Report No. 6509

OCS Study
MMS 87-0084

PREDICTION OF DRILLING SITE-SPECIFIC INTERACTION OF INDUSTRIAL ACOUSTIC STIMULI AND ENDANGERED WHALES IN THE ALASKAN BEAUFORT SEA

P.R. Miles, C.I. Malme (BBN)
W.J. Richardson (LGL)

November 1987

BBN Job Nos. 1153-58 (Ref. No. 2126)

This Study was funded by the Alaska Outer Continental Shelf Region of the Minerals Management Service, U.S. Department of the Interior; Anchorage, AK Under Contract No. 14-12-0001-30295

Contracting Officer's Technical Representative:

Dr. Jerome Montague; MMS-Alaska OCS Office

Prepared By:

BBN Laboratories Incorporated
10 Moulton Street
Cambridge, MA 02238

LGL Ltd
environmental research associates
22 Fisher St.
King City, Ontario,
Canada L0G 1K0

ABSTRACT

The underwater acoustic environment and sound propagation characteristics associated with six offshore oil drilling sites in the Alaskan Beaufort Sea were measured during the mid-August to mid-September 1985 and 1986 periods. 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. Results of previous research 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 two year effort are provided in this report.

The sound propagation findings indicate that sound attenuates less rapidly with increasing distance in the Beaufort Sea than in many other areas, i.e., there is very efficient cylindrical spreading (10 log Range) of acoustic energy to ranges of 25 to 40 km from the Alaskan Beaufort sites studied. Two acoustic criteria have been used in relating industrial noise levels to whale behavioral response: (1) predicted signal-to-noise ratio (S:N) in the 1/3-octave band of highest S:N, and (2) absolute received sound pressure level in either that same 1/3-octave band or in the overall effective bandwidth of the signal. Since it is not known whether S:N or absolute noise level is more important in eliciting responses by bowhead and gray whales, both have been considered in developing behavioral response predictions.

Site-specific zones of potential responsiveness of bowhead whales around to six continuous sources of industrial noise have been estimated. For instance, assuming that the threshold of responsiveness for some bowheads is an industrial noise to ambient noise ratio of 20 dB, the radii of response for two of the more intense continuous sounds are estimated to extend 6 to 34 km from two tugs holding a barge against a gravel island (bollard condition) and 5 to 12 km from a drillship drilling, depending on site. For the quietest source, drilling on an artificial island, the predicted radii of potential response vary from 0.05 to 1.8 km. A minority of the bowhead whales are expected to respond when the S:N = 20 dB; a few whales may respond somewhat further away.

Roughly half of bowheads are expected to respond (approximate avoidance probability of 0.5) when the S:N is 30 dB. At the sites investigated, 30 dB S:N conditions are expected to occur 1.6 to 12 km from the two tugs in bollard condition, 1 to 4 km from the drillship drilling and 0.02 to 0.2 km from drilling on an artificial island. Based on the absolute level criterion, for which the approximate threshold is 110 dB re 1 μPa, expected zones of responsiveness of roughly half of the bowhead whales are of the same order as for the 30 dB S:N condition.

For gray whales, the estimated radii of responsiveness to drillship operations vary from 4.8 to 9.6 km based on a received level of 110 dB re 1 μPa in the dominant frequency band, which is the level resulting in a 0.1 probability of avoidance (P_a). For 120 dB absolute level and a P_a of 0.5, the estimated zones of responsiveness around the drillship vary from 1.4 to 3.3 km, depending on site.

The zones of audibility, within which the industrial noise level equals or exceeds the ambient level (S:N = 0 dB), will be much larger than the zones of responsiveness. Under median ambient conditions they are predicted to vary from 21 km to greater than 50 km, depending on site, for the sources noted above. These values will depend strongly on ambient noise conditions. Behavioral changes in the outer portion of the zone of audibility, beyond the zone of responsiveness, are expected to be subtle at most.

A second important category of industrial noise, that which is intermittent or is fluctuating significantly in level, has also been considered. Icebreakers working on ice at drillsites, dredge operations and short-term operations of a tug towing a loaded barge are examples. Since we do not have specific data on responses of whales to this type of source, the zones of responsiveness have been estimated in two ways: (1) assuming that they respond similarly to man by reacting to an average of the fluctuating acoustic energy over a finite period of time, and (2) assuming that the whales respond to the highest short term signal level in the same way as they do to continuous noise. The peak levels of sound radiated by a working icebreaker are the most intense of the intermittent sounds that were considered. For that source, the zones of responsiveness (30 dB S:N and 110 dB absolute level criteria) vary from 4.6 to 12 km for the first assumption and from 19 to 34 km based on the second assumption. Given the widely varying predictions and their dependence on the assumptions about responsiveness, the issue of whale responsiveness to varying industrial noises should be studied further.

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 this project.

The cooperation extended to BBN by the operators at the sites visited in the Alaskan Beaufort Sea was very important: Shell Western (Sandpiper and Corona), Unocal (Hammerhead), Exxon (Orion), and Amoco (Sandpiper, 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 that 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 Western 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. During 1986 he coordinated and provided a Corona drillship activity log for the dates and times during which BBN was making field measurements.

The availability on short notice of the research vessels M.V. JUDY ANN in 1985, through Oceanic Research Services, Inc., and the M.V. ARCTIC ROSE in 1986, through Beaufort Transportation, Inc., was essential to the success of the field measurement efforts. The contributions and skills of Mr. Geoffrey Orth and Mr. Richard Schuerger of the JUDY ANN and Mr. James Adams and his crew of the ARCTIC ROSE, particularly during difficult ice and weather conditions, assured the acquisition of the needed field data.

Western Geophysical Inc. and Shell provided important information regarding their seismic survey operations in the Alaskan Beaufort in 1986. Data relating to survey runs of WESTERN POLARIS with its air gun array system during BBN field measurement periods permitted the computation of waterborne acoustic transmission loss to distances beyond the capability of the BBN sound projector system. Their willing cooperation and contributions to the project have been very useful.

The NOAA-Anchorage office of the National Oceanic and Atmospheric Administration (Mr. Erdogan Ozturgut) provided what proved to be very important information regarding profiles of ocean salinity and temperature as determined from icebreaker POLAR STAR in early to mid-October 1986. Their assistance was critical in establishing boundaries on estimates of zones of influence on endangered whales.

At LGL Ltd., environmental research associates, Ms. M.A. McLaren assisted Dr. Richardson in compiling data on whale response. Her help is greatly appreciated. Dr. Rolph Davis provided important editorial assistance during preparation of both the interim report and this final report.

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:

Mr. Bart Burkewitz: Field measurements and data analysis (1986)

Mr. Jeffrey Doughty: Field measurements (1985)

Mr. Arthur Margerison: Field measurements (1985)

Dr. Daniel L. Nelson: Field measurements (1985)

Mr. Arch Owen: Field measurements and data analysis (1986)

Mr. George Shepard: Field measurements, 1985-86, and data analysis (1985) and co-author of the interim report.

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.

Dr. Christopher Clark and Dr. Peter Tyack provided consulting services during the planning process for this project and reviewed the results of the first phase (1985) of the study. Mr. James Bird provided important assistance in the literature review portion of the first phase effort and prepared an annotated bibliography regarding the potential effects of industrial noise on bowhead whales in the Beaufort Sea. That bibliography is contained in the interim report of this project (Miles et al. 1986).

PROJECT ORGANIZATION

Although 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, and Study Area and Methods sections; and worked jointly with the other authors on the Conclusions and Recommendations sections. He was responsible for the overall management and coordination of the project and this report, and participated in the field measurement program.
Mr. Charles I. Malme:	Field Measurement Manager and Assistant Project Scientist. Co-authored the sections regarding industrial and ambient noise measurements. He prepared the sections on acoustic propagation models, the responses of gray whales to acoustic stimuli, and possible responses of whales to variable sounds. He organized and directed the field measurement effort and directed and performed analysis of the 1986 field data.
Dr. W. John Richardson:	LGL Ltd., environmental research associates, was contracted by BBN to use existing data on disturbance responses of bowhead whales, along with the acoustic environmental data obtained by BBN, to develop "zone of influence" projections. Dr. Richardson authored the sections on whale behavioral response analysis methods (Section 2.3), zones of influence for bowhead whales (most of Sections 3.4-3.6), and Appendices D and E.

In the preparation of the interim report under this project (BBN Report No. 6185, Miles et al. 1986), Mr. George Shepard, as data analysis manager, coordinated and performed analysis of the 1985 field data, the results of which are included here. He was also a key member of both the 1985 and 1986 field measurement endeavors.

EXECUTIVE SUMMARY

This report presents the results of a two year research effort concerning industrial noise sources associated with offshore oil exploration in the Alaskan Beaufort Sea and the anticipated behavioral responses of endangered whales to those sources. The basic purpose of the research was to estimate the distances between a sound source and whale where one may expect industrial noise (1) to be detected by whales, and (2) to elicit 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 and the second field period ran from 15 August to 13 September 1986. An essential ingredient in this research was the use of historical data on responses of bowhead whales and gray whales to underwater noise from industrial sources. These data were derived in recent years by LGL Ltd. and BBN Laboratories, respectively.

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

- Orion, a site in Harrison Bay, where the Concrete Island Drilling System (CIDS) was operated by Exxon; the CIDS was at the Orion site during 1985 but not in full operation, and was absent from the site in 1986; water depth, 14 m.
- Sandpiper Island, a man-made gravel island located northwest of Prudhoe Bay and used as a base for standard drilling equipment; operated by Shell in 1985 and by Amoco early in 1986; water depth, 15 m.
- Hammerhead Prospect, located north of Flaxman Island, was occupied by the drillship CANMAR EXPLORER II in 1985, on behalf of Union Oil of California (Unocal); water depth, 28 m.
- Corona, located off Camden Bay, was occupied by the drillship CANMAR EXPLORER II and its support vessels in 1986, on behalf of Shell Western; water depth 35 m.
- Erik and Belcher Prospects, located north and east of Barter Island, respectively; there was dredging at Erik in 1985 and no industrial activity at Belcher in 1985-86; operated by Amoco; water depths 40 m (Erik) and 55 m (Belcher).

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. These conditions combined to permit acoustic measurements during only 15 days in 1985 and 15 days in 1986. 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 BBN have been supplemented with copies of 1985 data tapes obtained by Greeneridge Sciences, Inc., providing acoustic signatures from drilling on Sandpiper Island and by drillship CANMAR EXPLORER II at Hammerhead.

Measurements of ambient or natural background underwater noise were acquired at the above sites during 5-15 minute periods at random intervals during various days. The resulting recordings were analyzed to provide both narrowband and one-third octave band spectra. These data, along with historical data on wind and ice conditions, were used to derive cumulative distribution functions estimating the 5th, 50th and 95th percentile statistical levels of ambient noise experienced at each site. The resulting ambient noise data presented in this report are critical in calculating signal-to-ambient noise ratios, which are used in predicting the behavioral responses of whales.

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 Corona, icebreaker noise (open water and pushing on ice) and drilling on a gravel island at Sandpiper, were all acquired and analyzed. Both narrowband and one-third octave band analyses were performed. These sources of drillsite-related noise have been rank-ordered according to sound pressure level in dominant bands from the most to the least intense. They are (1) icebreaker pushing ice (heavy propeller cavitation), (2) tugs working (propeller cavitation), (3) icebreaker underway in open water, (4) dredge operating, (5) drillship drilling and (6) drilling from an artificial gravel island. This does not represent the entire variety of noise sources associated with offshore drilling, but the list is representative of the variety of sources of continuous and intermittent sounds. In contrast, regularly-repeating impulsive noises from air gun arrays used for seismic surveys are considerably stronger; seismic pulses are the most intense of all industrial noises routinely introduced into the sea in the Alaska OCS region.

Measurements of the sound propagation or transmission loss (TL) characteristics from each site toward the expected locations of whales were obtained, 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. Data were acquired in this manner to distances of 25 km. By recording and analyzing seismic survey impulses to distances of 40 km and greater from the seismic vessel, it was possible to estimate propagation loss characteristics to distances as great as 50 km. Acoustic transmission loss in shallow continental shelf waters where oil industry activities occur is very site-specific. Hence, there is a need to measure the TL characteristics of each site. These TL 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, to a first approximation, a cylindrical spreading law applies at each of the sites visited. This law describes a loss of acoustic energy according to 10 log R (R = range from the source). Variations in ocean bottom and surface conditions at each site, e.g. bottom composition, ice cover, and wave conditions, cause site-specific differences in the TL algorithms. At least in 1986, temporal changes in water-mass characteristics also affected TL. A strong sub-surface incursion of warm Bering Sea water near the shelf-break in September-October 1986, along with cooling of the surface water as freeze-up approached, enhanced propagation considerably at moderate frequencies.

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 of similar water depth frequently is found to vary as 15 log R and sometimes as high as 25 log R in contrast to 10 log R in the Alaskan and Canadian Beaufort continental shelf regions.

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 where 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. BBN has summarized similar research conducted in California and the Bering Sea on the behavioral responses of 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: (1) predicted signal-to-noise ratio (S:N) in the 1/3-octave band of highest S:N, and (2) absolute received sound pressure level in either that same 1/3-octave band or 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 analyses assume that either one or both of these two criteria represent the basic causal acoustic measure(s) affecting behavioral response.

Zones of responsiveness to industrial noise have been predicted for bowhead whales, which commonly inhabit the coastal regions of the Beaufort Sea in the summer and, to a limited extent, for gray whales (which are rarely seen in that region). Major offshore industrial noise sources generally fall into two categories: (1) those which radiate continuous or near-continuous sound, and (2) those which radiate intermittent sound that fluctuates in level, often in a significant way. The major emphasis of this report has been placed on predictions of zones of influence for continuous noise sources since it is that category for which there exists important prior research results concerning bowhead and gray whale behavioral response. Intermittent sources are an important element in the industrial acoustic environment of the Alaskan Beaufort, however, and hence the possible zones of responsiveness around intermittent sources are also discussed briefly. A third category, directly approaching vessels, has received limited attention here. Clear-cut responses of bowheads to directly approaching vessels have been observed.

Whales are assumed to be able to hear an industrial noise if its level equals or exceeds the background ambient level in the corresponding frequency band. Zones of audibility have been estimated for all industrial noise sources and industrial sites studied. These zones of audibility are larger than the zones of responsiveness, since whales are not expected to react overtly to most weak sounds even though those sounds may be audible.

The zones of responsiveness of bowhead whales to continuous noise sources typically, depending on site, have a radius of:

Two tugs in bollard condition (forcing barge against island)	1.6-12 km
Icebreaker underway in open water	2-12 km
Tug underway in open water	1-8 km
Drillship drilling on site	1-4 km
Drilling on artificial island	0.02-0.2 km.

Estimates of zones of responsiveness to continuous noise from industrial sources are considered to be reliable for the environmentally related sound propagation and signal-to-noise conditions assumed in these calculations. These radii are based on the observation that roughly half of the bowhead whales show avoidance responses (probability of avoidance of about 0.5) to industrial sounds which have a 30 dB S:N. A smaller proportion of the bowheads react when the S:N is about 20 dB, which would occur at greater ranges than those summarized above and a few bowheads may react with even lower S:N (i.e., at even longer ranges). On the other hand, some bowheads apparently tolerate S:N ratios as high as 40 dB without exhibiting an avoidance reaction; for those individuals the zone of responsiveness is smaller. Thresholds of responsiveness are likely to be lower than average (i.e., larger zone of responsiveness) in the cases of rapidly increasing sounds. Thresholds may be higher than average (i.e., small zone) in the cases of continuous "non-threatening" sounds.

Zones of responsiveness around intermittent sources of sound are discussed using two alternative assumptions, since whale responsiveness to this type of source has not been studied: (1) that they respond as man does, to the average acoustic energy being received over a specific period of time and as bowheads and gray whales react to seismic sounds and (2) assuming that the whales respond as they would to continuous noise with level equal to the highest level of noise radiated during a time series of fluctuating signals. Analysis using these assumptions and a 30 dB S:N criterion yields the following radii:

Icebreaker pushing ice	4.6-20 km
Tug towing loaded barge	0.3-9.3 km
Clamshell dredge working	0.1-3.1

The lower values relate to the second assumption and are based on the duty cycle of observed fluctuations in sound levels radiated by these sources over a finite period of time. Duty cycle is the ratio of the operating time of an intermittent sound source to a total period of exposure potential. Presently available data are insufficient to show which assumption is more appropriate. Values for the icebreaker pushing ice are higher than for any continuous source because this was the strongest noise source studied.

The following estimates of the zones of responsiveness of gray whales in the Beaufort Sea to drillship noise are based on the absolute level criterion. 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, in the dominant frequency band, which generally included several 1/3-octaves. The radius of the zone of responsiveness is again site-specific.

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	9.6 km	0.9
Erik	5.9	2.0
Corona	4.8	1.4
Hammerhead	9.1	2.1
Sandpiper	8.1	3.3
Orion	8.6	3.3

Based on the signal-to-noise ratio criterion, about half of the gray whales show avoidance responses when the signal-to-noise ratio is 20 dB rather than the 30 dB which characterizes bowhead response. The difference may reflect the different bandwidths considered for the two species. For gray whales, the zone of responsiveness to drillship noise, based on the 20 dB S:N criterion, varies from 5-9 km depending on drillsite.

It should be noted that the natural ambient level varies widely from day to day. Consequently, the radius where S:N is 20 or 30 dB also varies widely. The radii quoted above refer to median ambient conditions. Considerably larger or smaller radii of responsiveness can be expected on days when ambient noise levels are lower or higher, respectively. Natural variability in sound propagation conditions can also affect predicted radii of responsiveness based on any of the response criteria.

For the details of this two year research effort, please refer to the body of this report and the supporting appendices.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

page

SECTION

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

LIST OF FIGURES
(Abbreviated Titles)

LIST OF FIGURES (Cont.)
(Abbreviated Titles)

LIST OF FIGURES (Cont.)
(Abbreviated Titles)

LIST OF FIGURES (Cont.)
(Abbreviated Titles)

LIST OF TABLES
(Abbreviated Titles)

LIST OF TABLES (cont.)
(Abbreviated Titles)

1. INTRODUCTION AND OBJECTIVES

The continuing exploration for and development of oil and gas resources in the Alaskan Beaufort Sea Outer Continential Shelf (OCS) region, has created a need for investigations relating to potential environmental impact. One issue is 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 April into October (e.g. Braham et al. 1980; Ljungblad et al. 1985a, 1986 a,b, 1987), including areas of oil and gas exploration and development. The gray whale (Eschrichtius robustus) also feeds in the Arctic during summer months, although this species is not sighted frequently in the Beaufort (Braham 1984; Marquette and Braham 1982). Concern regarding potential environmental impact has centered largely 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 site-specific underwater sound propagation characteristics of the region 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 behavior under natural undisturbed 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 industrial sound source and whale).

Accordingly, the Minerals Management Service (MMS) contracted BBN Laboratories Incorporated and their subcontractor, LGL Ltd. environmental research associates, to perform a two-year research project to develop the needed quantitative understanding of whale behavioral response to acoustic stimuli at specific sites in the Alaskan Beaufort Sea. Required tasks under the project include measurement and modeling of the acoustic environment at selected sites in the Alaskan Beaufort Sea OCS during the 1985 and 1986 summer/fall seasons by BBN and the use of the resulting data by LGL and BBN to predict the distances from the sites at which whales might respond. Field measurements, behavioral observations, 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, 1986a; 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 (Beaufort Sea) 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 final report summarizes the measurements made during the 1985 and 1986 field seasons (16 August-19 September and 15 August-13 September, respectively) and presents the results of the analyses performed on the field data, the synthesis of whale response in the context of the acoustic environment, and the derivation of zones of potential influence on whales. An interim report was prepared on the findings of this project for the 1985 field season (Miles et al. 1986). Most of the 1985 as well as the 1986 results are presented here.

Over the two years, data were acquired at six sites in the Alaskan Beaufort Sea:

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

Details on location and industrial activities at these sites are provided in Section 2. A good sampling of representative industrial noise associated with oil industry operations in the Alaskan Beaufort Sea was obtained during the 1985 and 1986 measurement seaons. Greeneridge Sciences, Inc. (Dr. Charles Greene) was also performing acoustic measurements under separate projects at three of these sites in 1985 and 1986. The industrial noise data matrix being compiled under this project was supplemented with some of the Greeneridge Sciences data (including some of their 1980-84 data from the Canadian Beaufort Sea), with approval from their clients, to provide a more complete summary. Detailed results from the Greeneridge studies in the Alaskan Beaufort are given in McLaren et al. 1986, Johnson et al. 1986, and Greene (in preparation).

Parts of both the 1985 and the 1986 field seasons were dominated by heavy drifting sea-ice conditions. After encountering the problem in 1985 using the fiberglass hull M.V. JUDY ANN, which was limited to operating in no more than 2/10 ice cover and in relatively light seas, it was decided to arrange for chartering a steel-hulled larger vessel for 1986. The M.V. ARCTIC ROSE was obtained, allowing work in heavier ice and sea conditions. Even with this improved capability, 10 field days were lost to the project because of ice and heavy wind in 1986. An additional reason for the larger vessel was the need for handling equipment capable of deploying and retrieving the heavier instrumentation required for acquisition of long-range acoustic sound propagation loss data. As a result, most of the acoustic environmental data needed in 1986 to supplement the 1985 data were acquired successfully. The eastern-most sites (Hammerhead, Corona, Erik, and Belcher) received first priority in 1986. Primary emphasis was on Corona, which was the only industrially active site in August and early September 1986. The drillship operating at Corona moved to Hammerhead late in September, following the BBN measurement period.

As noted in the stated purpose of this research project, the potential for behavioral response of both bowhead and gray whales to industrial acoustic stimuli 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 summer feeding grounds of the gray whale are in the Northern Bering Sea and Southern Chukchi Sea regions (Braham 1984). All of these areas are candidates for oil exploration and development. While the major thrust of this report relates to the bowhead whale, some attention is given to predicting gray whale zones of influence. BBN has performed research studies (Malme et al. 1983, 1984, 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 discusses the anticipated responses of gray whales to acoustic stimuli in the Alaskan Beaufort Sea by applying the results of BBN studies of migrating gray whales in California and feeding gray whales in the Northern Bering Sea and using the acoustic environmental data in the Beaufort obtained under this research project.

Section 2 of this report provides details of the study area and methods used to acquire the acoustic data needed near the selected sites. Also described are the analytical methods used to estimate potential zones of influence based on the new acoustic data plus existing data on behavioral responses to noise. The results of the 1985 and 1986 portions of this project are presented in Sec. 3 including

- a statistical description of the short-term ambient noise environment,
- levels and frequency characteristics of the underwater industrial sounds measured at various sites,
- sound propagation characteristics of each site (acoustic models), and
- estimated zones of potential influence for each combination of industrial noise source and site.

Conclusions and recommendations developed during this research project, which encompassed two field measurement seasons in the Alaskan Beaufort Sea, are given in Section 4 followed by a listing of cited literature (Section 5). Appendix A outlines bowhead whale migration corridors in relation to selected drillsites in the Alaskan Beaufort Sea. Appendix B presents typical short-term ambient noise statistics for the Orion, Sandpiper, and Corona drillsites. Appendix C provides a listing of the shallow water acoustic transmission loss program used during this project as well as a tabulation of TL characteristics. Appendix D presents sound propagation estimates used in calculating zones of influence of various industrial sources at each site. Appendix E provides, for the various sites, detailed zone of influence lookup tables usable for any source of continuous industrial noise. Appendix F is a tabulation of one-third octave band frequency allocations by band number to assist the reader in interpretation of some of the drillsite noise spectra included in Section 3.2.

One Appendix contained in the previous report on this project (Miles et al. 1986) which may be of interest to the reader is the 88 page Appendix B "Previous Data on Responses of Bowhead and Gray Whales to Noise from Oil and Gas Industry Activities." It will be referred to in this report, however, leaving it to the reader to investigate later if he desires a historical review. Also, Appendix C in that earlier report contains an annotated bibliography of selected literature regarding bowhead whale research in the Beaufort Sea. That Appendix has also been excluded from this Final Report of the project.

2. DESCRIPTION OF THE STUDY AREA AND METHODS

2.1 The Study Area and Selected Sites

The underwater acoustic environment of six actual or planned offshore drilling sites distributed along the Alaskan Beaufort Sea continental shelf was measured during the summers of 1985 and 1986 to serve as a basis for predicting industrially-related sound levels of noise as a function of distance from those sites. The purpose of that effort has been to provide the information needed to estimate zones of responsiveness of endangered whales to industrial noise associated with operations at typical sites. Figure 1 provides locations of the six sites which range from the most westerly site, Orion near Harrison Bay, to Belcher 408 km or 220 miles to the east, located north of Demarcation Bay. All sites except Hammerhead were visited for making acoustic measurements in 1985. Data were acquired at all sites except Orion in 1986, although only Corona provided industrial noise data. As shown in Figure 1, two sites are located in water shallower than 18 meters and the remaining four are in deeper water, ranging from 28 meters at Hammerhead to 55 meters at Belcher. Table 1 provides general information about the six drillsites and industrial activity during the acoustic measurement periods (16 August-19 September 1985 and 15 August-13 September 1986).

On the following pages we describe briefly a few environmental factors and bowhead whale migration and feeding habits which are relevant to the objectives of this study. Details of acoustic measurement and analysis methods and whale behavioral response analysis methods are also provided. Additional details on these subjects were contained in the 1985 field season report (BBN No. 6185, Miles et al. 1986) prepared under this contract. Excerpts from Section 2 of that report are included as Appendices A and B of this report for quick reference purposes.

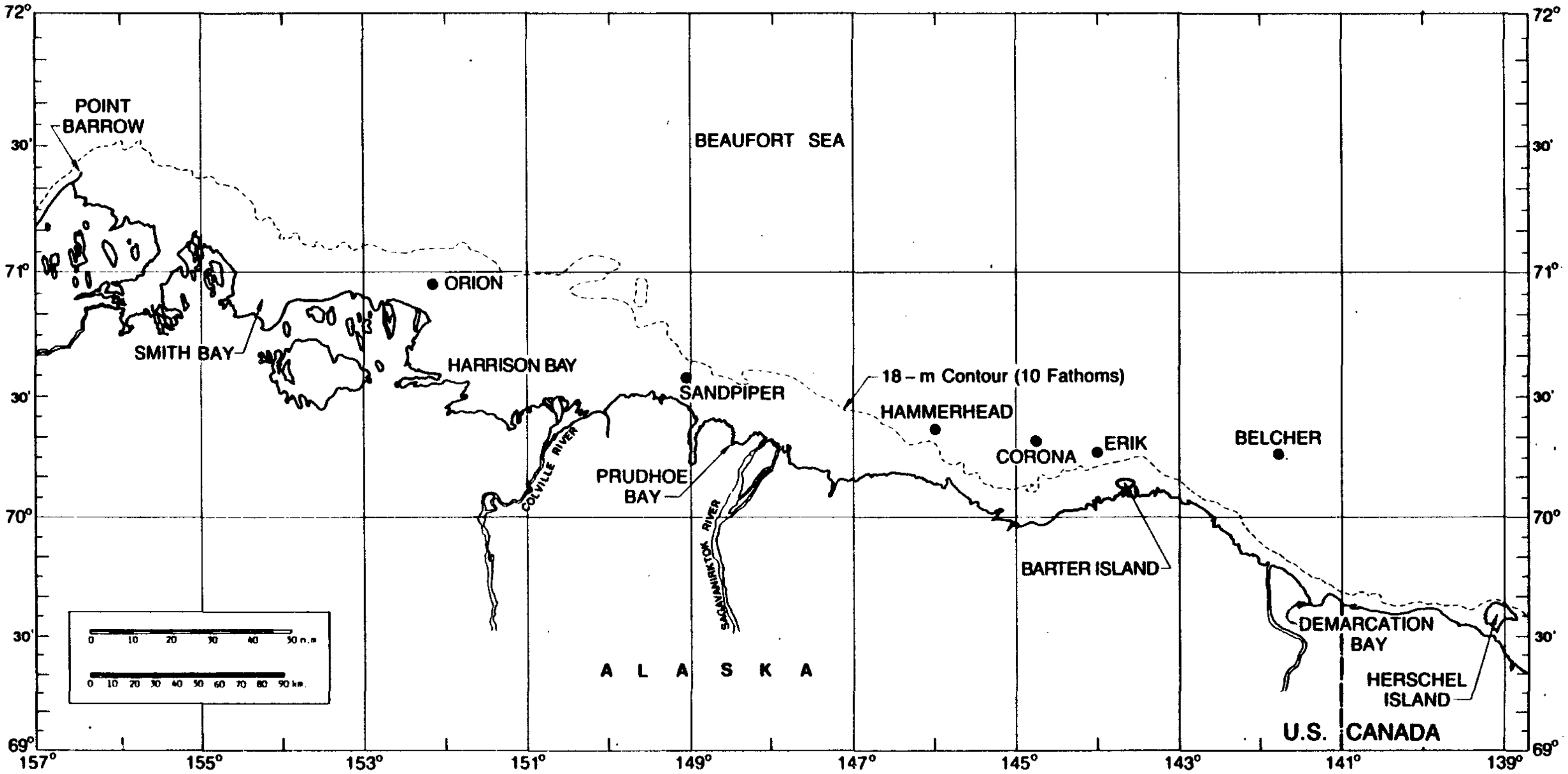


FIG. 1. SELECTED MEASUREMENT SITES IN THE ALASKAN BEAUFORT SEA.

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) -- 1985
Sandpiper	Northwest of Prudhoe Bay	70°35.08'N 149°05.81'W	15	Shell 1985 Amoco 1986	Artificial gravel island, drilling preparations, and support vessels 1985,* no activity late summer 1986
Hammerhead	North of Flaxman Is.	70°21.88'N 146°01.47'W	28	Unocal	CANMAR EXPLORER II -- 1985* (drillship not on site during BBN measurements)
Corona	N. of Camden Bay	70°18.88'N 144°45.53'W	35	Shell	CANMAR EXPLORER II -- 1986 with drillship support vessels ROBERT LEMEUR, KIGORIAK (ice breakers), and three supply vessels.
Erik	N. of Barter Is.	70°16.6'N 143°58.67'W	40	Amoco	Dredge and Tug -- 1985 No activity -- 1986
Belcher	N. of Demarcation Bay	70°16.4'N 141°47.0'W	55	Amoco	No operations on site either 1985 or 1986

*In 1985, Greeneridge Sciences Inc. provided underwater noise data from Sandpiper Island drilling operations and EXPLORER II drilling at Hammerhead (cf. McLaren et al. 1986).

2.1.1 Ocean bottom conditions

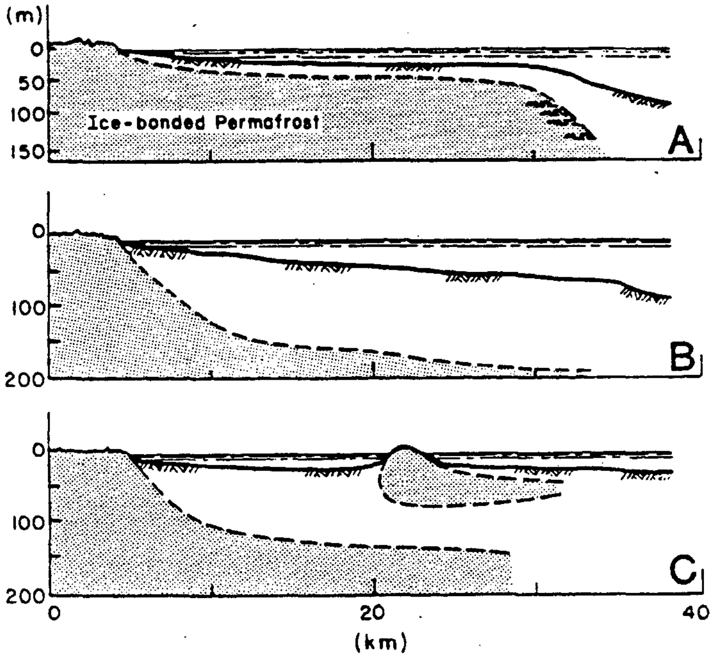
There are several important variables which influence the propagation characteristics of underwater sound, including water depth, the speed of sound (which in turn varies primarily with water temperature and salinity) and the physical characteristics of the ocean surface (roughness and ice cover) and 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 major region of interest lies on the continental shelf and south of the shelf edge or shelf break which, in the Alaskan Beaufort, occurs at a depth of 50-70 meters (27-38 fm) and about 65 km from shore. The average slope of the ocean bottom on the continental shelf and north to at least 20 km 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 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. The increasing steepness of the bottom slope north of the shelf break averages about 0.85° in the first 18 km (10 n.m.) and 2.0° in the second 18 km.

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 200 meter contour (Barnes and Reimnitz 1974; Morack and Rogers 1984; Naidu et 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: (1) subsea permafrost or ice-bonded sediments and (2) overconsolidated clay. These layers are important to discuss since they almost certainly influence underwater sound propagation. In fact, as will be discussed in Section 3, some low frequency sound propagation measurement results can be explained only by assuming a reflective surface occurring at a depth below the water/bottom interface which corresponds to suspected depths of subsea permafrost zones.

Ice-bonded subsea 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 and reflection survey data and physical sampling have located subsea 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. Based on careful analysis of seismic reflection data and substantiation of suspected subsea permafrost layers with borehole sampling, Neave and Sellmann (1984) have found that three general patterns frequently describe subsea permafrost distribution. Figure 2 (their Figure 12) demonstrates that subsea permafrost is often encountered 10 to 20 meters below the water/bottom interface as well as at a depth of 100-150 m below that interface. In the vicinity and offshore of barrier islands (where permafrost is at the surface) the relict sub-sea permafrost often occurs as a 20-40 meter layer within the bottom starting at a depth of 10-20 meters and above unfrozen sediments which, in turn, overlay a deep permafrost zone (Fig. 2c). 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) also present data which strongly indicate that both Orion in Harrison Bay and Sandpiper near Prudhoe will in all likelihood have subsea permafrost zones extending seaward from those sites. It is probable that ice-bonded sediments also exist at Hammerhead, Corona, Erik, and Belcher and extending offshore. These layers exhibit high seismic compressional wave speeds providing a strong acoustically reflective zone. Figure 3 in the interim report on this project (Miles et al. 1986) was adapted from Morack and Rogers (1984) and expanded to include typical "hard-rock" sound speed data. That figure demonstrated the compressional wave speed contrasts between unbonded and ice-bonded sediments (which in turn are similar to wave speeds in some types of rock). In ice-bonded sediments, it is common to measure wave speeds of 2500 m/sec to over 4000 m/sec compared to 1400 to 2000 m/sec for water-saturated sediments providing the needed compressional wave speed contrast for an acoustically reflective interface.

While the major objective of this research is to consider the acoustic environment, including sound propagation characteristics in the Alaskan Beaufort Sea, it is useful to establish that subsea permafrost zones have been found and reported at similar depths below the water/bottom interface in the Canadian Beaufort Sea. Blasco (1984), Hunter (1984), Hunter



From Neave and Sellman (1984)

FIGURE 2. THREE SUBSEA PERMAFROST DISTRIBUTION PATTERNS INTERPRETED FOR THE REGION STUDIED IN THE BEAUFORT SEA: A, SHALLOW RELICT PERMAFROST, B, DEEP RELICT PERMAFROST, AND C, LAYERED ICE-BONDED PERMAFROST.

and Hobson (1975), and Morack et al. (1983) have reported subsea permafrost zones which are very similar to the three distribution patterns reported by Neave and Sellman (1984) for the Alaskan Beaufort, and extending as far as 130 km from shore. As noted previously, these permafrost zones are quite variable in thickness and surface topography but they are frequently encountered and probably do influence underwater sound propagation characteristics in the continental shelf regions of the Beaufort Sea.

It has also been suggested* that overconsolidated bottom and 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 is widespread and geometrically homogeneous to depths of 20-m or more off the North Slope.* It is entirely possible that this dense clay zone works in concert with subsea 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.

2.1.2 Whale migration

Appendix A contains a brief summary of usual bowhead whale migration characteristics including an approximate layout of

---

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

spring and fall migration corridors with respect to the six industrial sites considered in this study. Gray whales are rarely seen east of Point Barrow and hence no migration corridor can be assumed. Ljungblad et al. (1985a, 1985c, 1986a,b), Hickie and Davis (1983), Davis et al. (1985), Carroll and Smithhisler (1980) and numerous others all discuss migration and feeding characteristics of the bowhead. Generally, the spring migration of bowheads eastward occurs in the April-early June time period following leads in pack ice of 8/10 to 10/10 cover from near Point Barrow to as far as 90 to 170 km from shore to their main feeding grounds in the Canadian Beaufort. They are well beyond expected influence from whatever continental shelf industrial noise may exist in that time period. However, the westward fall migration of the bowhead in late August to mid-October is closer to shore. The southern boundary of the corridor corresponds approximately to the 18-m depth contour shown in Fig. 1, although some bowheads occur even closer to shore (Johnson 1984; Richardson et al. 1987). There is evidence that the bowheads feed at least during the early phases of the westward migration before heavy ice starts to form near shore (Ljungblad et al. 1986a; Richardson et al. 1987). The corridor appears to be 50 to 80 km wide in the regions of the six industrial sites but whale counts appear to be heavily skewed to peak between the 18-m contour and the shelf break approximately 65 km from shore. The Orion and Sandpiper drill sites are located south of the southern boundary of the migration corridor while the remaining four industrial sites are in water >18 m deep and are within the general fall migration corridor.

2.2 Acoustic Environment Measurement and Analysis Methods

In achieving the objective of this project, the acoustic environment of the Alaskan Beaufort was defined before any site-specific analysis of potential whale behavioral response could be accomplished. The acoustic environmental measurements were scheduled to span two summer periods in 1985 and 1986 because of the seasonal variability of industrial activity at the sites of interest to this project, fluctuating weather and sea-ice conditions, and limited duration of the measurement season. The underwater acoustic environment during those periods was investigated by obtaining measurements of the ambient or natural background noise and its variability (with minimal contributions from industrial activity), the underwater radiated noise signatures of the various industrial operations at selected sites, and the underwater sound propagation characteristics (transmission loss or TL) as a function of distance from each site. Analysis of the resulting data provided the means for predicting industrial noise level as a function of distance or range from each site and for evaluating the detection of those sounds by whales in the presence of typical sound level variations of ambient noise.

The interim report of this project (Miles et al. 1986) summarized the results of the 1985 field measurement work, providing estimates of potential zones of responsiveness of whales to typical offshore oil industry sounds. Detailed discussions of acoustic measurement and analysis methods were included in that report. The second season measurement work in the Beaufort in 1986 provided additional oil industry noise data, but more important, it provided long range sound propagation data, reducing the need for extrapolation of short range TL data to long distances as had to be done in the 1985 field-season report. The following discussion of acoustic measurement procedures and analysis methods for the two season project contains much of the material presented in the interim report to avoid the need for frequent references to that report. The major differences in the measurement systems used in 1985 and 1986 relate to the need to obtain long range TL data in the second season.

Acoustic measurements in 1985 were made from M.V. JUDY ANN, a 13-m fiberglass vessel which was a good platform for the project but was limited to working in light sea ice conditions (2/10 cover) and moderate seas (state 3 or less). However, a larger, steel-hulled vessel was sought when it was determined that operations in 1986 during more severe environmental conditions would be required for the acquisition of long range acoustic TL data with larger and heavier measurement equipment than that used in 1985. M.V. ARCTIC ROSE (35m overall length) became available to the project in 1986. That vessel had a hydraulic winch capable of overside deployment and retrieval of the sound source system and a large 5-m remote recording sonobuoy, each weighing about 114 kg (250 lb).

Tables 2 and 3 provide a summary of the acoustic measurements performed in 1985 and 1986. During the two years, sufficient data were acquired at all six selected sites which are, listed in order from west to east, Orion, Sandpiper, Hammerhead, Corona, Erik, and Belcher. Some data were also obtained at three other sites (Northstar Island, Seal Island, and Tenneco SSDC). The parenthetical numbers in the table indicate the number of measurements or tests of each parameter at each site. The resulting data provide a description of the acoustic environment and site-specific characteristics of the Alaskan Beaufort Sea continental shelf area.

The sound transmission loss data resulting from measurements at each of the sites demonstrate the variability of TL throughout the region, emphasizing the importance of establishing site-specific acoustic characteristics for the purposes of this project. TL data obtained in 1985 were limited to maximum distances of 4 to 5 km due primarily to vessel and ice limitations. TL curves were extrapolated beyond that range in the interim report of the project through use of previously reported

TABLE 2. BEAUFORT SEA MEASUREMENTS (Test Period: 16 AUGUST - 19 SEPTEMBER 1985).

Site	Ambient Noise	Sound Transmission Loss (TL)	Sound Speed Profile	Signatures and Comments
Orion, Harrison Bay	8/28 (2) 8/29 (2)	8/28 8/29	8/28 (2) 8/29 (1)	8/28 Downhole pulsing GLOMAR BEAUFORT SEA I
Sandpiper Island	8/25 (3) 8/27 (1) 9/01 (1) 9/05 (4)	8/27 8/30	8/25 (2) 8/27 (1) 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
Hammerhead	None	-	-	Ice conditions prevented access
Corona Prospect	9/08 (2)	-	9/08 (1)	No activities on site
Erik Prospect	9/09 (9) 9/13 (6)	9/13	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 9/11	9/10 (1) 9/11 (1)	No activities on site
Northstar Island	9/01 (1) 9/03 (1) 9/04 (1)	9/01	9/01 (1) 9/03 (1) 9/04 (1)	9/01 Island construction activity
Seal Island	-	-	8/18 (1)	No activities on site

Notes:

1) Parenthetical numbers denote number of measurements or tests.

2) Ambient noise segments are 5 to 15 minutes long.

3) Sound source for TL experiments: single J-13 transducer

4) Acoustic signature tape data from Greeneridge Sciences (not in table)

5) Days: Acoustic measurements (15); weather/ice/vessel maintenance (13); transit time (4); preparation (3); 35 day charter period (M.V. JUDY ANN)
   (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

TABLE 3. BEAUFORT SEA MEASUREMENTS (TEST PERIOD: 15 AUGUST - 13 SEPTEMBER 1986).

Site	Ambient Noise	Sound Speed Profile	Sound Transmission Loss (TL)	Comment	
				Signatures	Industrial Activities
Orion	-	-	-	-	No data
Sandpiper	9/11 (1) 9/12 (1)	9/11 (2)	9/11, J-13 Short range 9/11, J-13 East	-	None
Hammerhead	9/09 (1)	9/09 (2)	9/09, J-13 Short range 9/09, J-13 NW	-	None
Corona	9/03 (4) 9/04 (4) 9/10 (1)	9/02 (2) 9/03 (2) 9/04 (2) 9/10 (21)	9/02, J-13 North 9/02, Seismic array 9/03, J-13 East 9/03, Seismic array 9/04, Seismic array 9/10, J-13 North	EXPLORER II Icebreaker (KIGORIAK) Icebreaker (LEMEUR) (various operational conditions)	Drillship: EXPLORER II Icebreakers: ROBERT LEMEUR CANMAR KIGORIAK Supply Vessels: SUPPLIER 2,4,7
Erik	8/18 (1) 8/28 (1) 8/30 (1) 8/31 (1)	8/18 (2) 8/28 (1) 8/30 (2) 8/31 (1)	8/18 Seismic array 8/30, J-13 North	Icebreaker (ROBERT LEMEUR) -- Transitting	None
Belcher	8/19 (1) 8/20 (1) 9/06 (2)	8/20 (2) 9/06 (1) 9/07 (2)	8/20, J-13 East 9/06, J-13 East 9/07, J-13 North	-	None
Tenneco (SSDC)	-	-	-	-	No data (weather) (Eastern Harrison Bay)
Other	8/26 (1)	-	-	-	0.8 ice cover near Pokok Bay

NOTES:

1. Parenthetical numbers denote number of measurements
2. Ambient noise segments are 5 to 15 minutes long
3. Sound sources for TL experiments: J-13 transducer pair or WESTERN POLARIS seismic survey air gun array
4. Days:

Acoustic Measurements	= 15	
Weather/ice	= 10	30 day charter period
Transit time between sites	= 3	(M.V. ARCTIC ROSE)
Mobilization/Demobilization	= 2	

seismic survey data (Ljungblad et al. 1985b) coupled with analytical sound propagation modeling. In 1986 with the larger research vessel and a remote recording sonobuoy, TL data were acquired for distances of 20 to 50 km from the selected sites using the J-13 sound transducer pair and air gun array impulses from WESTERN POLARIS, a seismic survey vessel of opportunity. WESTERN POLARIS, operated by Western Geophysical, Inc., in the eastern Alaskan Beaufort in 1986, cooperated with this research project by providing information permitting estimation of long distance waterborne sound propagation loss.

Underwater radiated noise signatures were obtained for offshore oil industry sources operating at or near the sites. These were tugs, a clamshell dredge, a drillrig operating on Sandpiper Island (Greeneridge Sciences data), the CIDS structure GLOMAR BEAUFORT SEA I, drillship CANMAR EXPLORER II, and icebreakers ROBERT LEMEUR and CANMAR KIGORIAK. Supply vessel noise was also obtained during measurements in 1986 at Corona. However, more than one supply vessel often worked with the drillship at a given time, invalidating the possibility of deriving an acoustic description of a single supply vessel. Additional data were acquired from Greeneridge Sciences from acoustic measurements performed at Hammerhead and Sandpiper Island in 1985 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 noted in Table 1.

Sound speed profile data were derived by BBN from measurements of water temperature and salinity at each site as a function of depth as described in detail later in this section. Also, it was learned through LGL that NOAA-Anchorage (under MMS sponsorship) was making detailed measurements of salinity and temperature vs depth from icebreaker POLAR STAR in early October over long transects running northerly from nearshore in the Alaskan Beaufort in the areas of interest to this project. Those transects ran from near the 18-m contour to beyond the shelf break. Important data were acquired during the latter phase of the bowhead migration in October, after the BBN field project was completed. NOAA provided typical profile data to this project through LGL. These data proved to be very important from the standpoint of estimating underwater sound propagation characteristics during the fall (late in the whale migration period), just before intrusion of heavy pack ice and freeze-up. The implications of the POLAR STAR data are discussed in detail in Section 3 of this report.

As noted in Tables 2 and 3, weather, pack ice and vessel maintenance (in 1985) limited acoustic measurements to 15 days out of a 35 day charter in 1985 and to 15 days out of a 30 day charter in 1986.

Results of the analysis of the data catalogued in Tables 2 and 3 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 to compare with industrial noise data 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 is presented as a 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 various intervals during the more lengthy period of site occupation. Analysis of the resulting data provides a statistical sample of the ambient noise conditions at that site under the conditions prevailing at the times of 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.

In addition to logging the above noted physical variables, which influence received levels of 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. 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.

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 either a second vessel (an inflatable AVON) in 1985, or a remotely-moored recording buoy in 1986. Measurements were made out to distances of 4 to 5 km in 1985 and 20 to 50 km in 1986. Additional long range TL data were derived from 1986 recordings of impulsive sounds originating from transects of a seismic survey vessel (WESTERN POLARIS) operating an array of 24 air guns.

2.2.1.1 Physical measurements

In 1985, 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 and 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. In 1986, range information was derived using the radar system of ARCTIC ROSE and a satellite navigation system.

A standard fathometer provided depth information and 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 measures temperature and conductivity of the ocean water as the sensor is lowered in depth. Salinity is computed within the instrument from corresponding values of conductivity and temperature. 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

Four 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, a sonobuoy system that permitted remote measurement of ambient noise and industrial noise, and an acoustic data recording buoy for acquisition of long range transmission loss data.

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 and industrial noise data. The hydrophone sensitivity and electrical noise-floor characteristics are shown in Fig. 3. The acoustic noise measurement system block diagram is shown in Fig. 4a. 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

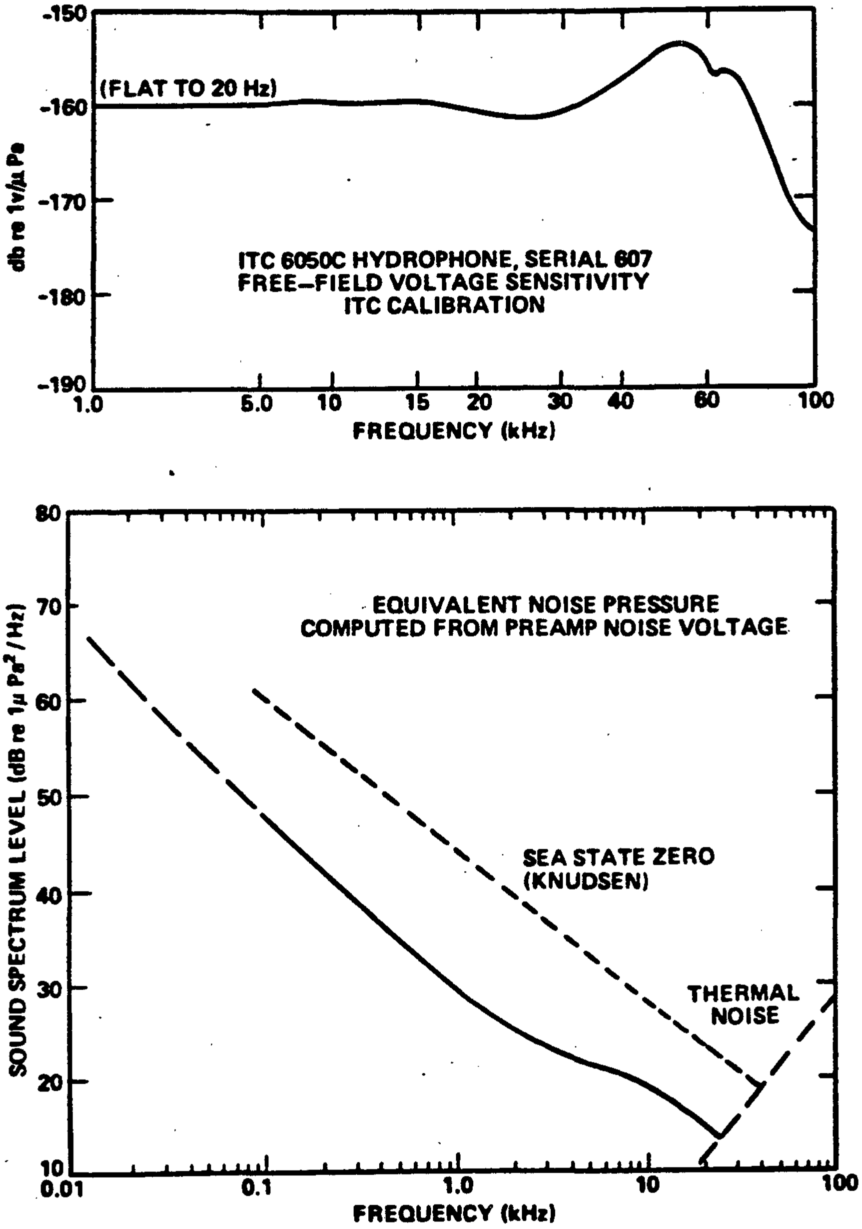


FIG. 3. MEASUREMENT HYDROPHONE CHARACTERISTICS.

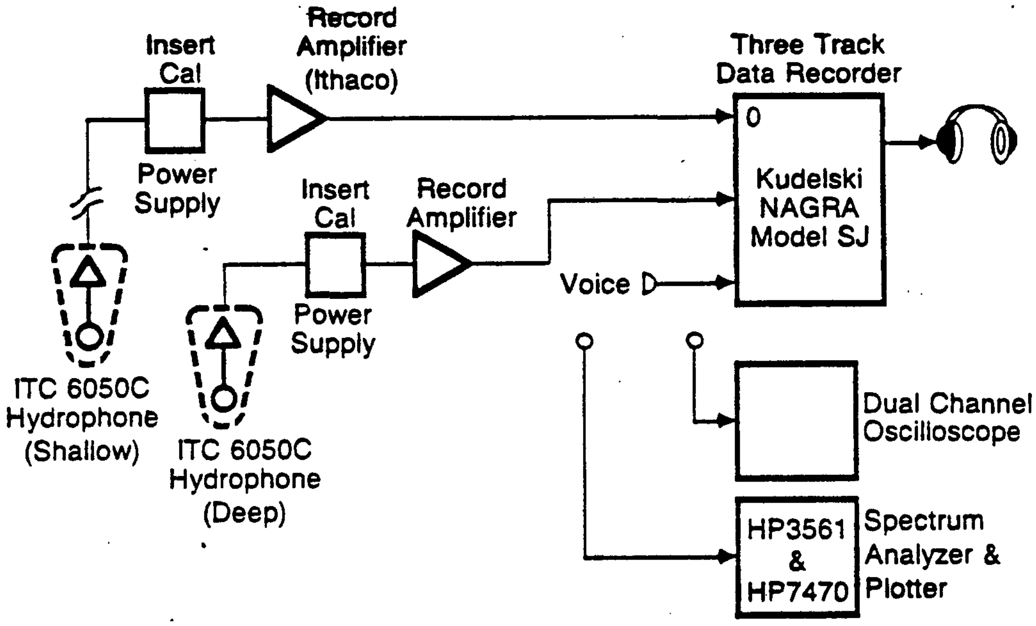


FIG. 4a: GENERAL PURPOSE ACOUSTIC MEASUREMENT SYSTEM.

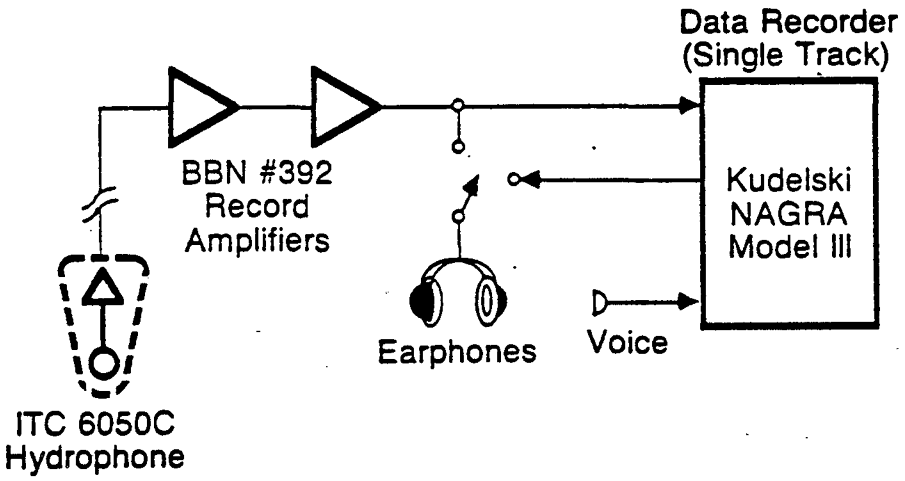


FIG. 4b. BATTERY POWERED ACOUSTIC MEASUREMENT SYSTEM FOR AVON TL MEASUREMENTS.

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 7.5 in. per second, the recorder has a nominal flat frequency response from 16 Hz to 16 kHz and a 60 dB dynamic range.

Single Hydrophone Receiver System (AVON)

Figure 4b 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).

Transmitting Sonobuoy Measurement System

This sonobuoy measurement system permits remote measurement of industrial noise, ambient noise, or transmission loss data, and is particularly useful when research vessel 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 vessel is performing other experiments or it can be used to receive acoustic transmissions during transmission loss experiments. Figure 5 is a block diagram of the sonobuoy/spar-buoy measurement system used

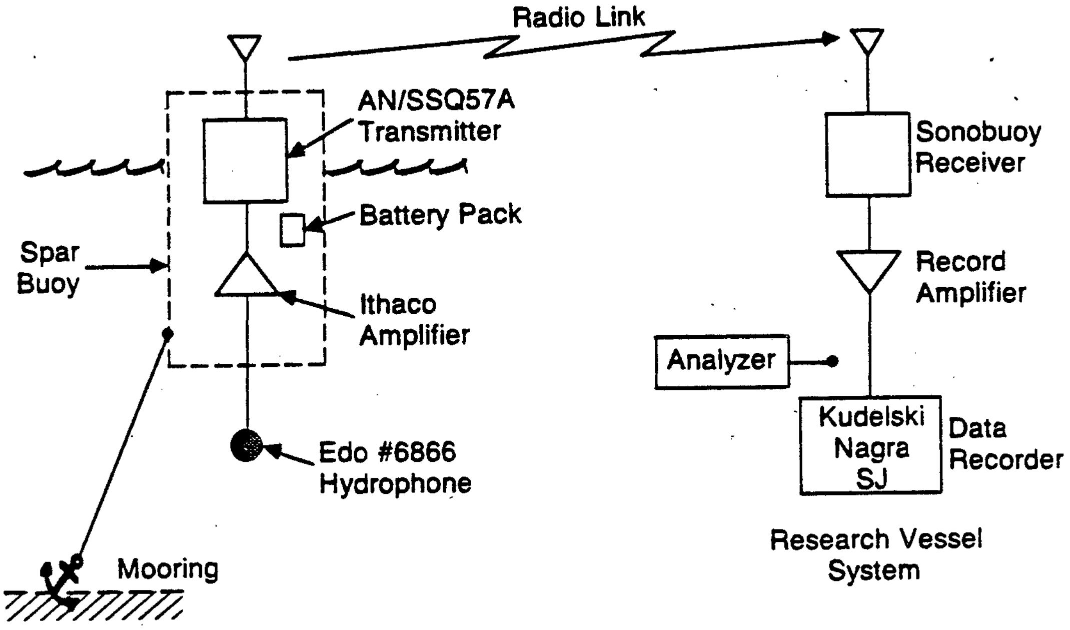


FIG. 5. TRANSMITTING SONOBUOY MEASUREMENT SYSTEM.

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.

Acoustic Data Recording Buoy System

The essential element in obtaining long range TL data under this project was the assembly and use of a large spar buoy system in 1986 which provided long term recording capability and could be moored and retrieved in water up to 100-m deep. Figure 6 outlines the system. The spar buoy assembly was fabricated from 10-in. I.D. PVC schedule 40 pipe, having an overall length of 10-ft with a 6-ft mast for mounting a radar reflector and flashing beacon. The unit, which was ballasted and included a damping plate to minimize buoyant surge due to wave action, had an in-air weight of about 250-lb. The battery operated acoustic recording system consisted of a calibrated Edo Model 6866 hydrophone, a BBN Model 392 decade amplifier and a dual channel Uher Model 4400 instrumentation recorder. Each of the two record channels were calibrated with different input gains (10 dB and 30 dB) to ensure that near and distant acoustic signals from the research vessel sound system were recorded within the dynamic range of the recorder. A single TL experiment required the research vessel to deploy the buoy 20 to 40 km away from a site (e.g., to the north) and then run at full speed toward the site, stopping at specific range increments for playback of signals from the sound projector for recording on the buoy. This procedure was used to accommodate the 4-hour recording period available using the lowest 15/16 in./sec (2.4 cm/sec) tape speed. The frequency response of the system was 25 Hz to 5 kHz which was compatible with the required test frequency range of 100 to 4 kHz.

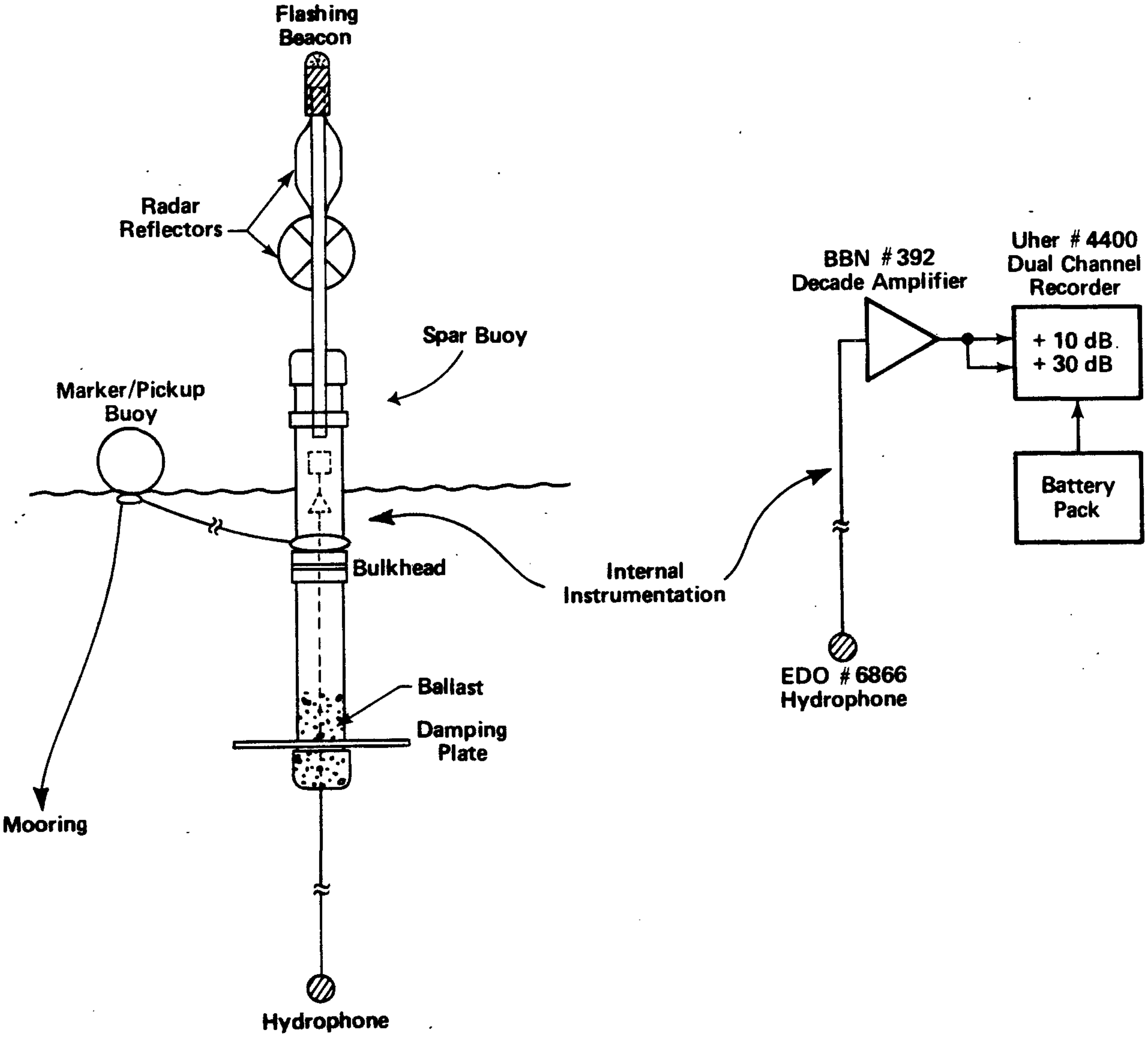


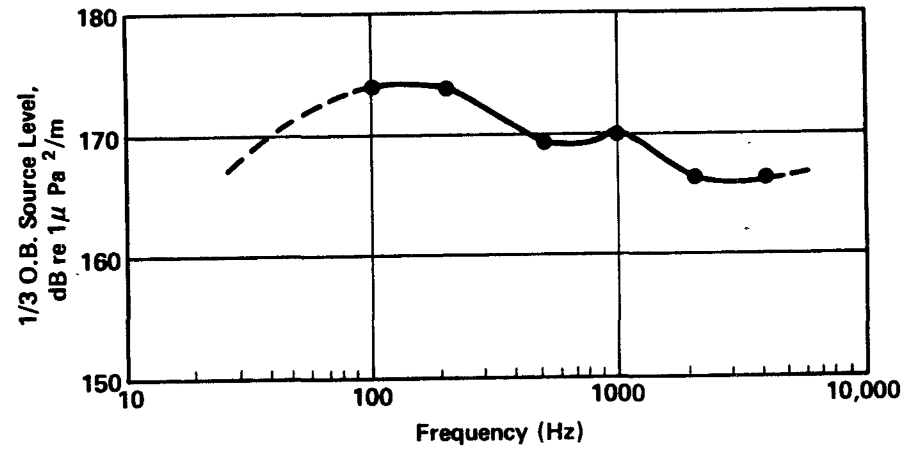
FIG. 6. ACOUSTIC DATA RECORDING BUOY SYSTEM.

2.2.1.3 Sound projector system for transmission loss experiments

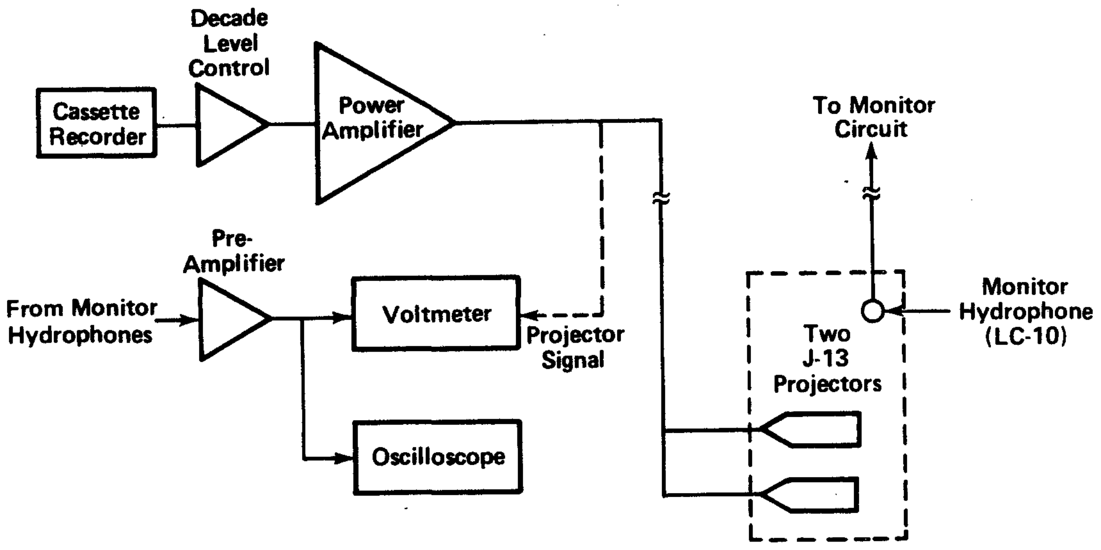
As described previously, it is necessary to determine the site-specific characteristics of sound propagation from the selected industrial sites. To accomplish this, a sound source with known frequency and sound level characteristics must be located near a site and the level of the controlled radiated 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 single standard U.S. Navy J-13 sound projector would suffice for the expected 1985 field measurement conditions. It was determined that a pair of J-13 transducers would be needed in 1986 to obtain needed long-range transmission loss data. Figure 7 provides a plot of the one-third octave band sound levels,* referenced to 1-meter distance, which were used during the 1986 experiments with a pair of J-13 transducers. A block diagram of the sound projector system used is also included. The J-13 projectors were 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

---

*One-third octave band levels represent the acoustic energy existing within discrete frequency bands which have a width of 23% of the center frequency and are spaced at one-third octave intervals. See Appendix F for a list of standard one-third octave band center frequencies.



J-13 TRANSDUCER PAIR OUTPUT SIGNAL LEVEL



PROJECTOR INSTRUMENTATION

FIG. 7. J-13 SOUND PROJECTOR SYSTEM AND ONE-THIRD OCTAVE BAND SOUND LEVELS USED IN TRANSMISSION LOSS EXPERIMENTS.

tones and pulses from 100 Hz to 4 kHz were recorded on a cassette tape. The output of that tape was amplified and adjusted for consistent and repeatable drive signals to the J-13 projector. As shown, the acoustic output of the J-13 was monitored continuously with an LC-10 hydrophone. The J-13 transducers mounted in a frame were suspended over the side of the research vessel and operated with the vessel free drifting (engines off) at each selected TL station. The vessel was not anchored for these measurements 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 the research vessel. Work with the data recording buoy involved mooring the buoy and then moving the research vessel away from the buoy on a radial course from a site stopping at pre-selected positions to deploy the J-13 system for the playback of pre-recorded 1/3 octave band tones and pulses. The procedure was repeated for 6 or more range increments until the full 20 to 24 km radial had been completed.

Since the variation of sound speed with depth is important to the interpretation of the measured transmission loss (TL) data, the sound speed profile was 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 on ambient noise, industrial noise, and underwater sound propagation data were analyzed to provide a quantitative definition of the underwater acoustic environment in the Beaufort Sea OCS planning area. 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 (see Section 2.3.1). The analysis procedures and results used by LGL are described in Section 2.3, and Section 3. 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 limited to collection of short-term samples of the ambient noise field during two 30 to 35-day periods. 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.

The 5th, 50th, and 95th percentile levels of the site-specific ambient noise statistics were estimated on a 1-Hz band basis as well as 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, this was not always possible. For instance, at Orion in 1985 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 amplitude envelope of the band limited signals was then defined by using a logarithmic amplifier and a 10 Hz low pass filter. A spectrum analyzer (Hewlett Packard Model 3562), was used for for histogram generation and calculation of the cumulative distribution function (CDF) of these signals. 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.

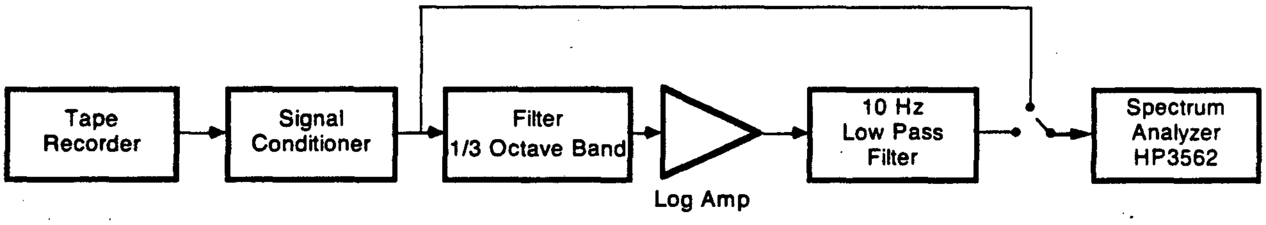


FIG. 8. AMBIENT NOISE DATA PROCESSING SYSTEM.

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 (50th 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 the goal was to characterize the site-specific noise statistics at the times we occupied the site. Ambient noise data were selected for analysis when seismic survey pulses were absent.

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) and the Alaska Marine Ice Atlas, AEIDC, University of Alaska (LaBelle et al. 1983). The atlas data were used together with reported shallow water ambient noise data to derive long-term ambient noise statistics for the September-October period in the test areas. The procedure involved combining the cumulative probability distributions of sea-state and ice-cover conditions in the test areas to determine the 95th, 50th, and 5th percentile effective conditions. Shallow water ambient noise data for the Beaufort Sea obtained by this study, as well as data reported by Greene (1985), Moore et al. n.d. [1984], and Urick (1985 p. 225), were examined to synthesize spectra corresponding to the required 95th, 50th (median), and 5th percentile conditions. The resulting 95th, 50th, and 5th percentile ambient 1/3 octave band level estimates were provided to LGL for their use in estimating zones of potential noise influence.

Ambient noise data recorded in 1986 were analyzed in sufficient detail to determine that the 1986 natural background noise levels fell within the 5th and 95th percentile statistical limits published in the interim report on the 1985 field season results. Those data, together with the 1985 ambient noise statistics, are provided in Section 3.1.

2.2.2.2 Industrial noise analysis

The objective of the industrial noise measurement and analysis effort was to determine the source levels of dominant frequency components of underwater noise related to industrial operations. The 1985 and 1986 field season measurements produced a reasonable sample of typical industrial noise existing during the summer in the Alaskan Beaufort region. 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 obtained. The durations of these averages varied depending on the noise source but typically were on the order of 1 to 2 minutes. Time segments were selected which were not influenced by seismic pulses. The spectra were corrected for system gains and hydrophone sensitivities to permit presentation of the data in terms of absolute received sound levels as a function of 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 3.2.5 of the 1985 field season report, Miles, et al. 1986).

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. In working with the 1985 data, for instance, 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 in 1985, requiring the initial use of the industrial noise itself (McLaren et al., 1986) to estimate the local site-specific TL characteristics. Transmission loss at Hammerhead was measured directly in 1986 (Table 3). 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. The resulting data were used to adjust the 1985 Sandpiper noise spectra to 1-meter source levels.

The results of the analysis of industrial noise appear in Section 3.2.

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 for both the source and the receiving hydrophone. These depths were below most observed surface layer effects and representative of mid-depth conditions. The tape recordings of each warble tone for each distance increment were played through a decade amplifier into a Hewlett Packard Model 3561A Dynamic Signal Analyzer which provided a sound level vs frequency spectrum of each signal being analyzed. Tabulation of the resulting received sound levels at each of the above center frequencies as a function of distance from the source provides the basis for plotting the transmission loss characteristic for each specific transect investigated.

Most TL data were obtained using the J-13 sound source on the research vessel and the receiver at the Acoustic Data Recording Buoy (1986) or on an inflatable boat (1985), as described earlier. This system provided useful TL data out to distances of 4-5 km in 1985 and out to about 20-24 km in 1986, as determined by the recording tape capacity in the buoy.

The derivation of TL information for distances beyond 20 to 24 km in 1986 relied on recordings of seismic survey impulses originating at the Western Geophysical vessel WESTERN POLARIS. Western Geophysical cooperated with this project by providing information which allowed us to derive air gun array (WESTERN POLARIS) distance from our receiver on M.V. ARCTIC ROSE as a function of time. Their survey operations proceeded uninterrupted during the BBN acoustic measurement work and only segments of those transects run in the vicinity of the selected sites were recorded at regular time intervals. Analysis of the recorded impulses provided water-path acoustic transmission loss data for distances of 4 to 40 km between the two vessels. The seismic array consisted of 24 air guns which were towed at a depth of 6.1 m and had a total volume of 1750 cubic inches operating with an air pressure of 4500 psi. The air guns were fired at intervals of approximately 10 seconds.

The tape recorded seismic array impulses were processed through a Hewlett Packard Model 3561A signal analyzer set up in the peak-hold mode. A series of three adjacent impulses were captured and the maximum root-mean-square impulse level derived for each 1/3 octave band from 16 to 315 Hz (the overall bandwidth containing most of the seismic impulse energy from an air gun array). The HP 3561A also provided plots of impulse signal amplitude vs time. This analysis procedure was applied to the recorded impulses at each range increment recorded during each transect of interest. Typical elapsed time between the beginning and end of a survey transect segment recorded for TL purposes was about six hours.

The results of the transmission loss data reduction procedure consists of tables of received level versus range for each test frequency. These tables were used in a computer-implemented procedure to fit a semi-empirical transmission loss model to the data using the method of least-squares (see Section 3.3.2). The model, based on an analysis by Weston (1976), provides for propagation following a spreading loss characteristic appropriate for the site-specific local conditions. In the process of fitting the model to the data, values of a bottom loss parameter and a local transmission anomaly factor are determined. This permits the model to be used for prediction of transmission loss to ranges extending well beyond the limits of the measured data. The procedure is discussed in Section 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 consider-

---

*By W. John Richardson, LGL Ltd., environmental research associates.

able 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; Johnson et al. 1986; McLaren et al. 1986). However, only a minority of these data came from the specific sites where the Alaskan oil industry is drilling or 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.

The type of industrial activity at a given site will affect the size of the predicted zone of influence because different industrial activities result in sounds with differing source levels and frequency composition. Furthermore, the size of the zone of influence for a given industrial activity will depend on the location of that activity because propagation conditions differ among sites. Thus, separate zone of influence analyses are needed for each combination of industrial activity and site. A further complication is that, 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, measure sound propagation characteristics at each site of interest, and 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). 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, responsiveness and masking. These subsections provide the justification for some of the procedures that we have applied in this study. These sections deal primarily with sources of continuous or near-continuous noise, which are the primary topic of 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. 1983 for review). Another consideration is the absolute hearing 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 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 5000 Hz (Ljungblad et al. 1982; Clark and Johnson 1984; Cummings and Holliday 1987). 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; Norris and Leatherwood 1981). Malme et al. (1983) demonstrated that migrating gray whales could detect the presence of Orca (killer whale) 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" around each frequency. The critical bandwidth is the range of frequencies within which background noise affects the ability of the animal to detect a signal. To a first approximation, 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. 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 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 as well as ambient noise is at least partly broadband in character. 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.

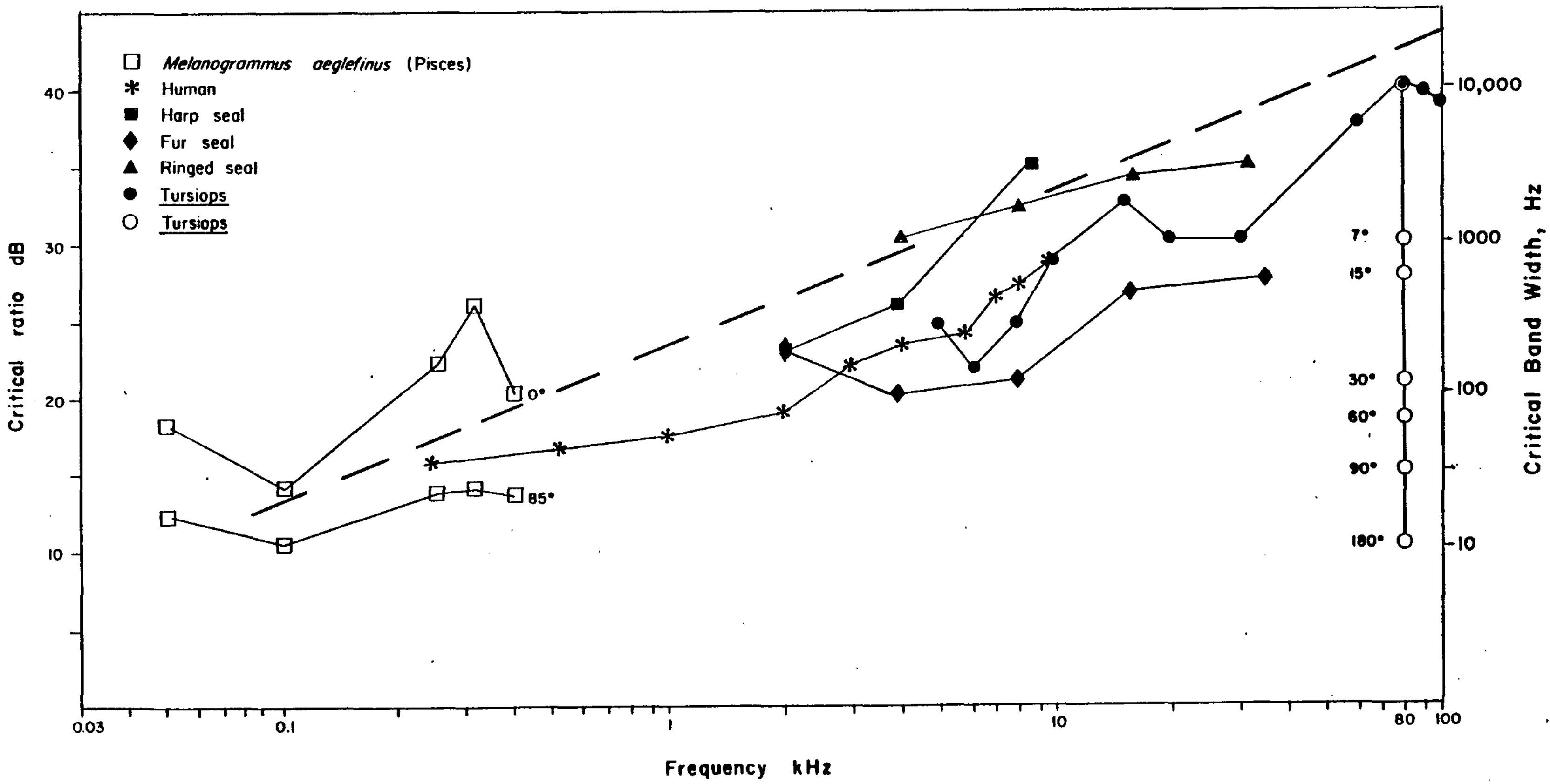


FIGURE 9. CRITICAL RATIOS AND ASSOCIATED CRITICAL BANDWIDTHS OF SEVERAL MARINE MAMMALS, MAN, AND HADDOCK. DASHED LINE REPRESENTS 1/3 OCTAVE. CRITICAL RATIOS FOR THE BOTTLENOSE DOLPHIN (Tursiops) AND HADDOCK ARE KNOWN TO DEPEND ON THE ANGULAR SEPARATION BETWEEN SIGNAL AND NOISE SOURCES (SEE OPEN SYMBOLS). SOURCES ARE CHAPMAN (1973) FOR HADDOCK, HAWKINS AND STEVENS (1950) FOR HUMAN, TERHUNE AND RONALD (1971) FOR HARP SEAL, MOORE AND SCHUSTERMAN (1987) 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).

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, because of the complex interactions of the sound with the bottom and surface. On the other hand, the large size of 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 assumed that baleen whales do not 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 in deep water 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. (As will be discussed later, the zone of audibility of low frequency sounds is expected to be much smaller in shallow water, such as that near drillsites on continental shelves.)

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. If their hearing abilities are limited by ambient noise rather than auditory sensitivity, as is expected, then the zone of audibility is not expected to differ appreciably among species of 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. Before this project there had been no specific estimates of the zone of audibility around oil industry sites in the Beaufort Sea, although several studies had provided measurements of received sound levels at various distances from such sites.

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 more-or-less continuous underwater sounds from industry have been studied intensively in recent years. Richardson and Malme (1986)--Appendix B in Miles et al. (1986)--summarized the data concerning reactions of bowhead and gray whales to drilling and island construction sounds. To assist in interpreting the bowhead data, that report also included previously unreported industrial 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, 1986). 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 previously-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, numerous bowheads have been seen to engage in seemingly-normal activities within several kilometers of drillships or dredges, where the broadband industrial noise level was up to 114 dB re 1 μPa, or 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 105 dB re 1 μPa, or 29 dB above average ambient (Table 4C,G). A few individual bowheads have been seen by biologists at locations with even higher noise levels--on a broadband basis, 127 dB re 1 μPa or about 29 dB S:N, and on a 1/3-octave basis 117 dB or 41 dB S:N (Table 4B,D,F; Fig. 10,11--data from Richardson et al. 1985b,c). Details about the occurrence of bowheads in these situations were reviewed by Richardson and Malme (1986).

Noise playback experiments have also indicated that some bowheads show no detectable reaction to broadband noise up to at least 20 dB above ambient levels (Table 5A). 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 (Table 5B,C; Fig. 10). Again, corresponding figures for the 1/3-octave band of maximum noise were higher--some bowheads avoided at S:N levels as low as 16 dB, whereas others showed no detectable reaction at S:N levels as high as 38 dB (Table 5; Fig. 11).

---

*The noise projected into the water during the drillship playback experiments was recorded by Greene (1985, 1987) 0.2 km from drillship EXPLORER II in 1981, and undoubtedly was dominated by sound from the drillship per se. This drillship recording was used for both LGL's playbacks near bowheads and BBN's playbacks near gray whales. The noise projected during LGL's 'dredge' playback experiments near bowheads was recorded 1.2 km from the suction dredge BEAVER MACKENZIE in 1980. This recording included composite sounds from the dredge and support vessels. LGL's playbacks all consisted of a 10-13 min period when sound level was increased gradually (to avoid a sudden onset of sound at peak level), a 10-20 min period at peak level, and a 10 min period of gradually decreasing level.

Table 4. Estimated noise levels (dB re 1 μPa) at locations where bowhead whales have been seen near drillships and dredges.***

		20-1000 Hz (dB)			1/3-Oct. Band (dB)*		
	Range (km)	Rcvd Lev.	Avg. Amb.	Approx. S:N	Rcvd Lev.	Avg. Amb.	Approx. S:N
EXPLORER drillships							
A. Closest ind. rep.**	0.2	135	98	37	132	78	54
B. Closest biol. "	4	118	"	20	112	"	34
C. Whales numerous at	13	104	"	6	93	"	15
KULLUK Conical Drilling Unit							
D. Closest biol. rep.**	10	117	98	19	104	74	30
BEAVER MACKENZIE suction dredge							
E. Closest ind. rep.**	0.1	137	98	39	127	76	51
F. Closest biol. "	0.8	127	"	29	117	"	41
G. Whales numerous at	5	114	"	16	105	"	29

*1/3-octave band with maximum signal-to-noise ratio; band centered at 250 Hz for EXPLORER, 630 Hz for KULLUK, and 400 Hz for BEAVER MACKENZIE.

**Closest reports by industry personnel and by biologists are shown.

***Received levels are based on equations fitted to Greene's (1987) measurements of received level vs. range from these three sources (see Richardson and Malme 1986, p 231, for equations). The "Approximate Signal-to-Noise Ratio" column assumes that ambient noise was near average (as determined by Greene 1987) when the whales were seen; actual ambient noise levels could not be measured in these situations because of the presence of stronger industrial noise.

Table 5. Noise levels and signal-to-noise ratios during playbacks of drillship and dredge noise near bowhead whales (based on Richardson et al. 1985c and unpublished data). These same data are shown graphically in Figure 10 (broadband) and Figure 11 (1/3-octave band). Source level, ambient level, and received level at sonobuoy were measured; received levels at other ranges were estimated, as were the ranges from the actual drillship or dredge at which these levels would be received (see Richardson and Malme 1986 for details). All levels are in dB re 1 μPa.

			20-1000 Hz Band				Max 1/3-Octave Band*			
	Source Level (dB)	Range (km)	Amb-ient (dB)	Rcvd Lev.; Peak Plbk (dB)	S:N, Plbk: Amb. (dB)	Equiv Range From Ship (km)	Amb-ient (dB)	Rcvd Lev., Peak Plbk (dB)	S:N, Plbk: Amb. (dB)	Equiv Range From Ship (km)
A. Drillship Playbacks--No Avoidance										
18 Aug 82	164									
Sonobuoy		2	97	110	13	9.0	79	108	29	5.7
Closest Bhd		3	"	107	10	11	"	105	26	7.0
Farthest Bhd		6.5	"	100	3	16	"	96	17	11
22 Aug 83	164									
Sonobuoy		1.2	93	113	20	7.1	75	111	36	4.5
Closest Bhd		.8	"	115	22	5.8	"	113	38	3.8
Farthest Bhd		1.8	"	111	18	8.4	"	108	33	5.7
B. Drillship Playbacks--Avoidance Observed										
16 Aug 82	155									
Sonobuoy		2	84	100	16	16	71	95	24	12
Closest Bhd		2	"	100	16	16	"	95	24	12
Farthest Bhd		4.5	"	94	10	21	"	87	16	16
18 Aug 83	164									
Sonobuoy		1.2	78	112	34	7.7	68	111	43	4.5
Closest Bhd		.4	"	118	40	4.2	"	117	49	2.5
Farthest Bhd		1.7	"	110	32	9.0	"	109	41	5.3
C. Dredge Playbacks--Avoidance Observed										
16 Aug 84	161									
Sonobuoy		1	102	118	16	3.3	81	110	29	2.8
Closest Bhd		.15	"	127	25	0.8	"	119	38	.6
Farthest Bhd		2.25	"	113	11	5.5	"	105	24	5.2
24 Aug 84	161									
Sonobuoy		.4	101	125	24	1.2	83	117	34	.8
Closest Bhd		.1	"	131	30	.4	"	123	40	.24
Farthest Bhd		.8	"	122	21	1.9	"	114	31	1.5

*1/3-octave band in which the S:N ratio was highest; centered at 250 Hz for drillship sounds, and at 400 Hz for dredge sounds.

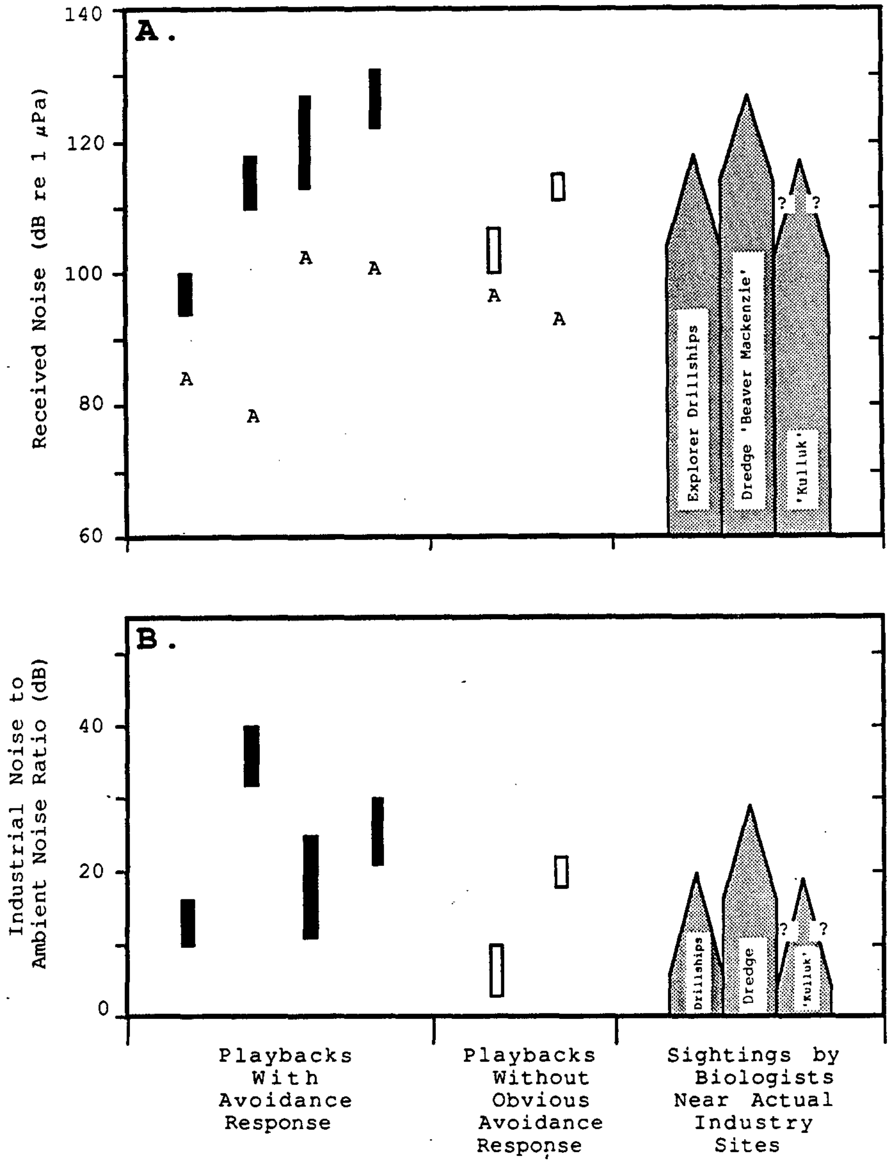


FIG. 10. SCHEMATIC SUMMARY OF BROADBAND (20-1000 HZ) NOISE DATA USED TO DEFINE THRESHOLD OF RESPONSIVENESS CRITERIA FOR BOWHEAD WHALES. A SHOWS ACTUAL RECEIVED AND AMBIENT NOISE LEVELS; B SHOWS INDUSTRIAL NOISE TO AMBIENT NOISE RATIOS. ALL DATA ARE FROM TABLES 4 AND 5. VERTICAL BARS AT LEFT AND CENTER SHOW RANGES OF NOISE LEVELS AT THE LOCATIONS OF ALL BOWHEADS OBSERVED DURING THE SIX PLAYBACK EXPERIMENTS WHEN NOISE LEVELS WERE MEASURED. THE TOP AND BOTTOM OF A BAR REPRESENT THE INDUSTRIAL NOISE LEVELS FOR THE CLOSEST AND MOST DISTANT WHALES UNDER OBSERVATION. EACH "A" SHOWS THE AMBIENT NOISE LEVEL CORRESPONDING WITH THE ABOVE BAR. SHADED BARS AT RIGHT SHOW, FOR THREE ACTUAL INDUSTRIAL SOURCES, THE ESTIMATED INDUSTRIAL NOISE LEVELS NEAR THE CLOSEST WHALES EVER SEEN BY BIOLOGISTS (PEAK OF BAR) AND AT THE DISTANCES WHERE WHALES WERE NUMEROUS (BROAD PART OF BAR).

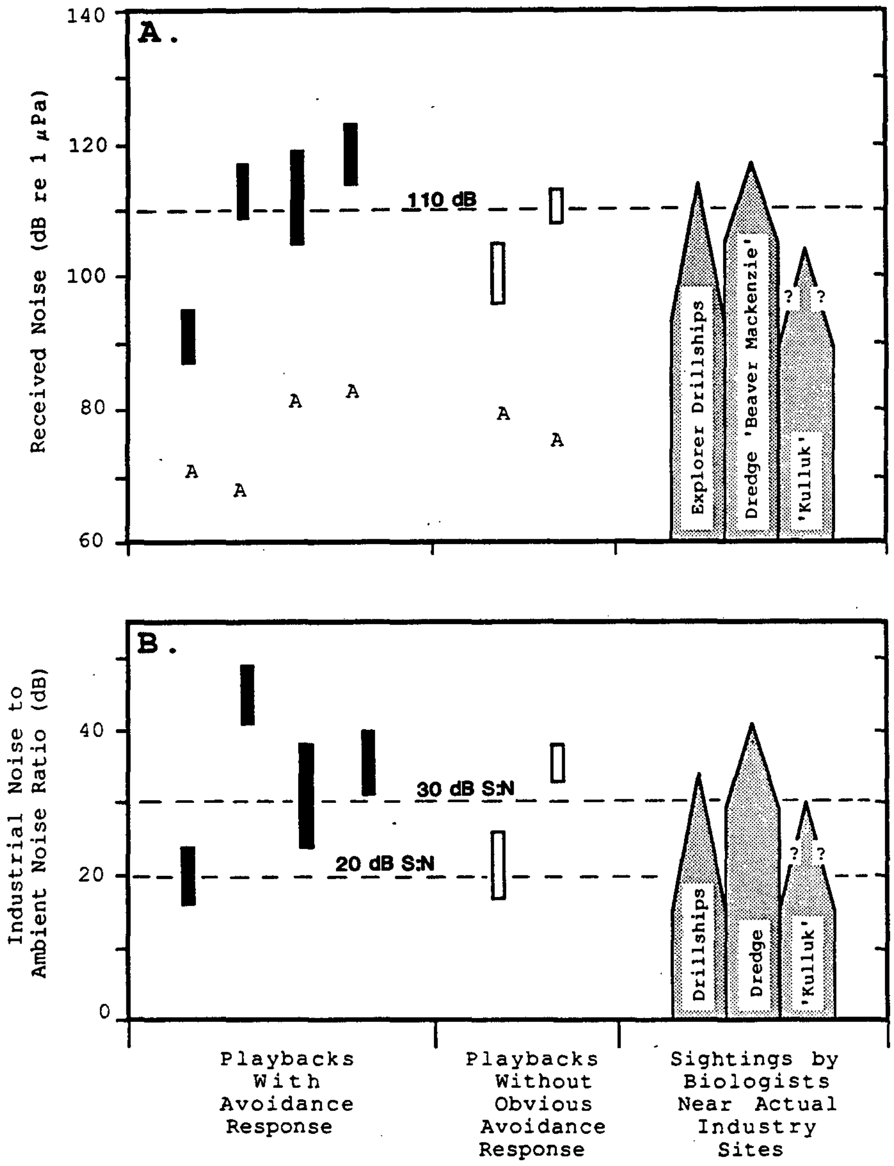


FIG. 11. SCHEMATIC SUMMARY OF 1/3-OCTAVE BAND NOISE DATA USED TO DEFINE THRESHOLD OF RESPONSIVENESS CRITERIA FOR BOWHEAD WHALES. DATA ARE FOR THE 1/3-OCTAVE BAND WITH MAXIMUM SIGNAL-TO-NOISE RATIO; OTHERWISE AS IN FIG. 10.

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.

Based primarily on the drillship and dredge noise playback data in Table 5, but supplemented by the observations of bowheads near actual industrial sites (Fig. 11; Table 4), we estimate that roughly half of the bowheads react by moving away when the received level of continuous industrial noise is 110 dB in the 1/3-octave band of maximum signal-to-noise ratio, or when the S:N ratio in that band is about 30 dB. These thresholds are based on a subjective evaluation of the data summarized in Figure 11, and are consistent with other corroborative evidence. Figure 11 shows clearly that these assumed thresholds of responsiveness are imprecise. Some individual bowheads react at considerably lower received levels or S:N ratios (e.g., 20 dB S:N), whereas others do not react unless the values considerably exceed 110 dB or 30 dB S:N.

The actual threshold for a given whale at a given time no doubt depends on the activity of the whale (e.g., resting, feeding, socializing, migrating), its situation (e.g., in shallow vs. deep water), and the nature of the sound source. These types of variations in sensitivity of bowheads to noise have been identified and discussed by Richardson et al. (1985b,c). Such variations in sensitivity are presumably responsible for the broad overlap between sound levels that can be tolerated vs. sound levels that can cause avoidance.

A rapidly approaching boat is probably perceived by bowheads as a greater threat than is the continuous noise from a distant stationary site. Hence, reactions to approaching boats would be expected to begin at lower noise levels or S:N ratios. Boats have been identified as the industrial activities that cause the strongest and most consistent responses by bowheads (Richardson et al. 1985b,c). The thresholds of responsiveness estimated from the playback experiments and opportunistic observations of bowheads near stationary sites (summarized in Tables 4-5 and Fig. 10-11) probably do not apply to rapidly approaching boats, although they may apply to the more consistent sounds from distant boats or from boats moving tangentially (see Section 3.5 for further discussion).

In the case of migrating and summering gray whales, more precise data are available concerning probability of avoidance as a function of received noise level (Malme et al. 1983, 1984, 1986a; see Richardson and Malme 1986). Observations for summering gray whales in the Bering Sea and generally consistent with those for migrating gray whales off California in indicating that 0.1 and 0.5 probability of avoidance would occur for received broadband industrial noise levels of 110 and 120 dB re 1 μPa, respectively (Figure 12). These values correspond to industrial : ambient noise ratios of about 20 to 30 dB, respectively, based on the median ambient noise levels expected in the Beaufort Sea in late summer (see Section 3.1).

To translate the above assumptions concerning response thresholds 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

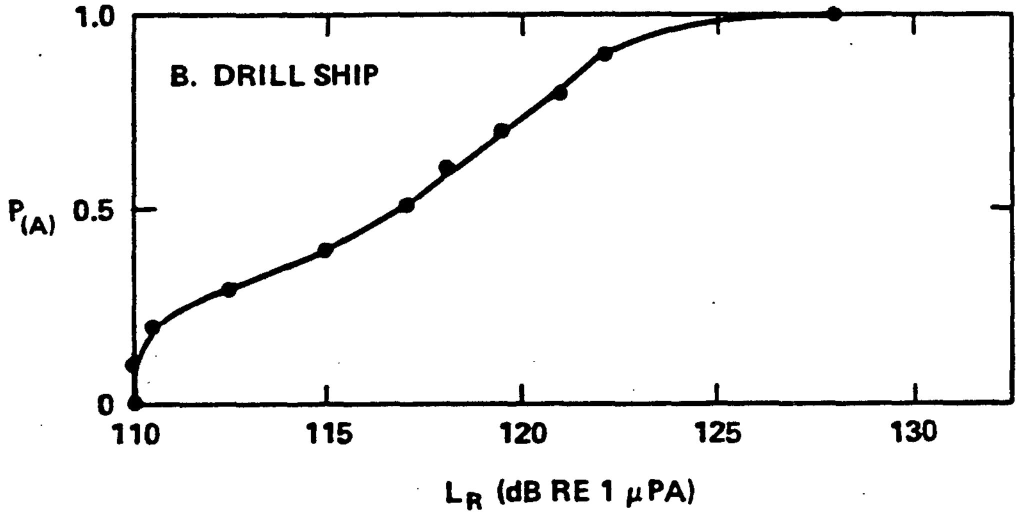


FIG. 12. PROBABILITY OF AVOIDANCE (P_a) OF MIGRATING GRAY WHALES TO SPECIFIC RECEIVED LEVELS (L_R) OF CONTINUOUS DRILLSHIP NOISE. DATA BASED ON OBSERVATIONS OF WHALE RESPONSE TO PLAYBACK SOURCE (MALME ET AL. 1984).* OBSERVATIONS OF RESPONSE OF SUMMERING GRAY WHALES TO THE SAME SOURCE SHOWED SIMILAR AVOIDANCE PROBABILITIES BUT LOW SAMPLE SIZES PREVENTED DETAILED CALCULATIONS (MALME ET AL. 1986a).

---

*Playback recording was made by Greene (1985, 1987) 0.2 km from drillship EXPLORER II in 1981. Playback periods consisted of 1-2 min. ramp-up period, a 60-90 min constant level period, and a 1-2 min ramp-down period.

necessary. The present project was designed to provide the necessary data, and to use those data to derive estimates of the zones of responsiveness.

Zone of Masking. -- 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 this 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). Source levels of bowhead calls are quite variable (Cummings and Holliday 1985, 1987; Clark et al. 1986)*, so it is possible that bowheads produce more intense calls when background noise levels are high. 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, 1987), 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

---

*However, some of the apparent variability in source levels may be an artifact of the transmission loss rates assumed in these studies, which appear to be oversimplified.

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 (see Richardson and Malme 1986). 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 close to industrial sites, 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. Some information about each of these factors is now available. The "Results" section of this report (Section 3.4.6) contains preliminary estimates of the "zone of masking" for representative industrial activities and one representative site (Corona) in the Alaskan Beaufort Sea.

2.3.2 Methods of estimating zones of influence

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.

To estimate the zone of audibility, 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. 13).

To estimate the zone of responsiveness, we had to allow for the fact that most whales apparently react to industrial sounds only if they are considerably stronger than the minimum audible level (see Table 5, Fig. 10, 11). Hence, we also aimed to estimate the radii at which industrial sounds would attenuate to an absolute level of 110 dB (and various other levels), or to 20 dB above ambient, 30 dB above ambient, etc. (Fig. 14).

2.3.2.1 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, six sources were selected for detailed "zone of responsiveness" as well as "zone of audibility" analyses:

1. Tug ARCTIC FOX underway near Erik site in 1985.
2. Pair of tugs forcing a barge against Sandpiper artificial island in 1985.
3. Icebreaker CANMAR KIGORIAK underway at 10 kt (18.5 km/h) near Corona, 10 Sept 1986; KIGORIAK was one of the support ships for the drillship operation at Corona. KIGORIAK was the most powerful ship (16,800 b.h.p.) whose sounds were studied.

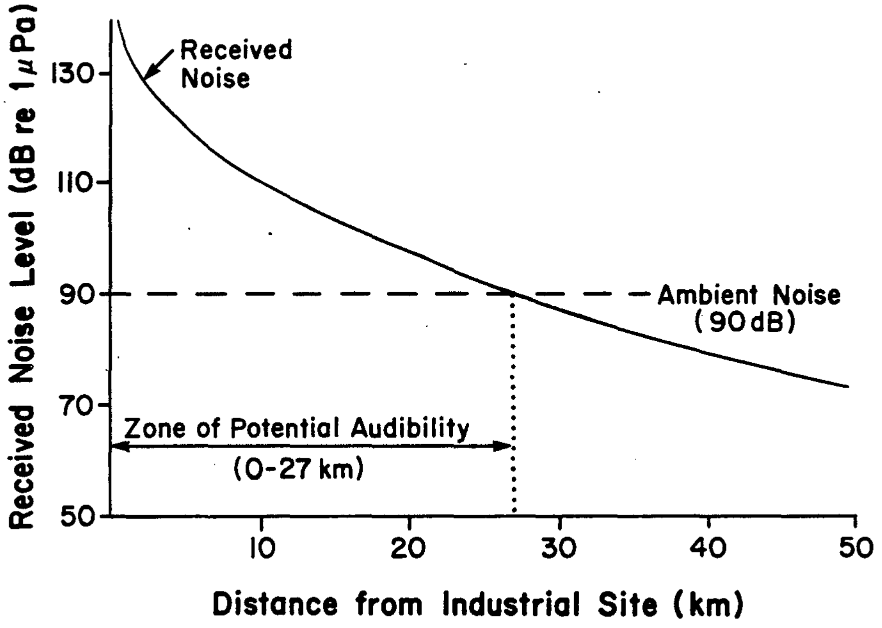


FIG. 13. PROCEDURE FOR ESTIMATING ZONE OF AUDIBILITY FROM INTERSECTION OF RECEIVED LEVEL VS. RANGE CURVE WITH AMBIENT NOISE LEVEL. DATA ARE ARTIFICIAL.

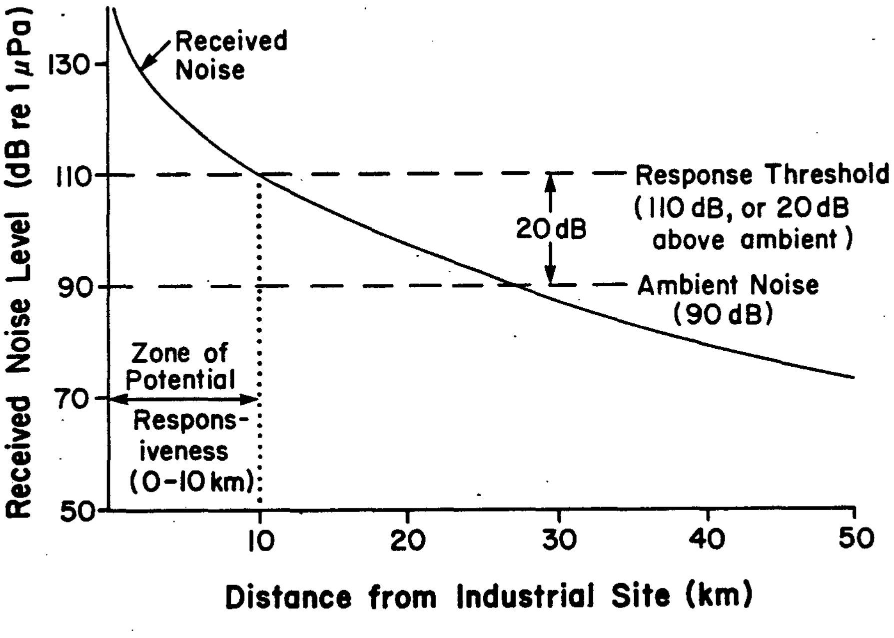


FIG. 14. PROCEDURE FOR ESTIMATING ZONE OF RESPONSIVENESS FROM INTERSECTION OF RECEIVED LEVEL VS. RANGE CURVE WITH RESPONSE THRESHOLD. THE RESPONSE THRESHOLD COULD BE EITHER AN ABSOLUTE NOISE LEVEL (110 dB IN THIS CASE), OR A "SIGNAL : AMBIENT" RATIO (20 dB IN THIS CASE). DATA ARE ARTIFICIAL.

4. Icebreaker ROBERT LEMEUR (9600 b.h.p.) underway at 10 kt (18.5 km/h) near Erik, 18 Aug 1986. LEMEUR was another of the support ships for drilling at Corona.
5. Drilling by EXPLORER II drillship at Corona drillsite in 1986.
6. Drilling at Sandpiper artificial island in 1985 (recorded by Greeneridge Sciences Inc.--Johnson et al. 1986).

Each of these six industrial activities produced more-or-less continuous noise.

The circumstances when these six sets of recordings were made are described in section 3.2. For each of these six 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 six 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 five 1/3-octave bands, not just the one band with maximum signal-to-noise ratio. We did this because propagation losses depend on frequency. The band with highest source level (or highest signal-to-noise ratio at the source) was sometimes one where propagation losses were high. In these cases, another band with slightly lower source level (or source S:N) resulted in higher received levels (or received S:N) because of a lower rate of propagation loss.

Three additional sources of intermittent (variable) sounds are examined in less detail. It is not certain whether the "threshold of responsiveness" criteria derived above are applicable to sounds whose levels or characteristics vary rapidly over time. The three intermittent sources that we considered were as follows:

1. Dredge bucket being hauled up, as recorded at Erik site in 1985. This operation produced stronger sounds than other phases of the dredging cycle at Erik.
2. Tug ARCTIC FOX towing a loaded barge away from Erik site in 1985. This was for a 5 minute run to the dump site. The strongest sounds emitted during any phase of the Erik tugboat/barge operation were recorded at this time, which was short-term with respect to other activities at the site.
3. Icebreaker ROBERT LEMEUR pushing ice near Corona, 4 Sept 1986. This operation produced the strongest sounds (other than seismic pulses) recorded during this study.

Section 3.2 includes information about the peak source levels and spectral characteristics of the sounds from these three intermittent sources, and Section 3.4.2 estimates the zone of audibility around each of them at times of peak sound output. Section 3.6 provides a brief discussion of the possible size of the zone of responsiveness around each of these intermittent sources.

2.3.2.2 Zone of audibility

The six sites studied in 1985, 1986 or both were considered in the zone of audibility analyses; they are Orion, Sandpiper, Hammerhead, Corona, Erik and Belcher. Their locations and descriptions were provided in Figure 1 and Table 1.

For each of these six sites, received levels at various distances were estimated assuming that, in turn, each of the 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 various 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 type of industrial operation listed above might occur at each of the six sites is not 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 have not drilled in water as shallow as that at Sandpiper or Orion. 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. 13). 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, Corona, Erik and Belcher. Insufficient data on ambient noise were collected during this study 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 D). 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. 15). However, the values tabulated in the Results section and Appendix D were actually determined mathematically and printed out by the computer program used to perform the model calculations (see sample printout in Fig. 15).

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 (Davis et al. 1985; Johnson et al. 1986; Ljungblad et al. 1986b, 1987). Consequently, for these sites, we made 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

```
WESTON SHALLOW-WAT. SOUND PROP'N MODEL                          Run date=870602
LGL version for Apple II, including absorption term; Vers. 1.5, 25 May 87

Site = CORONA                           Source type = LEMEUR.ICEBR

SOURCE LEV (DB)         183             LOCAL ANOMALY (DB)      2
FREQUENCY (HZ)          100             WAT.DEP @ SOURCE (M)    35
BOTTOM SLOPE (-1 TO 1) 0                SINE (CRIT.ANG.), 0-1   .2
BOTTOM REFL. 'B', 0-5   .3              SOUND SPEED (M/S)       1435


Max R for sph.spr. = .07 km             Max R for cyl.spr. = 4.5 km
Max R for multimode= 5.5 km
Max believable R    = 51.5 km           Max R with Data     = 30 km

Ranges where RL = various standard levels:
RL= 75    R= -9         RL= 80    R= 49.3       RL= 85    R= 43.6       RL= 90    R= 38
RL= 95    R= 32.5       RL= 100   R= 27.1       RL= 105   R= 22         RL= 110   R= 17
RL= 115   R= 12.4       RL= 120   R= 8.3        RL= 125   R= 5.4        RL= 130   R= 3.6
RL= 135   R= 1.1        RL= 140   R= .365       RL= 145   R= .119       RL= 150   R= .057

Ranges where RL = 5%, 50%, 95%ile of ambient:
5% (68 dB):  R= -9       50% (88 dB):  R= 40.2     95% (98 dB):  R= 29.3

Ranges where RL = median ambient +5 dB, +10 dB, etc.:
Med+5 :  R= 34.7      Med+10:  R= 29.3      Med+15:  R= 24        Med+20:  R= 19
Med+25:  R= 14.2      Med+30:  R= 9.9       Med+35:  R= 6.1       Med+40:  R= 4.6
```

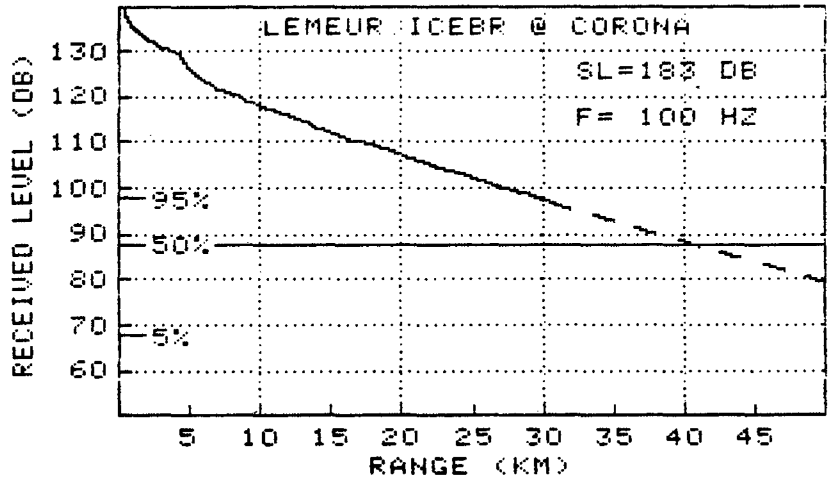


FIG. 15. SAMPLE RESULTS FROM WESTON/SMITH SHALLOW-WATER SOUND PROPAGATION MODEL APPLIED FOR PURPOSES OF ESTIMATING ZONES OF NOISE INFLUENCE AROUND A SPECIFIC INDUSTRIAL SITE. R = Range in kilometers; RL = Received level in dB re 1 µPa; SL = Source Level in dB re 1 µPa at 1m range; F = Frequency in Hz. "-9" means "not calculable--beyond range of model."

in question. The other four sites are within the autumn migration corridor of bowheads (Appendix A), and whales could travel westward either south or north of these sites. Hence, three estimates of the zone of audibility were made for those sites, assuming decreasing, constant, and increasing water depth with increasing range.

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.

2.3.2.3 Zone of responsiveness*

In this analysis, the "zone of responsiveness" is considered to be the area around an industrial site within which a significant fraction of the whales are expected to exhibit overt avoidance responses, to noise from that site. Based on field studies, responsiveness variables for bowhead whales included avoidance, changes in swimming heading, dive time, etc., while gray whale responsiveness experiments concentrated on measurement of avoidance. The industrial noise level at which whales exhibit a specific behavioral response, such as avoidance, can be specified as a level above the natural ambient (S:N ratio) or as an absolute received level (RL). The literature on animal responses to man-made noise is very sparse, and does not provide guidance on which of these two measures best represents observed reactions. Fortunately, the literature on human responses to industrial noise is much more extensive. Studies of human

---

*By W.J. Richardson, LGL Ltd., and C.I. Malme, BBN Laboratories Incorporated.

annoyance caused by sources such as traffic noise and aircraft flyover noise, as discussed by Kryter (1985), may be helpful in identifying the most appropriate threshold criteria for the avoidance reaction in whales.

In general, annoyance reactions in humans correlate better with the absolute level of the intruding noise than with the maximum S:N ratio (Robinson et al. 1963). However, when the background noise level is not much less than the received level of the intruding noise, the threshold of annoyance is shifted upward (Spieth 1956; Pearsons 1966) and the S:N ratio is the more relevant parameter. As a result, the usual practice in determining annoyance criteria for specific types of noise involves using psychoacoustic testing procedures to measure the sound levels that produce a quantifiable level of annoyance. Correction factors based on the prevailing background noise levels in specific locations may then be applied (Kryter 1985).

The "zone of responsiveness" criteria considered in this report include both the S:N ratio approach and the absolute received level approach. The available data for bowhead whales do not allow us to determine whether behavioral responses are better correlated with one or the other of the two possible measures of acoustic exposure. (The available database is too small and the observed values of S:N and RL are too closely correlated to allow a clear distinction between criteria.) The present report estimates the zone of noise influence based on both the S:N and absolute RL criteria for both bowhead and gray whales.

Data from recent studies of the behavioral reactions of bowhead and gray whales to industrial noise were summarized by Richardson and Malme (1986) and, briefly, in Tables 4 and 5 and Figures 10 and 11, above. These data were used to estimate the industrial noise levels and industrial : ambient noise ratios at which the two species do and do not react. There is no one threshold value of RL or S:N above which all whales react and below which none react. That is, there is a gradation of responsiveness for a given received level or signal-to-noise ratio. Instead, above some minimum industrial noise level, the probability of reaction increases with increasing noise level, at least in the case of migrating gray whales (Figure 12; Malme et al. 1983, 1984).

In the case of bowheads, few if any individuals appear to react overtly to near-continuous industrial noise levels less than 15 dB above the natural ambient level. Some individuals apparently tolerate much higher levels (see Tables 4, 5). However, a minority of the bowheads move away in response to the gradual onset (over 10-13 min) of drillship or dredge noise whose peak level is 20 dB or more above ambient. Roughly half of the bowheads move away in response to sounds with signal to noise ratio 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: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 (Fig. 11). As a first approximation, the median zone of responsiveness of bowhead whales to near-continuous industrial noise has been defined as the area where the received noise level is 30 dB or more above ambient. However, some individual bowheads respond at lower S:N ratios (i.e., greater ranges), and others apparently do not respond overtly unless S:N is more than 30 dB (i.e., closer ranges). Table 6 summarizes the assumptions associated with these response threshold criteria for bowheads.

As a first approximation, the zone of responsiveness of gray whales to near-continuous noise sources, similar to that of bowheads, is considered to be the area where the received noise level is 20 dB or more above ambient (see Section 2.3.1 and Table 6).

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 noise level would exceed 110 dB, which is another possible criterion of responsiveness. Separate calculations were done for each combination of industrial sources, six sites, and 2 or 3 bottom slopes per site, considering the 1/3-octave bands that had high source levels (Appendix D).

2.3.2.4 Alternative criteria and alternative industrial sources*

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. Responsiveness may depend on the type of noise and not just its level; whether the noise is constant, increasing, decreasing or fluctuating in intensity; on the activity of the whales, e.g., migrating, feeding, socializing or resting; and on the location, e.g., shallow vs. deep. Future studies are likely to 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

---

*By W.J. Richardson, LGL Ltd.

Table 6. Assumptions underlying response threshold criteria used for bowhead and gray whales.

NOTE: A basic general assumption used in this study is that whales respond to low frequency sound intensity above a given level.

A. BOWHEAD WHALES

Bowheads Near Actual Oil Industry Sites

1. It is assumed that bowhead whales rarely approach closer to industrial sites than the distances of closest approach observed by biologists during several seasons of work in the Canadian Beaufort Sea (Table 4, from Richardson and Malme 1986).

2. Received sound levels at the times and locations of those close sightings are assumed to be similar to those measured by Greene (1985, 1987) at corresponding distances from the same industrial activities.

3. Ambient noise levels at the times and locations of those close sightings, which were not measurable due to masking by industrial noise, are assumed to be similar to the average ambient levels recorded by Greene (1987).

4. Some bowheads are expected to exhibit avoidance reactions at greater distances, i.e. at lower received noise levels, than those associated with the closest whales.

Playback Experiments

5. Reactions of bowheads to a given level of industrial noise are assumed to be similar for whales exposed to (a) continuous noise from actual industrial operations vs. (b) the same received level of noise during LGL's short-term playbacks of drillship and dredge noise.

Other Assumptions

6. It is assumed, based on strong evidence (Richardson et al. 1985b,c; Richardson and Malme 1986), that bowhead whales do not necessarily react to any industrial sound that they can hear; the received level of the industrial sound must exceed some threshold of responsiveness before bowheads will react.

7. Thresholds of responsiveness are known to vary from time to time and whale to whale, probably depending on factors such as whale activity, water depth, nature of sound source, and variability in sound. The best that can be achieved with present evidence is to define noise thresholds at which roughly half of the bowheads would be expected to exhibit avoidance responses. The thresholds are statistical phenomena; in any single incident, all individual bowheads may react to the threshold sound level, or none may do so.

Table 6. (Cont). **Assumptions underlying response thresold criteria used for bowhead whales.**

8. Reactions to a given received level of continuous industrial noise are, to a first approximation, assumed to be similar regardless of the type of noise source. (This phenomenon has been demonstrated in gray whales by Malme et al. 1983, 1984.) Thus, criteria of responsiveness based on observations of bowhead reactions to noise from one drillship or dredge are assumed to be applicable to other sources of continuous noise.

9. As a specific case of assumption (8), bowhead sensitivity to more-or-less steady received noise levels from distant ships is assumed to be similar to sensitivity to drillship and dredge noise. However, sensitivity to increasing noise levels from approaching ships is not assumed to be the same as that to steady noise levels.

10. Present evidence is inadequate to show whether the thresholds of responsiveness derived for more-or-less continuous noise sources are applicable to "intermittent" sources whose source levels vary over time.

11. Present evidence is inadequate to show whether the most appropriate criterion of responsiveness is an absolute noise level or a signal-to-noise ratio (i.e. industrial noise to background ambient noise ratio). Consequently, both approaches are examined in this study.

B. GRAY WHALES

1. Assumptions 5 through 11 given above for bowhead whales are also relevant for gray whales.

2. No data are available from observations of gray whale response to industrial noise in the Beaufort Sea. It is necessary to assume that exposure level response criteria obtained from studies made elsewhere (Malme et al. 1983, 1984,, 1986a) are applicable in the acoustic environment of the Alaskan Beaufort coast.

besides 20, 30 and 40 dB (e.g., Fig. 15). 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. 15). All of these figures are tabulated in Appendix D but some are not considered in the Results.

The six industrial activities considered in detail in the "zone of responsiveness" section of this report (Section 3.4.3) do not include all possible industrial activities that could occur near drillsites in the Alaskan Beaufort Sea. Appendix E was prepared by LGL to allow readers to look up the expected zone of influence for other sources of continuous industrial noise. To look up the expected zone of influence of such an industrial activity, it is necessary to know the source level of its sounds in the dominant 1/3-octave band. Appendix E contains tables for each of the six sites considered in this report. For various combinations of frequency and source level, the expected zone of audibility under median ambient noise conditions was calculated and tabulated, as was the expected zone of response based on each of the S:N and RL criteria considered in the report. BBN's Weston/Smith propagation models for each site were used by LGL in order to derive these tables. Appendix E contains lookup tables for the "zero bottom slope" case, i.e., for east-west propagation along the isobaths. Similar tables for southward and northward propagation are available from LGL Ltd. on request.

As noted earlier, the threshold of responsiveness criteria developed above refer primarily to near-continuous industrial noise. It is not known whether the same criteria are applicable to <u>transient</u> sources such as an approaching boat, or to intermittent sources such as an icebreaker alternately pushing ice and then backing away. Therefore, our detailed zone of responsiveness estimates (Section 3.4.3) are restricted to sources of near-continuous noise. For transient sources such as an approaching boat, there is evidence that reactions may be more pronounced, and that the thresholds of responsiveness may be lower than for continuous sources (see Section 3.5). For intermittent sources, even if the criteria are generally applicable, it is not known whether the criteria should be applied to the maximum sound levels that are emitted at certain stages of the industrial operation, or to some type of average sound level; these questions are discussed in Section 3.6.

2.3.2.5 Zone of masking

The effect of industrial noise on communication range was estimated for whales near one site, Corona. The same methods would be applicable at other sites, but to simplify the presentation we have considered only east/west sound propagation near Corona.

The frequency and source level of whale calls affect the distance to which they can be detected. We considered whale calls near three frequencies: 100 Hz, 200 Hz and 600 Hz. Most bowhead calls are near 100-200 Hz, although "high" calls are typically near 600 Hz (Clark and Johnson 1984; Würsig et al. 1985). Source levels of bowhead calls have been reported to range from about 129 dB to 189 dB (Cummings and Holliday 1985, 1987) or from about 128 dB to 178 dB (Clark et al. 1986). We considered calls with levels 140, 150, ..., 190 dB.

The Weston/Smith sound propagation models derived for the Corona site were used to predict received levels of bowhead calls and of industrial noise in relation to source level, frequency and distance. The expected ambient noise level was taken into account, considering the 1/3-octave band centered at the frequency of the bowhead call. The results were used to evaluate the effect of distance from an industrial source on the radius of detectability of a bowhead call.

We assumed that a bowhead call will be detectable if its received level equals or exceeds both the ambient noise level and the received level of industrial noise. A whale call is assumed to be undetectable if its received level is less than either the ambient noise level or the received level of industrial noise. Ambient and industrial noise levels are based on the 1/3-octave band centered at the frequency of the whale call, on the assumption that the critical bandwidth for whale hearing is 1/3 octave (see Section 2.3.1).