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Report No. 6185

OCS Study
MMS 86-0046

Prediction of Drilling Site-Specific Interaction of Industrial Acoustic Stimuli and Endangered Whales: Beaufort Sea (1985)

Contract No. 14-12-0001-30295

October 1986

Prepared for:

U.S. Department of the Interior
Minerals Management Service
Alaska OCS Office

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PREDICTION OF DRILLING SITE-SPECIFIC INTERACTION OF INDUSTRIAL ACOUSTIC STIMULI AND ENDANGERED WHALES: BEAUFORT SEA (1985)

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October 1986

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ABSTRACT

The underwater acoustic environment and sound propagation characteristics associated with five offshore oil drilling industry sites in the Alaskan Beaufort Sea were measured during the mid-August to mid-September 1985 period, completing the first year field effort of a two-year program. Similar information on a sixth site had to be estimated since heavy sea-ice prevented research vessel access. Some of these sites were active. Analysis of the field data has resulted in a compilation of ambient noise statistics, noise signatures of sources of sound associated with oil industry activities at those sites, and a quantitative ability to predict noise levels from oil industry activities as a function of distance from the sound source. Previous research by LGL (environmental research associates) and BBN Laboratories regarding behavioral responses of bowhead whales (Balaena mysticetus) and gray whales (Eschrichtius robustus) to acoustic stimuli have been used in this study as well. The synthesis of the new acoustic data with prior information regarding whale behavioral response to underwater sound has permitted the derivation of site-specific estimates of zones of influence relating whale response to industrial noise. The results of this first year effort are provided in this report. The summer 1986 field measurement research will be used to supplement these results.

The sound propagation findings to date indicate that there is very efficient cylindrical spreading (10 log Range) of acoustic energy at least to ranges of about 5 km near the Alaskan Beaufort sites studied. A 10 log R algorithm is used to extrapolate losses beyond the 5 km measurement range but must be verified by experiment in 1986. Two acoustic criteria have been used in relating industrial noise levels to whale behavioral response; predicted signal-to-noise ratio (S:N) in the 1/3-octave band of highest S:N and absolute received sound pressure level in the effective bandwidth of the signal. Since it is not known at the present time which criterion is more important in eliciting response in bowhead and gray whales, both have been considered in developing behavioral response predictions. However, major emphasis has been on signal-to-noise ratio in the bowhead response discussions and absolute received level has received the most attention in gray whale response.

Site-specific zones of potential responsiveness of bowhead whales (for a signal-to-noise ratio at the whale of 20 dB) are estimated to extend to 6-22 km from a dredge noise source, 11-30 km for tug noise, 6-19 km for drillship noise and 0.1 to 1.7 km for man-made gravel island drilling noise. Only a fraction of the bowhead whales are expected to respond in the 20 dB signal-to-noise situation.

However, roughly half of bowheads have been observed to respond (approximate avoidance probability of 0.5) when the signal-to-noise ratio is 30 dB. At the sites investigated, 30 dB signal-to-noise ratios are expected to occur at distances of 1.5 to 7.4 km for dredge noise, 2.7 to 13 km for tug noise, 1.3 to 6.5 km for drillship noise and 0.02 to 0.7 km for island drilling noise.

Similar zones of responsiveness predictions for gray whale response to drillship noise in the Beaufort Sea are presented for signal-to-noise ratios of 20 and 30 dB.

With regard to using the absolute received level criterion associated with drillship operation at the selected sites, zones of responsiveness of gray whales vary in range from the sites from 1.9 to 16 km for a received level of 110 dB re 1 μPa and 0.1 probability of avoidance and 0.6 to 6.0 km for 120 dB received level (0.5 probability of avoidance). Bowhead whale zones of responsiveness on the other hand vary from 1.1 to 11 km and 0.2 to 2.9 km for received levels of 110 dB and 120 dB, respectively.

ACKNOWLEDGEMENTS

The research represented by this report was performed for and with support from the Alaska OCS Office of the U.S. Department of the Interior, Minerals Management Service, in Anchorage, Alaska. The support and interest in all aspects of the project provided by Dr. Jerome Montague, Contracting Officer's Technical Representative, of that office are particularly appreciated. The following groups and individuals were also very important to the completion of the first year effort under this contract.

The cooperation extended to BBN by the operators at the sites visited in the Alaskan Beaufort Sea was very important: Shell (Sandpiper and Corona), Unocal (Hammerhead), Exxon (Orion), and Amoco (Erik and Belcher) all provided helpful assistance during the field measurement portion of the project.

Dr. Charles Greene of Greeneridge Sciences, Inc., provided BBN with copies of selected portions of magnetic tape recordings which he acquired at Hammerhead and Sandpiper during the 1985 field season. The availability of those data, the release of which was approved by Unocal, Shell and LGL, was particularly important since heavy ice conditions during the BBN field measurement period prevented BBN from acquiring the needed data. Dr. Greene also contributed historical acoustic data from measurements in the Canadian Beaufort, including some unpublished data, which were reworked by LGL to provide additional 1/3 octave band information for Appendix B. Dr. Greene's interest and assistance to the project in these ways were very helpful and important to the first phase of this two-year project.

The availability of the M.V. JUDY ANN on short notice as research vessel for this project through Oceanic Research Services, Inc., of Ester, Alaska, and the operation of that vessel by Mr. Geoffrey Orth and Mr. Richard Schuerger under difficult weather and ice conditions were essential to the successful performance of the 1985 field measurement effort.

At LGL Ltd., environmental research associates, Ms. M.A. McLaren assisted Dr. Richardson in compiling data on whale response. Her help is greatly appreciated.

The following BBN staff members assisted the authors in several important ways in contributing to the success of the field portion of this project. Their enthusiasm and dedication were essential to the performance of that work:

Dr. Daniel L. Nelson, Senior Scientist

Mr. Jeffrey Doughty, Engineer

Mr. Arthur J. Margerison, Engineering Assistant

Dr. Preston W. Smith, Jr., provided important assistance in application of the Weston shallow water acoustic transmission loss model to Beaufort Sea conditions. The word processing talents and patience demonstrated by Ms. Judy Russo in the preparation of the manuscript of this report are especially appreciated.

PROJECT ORGANIZATION

While the authors of this report have been responsible for specific sections, they have worked closely together in the review of the full document to ensure continuity of technical content. The scientists and their individual report and project responsibilities are:

Mr. Paul R. Miles:	Program Manager and Project Scientist, prepared the Executive Summary, Introduction and Objectives, Methods and Description sections and worked jointly with the other authors on the Conclusions and Recommendations sections. He has been responsible for the overall management and coordination of the project and this report and has participated in field measurements.
Mr. Charles I. Malme:	Assistant Project Scientist and Field Measurement Manager, co-authored the section regarding industrial noise measurements and gray whale behavior and prepared the section on acoustic models and the discussions of gray whale response to acoustic stimuli. He organized and directed the field measurement effort as well.
Mr. George W. Shepard:	Assistant Project Scientist and Data Analysis Manager, coordinated and performed the necessary analysis of the field data, prepared the ambient noise section and co-authored the industrial noise chapter. He also was a key member of the field measurement task team.
Dr. W. John Richardson:	LGL Ltd., environmental research associates, was contracted by BBN to perform the analysis required to synthesize data on bowhead whale response to acoustic stimuli and to develop "zone of influence" projections based on the acoustic environmental data obtained by BBN.

	Dr. Richardson authored the sections on zones of influence (Sect. 2.3, 3.4, App. A) and Appendix B, a data summary of bowhead responses to industrial noise.
Mr. James E. Bird:	An independent consultant to this project, Mr. Bird has applied his specialized skills to the literature search and review aspects of the project. He prepared Appendix C, which is a review of selected literature associated with bowhead whale research in the Beaufort Sea.

In addition to these five team members, whale behavioral research scientists Dr. Peter Tyack and Dr. Christopher Clark have provided assistance in the form of review of the manuscript of this report.

Other project staff members who have contributed to the project are:

Dr. Daniel L. Nelson:	Senior Scientist, assisted in environmental acoustics measurements and provided technical support.
Mr. Jeffrey Doughty:	Engineer, assisted in field measurements.
Mr. Arthur Margerison:	Engineering Assistant, assisted in field measurements.

EXECUTIVE SUMMARY

This report presents the results of the first year of research applied in a two-year program concerning behavioral responses of endangered whales to industrial noise sources associated with offshore oil exploration in the Alaskan Beaufort Sea. The basic purpose of the research is to derive, compile and apply the data and support information needed to develop an understanding of the distances between a sound source and whale when one may expect industrial noise to be detected by whales as evidenced by elicitation of some behavioral response. The endangered whales of concern to this project are the bowhead whale (Balaena mysticetus) and gray whale (Eschrichtius robustus). Field work was required to develop a quantitative description of the acoustic environment, including definition of the sound propagation characteristics, at planned and active offshore oil drilling sites. The first increment of that work was performed from 16 August to 19 September 1985. Other essential ingredients in the research reported here are historical data regarding responses of bowhead whales and gray whales to industrial underwater noise, derived in recent years by LGL Ltd. and BBN Laboratories, respectively, and statistically based analytical techniques.

Five offshore drilling sites in the Alaskan Beaufort Sea were selected by Minerals Management Service to be studied:

- Orion, where the Concrete Island Drilling System (CIDS) was operated by Exxon in Harrison Bay; the CIDS was at the Orion site during our field period but not in full operation,
- Sandpiper Island, a man-made gravel island used as a base for standard drilling equipment, operated by Shell near Prudhoe Bay
- Hammerhead Prospect, drillship CANMAR EXPLORER II, north of Flaxman Island; Union Oil of California (Unocal)
- Erik and Belcher Prospects, drilling expected to be performed by drilling vessel KULLUK, north and east of Barter Island, respectively; Amoco.

In addition, Shell's Corona prospect was visited; CANMAR EXPLORER II was also scheduled to operate at Corona. Similarly, some acoustic data were acquired at Northstar and Seal Islands, two man-made gravel islands near Sandpiper, to supplement the description of the acoustic environment of the region.

The environmental conditions existing during the field measurement work were dominated by drifting sea ice and, at times, heavy winds, which combined to permit acoustic measurements during only 15 days of the contracted 35 day field period. The unusually heavy ice conditions in 1985 prevented the acquisition of any data at Hammerhead and hampered data acquisition at other sites. The acoustic data acquired by us have been supplemented with copies of 1985 data tapes obtained by Greeneridge Sciences, Inc., providing acoustic signatures from drilling at Sandpiper Island and drillship CANMAR EXPLORER II at Hammerhead.

Ambient or natural background underwater noise data were acquired at the above sites (except Hammerhead) during 5-15 minute periods at random intervals during the day. The resulting recordings were analyzed to provide both narrowband and one-third octave band spectra. Cumulative distribution functions were derived to estimate the 5th, 50th and 95th percentile statistical levels of ambient noise experienced at each site. The resulting data presented in this report are critical to the development of signal-to-noise ratio statistics which are used in predicting the behavioral responses of whales. The acoustic environmental characteristics of Hammerhead have been estimated based on measurements at similar sites, pending actual measurements in 1986.

The radiated noise or underwater sound signatures of two tugs working together at Sandpiper Island, one tug working with a dredge barge at Erik, a clam-shell dredge at Erik, EXPLORER II drillship operations at Hammerhead and gravel island drilling at Sandpiper were all acquired and analyzed. Both narrowband and one-third octave band analyses were performed.

Measurement of the sound propagation or transmission loss (TL) characteristics from each site toward the expected location of whales was performed, usually using a controlled sound source and measuring received sound level as a function of distance from that source. A second method used was to measure noise levels versus distance from some continuous industrial noise source associated with a particular site. These methods are range limited to a maximum distance of about 5 km. To estimate propagation loss rates over longer ranges, published data on received levels of seismic survey pulses in a typical Alaskan Beaufort Sea area were considered. Acoustic transmission loss is very site-specific and hence there is a need to measure the TL characteristics of each site. These data are the most critical element in the description of the acoustic environment of migrating or feeding whales since only a quantitative description of the site-specific TL will permit valid predictions of industrial noise levels at expected whale locations. The measurements have demonstrated that a cylindrical spreading law applies, at least over short ranges, at each of the sites visited. This law describes a loss of acoustic energy according to 10 log (range) from the source. Variations in ocean bottom and surface conditions at each site, e.g. bottom composition, ice cover, wave conditions, cause site-specific differences in the TL algorithms.

Sub-bottom conditions also influence sound propagation. There is strong evidence that the presence of sub-sea permafrost and overconsolidated clay sediments contribute in an important way to unusually efficient sound transmission over the continental shelf of the Beaufort Sea. In fact, comparison of the TL characteristics in the Beaufort with those measured in similar water depths in more temperate ocean areas demonstrates that the Beaufort TL characteristics are unusually efficient; TL in other areas frequently is found to vary as 15 log R and sometimes as high as 25 log R.

It must be emphasized that the 1985 TL data are based on short range (5 km) experiments. Extrapolation of the 10 log R algorithm to distances of 20-30 km can only be considered a preliminary estimate and must be substantiated through long-range experiments at each site in 1986.

The ambient noise statistics, industrial noise data and acoustic transmission loss data were combined in analyses performed by LGL Ltd. to estimate those distances from the sound sources when bowhead whales could be expected to detect and/or respond to the presence of industrial sounds. Zone of influence tables and figures are presented which relate predicted industrial sound levels at particular sites to historical data regarding whale response to acoustic stimuli. Similarly, BBN has summarized from prior yet similar research conducted in California and the Bering Sea investigating the behavioral responses migrating and feeding gray whales to industrial underwater acoustic stimuli, and has discussed those data as they may apply to gray whale response in the Beaufort Sea.

Two acoustic criteria have been used in relating industrial noise levels to whale behavioral response; predicted signal-to-noise ratio (S:N) in the 1/3-octave band of highest S:N, and absolute received sound pressure level in the effective bandwidth of the signal. Since it is not known at the present time which criterion is more important in eliciting response in bowhead and gray whales, both have been considered in developing behavioral response predictions. The analysis applied in this research has assumed that either one or both of these two criteria represent the basic causal acoustic measure(s) regarding behavioral response. Less emphasis has been given to other factors such as visual cues. For instance, both the previous bowhead and gray whale sound playback research discussed in this report considered visual cues as a possible influencing factor in the experimental protocol through observing whale behavior during vessel presence but without sound playback or seismic sound radiation. However, major emphasis has been on signal-to-noise ratio in the bowhead response discussions and absolute received level has received the most attention in gray whale response studies.

With regard to the bowhead whale, which commonly inhabits the coastal regions of the Beaufort Sea in the summer (the gray whale is rarely seen), LGL has estimated that depending on the specific site of interest, the zones of potential responsiveness (distance between sound source and whale) typically have a radius of:

Dredge:	1.5 to 7.5 km
Tug:	2.5 to 13 km
Drillship:	1.3 to 6.5 km
Artificial Island Drilling:	0.02 to 0.7 km.

These radii are based on the observation that about half of the bowhead whales show avoidance responses (probability of avoidance of about 0.5) to the onset of industrial sounds which have a 30 dB S:N. A small proportion of the bowheads react when the S:N ratio is about 20 dB, which would occur at greater ranges than those summarized above. On the other hand, some bowheads apparently tolerate S:N ratios as high as 40 dB; for those individuals the zone of responsiveness is smaller.

Predictions of gray whale zones of responsiveness based on S:N ratio are quite similar to those noted above for bowheads. The following zones of responsiveness to drillship noise are estimated for gray whales in the Beaufort Sea. The estimates have been calculated for 0.1 and 0.5 probability of avoidance corresponding to received levels of 110 dB and 120 dB re 1 μPa, respectively. The radius of the zone of responsiveness is site-specific, as is the case for use of the S:N ratio criterion for zone estimates.

Drillship Noise:	110 dB re 1 μPa	120 dB re 1 μPa
Probability of Avoidance:	0.1	0.5
	Est. Range (Zone of Responsiveness)	
Belcher	4.1 km	0.9
Erik	7.7	2.0
Hammerhead	8.0	1.8
Sandpiper	15.6	6.0
Orion	10.2	3.7

Bowhead whale zones of responsiveness estimated on the basis of these same absolute received levels of drillship noise are 1.1 to 11 km for 110 dB and 0.2 to 2.9 km for 120 dB, respectively, depending on the specific drillsite.

All of the details of the findings of this first year research effort covering the 1985 measurement season are contained in the body of this report.

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1. INTRODUCTION AND OBJECTIVES

The continuing exploration and development activities regarding oil and gas resources in the Alaskan Beaufort Sea, Outer Continental Shelf (OCS) region, carries with it the need for investigations relating to potential environmental impact. Included in that issue is a need to quantify the extent to which industrial acoustic stimuli may influence the behavior of endangered whales. The bowhead whale (Balaena mysticetus), in particular, frequents the Beaufort Sea from March into October (e.g. Braham et al, 1980, Ljungblad et al, 1985a), including areas of oil and gas exploration and development. The gray whale (Eschrichtius robustus) also feeds in the Arctic during summer months, although they are not sighted frequently in the Beaufort (Braham, 1984; Marquette and Braham, 1982). Concern regarding potential environmental impact has centered on these two endangered species. In the process of developing a quantitative understanding of whale behavioral response to acoustic stimuli, it is necessary to quantify the underwater ambient noise characteristics, the acoustic signatures of various industrial activities, and the underwater sound propagation characteristics of the region (which, more often than not, are site-specific) in order to predict sound levels at potential whale locations. The resulting data must be combined with the results of research into the behavioral response of whales to acoustic stimuli obtained through extensive observation of undisturbed behavior under natural conditions, during disturbed conditions from uncontrolled "intrusions" by industrial activity, and during controlled experiments. Statistical analysis of the resulting data provides the needed understanding of the behavioral response of whales to acoustic stimuli as a function of such variables as ambient background noise and the frequency content and level of the sounds (which vary with distance between the sound source and whale).

Accordingly, Minerals Management Service (MMS) contracted BBN Laboratories Incorporated and their subcontractor, LGL Ltd., (environmental research associates), to perform a two-year research project which will develop the needed quantitative understanding of whale behavioral response to acoustic stimuli at site-specific sites in the Alaskan Beaufort Sea. Required tasks under the project includes measurement and modeling of the acoustic environment at selected sites on the Alaskan Beaufort Sea OCS during the 1985 and 1986 summer/fall seasons by BBN and the use of the resulting data by LGL to develop an understanding of whale behavioral response. Field data and analytical experience gained by BBN and LGL in previous research projects regarding environmental acoustics and the responses of bowhead, gray and humpback whales to controlled acoustic stimuli (Malme et al., 1983, 1984, 1985, 1986; Richardson, 1985; Richardson, et al., 1985a,b,c) are key elements in the design and performance of this project. The following purpose and objectives of this project are quoted from the contract.

Purpose

The purpose of this project is "to provide information necessary to predict the range at which bowhead and gray whale behavior is likely to be influenced by sounds produced at specific offshore drilling sites."

Objectives

The objectives are "to develop and implement a research plan in the Beaufort Sea lease sale area to:

A. Acquire measurements of the acoustic environment prior to the onset of industrial operation.

B. Measure transmission loss characteristics of sounds associated with activities of each offshore drilling site concurrent with the major period of exploration (in 1985 and 1986) resulting from Diapir Field Lease Sales 71 and 87.

C. Monitor the characteristics of sounds associated with offshore drilling sites throughout the study period. As appropriate for the specific site, marine geophysical sounds will also be monitored as a secondary focus.

D. Synthesize, through mathematical/statistical techniques, the results of objectives A-C with data and/or simple models of bowhead and gray whale response to sounds associated with offshore drilling activities in order to develop site-specific "zone of detection/potential influence" projections.

E. Coordinate with ongoing endangered species studies in the Beaufort Sea area and maintain appropriate liaison with local residents and government agencies.

F. Prepare appropriate tabular or graphic results, synthesize with other recent literature and report findings."

This report summarizes the measurements made during the 1985 field season (16 August-19 September) and presents the results of the analyses performed on the field data, the synthesis of whale response in the context of the 1985 acoustic environment, and the derivation of zones of potential influence on whales. MMS requested that data be acquired at five sites within the specified lease sale area:

- Hammerhead (Unocal),
- Sandpiper (Shell),
- Orion (Exxon),
- Erik (Amoco),
- Belcher (Amoco).

One additional site was visited, Corona (Shell). Since a limited amount of industrial noise data were obtained at these sites within the contracted field period (BBN could not reach Hammerhead during drilling operations due to intervening pack ice, for instance), some noise data were obtained for Hammerhead and Sandpiper from Greeneridge Sciences Inc. through MMS, LGL, Unocal and Shell. Greeneridge (Dr. Charles Greene) acquired acoustic data for other purposes at Hammerhead and at Sandpiper (which conducted drilling operations before or after BBN was in the field) and provided those data to this project. Detailed results from the Greeneridge studies are given by McLaren, et al. (1986) and Johnson et al. (1986). More detail on site locations and site activity will be given in Sec. 2. The 1985 summer season in the Alaskan Beaufort Sea was dominated by unusually heavy drifting sea-ice conditions. Since our vessel, the M.V. JUDY ANN operated by Oceanic Research Services, could only work in up to 2/10 ice cover conditions, the fluctuating insurgence of ice and heavy wind at the sites resulted in acquisition of approximately half of the desired data.

As noted in the stated purpose of this research project, the potential impact of industrial acoustic stimuli on gray whales in the Alaskan Beaufort Sea must be evaluated. While the dominant endangered whale species in that area is the bowhead, gray whales are observed occasionally in the western regions of the Beaufort Sea and in the eastern Chukchi Sea (Braham 1984, Ljungblad et al. 1985a, Marquette and Braham, 1982). Some have also been seen at times near Prudhoe Bay, and near Tuktoyaktuk in the Northwest

Territories (Rugh and Fraker, 1981; Richardson, 1985). The primary gray whale summer feeding grounds are in the Northern Bering Sea and Southern Chukchi Sea regions (Braham, 1984). All of these areas are candidates for oil exploration and development.

BBN has performed research studies (Malme, et al. 1984, 1985, 1986) regarding behavioral responses of migrating and feeding gray whales to controlled acoustic stimuli (playback of underwater sounds associated with oil and gas exploration and development). This report will discuss the responses of migrating gray whales to acoustic stimuli in the Beaufort Sea environment by applying the results of BBN studies of migrating gray whales in California and feeding gray whales in the Northern Bering Sea.

Section 2 of this report provides details of the study area and methods used to acquire the data needed to describe the acoustic environment of the selected sites and to perform the behavioral response analysis. The results of the 1985 portion of this project are presented in Sec. 3 including:

- a statistical description of the short-term ambient noise environment,
- a presentation of the underwater industrial sounds measured at various sites,
- sound propagation characteristics of each site (acoustic models), and
- synthesis of whale response to sounds including derivation of zones of potential influence.

Conclusions and recommendations from this initial 1985 phase of the research effort are given in Secs. 4 and 5, followed by a listing of cited literature. Appendix A provides a summary of sound propagation (range) for various combinations of industrial noise types, signal-to-noise ratio, absolute received level, and bottom slope. Appendix B summarizes previous data on observed and measured endangered whale responses to industrial noise, and Appendix C presents a review of selected literature, regarding bowhead whale research in the Beaufort Sea.

2. DESCRIPTION OF THE STUDY AREA AND METHODS

2.1 The Study Area and Selected Sites

The study area for this project, as noted previously, is the continental shelf of the Alaskan Beaufort Sea. The specific sites to be studied were selected by Minerals Management Service. Figure 1 gives the layout of the coast from Point Barrow in the west to Demarcation Bay at the U.S./Canadian border to the east with the six sites located from Harrison Bay to the Barter Island region and Table 1 provides details of the site locations, water depths, operators and general comments. The field measurement period was 16 August-19 September 1985. Expected industrial operations on several of the sites were not begun during the field period, in part because of seasonal drilling restrictions designed to prevent drilling during the bowhead migration season. The Concrete Island Drilling System (CIDS), the GLOMAR BEAUFORT SEA I, did not reach the Orion site (coordinates shown in the table) until late in August and drilling operations there did not commence until after the BBN field period. Drilling at Sandpiper Island was curtailed during part of the bowhead migration period. The drillship CANMAR EXPLORER II was forced off the drillsite at Hammerhead by ice before the BBN vessel (JUDY ANN) could reach the site and did not resume operations until 19 September, when BBN had to stop measurement work. The circular drillship KULLUK did not occupy either Erik or Belcher sites as scheduled. A dredge (ARGILOPOTES) and tug (ARCTIC FOX) were working at Erik at the time of acoustic measurements by BBN, however.

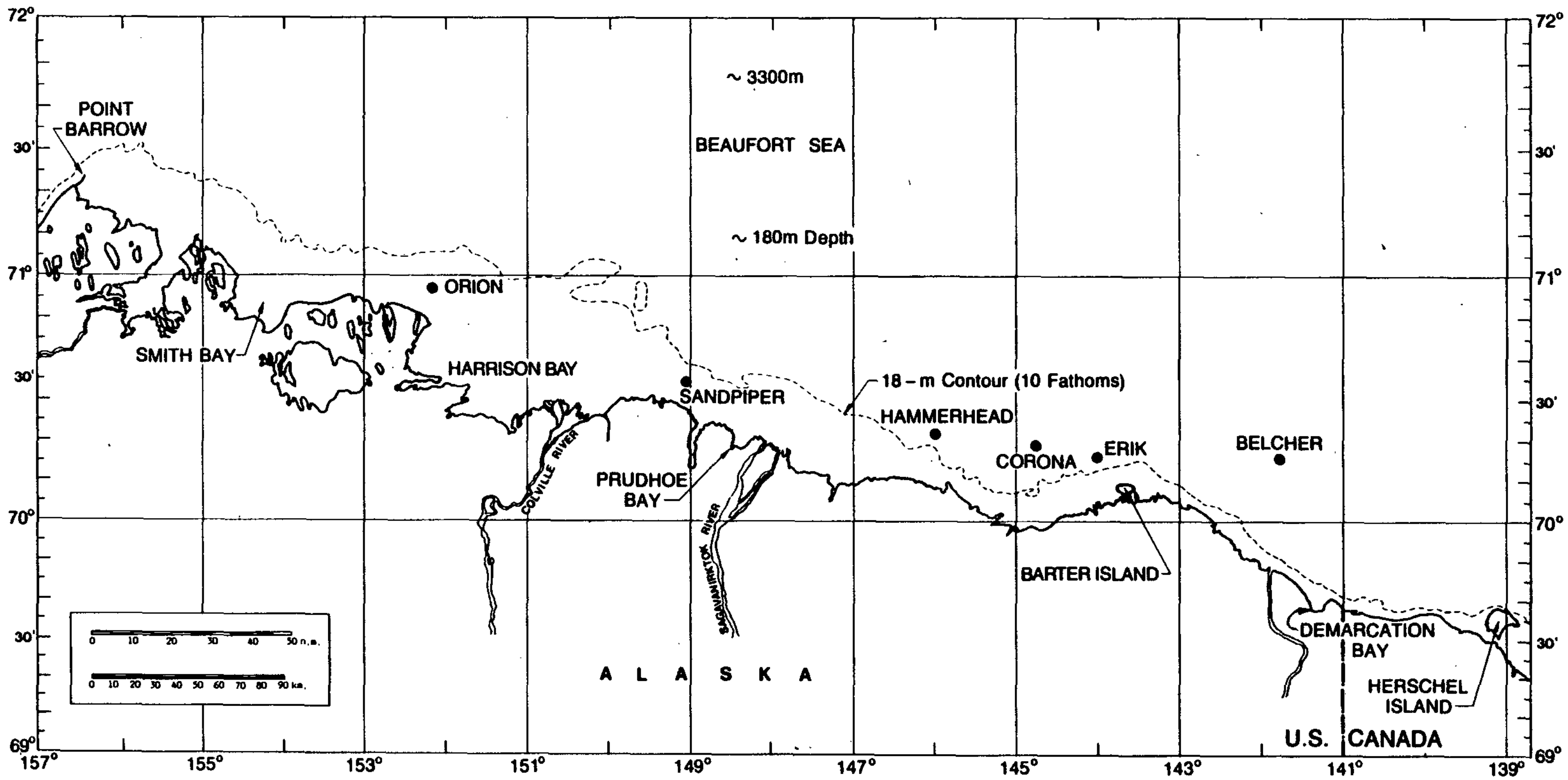

FIGURE 1. SELECTED MEASUREMENT SITES IN THE ALASKAN BEAUFORT SEA.

TABLE 1. GENERAL DETAILS OF SELECTED MEASUREMENT SITES IN THE ALASKAN BEAUFORT SEA.

Site	Area	Approx. Coordinates	Approx. Water Depth meters	Operator	Comments
Orion	Harrison Bay	70°57.41'N 152°03.78'W	14	Exxon	Glomar Beaufort Sea I Concrete Island Drilling System (CIDS)
Sandpiper	North of Pole Is.	70°35.08'N 149°05.81'W	15	Shell	Artificial gravel island
Hammerhead	North of Flaxman Is.	70°21.88'N 146°01.47'W	28	Unocal	CANMAR EXPLORER II (drillship not on site during BBN measurements)
Erik	N. of Barter Is.	70°16.6'N 143°58.67'W	40	Amoco	Dredge and Tug (site moved 4 n.m. So. from orig. MMS location)
Belcher	East of Barter Is.	70°16.4'N 141°47.0'W	55	Amoco	No operations on site
Corona	N. of Camden Bay	70°18.88'N 144°45.53'W	35	Shell	CANMAR EXPLORER II (drillship not on site during BBN measurements; site not on original MMS list)

2.1.1 Migration habits

It is important to summarize briefly the migration habits of the bowhead in relation to the study area and the selected operational sites. Figure 2 includes a general indication of the routes and/or corridors for spring and fall migration. The spring migration route in the March-May period heads eastward from near Point Barrow to 50-90 n.m. offshore following open leads in the ice cover, often categorized as 8/10-10/10 conditions. Most of the migration route is in deep water north of the continental shelf edge. Ljungblad (1985a) and Braham et al. (1980) provide ample evidence of the regularity of the spring migration route. Swimming speeds are generally between 3-8 km/h (Carroll and Smithhisler, 1980) and behavior consists primarily of traveling with some social activity once the whales leave the Barrow area. Ljungblad distinguishes between the specific migration corridor and the broad migration route since his year-to-year observations generally show that the "corridor" width may change from year-to-year but that the general route is relatively invariant. The general impression from the results of Ljungblad, Braham and others is that the offshore spring route is probably dictated by ice conditions. Bottom fast ice and floating fast ice extend at least north to the offshore shoal regions on the North Slope. In early spring the 10/10 solid ice cover extends far offshore.

The fall west-bound migration pattern is equally repeatable in all reported observations, with the Ljungblad data-base being the largest (Ljungblad, et al. 1985a). A few bowheads start to leave their traditional summering grounds in the Canadian Beaufort Sea in late August, but many whales do not enter Alaskan waters until late September, depending on the ice conditions. In their westerly movement, the bowheads travel parallel to the coastline, generally offshore of the 10-fathom (18-m) bathymetric

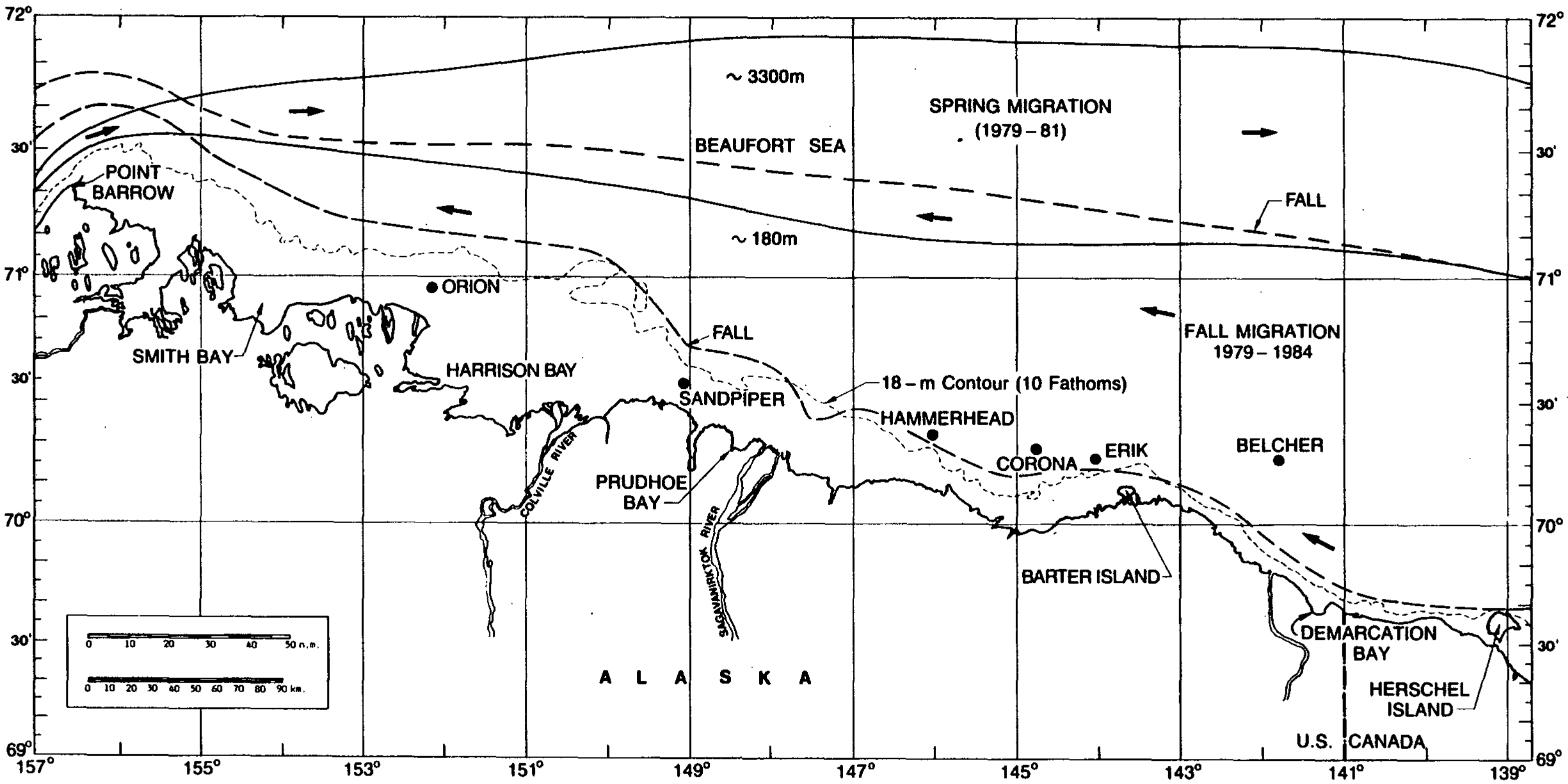

FIGURE 2. APPROXIMATE BOWHEAD WHALE MIGRATION CORRIDORS AND SELECTED DRILLSITES.

contour. The 10-fathom contour also defines the location of shoal regions in-shore of that contour where grounded ice occurs in winter (these regions are called stamukhi zones by Arctic marine geologists). The inshore fall migration route may be related to the need to continue summer feeding wherever possible during the return to the Chukchi and Northern Bering Sea regions for the winter. Ljungblad et al. (1985a, 1985c) report that feeding bowheads tend to migrate within a corridor which is approximately 40-50 km wide with the southern boundary at about the 18-meter contour. Particularly during 1983 he reports that non-feeding fall migrants were observed as much as 120 km offshore, traveling in the southern region of the spring corridor. Their southern boundary was again the 18-m contour. During light ice conditions, the westward migration is slow (~1 km/hr). It is accompanied or interrupted by feeding, and whale calls are frequently heard. In heavy ice years, the fall swimming rate is fast (3 to 5.5 km/hr) and there are few calls.

Drill-site noise is probably undetectable to bowheads in the spring migration corridor which is 60-90 miles away. However the potential exposure to detectable site noise during the fall migration is high. Note that Hammerhead, Corona, Erik and Belcher are all located within the migration corridor. Sandpiper and Orion are 10-15 n.m. (18-28 km) south of the south edge of the fall migration corridor as described by Ljungblad et al. (1985a). Some bowheads have been seen during fall migration in the general areas where oil exploration is underway (Hickie and Davis 1983; Davis et al. 1985; Ljungblad et al. 1985a, 1985c).

2.1.2 Ocean bottom conditions

There are several important variables which influence the propagation characteristics of underwater sound, including water depth, the speed of sound (which in turn varies primarily with water temperature and salinity) and the physical characteristics of the ocean surface (roughness and ice cover) and ocean bottom. There is ample evidence (for instance, see Urick, 1983) that the types and thicknesses of materials in the ocean bottom can cause significant differences in propagation characteristics as the acoustic energy interacts with the sand, silt or clay sediments. Exposed or sub-bottom regions of hard layers of bedrock, semi-consolidated and consolidated sediments often result in more efficient sound transmission than would occur with thick absorptive soft materials such as silt and clay. More will be said about site-specific sound propagation loss and the influence of the ocean bottom in Sec. 3. It is useful here, however, to discuss briefly the ocean bottom characteristics in the Beaufort Sea study area. The region of interest lies on the continental shelf and south of the shelf edge (which is commonly defined as the 100-fathom (180-m) contour*). The 180 meter contour in the study area is about 40-50 n.m. (>75 km) from shore. The average slope of the ocean bottom to at least 20 miles seaward from the selected sites is 0.02 degrees at Sandpiper, 0.04 degrees at Hammerhead, 0.06 degrees at Orion and Corona, 0.06 to 0.16 degrees at Erik and to about 0.04 to 0.6 degrees at Belcher. While these slopes are small, they do have an important influence on long range sound propagation.

Bottom materials at the water/bottom interface on the shelf are quite site-specific and poorly sorted but generally grade from sand and gravel near shore (except inside the barrier islands where silt and clay (or "mud") is common) to medium and fine sand, silt, and clay offshore, near the 100-fathom contour (Barnes and Reimnitz, 1974; Morack and Rogers, 1984; Naidu et

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*Some Arctic marine geologists place the Beaufort Sea continental "shelf break" at a depth of 50-70 meters (27-38 fm) which occurs about 35 n.m. from shore.

al., 1984). Sediment thicknesses below the water/bottom interface and above the bedrock interface in the vicinity of the sites apparently can be 750 meters or greater (Neave and Sellman, 1984).

Two forms of acoustically reflective intermediate layers occur within the oceanic sedimentary column of the Beaufort Sea continental shelf; sub-sea permafrost or ice-bonded sediments and "overconsolidated" clay. These layers are important to discuss since they almost certainly influence underwater sound propagation.

Ice-bonded sub-sea permafrost zones are commonly encountered in drilling operations offshore and have been attributed to relict permafrost which formed offshore approximately 18,000 years ago when sea level fell to a minimum (Morack and Rogers, 1984). These zones appear to be quite variable in thickness and horizontal extent. Seismic refraction survey data and physical sampling have located sub-sea permafrost at less than 10 meters below the near shore water/bottom interface to 20-40 meters as far as 20-60 km (11-32 n.m.) offshore from Prudhoe Bay and Harrison Bay (Morack and Rogers, 1984; Neave and Sellman, 1984). The depths to this ice-bonded sediment zone are quite variable both locally and from area to area. Thicknesses in some areas may be several hundred meters and seismic refraction data indicate a probable permafrost zone as deep as 200 to 450 meters. Neave and Sellmann (1984) present data which strongly indicate that both Orion in Harrison Bay and Sandpiper near Prudhoe will in all likelihood have sub-sea permafrost zones extending seaward from those sites. It is probable that ice-bonded sediments exist at Hammerhead, Corona, Erik, and Belcher as well. These layers exhibit high seismic compressional wave speeds providing a strong acoustically reflective zone. Figure 3, adapted from Morack and Rogers (1984) and expanded to include typical "hard-rock" data, demonstrates the compressional wave speed contrasts between unbonded and ice-bonded sediments. It is common to measure wave speeds of 2500 m/sec to over 4000 m/sec, providing the needed compressional wave speed contrast for an acoustically reflective interface.

It has also been suggested* that "overconsolidated" sub-bottom sedimentary layers, primarily in the form of dense clay, could also contribute to acoustic reflectivity. Laboratory tests and field observation of environmental parameters such as water and sediment temperatures and pressures indicate that exposure to many freeze-thaw cycles is a probable major contributor to the overconsolidation of the clay and silty-clay sediments*. The result is a material which is nearly impervious to diver-operated sampling devices and which is widespread and geometrically homogeneous to depths of 20-m or more on the North Slope. It is entirely possible that this dense clay zone works in concert with sub-sea permafrost regions to provide efficient acoustically reflective regions which strongly influence acoustic propagation. More will be said on this subject in Section 3 regarding the site-specific acoustic propagation measurements and models. Ideally, it would be very useful to this project to obtain substantiation of these two types of sub-bottom layers at each of the sites. Attempts will be made to do so through further literature search and discussions with off-shore operators (through MMS) and CRREL.

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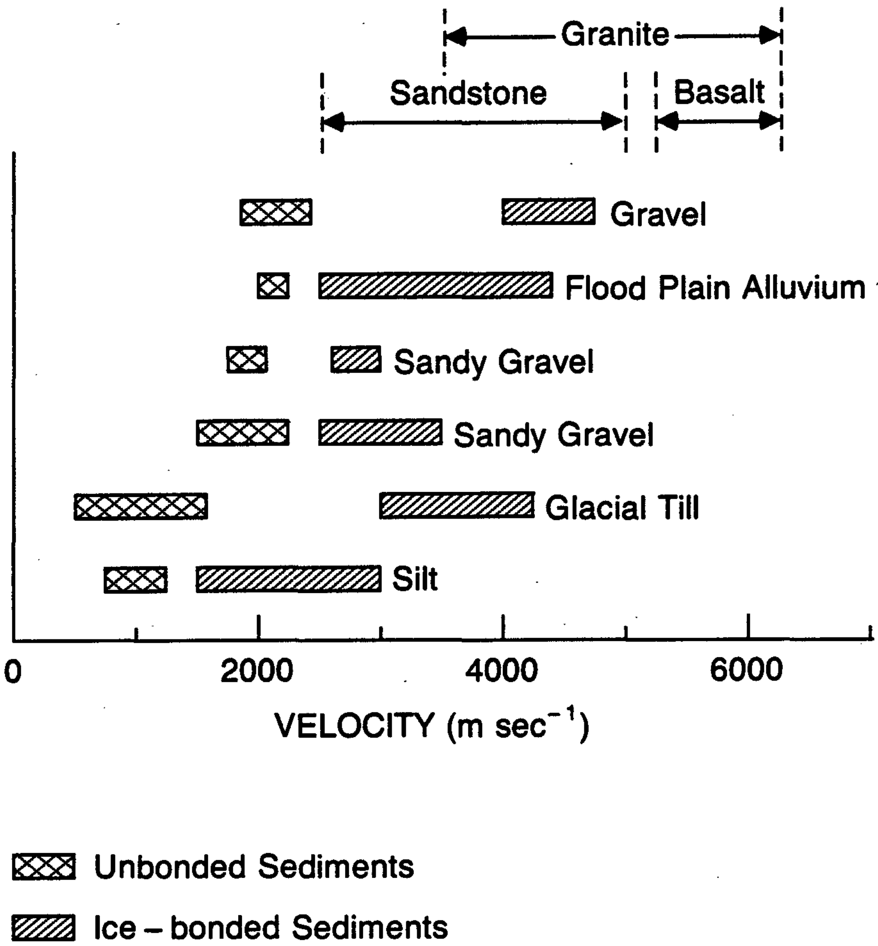
*Personal communication: Paul V. Sellmann, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH, 3/12/86.



Adapted from Morack and Rogers (1984)

FIGURE 3. COMPRESSIONAL WAVE SPEEDS IN ALASKAN BEAUFORT SEA SEDIMENTS COMPARED TO THOSE FOR TYPICAL BEDROCK.

2.2 Acoustic Environment Measurement and Analysis Methods

The basic objective of this research project is to use existing data on the behavioral responses of bowhead and gray whales to assess the potential zones of influence of underwater sounds associated with industrial activities at six pre-selected sites associated with Diapir Field Lease Sales 71 and 87 in the Alaskan Beaufort Sea. Therefore, the acoustic environment of that region must be defined before any site-specific analysis of potential whale behavioral response can be accomplished. Because of the variability of industrial activity at the sites, fluctuating weather and sea-ice conditions, and limited duration of the measurement season, the acoustic environmental measurements have been scheduled to span two summer periods. As noted, this report discusses details of the 1985 measurements and the results of the data analysis and interpretation in the context of whale behavioral response. Defining the underwater acoustic environment entails the measurement of ambient or background noise conditions (ideally without industrial activity contributions) and their variability, the radiated noise signatures of the various industrial operations proceeding at the selected sites, and the sound propagation characteristics as a function of distance from each site (transmission loss or TL). The analysis of the resulting data provides a basis for predicting industrial noise as a function of range from each site, and for evaluating the detectability of those sounds in the presence of typical variations in ambient noise.

Table 2 summarizes the data acquired during the planned 35 days of acoustic measurements during August and September 1985. As noted, some of the needed data were acquired during the 15 days when work was possible. Heavy sea-ice conditions and poor weather frequently caused lengthy delays in reaching the selected sites if not actual cancellation of departure of the

TABLE 2. BEAUFORT SEA MEASUREMENTS (Test Period: 16 August - 19 September 1985 = 35 Field Days).

	Site	Ambient Noise	Sound Transmission Loss (TL)	Sound Speed Profile	Signatures and Comments
MMS SPECIFIED SITES	Hammerhead	None	-	-	Ice conditions prevented access
	Sandpiper Island	8/25 (3) 8/27 (1) 8/30 (1) 9/01 (1) 9/05 (4)	8/27 (2) 8/30 (5)	8/25 (2) 8/27 (1) 8/30 (2) 9/01 (1) 9/05 (1)	8/25 Two workboats (distant) 8/30 Two tugs opposite side of island Whale calls during TL 9/05 Drilling scheduled but not detected
	Orion, Harrison Bay	8/28 (2) 8/29 (2)	8/28 (1) 8/29 (1)	8/28 (2) 8/29 (1)	8/28 Downhole pulsing GLOMAR BEAUFORT SEA I
	Erik Prospect	9/09 (9) 9/13 (6)	9/13 (1)	9/09 (1) 9/13 (1)	9/09 Clam-shell dredge and tug 9/13 Clam-shell dredge and tug; air gun in background
	Belcher Prospect	9/10 (3) 9/11 (1)	9/10 (1) 9/11 (1)	9/10 (1) 9/11 (1)	No activities on site
OTHER SITES	Corona Prospect	9/08 (2)	-	9/08 (1)	No activities on site
	Northstar Island	9/01 (1) 9/03 (1) 9/04 (1)	9/01 (1)	9/01 (1) 9/03 (1) 9/04 (1)	9/01 Island construction activity
	Seal Island	-	-	8/18 (1)	No activities on site
No. Site days per parameter		14	8	15	7

Notes: 1) Parenthetical numbers denote number of measurements or tests.
2) Ambient noise segments are 5 to 15 minutes long.
3) Acoustic signature tape data from Greeneridge Sciences:
(1) Hammerhead; CANMAR EXPLORER II Drillship 8/27-28/85
(2) Sandpiper Island; drill rig 10/17/85
(3) Corona Site; Icebreaker 10/21/85

research vessel, M.V. JUDY ANN, from port. The measurements achieved at the five sites specified by MMS are shown in the top five rows of the table. Other industrial sites visited because they were accessible when required sites could not be reached, include Corona (a site where drillship CANMAR EXPLORER II was expected to drill after our field season), Northstar Island, and Seal Island, which are both artificial islands near Sandpiper Island. The parenthetical numbers in the table indicate the number of measurements or tests of each type at each site. The ambient noise segments were selected at random times during occupation of a site, and lasted from 5 to 15 minutes each. Since Greeneridge Sciences was also performing acoustic measurements at Hammerhead and Sandpiper Island for other purposes and at a time when industrial activities were proceeding (Johnson et al. 1986; McLaren et al. 1986), it was arranged through MMS, LGL, Unocal, and Shell to obtain copies of the Greeneridge taped signatures. Those taped signatures are listed in the notes section of the table.

The results of the analysis of the data summarized in Table 2 are provided in Section 3. Presented below are brief discussions of the measurement and analysis methods applied under this project.

2.2.1 Measurement systems

Ambient noise data should be acquired at the selected sites either prior to the onset of industrial activity or, at least, during periods when such activities are intermittent or at a minimum. Such data on natural background noise are needed as a basis for comparison of industrial noise measured at each site, and to determine the potential zone of influence on whales. Ideally, an ambient noise model should be developed which could predict noise spectrum levels at each site as a function of easily measurable environmental parameters (e.g., sea-state and percent ice cover). Unfortunately, past experience in the arctic and in more temperate regions has shown that the relationship between noise level and the environment is a complex function and is dependent on a large number of environmental parameters. Accurate models require extensive amounts of data recorded over long periods of time. Clearly, this is beyond the scope of this project; but the work discussed in this report constitutes a useful step toward that goal. Our approach is to develop a simple empirical model which provides a statistical characterization of the ambient noise field. Five- to 15-minute recordings of ambient noise are recorded at random intervals during the more lengthy period of site occupation. Analysis of the resulting data provides a reasonable statistical sample of the ambient noise conditions at that site under the conditions prevailing at the times or recording. In addition to recording ambient noise at each site, it is necessary to document physical factors which influence background noise, such as sound speed profile, water depth, ice cover, sea state, wind speed, wind and wave directions and measurement hydrophone depth.

Similarly, the measurement of industrial noise data requires close coordination or communication with the industrial operator to relate any changes in received sound to specific industrial functions. In addition to logging the above noted physical variables, which influence industrial noise as well as ambient noise characteristics, it is necessary to measure and log the distance between the measurement system and the industrial noise source.

Measurements of the sound propagation or transmission loss (TL) characteristics associated with each site are a critical element in developing the ability to predict potential industrial noise levels at expected positions of whales. These site-specific measurements were accomplished through controlled projection of bands of noise from an underwater sound projector at the research vessel and measurement of sound received from that projector as a function of distance using a second vessel (an inflatable AVON). Measurements were made out to distances (4 to 5 km) which were limited by either the need for a measurable signal-to-noise ratio or environmental (wind, sea-state, and ice) conditions.

2.2.1.1 Physical Measurements

Distances and relative positions of M.V. JUDY ANN, industrial noise sources, and the Avon (during TL measurements) were obtained using the JUDY ANN's radar system. When the AVON radar return was difficult to measure at large distances due to clutter from drifting sea-ice, it was necessary to resort to measurement of the acoustic travel times of underwater impulses transmitted from the JUDY ANN received at the AVON. Radio transmission of the received impulse time was recorded on the JUDY ANN and compared with the recorded impulse initiation time.

A standard fathometer provided depth information at the JUDY ANN. Navigation charts were used to estimate depth profiles along the TL paths.

Sound speed profile data were obtained through use of a Beckman Model RS5-3 Induction Salinometer which provides temperature, salinity, and conductivity of the ocean water as the sensor is lowered in depth. Sound speed is calculated at discrete depth intervals using a hand calculator pre-programmed with Wilson's equation:

$$c = 1449.2 + 4.623T - 0.0546T^2 + 1.391\,(S-35)\ ,$$

where c is the sound speed in meters/second, T is the temperature (°C) and S is the salinity in parts per thousand (Urick 1983).

Wind conditions were obtained from the shipboard anemometer, and sea wave and swell heights were estimated visually. Ice cover estimates were also estimated visually.

2.2.1.2 Acoustic Measurement Systems

Three acoustic measurement systems were applied in this project; a primary dual channel system used for both ambient noise and industrial noise measurements, a single channel system used on the AVON during transmission loss experiments and for ambient noise and industrial noise data collection, and a sonobuoy system that permitted remote measurement of ambient noise, industrial noise, and is also useful for transmission loss data measurements.

Ambient and Industrial Noise Measurement System

A standard hydrophone system that combined an ITC Type 6050C hydrophone with a low-noise preamplifier and tape-recorder was used to obtain ambient noise data. The hydrophone sensitivity and electrical noise-floor characteristics are shown in Fig. 4. The acoustic noise measurement system block diagram is shown in Fig. 5a. Overall frequency response of the measurement system was generally flat from 20 Hz to 15 kHz. All components of the system were battery operated during ambient and industrial noise measurements. Cable fairings and a support float system were used to minimize strumming and surge noise effects on the ambient measurement hydrophone. At times, particularly when recording transient sounds and industrial noise requiring wide dynamic range, it was useful to record data from a single hydrophone at two different gain settings, using both record channels. At

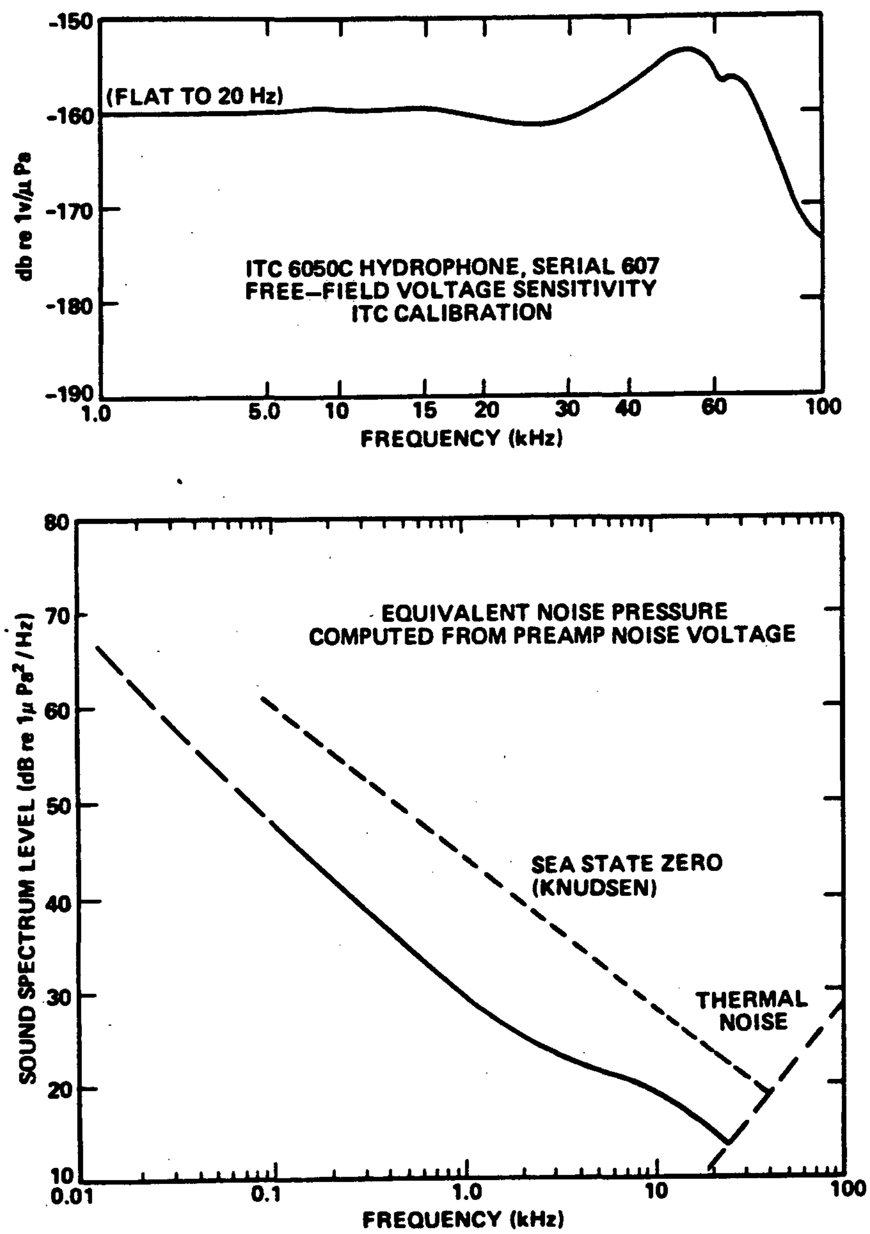


FIG. 4. MEASUREMENT HYDROPHONE CHARACTERISTICS.

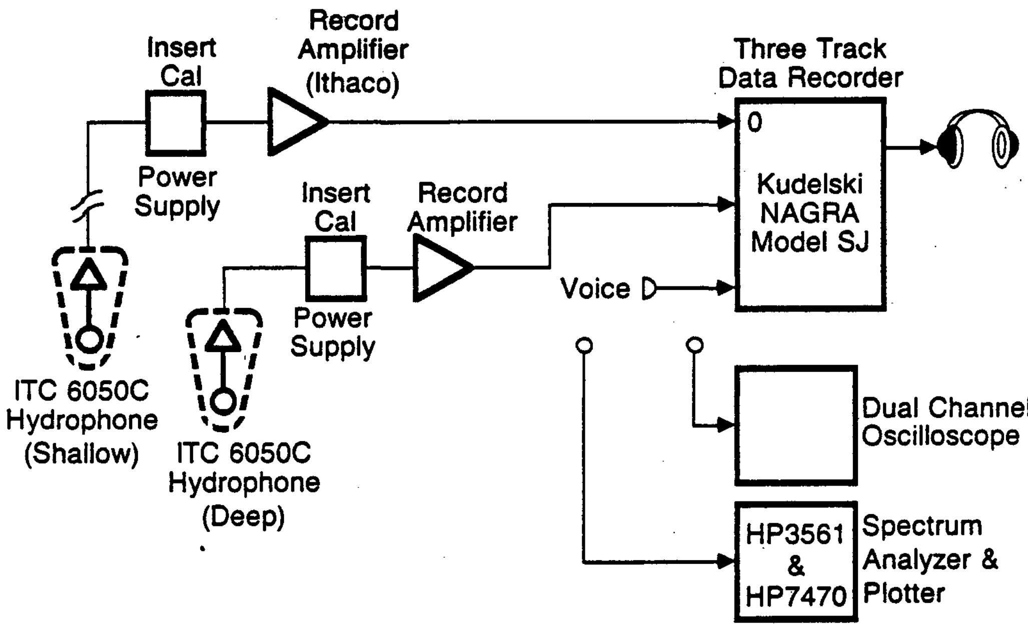


FIG. 5a: GENERAL PURPOSE ACOUSTIC MEASUREMENT SYSTEM.

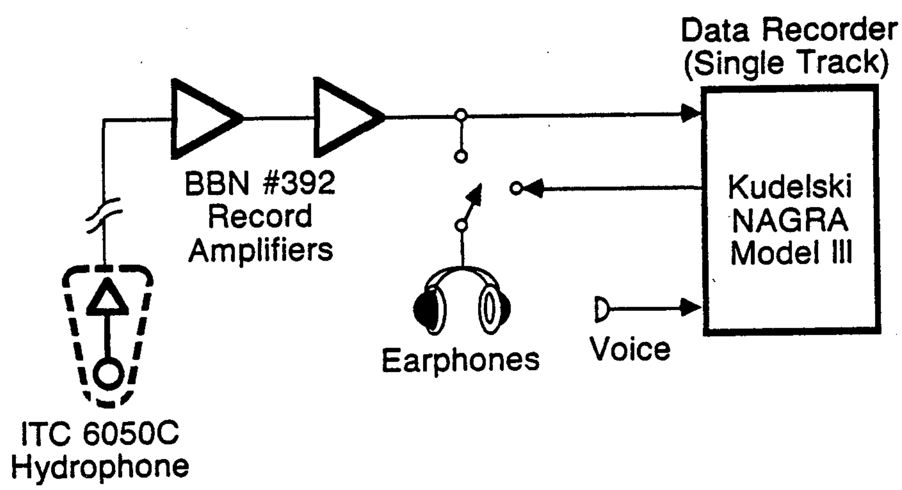


FIG. 5b. BATTERY POWERED ACOUSTIC MEASUREMENT SYSTEM FOR AVON TL MEASUREMENTS.

7.5 in. per second, the recorder has a nominal flat frequency response from 25 Hz to 20 kHz and a 60 dB dynamic range.

Single Hydrophone Receiver System (Avon)

Figure 5b provides a diagram of the single channel hydrophone system used by the second vessel (AVON). As noted, it also uses an ITC 6050C hydrophone and is compact, battery-operated, and provides the needed frequency response (30 Hz to 10 kHz at 7.5 in./sec) and dynamic range (60 dB).

Sonobuoy Measurement System

The sonobuoy measurement system permits remote measurement (3 to 4 km) of industrial noise, ambient noise, or transmission loss data, and is particularly useful when shipboard sound sources would cause contamination of the underwater acoustic data due to their proximity to a ship-mounted hydrophone. The sonobuoy electronics (a Navy SSQ57A transmitter coupled with an Edo hydrophone and Ithaco amplifier) are mounted in a 4 1/2-ft spar buoy which can either be free-drifting or moored. The frequency response of the system is flat from below 100 Hz to 10 kHz. When moored, it is often placed near an industrial site and sampled periodically during the day while the research vehicle is performing other experiments or it can be used to receive acoustic transmissions during transmission loss experiments. Figure 6 is a block diagram of the sonobuoy/spar-buoy measurement system used for this project. The buoy incorporates a high sensitivity, calibrated hydrophone, a low-noise signal preamplifier, and a sonobuoy radio transmitter. Battery life permits continuous operation for about three days. A range of about 5 km has been obtained depending on the available antenna height on the receiving vessel.

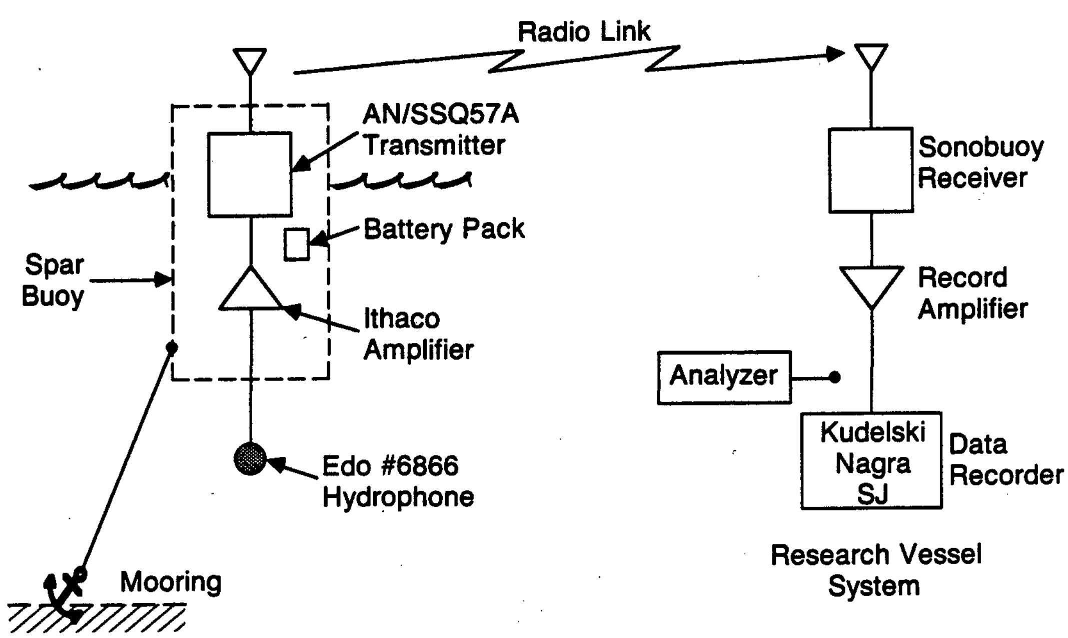


FIG. 6. SONOBUOY MEASUREMENT SYSTEM.

2.2.1.3 Sound Projector System for Transmission Loss Experiments

As described previously, it is necessary to determine the site-specific characteristics of sound propagation from the selected industrial sites. To accomplish this, a sound source with known frequency and sound level characteristics must be located near a site and the level of the controlled radiated signal measured as a function of distance from the source. If an industrial source radiates sounds in a continuous or invariant manner, that industrial source can be used as the "transducer". Recording that continuous sound as a function of distance provides the needed TL data. However, industrial sources rarely produce invariant sounds. Hence, a calibrated source of known characteristics is a more useful alternative. The industrial noise spectrum of interest to this project is primarily low frequency in character, mostly concentrated below 1 kHz (e.g., Greene 1985). Since some energy is encountered occasionally in the 1 to 4 kHz region, it was decided that a standard U.S. Navy J-13 sound projector would suffice for the expected 1985 field measurement conditions.* Figure 7 provides a plot of the transmit frequency response characteristics of the J-13 transducer together with a block diagram of the sound projector system used during this project. The J-13 projector is calibrated by the U.S. Navy Underwater Sound Reference Division of the Navy Research Laboratory. In order to maintain continuity from one experiment to the next, a series of 1/3 octave band tones and pulses from 100 Hz to 4 kHz were recorded on a cassette tape. The output of that tape is amplified and adjusted for consistent and repeatable drive signals to the J-13 projector. As noted, the acoustic output of the J-13 is monitored

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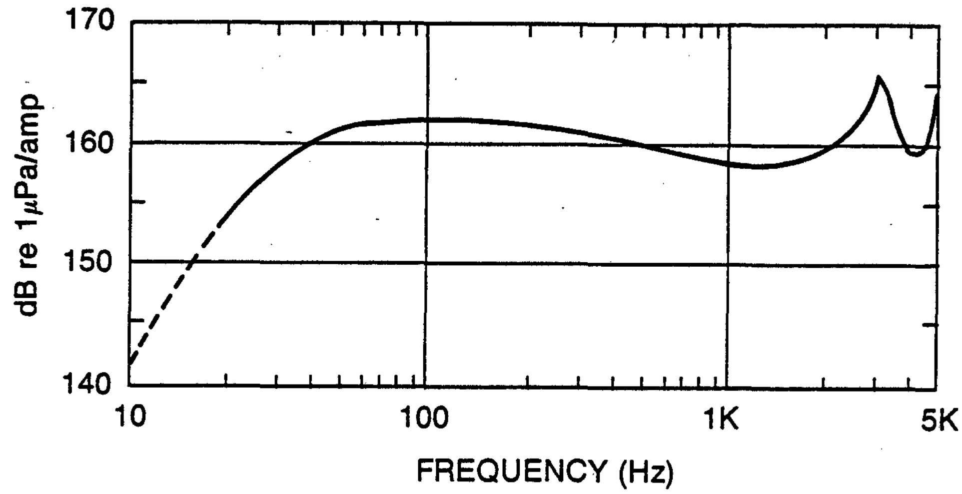
*It appears from analysis of the resulting data that two J-13 transducers operated in parallel from a single location probably should be used in 1986 to obtain transmission loss data to greater distances.



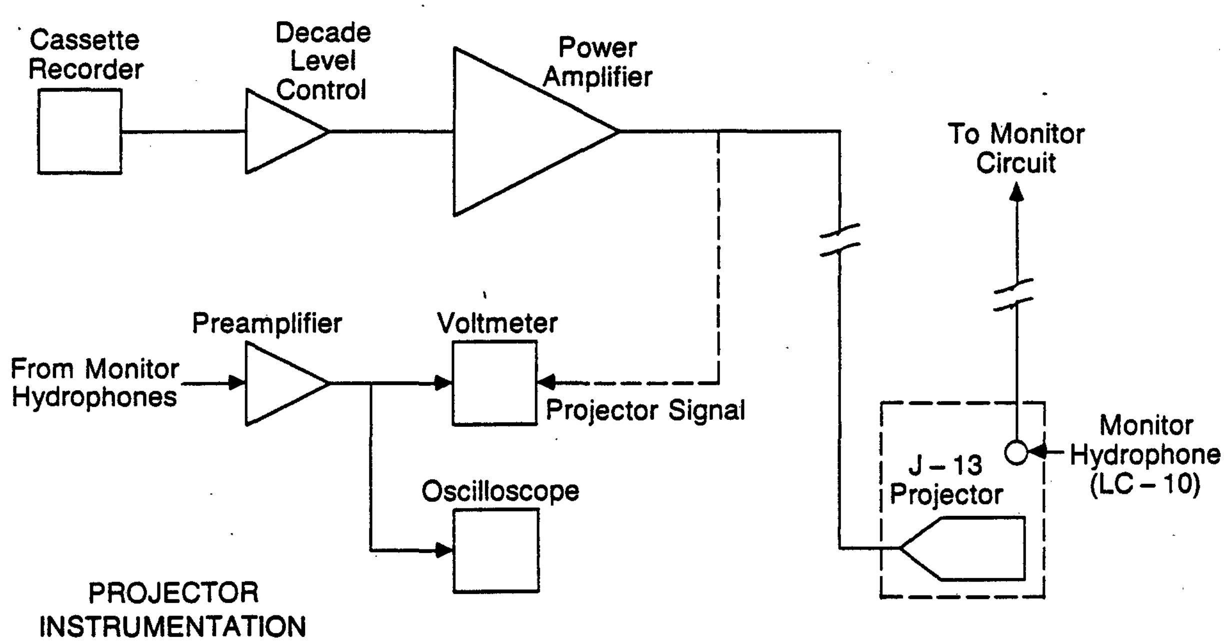


FIG. 7. J-13 FREQUENCY RESPONSE AND PROJECTOR SYSTEM.

continuously with an LC-10 hydrophone. The J-13 was suspended over the side of the JUDY ANN and operated with the vessel free drifting (engines off) next to a selected site. Ideally, the vessel should be moored but this was not possible in the Beaufort because of the potential for damage by drifting ice and because the water depths at some sites (Hammerhead, Erik, Belcher, and Corona) were beyond the anchoring capability of JUDY ANN.

Since the variation of sound speed with depth is important to the interpretation of the measured transmission loss (TL) data, the sound speed profile is determined at regular intervals with the Beckman salinometer at each site, not only before and after the TL experiments but at the time of measuring ambient noise segments and industrial noise signatures.

2.2.2 Analysis of acoustic data

Recorded data on ambient noise, industrial noise, and underwater sound propagation were analyzed to provide a quantitative definition of the underwater acoustic environment in the Diapir Field region of the Beaufort Sea. The analysis format was selected to be compatible with the requirements of the 'zone of influence' assessment to be performed by LGL Ltd. For example, the emphasis on third octave data in this report is a result of data requirements for the 'zone of influence' assessment. The analysis procedures and results used by LGL are described in Section 2.3, Section 3, and Appendix B. The methods used in analysis of the acoustic data are described below, the results of which are provided in Section 3.

2.2.2.1 Ambient Noise Analysis

The objective of the ambient noise measurement and analysis effort is to develop a statistical description of the variation of the underwater background noise conditions at each of the selected sites. Ideally this should include long-term measurement of noise conditions as a function of time of day, month, and season to permit a complete statistical description. For practical reasons, this project was only able to collect short-term samples of the ambient noise field during a 35-day period. This results in an incomplete description of the ambient noise condition for the sites of interest. In order to estimate the noise statistics over a wider range of conditions and times, additional analysis was done using published wind and ice data for the North Slope area to supplement the summertime measurements, resulting in noise statistics over a wide range of conditions and times.

Estimation of the 5^{th}, 50^{th}, and 95^{th} percentile levels of the site-specific ambient noise statistics was accomplished for both a 1-Hz band basis and for one-third octave bands spanning the frequency range of interest. Typically, estimates were derived for 1/3 octave bands centered at 100, 500, and 2000 Hz. However, at the Orion location there were interfering tonal sounds at 2 and 4 kHz, so we analyzed noise statistics at that site for bands centered at 100, 500, 1000, and 3000 Hz.

The data analysis procedure employed was as follows. The analog tape recordings were passed through a signal conditioner and then through a one-third octave band filter set at the desired frequency. The band limited signal was then amplified using a logarithmic amplifier, filtered with a 10 Hz low pass filter that acts as an envelope detector and fed into a spectrum analyzer (Hewlett Packard Model 3562) for histogram generation and calculation of the cumulative distribution function (CDF). Figure 8 is a block diagram of the data analysis system. Average narrowband power spectra were also developed to provide a general overview of the noise characteristics.

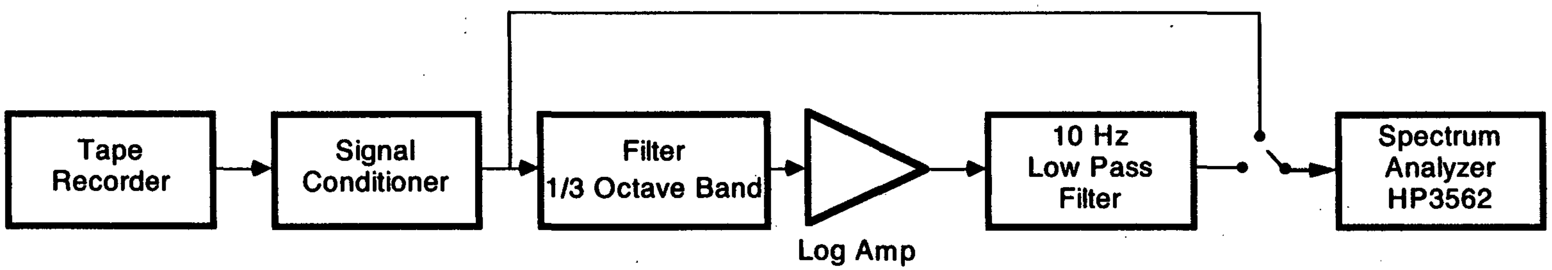


FIGURE 8. AMBIENT NOISE DATA PROCESSING SYSTEM.

From the CDFs, three ambient noise levels were collected: the level below which the third octave band noise remained 95% of the time, the median (50^{th} percentile) noise level and the level below which the noise occurs 5% of the time. The data samples were relatively short (3 to 5 minutes) since we are not trying to characterize the long term (seasonal or yearly) ambient noise statistics. This is beyond the scope of the current effort. Our goal is to characterize the site-specific noise statistics at the times we occupied the site. It is expected that the 1986 measurement effort will result in a strengthening of the 1985 ambient statistics described here and in Section 3.

Ice cover and wind statistics for the Beaufort Sea regions of interest to this study were obtained from a recent NOAA publication (Brower, et al., 1977). Those data, together with established algorithms used for estimating the dependence of ambient noise levels upon ice cover and wind speeds, permitted the derivation of long-term ambient noise statistics for ice and wind extremes not encountered in the 1985 field season. The resulting 95^{th}, 50^{th}, and 5^{th} percentile ambient spectral estimates were provided to LGL for their consideration in the synthesis of whale behavioral response.

2.2.2.2 Industrial Noise Analysis

A quantitative description of the underwater noise associated with industrial operations at selected sites on the North Slope is a necessary part of this research effort, as described previously. The objective of the industrial noise measurement and analysis effort is to determine the source levels of dominant frequency components of underwater noise related to industrial operations. The 1985 field season produced a relatively small sample of industrial noise due to limited site accessibility caused by unusually heavy sea-ice conditions. The 1986 field season should produce a larger sampling of industrial noise signatures. The analysis procedures used on the available data are described below.

The analog recordings of ambient noise and industrial noise obtained in the field were played back into a spectrum analyzer and average power spectra were measured. The durations of these averages varied depending on the noise source but typically were on the order of 1 to 2 minutes. The spectra were corrected for system gains and hydrophone sensitivities to produce data on absolute received levels versus frequency. These calibrated levels were then compared to ambient noise measurements taken at the specific sites to establish data validity in terms of acceptable signal-to-noise ratio. Narrowband tonals and broadband components that exceeded the ambient noise spectra were assumed to be due to the industrial activity.

In some cases, where measurements were made at various ranges, the noise components were examined as a function of range. Those which disappeared at short ranges are typically ignored in this analysis. (For example, the 90 and 100 Hz tonals observed during drilling at the Sandpiper site, discussed in Section 3.)

The final step in the analysis was to correct the received levels for the site-specific transmission loss (TL) characteristics to provide spectra in terms of radiated noise source level referred to a standard reference distance of 1 meter. Independent measurements of TL at the Erik site were used to derive source level estimates, corrected to a 1 m reference range for the two industrial activities at that site. For the Hammerhead data, no TL measurements with a calibrated invariant source were available, requiring the use of the industrial noise itself (McLaren et al. 1986) to estimate the local site-specific TL characteristics. The drilling activity at Sandpiper Island posed another problem. Although we had measured the TL characteristics, the environmental conditions had included 1/10-2/10 ice cover at the time. The Greeneridge Sciences drilling noise data (Johnson et al. 1986) were acquired later, with 8/10-10/10 ice cover. Since ice cover directly influences the sound transmission loss characteristics, rather than use potentially inappropriate TL estimates, the actual radiated noise measurements were used to estimate the site-specific local TL characteristics and thus to adjust the Sandpiper noise spectra to 1-meter source levels.

2.2.2.3 Transmission Loss Data Analysis

Sound propagation data were acquired and analyzed to determine the dependence of received level on the range from a calibrated source. Warble tones with a 1/3 octave bandwidth were projected in a sequence with center frequencies of 100, 200, 500, 1000, 2000, and 4000 Hz. Received sound levels of these controlled tones were measured at discrete distances from the sound projector. Measurements were made to determine the sound speed profile at each of the test sites. This information was used to select the sound source and receiving hydrophone depths for the TL measurements. Generally depths of 10 to 12 m were used which were below most observed surface layer effects and representative of mid-depth conditions.

The transmission characteristics were expected to follow either a 10 Log R or a 15 Log R spreading law depending on the prevailing sound velocity gradients and ocean bottom conditions. A 10 Log R relationship has been found to be widely applicable in the Canadian Beaufort Sea (Greene 1985), but few corresponding data for the Alaskan Beaufort were available previous to this project. Accordingly, a procedure was used to determine which of these characteristics provided the best fit to each data set using a 2-parameter, least-squares regression technique. Generally the 10 Log R characteristic was found to provide the lowest mean square error values between the measured data and model predictions.

The semi-empirical transmission loss (TL) models provided for a selected spreading loss and two empirically determined parameters to incorporate the effects of local conditions. A cylindrical spreading loss model is appropriate for conditions where the water depth is comparable to the dominant acoustic wavelengths, depth variation is small, and modal acoustic theory is applicable. It is also appropriate for conditions where acoustic ducting and upward refraction are dominant. The model used for these conditions can be stated as:

$$TL = 10\ \mathrm{Log}(H_{av}) + 10\ \mathrm{Log}(R) + A(R) + Av(R) - An + 30\ (\mathrm{dB\ re\ 1\ m}) \qquad (1)$$

where H_{av} = $(H_s + H_r)/2$, the average of the water depths at the source (H_s) and receiver (H_r) (m),

R = the range (km),

A = the attenuation (dB/km) caused by losses at the bottom and surface,

Av = the attenuation (dB/km) caused by volumetric absorption in the water (this term can be neglected for frequencies less than 500 Hz and ranges less than 20 km), and

An = the local anomaly in the source level caused by bottom- and surface-reflected energy (dB).

A spreading loss intermediate between cylindrical and spherical spreading is applicable to shallow water propagation conditions where ray theory is appropriate and a significant amount of downward refraction and bottom contacting ray paths are present. The propagation model used for these conditions is given as:

$$TL = 5\ \mathrm{Log}(H_{av}) + 15\ \mathrm{Log}(R) + A(R)/H_{av} + Av - An + 41\ (\mathrm{dB\ re\ 1\ m}) \qquad (2)$$

A is again the attenuation (dB/bounce) caused by bottom and surface reflections, but is different from that of Eq. (1) since the number of reflections is assumed to be proportional to R/H_{av}.

In applying these equations to the analysis procedure, a computer algorithm is used to solve automatically for the values of A and An which give the lowest mean-square error for a given data set. A data set consists of all of the data for a given frequency at a specific test site since no significant directional dependence was observed at any of the sites.

A computer-implemented analytic transmission loss model was also used to predict long-range sound transmission characteristics near the test sites. This model is based on a shallow water sound transmission analysis by Weston (1976) and was used to supplement the transmission loss data obtained during the 1985 field season. Long range transmission loss measurements are planned for the 1986 field work to check the predictions of this model and refine the zone of influence calculations. Further discussion of the use of this model is included in Sec. 3.3.

2.3 Whale Behavioral Response Analysis Methods*

To estimate the radius from a specific industrial site within which whales will react to its underwater sound, two main types of information are needed: (1) measurements or predictions of the levels of industrial noise at various distances from the site, and (2) information about the responsiveness of whales to varying sound levels. Previous studies have obtained considerable information about the characteristics of industrial sounds from oil industry activities in the Beaufort Sea (e.g., Ford 1977; Malme and Mlawski 1979; Cummings et al. 1981a,b; Greene 1983, 1985; Moore et al. n.d. [1984]; Davis et al. 1985; Ljungblad et al. 1985b). However, most of these data did not come from the specific sites where the Alaskan oil industry is planning to drill. Similarly, most of the available data on reactions of bowhead whales to oil-industry activities, and all of those for gray whales, came from locations different from those where drilling is now underway or planned in the Alaskan Beaufort Sea. A central objective of this project is to obtain the site-specific data that are necessary, along with existing non-site-specific data, to estimate zones of potential noise influence for various industrial activities at several specific sites in the Alaskan Beaufort Sea.

Because different industrial activities result in sounds with differing source levels and frequency composition, the type of industrial activity at a given site will affect the size of the predicted zone of influence. Furthermore, because propagation conditions differ between sites, the size of the zone of influence for a given industrial activity will depend on the location of that activity. Thus, separate zone of influence

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analyses are needed for each combination of industrial activity and site. At locations where water depth or bottom composition are different on different bearings, the zone of influence is likely to extend farther in some directions than in others.

It is impractical to conduct propagation experiments to measure received sound levels for each potentially relevant combination of site, bearing, and type of industrial sound. It would be even more impractical to test the reactions of whales to all of these combinations. The approach used in this study has been to determine the levels and frequency characteristics of the sounds emitted by the key types of industrial activity, to measure sound propagation characteristics at each site of interest, and to develop site-specific models that predict received sound levels as a function of source level, frequency, distance and bottom slope (i.e., bearing). These models can then be used to make site-specific estimates of received levels of sounds from any industrial activity that might occur at that site, provided that its source level and frequency characteristics are known. Zones of potential influence can then be estimated, to a first approximation, by relating these acoustic results to behavioral data from previous studies of the responsiveness of whales to various types and levels of industrial sounds.

2.3.1. Definition of zone of influence

Noise can affect animals in several different ways, at least in theory. The sizes of the zones of audibility, responsiveness, masking, and hearing damage will differ greatly (Richardson et al. 1983). The time element (sustained vs. impulsive high level noise) is also a potential factor to consider. When the noise level is extremely high, discomfort or permanent damage to the auditory system is possible (Kryter 1985). Industrial noise levels high enough to cause auditory damage would be expected to be restricted to relatively strong noise sources and to relatively close distances. Auditory damage would not occur at any distance unless the source level of the noise was quite high. Thus the 'zone of auditory damage' is expected to be small or absent. At the other extreme, the behavior of an animal might be affected, at least subtly, at any distance where the industrial noise was audible. The 'zone of audibility' would be much larger than that where auditory damage is possible. The zone of influence of a noise source might also be defined as the area where animals respond overtly by avoidance or some other alteration in behavior. This 'zone of responsiveness' might, in theory, be as large as the zone of audibility if animals responded to any industrial sound that they could hear. However, it might also be considerably smaller than the zone of audibility if animals responded only to industrial sounds that exceeded a specific absolute level, or to sounds that exceeded the detection threshold by some minimum amount. Still another possibility is a 'zone of masking' which would be the area within which the ability of an animal to hear important environmental sounds (calls from other members of its own species, etc.), would be impaired by the masking effect of industrial noise.

The size of the estimated zone of influence around an industrial site will vary greatly depending on the definition of zone of influence that is used. The following subsections review the major factors known or suspected to affect the sizes of the zones of audibility, masking and responsiveness. These subsections provide the justification for some of the procedures that we have applied in this study.

Zone of Audibility. -- This is the largest of the zones of possible influence. The radius of audibility will depend partly on the source level of the industrial noise and on its rate of attenuation with increasing range. However, the size of this zone will also depend on the ambient noise level and the minimum ratio of industrial noise to ambient noise that can be detected. This ratio is often taken to be 0 dB, i.e., assuming that a sound can be detected provided that it is no less intense than the background noise at corresponding frequencies. However, in some circumstances sounds can be detected even when they are somewhat less intense than the background noise, i.e., at a signal-to-noise ratio slightly less than 0 dB (see Richardson et al. 1983a for review). Another consideration is the hearing absolute sensitivity of the animal. If the absolute detection threshold is above the ambient noise level, then the zone of audibility will be limited by detection threshold, not ambient noise.

Any attempt to estimate the zone of audibility of a sound to bowhead or gray whales is hampered by the fact that there have been no measurements of the hearing thresholds of any baleen whales. Baleen whales apparently communicate with one another by calls at low to moderate frequencies (Thompson et al. 1979; Clark 1983). Most bowhead calls are at frequencies 50-500 Hz, but some calls contain energy up to 4000 Hz (Ljungblad et al. 1982; Clark and Johnson 1984). It seems safe to assume that whales are sensitive to the frequencies contained in their calls; there is behavioral evidence that some baleen whales detect and respond to calls from conspecifics many kilometers away (Watkins 1981; Tyack and Whitehead 1983). The structure of the hearing apparatus of baleen whales is appropriate for detection of low and moderate frequencies (Fleischer 1976). Malme et al. (1983) demonstrated that migrating gray whales could detect the presence of Orca sounds in a tape playback experiment when the signal-to-noise ratio was about 0 dB.

Payne and Webb (1971) pointed out that, at 20 Hz, detection range would be limited by background noise rather than auditory sensitivity even if auditory sensitivity were as much as 30 dB poorer than human auditory sensitivity at humans' most sensitive frequency. Thus, following Payne and Webb (1971) and Gales (1982a,b), we assume that ambient noise, not limited auditory sensitivity, sets the upper limit on the zone of audibility.

In estimating the zone of potential audibility, another factor that must be considered is the 'critical bandwidth' at each frequency. The critical bandwidth is the range of frequencies at which background noise affects the ability of the animal to detect a signal. Critical ratio, in dB, is equal to 10 log (critical bandwidth). Here we are concerned with the detection of an industrial sound signal in the presence of natural background noise from wind, waves, ice, etc. In those mammal species that have been studied, the only background noise that has a significant effect on detection of a sound signal is the noise within a band roughly 1/3 octave wide, centered at the frequency of the sound signal (Fig. 2-9; Popper 1980; Gales 1982a,b). A 1/3-octave band around any frequency x extends from

$$x(2^{-1/6}) \text{ to } x(2^{1/6}) ,$$

i.e., from 0.891x to 1.122x. The width of a 1/3-octave band is 23% of the center frequency. For example, the 1/3-octave bands around 50, 500 and 5000 Hz are approximately 45-56, 450-560, and 4500-5600 Hz, respectively.

Critical bandwidths have not been determined for any baleen whale, but the 1/3-octave 'rule of thumb' seems to be a good first approximation for in-air and in-water hearing by a variety of mammals and even fish (Fig. 9). Again following Payne and Webb (1971) and Gales (1982a,b), we have assumed that the critical bandwidth is 1/3 octave. (Gales also considered a wider bandwidth when the frequency was <450 Hz.) It should be noted

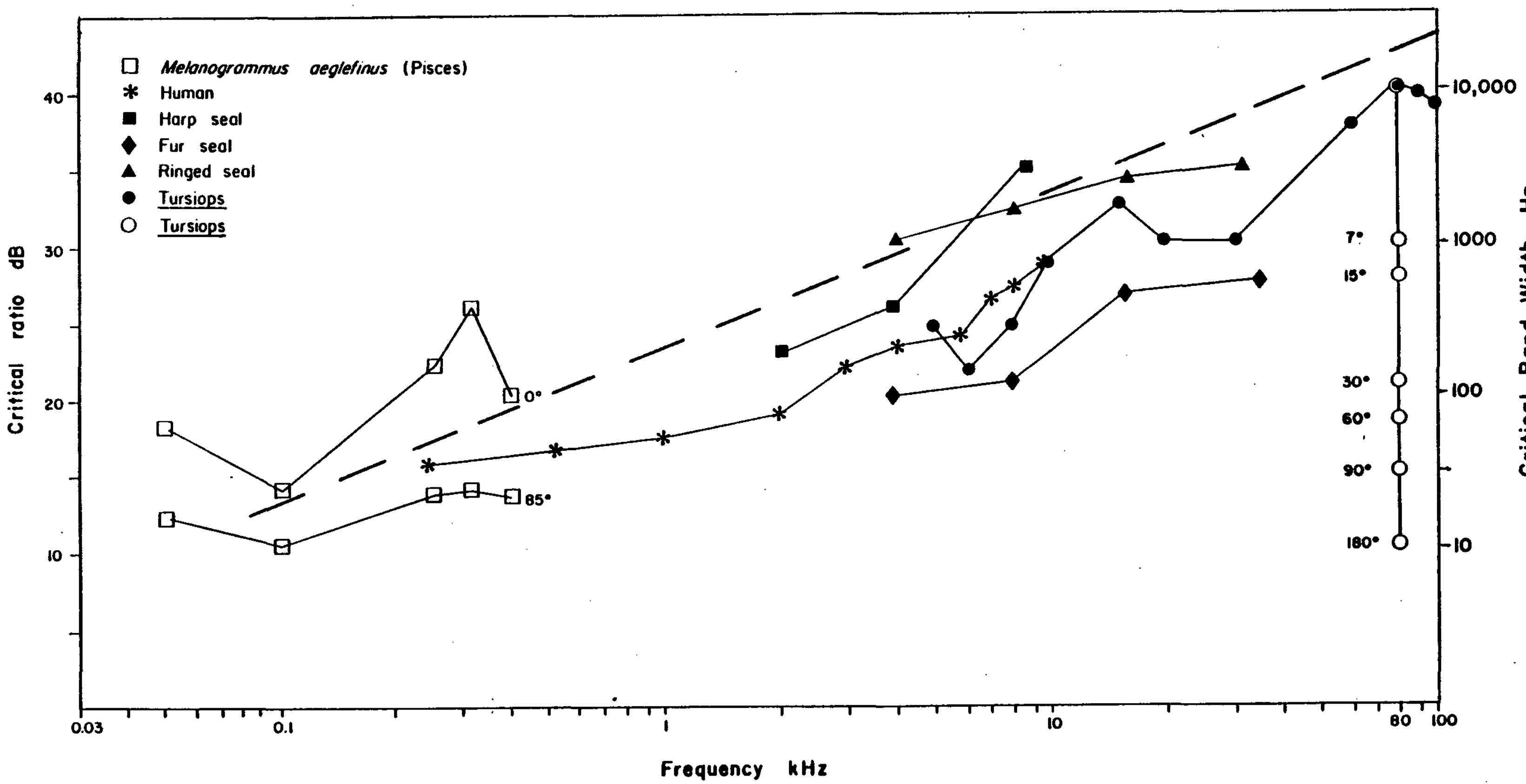

FIGURE 9. CRITICAL RATIOS AND ASSOCIATED CRITICAL BANDWIDTHS OF SEVERAL MARINE MAMMALS, MAN, AND HADDOCK. DASHED LINE REPRESENTS 1/3 OCTAVE. CRITICAL RATIOS FOR THE BOTTLENOSE DOLPHIN (Tursiops) AND HADDOCK ARE KNOWN TO DEPEND ON THE ANGULAR SEPARATION BETWEEN SIGNAL AND NOISE SOURCES (SEE OPEN SYMBOLS). SOURCES ARE CHAPMAN (1973) FOR HADDOCK, HAWKINS AND STEVENS (1950) FOR HUMAN, TERHUNE AND RONALD (1971) FOR HARP SEAL, P. MOORE (NOSC, pers. comm.) FOR FUR SEAL, TERHUNE AND RONALD (1975) FOR RINGED SEAL, AND JOHNSON (1968) AND ZAYTSEVA ET AL. (1975) FOR Tursiops. MODIFIED FROM RICHARDSON ET AL. (1983).

that signal-to-noise ratios for many industrial sounds relative to ambient noise do not depend strongly on the bandwidth chosen for analysis. Industrial noise and ambient noise typically include broadband peaks in their spectra which are greater than 1/3 octave band in width. In this situation, if a bandwidth wider or narrower than 1/3 octave is chosen, the industrial and ambient noise levels will increase or decrease more or less proportionately, and the signal-to-noise ratio may not change much.

The directional hearing abilities of baleen whales are unknown. In theory, if they can determine the direction from which a sound signal (e.g., industrial noise) is arriving, they might be able to detect it even at a signal-to-noise ratio well below 0 dB. An ability to detect a sound in the presence of much noise is in some respects equivalent to having a very narrow critical bandwidth. The sound detection ability of dolphins has been shown to depend strongly on the relative directions of the signal and noise sources, at least at high frequencies (Fig. 9). The directional effect is not expected to be as great at low frequencies because of the longer wavelengths and, in shallow water, the complex interactions of the sound with the bottom and surface. On the other hand, the large separation of hearing organs in baleen whales may partly compensate for the long wavelengths of the dominant industrial sounds. Following Payne and Webb (1971) and Gales (1982a,b), we have not assumed that baleen whales gain any increased auditory sensitivity through directional hearing.

Payne and Webb (1971) provided the first comprehensive attempt to estimate the zone within which a baleen whale could detect a particular sound. Their analysis concerned the range to which fin whales might detect the intense 20-Hz calls made by other fin whales. However, the principles described in their paper are equally relevant to the detection of industrial sounds, many of which are predominantly at low frequencies. Payne and Webb showed that, in certain deep-water situations, the intense calls of fin whales might be detectable hundreds or even thousands of kilometers away. The source levels of fin whale calls, about 180 dB re 1 μPa at 1 m, are not dissimilar to source levels of some industrial sounds. Thus, the zone of audibility might be very large in some situations.

The first detailed attempt to estimate the zone of audibility of underwater sounds from an oil industry activity involved noise from proposed icebreaking Liquefied Natural Gas 'tankers' (Peterson [ed.] 1981). To estimate the expected source levels and frequencies, theoretical models and measurements from existing large ships were considered (e.g., Leggat et al. 1981). Existing data on propagation losses within the proposed operating area were used, along with existing ambient noise statistics (Leggat et al. 1981; Verrall 1981). It was tacitly assumed that marine mammals would be able to hear ship noise if its received level was above the ambient noise level at corresponding frequencies. It is noteworthy that many of the data and analyses used in this assessment came from naval investigations, only a minority of which have been reported in the open literature. Data on sound propagation and background noise in some other areas of interest to the oil industry are undoubtedly available in restricted sources.

Gales (1982a,b) estimated zones of audibility around a semi-submersible drilling rig and two fixed drilling platforms. His estimates were based on measurements of sound levels and spectral characteristics near the industrial sites, along with a series of alternative assumptions about propagation losses (spherical vs. cylindrical) and ambient noise (low, moderate and high). Gales made the same types of assumptions about baleen whale hearing as were made by Payne and Webb, with one elaboration: Gales considered the possibility that the critical bandwidth for low frequencies is wider than 1/3 octave. Gales concluded that noisy platforms radiate low frequency underwater sounds that could be audible at ranges 'on the order of hundreds of miles' under favorable conditions of propagation and ambient noise. However, under unfavorable conditions, i.e., poor propagation and high ambient noise, even the noisiest platforms might be detectable only within ranges 'of the order of 100 yards'. Estimated ranges of audibility differed by factors of 10-1000 depending on the assumed propagation conditions and ambient noise levels.

Gales (1982b) concluded that accurate site-specific predictions of detection range will require data on (1) the acoustic source spectrum for the particular industrial source of interest, (2) propagation conditions for the particular location and season, and (3) ambient noise under the specific conditions of interest. Gales also suggested that it would be important to consider the particular species of animal involved as listener. However, in the case of baleen whales, species-specific predictions of the zone of audibility will not be possible until something is learned about the relative auditory capabilities of different baleen whales.

In shallow waters where most oil industry activities take place, the zone of audibility is expected to be restricted by the greater rate of attenuation of underwater sound in shallow water. There have been no previous specific estimates of the zone of audibility around oil industry sites in the Beaufort Sea, although several studies have provided measurements of received sound levels at various distances from such sites.

<u>Zone of Masking</u>. -- When there is an increase in the background noise level against which an animal is attempting to

detect a sound signal, the signal-to-noise (S:N) ratio is reduced. If, for example, the signal of interest is a whale call, the background noise consists of natural ambient sounds plus any industrial noise that may be present. If the receiving whale is close to an industrial source, the received industrial noise level will probably exceed the natural ambient level, and thus will reduce the S:N ratio for the whale call. If the received whale call is intense, it will still be audible despite the reduced S:N ratio. However, if the whale call would be barely detectable in the absence of industrial noise, it may not be detectable in the presence of the noise. Such a call is said to be masked by the industrial noise (Terhune 1981).

The received level of a whale call is likely to be at least roughly related to the distance between the calling and the receiving whales. If the S:N ratio of a whale call received in the absence of industrial noise is low, the call was probably made by a distant whale. Thus, it is primarily the calls from distant whales that will be inaudible if the background noise level increases. Masking by elevated industrial noise levels has the potential to reduce the distance to which a whale can hear calls from other whales, or from other sources of interest.

It is emphasized that the actual importance of masking to whales, particularly baleen whales, is largely unknown. There is little information about the importance of long-distance communication to whales, or about the significance of a temporary interruption in this ability. Long-distance communication must often be interrupted by the natural masking effect of the elevated noise levels associated with storms and moving ice. It is not known whether baleen whales can adapt to increased background noise levels by increasing the intensities or altering the frequencies of their calls; certain toothed whales apparently do this (Au 1980; Au et al. 1985). If the calls or the auditory system of baleen whales have any directional properties, this may provide some resistance to masking. These complications are discussed in more detail by Richardson et al. (1983, 1985c).

Even a slight increase in background noise level has the potential to mask a sound signal that is barely audible. Hence, masking of faint sounds could occur anywhere within the zone where the received level of industrial noise exceeds the natural ambient noise. By this extreme criterion, the zone of masking would be the same as the zone of audibility of the industrial sound. However, many sounds that are relevant to a whale, e.g., sounds from other whales nearby, will have received levels well above natural ambient levels. These sounds would still be detectable, albeit with reduced S:N ratios, even if the background noise level were considerably elevated by industrial noise.

For example, for a bowhead call with source level 180 dB re 1 μPa at 1 m and a bandwidth <1/3 octave (Clark and Johnson 1984; Cummings and Holliday 1985), the received level would be about 140 dB at range 100 m and at least 120 dB at 1 km. Near most drillsites and island construction operations in the Canadian Beaufort Sea, received 1/3-octave noise levels exceed 140 dB only within about 100 m of the industrial site. Received noise levels exceed 120 dB only within about 0.5 to 5 km (Appendix B). At distances greater than 0.5 to 5 km from the industrial site, a bowhead could probably hear other bowheads up to at least 1 km away, assuming a detection threshold of about 0 dB S:N. Thus, short-distance communication would be prevented only for whales closer to industrial sites than to potentially responding whales, and the zone where masking is likely to be important will be substantially smaller than the zone of audibility.

To calculate the degree to which masking might reduce communication range for a receiving whale at a given distance from an industrial site, several factors must be estimated. The ambient noise level and the received level of industrial noise at the whale's location must be determined. In addition, the source levels and propagation characteristics of whale calls (or other sounds of possible interest to whales) must also be estimated. Since propagation from two different sources must be considered, uncertainties about propagation losses will result in large uncertainties in the 'range reduction factors' attributable to masking. Hence, we have deferred any detailed quantitative analysis of masking until the end of this project, when more refined site-specific data on sound propagation are expected to be available.

Zone of Responsiveness. -- Gales (1982a,b) emphasized that the zone of influence should be estimated based on the noise levels that cause whales to react overtly. However, when his analyses were done, there was little specific information about the noise levels that would and would not elicit responses from baleen whales. Consequently, Gales could only estimate zones of potential audibility, not zones of responsiveness.

Reactions of several species of baleen whales to underwater sounds from industry have been studied intensively in recent years. Appendix B summarizes the data concerning reactions of bowhead and gray whales to drilling and island construction sounds. To assist in interpreting the bowhead data, Appendix B also includes previously unreported noise data on a 1/3-octave band level basis (unpubl. noise data from C.R. Greene, compiled by LGL). With the data that are now available, we can make at least rough estimates of noise levels that do and do not elicit responses from bowhead and gray whales. For gray whales, the data are from Malme et al. (1983, 1984). For bowheads, the behavioral data are from Richardson et al. (1985b,c), and the noise data are from Greene (1985 and unpubl.).

The studies mentioned above provided some direct indications about the ranges from industrial sites at which reactions were observed. However, the studies were not done at the specific sites in the Alaskan Beaufort Sea where drilling is occurring or planned. Hence, the zones of responsiveness determined in the previous studies provide only an indication of the likely zones of responsiveness at any particular site. Sound propagation phenomena at the site of interest must be taken into account before the presently available data can be translated into site-specific estimates of zones of responsiveness.

Whales might, in theory, react to underwater industrial noise at any range where it is audible. If so, the zone of responsiveness would be the same as the zone of audibility. However, the recent studies of bowhead and gray whales, and less detailed observations of some other species of baleen whales, indicate that whales often are seen within areas ensonified by industrial activities. In the Canadian Beaufort Sea during summer, bowheads have often been seen to engage in seemingly-normal activities within several kilometers of drillships or dredges, where the broadband industrial noise level was up to 16 dB above the average ambient level. In these cases, noise levels in the 1/3-octave band of maximum signal-to-noise ratio were up to 29 dB above average ambient (see Table B3 in Appendix B). A few individual bowheads have been seen at locations with even higher noise levels (Appendix B; Richardson et al. 1985b,c).

Noise playback experiments have also indicated that some bowheads show no detectable reaction to broadband noise up to about 20 dB above ambient levels (Table B4). On the other hand, some other bowheads show avoidance reactions (orient and move away) when drillship or dredge noise is received at broadband levels as low as about 10 dB above ambient (Appendix B). Again, corresponding figures for the 1/3-octave band of maximum noise were higher -- some bowheads avoided the source for S:N ratios as low as 16 dB whereas others showed no detectable reaction to S:N ratios as high as 38 dB. In the case of summering gray whales, avoidance reactions were observed when the broadband drillship noise is about 20 dB above ambient (i.e., when the one-third octave band of drillship noise having the highest signal-to-noise ratio exceeds the 50%ile ambient by 20 dB).

These results show that there is indeed a 'zone of responsiveness' for baleen whales near drillsites and island construction operations. However, if our assumption that whales can hear sounds with signal-to-noise ratios as low as 0 dB is even approximately correct, then the zone of responsiveness is considerably smaller than the zone of audibility. Not surprisingly, given the natural variability of whale behavior, the outer boundary of the zone of responsiveness is indistinct. Some individual whales react to industrial noise at lower received noise levels and signal-to-noise ratios than do others.

To translate the above information into estimated radii of responsiveness around specific industrial sites, data on source levels of the industrial sounds and on propagation losses at the specific sites of interest are necessary. The present project was designed to provide the necessary data, and to use those data to derive estimates of the zones of responsiveness.

2.3.2 Methods used for estimating zones of influence on whales

A primary objective of this study was to estimate the zone of potential influence of various drilling and dredging sounds that might occur at several specific sites in the Alaskan

Beaufort Sea. To do this, it was necessary to determine the source levels and spectral characteristics of those sounds. Propagation losses had to be estimated in order to calculate received levels at various distances from each site. We assumed that whales can detect sounds whose received levels equal or exceed the ambient noise level. By knowing the range of expected ambient levels at each site, we attempted to estimate the radii at which industrial sounds would attenuate to levels below ambient, and therefore become inaudible (Fig. 10). Given that most whales apparently react to industrial sounds only if they are at least 20 dB above the natural ambient level (Appendix B), we also aimed to estimate the radii at which industrial sounds would attenuate to 20 dB above ambient, 30 dB above ambient, etc. (Fig. 11).

2.3.2.1 Industrial Noise Level Measures*

The industrial noise level at which a specific whale behavioral response, such as avoidance, is expected can be specified as a level above the natural ambient (S:N ratio) or as a specific received level (Lr). The literature on animal response to man-made noise is very sparse and does not provide guidance on the best acoustic measure for quantizing observed reactions. Fortunately, the literature on human response to industrial noise is much more extensive. The studies of annoyance caused by specific sources such as traffic noise and aircraft flyover noise, as discussed by Kryter (1985), were reviewed since the annoyance reaction in humans can be considered to be analogous to the avoidance reaction in whales.

In general, annoyance reactions in humans have been found to correlate better with the absolute level of the intruding noise

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*By C. Malme, BBN Laboratories Incorporated.

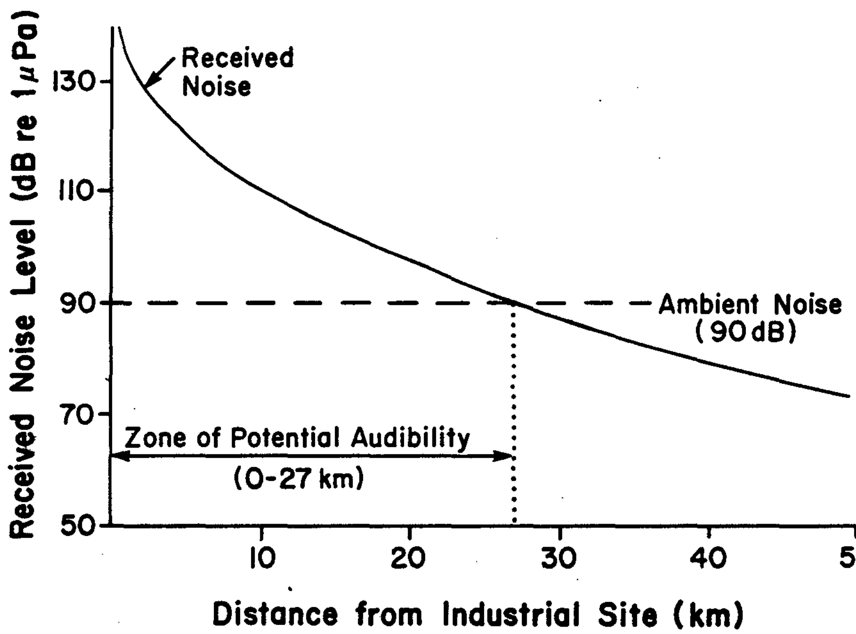

FIG. 10. PROCEDURE FOR ESTIMATING ZONE OF AUDIBILITY FROM INTERSECTION OF RECEIVED LEVEL VS RANGE CURVE WITH AMBIENT NOISE LEVEL. DATA ARE ARTIFICIAL.

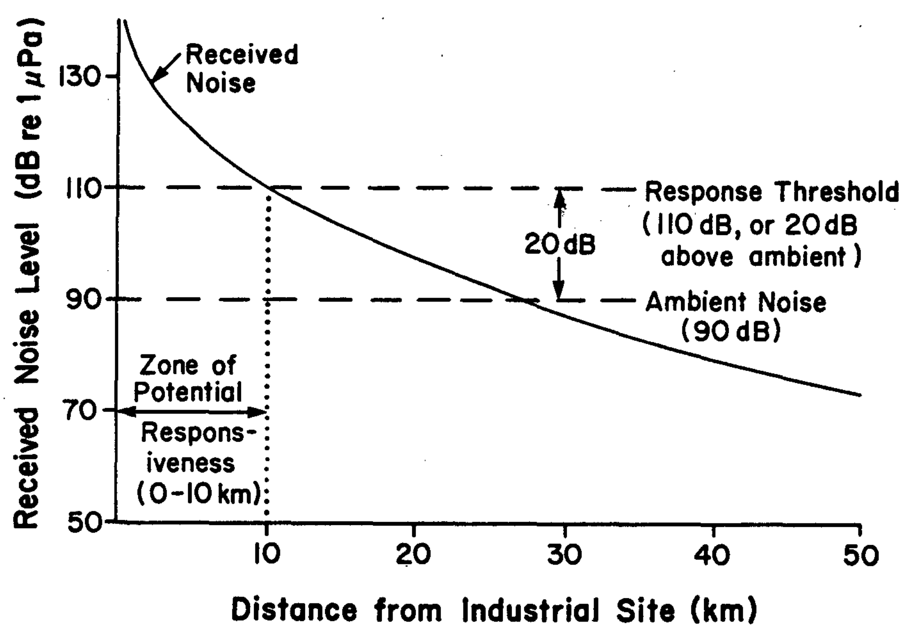

FIG. 11. PROCEDURE FOR ESTIMATING ZONE OF RESPONSIVENESS FROM INTERSECTION OF RECEIVED LEVEL VS RANGE CURVE WITH RESPONSE THRESHOLD. THE RESPONSE THRESHOLD COULD BE EITHER AN ABSOLUTE NOISE LEVEL (110 dB IN THIS CASE), OR A "SIGNAL : AMBIENT" RATIO (20 dB IN THIS CASE). DATA ARE ARTIFICIAL.

than with the maximum S:N ratio (Robinson et al. 1963). However, when the background noise is high, the threshold of annoyance with intruding noises has been found to be shifted upward (Pearsons 1966), (Spieth 1956). As a result, the usual practice in determining annoyance criteria for specific types of noise involves measurement of the sound levels which produce a quantifiable level of annoyance using psychoacoustic testing procedures. Correction factors based on the prevailing background noise levels in specific locations may then be applied to the criteria values (Kryter 1985).

The bowhead whale response data considered in this report have been analyzed by LGL considering a S:N ratio measure of response, whereas the gray whale response data were analyzed by BBN using, primarily, absolute received pressure levels. The data bases have not been reanalyzed to determine if a greater correlation with response is obtained for one or the other of the two possible measures of acoustic exposure. Until this is done, it is not appropriate to select a single acoustic parameter as the "correct" measure based on results for human noise exposure tests, since both the environment and the subject species are greatly different. As a result, the present report will provide both S:N ratio and absolute level measures of response for bowhead and gray whales.

2.3.2.2 Sources of Industrial Noise Considered

Zone of influence analyses were done for those drilling and island construction operations whose source spectra could be estimated reliably. After review of the industrial sources whose sounds were recorded during this study, five sources were selected for zone of influence analyses:

1. Dredge bucket being hauled up, as recorded at Erik site. This operation produced stronger sounds than other phases of the dredging cycle at Erik.

2. Tug ARCTIC FOX beginning to tow loaded barge away from Erik site. The strongest tug sounds emitted during any phase of the Erik tugboat/barge operation were recorded at this time.

3. Pair of tugs forcing a barge against Sandpiper artificial island.

4. Drilling by EXPLORER II drillship at Hammerhead drillsite (recorded by Greeneridge Sciences Inc. -- McLaren et al. 1986).

5. Drilling at Sandpiper artificial island (recorded by Greeneridge Sciences Inc. -- Johnson et al. 1986).

The circumstances when these recordings were made are described in Section 3.2. For each of these five types of industrial activity, BBN estimated source levels (i.e., theoretical levels at 1 m range) for various 1/3-octave bands, including the bands where levels were highest (see Section 3.2).

For each of these five industrial sources, detailed analyses were done on data from various 1/3-octave bands within the 40-4000 Hz range. The selected bands were those for which the source level was high relative to either (a) typical ambient levels in the corresponding band, or (b) source levels in adjacent bands. In most cases, the selected bands met both criteria. The rationale was that sound components whose source levels were high would be the ones that would be detectable at longest ranges. For most sources we considered two to four 1/3-octave bands, not just the one band with maximum signal-to-noise ratio. We did this because propagation losses depended on frequency. It was possible that the band with highest signal-to-noise ratio at the source might be one where propagation losses were high. If so, another band with slightly lower source level (or source S:N) might result in higher received levels because of a lower rate of propagation loss.

2.3.2.3 Zones of Audibility

Five of the six sites studied in 1985 were considered in the zone of audibility analyses; they are Orion (CIDS), Sandpiper, Hammerhead, Erik, and Belcher. Their locations and descriptions were provided in Table 1.

For each of these five sites, received levels at various distances were estimated assuming that, in turn, each of the five industry sources listed in the previous subsection were present. This was done by applying the site-specific propagation models (Section 3.3) to the source level estimates for the five industrial sources (Section 3.2). The site-specific propagation models are of the general form developed by Weston (1976), and take account of frequency, water depth, bottom slope, bottom reflection losses, and absorption. For each industrial source, LGL used BBN's propagation models and source level estimates to calculate received level as a function of distance, considering each of the 1/3-octave bands that had relatively high source levels.

The assumption that each of the five types of industrial operation listed in Section 2.3.2.1 might occur at each of the five sites is not completely realistic. An artificial island of the type at Sandpiper would not be built in water as deep as that at most of the other sites. Conversely, drillships like EXPLORER II do not drill in water as shallow as that at Sandpiper Island. Thus, some of the combinations of industrial sources and sites considered in this analysis are of only theoretical relevance.

For each analysis band, the range of potential audibility was considered to be the range where the received level equaled the expected ambient noise level (Fig. 10). Three different estimates of ambient noise were considered: the 5th, 50th and 95th percentiles. These represent situations when ambient noise is low, average, and high. Section 3.1 describes how BBN estimated these three percentiles for two groups of sites: (1) the shallow westernmost sites, Orion and Sandpiper; and (2) the deeper more easterly sites, Hammerhead, Erik and Belcher. Insufficient data on ambient noise were available to develop separate ambient noise statistics for each individual site, e.g., for Orion as distinct from Sandpiper.

For a given site, industrial source, and ambient noise condition, we obtained estimates of the radius of audibility of sounds in each of the 1/3-octave bands with relatively high source levels (Appendix A). The zone of audibility was considered to be the maximum of these values. The radius at which the received level equaled the assumed ambient level can be determined from graphs of received level vs. range (Fig. 12). However, the values tabulated in the Results section and Appendix A were actually determined mathematically and printed out by the computer program used to perform the model calculations (see sample printout in Fig. 12).

Because the sites of interest are on a continental shelf where the water depth increases gradually from south to north, radii of audibility were expected to depend on bearing from the site. Orion and Sandpiper Island are south of the main autumn migration corridor of bowhead whales (Fig. 2; Davis et al. 1985; Ljungblad et al. 1985a). Consequently, for these sites, we made

WESTON SHALLOW-WAT. SOUND PROP'N MODEL Run date=860412
LGL version for Apple II, including absorption term; Vers. 1.3, 5 Apr 86

Site = ORION/CIDS Source type = EXPL.II.HAMHD

SOURCE LEV (DB)	161	LOCAL ANOMALY (DB)	14
FREQUENCY (HZ)	240	WAT.DEP @ SOURCE (M)	27
BOTTOM SLOPE (-1 TO 1)	0	SINE (CRIT.ANG.), 0-1	.8
BOTTOM REFL. 'B', 0-5	.7	SOUND SPEED (M/S)	1435

Max R for sph.spr. = .01 km Max R for cyl.spr. = .09 km
Max R for multimode= 6 km Max believable R = 32 km

Ranges where RL = various standard levels:

RL= 75	R= 46.4	RL= 80	R= 40.1	RL= 85	R= 34	RL= 90	R= 28.1
RL= 95	R= 22.4	RL= 100	R= 16.9	RL= 105	R= 12	RL= 110	R= 7.6
RL= 115	R= 4.7	RL= 120	R= 2.5	RL= 125	R= 1.3	RL= 130	R= .619
RL= 135	R= .298	RL= 140	R= .15	RL= 145	R= .06	RL= 150	R= .024

Ranges where RL = 5%, 50%, 95%ile of ambient:
5% (60 dB): R= -9 50% (84 dB): R= 35.2 95% (95 dB): R= 22.4

Ranges where RL = median ambient +5 dB, +10 dB, etc.:

Med+5 :	R= 29.3	Med+10:	R= 23.5	Med+15:	R= 18	Med+20:	R= 12.9
Med+25:	R= 8.4	Med+30:	R= 5.3	Med+35:	R= 2.9	Med+40:	R= 1.4

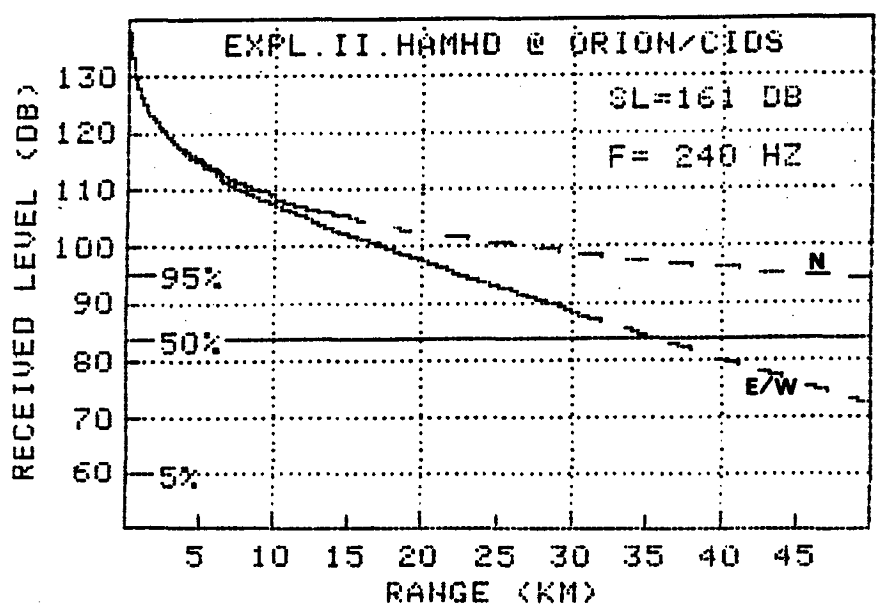

FIG. 12. SAMPLE RESULTS FROM WESTON SHALLOW-WATER SOUND PROPAGATION MODEL APPLIED FOR PURPOSES OF ESTIMATING ZONES OF NOISE INFLUENCE AROUND A SPECIFIC INDUSTRIAL SITE. THE PRINTOUT IS FOR THE 'BOTTOM SLOPE 0' (EAST/WEST OF SITE) CASE. THE GRAPH ALSO SHOWS RESULTS FOR THE 'BOTTOM SLOPE 0.001' (NORTH OF SITE) CASE. R = Range in kilometers; RL = Received level in dB re 1 μPa; SL = Source Level in dB re 1 μPa at 1m range; F = Frequency in Hz.

two estimates of the zone of audibility. One analysis assumed a constant water depth with increasing range (representing propagation parallel to the depth contours, i.e., east-southeast and west-northwest). The other analysis simulated propagation to the north-northeast, and assumed that water depth increased with increasing range at a rate appropriate to the site in question. The Erik and Belcher sites are within the autumn migration corridor of bowheads (Fig. 2), and whales could travel westward either south or north of these sites. Hence, three estimates of the zone of audibility were made for Erik and Belcher, assuming decreasing, constant, and increasing water depth with increasing range. Since the propagation model for Hammerhead was less well established than that for the other four sites, only the 'constant water depth' approach was applied there.

In the absence of information about the relative auditory sensitivities of bowhead and gray whales, both species were assumed to be able to detect industrial noise only when its received level equaled or exceeded the ambient level in the corresponding 1/3-octave band. Thus, the estimated zones of audibility were the same for both species.

2.3.2.4 Zones of Responsiveness

Data from recent studies of the behavioral reactions of bowhead and gray whales to industrial noise are summarized in Appendix B. These data were used to estimate the industrial noise levels and industrial noise-to-ambient noise ratios at which the two species do and do not react. There is no one threshold value above which all whales react and below which none react. Instead, above some minimum industrial noise level the probability of reaction appears to increase with increasing noise.

In the case of bowheads, few if any individuals appear to react overtly to industrial noise levels less than 15 dB above the natural ambient level. Some individuals apparently tolerate much higher levels (see Tables B.3, B.4 in Appendix B). However, a minority of the bowheads move away at the onset of drillship or dredge noise whose level is 20 dB or more above ambient. Roughly half of the bowheads move away at the onset of sounds with a signal-to-noise ratio of 30 dB, or an absolute received level of 110 dB. A few bowheads apparently tolerate noise levels up to 40 dB above ambient. These levels and industrial-to-ambient ratios are based on levels in the 1/3-octave band with the maximum level of industrial noise relative to average ambient noise in the corresponding band (Appendix B). As a first approximation, the median zone of responsiveness of bowhead whales could be defined as the area where the received noise level is 30 dB or more above ambient. However, it should be noted that some individual bowheads probably respond at lower S:N ratios (i.e., greater ranges), and others apparently do not respond unless S:N is more than 30 dB.

In the case of migrating and summering gray whales, more precise data are available concerning the probability of avoidance as a function of received noise level (Malme et al. 1983, 1984, 1986; Appendix B). Calculations for summering gray whales in the Bering Sea applied to the Beaufort Sea environment, indicate that a 0.1 probability of avoidance would occur for received broadband industrial noise levels of 110 dB re 1μPa and a 0.5 probability of avoidance would occur when the absolute received level is 120 dB. This corresponds to industrial : ambient noise ratios of about 20 to 30 dB, respectively.

As a first approximation, the zone of responsiveness of gray whales, like that of bowheads, is considered to be the area where the received noise level is 20 dB or more above ambient.

The radii within which the industrial noise level would exceed the median ambient level by 20 dB, 30 dB, and 40 dB (possible criteria for zone of responsiveness) were determined in the same way as the radii where industrial noise equaled ambient noise (zone of audibility, Section 2.3.2.2). We also estimated the radii within which the absolute level would exceed 110 dB which is another possible criterion of responsiveness. Separate calculations were done for each combination of five industrial sources, five sites, and 1 to 3 bottom slopes per site, considering the 1/3-octave bands that had high source levels.

It should be recognized that there is considerable variability in responsiveness of different whales, and there may be differences of opinion about the most appropriate criterion for defining the zone of responsiveness. In addition, future studies may refine present information about response thresholds. Hence, we have also calculated the ranges where the received levels would diminish to a variety of other S:N ratios besides 20, 30, 40 dB (Fig. 12). Furthermore, we determined the ranges where the received level would equal various absolute levels, e.g., 100, 110, 120 and 130 dB re 1 μPa (Fig. 12). All of these figures are tabulated in Appendix A but some are not considered in the Results.