AN ACOUSTIC STUDY OF BOWHEAD WHALES,
BALAENAs MYSTICETUS, OFF POINT BARROW, ALASKA
DURING THE 1984 SPRING MIGRATION

Final Report
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Disclaimer
The opinions, findings, conclusions, and recommendations expressed in this report are those of the authors only and do not necessarily reflect the views of the North Slope Borough.

1986
1984 Acoustic Study

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EXECUTIVE SUMMARY

The overall goal of the 1984 acoustic study was to determine whether the technique of passive acoustic location, could be used to improve the existing methods for estimating the size of the bowhead population based on visual observation of the whales during their spring migration. Special importance was placed on the specific question of determining whether there were bowhead whales either passing by the visual observation sites beyond reliable visual range or unseen due to poor visibility. If it could be demonstrated that the acoustic methods were detecting whales beyond the range of reliable visual observation and during periods of poor visibility then this would strongly support the inclusion of acoustic results into the methods for estimating the number of migrating bowheads.

The specific objectives of the 1984 acoustic study were to:

1) record and monitor bowhead sounds for as much of the migration period as possible,

2) provide acoustic data for a concentrated acoustic/visual correlation study centered on an area in front of the visual observation site where both acoustic and visual accuracy are high,

3) provide verification of the acoustic location technique by performing one-for-one real time acoustic and visual sightings for twelve whales (referred to as the 12 Whale Experiment).
4) conduct a post season detailed analysis of the recorded vocalizations
in order to develop information in support of a more accurate
population estimate for 1984, and
5) engage in an early and late monitoring effort (a North Slope Borough
option).

The first three objectives were met during the spring 1984 season when Drs.
Ellison and Clark directed the field data collection effort for the acoustic
study from 5 April to 26 May. The fourth objective was accomplished in the 10
months following the field season through the efforts of all three authors
with the help of one part-time research assistant. The late monitoring effort
in the last objective was carried out by North Slope Borough personnel.

The major results of this study are as follows.

1) Whales were migrating past Barrow even during heavy ice conditions when
visual observers saw very few whales.
2) The ability to acoustically detect and locate whales was independent of
visibility conditions as described by visual observers. The acoustic
method allowed the detection and counting of whales to continue through
periods when local conditions, such as ice, fog or snow, precluded the
collection of visual observation data.
3) The average source levels of the two most common types of bowhead
calls, up calls and down calls, were not significantly different, and
these call types do not appear to be directional.
4) The distribution of whales during open lead conditions was very different than their distribution during periods of heavy ice. Under open lead conditions 80% of the whales were within 2.5 kilometers (km) of the visual observation perch, while under closed lead conditions 78% of the whales were further than 2.5 km from the visual observation perch.

5) The techniques of acoustic location and tracking resulted in the computation of a minimum number of acoustic whales which, over a given time period, was always greater than the number of whales counted using only visual methods. There was an increase in the number of whales counted when both the acoustic and visual data were combined compared to the count when only visual data were used. In the case of a closed lead condition, the count increased from 3 to 139 whales. In the case of the open lead condition, the count increased from 96 to 242 whales.

6) The methods of acoustic location and tracking are extremely powerful tools for improving the accuracy of the nearshore (closer than 2.5 km) whale count and extending the censusing effort to include areas beyond the range of reliable visual observation (greater than 2.5 kilometers). Even when visibility conditions were good or very good, the acoustic methods detected 42% more whales in the nearshore area than the visual methods and 540% more whales in the offshore area than the visual methods. Thus, even in the prime visual observation area and under conditions when the visual method is assumed to be reliable, a large proportion of whales are not detected by the visual observers, but are detected by acoustic observation methods.
The major objective of the 1984 acoustic study was to provide data which would result in a more precise estimate of the bowhead population migrating past Point Barrow in the springtime. Due to the severity of the ice conditions and the resulting lack of visual sighting data, a population estimate was not derived for the 1984 season. However, based on the results of the acoustic study, it is clear that the responsible application of acoustic techniques can significantly augment the traditional visual censusing methods. The overall conclusion from this acoustic work is that the methods of acoustic location and tracking are powerful techniques for improving the nearshore whale count and extending the censusing effort to include offshore areas beyond the range of reliable visual observation.

The ability of the acoustic methods to both detect and count whales under a wide variety of lead conditions and out to distances well beyond the range of visual detection means that the spring censusing effort can operate effectively for the majority of the two month migratory period. Because of this it is expected that the continued use of acoustic methods for censusing migrating bowheads will result in a more comprehensive and more definitive estimate of the bowhead whale population then has been arrived at using the traditional visual methods alone.
INTRODUCTION

Bowhead whales, *Balaena mysticetus*, produce loud, low, frequency-modulated (FM) calls which have excellent sound characteristics for long range underwater transmission (Payne and Webb, 1971). The acoustic energy of most calls is restricted to the band between 100 and 400 Hz (Clark and Johnson, 1984; Ljungblad, Thompson and Moore, 1982; Ljungblad, Moore and Van Schoik, 1984) and calls have been recorded with received levels as high as 156 dB (re 1 μPa) when animals were 100-150 meters (m) from a hydrophone (Clark and Johnson, 1984). Bowheads are remarkably vocal during their spring migration past Barrow, Alaska. In 1980 during a nine day period when over 1500 whales were seen (Johnson, Braham, Krogman, Marquette, Sonntag and Rugh, 1981), over 6000 calls were recorded on just 17.5 hours (h) of tape recordings (Clark and Johnson, 1984; see also Ljungblad et al., 1984). These acoustic characteristics of bowhead calls and their relatively high rates of vocal activity provide an excellent opportunity for locating the whales by passive acoustic methods during their spring migration.

The technique of locating a sound source at long ranges in the ocean by differences in the sound's time of arrival at an array of hydrophones has had limited success when applied to the vocalizations of large whales. A combination of factors has been responsible for this situation; the physical geometry of an array of sufficient size is difficult to establish and maintain, data recording and analysis requires multiple channel systems and sophisticated signal processing techniques, and verification that a whale was
in the place where the sound was located is initially dependent upon simultaneous visual confirmation that a whale was indeed seen in the place where it was heard.

Four-hydrophone time-of-arrival arrays have been developed and successfully used by scientists at the Woods Hole Oceanographic Institute (WHOI) to track sperm whales, *Physeter catodon* (Watkins and Schevill, 1972, 1977). One of these authors (CWC) has used a three-hydrophone phased array to track southern right whales, *Eubalaena australis* (Clark and Clark, 1980; Clark, 1980) and bowhead whales (Clark and Johnson, 1984). Both these methods have limitations; the WHOI array is quite small (30 m) which limits its effective range to less than 300 m; the phased array technique is dependent on very favorable visual conditions and only really provides a direction to the whale, not its location.

In 1982 another of these authors (WTE) participated in a North Slope Borough sponsored study aimed at acoustically locating bowhead whales off Barrow, Alaska during the spring migration using a three-hydrophone array (Cummings, Holliday, Ellison and Graham, 1983; Cummings and Holliday, 1985). Although location data were only obtained for a short portion of the migration period this effort did demonstrate the feasibility of the multi-hydrophone arrival-time difference technique as applied to acoustically locating migrating bowhead whales.

It has often been proposed in the context of cetacean acoustics that the number of sounds heard could provide information not only on the presence but the number of whales in a given area. As with acoustic location methods,
there has been very limited success with this approach to acoustic censusing. Estimates of the number of singing humpback whales, *Megaptera novaeangliae*, have been made using a dipole array (Winn, Edel and Taruski, 1975). For southern right whales in the Golfo San Jose, Argentina, there was a significant correlation between the number of whales in the gulf and the number of contact calls (low, FM upsweeps) recorded (Clark and Clark, 1981). For bowheads during the 1980 spring migration there was a significant correlation between the number of whales seen per hour and the number of calls heard per hour (Clark, 1983). Although such evidence gives some support to the idea that numbers of sounds are an indicator of numbers of animals in an area, there are no data on the variation in and factors affecting the vocal production of individual whales. Without such evidence the accuracy and precision of any correlation between numbers of sounds heard and visual sightings is difficult to interpret.

One means of relating numbers of sounds to actual numbers of whales is to locate as many sounds as possible, link sequences of acoustic locations together to form acoustic tracks and then compare the number of acoustic tracks to the number of tracks constructed from the visual sighting data or from the combination of both the acoustic location and visual sighting data. Such comparisons determine how many whales are heard but not seen, how many whales are both heard and seen and how many whales are seen but not heard. These results provide important information on the efficiency and reliability of the acoustic method as well as data on the actual numbers of whales detected. All such data are critical in the application of acoustic location data to a population estimate.
In the spring of 1984, an acoustic field study was undertaken off Point Barrow, Alaska in order to determine whether passive acoustic location techniques could be used to augment the bowhead censusing effort. In January 1985, a series of papers were presented at the Third Conference on the Biology of the Bowhead Whale (Ellison, Clark and Beeman, 1985; Clark, Ellison and Beeman, 1985a, 1985b, and 1985c) describing the methods and initial results from the 1984 acoustic field study. These papers were later condensed into a single working paper and presented to the Scientific Committee Meeting of the International Whaling Commission in June 1985 (Clark, Ellison and Beeman 1986). The balance of this report provides a detailed presentation of the methods used to meet the above objectives, the results obtained from the field work and subsequent analyses, and a discussion of these results as they pertain to the overall objective of using acoustic techniques to improve the estimate of the migrating bowhead population. Two appendices are included: Appendix A provides detailed technical information on the field equipment and analysis system specifications, Appendix B provides the details of the sound velocity calibration for the acoustic arrays.
METHODS

The methods used to accomplish the objectives of the 1984 acoustic study can be divided into two major categories, field work for the collection of the acoustic data and later laboratory analyses of these field data. All the acoustic field data were obtained off Point Barrow, Alaska as illustrated in Figure 1. In this figure an enlargement of the Point Barrow region is shown which includes the acoustic field study area. All subsequent acoustic data analyses, except when specifically mentioned in the text, took place at either The Rockefeller University Field Research Center in Millbrook, New York, or at Marine Acoustics in Cotuit, Massachusetts.

The following methods are presented in three sections. The first section is a description of the equipment used in the field. The second section is a description of the procedures for maintaining that equipment and collecting acoustic data from it. The third section is a description of the procedures used to analyse these field data.

Throughout this report references will be made to lead conditions, visual observation conditions and visual observation data. This information was graciously provided by John C. George of the North Slope Borough and Bruce Krogman of Analytical Software Inc. (ASI) (1). The visibility terms used to describe the visual observation conditions are based on the system as described by Krogman and Rugh (1983). Visual observation data are any data on bowhead whales obtained by visual observers. There are two types of visual observation data referred to throughout this text: whales seen and visual

1 Analytical Software Inc., P.O. Box 51048, Seattle, WA 98115.
Figure 1. Map of Alaska (inset) and map of Point Barrow, Alaska showing the acoustic study area with water depth isobars in feet. Both maps are Mercator projections.
sighting. The term whales seen refers to the number of individual whales seen as estimated by the visual observers during an observation period. The term visual sighting refers to any visual observation for which the location of a whale was recorded using theodolite techniques (Clark and Clark, 1980; Krogman and Rugh, 1983; Tyack, 1981; Würsig and Würsig, 1979).

A: Field Equipment

The equipment developed to meet the field data objectives of this study was designed to a top level specification requiring that the equipment survive in the arctic environment for the duration of the study, that it be easily transportable in the field, and that backup replacement systems be available for all key components. Additionally, the total system was to be designed for ultimate total system delivery to, and ownership by the North Slope Borough.

The data acquisition and analysis equipment built for the 1984 field season is composed of three systems: 1) the sonobouy system consisting of an array of three to four sonobuoys for detecting underwater sounds and transmitting that information via radio signals; 2) a receiving and sound recording system consisting of a radio for receiving the sonobouy transmission, a signal-amplifier unit for monitoring the bowhead sounds, and an analog tape recorder for permanently storing the sounds; and 3) a computer-based data processing and analysis system for converting the taped analog data into digital data and processing it in order to locate the whale that made the sound. The following is a brief description of each of these systems. A technical description of these systems and an outline of their operating procedures is provided in Appendix A.
A-1 Sonobuoy System: Sonobuoys are electronic devices designed for the remote
detection of underwater sounds. All sonobuoys (2) consist of a hydrophone
which detects acoustic pressure and a radio transmitter which sends these data
to a distant radio receiver. The hydrophone converts the mechanical energy of
the received sound into an electrical output and amplifies the resultant
signal in a preamplifier located next to the hydrophone. This output is linked
directly by cable to the radio transmitter where the signal is amplified a
second time and converted into an FM radio transmission which is broadcast
from an antenna on the sonobuoy. This radio signal has a power of
approximately 1 Watt and is transmitted on one of 31 standard wideband
channels with the amplitude of the original signal being proportional to the
frequency deviation of the transmitted FM signal. All sonobuoys used in the
1984 study were AN/SSQ 57A's designed and calibrated to a primary sensitivity
of 110 + 1dB re 1µPa/19kHz deviation. In addition to the manufacturer's
sensitivity, we added an extra gain switch at the sonobuoy so that hydrophones
with different sensitivities could be used and still stay within the design
specifications of the sonobuoy. For the hydrophones used during this study
this gain setting was -8 dB.

In order to enhance survival times, sonobuoys were modified for use on the
arctic ice by redesigning them on a modular basis so that the power supply,
antenna, or hydrophone could be replaced after failure. In practice it was
found that we used 14 of 16 available sonobuoys and 24 of 36 available
hydrophones for the extended season from 17 April to 11 June 1984. A typical
sonobuoy installation of one of the units is shown in Figure 2. In this figure
Figure 2. Typical sonobuoy installation showing the sonobuoy, antenna and 12 volt power supply.

Figure 3. The acoustic hut showing the receiving antenna.
the sonobuoy's radio transmitter case is strapped to a wooden pole for support, and the power supply is a 12V battery.

A-2 Radio receiving and sound recording system: The sonobuoys use an FM radio link to communicate with the radio receivers which must be located such that the transmitting and receiving antennae are within line of sight. For this study, radio receivers were located in a portable acoustic hut. This hut was mounted on steel runners so that it could be moved quickly by snow machine from one place to another on the shorefast ice. The hut is shown in Figure 3 with the single receiving antenna mounted on a mast above the roof. The radio receivers are Bearcat scanners (3), modified to allow reception over the full dynamic range of the sonobuoy transmission. The receiver converts the received frequency deviation of the FM signal into a voltage versus time signal referred to as an amplitude-time signal. The signals received on each of the four receivers are connected independently to a custom designed audio monitor box that allows the operator to amplify or attenuate the signal in 10 dB steps on each channel, as well as monitor by stereo headset any two channels independently. With the signal level appropriately set for recording, the signal from each channel is recorded on a TEAC R61-D four channel cassette tape recorder (4). Recordings are made on the full width of a standard 90 minute cassette tape resulting in 45 minutes of data per cassette. The entire receiving and recording system is powered by a 12V battery. Figure 4 shows the receiving and recording system installed and operating in the acoustic hut. In the figure, the receivers are shown at the

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3 Uniden Corp. of America, 6343 Castleway Court, Indianapolis, IN, 46250.
Figure 4. The receiving and recording system installed in the acoustic hut. The four FM receivers are to the left. The audio monitoring box is in the foreground with the TEAC cassette recorder on top.

Figure 5. The computer data acquisition and analysis system operating in the laboratory. Dr. Clark is shown operating the system while monitoring a tape for bowhead calls.
extreme left, the tape recorder is on top of the monitor box, and the stereo headphones are on the table in the foreground.

A-3 Computer-based acoustic processing and analysis system: The acoustic location analysis system consists of an LSI 11/23 minicomputer (5) with an array processor (6) for high speed data manipulation, a video terminal (7) for graphics display, and a set of software programs designed and written by these authors for the specific purpose of analysing and locating bowhead sounds. Although the computer system can and has been used in the field, it is typically located in a laboratory. There a second four channel tape recorder is used to play back the data recorded in the field. These four channel data are played directly into the analog front end of the computer which consists of four 901F Frequency Devices lowpass filters (8) and an ADAC analog to digital converter (9). The lowpass filters remove high frequency noise which interferes with the proper computation of frequency spectra and acoustic locations. The analog to digital converter translates the analog voltage levels of sounds from the tape recorder into digital levels which can then be processed by the minicomputer. An operator controls the analysis process through keyboard entry of simple commands. Using these commands, the operator sets the acquisition bandwidth and digital sampling rate, selects the sounds to be analysed, and otherwise guides the analysis process. A listing of these keyboard entry commands and a brief description of each command function is given in Table A-1 of Appendix A. Figure 5 shows this system being operated in the laboratory.

5 Digital Equipment Corporation, Maynard MA 01754.
7 Visual Technology, Inc., 540 Main St., Tewksbury, MA 01876.
8 Frequency Devices, 25 Locust St., Haverhill, MA 01830.
9 ADAC Corp., 70 Tower Office Park, Woburn, MA 01801.
B: Field Procedures

In order to accomplish the primary goal of acquiring multi-channel acoustic data of bowhead whale sounds, it was necessary to install and maintain arrays of sonobuoys, calibrate the arrays and collect three-channel recordings along with information on any relevant environmental conditions and equipment settings. These tasks were carried out on the arctic ice which meant that the availability and quality of basic life support systems were critical to the success of the project. The next four sections describe how each of the three major field tasks was accomplished, followed by a short description of the logistic support provided by the North Slope Borough during the study.

B-1 Sonobuoy deployment and array installation: Deployment of the equipment in the field consisted mostly of establishing and maintaining the multi-sonobuoy arrays necessary for obtaining multiple channel tape recordings of bowhead whale calls. There were periods when ice conditions were so severe that it was not possible to install an array. In these cases a single sonobuoy was deployed from which sounds were monitored and recorded on a single channel of the cassette recorder. A few hours of stereo recordings were obtained during the periods when either an array was being installed, or one of the sonobuoys was being repaired or an array was being destroyed by ice. Because of the need for integration between the acoustic and visual observation efforts, sonobuoys were always installed close to the visual observation sites. Hydrophones were always deployed to depths of 8 to 14 m either in a hole made through the ice or over the edge of the ice into an area of open water. For an array, all hydrophones were placed at the same depth.
The size of an array was governed by maintenance and support considerations such as the changing of batteries or the replacement of damaged hydrophones, and by location accuracy requirements. The accuracy of a location is directly affected by three factors; 1) the time resolution of the computer program used for measuring a time delay, 2) the quality (loudness, amount of FM sweep, signal to noise ratio etc.) of the bowhead call as it is recorded on the different tape recorder channels, and 3) the size of the angles between the hyperbolic crossbearings pointing to the whale's location.

The time resolution of the computer program is a known value of ± 2-5 milliseconds, and the effect of this time resolution on the accuracy of a location decreases as the size of the hydrophone array increases. The quality of a bowhead call is partially a function of a hydrophone's distance from the vocalizing whale. As distance from the whale increases, the quality of the sound received at the hydrophone decreases. Therefore, increasing the size of the array has the effect of reducing the quality of the sound received on at least one hydrophone, thereby reducing the accuracy of the location. The crossbearing angle is a well defined geometric function of hydrophone separation (Skolnik, 1969). The greater the distances between hydrophones in an array, the greater the crossbearing angle between any two pairs of hydrophones, and the greater the crossbearing angle the more accurate the location. Therefore increasing the size of an array has the effect of increasing the crossbearing angles, thereby improving the accuracy of a location. Taking all of these factors into consideration, a practical optimum array size is about 2000-3000 m overall with a minimum spacing between any two hydrophones of 700 m. This interbuoy spacing of 700 m yields a maximum time delay of 500 milliseconds and thereby reduces the effect of the computer
processing error (± 2-5 milliseconds) to less than 1% of the maximum delay time.

B-2 Array calibration: Calibration of the acoustic array included determining the velocity of sound in water and surveying the positions of all hydrophones in an array relative to the visual coordinate system. Sound velocity in adjacent waters was determined through a combination of on-site experiment, the calculation of the maximum time delay between the occurrence of a known sound at two known hydrophone locations, and a review of relevant oceanographic data for nearshore water off Point Barrow during the months of April and May (see Appendix B). Based on this information, the sound velocity value of 1437 meters per second was used in all acoustic location analyses.

The relative positions of hydrophones in the array were the most critical factor in the accuracy of the location process. These positions were determined by theodolite survey of all hydrophone locations relative to the visual observation perch. Distances between hydrophones, and between hydrophones and their respective sonobuoys were measured with a 100 meter tape accurate to 0.5 centimeter. Angles between hydrophones, sonobuoys and the visual observation perch were measured with a Nikon NT2A (10) theodolite accurate to 10 seconds of arc. This surveying technique resulted in relative hydrophone positions which were accurate to ± 15 m, worst case. This translates to an error of ± 2% for a hydrophone separation distance of 700 m.
B-3 Data collection: A single person, referred to as an acoustic observer, was on acoustic watch during all periods when at least one sonobuoy was operating. For any day there were eight watch periods; four, 2 h watches from midnight to 8 AM and four, 4 h watches from 8 AM to midnight. During most of the season, watches were stood in the acoustic hut. This duty was rotated among all acoustic team personnel on an assigned schedule. Personnel not on watch were on standby to help with maintenance chores such as replacing batteries or changing a sonobuoy's location. The acoustic observer was responsible for monitoring the quality of the sounds being received on each sonobuoy and ensuring that these sounds were recorded and documented properly. In addition, the acoustic observer was the onsite spokesperson for the acoustic team when communicating with the visual observers and base camp personnel. In the event of an emergency the acoustic observer was required to notify the acoustic team leaders (WTE and CWC) and take any appropriate initial actions.

The acoustic observer was responsible for operating the entire acoustic monitoring system. This included the installed sonobuoy array, the receiving and recording system located in the acoustic hut, and all associated power supplies. A continuous monitoring effort was required of the acoustic observer throughout their watch to ensure that each of these components was operating properly. This was accomplished by listening to the incoming sounds via the stereo headphones, and checking for audible signal to noise ratios and the general quality of the sounds on each of the hydrophones. In the event of a major deviation in signal quality on any channel, the acoustic observer notified one of the acoustic team leaders who would then become responsible for determining the nature of the problem and solving it.
The acoustic observer's two primary tasks were the changing of tape cassettes in order to ensure the continuous recording of sounds and the documenting of all acoustic information into a logbook. The purpose of this logbook was twofold. First, it provided a supportive background narrative for the data record including: 1) comments on unusual sounds heard; 2) details related to any of the equipment including hydrophone locations, modifications in array configuration, battery changes, equipment malfunctions, and ice and weather conditions; 3) recommendations for improvements in procedures or equipment design; and 4) any germane comments on the overall acoustic effort. Second, this logbook served as part of the primary data record itself. At the start of each tape, the acoustic observer announced onto the voice channel of the tape recorder the tape identification number, the time, the equipment status settings and any other pertinent information regarding the acoustic effort (e.g. a battery change, improving ice conditions etc.). This same information was written into the logbook thereby providing a duplicate record of all the information announced onto each cassette tape. The tape identification number was a unique number coding for the date and the tape number sequence for that date. For example, the identification number for the twentieth tape recorded on April 24th would be 042420; 04 being the month, 24 the day of the month, and 20 the tape sequence number. The time was the time at which the acoustic observer announced a time mark onto the tape via a microphone. This time was based on a clock kept in the acoustic hut and synchronized regularly throughout the day with the clock kept by the visual observers. During later analysis of the tape in the laboratory, this time mark was located by relistening to the tape and then used to determine the exact start time for that tape.
The equipment status was also entered in the logbook at the time of each tape change and whenever any change in equipment settings occurred. The equipment status information included the relative position of each operating sonobuoy, the FM transmission frequency of each sonobuoy, the receiver number and tape recorder channel number for each sonobuoy, and the audio monitor box gain and attenuation settings. The acoustic observer was also responsible for keeping a tally of the number of bowhead sounds heard per 15 minute interval. This tally served as a rough estimate of the number of bowhead sounds and is referred to as the raw count of bowhead sounds. The sensitivity settings and hydrophone depths for each sonobuoy in the array were also entered in an appendix to the logbook by the acoustic team leaders whenever there was a change in one of these values.

Communication between the acoustic and visual observation efforts was accomplished via FM radios. Stations using these radios included the acoustic hut, the visual observation perches, the North Slope Borough science building and various other North Slope Borough personnel. In general, communications were also monitored by both acoustic and visual personnel who were not on watch but awake at any of the ice camp sites. This FM radio communication network was used primarily for transmitting general environmental information and synchronizing time checks. The transfer of bowhead whale acoustic information to the visual observers was discouraged by the visual team leaders as it was felt that this information changed some of the basic assumptions regarding the two-perch observation methods used by the visual observers. During the 12 Whale Experiment, this restriction was waived and acoustic information was continuously passed on to the visual observers.
B-4 Logistic support and training: A significant factor in our success during the 1984 field season was the excellent logistic support provided by the North Slope Borough staff. This support included the provisioning of food, tents, fuel, recharged batteries, radios, snow machines etc. throughout the entire field season. Coordination with the visual census team was provided primarily through a central coordinator, Bruce Krogman. Numerous planning meetings were held throughout the season to enhance the quality of the acoustic and visual study efforts. Particular attention was given to ensuring that the same time base and geographic reference system were used by both teams. In practice, acoustic team personnel often participated in both the layout of the visual coordinate system and the installation of the hydrophone arrays.

We devised and implemented training sessions to increase the capabilities of acoustic observers in the use of all aspects of system operation and data collection techniques. The purpose of these sessions was to increase observer expertise and train North Slope Borough personnel so that they could properly operate the equipment in our absence. Each participant was required to completely assemble the system from a packed condition, prepare and deploy a hydrophone and sonobuoy, record a sonobuoy signal, disassemble the system, and repack it for transport. All trainees were able to accomplish this task upon completion of the training period.

C: Data Analysis

There were three primary and one secondary data reduction efforts. The first was to analyse as many tapes as possible in order to count the numbers and types of sounds contained on the field recordings. The second was to compute the locations of as many bowhead sounds as possible when visual observation
conditions were good or very good. These conditions corresponded to periods when multiple channel recordings of bowhead sounds and visual sightings of the whales were obtained concurrently, and the lead was generally described as open. The third primary data reduction effort was to compute the locations of bowhead sounds when visual observations were fair to unacceptable. These conditions corresponded to periods when multiple channel recordings of bowhead sounds were obtained but the lead was either obscured by ice, fog or snow, or was generally described as closed. The secondary data reduction effort was to compute the source levels for as many of the located sounds as possible.

All data on numbers and types of bowhead whale sounds per tape, numbers and types of sounds per hour, and acoustic locations were given to Dr. Judith Zeh as part of the collaborative data analysis effort. Dr. Zeh of the University of Washington in Seattle, Washington, and her student, Dajin Ko, used these data to test for the significance of any correlations between acoustic results and a variety of non-acoustic parameters such as lead conditions, weather conditions, diurnal effects, numbers of visual sightings etc. (see Ko, Zeh, Clark, Ellison, Krogman, and Sonntag, 1986). The acoustic location data from the period of concurrent acoustic locations and visual sightings were analysed by Zeh and Ko in order to test for the occurrence of concurrent acoustic and visual locations. This effort was undertaken based upon the recommendation of the 1983 meeting of the Scientific Committee of the International Whaling Commission which stated that 12 simultaneous acoustic locations and visual sightings would be needed to demonstrate the validity of the acoustic location method. The results of these analyses are referred to as the 12 Whale Experiment.
The acoustic location data also serve as the sole basis for constructing acoustic whale tracks and acoustic distributions of whales across the lead relative to the primary visual observation perch. These distributions, referred to as closest point of approach (CPA) distributions, are conceptually similar to those used in the past for displaying the distribution of whales based on visual sighting data. For this reason CPA distributions based on acoustic data are directly comparable to those based on visual data. For the purpose of constructing acoustic tracks and CPA distributions, all acoustic data were given to Ronald Sonntag and Bruce Krogman of ASI as part of a collaborative data analysis effort. ASI processed these acoustic location data, the visual sighting data and the combined acoustic/visual data sets into whale tracks and CPA distributions (see Sonntag, Ellison, Clark, Corbitt, and Krogman, 1986). The resulting information was then used for computing the minimum number of bowhead whales either detected by the acoustic method alone, by the visual methods alone or by both methods together and for counting the number of whales that passed at different distances from the visual observation perches. In order to compare the acoustic results with the visual results, ASI has kindly provided us with all the necessary data analysis as well as the figures of whale tracks and CPA distributions.

**C-1 Ambient noise considerations:** Before proceeding with a description of the methods used to detect, categorize and acoustically locate a bowhead call, it is important to discuss the ambient noise factors which might affect these analyses.

Ambient sounds arise from biological and physical sources. The two major contributors to the biological ambiance are bearded seal, *Erignathus barbatus,*
and beluga whale, Delphinapterus leucas. Since both the seals and the beluga whales are often near the shorefast ice boundary, they are often very near the hydrophones and therefore the intensity of their sounds can be considerably greater than a bowhead's. Most of the sounds of the bearded seal at this time of year are repetitive sequences of highly modulated vocalizations, lasting several minutes in length and containing frequencies between 200 and 3000 Hz (Ray, Watkins and Burns, 1969). Although most of the acoustic energy in the bearded seal calls is above 400 Hz (the practical upper range of the bowhead), and can therefore be removed by filtering, there are portions of their calls which are below this frequency and therefore overlap with the calls of the bowhead whale. The beluga whales also make some sounds which are below 400 Hz and are therefore another potential source of interference with the bowhead whales' sounds. This problem of biological interference is alleviated to some extent by filtering out any signals above 400 to 500 Hz. This filtering process provides two benefits since it attenuates the loud, high frequency sounds which interfere with both the acoustic observer who is monitoring the hydrophones for bowhead calls and the acoustic analysis process used for locating a bowhead sound. For these reasons low pass filters were incorporated at two places in the overall acoustic system. The first set of low pass filters were built into the custom designed monitor system so that the acoustic observer could concentrate on listening for bowhead calls without having to listen to bearded seals or beluga whales. The second set of low pass filters were inserted between the tape recorder outputs and the computer analysis system thereby removing the high frequency signals that might degrade the acoustic location process. The basic tape recorded data, however, were all recorded in their original unfiltered conditions.
The bulk of nearshore background noise in the Arctic comes from physical sources (Urick, 1975; Milne, 1967). The three most prevalent physical sources are: 1) flow noise resulting from ocean currents flowing by the stationary hydrophones, 2) wave noise resulting from areas of open water near the hydrophone, and 3) ice noise resulting from the movement of ice.

Flow noise is largely the result of the movement of turbulent eddy patches over the sensitive face of the hydrophone. The hydrodynamic energy of these patches is transduced by the hydrophone into acoustic noise. The amount of flow noise produced by water at current speeds of 3 to 4 knots can reduce the number of acoustically located bowhead sounds by at least a factor of two. This problem is alleviated to a certain extent by placing a soft spring between the hydrophone and the supporting cable as well as by covering the hydrophone with a fine open mesh which reduces the sizes of the eddy patches.

Waves breaking on the surface of the water or against the ice edge generates acoustic noise which can obscure bowhead sounds. In general, wave noise is only a problem when the hydrophones are located right at the edge of open water where waves are impacting against the ice. With respect to wave noise, it is important to note that the open lead conditions which are best for visual observations usually create the greatest amount of flow and wave noise, and are therefore not the best conditions for acoustic observations.

Ice noise results from interaction between individual pieces of ice, the response of ice to thermal transients, and the flow of wind and water over the ice. The only ice generated noise that had any potential for interfering with the analysis effort was from either the interaction of ice pieces during
pressure ridging or the movement of ice due to high currents. In this latter case, the ice field in the shear zone would move past the shorefast edge producing a sound similar to the rumbling of a freight train. Due to the unusual prevalence of a northwest wind in 1984, we experienced a very high incidence of pressure ridging in the vicinity of the arrays. In fact, most of our arrays were lost because of such pressure ridging events. The noise from these pressure ridging events almost always obscured all biological sounds if the event was occurring within half a kilometer from the hydrophone. Its effect at greater distances depended on the size and speed of the event. In 1984 about 20% of our recordings from hydrophone arrays were seriously affected by pressure ridging noise.

C-2 Numbers and types of bowhead whale calls: The procedure for categorizing and counting bowhead whale sounds was as follows. All tapes selected for analysis were converted into continuous visual representations of sounds known as spectrograms which display sounds in a format such that the loudness and frequency content of a sound correspond to the darkness and shape of the visual image in the spectrogram. Spectrograms were produced either as single channel representations of sounds from a single hydrophone or as stereo representations of sounds from the two most distant hydrophones in an array. In all further discussions in this report these stereo visual representations of sounds will be referred to as stereograms. Figure 6 is an example of a stereogram showing three bowhead calls recorded at the northern hydrophone (upper half of figure 6) and the southern hydrophone (lower half of figure 6) in the array. In this figure the vertical axis is frequency, while the horizontal axis is time, increasing from left to right. This figure illustrates how the same sound received on two separate hydrophones is
Figure 6. Stereogram showing three bowhead calls as they were recorded at the two most distant hydrophones of the sonobuoy array. The approximate time delay between the arrival of the third call in this example is indicated as $\Delta T_{1-3}$.
displayed as two almost identical shapes separated by a time delay $\Delta T_{1-3}$. The stereogram format therefore provides a rapid means of recognizing the occurrence of a bowhead sound, the shape of the call, the time it occurred and whether it was detected at the two most distant hydrophones. The recognition of a bowhead call is essential for all aspects of this study. The shape of a call is the means by which it is categorized into one of the several call types. The time at which a call occurred is necessary for proper collation of the acoustic and visual data sets. The occurrence of a call at the two most distant hydrophones is the initial basis for deciding whether the call can possibly be located. The procedure for converting a tape recording into a stereogram was similar to that used in previous studies (Hopkins, Rossetto and Lutgen, 1974; Clark and Johnson, 1984), only in this case a single channel analyser converted two channels of tape input simultaneously. This was accomplished by heterodyning the second channel with a 400 Hz oscillator, bandpassing the output between 400-800 Hz and then mixing the two channels on a stereo mixing console. The mixed output was then fed into a Spectral Dynamics SD301C real-time analyser (11) for conversion into frequency spectra that were then photographed onto 35 millimeter paper using a C4R Grass kymograph camera (12). Tapes recorded during non-array periods were converted into single channel spectrograms. All spectrograms, stereo or mono, were then labelled with start and end times and minute by minute time marks.

There were two ways by which these spectrograms were scored for numbers and types of sounds. The majority were scored simply by visual inspection; bowhead calls were identified and then categorized into one of seven sound categories.

11 Scientific Atlanta, P.O. Box 671, San Diego, CA 92112.
12 Grass Instruments Inc., 101 Old Colony Rd., Quincy, MA 02169
as illustrated in Figure 7 (see also Würsig, Clark, Dorsey, Fraker and Payne, 1982; Clark and Johnson, 1984). Total numbers and types of sounds were then tallied on a minute by minute basis. Some tapes were also scored by relistening to them at the same time as the spectrogram was inspected. Comparison of the results obtained by these two types of analyses for the same tape was used to assess the error in the common method of counting and categorizing sounds by visual inspection of the spectrograms alone.

C-3 Acoustic locations: There were three basic steps in the sound location process. First, a bowhead sound which could possibly be located was identified. Then the time delays between the arrival of that sound at each pair of hydrophones were computed. Finally the location of the whale that made the sound was located based on these time delay values.

The analytical procedure was as follows. Potential sounds for location analysis were identified by time and type using the stereograms as a visual guide. Selection was initially based only on the criteria that the sound be detected at the two most distant hydrophones and be on a bearing somewhere within the 120° sector directly in front of the visual observation perch as illustrated in Figure 8. In this figure the array axis is the line running through the hydrophones at the ends of the array (Hy#1 and Hy#3), while the center line of the array is the line, C, perpendicular to the midpoint of the array axis. The 120° sector excluded sounds which came from areas which were greater than 60° to the right or left of the center of the array. Sounds from these areas were not included in any acoustic analysis results because the range errors associated with crossbearings in these areas were unacceptably large. The decision as to whether a sound originated from within the 120°
Figure 7. Spectrographic examples of the seven different types of bowhead whale calls. There are two examples shown for each of the call types, which are referred to as: 1) up calls, 2) down calls, 3) constant calls, 4) inflected calls, 5) high calls, 6) pulse tonal calls, and 7) pulsive calls.
Figure 8. Diagram of the 120° sector area in which acoustic locations were computed. The axis of the array is the line running through the hydrophones at the ends of the array (Hy#1 and Hy#3), while the center of the array is the line, C, perpendicular to the midpoint of the array axis.
sector was made by measuring, from the stereograms, the approximate time delay between the arrival of the same sound at the two most distant hydrophones (see Fig. 5 for an example of this time delay). Since any delay greater than \(\pm 87\%\) of the maximum delay (\(\arcsin 0.87 = 60^\circ\)) would translate into a bearing outside the acceptable region, only sounds with shorter delays were selected for location analysis. We tended to be lenient in the initial acceptance of a sound for location analysis since such analysis would quickly reveal if the sound was indeed outside of the acceptable 120° sector. This approach was used in order to reduce the chances of rejecting a sound that was actually within the sector.

Once a sound was identified as originating from within the 120° sector, the exact time delays between its occurrence at each pair of hydrophones were computed using the minicomputer sound analysis system. There were two methods for computing these time delays. The first method, hereafter referred to as amplitude cross-correlation, computes the delay time between the occurrence of a bowhead call at any two hydrophones by one dimensional cross-correlation of their amplitude-time signals. This process can be described mathematically in the following manner. If the two amplitude-time signals to be cross-correlated are \(a(t)\) and \(b(t)\), then the cross-correlation function, \(C(\Delta T)\), is given by,

\[
C(\Delta T) = \sum_n a(n\Delta t) b(n\Delta t + \Delta T)
\] (1)
where,

\[ \Delta t = \text{time interval between successive data points in the signals}, \]
\[ n = \text{index of time}, \text{ and} \]
\[ \Delta T = \text{the time offset between the two signals}. \]

The time delay between the two signals is the value of \( \Delta T \) at which the function \( C(\Delta T) \) is a maximum value.

This amplitude cross-correlation function was implemented as follows. In the actual computer analysis procedure, the computer acquires the bowhead call from each of the tape channels and converts it into an amplitude-time signal as illustrated in Figure 9. Before any time delay analysis, each of the amplitude-time signals is transformed into a frequency-amplitude spectrum and displayed on the video graphics terminal as illustrated in Figure 10. The lowest, \( f_{\text{low}} \) and highest, \( f_{\text{high}} \) frequencies in the call are then measured directly from this graphics display, with \( f_{\text{low}} \) being the lowest frequency at which the spectrum is ca. 3 dB above the ambient noise level and \( f_{\text{high}} \) being the highest frequency at which the spectrum is ca. 3 dB above the ambient noise level. The call's effective spectrum bandwidth, \( \text{BW-eff} \), is then calculated by subtracting \( f_{\text{low}} \) from \( f_{\text{high}} \). A bandpass filter with a bandwidth identical to the call's \( \text{BW-eff} \) is then made using the analysis program's software. Finally, each of the amplitude-time signals is filtered by this custom made bandpass filter, resulting in amplitude-time signals which contain much less noise than their original representations and therefore result in
Figure 9. Amplitude-time plots of the amplitude-time signals for the same bowhead call as it occurred on the three different hydrophones in an array. The three waveforms do not appear as identical signals because of their different arrival paths to the three hydrophones.
Figure 10. Frequency-amplitude spectrum of a bowhead call for a single hydrophone in an array. The lowest frequency in the call is labelled $f_{\text{Low}}$, while $f_{\text{High}}$ is the highest frequency in the call. BW-eff is the call's effective bandwidth, calculated by subtracting $f_{\text{Low}}$ from $f_{\text{High}}$. AL is the call's peak spectrum level, also referred to as the signal's analysis level.
more accurate computations of time delays. During this step in the analysis procedure, the peak levels of the frequency spectra for the call on each hydrophone channel are also measured directly from the graphics display. Each of these peak spectrum levels is referred to as the signal’s analysis level, AL. In cases where the ambient noise level is within 3 dB of the peak level, these peak levels are subject to too much uncertainty and are not considered reliable measurements. Therefore, sounds with peak levels within 3 dB of the ambient noise level were not included in any source level measurements. The frequency range and peak levels in a call are given specific names, BW-eff and AL respectively, because these values are used in the computation of bowhead sound source levels as presented in Methods section C-4 Source levels on page 48 of this report.

The next step in the location process is to take each pair of filtered amplitude-time signals and shift one signal over the other, time increment by time increment, computing a correlation value for each possible time shift. The amount of time shift that produces the highest correlation value is the time delay between the occurrence of that sound at that particular pair of hydrophones. This analytical process can be visualized in the following manner. If the plots of two amplitude-time signals are viewed as two separate photographic transparencies (with both signals plotted in proper relative time of occurrence on the same absolute time scale), then the time delay between the two signals is found by overlaying the two transparencies and sliding one over the other along the time axis until the two plots are optimally aligned.

Although the amplitude cross-correlation method is straightforward and easy to apply, it does not take advantage of the additional frequency information
available in most bowhead calls. In order to incorporate this frequency information into the analysis process, a second, more sophisticated time delay analysis method (Altes, 1980) was implemented in December 1984 near the end of the first 1000 sound location effort. This second method, hereafter referred to as frequency-amplitude cross-correlation, computes the time delay between the occurrence of the same bowhead call at two different hydrophones by two dimensional cross-correlation of their frequency-amplitude-time signals. In this process each amplitude-time signal is first converted into a sequence of frequency-amplitude signals using a sliding discrete Fourier transform (Brigham, 1974). This process can be described mathematically by the following notation. If the two original amplitude-time signals are \( a(t) \) and \( b(t) \) then their sequences of Fourier transforms can be represented as \( A[f(k), t] \) and \( B[f(k), t] \), respectively. Here, for each time increment, \( \Delta t \), there is a set of amplitude values, \( f(k) \), representing a spectrum of frequencies rather than a single amplitude value as was used in the first method for computing time delays. The correlation of the two sequences of frequency-amplitude values therefore involves a correlation in both the time and frequency dimensions; hence this process is described as a two dimensional cross-correlation. This correlation can be represented in general form as:

\[
g(\Delta t) = \sum_{n} \sum_{k} A[f(k), n\Delta t] B[f(k), n\Delta t + \Delta t]
\] (2)
where,

\[ f(k) = \text{frequency-amplitude spectrum at time } t, \]
\[ \Delta t = \text{time interval between successive frequency-amplitude spectra,} \]
\[ n = \text{index for successive spectra, and} \]
\[ \Delta T = \text{the time offset between the two signals.} \]

The time delay between the two signals is the value of \( \Delta T \) at which the correlation function, \( C(\Delta T) \), has a maximum value.

In the actual computer implementation of the above algorithm, the computer acquires each sound, converts it into a frequency-time-amplitude matrix and displays these matrices on the video graphics terminal as illustrated in Figure 11. At this point the person operating the computer selects the size of the time increment, \( \Delta t \), and the number of frequency bands, \( k \), in the frequency spectrum \( f(k) \). The computer then computes a new set of matrices based on these parameters, takes each pair of matrices and shifts one over the other, time increment by time increment, computing a correlation value for each possible time offset. The amount of time offset that produces the highest correlation value is the time delay between the occurrence of that sound at that particular pair of hydrophones.

Like the amplitude cross-correlation method, this frequency-amplitude cross-correlation method can be explained using a visual analogy. If the plots of two frequency-amplitude-time matrices are viewed as separate photographic
Figure 11. Frequency-amplitude-time plots of the frequency-amplitude-time matrices for the same bowhead down call as shown in Fig. 9. These plots illustrate how the three calls which appear different when displayed as amplitude-time waveforms in Fig. 9, appear quite similar when displayed as frequency-amplitude-time plots.
transparencies (with both signals plotted in proper relative time of occurrence on the same absolute time scale as is represented in Figure 11), then the time delay between two signals is found by overlaying the two transparencies and sliding one over the other along the time axis until the two plots are optimally aligned.

It is important to note that in both of these time delay methods it is not necessary to either know or calculate the signal's exact onset time or time-of-arrival in order to determine delay times. Instead, time delays are determined by computing the amount of time that the two matrices representing the same call on two hydrophones must be shifted or delayed in order to produce the maximum correlation between the two matrices. Both these correlation methods incorporate significantly more of the sound's information than the time-of-arrival technique to compute delay times. As a result, a greater percentage of calls can be located by these methods and calls are located with greater accuracy compared to results from the time-of-arrival technique.

Both the amplitude and frequency-amplitude cross-correlation methods result in a time delay for each possible pair of hydrophones. Each of these time delays, together with the velocity of sound in water and the hydrophones' positions provide the necessary information for computing the location of the whale making the sound.

The process of locating the origin of a sound in two dimensions using time delays can be explained using a few mathematical expressions. Simply stated, the loci of points of equal time delay between the occurrence of a sound at
each of two hydrophone locations is a hyperbola (referred to earlier in the

text as a crossbearing). Using a polar coordinate system with its origin at

the midpoint of the two hydrophone locations, the θ = 0° azimuth corresponding
to the axis of those hydrophones and R being the range from the origin, then a
time delay, T, corresponds to a family of locations (R, θ) where,

\[ T = \frac{(d/c)}{\left\{ \left[R^2 + \hat{R}\cos(\theta) + 1/4\right]^{1/2} - \left[R^2 - \hat{R}\cos(\theta) + 1/4\right]^{1/2} \right\} } \]  (3)

where,

c = velocity of sound in water,

d = distance between the hydrophones, and

\[ \hat{R} = R/d. \]

These relationships are shown in the nondimensional plot of Figure 12 where

\[ \tau = \frac{T}{t_{\text{max}}}, \quad \text{and} \quad t_{\text{max}} = \frac{d}{c}, \text{the maximum time delay.} \]

Note that for large values of \( \hat{R} \) the asymptotic result is

\[ T = t_{\text{max}} \cos(\theta) \]

The symmetry of the cosine in equation (3) provides the basis for the apparent

ambiguity in determining the proper quadrant in which to place the hyperbola.

The left/right ambiguity is resolved by knowing at which of the two

hydrophones the sound first arrives. The front/back ambiguity is resolved in

this application by installing the array at the edge of the shorefast ice so

that the whales are located on only one side of the array.
Figure 12. Plot of hyperbolic loci relative to two hydrophones (#1 and #2) separated by 1 kilometer for a variety of time delays \( \tau \), where \( \tau = T/t_{\text{max}} \) and \( t_{\text{max}} \) is the maximum time delay between the two hydrophones.
It is apparent from these results that for a three hydrophone array there are three pairs of hydrophones and therefore three hyperbolic solutions. The common point of intersection of the hyperbolae represents the location of the whale that produced the sound. In most acoustic location analyses the hyperbolae do not all intersect at the same exact point but instead intersect so as to produce a triangle. Figure 13 is an example of this location process. In this case the whale’s location is the centroid of the triangle and the size of the triangle is directly proportional to the range and bearing errors associated with the whale’s location. The range error is half the hypotenuse, L, of the triangle, while the bearing error is half the angle with its origin at the visual observation perch (0,0) that subtends the maximum width, W, of the triangle. In actual practice, the hyperbolic crossbearings for each sound processed by the acoustic location methods are drawn on the video terminal, and the computer operator measures the X,Y coordinates of the centroid, the length L and the width W directly from this graphics display. These values are then entered into the computer which computes the range, bearing, range error, and bearing error values for that sound location.

For each sound successfully located by the above procedures the following information was included as a single record in a data file stored on an 8 inch floppy disk; location identification number (coding date, tape number, and location sequence number for that tape), time, call type, X and Y coordinates relative to the visual observation perch, range and bearing from the visual observation perch, and errors in range and bearing. In all further discussion the term acoustic location refers to all the data in a single record file.
Figure 13. Example plot of a whale-location as determined using either the amplitude or frequency-amplitude cross-correlation techniques. The three hyperbolic solutions for the three time delays cross to form a triangle as shown in the inset. The whale's location is the centroid of the triangle. The range error for that location is half the hypotenuse length, L, of the triangle, while the bearing error for the location is half the width, W, of the triangle.
C-4 Source levels: Source levels were computed for bowhead sounds in order to investigate the variation in signal intensity as a function of call type and the suggestion, reported elsewhere (Clark, 1983; Cummings et al., 1983), that bowhead calls might be directional. Source levels computed for different sound types at the same hydrophone were used to calculate the mean and standard deviation of a call type, while source levels computed for the same sound at two different hydrophones were used to describe the intensity of sounds as a function of direction to the source.

The term source level is used to quantify the acoustic energy emitted by a sound source in any given direction. Unless the source is omnidirectional, i.e. emits equal energy in all directions, source level is not necessarily a measure of the total power output of the source. In order that scientists can compare different sound sources, certain standards of usage have arisen with regard to the term source level. The level is given in decibels, dB, referenced to the international unit of acoustic pressure, 1 \( \mu \)Pa, measured at a distance of 1 meter from the source. This latter requirement is clearly artificial since, except at very high frequencies and for very small sources, this would be a meaningless measurement due to a variety of nearfield effects. However, if the level is measured some known distance from the source then a simple addition,

\[
SL(\text{dB}/1 \text{ meter}) = RL(\text{dB}/\text{measurement point}) + TL
\]  

provides the standardized value of the source level, \( SL \), in dB referenced to a distance of 1 meter. In equation (4) above, the term \( RL \) is referred to as the received level and is the sound level as originally measured at some known
distance from the source. The TL term is referred to as the transmission loss and is a measure of how much acoustic energy is lost as a function of distance from the source. TL is either measured by using a source of known strength with a calibrated receiver or estimated from empirically derived formulae that exist for a variety of environmental conditions (Urick, 1975).

The description of the source level is not complete until the frequency bandwidth over which the sound measurement was made is specified. Here the standard is 1 Hz; that is, the amount of sound energy measured through a filter 1 Hz wide. To be precise then, a source level measurement is given in terms of its distance from the source as well as the bandwidth in which the energy was measured. In the case of this report we are providing source levels for calls that are FM sweeps. These calls tend to have a relatively uniform energy distribution over any 100 Hz band starting as low as 80 Hz and extending as high as 400 Hz, and therefore our source levels are referenced to 100 Hz, i.e. SL(dB//1 meter re 1 μPa/100 Hz).

The term transmission loss implicitly includes all acoustic energy losses between the source and the receiver. In seawater these losses can include: 1) scattering from the surface, the bottom, or inhomogeneities in the water; 2) energy spread into adjacent media; 3) geometric spreading; and 4) chemical relaxation phenomena. Since we did not conduct experiments in order to obtain direct measurements of transmission loss, we have selected a simple relationship for TL based on a large body of measured data (Urick, 1975; see page 164) in order to estimate TL. This relationship states that,
TL = 20 \log(R) - k_1 \quad (5)

where R is the range from the source to the receiver in meters and k_1 is a nearfield anomaly constant related to forward shallow water scattering at the surface and bottom. At the frequencies used by the bowhead, the effect of absorption by chemical relaxation is negligible for ranges less than 10 km. The above relationship is directly applicable for the recording situations in 1984 where water depths ranged from 18 to 250 m, distances to the whales were from 100 to 10,000 m and the frequency range of bowhead calls was from 80 to 400 Hz. For frequencies between 100-400 Hz and independent of bottom type, the empirically determined value of k_1 is nominally 6 dB. This is the value of k_1 used in all calculations of TL in this report.

In order to determine the source level of a received sound the receiving system must be calibrated to an absolute standard. As discussed earlier in the methods section A-1 describing the sonobuoy system, all sonobuoys used in this study were calibrated by the manufacturer to a primary sensitivity of 110±1dB re 1 \mu Pa/19 kHz deviation. The extra gain switch that we installed was always set to the -8 dB setting. Each receiver was calibrated by one of us (KB) at the time of manufacture to a sensitivity of -16.5 dB/1 volt/19 kHz deviation. The recording and analysis system had several locations where the signal could be amplified or attenuated in 10 dB increments. These settings were entered by time and cassette number into the acoustic logbook. The combined value of these recording and analysis system settings is referred to as the gain, G, in dB.
The absolute received level for a bowhead call is calculated using each of the above sensitivities and the call's BW-eff and AL values (measured from the video display of call spectra as discussed in the previous section) by the following equation:

\[ RL = 110 + 8 + 15.5 - G + AL + 10 \log(100/BW-eff) \] (6)

Where the received level, RL, is given in dB re 1 μPa/100 Hz.

The value of TL is computed using equation (5) and knowing the distance, R, between the hydrophone and the whale making the sound, computed during the sound location process.

Finally the source level, SL, of a particular bowhead call is calculated using equation (4) and knowing the respective RL and TL values for that call. Computation of source level was performed only for sounds that were actually located during Array E, since the heavy ice conditions of Array C made it impossible to properly compute TL values. For each call, two source levels were computed. One using the call's received level at the southwestern hydrophone (Hy#1) and the other using the call's received level at the center hydrophone (Hy#2) of the array.

C-5 Tracks: Acoustic locations were analysed for acoustic tracks using the location data and following the procedures of Sonntag et al. (1986). The original algorithm used in this procedure was written and developed by two of the authors (WTE & CWC) and subsequently programmed with our advise by Ronald Sonntag and Daniel Corbit of ASI. This tracking procedure links a series of
acoustic locations together into a track based on a minimum swimming speed of 1 km/h, a migratory direction of 48° magnetic and a maximum possible deviation in migratory direction of ± 30°. These swimming speed values and deviation in migratory direction values were selected so as to maximize the number of linkages made. Since the number of linkages is inversely proportional to the number of whale tracks, these swimming and deviation values minimize the number of whales detected and thereby result in a conservative estimate of whales counted. Starting at the first acoustic location in the data file, the tracking procedure looks ahead in the data file and finds the next possible location that could link to the first location based on the values for swimming speed, migratory direction and deviation in migratory direction. This procedure is repeated until all possible linkages are made. The range and bearing errors associated with each location are incorporated into this procedure and affect the chances of one location being linked to another; large errors increase the number of linkages, while small errors decrease the number of linkages. Thus, the smaller the errors associated with the locations, the fewer the number of linkages and the greater the number of whales counted. Some proportion of acoustic locations can not be linked to any other location and are therefore not counted as acoustic tracks. However, each unlinked acoustic location does represent a whale and therefore contributes to the total number of whales counted.

Once all possible linkages are made, the total number of tracks and unlinked acoustic locations are summed to produce a whale count for that time period of acoustic location analysis. This count represents an estimate of the number of whales acoustically observed during that period of time. This estimated number is referred to as a minimum estimate since the parameters of swimming speed,
migratory direction and deviation in migratory direction were chosen so as to maximize the number of linkages between locations. Since more linkages between locations mean fewer tracks and therefore fewer whales, maximizing the linkages results in a minimum estimate of whales. Although this is not an absolute minimum, it does represent a very conservative estimate since the swimming speed of 1 km/h and a deviation of ± 30° in migratory direction are well below the average swimming speed and deviation in migratory direction for bowhead whales (Carroll and Smithhisler, 1980; Ljungblad et al., 1984).

In order to compare and integrate the acoustic location data with the visual sighting data, these same tracking procedures were performed using the visual sighting data alone and the acoustic location and visual sighting data sets combined. In all further discussion acoustic tracks are those tracks and unlinked acoustic locations computed by the above procedures using only acoustic location data. Visual tracks refer to those tracks computed by these same procedures using only visual sighting data. Mixed tracks are tracks computed using the acoustic location and visual sighting data combined. The term whale-location refers to the location of a whale as determined by either the acoustic location or visual sighting method.

C-6 Closest point of approach (CPA) distributions: Closest point of approach (CPA) distances of whales from the primary visual observation perch were made by projecting the first whale-location for all whale tracks and all unlinked whale-locations onto the line originating at that perch and perpendicular to a migratory direction of 48° magnetic (Ko et al. 1986; Sonntag et al. 1986). Figure 14 illustrates the procedure by which a CPA distance is calculated. In this figure the first whale-location for a whale track (consisting of four
Figure 14. Diagram of the method for calculating a whale's closest point of approach (CPA) distance from the visual observation perch. The CPA distance is computed by projecting the first whale-location in a whale track or an unlinked whale-location onto the line, P, originating at the perch and perpendicular to the migratory direction. Points 1-4 are the four acoustic locations from which the track is composed.
whale-locations) is projected onto the line, P, perpendicular to the direction of migration, and the CPA distance is shown. The distribution of all these CPA distances is referred to as a CPA distribution. CPA distributions are computed based on tracking analysis of acoustic locations, visual sightings and both data sets combined. For these CPA distributions, only the first location of each whale track plus all remaining whale-locations that could not be linked are projected. By this procedure each whale is represented only once in the CPA distributions. In an effort to demonstrate the reliability of the CPA distribution method, a second CPA distribution was made using the second whale-locations in the acoustic tracks and compared to the distribution made using the first whale-locations in the tracks. The two resulting distributions were not significantly different (Kolmogorov-Smirnov two sample test; $D = 0.106, n = 171, p > 0.2$). Based on these results and the fact that whale tracks tended to be quite straight, we believe that the CPA distributions based on the projection of the first whale location in a track and all unlinked whale locations are an accurate representation of the actual distribution of whales observed. For acoustic CPA distributions it is important to note that the acoustic tracking technique assumes that there is only one whale per acoustic track. In actual fact, some percentage of the whales are travelling within several body lengths of one or more other whales which means that groups of two or more whales are being counted as only one whale by the acoustic method.

A quantitative measure of how many whales were detected and how far away they were from the visual observation perch is computed by adding up all the whales in a CPA distribution. Since this distribution counts each whale only once independently of how many times the whale was either acoustically located or
visually sighted, it therefore is a reliable means of comparing the total number of whales detected based on either of the two observation methods. This count of whales from the CPA distribution is referred to as a minimal estimate because of the conservative values of minimal swimming speed and deviation in migration direction used in the tracking methods. The CPA distribution also has the added advantage of displaying information on how far away from the visual observation perch the whales passed. This provides a means of comparing the distributions of whales as detected by the two observation methods. Thus, from the CPA distribution a minimal estimate or count of how many whales were closer than 2.5 km from the visual observation perch is made by adding up all the whales in the distribution that were within 2.5 km of the perch, while an estimate of the number of whales further than 2.5 km from the perch is made by adding up all the whales in the distribution that were further than 2.5 km. This 2.5 km value is selected because this appears to be the greatest distance to which reliable visual theodolite sightings can be made. In all further discussion, whales closer than 2.5 km from the visual observation perch are referred to as nearshore whales, while whales that are further than 2.5 km from the perch are referred to as offshore whales.
RESULTS

The following results are presented in eight sections. The first section is a brief narrative of the acoustic field season. The next four sections are descriptions of the four primary data analyses efforts; numbers and types of bowhead sounds, acoustic locations during Array E, acoustic locations during Array C, and bowhead call source levels during Array E. These sections are followed by a description of the results from the 12 Whale Experiment. Finally there are the two sections presenting the results of the tracking analysis and CPA distributions for Array E when good to very good visual conditions predominated, and for Array C when visual conditions were fair to unacceptable. In these last two sections the tracking and CPA distribution results based on acoustic locations data will be compared to the tracking and CPA distribution results based on visual sightings alone and the results based on the combined acoustic and visual data sets. These comparisons will be made in terms of the actual numbers of whales counted and the proportions of nearshore and offshore whales detected.

A: Acoustic Field Season Narrative

Sonobuoys were installed and monitored from 17 April until 27 May. Five arrays, each consisting of three sonobuoys positioned in an approximately linear arrangement, were established between 18 April and 22 May 1984. The time required to install an array ranged from 6 to 14 h depending on the size of the array and the severity of the ice conditions during the installation. The lifespan of the arrays ranged from 13 to 65 h and again depended mostly on the severity of the ice conditions. Deploying and maintaining sonobuoys for
acoustic arrays was the single most difficult effort of the 1984 acoustic field season. This was a result of the unusually severe ice conditions brought on by the almost continuous northwesterly winds. Deployment of a single array required backpacking three sonobuoy systems, including heavy duty marine batteries, a theodolite and ice chopping gear, for distances of up to several kilometers, often entirely through heavy pressure ridges. Because of the severe ice conditions we were never able to establish more than a three sonobuoy array, even though our goal was to use four sonobuoys. Sonobuoy batteries were changed every 4 to 7 days depending on the air temperatures; with lower temperatures reducing the duration of useful battery operation. A simple battery change would take from 2 to 4 h to complete depending on the distance from the acoustic hut to the sonobuoy and the severity of the ice. Replacement of and damage to hydrophones and sonobuoys was an almost continuous problem in 1984. Moving ice often severed the cable connecting the sonobuoy to the hydrophones, resulting in the loss of the hydrophone. In at least three cases the offshore winds drove the pack ice into the ice from which an array was deployed so rapidly and with such force that the entire array, including the sonobuoys and their hydrophones, were crushed and buried beneath the newly formed ice ridge.

Table I presents a listing of the locations (relative to a visual observation perch), dates, times of operation of one or two sonobuoys, times of operation of sonobuoy arrays, and array names for the six acoustic observation periods in 1984. Figure 15 shows the relative positions of the visual observation perches, and the letter names of the arrays installed at those perches are given in parenthesis.
Figure 15. Positions of the four visual observation perches in 1984 relative to Point Barrow, Alaska. The letter names of the five different hydrophone arrays are given in parentheses after each of the perches at which they were installed.
TABLE I. Summary of 1984 acoustic recording effort during the six acoustic observation periods from 17 April to 27 May. Non-array recording times refer to times when only one or two sonobuoys were operating. Total hours are in parentheses.

<table>
<thead>
<tr>
<th>Visual Observation Perch name</th>
<th>Date</th>
<th>Non-array Recording times (start-end)</th>
<th>Array Recording times (start-end)</th>
<th>Array Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foxtrap</td>
<td>17 APRIL</td>
<td>1530-2253</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>18 APRIL</td>
<td>0850-2400</td>
<td>1813-2400</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>19 APRIL</td>
<td>0000-2400</td>
<td>0000-1230</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>20 APRIL</td>
<td>0000-1750</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(54.3 h)</td>
<td>(18.2 h)</td>
<td></td>
</tr>
<tr>
<td>Three Cold Brothers</td>
<td>24 APRIL</td>
<td>0620-2400</td>
<td>2000-2400</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25 APRIL</td>
<td>0000-2400</td>
<td>0000-2400</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>26 APRIL</td>
<td>0000-1400</td>
<td>0000-1400</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(55.7 h)</td>
<td>(42.0 h)</td>
<td></td>
</tr>
<tr>
<td>Snowy Owl</td>
<td>3 MAY</td>
<td>0740-2400</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 MAY</td>
<td>0000-2400</td>
<td>1258-2400</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>5 MAY</td>
<td>0000-2400</td>
<td>0000-2400</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>6 MAY</td>
<td>0000-2400</td>
<td>0000-2400</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>7 MAY</td>
<td>0000-1200</td>
<td>0000-0930</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(100.3 h)</td>
<td>(68.5 h)</td>
<td></td>
</tr>
<tr>
<td>Foxtrap</td>
<td>8 MAY</td>
<td>1835-2400</td>
<td>2214-2400</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>9 MAY</td>
<td>0000-2400</td>
<td>0000-1115</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>10 MAY</td>
<td>0000-0051</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(30.3 h)</td>
<td>(13.0 h)</td>
<td></td>
</tr>
<tr>
<td>Midget</td>
<td>17 MAY</td>
<td>1410-2400</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>18 MAY</td>
<td>0000-2400</td>
<td>1800-2400</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>19 MAY</td>
<td>0000-2400</td>
<td>0000-2400</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>20 MAY</td>
<td>0000-2400</td>
<td>0000-2400</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>21 MAY</td>
<td>0000-2400</td>
<td>0000-1123</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>22 MAY</td>
<td>0000-0345</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(109.5 h)</td>
<td>(65.4 h)</td>
<td></td>
</tr>
<tr>
<td>Foxtrap After E</td>
<td>25 MAY</td>
<td>0012-2400</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>26 MAY</td>
<td>0000-1853</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>27 MAY</td>
<td>0035-1947</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(61.8 h)</td>
<td>(0.0 h)</td>
<td></td>
</tr>
<tr>
<td>Season Totals</td>
<td></td>
<td>(411.9 h)</td>
<td>(207.1 h)</td>
<td></td>
</tr>
</tbody>
</table>
The following is a brief synopsis of the times of operation and fates for the sonobuoys established during the 1984 season. These descriptions emphasize the arrays since these were the primary source of acoustic data. For a detailed description of the environmental conditions experienced in 1984, the reader is referred to Krogman and Sonntag (1985).

The first sonobuoy of the season was installed off Foxtrap visual observation perch on stable but non-shorefast ice at 1530 h on 17 April when there was no open water. Array A became operational on 18 April at 1813 h. During the early morning hours of 19 April the first recordings of bowhead sounds for the season were made, and the first visual sighting of a bowhead occurred approximately 6 h later. Locations for a series of whale calls coincided with this visual sighting. The array was maintained until 1230 h on 19 April at which time pressure ridging disrupted its operation. A single sonobuoy was maintained until 1750 h on 20 April when the sonobuoy was pulled out due to heavy ice ridging caused by strong westerly winds. Visibility conditions were good to poor and only one whale was seen during the 54.3 h of acoustic observation at this site of which 18.2 h were made with an array.

The first sonobuoy at Three Cold Brothers visual observation perch was operational by 0620 h on 24 April. The ice in this location was extremely rough, and the nearshore edge of the lead was approximately 800 m from the perch. It was not until 2000 h on 24 April that Array B was fully installed. Whale sounds were recorded throughout the next day. At 1400 h on 26 April this array was destroyed by heavy pressure ridging under northwesterly winds. The pressure ridge that engulfed this array became the site for the next visual observation perch. Visibility conditions were unacceptable throughout
the duration of this array and no whales were seen during the 55.7 h of acoustic recording at this site, of which 42.0 h were made with an array.

As a result of continuing westerly winds and unsafe ice conditions, we were unable to install another sonobuoy until 0740 h on 3 May. Array C was not established until 1258 h on 4 May. The array was located approximately 900 m offshore of Snowy Owl visual observation perch on non-shorefast ice. During the next four days, when only a few intermittent cracks and holes of open water were visible, some of the highest call rates for the season were noted. At 0930 h on 7 May one sonobuoy in the array was destroyed by an advancing pressure ridge, and the other two buoys were destroyed by 1200 h. Visibility conditions were fair to unacceptable during this array period and only 45 whales were seen throughout the 100.3 h of acoustic recording at this site, of which 68.5 h were made with an array.

On 8 May at 1835 h, the first sonobuoy for Array D was installed off Foxtrap visual observation perch. The entire array was functioning by 2214 h. High rates of sounds were recorded on this array from both bowhead and beluga whales. The ice conditions were dominated by moving pack and slush ice with occasional, temporary polynyas. The array was destroyed at 1115 h on the morning of 9 May by heavy pressure ridging driven by northwestly winds, but a single sonobuoy continued to function until 0051 h on 10 May. Visibility conditions were fair to poor during this array period and 49 whales were seen during the 30.3 h of acoustic recording at this site, of which 13.0 h were made with an array.
Due to continuous onshore winds it was not until 17 May that an open lead finally developed off of Midget visual observation perch, and a single sonobuoy was installed by 1410 h. Array E was established at the edge of the lead by 1800 h on 18 May. This was the first array at which good visual observation conditions prevailed, making it possible to conduct a simultaneous visual and acoustic census under conditions favorable to both methods. The computer analysis system was brought out to the ice camp and operated in real-time for over 57 h in conjunction with the visual effort. This constituted the field experiment aimed at demonstrating the simultaneous acoustic-visual detection of whales (see 12 Whale Experiment section on page 31). The array was partially destroyed at 1123 h on 21 May, but we were able to maintain a single sonobuoy at this site until 0345 h on 22 May. Visibility conditions were very good to poor during this array period and 129 whales were seen during the 109.5 h of acoustic recording at this site, of which 65.4 h were made with an array.

A single sonobuoy was installed off of Foxtrap perch from 0012 h on 25 May until 1947 h on 27 May. This period from 25-27 May when only one hydrophone was functional is referred to as the "After E" period. Visibility conditions for this period were poor to unacceptable and only 16 whales were seen during the 61.8 h of acoustic recording at this site.

Monitoring of bowhead calls after 27 May was conducted until 11 June by North Slope Borough staff personnel under the guidance of John Craighead George.
B: Numbers and Types of Bowhead Calls

From the total of 411.9 h of recordings in 1984, there were 207.1 h of three-channel recordings made when an array was fully operational. The remaining 204.8 h were either monaural or stereo recordings made when only a single hydrophone was installed for monitoring purposes or when an array was only partially functional (i.e. being installed or in the process of being destroyed by ice).

A total of 330.2 h (422 tapes, 13.8 days) of recording were converted into either single channel spectrograms or stereograms. This included all three channel tapes from the five arrays (207.1 h of stereograms), the entire recording period after Array E ended (61.5 h of single channel spectrograms) and intermittent samples from throughout the remaining monitoring period (61.6 h of single channel spectrograms).

All analysed tapes were scored for numbers and types of sounds by visual inspection of the continuous spectrograms (stereo or mono) and of these, 46 tapes were also scored by the method of simultaneously relistening to the tape while visually observing its continuous stereogram. The duplicate analysis revealed that the number of sounds per tape as scored by the visual counting method alone were, on average, 5.3% lower than the number of sounds per tape as scored by simultaneously relistening to the tape and visually observing the stereogram. All of the additional sounds noted by the simultaneous counting method were either very faint or recorded on only one channel and therefore could not be located.
Figure 16 illustrates the hourly totals for numbers of sounds recorded during the six acoustic observation periods of time including each of the five array periods. Table II, below, gives a breakdown of total sounds recorded by sound type and observation period. All these data for numbers and types of sounds on a minute by minute basis are logged in written tables. Originally the exact time and type of each sound was to be logged into a file stored on computer disk. At the coordination meeting held in Seattle on 16 August 1984 it was decided that such detail was not useful for any of the data analysis methods. Instead, total numbers and types of sounds on an hour by hour basis were stored in a file on computer disk. These were the data used by Dr. Judith Zeh and Daijin Ko in their analysis of correlations between numbers of sounds and other non-acoustic variables (Ko et al. 1986).

Altogether these data represent a total of 16,338 bowhead calls with an error of ± 866 calls (± 5.3%) from a total of 330.2 h of analysis. Although these values represent our best effort at counting and categorizing the bowhead calls, it is important to note that there are several inherent biases against correctly counting the high call and pulsive call types. High calls are typically greater than 400 Hz meaning that they would not be displayed on the stereogram, while pulsive calls have complex acoustic structures which make them difficult to identify in the visual format. In addition, beluga whales produce a great variety of sounds some of which are very similar to the pulsive calls of the bowhead. A few beluga whistles can also be confused with the high calls of the bowhead. The above caveat is meant as a caution for the interpretation of total high call and pulsive call counts. Our (CWC) analysis bias was to score a call of these types only when we were very certain that it
Figure 16. Histograms showing the total number of bowhead calls recorded per hour for each of the six acoustic observation periods in 1984. The name of the observation period and the beginning and end times for the hourly counts are given above each of the histograms. Five of the six periods are referred to by the name of the Array (A, B, C, D, and E) installed during that period. Only one sonobuoy was operating during the After E period. The lines below the x-axis indicate hours when no data were collected.
TABLE II. Summary of the total number of seven different bowhead sound types as analysed from recordings in 1984 for the six different acoustic observation periods (13).

<table>
<thead>
<tr>
<th>Observation Period</th>
<th>Analysed Hours</th>
<th>Total Calls</th>
<th>Bowhead Call Types</th>
<th>Whales Seen / Visual Sightings</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>21.0</td>
<td>322</td>
<td>14 Up</td>
<td>79 Down</td>
</tr>
<tr>
<td>B</td>
<td>38.3</td>
<td>244</td>
<td>89 Constant</td>
<td>35 Inflated</td>
</tr>
<tr>
<td>C</td>
<td>95.9</td>
<td>8958</td>
<td>3918 Down</td>
<td>587 High</td>
</tr>
<tr>
<td>D</td>
<td>22.8</td>
<td>1526</td>
<td>43077</td>
<td>79 Inflated</td>
</tr>
<tr>
<td>E</td>
<td>96.8</td>
<td>2731</td>
<td>97631</td>
<td>531 High</td>
</tr>
<tr>
<td>After E</td>
<td>55.4</td>
<td>2557</td>
<td>67041</td>
<td>731 High</td>
</tr>
</tbody>
</table>

Total 330.2 16338 6097 3163 1910 2776 42 1874 476 232/324

| %                  | 100.0          | 37.3        | 19.4              | 11.7                          | 17.0 0.3 11.5 2.9 |

was from a bowhead. This meant that in cases where belugas were in the area (eg. Array D) we would tend not to score many high calls or pulsive calls. This conservative bias does not really affect the usefulness of the overall count since both these call types were very rare even for tapes that were analyzed by the visual/aural approach.

There was no significant correlation ($r^2 = 0.250$, $n = 56$) between the hourly sound counts as determined from analysis of the recordings and the hourly number of visual sightings during the Array E observation period (Ko et al.)

13 The total number of whales seen and visual sightings during the six acoustic observation periods are also included in the last column of the table. Five of the six observation periods are referred to by the name of the array (A,B,C,D, or E) that was operating during that period, but include data from times contiguous with the array period when only one or two hydrophones were operating. Only one sonobuoy was operating during the "After E" period. The first five bowhead call types are tonal calls and have names that indicate the type of FM modulation in the call. For example, an FM upsweep is referred to as an Up call, while an FM downsweep is referred to as a Down call. The last two call types are complex calls. The pulse tonal call type is a tonal FM call with amplitude modulation, while the pulsive call type refers to a call with a complex frequency spectrum and a mixture of both frequency and amplitude modulations.
1986). For 35 of the 57 h of simultaneous acoustic/visual data used to
determine the correlation values either no whale sounds were recorded (n=5) or
only one whale was seen (n=30) even though these data were collected when the
visual observation conditions were good.

Table III, below, presents the same bowhead call count data and visual
sighting data as presented in Table II only here these data are grouped by
visibility condition.

<table>
<thead>
<tr>
<th>Visibility Condition</th>
<th>Hours of Acoustic Observation</th>
<th>Number of Calls Recorded</th>
<th>Whales Seen / Visual Sightings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Good</td>
<td>28.3 (8.6)</td>
<td>1019 (6.2)</td>
<td>49/83</td>
</tr>
<tr>
<td>Good</td>
<td>45.4 (13.7)</td>
<td>1669 (10.2)</td>
<td>85/121</td>
</tr>
<tr>
<td>Fair</td>
<td>90.3 (27.3)</td>
<td>5067 (31.0)</td>
<td>50/65</td>
</tr>
<tr>
<td>Poor</td>
<td>68.8 (20.8)</td>
<td>3749 (22.9)</td>
<td>47/54</td>
</tr>
<tr>
<td>Unacceptable</td>
<td>97.4 (29.5)</td>
<td>4834 (29.6)</td>
<td>1/1</td>
</tr>
<tr>
<td>Total</td>
<td>330.2</td>
<td>16338</td>
<td>232/324</td>
</tr>
</tbody>
</table>

C: Acoustic Locations, Array E

There were 57.5 h of continuous recordings analysed for locations regardless
of visual conditions during Array E. All locations were computed using the
simpler method of amplitude cross-correlation. The location analysis was not
selective; an attempt was made to locate every sound within the 120° sector on
all tapes starting at the beginning of the array (1800 h, 18 May 1984) to the
end of the useful array operation (0800 h, 21 May 1984). The first acoustic
location occurred at 2052 h on 18 May, while the last acoustic location occurred at 0741 h on 21 May. The analyses included 8.3 h of recordings when visual observation conditions deteriorated below the level of good because either fog or snow obscured the visual observers' view of the lead. The number of acoustic locations obtained during these periods of fair or poor visual conditions serve as an important comparison to the number of acoustic locations obtained during periods of good to very good visibility. Table IV gives the details of these location data partitioned by visibility conditions.

| Array E Visibility Condition | Hours Anal.- Calls | Total in | Atte- Loc. | Good >60° | >60° Whales Seen / Visual Sightings |
|-----------------------------|-------------------|---------|-----------|----------|-----------------|-------------------------------|
| Very good or good           | 49.2              | 1638    | 1039      | 631      | 308             | 442                           | 157                           | 117/168                       |
| Fair or poor                | 8.3               | 358     | 253       | 153      | 48              | 64                            | 41                            | 4/5                           |
| Total                       | 57.5              | 1996    | 1292      | 784      | 356             | 506                           | 198                           | 121/173                       |

14 "Total Calls" are the total number of sounds recorded. "Within 120°" is the total number of sounds that originate from within the 120° sector in front of the visual observation perch. "Loc. Attempts" are the number of attempts made to acoustically locate a sound that originated from within the 120° sector. "Good Locs" are the number of successful location attempts. "> 60° left" are the number of sounds that originated at a bearing greater than 60° to the left of the center of the array. "> 60° right" are the number of sounds that originated at a bearing greater than 60° to the right of the center of the array.
For the entire Array E period analysed for locations, a total of 1996 calls were recorded. Of these, 1292 (65%) were within the 120° sector. Of the remaining 704 calls, 506 were greater than 60° to the left of the center of the array, while 198 were greater than 60° to the right of the center of the array, where the center of the array is the line perpendicular to the axis of the array.

Not all of the 1292 calls produced somewhere within the 120° sector could be located. There were several reasons for this inability to locate every call within the sector; either a call was so faint that it was not detected on all three hydrophones, or the cross-correlation analysis did not converge on a location, or the peak delay times calculated from the location analysis procedure were not distinct enough. We believe that the more robust frequency-amplitude cross-correlation method would have provided more locations from this data set, but the technique was not operational at the time the Array E analyses were performed. For Array E a total of 784 location attempts were made on the 1292 calls available. Of these 784 calls, 356 (45%) were acceptable acoustic locations, while the remaining 428 calls could not be reliably located. Originally we were expecting to process at least 1000 calls for acoustic locations during Array E. However, as this turned out not to be the case, the remaining 216 calls (1000 minus 784) were applied to the second 1000 acoustic location analysis effort carried out on the Array C data.

When these same data were partitioned by visibility conditions and compared in terms of the number of acoustic locations computed per hour of recording, the following results were obtained. There were 6.3 acoustic locations per hour (308 locations divided by 49.2 h) when visibility conditions were good or very
good, while there were 5.8 acoustic locations per hour (48 locations divided by 8.3 h) when visibility conditions were fair or poor. There was no significant difference between the number of sounds located per hour depending on the visibility conditions (Mann-Whitney U-test, Student's t value = 1.13; 0.2 > p > 0.4; n = 47, good or very good; n = 7, fair or poor, where n is the number of complete one hour intervals during which acoustic analyses were performed)

D: Acoustic Locations, Array C

Analysis of Array C acoustic data was done for three different sample periods. Starting times for each period were randomly selected by Dr. Judith Zeh in order to provide an unbiased sampling of the array data. The acoustic analysis procedure was to begin locating sounds at the start of a sampling period and continue locating every possible sound within the 120° sector until 200 locations were obtained. Two hundred was chosen as the limit because this provided a large enough sample for determining migration direction. By this procedure a total of 31.4 h of the possible 68.5 h of array recordings were analysed for locations regardless of visual conditions during the three sampling periods from Array C. The analysis was not selective; an attempt was made to locate every sound within the 120° sector on all tapes starting at the beginning of the sampling period and ending when 200 acceptable locations were obtained. All 600 locations, except the first 44 from block C3, were computed using the frequency-amplitude cross-correlation method. The other 44 were computed using the amplitude cross-correlation method. Table V, below, gives the breakdown of the analysis effort for each of the three Array C sample periods.
For the 31.4 h during the Array C period analysed, a total of 2978 bowhead sounds were recorded. Of these, 2504 (84%) were within the 120° sector. Of the remaining 474 calls, only 10 were from the sector greater than 60° to the left of center of the array, while 464 were from the sector greater than 60° to the right of the center of the array. The high percentage of sounds in the 120° sector and the very low number of sounds from greater than 60° to the left of center are a result of the fact that the axis of the array was rotated approximately 48° counterclockwise relative to the whales' direction of migration.

Although 1870 acoustic location attempts were made, only 600 of the 2504 calls produced somewhere within the 120° sector could be located. No attempt was made to locate 634 of the 2504 calls because they were either too faint or the call was not detected on all three hydrophones. 1270 of the 1870 acoustic

---

**TABLE V.** Summary of acoustic location analysis results for Array C sample periods C1, C2 and C3 when visual observation conditions were fair to unacceptable (15).

<table>
<thead>
<tr>
<th>Array C Sample Period</th>
<th>Hours Analysed</th>
<th>Total Calls in 120</th>
<th>With Loc. Attempts</th>
<th>Good Locs</th>
<th>&gt;60° Left</th>
<th>&gt;60° Right</th>
<th>Whales Seen / Visual Sightings</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>4.1</td>
<td>1093</td>
<td>946</td>
<td>634</td>
<td>200</td>
<td>1</td>
<td>146</td>
</tr>
<tr>
<td>C2</td>
<td>21.7</td>
<td>735</td>
<td>625</td>
<td>494</td>
<td>200</td>
<td>5</td>
<td>133</td>
</tr>
<tr>
<td>C3</td>
<td>5.6</td>
<td>1122</td>
<td>933</td>
<td>742</td>
<td>200</td>
<td>4</td>
<td>185</td>
</tr>
<tr>
<td>Total</td>
<td>31.4</td>
<td>2978</td>
<td>2504</td>
<td>1870</td>
<td>600</td>
<td>10</td>
<td>464</td>
</tr>
</tbody>
</table>

15 Array C sampling period C1 was from 1310–1715 h on 3 May. C2 was from 0000–2140 h on 4 May. C3 was from 0031–0604 h on 5 May. The table shows how many bowhead sounds were recorded and how many acoustic location attempts were made in order to locate 200 calls in each of the three sampling periods. See the footnote for Table IV for an explanation of the column headings.
location attempts (68%) were unacceptable because either the location analysis could not converge on a location or the correlation values of the delay times were not distinct enough. Originally when location analysis of the Array C data began, we were aiming to locate at least 1216 bowhead calls; the remaining 216 from the first 1000 acoustic location effort plus the additional 1000 from the second acoustic location effort. As it turned out, the acoustic recordings from Array C were extremely difficult to process because 1) the whales were far away and therefore their calls were fainter and 2) the relative locations of the hydrophones in the array were subject to greater uncertainty due to the rugged ice conditions during the surveying of the array. The end result was that although we analysed 1870 calls for acoustic locations we obtained only 600 (32%) acceptable locations. For the entire acoustic location effort, including both Array E and Array C, we processed 2654 calls for acoustic locations but obtained 956 (36%) acceptable locations.

E. Bowhead Call Source Levels.

The tapes recorded during Array E were used as the basis for the source level analysis. Array C data were not used because we could not properly apply the transmission loss relationship to the data set due to the extremely rough ice conditions during this array. 265 of the total 356 calls from Array E for which acceptable acoustic locations were obtained were analysed for source level. The remaining 91 acoustic locations were not used because their peak analysis levels (AL) were less than 3 dB above the ambient noise level. Only 115 calls, consisting of two types of FM calls, up calls (n = 77) and down calls (n = 38), were used in actual computations of source level. These two most common types were chosen for analysis because they have their energy in a
definite frequency band and therefore an accurate estimate of the received signal level (RL) can be made, and because there were enough of them to allow for meaningful statistical analysis. The pulse tonal and pulsive call types were not used since these types have broad, complex frequency spectra meaning that their peak level values, AL, were not representative of the received signal level and could not be compared to the values as measured for the two FM call types. Two source levels were computed for each of the 77 up calls and 38 down calls resulting in a total of 230 source levels. These data were used to: 1) determine the average source levels of up calls and down calls and test for the significance of any differences in these values, and 2) investigate whether these bowhead call types are directional.

Figure 17 is a plot showing the 230 bowhead call source levels as a function of the whale's magnetic bearing from the hydrophone on which the call was received. In this figure the two call types are plotted with different symbols: closed triangles for up calls (n = 77) and open circles for down calls (n = 38). The mean source level for upcalls was $153.0 \pm s.d. \ 9.4 \ dB \ re \ 1 \ \mu Pa/100 \ Hz$. The mean source level for downcalls was $147.1 \pm s.d. \ 9.5 \ dB \ re \ 1 \ \mu Pa/100 \ Hz$. These source levels for the two call types are not significantly different ($0.05 > p > 0.1$). The regression line for these data (see Figure 17) has a slight negative slope of $-0.06 \ dB \ per \ degrees \ magnetic \ with \ a \ correlation \ coefficient \ of \ -0.261$.

Figure 18 illustrates the same data as in Figure 17 only this time the data are presented as 135 pairs, with the source level for the call at hydrophone #2 (Hy#2) on the abscissa and the source level for the same call at hydrophone #1 (Hy#1) on the ordinate. The mean source level from hydrophone #1
Figure 17. Scatterplot showing the 230 source levels for 77 up calls (closed triangles) and 38 down calls (open circles) as a function of the whale's magnetic bearing from the hydrophone. Two source levels are included from each of the 115 calls based on the received levels at hydrophone #1 and hydrophone #2 of Array E. The regression line for all 230 points is drawn (solid line) and has a slope of -0.06 dB per degree magnetic bearing.
Figure 18. Scatterplot showing the source levels for 115 bowhead calls recorded simultaneously at hydrophones $h_1$ and $h_2$ of Array E. The regression line for all 115 points is drawn (solid line) and has a slope of 1.06 and an intercept of 3 dB.
was 154.4 ± s.d. 7.0 dB, while the mean source level determined from
hydrophone #2 was 152.3 ± s.d. 11.4 dB. The regression line for these data
has a correlation coefficient of 0.72 (student's t distribution, 0.001 > p >
0.005), a positive slope of 1.06, and an intercept of 3 dB indicating a
slightly higher level for hydrophone #1 than hydrophone #2. This high
correlation between source levels for the same sound at two different
hydrophones indicates that the two hydrophones and their associated channels
had equal sensitivities, and that the TL relationship (equation (5)) chosen in
the analysis was quite acceptable.

F. The 12 Whale Experiment.

All 356 acoustic locations and 183 visual sightings from the 57.5 h of
simultaneous acoustic and visual observations for Array E were used to
validate the acoustic location method. The actual analysis of the 12 Whale
Experiment data was performed by Dr. Judith Zeh and Daijin Ko.

The analytical procedure used by Zeh and Ko to confirm a simultaneous
acoustic/visual observation was quite simple; an acoustic location was
considered simultaneous with a visual sighting if the two observations
occurred within 3 minutes of each other, their positions were less than 600 m
apart and the direction of travel between those two positions was less than 90
from the direction of migration. By these criteria there were 16 simultaneous
acoustic/visual observations during the Array E period, thereby satisfying the
recommendation of the International Whaling Commission that there be 12
simultaneous acoustic/visual observations. These 16 linkages between acoustic
locations and visual sightings indicate a significantly greater correspondence
between acoustic and visual observations than would be expected by chance (Ko et al., 1986).

G. Tracks, CPA Distributions and Minimum Estimates, Array E.
All 356 acoustic locations with associated errors for the Array E period were analysed for acoustic tracks using an algorithm designed to maximize the number of linkages between locations and therefore minimize the number of whales counted (Sonntag et al., 1986). This resulted in a total minimum count of 171 acoustic whales, 91 of which were acoustic tracks with an average of 3.2 acoustic locations per track. All 173 visual sightings for the same period of time were analysed by the same tracking procedure resulting in a total minimum count of 96 visual whales, 58 of which were visual tracks with an average of 2.5 sightings per track. All the acoustic locations were combined with all the visual sightings and analysed by the same tracking procedure resulting in a total minimum count of 242 acoustic/visual whales, 138 of which were tracks with an average of 3.1 whale-locations per track. Figures 19 and 20 are examples of the tracking results as applied to the combined acoustic and visual data for two different periods during Array E. Figure 19 shows all the whale tracks and unlinked whale-locations computed by analysing all acoustic locations (open circles) and all visual sightings (closed circles) combined for the time period 2000-0531 h on 18-19 May, a period when visual observation conditions were good. Altogether there is a minimum of 34 whales represented in this 9.5 h time period; 15 were heard but not seen, 11 were both heard and seen, and 8 were seen but not heard. Figure 20 shows all whale tracks and unlinked whale-locations for the time period 1349-1615 h on 19 May, when visual observation conditions were good. Altogether there is a minimum of 23 whales represented in this 2.4 h time period; 17 were heard but not seen, 2
Figure 19. Plot showing all whale tracks and unlinked whale-locations computed from all acoustic locations (closed circles, n = 57) and visual sightings (open circles, n = 28) combined for the time period 2000-0532 h on 18-19 May 1984 during Array E when visual observation conditions were good. Altogether there is a minimum of 34 whales for this 9.5 h period; 15 were heard but never seen, 11 were both heard and seen, and eight were seen but never heard.
Figure 20. Plot showing all whale tracks and unlinked whale-locations computed from all acoustic locations (closed circles, n = 33) and visual sightings (open circles, n = 8) combined for the time period 1349-1615 h on 19 May 1984 during Array E when visual observation conditions were good. Altogether there is a minimum of 23 whales for this 1.5 h period; 17 were heard but never seen, 2 were both heard and seen, and 4 were seen but never heard.
were both heard and seen, and 4 were seen but not heard. The results as illustrated in these examples are very typical of any period during Array E when simultaneous acoustic and visual observations were made. That is, in all cases the minimum number of whales detected acoustically was always greater than or equal to the number detected visually. Figures 19 and 20 also illustrate three other important results from these analyses: 1) most of the whales that were detected at distances greater than 2.5 km from the visual observation perch were never seen by visual observers, 2) there were whales detected acoustically that were not seen even though they passed closer than 2.5 km from the perch and 3) the spatial distribution and density of whales within the lead is not constant but can change over short periods (less than 12 h) of time.

A quantitative measure of the differences in the results obtained by the acoustic and visual methods in terms of numbers of whales counted at different distances from the visual observation perch, is obtained by counting all the whales detected by the two methods in terms of their CPA distributions. The CPA distribution based on acoustic data alone is shown in Figure 21 and has a minimum of 171 whales. The CPA distribution based on the visual data alone is shown in Figure 22 and has a minimum of 96 whales. The CPA distribution resulting from the combined acoustic and visual data sets is shown in Figure 23. For the combined data sets there was a minimum of 242 whales detected. 135 of these whales were heard but never seen, 49 were both heard and seen, and 58 were seen but never heard.

The minimum estimates of bowhead whales as computed from these CPA distributions for acoustic locations, visual sightings and the combined
Figure 21. Histogram showing the closest point of approach (CPA) distribution for all whales detected using the acoustic location and tracking methods (n = 171) as a function of their distance from the visual observation perch during Array E (1800 h, 18 May to 0800 h, 21 May) in 1984.
Figure 22. Histogram showing the closest point of approach (CPA) distribution for all whales detected using the visual sighting and tracking methods (n = 96) as a function of their distance from the visual observation perch during Array E (1800 h, 18 May to 0800 h, 21 May) in 1984.
Figure 23. Histogram showing the closest point of approach (CPA) distributions for all whales detected using the combined acoustic and visual data sets as a function of the whale's distance from the visual observation perch during Array E (1800 h, 18 May to 0800 h, 21 May) in 1984.
acoustic/visual data sets for Array E are given in Table VI. In the table minimum estimates are given for numbers of offshore whales, whales that were further than 2.5 km from the visual observation perch, and nearshore whales, whales that were closer than 2.5 km from the perch.

Table VI. Summary of the minimum estimates of bowhead whales during Array E based on tracking analysis applied to acoustic locations alone (Acoustic Counts), visual sightings alone (Visual Counts), and all whale-locations (acoustic locations and visual sightings) combined (Combined Counts). The results of the analysis on the combined data sets are divided into three subcounts: Acoustic, Mixed and Visual, representing whales that were heard but not seen, both heard and seen, and seen but not heard, respectively. Counts are tabulated for offshore and nearshore whales. Percentages are in parentheses.

<table>
<thead>
<tr>
<th></th>
<th>Acoustic Counts</th>
<th>Visual Counts</th>
<th>Combined Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Acoustic</td>
</tr>
<tr>
<td>Offshore</td>
<td>45 (92)</td>
<td>7 (14)</td>
<td>42</td>
</tr>
<tr>
<td>Nearshore</td>
<td>126 (65)</td>
<td>89 (46)</td>
<td>93</td>
</tr>
<tr>
<td>Total</td>
<td>171 (71)</td>
<td>96 (40)</td>
<td>135</td>
</tr>
</tbody>
</table>

The total minimum estimate based on acoustic locations alone was 171 whales compared to a total minimum estimate of 242 whales when the acoustic data were combined with the visual data. For offshore whales, the acoustic method detected a minimum of 45 whales compared to 49 whales using the combined data sets, while for nearshore whale, the acoustic method detected 126 whales compared to 193 whales using the combined data sets. In contrast, the total minimum estimate based on visual sightings alone was 96 whales compared to a total minimum estimate of 242 whales when the acoustic data were combined with the visual data. For offshore whales the visual method detected only 7 whales compared to the 49 whales detected using the combined data sets, while for nearshore whales the visual method detected 89 whales compared to the 193 whales detected using the combined data sets.
H: Tracks, CPA Distributions and Minimum Estimates, Array C.

All 600 acoustic locations and associated errors from the three sample periods during Array C were analysed for acoustic tracks using the same procedures as in Array E. This resulted in three minimum estimates for each of the sample periods of 46, 46, and 47 acoustic whales, respectively. Of the total minimum estimate of 139 whales, 125 were acoustic tracks with an average of 4.7 acoustic locations per track. Only three whales were seen but none was visually sighted with theodolite during any of the three Array C periods and therefore there were no visual or mixed tracks for Array C. Thus the total minimum count of whales for all three Array C periods combined was 139, all of which were detected by the acoustic method. Figure 24 is an example of whale tracks during Array C based on acoustic locations for the time period 0000-0128 h on 4 May. This figure shows 8 acoustic tracks and a single acoustic location which was not linked to any other location in this time period.

During this same period, when visual observation conditions were unacceptable, observers saw no whales. In this figure the tracks are often irregular. This is a direct result of the large range errors associated with the acoustic locations for array C. These large errors increase the chances of linking two locations and therefore result in a lower minimum estimate compared to the an estimate based on the same locations with smaller range errors. Figure 24 also illustrates two other important results from these acoustic analyses for Array C; 1) whales were migrating through the observation area despite the extremely rough ice conditions and 2) almost all the whales detected were greater than 2.5 km from the visual observation perch and were never seen by the visual observers.
Figure 24. Plot showing all whale tracks and unlinked whale locations computed from all acoustic locations (closed circles, n = 41) for the time period 0000–0128 h on 4 May 1984 during Array C when visual observation conditions were unacceptable, and visual observers saw no whales. Altogether there is a minimum of eight whales for this 1.5 h period.
Figure 25. Histogram showing the closest point of approach (CPA) distribution for all whales detected using the acoustic location and tracking methods ($n = 139$) as a function of their distance from the visual observation perch during the three Array C sample periods (1310-1715 h, 3 May; 0000-2140 h, 4 May; 0031-0604 h, 5 May) in 1984.
A quantitative measure of the number of whales counted at different distances from the visual observation perch is obtained by adding up all the whales in terms of their CPA distributions. The CPA distribution based on the acoustic tracking analysis for all three Array C periods combined is shown in Figure 25. This resulted in a minimum of 139 whales. There were three sightings made during one of the Array C sampling periods but none of the three were theodolite sightings and therefore we could not determine whether any of the three were linked to any of the acoustic locations. Conservatively we will assume that the three sightings were of three different whales and that each of the sightings would have linked to an acoustic location. Thus, of the 139 whales detected, at least 136 were never seen, at most three were both heard and seen, and at most three were seen but never heard.

The minimum estimates of bowhead whales as derived from the CPA distribution for acoustic locations and the three visual sightings for the Array C period are given in Table VII. In the table minimum estimates are given for both offshore and nearshore whales.

<table>
<thead>
<tr>
<th></th>
<th>Acoustic Counts</th>
<th>Visual Counts</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offshore</td>
<td>109 (100)</td>
<td>0 (0)</td>
<td>109 (100)</td>
</tr>
<tr>
<td>Nearshore</td>
<td>30 (91)</td>
<td>3 (9)</td>
<td>30-33 (100)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>139 (98)</strong></td>
<td><strong>3 (2)</strong></td>
<td><strong>139-142 (100)</strong></td>
</tr>
</tbody>
</table>
Table VII shows that 109 of the 139 acoustic whales detected were greater than 2.5 km from the visual observation perch. Of the 30 acoustic whales detected within 2.5 km of the perch, it is not known whether any of these were the same whales as the three seen by visual observers. In any case, this means that at least 27 of the 30 whales detected by the acoustic method within 2.5 km of the visual observation perch were never seen.
DISCUSSION

Environmental conditions were severe in 1984, principally due to a prevailing northwesterly wind which intermittently drove the offshore ice into the shorefast ice resulting in unstable ice conditions and the loss of sonobuoy equipment. Despite the obstacles imposed by the ice, we were able to maintain a recording effort for 18.3 days during the 17 April to 27 May acoustic observation period. The amount of useful acoustic data collected far surpassed our expectations given the poor conditions throughout the season. These acoustic recordings fulfilled the first specific objective of performing acoustic surveillance of bowhead sounds for as much of the season as possible, and the second specific objective of providing data for an acoustic/visual correlation study.

Overall, fair to unacceptable visual observation conditions dominated most of the season reducing the amount of simultaneous acoustic/visual data during good or very good visibility to less than 25% of the total acoustic/visual data set. There was only one period, during Array E, when visibility conditions were good or very good and the acoustic and visual observation efforts were operating simultaneously for any reasonable period of time. The acoustic location analyses of 57.5 h of Array E data fulfilled the third specific objective of providing data for the 12 Whale Experiment and fulfilled part of the fourth specific objective of providing information for a more accurate population estimate. The acoustic location analyses of 31.4 h of Array C data completed the fulfillment of the fourth specific objective and provided important information on the acoustic behavior of the whales when visibility conditions were fair to unacceptable.
A: Acoustic Observations of Bowhead Whales as Related to Visibility Conditions

Because so much of the acoustic data were collected during periods when visual observation conditions were fair to unacceptable, acoustic observers were definitely aware of the fact that whales were in the area even when visual observers saw few, if any, whales. Furthermore, acoustic observers were aware of periods when a group of whales approached from the southwest, passed by the observation area, and departed to the northeast. This migratory pattern from southwest to northeast was documented simply by listening to the bowhead whale calls stereophonically as received at two sonobuoys. Bowhead calls would first be heard on the southwestern sonobuoy for several hours indicating that the whales were southwest of the array. Then there would be a gradual change in call arrival times until calls were heard simultaneously on both the southwestern and northeastern sonobuoys indicating that the whales were directly out in front (northwest) of the array. And finally the arrival times would change so that the calls were heard first on the northeastern sonobuoy indicating that the whales had passed and were now to the northeast of the array. This migratory sequence of southwest to northwest to northeast was perceived over the course of four to eight hours and during periods when the acoustic observers, by communicating with the visual observers, knew whether whales had or had not been seen. Thus, both the presence of bowhead whales and their migration through the observation area were acoustically observed in the field simply by monitoring the bowhead calls received over the sonobuoy array. These field results not only emphasize the importance of the acoustic technique as an observational tool but demonstrate that bowhead whales were migrating when ice conditions were extremely heavy and visual observers saw very few whales. Later laboratory analysis of the tape recordings provided
quantitative documentation on the number of calls per hour for each of the six acoustic observation periods (see Figure 15 and Table II) and verified the field observations that many calls were recorded but few whales were seen. For example, during the initial fifty hours of recording off of Snowy Owl visual observation perch (Array C), there were over 6200 bowhead calls recorded but only three whales were seen. These results based simply on the number of calls per hour throughout the season further support the conclusion that whales were in the area when ice conditions were extreme and no one could see them. We stress these points since many people felt that whales would not migrate under such severe conditions.

A logical assumption regarding the occurrence of sounds has been that greater numbers of sounds heard indicate a greater number of whales. For the 1980 migration there was a significant correlation between the hourly totals of sounds heard and whales seen (Clark, 1983). This correlation was based on almost nine continuous days of simultaneous acoustic/visual data when the numbers of whales migrating were very high (Johnson et al., 1981). Unfortunately, such a long period of concurrent acoustic and visual observation was not obtained in 1984 because of the severe ice conditions near Point Barrow. A short 2.5 day period of simultaneous acoustic/visual data was finally obtained near the end of the season (Array E) after the peak of the migration had presumably passed. The lack of any significant correlation between numbers of sounds and numbers of sightings for this period is probably a result of both the reduced sample size and the low number of whales. The fact that 35 of the 57 hours of simultaneous acoustic and visual observation had either no sounds recorded or at most only one whale seen has the effect of
reducing the correlation between numbers of sounds and numbers of whales.

It is very clear that many bowhead sounds were recorded but relatively few bowheads were seen during the 330.2 h of analysed recordings made throughout the six acoustic observation periods. A quantitative measure of this discrepancy between the overall acoustic counts and visual counts is found in Table III. Here the number of calls recorded and whales seen are given in terms of visibility condition. These results show that during good or very good visibility there were 20.1 calls recorded per whale seen, while during fair to unacceptable conditions there were 132.5 calls recorded per whale seen! These very different overall call rates for the two different sets of visibility conditions are best explained by the fact that the acoustic behavior of the whales (in this case observed as the number of calls per whale seen) is not directly related to the visibility conditions as described by the visual observers. For the most part, visibility conditions are not indicative of the lead conditions as experienced by the whales, and therefore we would not expect acoustic results to be related to visibility conditions. However, some of the lead conditions as experienced by the whales are perceived by visual observers and incorporated into judgments concerning visibility conditions. Therefore, it is important to recognize that visibility as described by visual observers and the acoustic results obtained during those conditions will be indirectly related due to the lead conditions which happen to affect both visual observation efforts and the vocal behavior of the whales. This independence of acoustic results from visibility condition is supported by two results. First it is apparent from the data presented in Table III that the number of whales seen is not directly proportional to hours of observation but is directly proportional to visibility condition; the
number of whales seen is a function of visibility condition. On the other hand, the number of sounds heard is directly proportional to hours of recordings analyzed but is not directly proportional to the visibility conditions; the number of calls recorded is not a function of visibility condition. Secondly, sound location analysis for the Array E period when visibility conditions were mostly good or very good (49.2 h) but occasionally fair or poor (8.3 h) demonstrated that visibility conditions did not affect the ability to acoustically locate a whale. These results strongly suggest that the visibility conditions which adversely affect the ability to see a whale do not necessarily affect the ability to hear a whale or acoustically locate it.

B: Numbers, Types and Source Levels of Bowhead Calls

One of the values of the acoustic method comes from the fact that its successful operation is directly related to conditions as experienced by the whales rather than visibility conditions as described by the visual observers. It is in this respect that the acoustic method permits observation to continue when conditions above the water make the visual observation effort ineffective. On the other hand, it must be pointed out that the reverse is also true; there will be times when conditions are very good for seeing whales but poor for recording and locating them. This state arises when the lead is wide open, there is a strong offshore wind and the shorefast ice is very deep. Under these conditions high ambient noise levels from surface wave action and reverberation from the deep keels of underwater ice decrease the chances of both acoustically detecting and locating whale calls.
The effects of lead conditions on acoustic results can be divided into two general categories; behavioral and physical. By behavioral we mean how the environmental conditions as experienced by the whales affect their acoustic behavior. For example, how rates of calling, types of calls produced or loudness of calls are affected by different ice conditions. By physical we mean how the environmental conditions actually affect the acoustic methods by which we record, detect and locate the whales. It was not the specific objective of this study to investigate the acoustic behavior of the bowheads as a function of environmental condition or to describe the effects of ambient conditions on the location analysis process. However, the results obtained in 1984 do provide some information on the direction and degree of these effects. Furthermore they raise very important concerns related to acoustic behavior since the ultimate interpretation of acoustic results for censusing efforts depends on knowing the extent to which various factors modify the number, types and intensities of calls produced by an individual whale.

There are two aspects of the general acoustic results as presented here that relate to acoustic behavior and environmental conditions; numbers of sounds recorded per hour of observation and the proportions of call types produced. The source levels of calls for different environmental conditions can not be compared because no levels were measured during the Array C period. During Array E when ice conditions were generally good and the lead was open, there were 28.2 ± s.d. 30.4 calls per hour, while during Array C when there really was no lead and the observation area was blocked with ice, there were 93.4 ± s.d. 93.1 calls per hour. In general, the relative proportions of tonal calls and complex calls were very similar for both lead conditions; 85% of the Array C calls were tonal as compared to 88% for Array E. Within the five tonal call
types, proportions were not dramatically different although the proportion of up calls produced during closed lead conditions, 43.6%, was greater than the proportion produced during open lead conditions, 35.7%. This increase in the proportion of up calls is possibly a result of a difference in lead conditions by the following reasoning. In the closely related southern right whale the up call, which is acoustically identical to the bowhead's up call, serves as a contact call; whales use this call to maintain acoustic contact and find each other when they are out of visual range (Clark, 1981; 1982). If the up call of the bowhead serves the same acoustic function as the up call of the right whale, then one would expect that when a bowhead is attempting to navigate through heavy ice it would produce more contact calls than it would when swimming through open water. This possible change in acoustic behavior related to lead condition needs more careful study with proper quantification of environmental conditions such as ambient noise level and reverberation index.

There was a difference in the proportion of the pulse tonal calls produced depending on lead condition; 14.2% of Array C calls were pulse tonals as compared to only 4.2% for Array E. As yet we do not know the function of the pulse tonal call in the bowheads acoustic repertoire and so the reason for the increase in pulse tonals under closed lead conditions is not clear. There was also a difference in the proportion of pulsive calls produced depending on lead condition; 0.9% of Array C calls were pulsive as compared to 7.9% for Array E. Pulsive calls have been associated with active socializing (Ljungblad et al. 1983, 1984; Wursig et al.; 1985), although this association was never observed in this study. However, due to the broadband, complex nature of the pulsive call they can not be heard as far away as the FM calls. Since most of the whales in Array C were at distances greater than 3 km (see Figures 24 and
25), then the reduced proportion of these calls during this period is most probably a result of their not being detected at distances beyond 3 km. In contrast, Array E whales were closer to the hydrophones and therefore more of their pulsive calls were recorded.

The topic of detection raises interesting questions concerning variations in source levels both within and between call types, and whether there is any directionality in bowhead calls. In this study we did not find any significant difference between the source levels for up calls and down calls although up calls were, on average, 3 dB louder than down calls. If the up call serves as a contact call then we would expect up calls to be louder than down calls. However, it has also been suggested that the down call serves as a contact call (Würsig et al., 1982), so it is not unreasonable to find that source levels for these two types of calls are statistically equivalent. We might expect to find differences between source levels for these two call types and either the high, pulse tonal or pulsive calls since these last three calls have been observed to occur most often in highly social contexts. There was only a slight indication of directionality for up calls and down calls, with sounds being louder in the front of the animal than behind the animal. This result is not unexpected since there should be a slight attenuation of sound due to the interposition of the animal's body when recording sounds at its posterior. Furthermore, if both these call types are contact calls, then one would expect them to be omnidirectional in order to increase the total area over which they could be heard.

The fact that we were unable to demonstrate any significant difference in the source levels for the two call types or any strong directionality is partially
due to the variations in received levels for the two call types. These variations arise from both biological variation and physical phenomena. Biological variation is a result of the same whale producing sounds with different amplitudes and different whales producing sounds with varying amplitudes. Physical phenomena contribute to the measured variation in the following way.

The acoustic boundary at the air–water interface is often termed a free surface where the particle velocities are equal on both sides and the acoustic pressure effectively goes to zero. The effect of this physical condition is that this air–water boundary is a very inefficient place to either produce or receive sound. The depth at which this boundary attenuation phenomenon comes into effect is largely a function of the frequency of the sound produced. In practice, this boundary includes depths which are within a quarter wavelength's distance (1/4 x sound velocity divided by the frequency) of the surface. Since most of the up calls and down calls are modulated between 80 and 200 Hz, and we were operating in water depths often on the order of only 20 m, then both our measurement equipment and the whales producing the sounds were functioning close to the conditions where boundary phenomena come into effect. The result of such a boundary effect will be to introduce some uncertainty into our ability to convert the measured received levels into a coherent source level data set, since these received levels have been subject to some unknown amounts of attenuation.

The shallowness of the water in which acoustic recordings were made is another factor that could possibly affect the measured received levels. As a result of the narrow channel between the surface and bottom, a sound travels along
several paths from the whale to the receiver due to multiple reflections. For a very narrowband constant frequency source this can result in large fluctuations in received levels due to superposition and cancellation effects. Since the calls used in the source level analysis were frequency sweeps and not constant tones, these superposition and cancellation effects are probably not substantial but still might have contributed to the variation in the observed received levels.

C: Verification of the Acoustic Location Technique

Although it was acoustically apparent by listening stereophonically to bowhead calls that the whales were migrating past Point Barrow during heavy ice as well as during open lead conditions, it was not clear how many whales were actually present. The first step in acoustically counting the number of whales relied on the method of acoustic location. Despite the fact that the general method of locating an underwater sound source using time delays is theoretically plausible and quite straightforward (Schultheiss, 1979; Weinstein, 1982), there has been considerable difficulty in implementing the method into a practical tool. For this reason, in 1983, the Scientific Committee of the International Whaling Commission recommended that an experiment be conducted in order to empirically demonstrate the acoustic location method. The results of the 12 Whale Experiment (Ko et al. 1986) show that 16 whales were simultaneously visually sighted and acoustically located (+ 3 minutes). These 16 simultaneous acoustic/visual whale-locations are significantly greater than would be expected by chance alone, thus demonstrating that the acoustic location methods can be verified by actual visual sightings of the whales that produced the sounds.
One common concern regarding the time delay method of locating an underwater sound source has been the possibility that the sound becomes distorted due to refraction or reflection phenomena. In fact, both these effects are negligible for the conditions under which the arrays were operating. There is no significant refractory effect since the water off Point Barrow is isothermic (Urick, 1975). There could be reflections off of large underwater ice walls which could cause signal distortion, but reflection was not a concern during Array E when the lead was open and there were no large pieces of ice in the area. There was a potential problem with reflections during Array C when ice conditions were severe. However, because of the process by which the time delays were computed, indistinct time delays resulted if one or more of the signals was contaminated by a reflection. As mentioned in the methods section, such indistinct time delays resulted in crossbearings that did not converge and no acoustic location data were entered into the record file for a sound with indistinct time delays. This rejection of potential acoustic locations for which one or more of the delay times were indistinct was partially responsible for the fact that only 36% of all location attempts resulted in acceptable locations. Thus, refraction and reflection phenomena were not a concern in terms of the accuracy of the location process since we were working in very cold, well-mixed water and we were rigorous in our acoustic location methods. Furthermore, all acoustic location data included range and bearing errors which incorporated the cumulative effects of errors due to signal distortion, sonobuoy array geometry, speed of sound measurement and computer analysis system time resolution.
D: Improvements in Minimum Estimates for Numbers of Bowhead Whales Due to Acoustic Methods

The importance of the acoustic location method as an observational tool is best demonstrated by the comparison of acoustic results with those from the traditional visual observation methods. The most compelling results of the 1984 acoustic study are found by comparing the CPA distributions from the acoustic location data and the visual sighting data, with the distributions obtained when both data sets are combined. There are two major points of comparison between the results of the two different observation methods; 1) the number of whales counted as a function of lead condition and 2) the number of whales counted as a function of CPA distance from the visual observation perch.

Results for the two different lead conditions, the open lead during Array E and the closed lead during Array C, provide dramatic constraints between the numbers of whales counted by the acoustic method alone, the visual method alone and the two methods combined.

Results from the tracking analysis and CPA distributions during Array E (see Table VI) demonstrate that acoustic methods alone detected 71% of the total number of whales counted when both methods were combined, while visual methods alone detected only 40% of that total. Thus, even under open lead conditions when visibility was mostly good or very good, the acoustic method detected 78% more whales than the visual method. Since the acoustic method has the presumed advantage of detecting whales beyond the nearshore area of visual observations, we can further divide this comparison into the nearshore and offshore areas. As Table VI shows, within the nearshore area the acoustic method detected 65% of the total number of whales counted when both methods were combined, while visual methods detected only 46% of that nearshore total.
For the offshore area, the acoustic method detected 92% of the total number of whales counted when both methods were combined, while visual methods detected only 14% of that total. In the case of the nearshore comparison, the visual method actually had several advantages which would tend to increase the visual counts; visual theodolite sightings were not restricted by the 120 sector boundaries, visual theodolite sighting data did not include range and bearing errors, and the density of whales during this observation period was low. The 120 sector boundaries were imposed on the acoustic methods because of acoustic location error considerations. These boundaries reduce the nearshore acoustic observation area by 33% compared to the visual observation area. The lack of range and bearing errors associated with visual theodolite sightings reduces the number of linkages between sightings and thereby increases the number of whales counted based on visual sightings alone. The density of whales during Array E was on the order of 4-6 whales per hour, a rate which is relatively modest compared to the high density rates of 20-30 whales per hour during peak days of migration. During modest rates of whale passage it is assumed that visual observers will see all whales that surface within 2.5 km of their perch and that the actual number of whales missed will be low.

Despite these methodological differences which would tend to increase the number of whales detected visually in the nearshore area, nearly half (48%) of the total whales detected within 2.5 km of the visual observation perch were never seen.

For Array C, when lead conditions were poor, the disparity between acoustic and visual counts was even more dramatic. Acoustic methods counted a minimum of 139 whales compared to the three whales that were seen. As Table VII shows, 77% of all the whales counted were offshore of the visual observation perch
and none of these whales was seen by the visual observers, and least 90% of all the whales detected within the nearshore observation area were never seen by visual observers.

E: Conclusions

There are two important conclusions to be drawn from these comparisons between the acoustic and visual results. The first conclusion is that even during open lead conditions the acoustic method always detected more whales than the visual method, regardless of the observation area over which results were compared. What is even more remarkable about this result is the extent to which the acoustic methods increased the total minimum count; from 96 to 242 whales over the entire observation area and from 89 to 193 whales over just the nearshore area (see Table VI), an area in which traditional visual observation methods are assumed to be optimal. Thus, the acoustic data more than doubled the number of whales counted under even the best conditions for visual censusing. It is clear that assumptions on the efficacy of the visual observation method in the nearshore area need to be reconsidered.

The second conclusion is that many whales are migrating offshore of the visual observation perch and are never seen by the visual observers. In the case of open lead conditions, visual observers never saw 42 of the 49 whales that were offshore of the perch. This represents 44% of the total visual whales seen. In the case of the closed lead condition, there were at least 136 whales that passed offshore of the perch and were never seen (see Table VII). The fact that visual observers only saw three whales (all in the nearshore area) during the closed lead period only underscores the ineffectiveness of the visual method when the lead is closed.
The major objective of the acoustic study was to provide information which would result in a more precise estimate of the bowhead population migrating past Point Barrow in the springtime. Unfortunately, due to the severity of the ice conditions and the resulting lack of visual sighting data, a population estimate was not derived for the 1984 season. However, based on the results of the 1984 acoustic study, we unambiguously conclude that the responsible application of acoustic techniques can significantly augment the traditional visual censusing methods. The overall conclusion of the acoustic study is inescapable: the methods of acoustic location and tracking are extremely powerful techniques for improving the nearshore whale count and extending the censusing effort to include offshore areas beyond the range of reliable visual observation. Although it has generally been assumed that the acoustic method is a secondary observation method which serves to support and augment the visual effort, it now appears that the reverse is actually true. Acoustic methods result in nearshore and offshore estimates of migrating bowhead whales that are higher than the estimates obtained using traditional visual techniques. Furthermore, the acoustic methods provide a permanent record of the acoustic data and utilize analytical methods that are highly quantified and repeatable.

These results are extremely encouraging. They demonstrate that acoustic techniques can provide information on the number of bowheads during different lead conditions, including closed lead conditions during which it was previously believed by some that no whales were even in the area of Point Barrow. This ability of the acoustic methods to both detect and count whales under a wide variety of lead conditions and out to distances well beyond the
range of visual detection means that the spring censusing effort can operate effectively for the majority of the two month migratory period. The results show that acoustic observation techniques detect more nearshore whales than the visual observation methods and underscore the importance of acoustics as an extremely powerful tool for censusing the bowhead whale. Based on these results it is expected that the continued use of acoustic methods for censusing migrating bowheads will provide a more comprehensive and more definitive estimate of the bowhead whale population then has been arrived at using the traditional visual methods alone.

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REFERENCES


Appendix A

Technical Description and Operating Instructions for Data Acquisition and Analysis Systems

Introduction

The following are technical descriptions and general operating instructions for the three systems which were developed to transduce, transmit, receive, record and locate the sounds of bowhead whales. These three systems consist of 1) the sonobuoy system, 2) the receiving and sound recording system, and 3) the computer-based acoustic processing and analysis system. Each of these systems was designed to operate in the arctic environment for the duration of the study, be easily transportable in the field, and have replacement parts available for all key components. All systems were designed for complete delivery to, and ownership by the North Slope Borough. Each sonobuoy system comes in its own travel case, and the two other systems pack into six rugged, hard-shell travel cases.

Sonobuoy System

The sonobuoy system consists of a hydrophone for transducing acoustic pressure into electronic signals, transmitter circuitry for converting those signals into radio-frequency transmissions, and an antenna for broadcasting those transmissions to a distant radio receiver. A block diagram of the sonobuoy system is shown on the left-hand side of Figure A-1.
A. Technical description of sonobuoy system

The sonobuoys used in the 1984 acoustic study were modified AN/SSQ-57A sonobuoys. Each sonobuoy system was modified electrically to operate off a 12 volt storage battery and have three switchable input attenuation settings of 0, -8, and -20 dB. These settings allowed the radio transmitter section to be used with the two types of hydrophones used during this study. These two types of hydrophones are referred to as old hydrophones (identified by an irregularly shaped, black casing) and new hydrophones (identified by a 12 inch long cylindrical, black casing with red end caps) and differed in their sensitivities, with the new hydrophones being 6 dB more sensitive than the old hydrophones. Each sonobuoy was also modified mechanically so that both the hydrophone and antenna were modular and could be replaced if either became damaged. The acoustic sensitivity response for each sonobuoy/hydrophone unit was calibrated by the original manufacturer (see footnote (2) on page 6 of Methods section) to a primary sensitivity of $110 \pm 1 \text{ dB re } 1 \mu \text{Pa/19 kHz}$ deviation at 400 Hz. The operating frequency range for all sonobuoys was 10 to 20,000 Hz.

B. Operating instructions for sonobuoy system

These operating instructions refer to the sonobuoy system used during the 1984 acoustic study. They are best read with a system in hand for ease of interpretation and understanding.

1. Hydrophone connections to sonobuoy transmitter: Connect the two-prong, red banana plug on the end of the hydrophone cable to the two, red banana plug receptacles on the sonobuoy terminal plate. If the sonobuoy does not transmitt
Figure A-1. Block diagram of the sonobuoy system and the radio receiving and sound recording system for remote detection and recording of bowhead whale sounds.
a signal, reverse the receptacles into which the two-prong, red banana plug is inserted. This will not damage the hydrophone.

On the new hydrophones the single, black banana plug is the cable shield. Connect this to the black receptacle on the terminal plate of the sonobuoy.

2. Hydrophone sensitivity values: Hydrophone sensitivity is marked on each hydrophone. The sensitivity for an old hydrophone is marked on the inside of the hydrophone packing case, while the sensitivity for a new hydrophone is marked on the outside of the hydrophone packing case. The positive number printed on the case represents:

- $\text{dBV output per 1 microbar pressure input.}$

Therefore, larger printed numbers represent lower sensitivities.

3. Sonobuoy sensitivity settings: To avoid overloading the sonobuoy preamplifier, and to compensate for differing hydrophone sensitivities, an input attenuator with settings of 0, -8, and -20 dB is provided on the sonobuoy terminal plate at the base of the sonobuoy. Set this switch for least attenuation without overload distortion. The 0 dB setting gives the least attenuation. It is recommended that the 0 dB setting be used with the old hydrophones and the -8 dB setting be used with the new hydrophones.

Radio Receiving and Sound Recording System

The radio receiving and recording system consists of three subsystems: a radio receiver, an audio monitor box, and a multi-channel tape recorder. In the field, all three of these subsystems can be run off a common 12 volt storage
battery. However, in order to avoid grounding problems, it is recommended that the radio receiver subsystem be run off a 12 volt battery which is separate from the 12 volt battery running the audio monitor box and the tape recorder. All connections between these subsystems are made using the customize cables provided with the system. All cables are marked with labels which match their corresponding connections on the equipment. A block diagram of the radio receiving and sound recording system for a single sonobuoy is shown on the right-hand side of Figure A-1.

A. Technical description of radio receiving and sound recording system

The radio receiving subsystem consists of four Bearcat 210XL VHF receivers, custom-modified for extended dynamic range reception of at least 50 dB. The four receivers are mounted in a single customized field rack with integral electrical connector panel.

The audio monitor subsystem is custom designed for this project. It consists of two modules; a record preamplifier module and an audio monitor module. Both modules are rack-mounted in a single rugged case, together with an internal loudspeaker. Modules and loudspeaker are individually replaceable in the field. Both modules are designed for low noise, and have a calibrated uniform frequency response from 10 to 20000 Hz.

The record preamplifier module is a four-channel record preamplifier which provides attenuation, master gain control, peak level indication, and low level indication for each of the four channels of input from the radio receiving subsystem. These controls allow the user to optimize recording signal levels for each of the incoming signals. The preamplifier also
includes fully differential input and output stages and internal filtering, which serve to reduce system noise.

The audio monitor module is a stereo amplifier which provides low-pass filtering, switch selection of the monitor channels, frequency compensation, and loudspeaker output. These controls allow the user to listen to any pair of incoming signals on stereo headphones with the high frequency ambient noise filtered out and with full frequency compensation.

The recording subsystem consists of a TEAC Model R61-D four-channel cassette recorder. The recorder operates at a tape speed of 1-7/8 inches per second, and fills a conventional 90-minute cassette tape with approximately 45 minutes of four-channel data. The tape recorder has a frequency range of 50 to 8000 Hz.

B: Operating instructions for radio receiving and sound recording system

The following are operating instructions for using the radio receivers, multi-channel tape recorder and audio monitor box subsystems. These instructions are best read with the subsystems in hand for ease of interpretation and understanding.

1. Radio receivers: The Bearcat receiver is tuned digitally from a numeric keypad on the front of the receiver. This gives great ease and flexibility in the selection of the receiving frequency which must be tuned to the transmitting frequency of the sonobuoy. A small built-in loudspeaker allows the user to monitor the received signal and determine whether both the receiver and sonobuoy are functioning properly. Precise instructions for
tuning and operating the receiver are given in the Bearcat instruction manual.

Each Bearcat receiver is individually connected to a customized panel assembly located at the lower rear of the receiver system rack. The connections made from each receiver to this panel include a chassis ground, an antenna input (the receiving antenna is located outside on the top of the acoustics hut), a 12 volt DC power supply input, and a receiver output which is connected directly to the audio monitor box.

2. Audio monitor box: record preamplifier module: The record preamplifier module contains four independent recording preamplifiers. Figure A-2 shows a block diagram of the record preamplifier module for a single channel of input. The module receives multiple signal inputs from the radio receivers via a multiple connection on the rear of the module. Each of these signals is high-pass filtered, attenuated and/or amplified, and returned as a differential output to a multiple connection on the rear of the module, where the signals are sent to the inputs of the TEAC cassette tape recorder. Descriptions of the rear panel and front panel controls for the record preamplifier module are given below.

i. Rear panel controls: The input connections, output connections and ground controls for the record preamplifier module are found on the back right side of the audio monitor box under the panel labelled RECORD.

IN This is a 5-pin connector which accepts the signals from the rear panel assembly of the radio receiving subystem into the record
preamplifier module. Four of the pins carry the signals from the four individual receiver channels, while the fifth pin is the common ground.

OUT This is a 5-pin connector which links the signals coming out from the record preamplifier module to the inputs of the cassette tape recorder. Four of the pins carry the signals from the four individual record preamplifier channels, while the fifth pin is the common ground.

There are two silver toggle switches on the record preamplifier module which enable the user to operate all four channels of the record preamplifier module in either the differential or ground-referenced mode. This allows the record preamplifier to be used in a variety of situations as a general purpose instrumentation amplifier. When the toggle is in the down position facing the ground symbol $\frac{1}{\Omega}$, the module is operating in the ground-referenced mode. When the toggle is in the up position the module is operating in the differential mode. Input and output amplifiers in the record preamplifier are fully differential, rather than being implicitly referenced to the power supply ground. This affords maximum cancellation of any noise voltages appearing between the various signal grounds in the system. In particular, the TEAC R-61D recorder (1) generates a significant noise voltage between its signal ground and the system power supply ground. Using the differential ground connection considerably reduces this noise problem.

IN Ground This is a toggle switch for adjusting the ground connections for the inputs to the record preamplifier module. This switch can be in either

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1 All connections to the TEAC cassette tape recorder should be differential for maximum noise rejection.
Figure A-2. Block diagram for a single channel of the record preamplifier module in the audio monitor box.
the up or down position. In practice it is best to try both positions and use whichever results in the lowest level of audible power line hum and radio-frequency interference.

**OUT Ground** This is a toggle switch for adjusting the ground connections for the outputs of the record preamplifier module. This switch should always be in the up position (differential mode) when the module is connected to the TEAC R61-D cassette tape recorder.

**ii. Front panel controls:** The amplifier controls and amplifier indicator lights are found on the front left of the audio monitor box under the panel labelled **RECORD**.

**MASTER GAIN** This rotary switch sets the gain on all 4 channels simultaneously in 10 dB steps from -10 to +30 dB. Typically this switch is set to either -10 or 0 dB.

**CHANNEL ATTENUATION** These four toggle switches set the attenuations on the individual channels in order to approximately equalize the gains on all channels. The attenuation is in 10 dB steps from -20 to 0 dB. Switches are adjusted according to the specifics of the field situation, but are typically set to either 0 or -10 dB.

There are eight indicator lights, four red and four green, on the front RECORD panel of the audio monitor box. These lights indicate excessive or inadequate output voltage levels for each of the four output channels (labelled as 1, 2, 3, and 4 above and below the lights) of the record preamplifier module. They
serve to help prevent signal distortion and unacceptable signal levels on the tape recording due to either excessive input voltage levels or inadequate voltage levels to the tape recorder.

HI REC LEVEL  The HI REC LEVEL red indicator light turns on when the peak output voltage level from a particular channel is within 3 dB of the input voltage clipping level for the tape recorder. There are four such lights, one for each of the four record preamplifier output channels. To correct for a light indicating clipping, reduce the MASTER GAIN switch and/or increase the CHANNEL ATTENUATION switch for the particular channel until the light goes off.

LO REC LEVEL  The LO REC LEVEL green indicator light turns on when the average output voltage level from a particular channel is less than 5 dB above system noise level for the tape recorder. There are four such lights, one for each of the four record preamplifier output channels. To correct for a light indicating a low record level, reduce the MASTER GAIN switch and/or reduce the CHANNEL ATTENUATION switch for the particular channel until the light goes off.

3. Audio monitor box: audio monitor module: The audio monitor module contains two independent audio monitoring channels and one loudspeaker. Figure A-3 shows a block diagram for the left channel of the audio monitor module. The module receives inputs from the output channels of the cassette tape recorder via a multiple connection on the rear of the module. Two of these possible four inputs are selected for monitoring, low-pass filtered (optional), frequency compensated (optional), returned to two output connectors on the
rear of the module connected to a loudspeaker (optional), and connected to a
phono jack on the front of the module for stereo headphone monitoring.
Descriptions for the rear and front panel controls for the audio monitor
module are given below. This module is labelled MONITOR on both the back and
front panels of the audio monitor box.

i. Rear panel controls: The input connections, frequency compensator output
connections and ground controls for the audio monitor module are found on the
back of the audio monitor box under the panel labelled MONITOR.

MONITOR IN  This is a 5-pin connector which connects the signals from the
outputs of the TEAC cassette tape recorder to the audio monitor module. Four
of the pins carry the signals from the four individual recorder channels,
while the fifth pin is the common ground.

DUP IN      This is a 5-pin connector which is identical to the MONITOR IN
connections. This provides a means of passing the signals going to the audio
monitor module directly to the computer analysis system during the acoustic
location process. Four of the pins carry the signals from the individual
recorder channels, while the fifth pin is the common ground.

COMP LEFT/RIGHT  These two output connectors provide access to the output
from the two frequency compensator channels. These connectors allow frequency
compensated output to be monitored on an oscilloscope, or delivered to a 2-
channel tape recorder.
Figure A-3. Block diagram for a single channel of the audio monitor module in the audio monitor box.
Like the record preamplifier module, all input and output amplifiers in the audio monitor module are fully differential (see the explanation in the record preamplifier section above). The two ground toggle switches on the rear MONITOR panel allow the user to operate the audio monitor module in either differential or ground-referenced mode.

**IN Ground**  This is a toggle switch for adjusting the ground connections for the inputs to the audio monitor module. This switch should always be in the up position (differential mode) when the module is connected to the TEAC cassette tape recorder.

**OUT Ground**  This is a toggle switch for adjusting the ground connections for the frequency compensated outputs of the audio monitor module. This switch can be in either the up or down position. In practice it is best to try both positions and use whichever results in the lowest level of audible power line hum and radio frequency interference.

**ii. Front panel controls:** The controls for selecting which of the input channel are monitored, the frequency compensator option, the loudspeaker option, and the headphone outputs are found on the front of the audio monitor box under the panel labeled MONITOR.

**AUDIO CHAN**

**LEFT/RIGHT**  The audio monitor module accepts 4 input channels and allows the listener to select any two audio channels for stereophonic monitoring using a pair of stereo headphones. There are two rotary switches, labelled LEFT and RIGHT, which select the two channels that are heard on the stereo
headphones. Each switch has four positions, labelled 1, 2, 3, and 4, which designate the input channel selected. By having the LEFT and RIGHT switches set on the same channel and concurrently rotating through each of the four settings, the user can successively monitor each of the hydrophone channels. This provides a reliable means of checking that each channel is working properly, that the gain settings (described under the Record preamplifier module, Front panel controls section above) are properly set, and that the quality of the bowhead whale sounds are acceptable for later analysis. During normal operation, both LEFT and RIGHT switches are set on two different hydrophone channels so that the acoustic observer has the benefit of listening over two separate channels. For example, if one wanted to listen stereophonically to channels 1 and 3, the LEFT switch is set to position 1, while the RIGHT switch is set to position 3. The left audio channel now carries channel 1 and the right audio channel carries channel 3. The left audio channel is also the channel delivered to the loudspeaker.

Each audio monitor module channel contains dual frequency compensating circuitry that compensates for 1) the frequency response of the new hydrophones, 2) the frequency pre-emphasis imposed by the sonobuoy electronics, and 3) all other accumulated frequency errors in the sonobuoy transmitting and radio receiving systems. Frequency compensation is applied to the two channels of input selected by the AUDIO CHAN LEFT/RIGHT switches. The overall system frequency response using the frequency compensator is given by the ratio:

\[
\frac{\text{frequency compensator voltage output}}{\text{hydrophone pressure input}}
\]

The effect of compensation is to provide an approximately flat frequency response from 10 to 20000 Hz. This response varies somewhat with individual
sonobuoys, and is obviously conditional upon using the types of sonobuoys and hydrophones for which the circuitry was designed. The following are the compensator controls found on the front panel of the audio monitor box. The following are controls for the frequency compensator section of the audio monitor module. This section is marked COMP on the front panel of the MONITOR panel.

**IN/OUT**

This toggle switch allows the user to select whether both channels of the audio monitor module are compensated (IN) or not compensated (OUT). When the frequency compensator circuit is activated, the audio signals to the stereo headphones, loudspeaker and rear panel frequency compensator outputs (COMP LEFT/RIGHT) are all frequency compensated.

**0/-20**

This toggle switch allows selection of a frequency compensator gain of either 0 or -20 dB.

**OVLD**

There are two red overload indicator lights, one for each of the two audio channels being monitored. When a light is on, it indicates that the peak signal level for the indicated channel is within 3 dB of the clipping level for the frequency compensator circuitry. To correct for an overload condition first set the 0/-20 dB toggle switch to -20 dB. If the condition persists, then reduce the CHANNEL GAIN switch for the overloaded channel by 10 dB. When the indicator light is on, it does not imply an overload condition in other sections of the audio monitor module. These overload lights operate independently of the IN/OUT switch.
PHONE  This receptacle delivers the two channels of audio signal from the audio monitor module to the stereo headphones through individual headphone amplifiers.

VOL  This dial controls the volume levels at the stereo headphone jack and the loudspeaker.

SPKR ON/OFF  The output of the left audio channel is passed to a 25-Watt power amplifier and loudspeaker. The amplifier and loudspeaker are electronically equalized to deliver roughly uniform acoustic power from 50 to 15000 Hz. Use of the loudspeaker is optional and is controlled by a toggle switch that turns the loudspeaker on or off.

The gain of the loudspeaker power amplifier is internally calibrated to the TEAC cassette recorder output such that when the volume control dial, VOL, is set to the 12 o'clock position a signal level of 0 dB on the TEAC VU meter will drive the loudspeaker power amplifier to full power.

For low recorded signal levels, a second calibration applies so that if the volume control dial, VOL, is set in the full clockwise position a signal level of -15 dB on the TEAC VU meter will drive the loudspeaker power amplifier to full power. By this design, the loudspeaker power amplifier can achieve full power with input signals as low as -15 dB on the TEAC VU meter. To avoid unpleasant transient noises upon turning on the power, the power amplifier contains a delay circuit which delays the delivery of full DC power to the power amplifier by 60 seconds. The loudspeaker can temporarily withstand, without damage, any signal level generated by the power amplifier. However,
the user's ears may not be able to tolerate such high levels of acoustic power. It is therefore recommended that the VOL control dial be reduced before connecting signals to the audio monitor module.

4. Tape recorder: The TEAC cassette recorder receives input from the record preamplifier module and delivers output to the audio monitor module. The cassette recorder is powered off a 12 volt battery or an AC powered 12 volt power supply through an adapter cable provided with the recorder. This cable conditions the 12 volt DC power supply to the 9 volt DC required by the recorder. DO NOT under any circumstances connect the recorder directly to a 12 volt DC supply without using the adapter cable.

Detailed operating instructions and technical specifications for the TEAC cassette recorder are provided in the TEAC instruction manual.

Computer-based Data Acquisition and Analysis System

The computer-based data acquisition and analysis system consists of a cassette recorder, an audio monitor box, four lowpass filters, and the acoustic location analysis computer. The entire system is designed to operate in the arctic environment in an acoustic hut. The system is driven off a 120 volt AC power supply. Under field conditions, this power is supplied by a Honda 1800 Watt portable generator which is both acoustically quiet and emits very little electrical noise.
A: Technical description of computer data acquisition and analysis system

1. Cassette recorder: The cassette recorder used to playback field tape recordings for computer location analysis is a TEAC R61-D four-channel cassette recorder identical to the cassette recorder used to record the original acoustic field data. This instrument is described above in section B.4 above.

2. Audio monitor box: The audio monitor box consists of an audio monitor module, including headphone set and loudspeaker. This subsystem was described above in section B.3 above.

3. Lowpass filters: The filter subsystem consists of four adjustable lowpass filters. These filters are required in order to eliminate high frequency signals and noise which would interfere with the proper computation of frequency spectra and acoustic locations. In digital signal processing such filters are referred to as anti-aliasing filters.

4. Computer analysis hardware and software: The acoustic location analysis computer consists of an LSI 11/23 minicomputer with 1) an analog to digital (A/D) converter for digitizing four channels of acoustic data coming from the cassette recorder, 2) an array processor for very rapid computation of complex and extensive mathematical calculations, such as are required for the two-dimensional cross-correlation location technique, 3) computer memory and floppy disk for program and data storage, respectively, 4) a video terminal for graphics display and communication with the user, 5) a graphics printer for plotting graphs and printing the software programs, 6) a minicomputer (CPU) for controlling and integrating the above systems, and 7) the customized
software for actually processing the acoustic data and computing acoustic locations. In the computer system the analog to digital converter, array processor, memory and controller for the floppy disk are computer boards which fit into the backplane within the minicomputer chassis.

**B: Operating instructions for computer data acquisition and analysis system**

A schematic diagram of the computer data acquisition and analysis system is shown in Figure A-4. For computer analysis of the bowhead sounds, the output channels of the TEAC cassette recorder are cabled into the MONITOR IN connection on the back of the audio monitor box. Another cable from the DUP IN connector delivers these same signals to the anti-aliasing filters. The filtered and amplified output of the filters are connected directly into the analog to digital converter which resides inside the computer chassis box. The following are operating instructions and typical operating settings for each of the above components in the data acquisition and analysis system except the cassette recorder and audio monitor box both of which have been discussed in section B of this appendix.

i. **Lowpass filters:** Each lowpass anti-aliasing filter has a variable cut-off frequency which is adjustable from 1 to 30000 Hz. An adjustable gain of either 0, +10, or +20 dB is also provided on each filter. This gain is useful for equalizing any major gain discrepancies between channels and in optimizing the input signal levels presented to the computer (see below). All four filters are custom-mounted together in a rugged transport case and connected at the back of the case to an input-output assembly rack. The two connections to the assembly rack are as follows:
Figure A-4. Block diagram of the computer data acquisition and analysis system for acoustic location analysis on bowhead whale sounds.
INPUT

This is a 5-pin connector which delivers the signals from the DUP IN connector on the rear panel of the audio monitor module of the audio monitor box. Four of the pins carry the signals from the individual recorder channels, while the fifth pin is the common ground.

OUTPUT

This is a 50-pin connector which delivers the output of the filters to the input of the A/C converter board in the computer chassis. Four pins carry the signals and one pin is the common ground.

ii. Computer analysis hardware and software: The analog to digital converter accepts input signals with maximum signal levels of ± 10 volts. The converter has a digital noise level of 5 millivolts, and a dynamic range of 72 dB. For maximum signal to noise ratio it is recommended that incoming signals have their peak signal levels as close to the ± 10 volt limit of the converter as possible. To assist in this, the signal levels for each channel relative to 10 volts are printed on the video terminal each time a sound is acquired.

In the process of acquiring a sound via the multiple channels of the tape recorder, the analog to digital converter samples the analog voltage level of the filtered tape output at a programmable sampling rate, converts these voltages into discrete digital levels, and stores them in predefined memory locations referred to as time buffers. There are four time buffers in the computer's memory, each buffer identified by a number corresponding to the channel of the tape recorder from which the time buffer's data came. By this method time buffer 1 holds the amplitude-time matrix of the sound from tape recorder channel 1. Within the computer memory there are also four other
buffers, referred to as frequency buffers, for storing the frequency-
amplitude-time matrices of their respective amplitude-time matrices.

The computer-based analysis of the acoustic data is controlled through a
series of simple English commands. These commands are typed in at the
computer keyboard. Each command is between 2 and 4 letters long, and serves
as an abbreviation and mnemonic of the command's function. For example, the
command GT instructs the computer to G(raph) the amplitude-T(ime) matrix of
the sound. By using such abbreviations for the commands, the commands are
readily learned by a beginning user.

Table A-1 is the list of keyboard entry commands used in the computer
processing of an acoustic location. This is not considered an instruction
manual for the computer-based acoustic location analysis software. The table
lists the functional groups, the individual commands in each group, and a
brief functional description of each command. When any command is typed and
entered through the keyboard, a separate program subroutine within the main
program is activated, and this subroutine then performs the command. As an
example, a whale's location is obtained by first acquiring the sound from the
tape recorder using the AC (ACquire) command, transforming the sound from an
amplitude-time signal into a frequency-amplitude-time matrix using the XFT
command, and then cross-correlating these transform matrices to compute the
time delays using the CCFT command. Most often other operations such as
filtering (SF, FI) and graphing (GT, GF, GFT) are used to improve the accuracy
of the time delay computation. The time delays are then used to compute and
draw the hyperbolic solutions on the terminal using the GL command. Next, the
whale's location, the range error and the bearing error are measured from the
graph using the cursor command, CU. Finally, this acoustic location information is typed into a computer record file using the RL command and stored using the LS command.
**TABLE A-1.** The following is a listing of the keyboard entry commands in the software program for the acoustic location analysis process. The listing is organized into functional groups with the heading for each functional group given above the commands in the group. A brief description is given for each command. Words in parentheses at the end of a command description indicate the default values initially programmed for that command, but changed by that command. For example, the value (400 Hz) in the description of the BA command indicates that the initial acquisition bandwidth is at 400 Hz. By typing BA 800, the acquisition bandwidth is changed from 400 Hz to 800 Hz.

<table>
<thead>
<tr>
<th>Command</th>
<th>Command description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data acquisition functions</strong></td>
<td></td>
</tr>
<tr>
<td>BA</td>
<td>sets the acquisition bandwidth (400 Hz).</td>
</tr>
<tr>
<td>AC</td>
<td>acquires 4 channels of analog data through the analog to digital converter.</td>
</tr>
<tr>
<td><strong>Spectral analysis functions</strong></td>
<td></td>
</tr>
<tr>
<td>XF</td>
<td>converts an amplitude-time signal into a frequency-amplitude spectrum using the Fourier transform.</td>
</tr>
<tr>
<td>XFT</td>
<td>computes the frequency-amplitude-time matrices from the amplitude-time signals.</td>
</tr>
</tbody>
</table>
SM smooths a frequency-amplitude spectrum.

Filtering functions
SF constructs a low-pass, high-pass, or band-pass filter
FI filters amplitude-time signals.

Graphic functions
GT graphs amplitude-time signals.
GF graphs frequency-amplitude spectra.
GX graphs cross-correlation function(s) for the amplitude-time signals.
CU turns the graphics cursor on.
GFT graphs frequency-amplitude-time matrix or matrices.
GL graphs hyperbolic loci for the time delays.
FT sets the start time for GT and GFT graphs (0 seconds).
TT sets the end time for GT and GFT graphs (maximum seconds).
FF sets the lower frequency for GF and GFT graphs (0 Hz).
TF sets the upper frequency for GF and GFT graphs (400 Hz).
FX sets the lower x axis limit for the GL graph (-4000 m).
TX sets the upper x axis limit for the GL graph (-4000 m).
FY sets the lower y axis limit for the GL graph (-500 m).
TY sets the upper y axis limit for the GL graph (3500 m).
SY sets the y step size for the GL graph (50 m).
SET
GFAST sets the graphics display to be either fast or slow.
Cross-correlation functions

XC computes the cross-correlation function, \( C(T) \), and the time delay for each pair of amplitude-time matrices.

CCFT computes the cross-correlation function, \( C(T) \), and the time delay for each pair of frequency-amplitude-time matrices, and graphs the cross-correlation functions.

Location parameter functions

HL prompts user for the speed of sound in water, number of hydrophones in the array, the \( x, y \) coordinates for each hydrophone, and the orientation of the array axis relative to magnetic north.

EH allows the user to exclude hydrophone(s) from the CL graph.

SD allows the user to manually enter time delays.

Acoustic location data file functions.

LI opens a data file for acoustic location data input.

RL prompts the user for acoustic location information and stores this as a data record.

LS stores the data record in the data file as specified by LI.
Data management and storage functions

ST  lists status of all the time and frequency buffers.

CO  copies contents of one time buffer to another time buffer.

WT  writes the contents of a time buffer to the disk.

RT  reads an amplitude-time signal from the disk into a time buffer.

WF  writes the contents of a frequency buffer to the disk.

RF  reads a frequency-amplitude spectra from the disk to a frequency buffer.

Exit from program function.

QU  closes the current data file and quits the program.
Appendix B

Sound Velocity Calibration

The sonobuoy array approach that we have used as the basis for determining the location of sound producing whales requires calibration of the sound velocity in the vicinity of array locations. Three approaches to this calibration were taken; an historical review of sound velocity measurements in the Point Barrow, Alaska area, analysis of whale sounds originating somewhere along the axis of the array, and analysis of a sound velocity experiment conducted near the array locations. Each approach produces approximately the same value of sound velocity, 1437 meters per second (m/s), with a maximum deviation of ±12 m/s which represents an error of less than 1%. The value of 1437 m/s was used as the velocity of sound in water for all our location analyses.

The first method for determining the sound velocity relies on historical measurements in the Point Barrow area. The nearshore water during the months of April-May has been well studied for its temperature (-1.7 ± s.d. 0.2 degrees centigrade), and salinity (32 ± s.d. 2.0 parts per million) stability (Garrison, 1976; Garrison, Pence, Feldman and Shah, 1974). Measured temperature and salinity profiles for this time of year are provided in Figure B-1. In the left-hand figure the profile was taken at the ice edge in 38 m of water on 29 April 1972. Curve C-6 of the right-hand figure of Figure B-1 is the nearshore station off Point Barrow at a water depth of 120 m. Note that in both cases the temperature is -1.7 degrees centigrade and the salinity varies from 31 to 34 parts per million. Figure B-2 (from Urick, 1975)
Figure B-1. Temperature and salinity profiles off Point Barrow, Alaska on 29 April 1972 (from Garrison, 1967; and Garrison, Pence, Feldman and Shah, 1974). The data in the left-hand figure were taken at the nearshore ice edge in 38 m of water, while the data in the right-hand figure were taken at the nearshore ice edge in 120 m of water.
Figure B-2. Nomograph for calculating the sound velocity as a function of both water depth and water temperature (from Urick, 1975).
provides a nomograph for calculating the sound velocity for these temperature and salinity values. The result for the near surface condition is 1440 m/s at the higher salinity value and 1438 m/s at the lower salinity value. In 1982, a sound velocimeter was used to measure the sound velocity at the edge of the offshore lead (Cummings, Holliday, Ellison and Graham, 1983). This resulted in a measured sound velocity of 1438.2 m/s at a depth of 1 m with a maximum value of 1437.2 m/s at a depth of 9 m.

The second method for determining the sound velocity is provided by the whales themselves. That is, since the array is deployed in a relatively linear manner along the shorefast ice edge of the lead, then when a whale that is swimming very close to the nearshore edge of the lead (along the axis of the array) produces a sound, the sound will be received at the different hydrophones with maximum time delays. By examining the bowhead sounds recorded on the tapes for maximum time delays, we were able to closely estimate the sound velocity. To illustrate this procedure, we note that the velocity can be determined with an accuracy of 0.5% for any sound produced within 6 degrees of the axis of the array, measured from the center of the array. For example, a sound produced by an animal 5000 m from the array's center but within 500 m of the array axis could be used in this method of estimating sound velocity. An accuracy of 1.0% can be achieved by including sounds from animals that are twice this distance offshore and at the same range. Applying this method to the three maximum time delays received on Array E, the resultant sound velocities were 1441, 1446, and 1436 m/s.

The third measure of sound velocity was obtained from a sound velocity experiment. A test range was constructed consisting of two sonobuoys separated
by a known distance on the pan ice. The hydrophones were inserted into a long crack that was open to the water on the nearshore side of the grounded ridge system just south of Foxtrap visual observation perch. The measured distance between the two sonobuoys was 765.2 m. An explosive charge was dropped into the crack and ignited ca. 100 m from the nearest sonobuoy and on the axis of the two sonobuoys. The time delay between the arrival of the resultant sound at the two sonobuoys was 537 milliseconds, resulting in a calculated sound velocity of 1425 m/s.

REFERENCES


