophone cable connector. The hydrophone, buoyed up 2 m above the bottom, was an ITC model 8212, a cylindrical unit containing a low-noise preamplifier. The frequency response was flat below 3.5 kHz and was within ±3 dB of being flat to 30 kHz. An amplifier/filter in the bottom recorder unit low-pass filtered the hydrophone signal into two bands, 5-500 Hz and 5-1000 Hz. The remaining electronics, provided by Dr. David Jacobs of Scripps Institute of Oceanography, included an Onset Tattletale 7 controller with a two-channel analog-to-digital converter and SCSI interface for a 4 GByte disk drive. The hydrophone signal was sampled continuously 1000 times per second (500 Hz passband) for 13 minutes and 24 seconds, after which the sample rate doubled (1000 Hz passband) for one minute. Once every 14 min 24 s, the buffer memory was dumped to the disk, requiring disk operation for about 50 s. The disk capacity was 24.94 days, and the battery capacity, limited by the disk power requirements, exceeded 22 days.

This procedure provided a continuous record of sounds at frequencies up to 500 Hz. In addition, exactly 100 times per day (every 14.4 min), sounds at frequencies up to 1000 Hz were recorded for 1 minute. These wider band sounds were analyzed for ambient noise.

A test deployment of four bottom units offshore of Northstar on 24 August was largely successful. During deployment, the locations of the units and their 100-m tag line anchors were recorded with Differential GPS. The units were installed at water depths ranging from 25 to 44 m, based on *La Brisa*'s fathometer. These depths occurred at locations expected to bracket the bowhead whale migration corridor, whose center is estimated to be at a depth of 35 m. The four units were programmed to begin sampling at 00:00 local time (ADT) on 25 August. On 28 August the four units were retrieved without difficulty by grappling at those locations for the tag line attached to each unit. The disk drive had not operated properly on one of the four units. However, about 80 hours of data were recorded on each of the three successful units.

Seven units were deployed on 27-28 August for longer-term acoustic monitoring. All units were programmed to begin operation at 00:00 ADT on 31 August. The units were deployed along two lines extending offshore from Northstar and offshore from Narwhal Island, east of Cross Island (Fig. 3.1).

- Three units were deployed on 27 August on an 030° True line starting 20 km ENE of Cross Island (14 km north of Narwhal Island). One unit was deployed at a location where water depth was 31 m, and two units were deployed ~350 m apart where water depth was 42 m (water depths based on *La Brisa*'s fathometer). Heavy seas prevented us from deploying a planned fourth unit farther offshore along that line.
- Four units were deployed on 28 August on a line oriented perpendicular to shore (030° True) seaward of Northstar at water depths 25 m, 36 m (2 units ~1 km apart) and 44 m.

Two units were deployed at the "middle" location along each line in order to increase the probability that data would be acquired from the center of the bowhead migration corridor both east of and offshore of Northstar.

The southernmost recording unit from each line was retrieved successfully on 14 and 15 September, despite the presence of significant ice cover. Heavier ice prevented retrieval of the five units at more northerly locations. Those units are at locations deep enough for there to be little chance of damage by ice scour during one winter. It is planned to retrieve as many of those units as possible during August 1997, and to analyze the 1996 data recorded by those units as part of BPXA's 1997 seismic monitoring program.

Signal Analysis

Seismic Survey Pulses.—For each airgun pulse recorded on *La Brisa*, the recorded signal was sampled at a rate of 8192 samples per second during a 60-s to 90-s block of time containing several pulses. This process effectively determined the instantaneous pressure 8192 times per second throughout that block of time. For each pulse studied, the time series of these instantaneous pressure measurements was analyzed.

Seismic pulses received via sonobuoys were similarly digitized. These digitized signals required special attention because sonobuoy sensitivity increases steeply with increasing frequency from 10 to about 3000 Hz (see Fig. 3.1B in Richardson et al. 1995). This shaped frequency response increases the buoy's dynamic range by de-emphasizing the low frequency sounds, which often are at higher levels, and enhancing the higher frequencies, which tend to be at lower levels. (Note the negative slope in ambient sea noise spectra such as those shown in Fig. 5.2 in Richardson et al. 1995.) The frequency shaping distorts the pulse shape depending on the frequency content in the pulse. To compensate for this sloped frequency response, the block of samples containing an airgun pulse was Fourier transformed, the transform magnitude was altered based on the frequency calibration of the individual sonobuoy to achieve an overall flat response, and the block was inverse Fourier transformed to obtain a corrected time series. This process was designed to yield the waveforms, peak pressures, energies, and rms pulse pressures that would have been measured if the sonobuoy frequency response had been flat.

Airgun pulses recorded on the bottom units were digitized at 1000 samples/s when they were recorded. Otherwise, their analysis was like that of the boat-based recorded pulses.

Clipping: Overloading is recording distortion that occurs when signal amplitude exceeds the range of the amplifier or recorder. Cases of overloading were detected by looking for clipping. A clipped signal includes many samples with apparent amplitudes at or close to the maximum amplitude. The computer program doing the analysis counted the samples within one percent of the highest amplitude in the segment being analyzed. Results were considered to be clipped, and were discarded, when more than 5-10 samples had amplitudes within 1% of the maximum. This process was most important with the sonobuoys, when there was no second, less-sensitive channel against which to compare results (as there was on the boat).

Generally, overload distortion occurred on the channel with the ITC 6050C hydrophone when it was within 1-2 km of the operating full array, or about 100-200 m of a single airgun. As the range to the airguns decreased, the pulse amplitudes from that channel appeared to stay at the same level while the pulse amplitudes from the ITC 1103 hydrophone channel continued to increase. In those cases it was clear that the 6050C channel had overloaded.

Quantification of Pulse Levels: No single standard method has been used in the literature to report airgun signal levels with respect to their effects on marine mammals. We use and compare three measures during this study. These measures are illustrated in Figure 3.2.

1. *Peak pressure* (in micropascals), either positive or negative, of each pulse. This is the instantaneous maximum or minimum pressure observed during the pulse, in μPa, and neglects any consideration of pulse duration.

2. *Energy in the pulse*, in μPa^2-s. To compute the energy, one must first determine start and end times for the pulse, which is difficult because of noise present at the beginning of the pulse and reverberation at the end. The approach developed in this study was as follows. The analysis program computes the standard deviation of the acoustic pressures in the total sample (nominal length 60 s) and then identifies those samples whose pressures are at least 6.25 times the standard deviation. Most of these samples represent airgun pulses. The program identifies sequences of such pulses, and extends these sequences by 1 s in advance of the first high-valued sample and by 2 s following the last high-valued sample in the sequence. These extended segments, typically slightly more than 3 s in duration, are presented to the operator as a graph of pressure vs. time. If he accepts the program's identification of the sequence as an airgun pulse, the program proceeds; otherwise, the operator manually selects the airgun pulses. Samples outside these extended segments are taken to be noise and are used to compute the level of the ambient noise. Again, the operator can override the program's selection of noise periods.

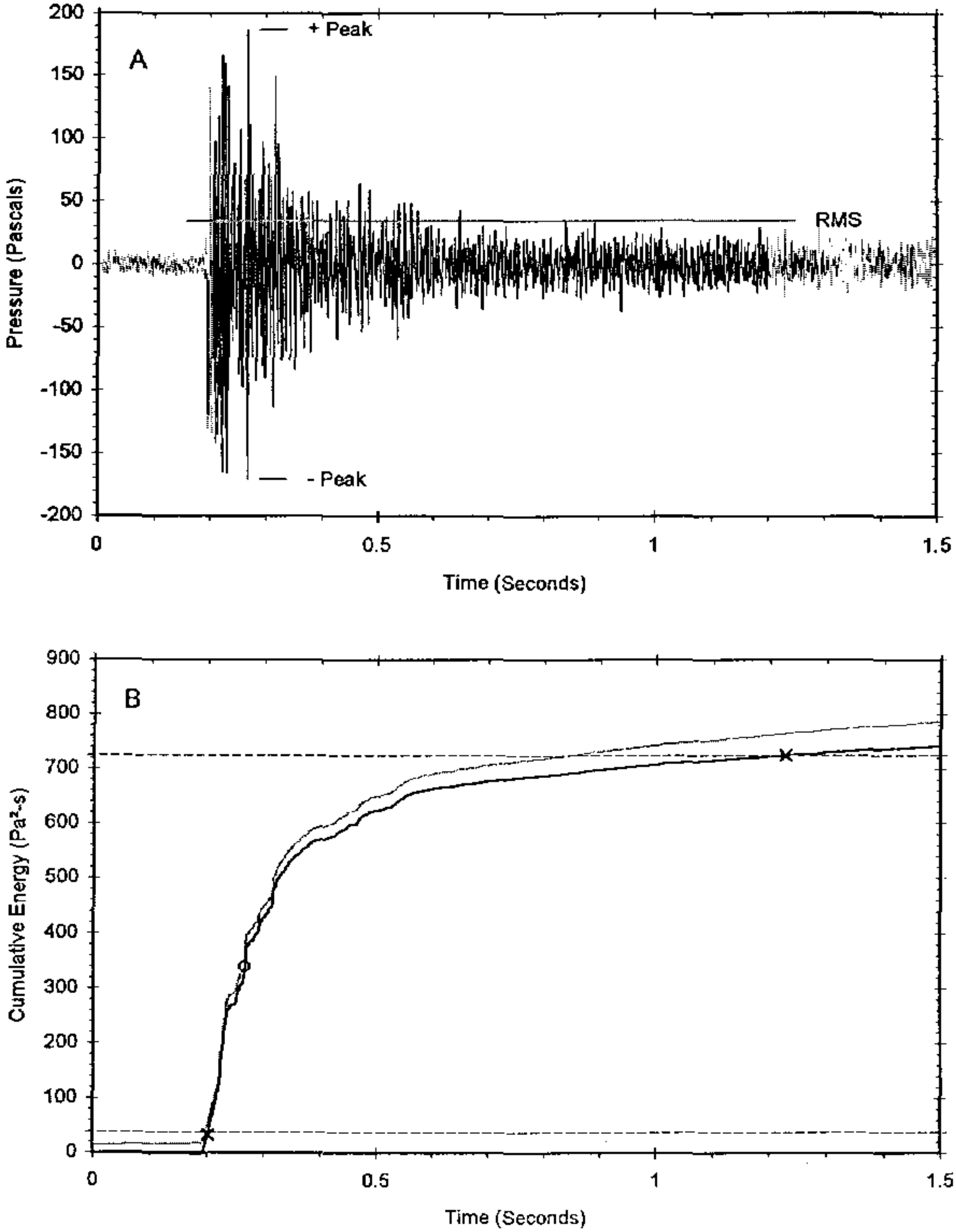

FIGURE 3.2. Airgun sound pulse measures. *(A)* shows waveform of an airgun pulse. *(B)* shows the cumulative squares of the unadjusted pressure samples (faint line) and the cumulative squares of the pressure samples excluding ambient noise (thick line). The point of maximum instantaneous pressure magnitude is identified by an O, and the 5th and 95th percentiles of the energy summation are marked (horizontal dashed lines).

Within an extended segment containing an airgun pulse, the computer program sums the squares of the time series of instantaneous pressure measurements, subtracts the average of the squared noise samples, and multiplies by the sample period Δt:

$$\text{Sum} = \Delta t^{*}\Sigma(p^2 - n^2_{avg})$$

The program develops a table of values giving the cumulative energy from the start to the end of the sequence of samples being analyzed. This cumulation increases slowly (because of the background noise) until the pulse starts, then increases rapidly through the pulse duration, and finally (after the end of the pulse) increases slowly again (Fig. 3.2B). From this cumulative table, the 5th and 95th percentile values are determined; these are taken as the effective starting and stopping times of the pulse, thereby determining the *pulse duration*. The pulse energy is taken as the accumulated value, exclusive of the estimated ambient noise contribution, at the 95th percentile time less the accumulated value at the 5th percentile time.

3. *Rms pressure* during the pulse. This is the square root of the energy divided by the duration. When presented as a level, in dB re 1 µPa, the rms pressure level is equivalent to the mean square pressure level of the pulse. This third measure, which might be called the average pulse pressure, has been used by BBN in its measurements of airgun signals (C.I. Malme, pers. comm.). National Marine Fisheries Service criteria concerning apparent reaction thresholds of whales to seismic signals (e.g., NMFS 1995) are based largely on those BBN measurements. Rms pressure levels are expressed in dB re 1 µPa.

Except where otherwise noted, pulse levels reported in this chapter are rms pressure levels. It is natural to want to compare the relationships of rms pulse pressure levels with the other two measures, but one must be careful because the unit of energy differs from the unit for pressure. Although all three may be expressed as levels in decibels, the reference unit for the energy measure is different from the reference unit for the peak and rms pressures. As an illustration, Figure 3.3 shows all three measures for a series of received pulses.

Spectrum Analysis.—Standard spectrum analysis techniques were used to study ambient noise, boat and aircraft noise, and acoustic transmission loss. A series of samples was segmented into blocks of a varying number of samples depending on the application, with successive blocks overlapping by 50%. Each block was "windowed" by the Blackman-Harris minimum three-term window (Harris 1978) to minimize "leakage", and then transformed by fast Fourier transform to obtain the magnitude of the power in each frequency cell. The successive results of the block transforms were averaged, divided by the effective analysis bandwidth (including the windowing effects), and log transformed to obtain power spectral density levels in dB re 1 $\mu Pa^2/Hz$. These "raw" results were then adjusted to allow for the frequency-specific sensitivity curves of the hydrophones, amplifiers, sonobuoys, sonobuoy receivers, and tape recorders as appropriate for the particular measurement in question.

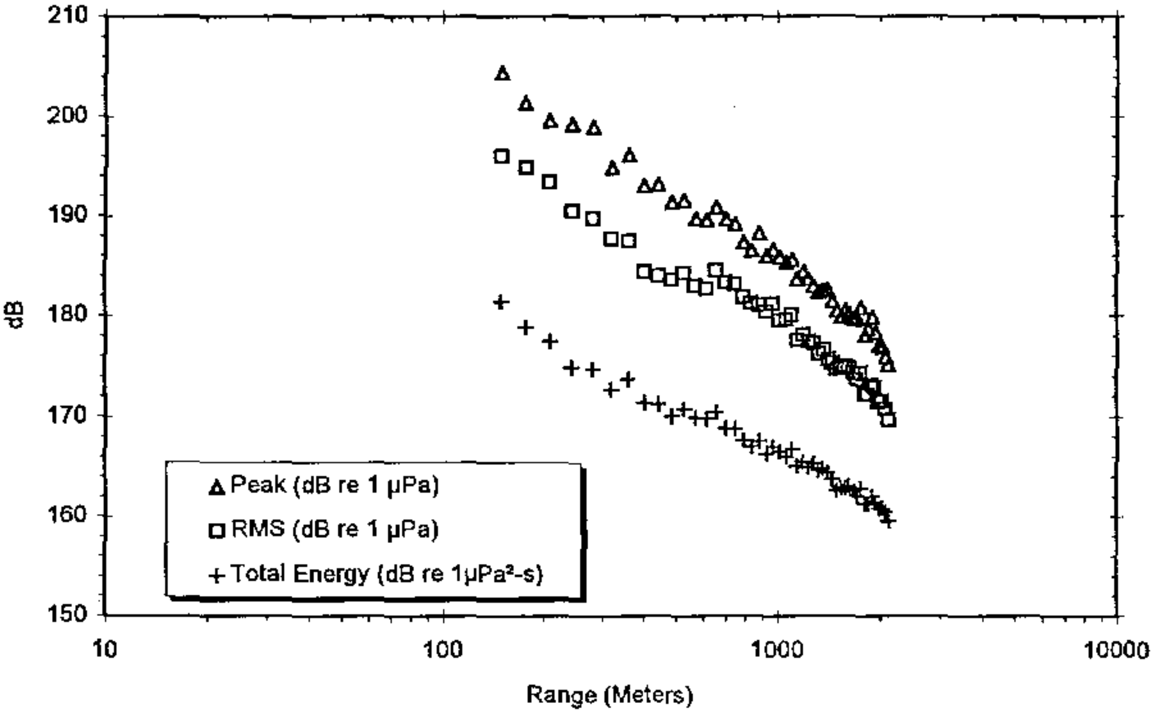

FIGURE 3.3. Examples of the range-dependence of peak pressure levels (in dB re 1 µPa), rms pressure pulse levels (also in dB re 1 µPa), and pulse energy levels (in dB re 1 μPa^2-s) from the 11-airgun array operating on 15 August 1996 in water 9-11.5 m deep, stern aspect.

3.3 Seismic Source Characteristics

An 11-airgun array was towed behind the tug *Point Barrow* as the source of sounds for the 3-D seismic survey at Northstar. The array configuration is shown in Figure 3.4. The nominal depth of the array was 3.5 m, with one airgun below the others by an additional 0.64 m. The array consisted of two strings, one on the left (port) side with five airguns and the other on the right (starboard) side with six airguns. Each airgun's capacity was 120 in^3 and all airguns were fired simultaneously.

An airgun "fires" when a solenoid actuates to cause a volume of high-pressure air to suddenly vent to the water outside, forcing the water back as a bubble forms around the airgun (Kramer et al. 1968). A sharp pressure pulse is created when the water moves.

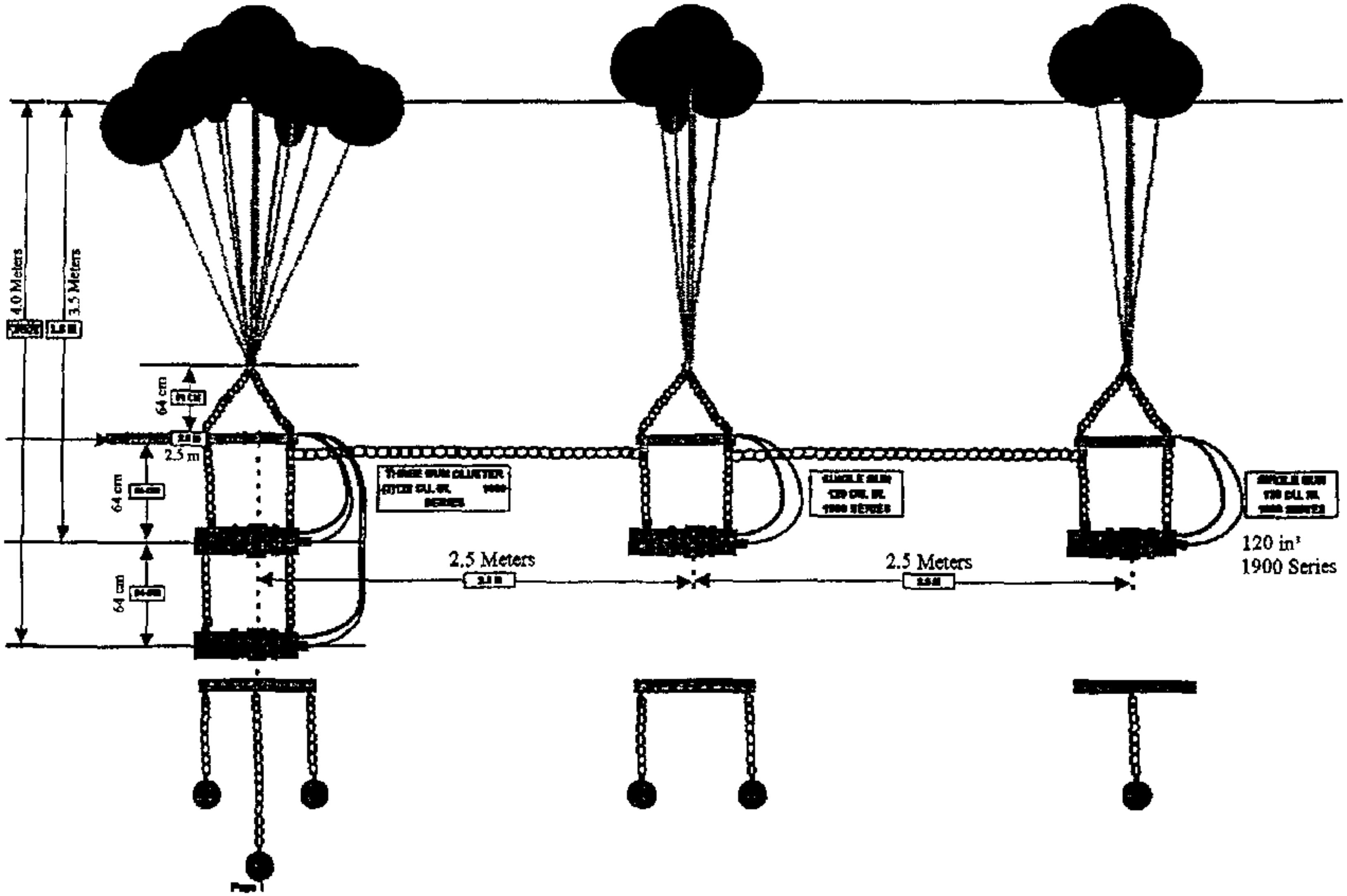

FIGURE 3.4. Airgun array configuration. This is an elevation view of the left (port) array with five airguns showing the three sets of surface floats holding up the airguns. The right (starboard) array parallels the left array, separated by 5 m, with two airguns at the center position where there is one airgun on the left array. Each gun has a 120 in^3 capacity; the 11 airguns total 1320 in^3. The centers of the forward airguns are 11.5 m behind the stern of the towing vessel, the *Point Barrow*.

Generally, the larger the airgun volume and the larger the air pressure, the larger the pulse pressure. The pressure used at Northstar was nominally 2000 psi (13.8 MPa). When several guns are relatively close together and fired simultaneously, as they were for the 1996 Northstar seismic program, the individual pulses add together to increase the total pressure pulse amplitude.

The underwater sounds from the array of 11 airguns were measured under several conditions of distance, water depth, and aspect. Sounds from single airgun operations were also measured. The single airgun results are described first, followed by full array results. Finally, the results of measuring the sounds from a partial array of six airguns (a subarray) are presented. Arrays with less than 11 operating airguns were used occasionally during the 1996 Northstar program.

Single Airgun

Characteristics of sounds from a single 120 in^3 airgun were relevant because only one airgun was operating during some of the line changes and during OBRL work (Ocean Bottom Receiver Localization), as described in Chapter 2. A single airgun was also used at the start of a ramp-up to full array operation. In addition, a comparison of the levels from a single airgun with the levels from a full or partial array shows whether the sounds of individual airguns add coherently when operated in an array (i.e., whether the received levels increase by 6 dB when the number of airguns doubles).

Pulse sounds from a single airgun were recorded from *La Brisa* at anchor in water 12 m deep on 14 August. The tracks of the source and of *La Brisa* are shown in Figure 3.5. The source was moving WNW except near the end, when it turned back toward the ESE. Figure 3.6 shows both the pressure waveform and the pressure spectral density of the pulse that occurred at the closest point of approach (CPA) to the receiving hydrophone, which was at range 33 m. The peak pressure level in this pulse was 186 dB re 1 μPa, the rms pulse level was 173 dB re 1 μPa, the pulse energy was 161 dB re 1 μPa^2-s, and the pulse duration was 56 ms. (Pulse duration is the interval containing 90% of the pulse energy, as described in §3.2.) The pulse spectrum shows that sound energy peaked within 8-Hz frequency bands centered at 50 and 80 Hz.

Figure 3.7 shows the rms pulse pressure levels vs. distance for the opening range (stern aspect) phase of the run whose track is shown in Figure 3.5. The data were recorded between 15:19 and 16:16 ADT at ranges 33 to 6400 m. The water depth was 12 m at the receiver and varied from 11 to 13.8 m at the airgun source. The fitted equation (given in the figure caption) includes a forced cylindrical spreading loss term of $-10*\log(R)$ and a loss term of 4.8 dB/km. The sounds from a single airgun propagate omnidirectionally. Aspect is not expected to be a significant factor for single-airgun sounds except insofar as there may be shadowing at bow aspect by the vessel towing the airguns.

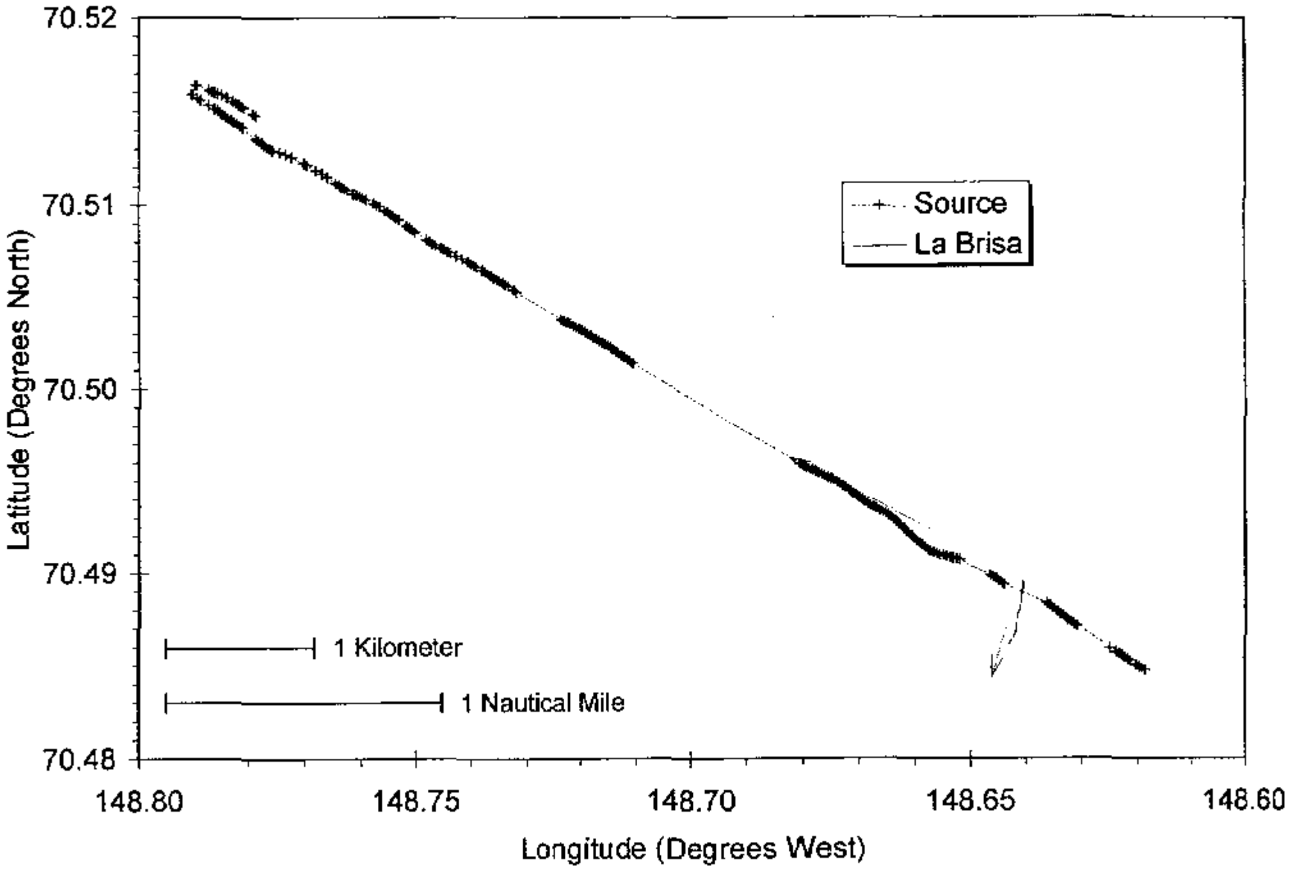

FIGURE 3.5. Track of seismic source vessel *Point Barrow* operating a single 120 in^3 airgun past *La Brisa* on 14 August 1996, 15:20-16:13 ADT, water depth 12 m at hydrophone, airgun depth 3.5 m, hydrophone depth 9 m, source vessel traveling from ESE to WNW. Latitude and longitude are in decimal degrees.

Received Levels.—The received levels (rms pulse pressure) from the full 11-airgun array were recorded at short ranges on 15 August. Recording vessel *La Brisa* was anchored in water 10.5 m deep at a position close to a regular production survey line along which source vessel *Point Barrow* would travel while towing the airguns. Figure 3.8 shows the survey line, which was oriented from SSW to NNE, relative to *La Brisa*'s positions. The water depths at the source were 7.1-10 m for the approaching phase of this run and 10.1-11.4 m for the opening range phase. Figure 3.9 shows both the pressure waveform and the pressure spectral density for the airgun sound at the CPA distance of 116 m. The peak pressure level in this pulse was 205 dB re 1 μPa, rms pulse level was 198 dB re 1 μPa, pulse energy was 183 dB re 1 μPa^2-s, and pulse duration was 32 ms. The pulse spectrum shows that sound energy peaked in the 8-Hz bands centered at 56 Hz, 160 Hz, 280 Hz and 360 Hz.

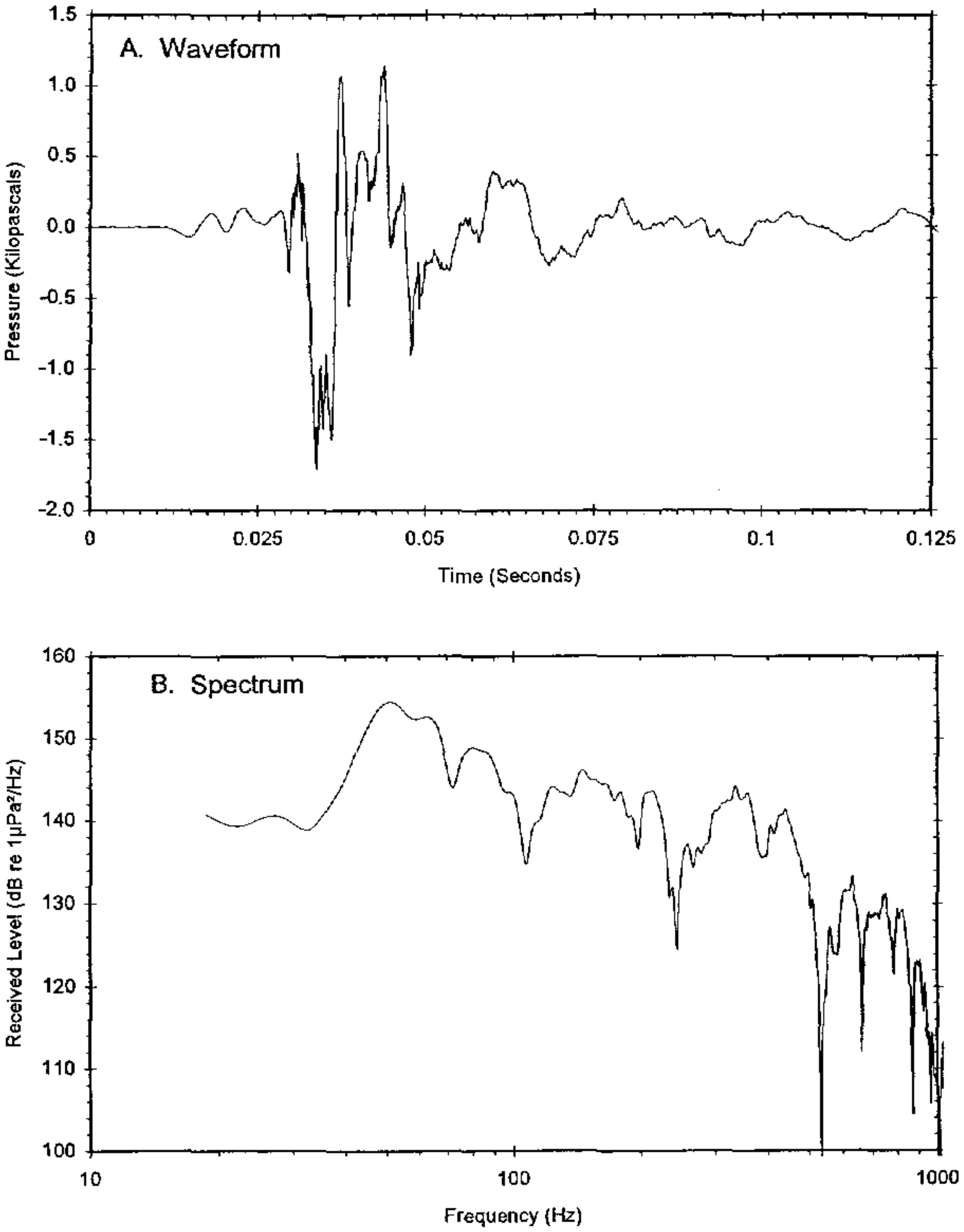

FIGURE 3.6. Waveform (A) and spectrum (B) of pressure pulse from a single 120 in^3 airgun at 33 m distance, 14 August 1996. Recording location and depths were as shown in Fig. 3.5. For (B), averaging time was 0.125 s and analysis bandwidth was 8 Hz.

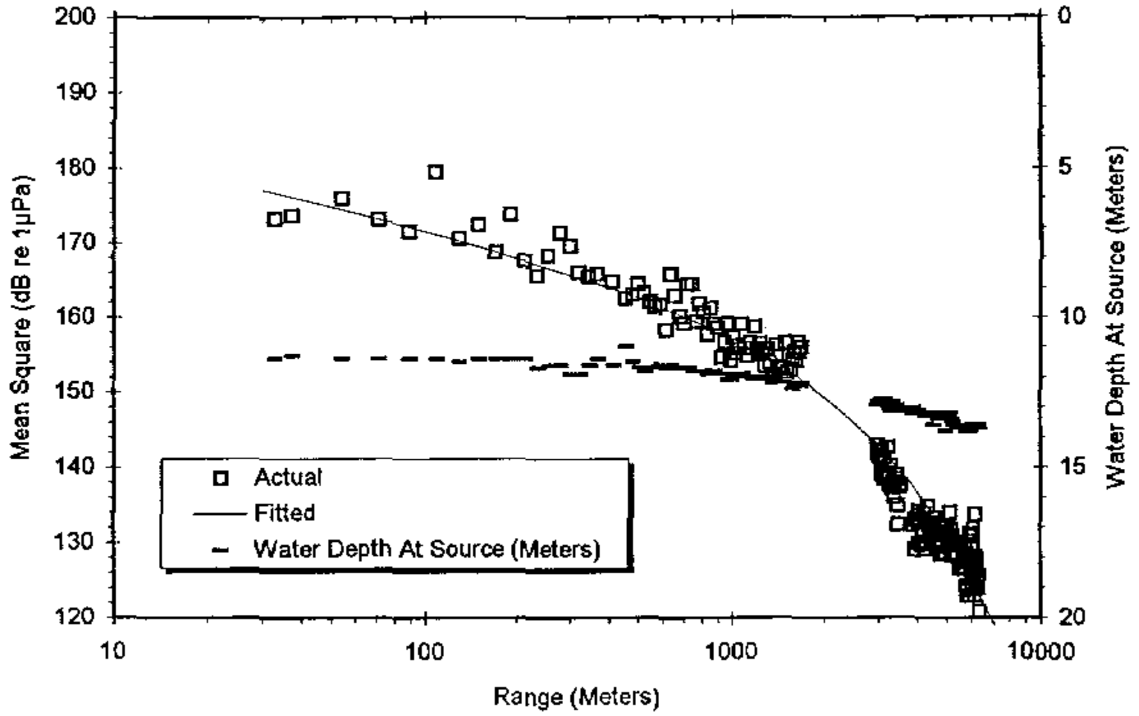

FIGURE 3.7. Received levels of pulses from the single 120 in^3 airgun measured as the source vessel was moving away to the WNW on 14 August 1996 (see Fig. 3.5). The fitted line corresponds to the equation

RL = 161.9 - 10*log(R) - 4.8*R

(R in km, RL in dB re 1 µPa). Received levels are the rms pressure pulse levels (see text). Water depth at the airgun array is also plotted.

Also shown in Figure 3.9B is the predicted spectrum of this airgun array (Painter 1996) based on 11 airguns in the array at a depth of 4 m. This estimate is for the farfield in the vertical direction (beneath the array) and includes the surface reflected energy. The differences in level and shape between the predicted array spectrum level and the measurements shown in Figure 3.9B are caused by propagation in the water channel, as discussed in §3.4.

Figure 3.10A shows the 35 received rms pulse levels from the full airgun array during the approaching phase of the run shown in Figure 3.8. Also shown is a fitted curve for which a cylindrical spreading term, -10*log(R), is forced into the best-fit model. The reason for forcing the cylindrical spreading term is discussed in §3.4, where the propagation properties of the Northstar area are analyzed. The equation, given in the caption, is most useful for distances within the measurement ranges, 158-1647 m. Except during the closest portion of the measurement run, the receiving hydrophone was very close to bow-aspect relative to the source vessel and airgun array. The -12.9 dB/km coefficient of R accounts for absorption and scattering losses and explains the downward turn in the best-fit curve at the longer ranges. This is typical of shallow water sound propagation; the depth at the location of the airgun

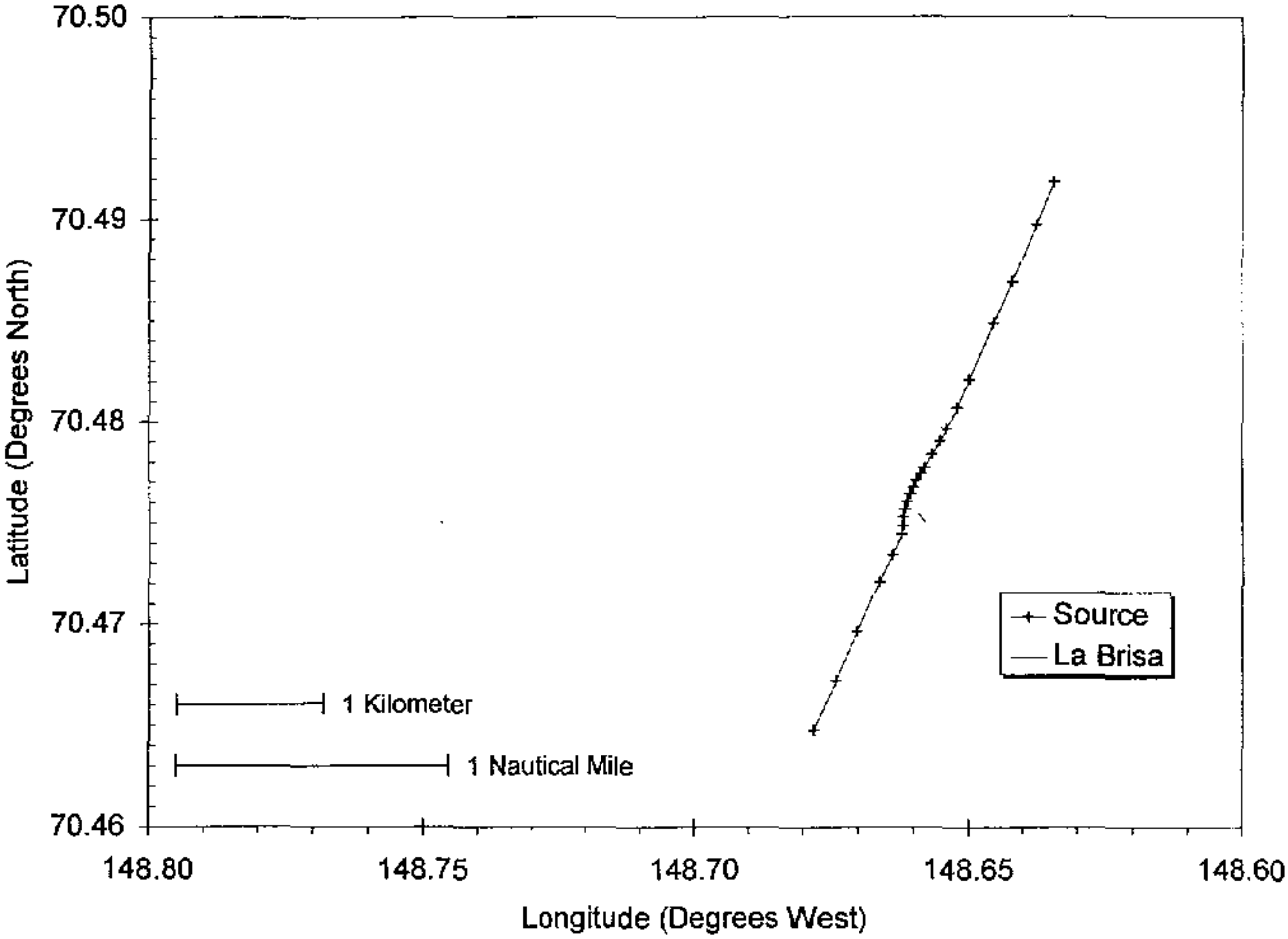

FIGURE 3.8. Track of seismic source vessel *Point Barrow* towing the operating airgun array (11 airguns) past recording vessel *La Brisa* during full airgun array recording on 15 August 1996, 10:00-10:40 ADT, water depth 10.5 m at hydrophone, hydrophone depth 9 m, source vessel traveling from SSW, heading 030° T. *La Brisa* moved slightly on its anchor mooring. Latitude and longitude are in decimal degrees.

array was near 7 m at the longer ranges and increased to 10 m as the source vessel approached the receiving hydrophone.

Figure 3.10B shows the 46 rms pressure pulse levels during the opening range phase of the run shown in Figure 3.8. In this case, all except the closest measurements were near stern-aspect. The ranges were 177 to 2113 m. Again forcing cylindrical spreading, the fitted equation given in the Figure caption has an absorption/scattering loss coefficient of -5.4 dB/km. This is indicative of less loss than was occurring during the "approaching" phase (*cf.* Fig. 3.10A, where loss was -12.9 dB/km) . This difference is probably related to the deeper water at the source and correspondingly lower bottom interaction during the outbound phase: water depth about 7-10 m during the approach vs. 10-11.5 m during the outbound phase.

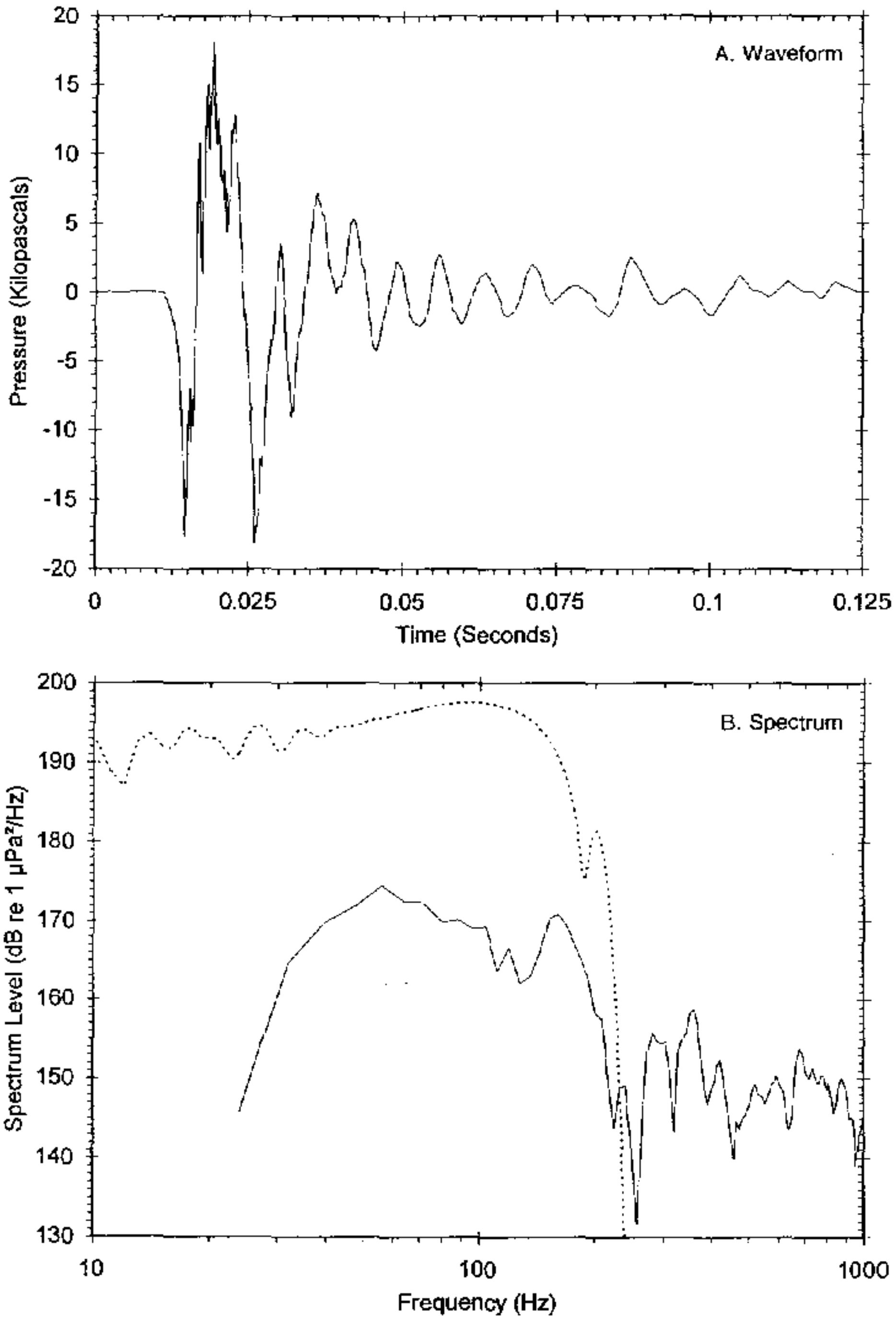

FIGURE 3.9. Waveform (A) and spectrum (B) of pressure pulse from the full 11-airgun array at 116 m distance, 15 August 1996. Dotted line in (B) shows the predicted source spectrum for the array at depth 4 m (Painter 1996). Recording location and depths were as shown in Fig. 3.8. For (B), averaging time was close to the pulse length, 0.125 s and analysis bandwidth was 8 Hz.

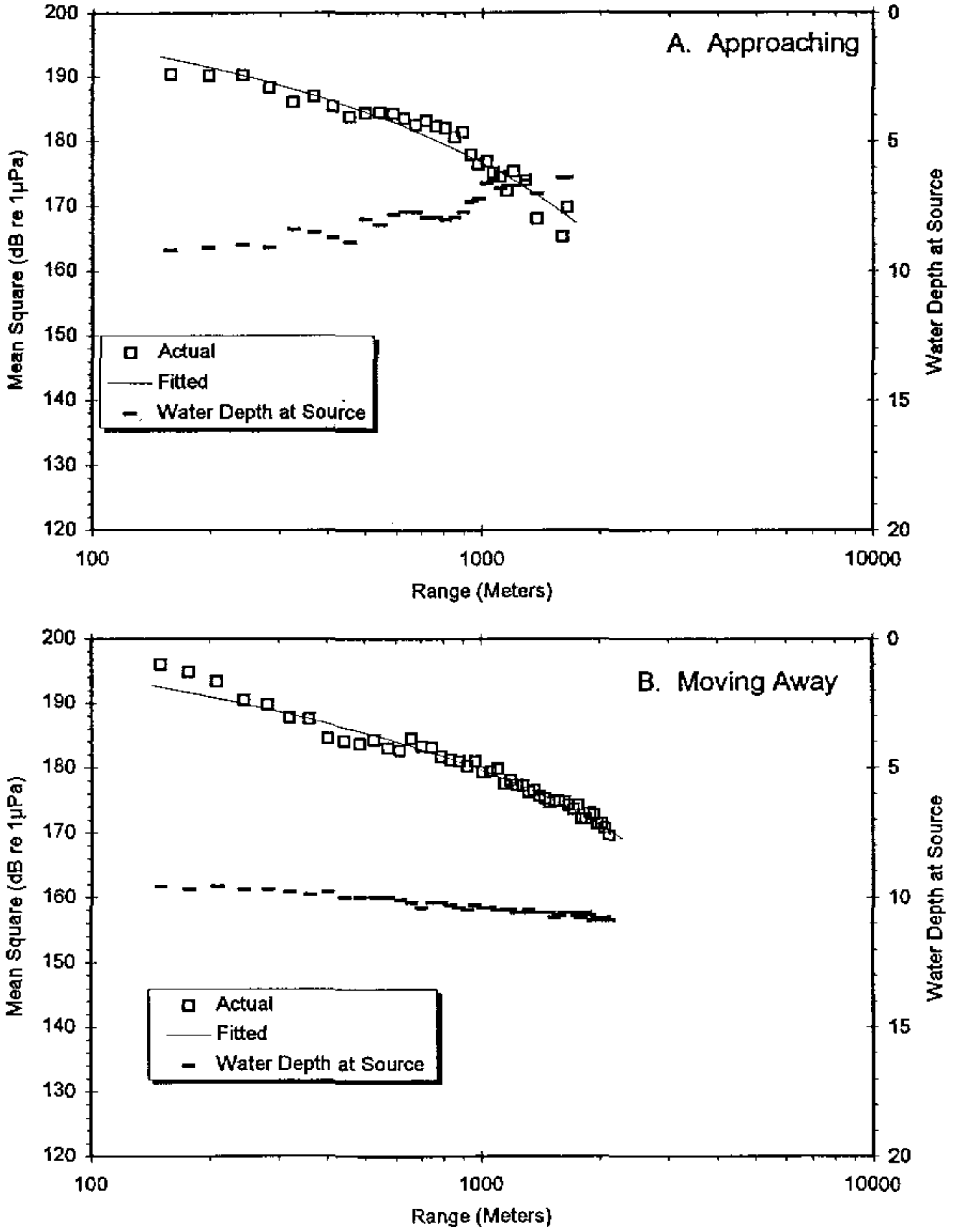

FIGURE 3.10. Received levels of pulses from full 11-gun array measured as the source vessel was ***(A)*** approaching from the SSW, water depths 7-10 m, and ***(B)*** moving away to the NNE, water depths 10-11.5 m, on 15 August 1996 (see Fig. 3.8). The fitted lines correspond to the following equations:

(A): $RL = 188.1 - 10*\log(R) - 12.9*R$

(B): $RL = 185.1 - 10*\log(R) - 5.4*R$

(R in km, RL in dB re 1 µPa). Received levels are the rms pressure pulse levels (see text). Water depth at the airgun array is also plotted.

The deeper water supports propagation of lower frequencies, which are important components of airgun pulses.

Figure 3.11 shows the predicted far-field azimuthal radiation pattern of the full 11-airgun array at four frequencies. Urick (1983:54*ff*) discusses beam pattern computation for arrays of elements. At 50 Hz the array is essentially omnidirectional. At 100 Hz the beam aspect radiation level is about three decibels less than the level at endfire (ahead or astern). At higher frequencies the array directionality increases, as manifest by the peaks and nulls in the azimuthal pattern (Fig. 3.11). However, the pulses contain little energy at frequencies above 150 Hz.

Levels for Full Array vs. Single Airgun.—The constant term in the fitted equation for the single airgun sound, 161.9 dB re 1 µPa, is about 23 dB less than the constant term

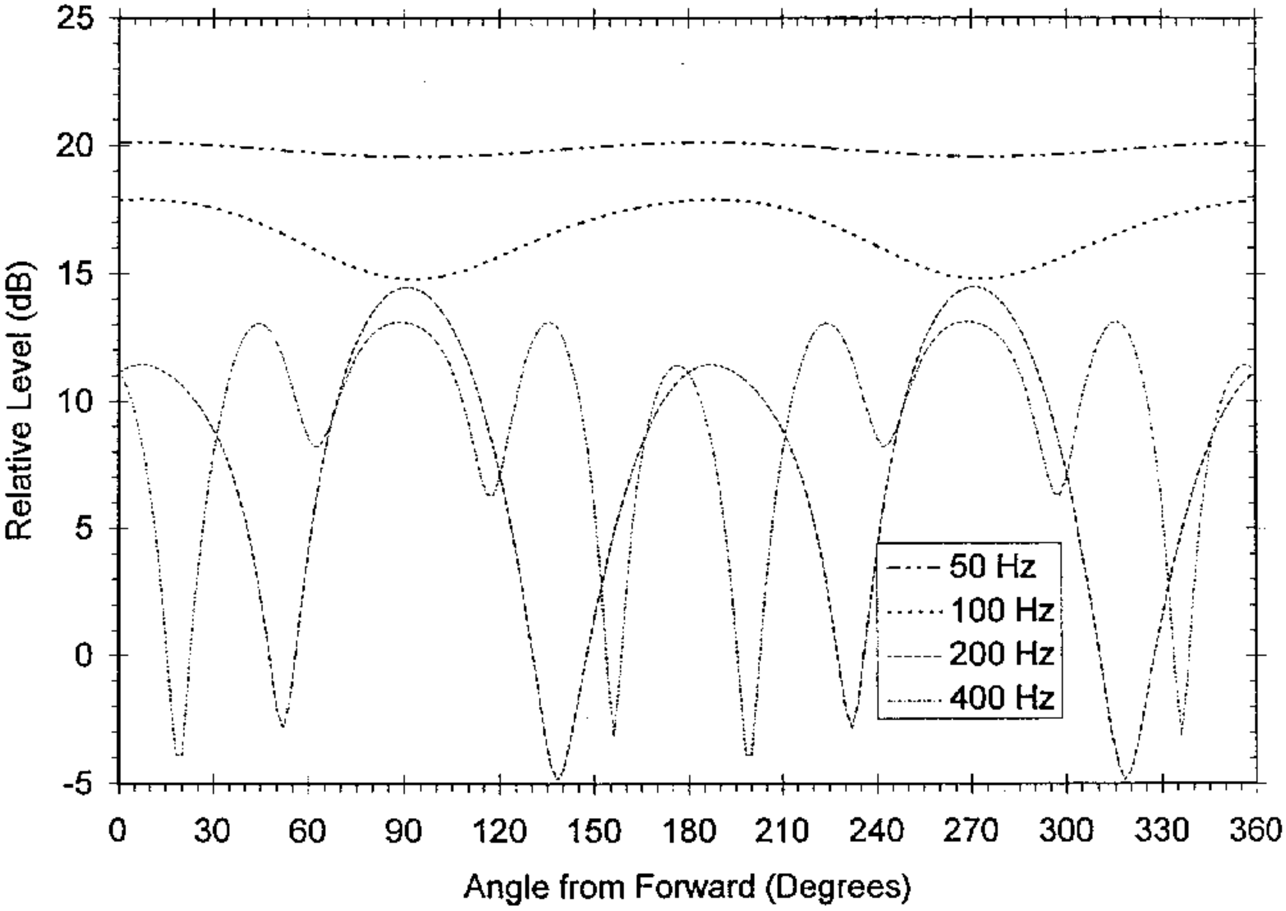

FIGURE 3.11. Predicted azimuthal patterns at 50, 100, 200 and 400 Hz for the full 11-airgun array used at Northstar. These patterns presume the receiver is in the farfield, or beyond 50-100 m.

in the equation for the full array, stern aspect, 185.1 dB. To the extent that the measurement conditions were close to the same, this difference is indicative of the difference in source levels for a single airgun vs. the full array. This 23 dB difference implies that the airgun sounds are adding coherently, or at a rate of 6 dB per doubling of the number of airguns. For such coherent addition, the idealized difference between 1 airgun and 11 airguns would be 20*log(11/1) = 21 dB.

Source Levels for Full Array.—To estimate the effective source level of the full 11-airgun array, it is necessary to take account of transmission loss effects. Therefore, the "Source Level" topic is deferred to section 3.4. That section also includes estimates of the radii corresponding to certain specific received sound levels (e.g., 190, 180 and 160 dB re 1 µPa), which are of interest in relation to potential effects on marine mammals (*cf.* Chapters 4, SEALS, and 5, WHALES).

Partial Arrays

Several configurations of reduced airgun arrays with four to nine airguns operating were measured during the field season. These measurements were obtained because a partial array was used for a small fraction of the production shooting, and because a partial array was sometimes operated during line changes.

Received levels from a six-airgun "partial" array as it moved away are shown in Figure 3.12 along with the least-squares fitted equation with cylindrical spreading forced, i.e. -10*log(R) term included. These data were collected with the array at a depth of 3.5 m in water 9 m deep; the receiving hydrophone was at a depth of 8 m. The difference between the intercept constant in the full array equation (see Fig. 3.10B, 185.1 dB) and in the equation for this partial array (180.6 dB) is 4.5 dB. The predicted decrease under the assumption of coherent addition is given by 20log(6/11) = -5.3 dB. The difference between the predicted and measured decrease in level is less than one decibel. Subtracting the regression equation intercepts corresponds to comparing the measurements at short range. If the regression equations are used to estimate the received levels from the full 11-gun and 6-gun arrays at range 200 m, the difference in the estimates is 5.2 dB. That difference is very close to the predicted 5.3 dB decrease assuming coherent addition of the airgun elements in the array.

Summary

Most of the pulse level measurements given above are rms levels. Rms levels are, in effect, average levels over the duration of the seismic pulse. As shown in Figure 3.3, rms levels are several decibels less than peak levels. The difference between the two measures averages about 10 dB.

Figure 3.13 compares the rms pulse pressure levels in relation to range for varying numbers of airguns, based on data from Figures 3.7, 3.10B and 3.12. Comparisons should be made for the shorter ranges, say <500 m, to avoid marked sound propagation effects.

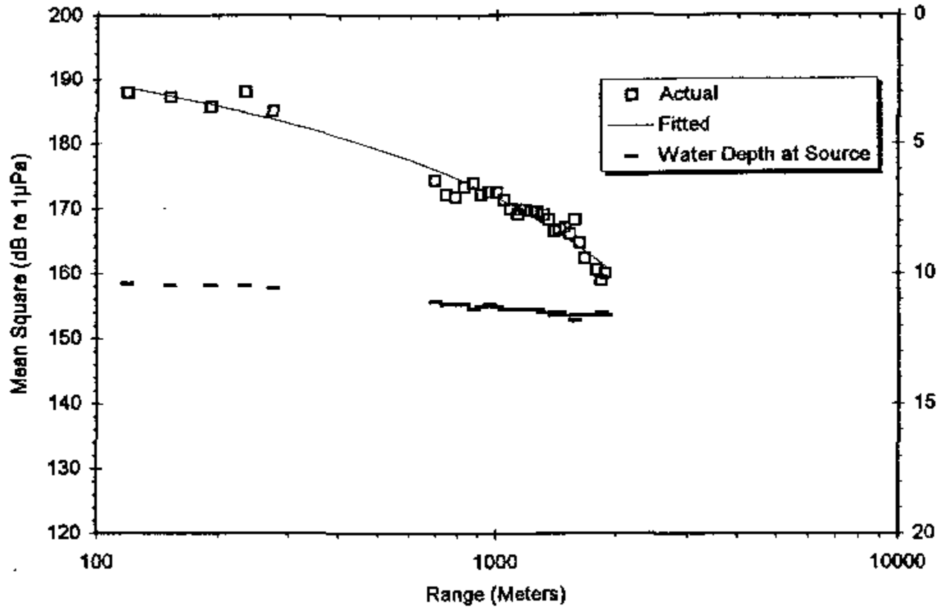

FIGURE 3.12. Received rms pulse levels vs. range (moving away) for array NGC #3, a 6-gun partial array. The line fitted to these 31 points corresponds to the equation

RL = 180.6 - 10*log(R) - 8.9*R

(R in km, RL in dB re 1 μPa). Water depth at the airguns is also plotted.

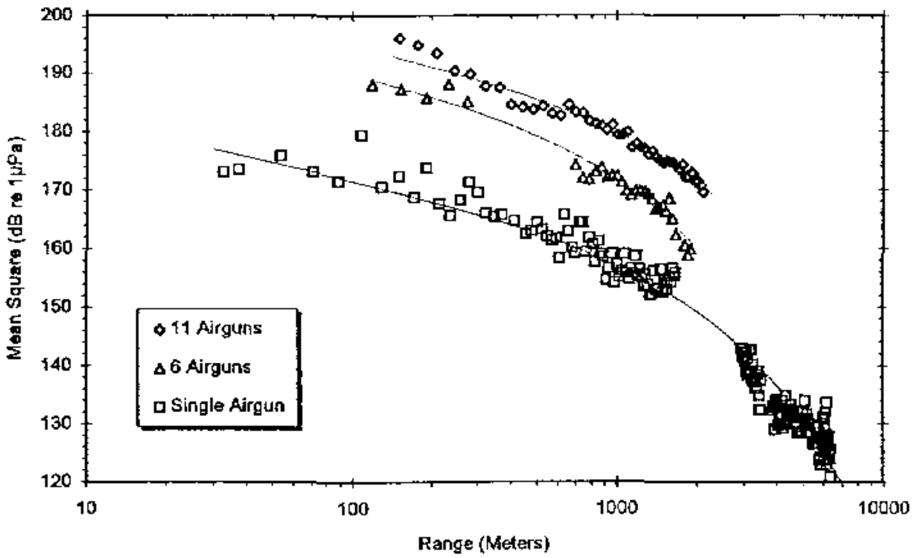

FIGURE 3.13. Received rms pulse levels vs. range for 11, 6 and 1 airguns. All measurements came from the "outbound" operational condition. The fitted lines all have the same spreading loss term, -10*log(R), but differing intercept constants depending primarily on the source levels and differing linear range coefficients (dB/km) depending on the water depths of the measurements.

The results affirm the hypothesis that, for the size of airguns (120 in^3) and array geometry (5 m square) used at Northstar, the sound pressures from the individual airguns added coherently. The pressures will double for each doubling of the number of airguns, which is equivalent to saying that the sound levels will increase by six decibels for each doubling of the number of airguns. Purely coherent addition would result in the 6-airgun array having a pressure level 5.3 dB less than the full array, i.e., 20*log(6/11) = -5.3 dB. The actual differences were -4.9 dB for range 100 m and -5.2 dB for range 200 m. Correspondingly, the single airgun pressure level would be expected to be 21 dB less than the full array, i.e., 20*log(1/11) = -21 dB. The actual differences for ranges 100 and 200 m were both -23 db.

3.4 Transmission Loss and Received Levels of Seismic Pulses

This section begins by describing sound transmission loss at short ranges in and near the Northstar Unit. This description is based on received levels of airgun pulses (single gun and full array) at different ranges and on variations in the frequency content of the received pulses. Secondly, we use the information about transmission loss at short ranges to estimate the source levels of the airguns and to estimate the radii where certain "standard" received levels (190, 180 and 160 dB re 1 µPa) would occur. Thirdly, we describe propagation of airgun pulses to receivers at long ranges (up to 67 km, or 36 n.mi.) in deeper water, mostly to the north or northeast of Northstar.

The effect of source depth on sound transmission was not addressed in this field study as the airgun array depth was the same for all our measurements: 3.5-4 m. However, the effects of surface reflections are well known, giving rise to the Lloyd mirror effect (Richardson et al. 1995:73). The effect is most notable at low frequencies, when the depth is less than ¼-wavelength; the surface reflection interferes with the direct sound paths and sound transmission is poor. For a source depth of 3.5 m, frequencies below about 100 Hz will be severely attenuated during horizontal transmission. This is important because much of the airgun energy is at frequencies from 40 to 150 Hz (Fig. 3.6B, 3.9B).

Transmission Loss Features Near Northstar

Single Gun Data.—On 14 and 17 August, hydrophones deployed from *La Brisa* were used to monitor the levels of a single airgun in two different depths of water. On the 14th, the water depth at the source was 11-13 m, while on the 17th the depth was about 5 m. The frequency content of the pulses was different in those two water depths and the decrease of the rms pulse levels with range was also markedly different. These two data sets support some conclusions about the effect of water depth on the ranges where received sound levels would be expected to diminish below various specified levels that may be relevant to marine mammals, e.g., 190, 180, and 160 dB re 1 µPa.

Figure 3.14 compares the power spectra near CPA for each of the two data sets; the ranges were 128 m and 129 m on the 14th and 17th, respectively. Two points about this comparison are significant. First, there is a sharp decrease in the level below about 40 Hz for both cases. A shallow water channel cannot support propagation of energy below a

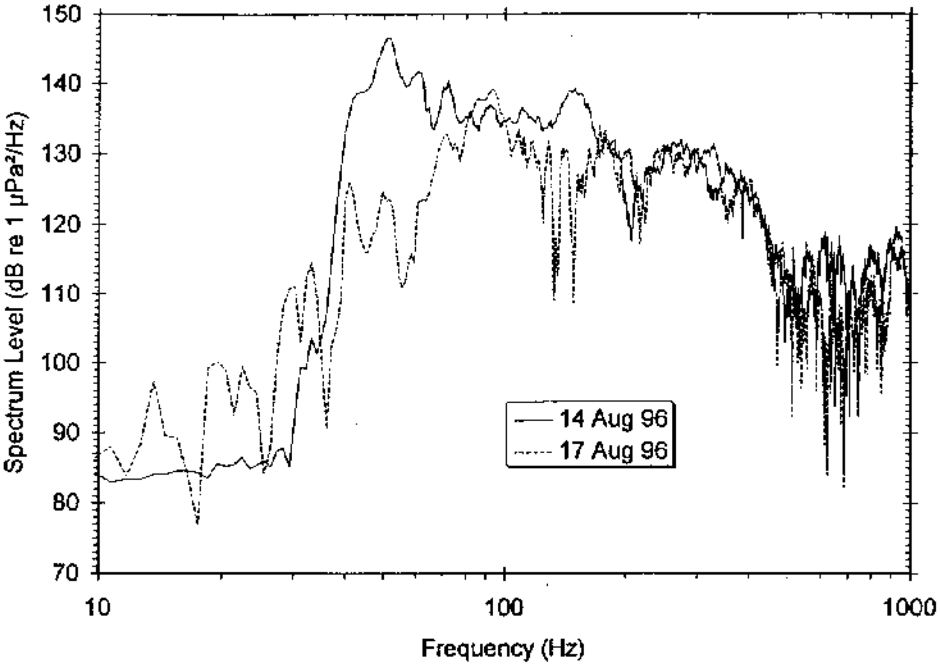

FIGURE 3.14. Power spectra from single airgun at close-range: 14 Aug., distance 128 m and water depth 12 m; 17 Aug., distance 129 m and water depth 5 m. Averaging time was 1 s; analysis bandwidth was 1 Hz.

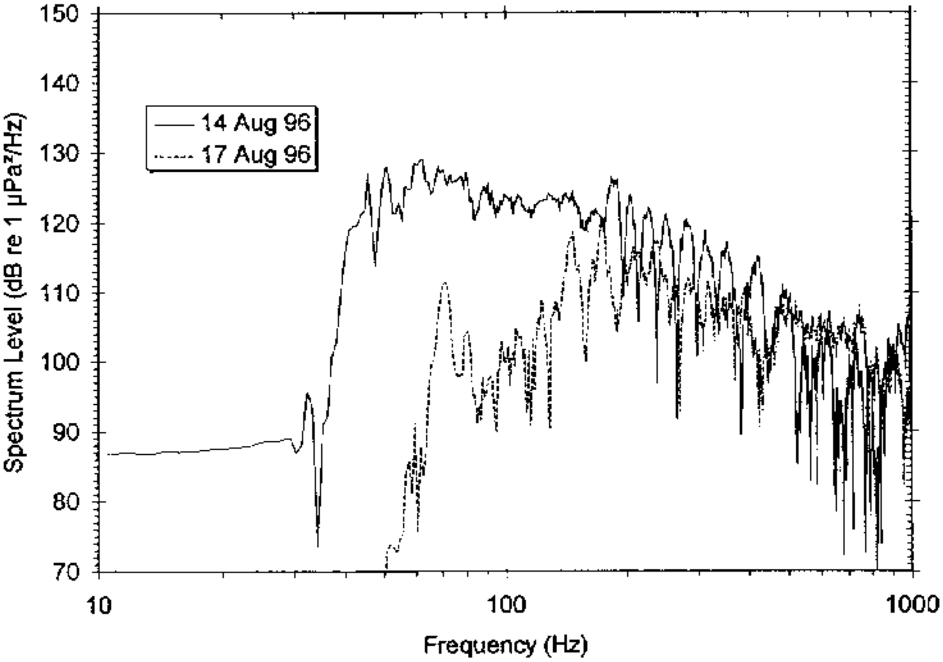

FIGURE 3.15. Power spectra from single airgun at moderate distances: 14 Aug., 910 m; 17 Aug., 820 m. Otherwise as in Fig. 3.14.

critical frequency to horizontal ranges exceeding a few times the water depths. This critical frequency is determined by the water depth and the properties of the bottom. For the simple case of a shallow water layer over a single bottom layer, this frequency is inversely proportional to the water depth (Brekhovskikh 1960). Since the water depth on the 17th was about half that on the 14th, the cutoff frequency on the 17th should have been about twice that on the 14th. Note that the level of the spectrum for the 17th decreased below 70 Hz, and then decreased again, steeply, at 40 Hz. In slightly deeper water on the 14th, there was a steep decrease below 40 Hz, but not at 70 Hz. The difference between the two spectra in the 40-70 Hz range is essentially caused by this waveguide effect.

This behavior of the received levels at low frequencies can be seen even more clearly in Figure 3.15, which compares the spectra at ranges of 910 and 820 m on the 14th and 17th. A sharp decrease in level is quite evident below frequencies of about 40 Hz on the 14th and 70 Hz on the 17th. The ratio of observed cutoff frequencies is not exactly the ratio of water depths (12 m vs. 5 m). This small "discrepancy" probably occurred because the actual environment, e.g., bottom conditions, is more complicated than allowed for by the simple model suggested above.

It is also clear from Figure 3.15 that the total energy level of the received signal is lower in the shallower water, given that the spectral levels at many frequencies are lower on the 17th than those in the slightly deeper water on the 14th. This is more evident in Figure 3.16, which compares the behavior of the rms pulse levels as a function of range for the two data sets. The levels received in 5 m water depth on the 17th decreased much more rapidly with range than did those received in 12 m water depth on the 14th. This result is consistent with the data in Figure 3.15.

The most important implications of these data are that both the frequency content of the propagating airgun signals and the rate of fall-off with range are significantly affected by the water depth in the shallow waters of the survey area. In particular, as water depth decreases, there is ▸ an increase in the cutoff frequency (below which signal components cannot propagate to significant distances) and ▸ an increase in the rate at which the received levels diminish with increasing range.

In Figure 3.16, the data from each day are divided into two subsets corresponding to the measurements while the source vessel *Pt. Barrow* was approaching the recording vessel *La Brisa* ("Before CPA") and while receding from *La Brisa* ("After CPA"). This was done because there is a suggestion in the data of a dependence on aspect. Because the single gun is expected to be omnidirectional at the frequencies which dominate the signal, we speculate that the vessel towing the airgun, the *Pt. Barrow*, may have shadowed the sound to some extent. This could account for the somewhat higher received levels after than before CPA on 14 August. However, the pronounced difference in the opposite direction on the 17th must have been caused by a propagation difference along the corresponding track segments.

Full Array Data.—One of the important considerations in this project is the amount of energy that propagates from the airgun array into the deeper water north of the survey

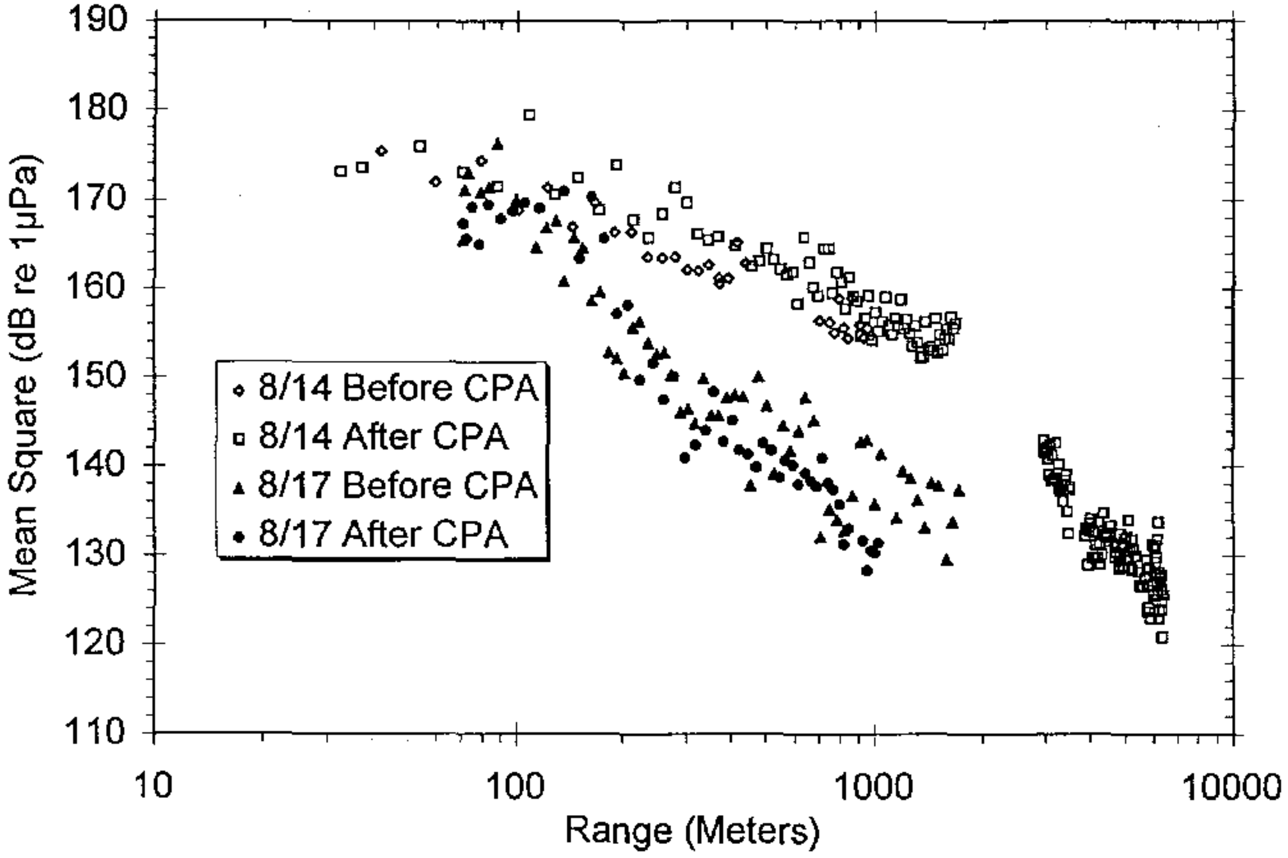

FIGURE 3.16. Rms pulse levels vs. range for single 120 in^3 airgun operating in water ~12 m deep (14 Aug.) and 5 m deep (17 Aug.).

area. Hence, it is important to examine the longer range data when the full array was operating. The data considered here were collected on 15 August 1996 in the morning at ranges up to 2 km and in the afternoon at ranges to about 12 km. Spectra from representative pulses are shown in Figure 3.17 at selected ranges. Two features of the spectra are significant here:

- The low frequency cutoff observed in the single gun data can be seen in these spectra as well. The evolution of the full-array spectra from the shortest range of 115 m out to 2 km shows the development of the same sharp drop as was seen in the single gun data. At the two longer ranges, the low frequency cutoff can still be seen.
- The effective bandwidth of the spectra decreases with increasing range. At 115 m the dominant frequencies in the received pulse extend from about 30 to 200 Hz, while at 2 km the dominant frequencies extend from about 50 to 150 Hz. This

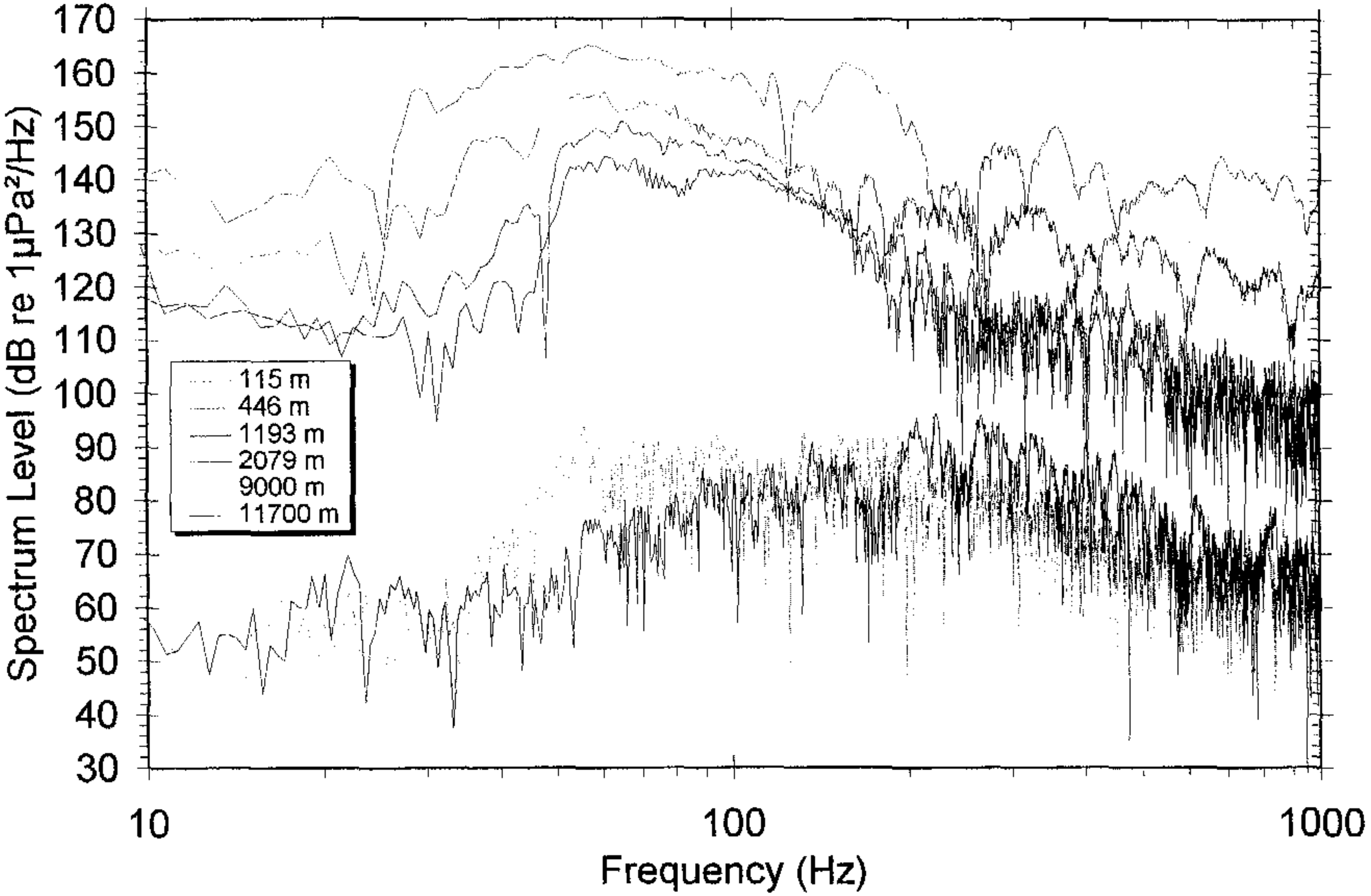

FIGURE 3.17. Representative power spectra at six distances from the 11-airgun array, 15 Aug 1996. Averaging time was 1 s and analysis bandwidth was 1 Hz for the top four spectra; 2 s and 0.5 Hz for the lowest two spectra.

amounts to a change of about a factor of 1.7 in the effective bandwidth. In the simple case of a flat spectrum, the acoustic power or energy is proportional to the bandwidth, which means that a factor of 1.7 change in bandwidth will change the sound level by 10*log(1.7) = 2.3 dB.

Effect of Water Depth on Received Level Radii.—In §3.3, it was shown that the expected difference in radiated level between the full 11-gun array and a single airgun is 21 dB. With this in mind, we can use the single gun data to illustrate the effect of water depth on the 190 dB, 180 dB and 160 dB radii for the full array; these radii may be relevant to marine mammals. To make such comparisons, regression lines were fitted to the data from the 14 and 17 August (Fig. 3.18, 3.19). The slopes of these lines are -15 dB/decade for the data from the 14th and -21 to -30 dB/decade for the data from the 17th (i.e., a reduction in sound level of 15 dB or of 21 to 30 dB per 10-fold increase in range).

Seismic pulses from the full 11-gun array are about 21 dB stronger at any specified range than are those from a single gun. Thus, the range at which sounds from a full 11-gun array diminish to 160 dB is about the same as the range at which sounds from a single airgun would diminish to 139 dB. The data from the deeper (12 m) water on 14 August imply that this level will be reached at 3.6 km (see Fig. 3.7), while the data from the shallower water on 17 August give a range of 0.6-1 km (see Fig. 3.19).

This example demonstrates that the water depth has a substantial effect on the received level at a given range and, hence, on the ranges where levels potentially relevant to marine mammals, e.g., 160 dB, 180 dB and 190 dB, will occur. We do not have acoustic measurements with the array operating in water much deeper than that on the 15th (10 to 12 m). However, this analysis of the single gun data from two depths (~5 and 12 m) implies that, if the array did operate in deeper water, the received levels would change in two ways. First, the received levels would fall off more slowly with range. Second, the spectrum of the pulses as received at substantial distances would contain more low frequency energy. The expected change in the spectrum would occur because the waveguide cutoff frequency would be lower if the water were deeper. The airgun source is energetic at these lower frequencies and higher overall peak and rms levels would be expected.

This implies that, when comparing the apparent disturbance from various seismic surveys, it is important to account for two differences: water depth and the size and number of guns in the array. These two factors can cause significant differences in the received pulse levels at long ranges. For this physical reason (in addition to probable biological reasons), it is not possible to establish a single range beyond which migrating whales would not be affected by a survey. Surveys in deeper water or with larger arrays than were used at Northstar could be expected to produce significantly higher levels at equal or longer ranges than those shown here.

Transmission Loss Model.—Transmission loss in an underwater channel depends primarily on the depth of the channel and the loss of energy that interacts with its boundaries. If these boundaries are perfectly reflecting, the transmission loss will exhibit the