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MMS 85-0076

OBSERVATIONS ON THE BEHAVIOR OF BOWHEAD WHALES (Balaena mysticetus) IN THE PRESENCE OF OPERATING SEISMIC EXPLORATION VESSELS IN THE ALASKAN BEAUFORT SEA

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INTRODUCTION

The potential effects of seismic survey activities on westward-migrating bowhead whales (Balaena mysticetus) in the Alaskan Beaufort Sea has been a concern of U.S. Minerals Management Service (MMS), and the U.S. National Marine Fisheries Service (NMFS). In response to this concern, the MMS with advice and assistance from NMFS has implemented a program to monitor and regulate seismic exploration in the Alaskan Beaufort Sea each fall since 1981 (Ljungblad et al. 1981). In 1982 and in 1983, a twin-turbine, high wing aircraft was used to systematically survey the Alaskan Beaufort Sea near actively "shooting" seismic vessels (Reeves et al. 1983, Ljungblad et al. 1984). Visual observations were supplemented with sonobouys to listen to and record underwater sounds made by vessels, their airguns, and bowhead whales. In addition, observations of presumed non-disturbed whales (in the absence of seismic sounds) were made on an opportunistic basis. This established a limited baseline of information which could be used to compare differences in behavior between whales exposed and whales not exposed to seismic sounds. Daily summaries of field observations were reported to the MMS and NMFS, and these were utilized to formulate decisions relating to the regulation of seismic activities.

In conjunction with the monitoring effort in 1983, a third aircraft and scientific team was tasked with conducting "controlled" field experiments designed by MMS to collect data on the responses of bowhead whales to the approach of active geophysical vessels. These experiments were to be conducted with the cooperation of seismic vessels operating in the Alaskan Beaufort Sea. However, due to the extremely severe ice conditions that prevailed in the fall of 1983, no experiments were completed.

In fall 1984, bowhead whale seismic response experiments were again undertaken and four experiments successfully completed by the Naval Ocean Systems Center (NOSC) with support provided by the MMS. These experiments were conducted under the provisions of Scientific Research Permit No. 459 issued to MMS by NMFS, and with the cooperation of geophysical vessels operating in the Alaskan Beaufort Sea. The findings of these experiments and comparison with similar studies are presented in this report.

OBJECTIVES

Experimental Design and Research Protocol

The central objectives of the seismic response experiments was to gauge bowhead whale behavioral response to seismic activities and to determine at what distance from an active geophysical vessel avoidance behaviors or other manifestations of disturbance were likely to be displayed by bowhead whales. Such information is vital in defining a "zone of influence" that presumably exists around an active geophysical vessel emitting low-frequency, high energy seismic sounds.

The specific objectives of this study were to:

1. quantify the distance at which bowhead whales display an avoidance or other conspicuous behavioral change with the approach of an active geophysical vessel, including qualitative and quantitative description of:

   a. time at surface, dive time, respiration (breathing) rate, rate of movement, direction of movement, sound production, and other relevant behavioral parameters prior to, during, and following approaches by active geophysical vessels toward bowhead whales,

   b. variables associated with the source of seismic sounds, such as vessel movement, location of the vessel from the whales, airgun array size and configuration, acoustic source level and frequency received near the whales, as well as environmental factors such as water depth, time of day, ice coverage sea state, and aircraft altitude,

   c. the degree of association between bowhead whale behavior and relevant independent variables (a and b above),

2. replicate experiments as possible and as judged advisable through daily analyses of new data,

3. provide daily information to government representatives as background for their decision making processes,

4. assess the biological significance of conspicuous behavior changes that appear correlated with seismic activity for individual whales and groups.

Objective 1 and its subordinate objectives (a-c) were motivated by the following generalized null hypothesis: "There is no change in bowhead whale behavior related to the distance between whales and a moving, fully operating (shooting) geophysical vessel." If the distance between a geophysical vessel and a whale or group of whales can be expressed as a progression of increasingly shorter increments, the following subordinate null hypotheses were to be tested. Changes in distance do not result in changes in bowhead whale:

a. qualitative behavior mode, i.e., traveling, milling, or socializing,
b. direction of movement,
c. rate of movement,
d. average length of surfacing,
e. average number of blows per surfacing,
f. average blow interval,
g. average length of dive,
h. average blow rate.

METHODS

The general approach for the behavioral seismic response experiments was to (1) place an aircraft and scientific team in the field to locate bowhead whales, and once whales were located, (2) observe and measure whale behavior, waterborne noise, and environmental variables, while at the same time (3) controlling, via radio communication, the approach and operation of the geophysical vessel selected for each of the experiments. Experimental data were subjected to a preliminary analysis in the field, and these findings along with initial interpretations of their significance were reported to the MMS and NMFS in Anchorage, Alaska, on a daily basis.

Aircraft Operation and Observation Procedures

The field conditions necessary for the initiation of a seismic response experiment constituted important limiting factors. Prerequisites to the initiation of an experiment included adequate visibility (little or no fog and a sea state of Beaufort No. 3 or less), and manageable numbers of bowhead whales in close proximity 9-18 km (5-10 nm) to geophysical vessels selected for each experiment. To minimize potential aircraft noise disturbance to the whlaes, the aircraft was required to fly at altitudes greater than 457 m (1,500 ft.) (Richardson et al. 1984) thus, necessitating cloud ceilings in excess of that altitude to conduct experiments. In addition, experiments would only be conducted within the limits of standard operation procedures and safety requirements of the vessels.

The aircraft and crew of six (pilot, co-pilot, data video recorder/acoustic engineer, and three scientific observers) were based at Deadhorse, Alaska, near Prudhoe Bay, from 15 August through 3 October. The survey aircraft was a de-Havilland Series 300 High Wing Twin Otter, N545N, capable of 9 hrs of continuous flight. The aircraft was equipped with bubble windows to enhance viewing, a radar altimeter for precise altitude determination, and a Global Navigation System 500A Series VLF computer (GNS) to provide continuous position updates. This system is accurate to $\pm$ 0.6 km (0.37 nm) per hour of flying. Crew members were linked to a common communication system to insure that all comments were heard and recorded onto the tape recording system (see below).

Flight data were stored on a portable computer interfaced to the aircraft's GNS. The computer was programmed to automatically input the following variables at 4 minute intervals: entry number, time (local and GMT), latitude, longitude, and altitude. Specific comments such as sightings, change in environmental conditions, etc. could be entered at any time during a flight. The computer was accessed to a serial plotter/printer to provide a hard-copy of all data stored in the computer's memory.

Sonobuoys were dropped to determine if geophysical vessels were actively shooting, and if active, to obtain measurements of received signal levels at known distances from the vessels. Bowhead whale sounds and other sounds were also received and recorded. The aircraft carried three types of sonobuoys: AN/SSQ-57A, AN/SSQ-41B, and AN/SSQ-41A. The latter was modified to eliminate low frequency overloading problems (Appendix A). Sonobuoys are designed to be dropped from the air and to transmit underwater sounds to th^ aircraft via VHF radio signals. Sound transmissions from the sonobuoys were received on a broadband receiver (Modified USQ-42) and recorded on a dual track Nagra IV-SJ reel-to-reel tape recorder and a cassette recorder. Three receivers were carried on the aircraft to permit the simultaneous monitoring of up to 3 sonobuoys. The entire system had a frequency response of 25 Hz to 10 KHz ± 1.5 dB at 9.5 cm/s. Waterborne sounds were heard on the crew's headsets at the same time they were recorded on one tape track. Both the sonobuoy transmission and verbal comments were recorded on the second tape track. Prior to field use, this system was calibrated using methods described in Appendix A. For analysis, least square logrithmic regression lines were fit to the seismic sound levels measured at known distances from their sources (the geophysical vessels), and the regression coefficients of these lines were then used to estimate the received sound levels at specific times and ranges from the whales' positions throughout each experiment.

Additional onboard equipment included 35 mm single-lens reflex cameras with 70-210 mm zoom lenses, ASA-200 color slide film, binoculars, clinometers, stopwatches, and a video recorder with 75 mm lens (6:1 zoom ratio). Video records proved to be a valuable backup for all observation records.

Coordination with Seismic Vessels

Arrangements were made in advance of the field season for the research team on board the aircraft to establish direct VHF radio and marine-band radio communications with the seismic vessels working in the Beaufort Sea. In addition, the research team communicated daily with the geophysical base camps of Western Geophysical Co. and Geophysical Service Inc. in Deadhorse. This close coordination between the aerial research team and the cooperating geophysical companies was designed to provide reasonable notice to vessel operators of when and where a seismic response experiment might be initiated. Both parties agreed to the following experimental protocol: whenever the necessary minimum field conditions for an experiment were met (see above), the operator of the vessel nearest the whales under observation was notified by the principal investigator and requested to operate the vessel as required to conduct an experiment under the conditions of Scientific Research Permit No. 459. Both the principal investigator and the vessel operators were required to log the time of any request to participate in an experiment and the time of its termination.

Experimental Design

The primary experimental procedure was to guide a dedicated vessel directly toward bowhead whales while the vessel was operating as if conducting full-scale seismic operations (Fig. 1A). A pre-exposure, exposure and post-exposure scenario was considered desirable, although it was understood that this ideal would not necessarily be achieved in every case. In some instances, for example, the sounds produced by a vessel participating in a given experiment were accompanied by sounds from other vessels operating in the same general area. In these cases, where no pre-exposure period was possible, observations made when

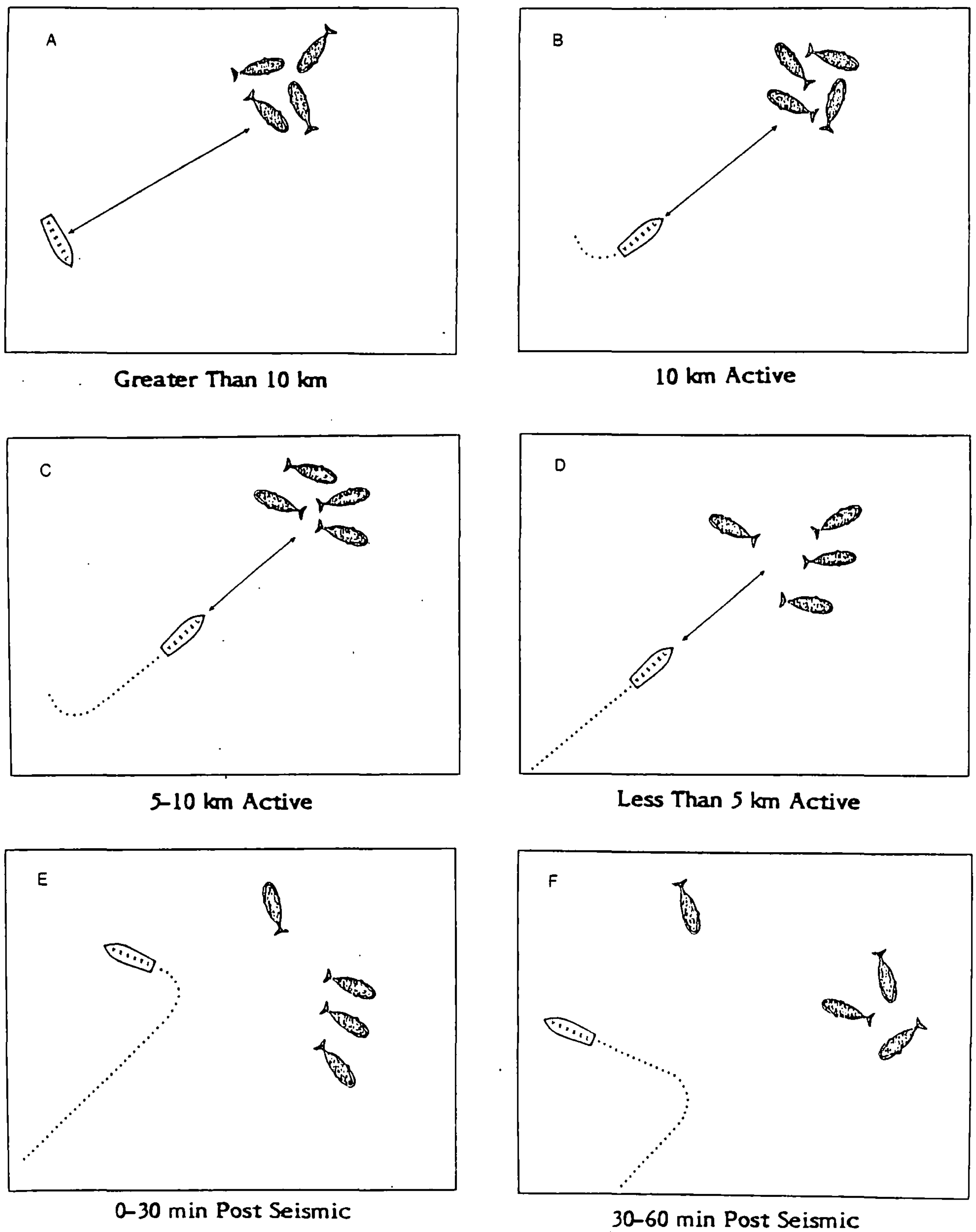

Figure 1. Experimental design for bowhead whale seismic response experiments.

the vessel was 10 km (5.4 nm) or more from the whales served as the pre-exposure sample. Distance categories used in the analysis of the active vessel's approach were, less than 5 km (2.7 nm), 5-10 km (2.7-5.4 nm), and greater than 10 km (5.4 nm) from the whales (Fig. 1B-D).

Post-exposure observations followed each "active" approach by a vessel, and consisted of two periods: 0-30 and 30-60 minutes after termination of seismic sounds (Fig. 1E-F). In one instance, a "no-stimulus" versus "stimulus" experiment was conducted when the geophysical vessel was initially inactive and at the request of the investigators became active when less than 10 km (5.4 nm) from the whales. Although less desirable, results from this type of experiment are useful because vessels do shut down and start up their airgun arrays during the course of normal seismic exploration activities.

When either the vessel had approached to within 1 km (0.54 nm) of the subject whales or, in the judgment of the investigators the whales were obviously responding adversely to the vessel, the principal investigator requested that the operator of the vessel shut down its airgun. The conditions of Scientific Research Permit No. 459 stipulated that seismic vessels were not to approach bowhead whales closer than 1 km (0.54 nm) during the initial experiments. Therefore, mid-course changes in vessel direction during an experiment were only to be made to ensure an approach of 1 km (0.54 nm) or greater. Additional changes in the vessel's course and its operations status were made only to avoid collisions with ice, and other hazards.

Behavioral Observations

Standard observation procedures were for one observer to be stationed in the co-pilot seat (right side of cockpit), and two or more observers stationed on each side of the aircraft during searches for whales. During experiments all members of the crew, as well as occasional guests onboard, maintained a continuous watch from the right side of the airplane.

Observations from the aircraft were conducted at an altitude of 457 m (1,500 ft.) or greater to minimize possible noise disturbance to the whales under observation. An airspeed of approximately 100 knots (204 km/hr) was maintained while searching and circling. When ice floes were present in an observation area they were used as reference points while the whales were submerged. When suitable natural reference points were not available, fluorescein dye markers and/or smoke flares (U.S.N. Model Mark 1 Mod 0) were dropped from the aircraft. Sonobuoys were also dropped to monitor underwater sounds as previously described.

Data collected for each sighting included the following categories:

1. local time (Alaska Daylight Time, ADT) and Greenwich Mean Time (GMT = ADT + 9 hrs),

2. location of sighting, water depth, distance from shore and distance from geophysical vessel,

3. estimated distance from ice and ice cover (when appropriate),

4. group size including the number of female-calf pairs,

5. distance between individual whales, estimated in whale-lengths,

6. orientations (relative to the position of the participating geophysical vessel) of each whale in degrees magnetic, which were converted to degrees true for analysis,

7. age category; non-calves (adults and subadults), probable mothers, and calves,

8. individually distinguishing features, if any, that could be used to re-identify a whale,

9. the time of first surfacing or first sighting, and individual behavior while at the surface,

10. duration of time at the surface and, for recognizable individuals, the duration of dives,

11. general behavior i.e., socializing (whales within one body length of each other), milling (which included skim-feeding, possible water-column feeding, bottom-feeding evidenced by mud plumes), and traveling,

12. speed of whales (if traveling), subjectively judged as slow, medium, or fast swimming,

13. number of blows per surfacing (exhalations), and thus the blow interval.

Analysis Procedure

Measures of surfacing, respiration, and dive characteristics were used to identify behavior changes associated with the presence or absence of seismic sounds as these characteristics may vary according to the nature of a whale's response to an adverse stimulus. Data were also gathered under presumed undisturbed conditions as a prerequisite for interpretation of behavior from potentially disturbed whales during exposure to seismic disturbance. We adopted the five major quantitative behavioral characteristics that have been used by Reeves et al. (1983), Richardson et al. (1984) and Würsig et al. (1984b) to describe the surface/dive profiles of bowhead whales. These are:

1. interval between blows (respiration),
2. number of blows per surfacing,
3. length of time at the surface (surface interval),
4. length of time below the surface (dive time), and
5. blow rate, the number of blows divided by the combined length of the surface interval and subsequent dive.

The first three of these behavioral characteristics may be ascertained while watching individual whales which do not have to be re-identified. Dive time, however, requires that a whale be recognized by some distinuguishing feature or features, i.e., unique white chin patches, distinctive scars, or other reliable marks on the head, back or tail. Since dive times required the identification of the same individual at the initiation of a dive and at the subsequent moment of surfacing, they were gathered less frequently. Similarly, blow rate is calculated from a complete surface and adjacent dive cycle, with the number of blows known during the surface interval; however, due to its dependence upon obtaining the time of surfacing, time of dive and adjacent surface time, blow rate is also infrequently obtained. The interval between blows, on the other hand, is the only characteristic which does not require observation of a full surfacing, consequently it was the most frequently collected datum.

Seismic sounds combined with associated vessel noise were the only potential sources of disturbance considered during the experiments described in this report. We utilized a twofold approach in assessing the responses of bowhead whales exposed to seismic sounds at close ranges.

First, the data from all experiments for adult (all non-calf whales including juveniles) were pooled and sorted into either "presumed-undisturbed" (no seismic sounds present) or "disturbed" (exposed to seismic sounds whose source was less than 10 km (5.4 nm) away. Data from presumed undisturbed versus disturbed comparisons included surfacng, respiration, and dive characteristics; depth of water, and speed of movement. Behavioral characteristics for disturbed whales were examined for correlations that may be useful in evaluating the effects of disturbance.

The second approach was to assess changes in behavior characteristics during each individual experiment independent of the others. Observations were sorted into the following groups for comparison: "pre-disturbance" (no seismic sounds or a source greater than 10 km (5.4 nm) away, "disturbance" with the sound source 5-10 km (2.7-5.4 nm) away, "close-disturbance" with the source less than 5 km (2.7 nm) away, "post-disturbance" 0-30 to 30-60 minutes following the termination of seismic sounds. In some instances sample sizes for individual categories of disturbance for an experiment were too small for meaningful statistical analysis. In these cases, the data from similar categories were pooled (e.g., pre-disturbance with 30-60 minutes post-disturbance as the presumed-undisturbed sample, and disturbance at 5-10 km (2.7-5.4 nm) with less than 5 km (2.7 nm) as the disturbed sample) to obtain sample sizes adequate for analysis.

Sample sizes of behavioral characteristics for mother-calf pairs were low compared to sample sizes for adult whales. Therefore, data for mothers and for calves were not included in the analysis. We have, however, presented the data for mother and calves during "disturbed" conditions in Table 1 for comparison.

Whale positions and aircraft altitude were taken from the computerized flight data, while behavioral observations were transcribed from audiotape onto data recording sheets in the laboratory. Videotaped behavioral sequences were compared to the audiotape commentary to clarify and correct the behavioral records. Water depth at whale locations was dichotomized as "shallow"

(0 to 29.9 m) or "deep" (30 to 59 m) to correspond with the same depth categories used in previous studies.

Following the field season, the behavioral data were converted into a numerical format with individual records of surfacing, respiration, and dive characteristics for each whale. These records were then cross checked by an individual other than the one who converted them to standardized the format and then entered into a Hewlett-Packard 9825 computer. The computer record was then checked a third time prior to data tabulation and statistical anlayses. A Hewlett-Packard 9827-A Plotter driven by the 9825 computer drew the numerically based figures.

Parametric and nonparametric statistical tests were employed as appropriate, and are referred to in the sections in which they appear. All statistical tests used may be found in Sokal and Rohlf (1981) and Zar (1984).

RESULTS

Effort

Thirty-five flights in support of behavioral seismic response experiments were flown between 18 August and 3 October 1984. These flights, representing 136.9 hrs of effort, extended east to Herschel Island, Canada and west to Barrow, Alaska (Fig. 2). Flights ranged from 1.3 to 8.3 hrs with an average duration of 4.15 hrs. Twelve (34%) of these flights were either aborted due to inclement weather or terminated when no bowhead whales were sighted. During nine (26%) flights bowhead whales were sighted but behavioral data were not collected due to the short duration of the sightings. Behavioral data were collected from bowhead whales presumed to be undisturbed during nine (26%) flights, and one (3%) flight consisted of an aborted experiment. Four (11%) flights resulted in complete seismic response experiments. The geophysical vessels participating in the four experiments were the Western Beaufort on 18 September, the Western Aleutian on 20 September, the Arctic Star on 23 September, and the Western Polaris on 26 September (Fig. 2, 1-4). The average length of flights during which experiments were conducted was 8.1 hrs with a range of 7.9 to 8.3 hrs. Measured or estimated seismic sound levels received at the whale's location at specific times and ranges from the vessels during each experiment are presented in individual experiment narratives. A complete anlaysis of all acoustic information, including analysis methodology, is presented in Appendix A.

Surfacing, Respiration, and Dive Characteristics

Correlations Between Behavior Characteristics

Strong correlations were found between some behavioral characteristics for disturbed bowhead whales (Fig. 3A-D), which were similar to those correlations documented for undisturbed whales in previous studies (Ljungblad, et al. 1984; Würsig et al. 1984a). Length of surfacing was correlated with number of blows per surfacing ($r = 0.896$, $p < 0.001$, $n = 182$), and with length of previous ($r = 0.566$, $p < 0.001$, $n = 37$) and subsequent dives ($r = 0.526$, $p < 0.001$, $n = 37$). Length of dive

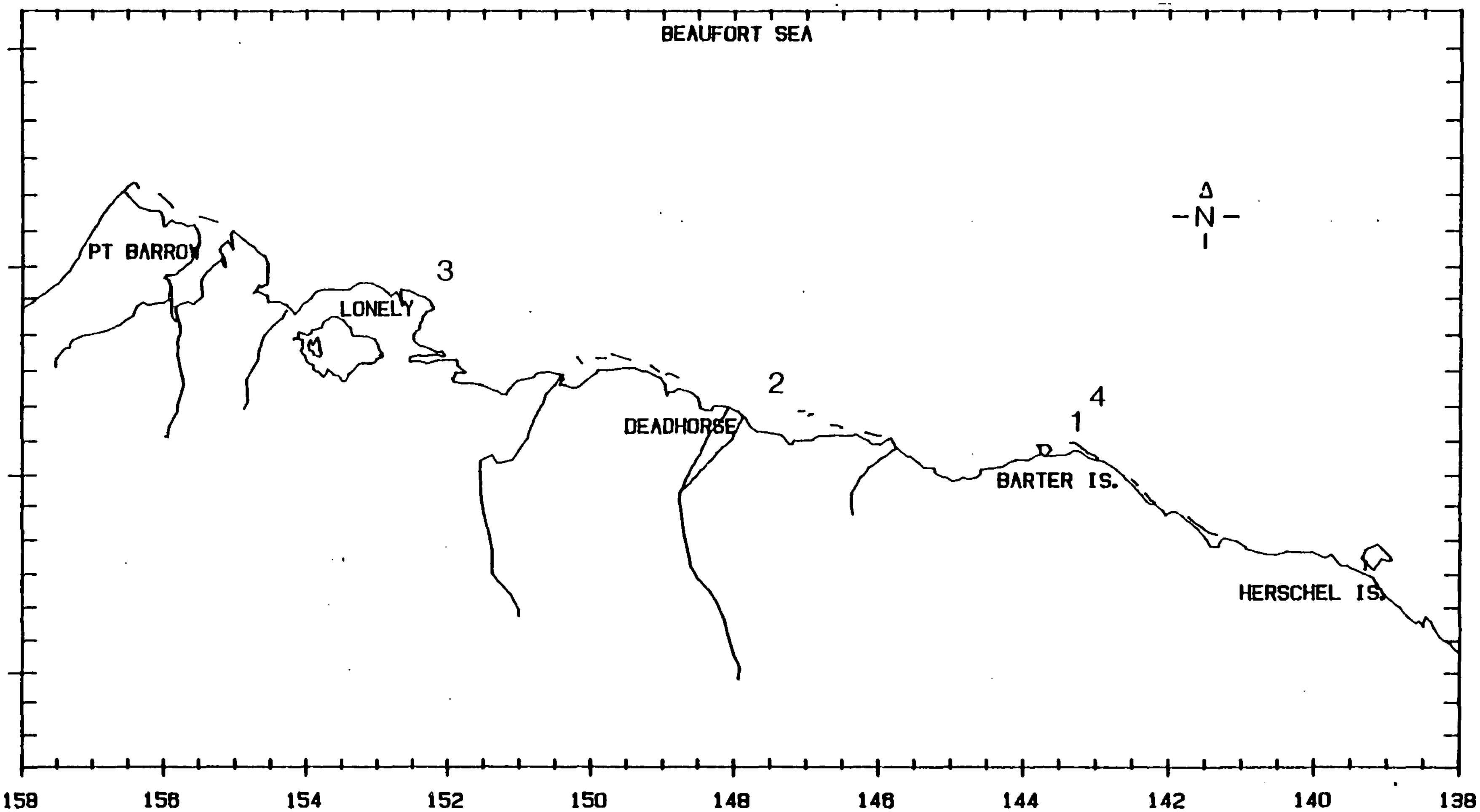

Figure 2. Study area in the Alaskan Beaufort Sea showing the locations of seismic response experiments: No. 1, 18 September - Western Beaufort; No. 2, 20 September - Western Aleutian; No. 3, 23 September - Arctic Star; and No. 4, 26 September - Western Polaris.

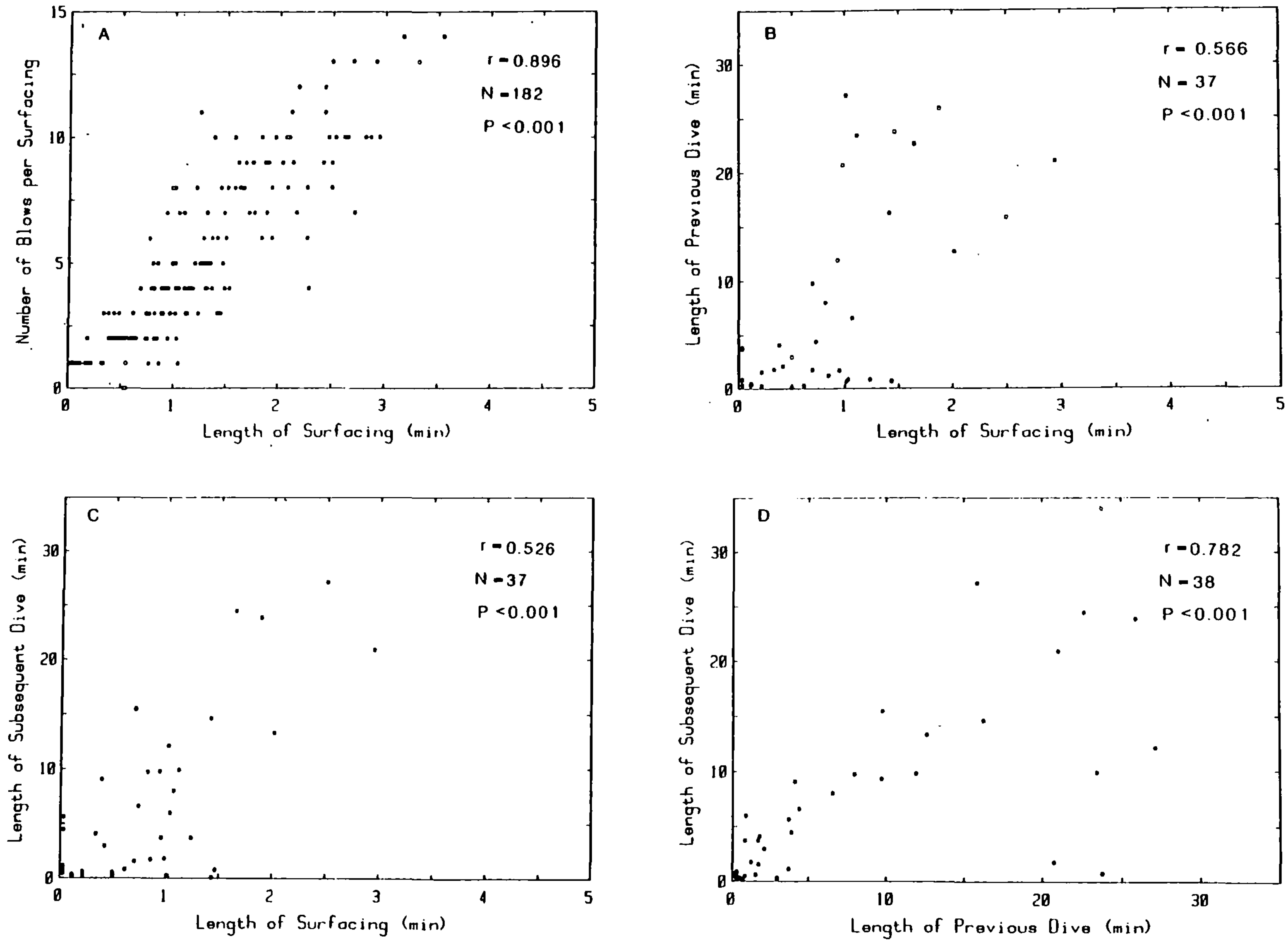

Figure 3. Correlations between select surfacing, respiration, and dive characteristics.

previous to a surfacing was correlated with length of dive subsequent to that surfacing ($r = 0.782$, $p < 0.001$, $n = 38$), indicating that particular dive patterns tend to occur in bouts. These data further indicate that the surfacing, respiration, and dive characteristics are related, for both physiological and behavioral reasons, and that one variable may be predicted by the changes or pattern of another.

Undisturbed versus Disturbed Comparisons

The pooled data on presumed undisturbed whales consisted of 1,131 blow intervals, 151 number of blows per surfacing, 155 length of surfacings, 30 dive times, and 22 measures of blow rate, while those for disturbed adults accounted for 812, 127, 136, 63, and 56 respectively (Table 1). The frequency distributions of these five characteristics for presumed undisturbed whales are shown in Figure 4A-E, and for whales exposed to seismic sounds (disturbed) in Figure 5A-E.

Blow interval, number of blows per surfacing, and length of surfacing showed distributions approaching normality, but length of dive and blow rate were less normally distributed. Therefore, throughout this report the first three variables have been compared with parametric testing procedures, while the last two variables were treated non-parametrically.

The data for all adult whales were pooled into presumably undisturbed and disturbed categories and these tested for significant differences. All of the surfacing, respiration and dive characteristics showed changes with exposure to seismic sounds, but only two were significant (Fig. 6A-E). Mean blow interval was the only character to increase, from 12.7 to 15.0 sec ($t = 7.854$, $p < 0.001$). The remaining characteristics all decreased with exposure to increasing levels of seismic sounds; the number of blows per surfacing decreased from 5.5 to 4.6 blows ($t = 2.221$, $p < 0.02$), length of surfacing decreased from 1.19 to 1.14 min ($t = 0.501$, $p < 0.50$), length of dive decreased from 9.61 to 8.15 min ($t = 0.730$, $p < 0.20$), and blow rate declined from 1.43 to 1.25 blows per min ($t = 0.641$, $p < 0.50$).

Depth of Water

To evaluate the influence of water depth on the surfacing, respiration and dive characteristics, we first compared both shallow (0-29.9 m) (one experiment) and deep (30-59 m) (three experiments) depth categories for presumably undisturbed and disturbed whales separately (Fig. 7A-E, Fig. 8A-E). We then compared each behavioral characteristic during presumed undisturbed and disturbed conditions for both shallow and deep water (Table 1).

Significant differences were found between different depth categories for both presumed undisturbed and disturbed whales. For instance, for presumed undisturbed whales, the mean blow interval increased significantly with increasing depth from 11.8 to 13.5 s ($t' = 22.078$, $p < 0.05$), as did the mean number of blows per surfacing from 4.2 to 8.0 ($t' = 7.909$, $p < 0.001$), and the mean length of surfacing from 0.82 to 1.88 min ($t' = 7.918$, $p < 0.001$). Mean length of dive also increased with depth from 6.90 to 13.16 min, but mean blow rate declined from 1.95 to 0.68 blows/min; however, these changes were not statistically significant. (Fig. 7A-E, Table 1).

Table 1. Summary of Statistics of the Principal Surfacing, Respiration and Dive Characteristics, fall 1984. All categories except these marked otherwise are for non-calves.

	BLOW INTERVAL (S)			NO. BLOWS/SURFACING			LENGTH OF SURFACING (MIN)			LENGTH OF DIVE (MIN)			BLOW RATE (NO./MIN)		
	$\bar{x}$	S.D.	n	$\bar{x}$	S.D.	n	$\bar{x}$	S.D.	n	$\bar{x}$	S.D.	n	$\bar{x}$	S.D.	n
AGE CLASSES															
ALL ADULTS															
Undisturbed[a]	12.7***	5.61	1131	5.5*	3.36	151	1.19	0.868	155	9.61	8.140	30	1.43	1.404	22
Disturbed[b]	15.0	7.29	812	4.6	3.37	127	1.14	0.828	136	8.15	9.407	63	1.25	0.985	56
MOTHERS															
Disturbed	17.8	7.94	144	5.4	3.57	21	1.68	1.026	22	9.14	9.811	12	1.03	0.974	11
CALVES															
Disturbed	18.7	12.65	113	3.1	3.90	21	0.87	1.084	22	8.14	9.470	11	0.68	0.814	10
DEPTH OF WATER															
0-29m															
Undisturbed	11.8***	4.86	516	4.2	2.81	98	0.82*	0.572	100	6.90**	7.086	17	1.95*	1.583	13
Disturbed	16.1	5.83	183	3.8	2.15	28	1.10	0.596	29	16.53	10.326	11	0.54	0.538	8
30-59m															
Undisturbed	13.5*	6.05	616	8.0***	2.88	53	1.88***	0.899	55	13.16**	8.317	13	0.68*	0.587	9
Disturbed	14.7	7.63	629	4.8	3.62	99	1.15	0.882	107	6.38	8.257	52	1.36	0.997	48
SPEEDS															
NONE															
Undisturbed	13.1	5.55	274	8.4	2.59	27	1.85	0.740	27	16.17	8.045	4	0.33	0.114	3
Disturbed	13.7	7.07	223	6.5	3.62	15	1.64	0.790	20	15.43	5.803	8	0.45	0.189	7
SLOW															
Undisturbed	13.4	6.40	348	5.1*	2.63	50	1.12*	0.622	48	10.57	8.169	10	1.11	1.251	7
Disturbed	13.9	5.82	179	6.8	3.04	26	1.52	0.755	25	17.00	10.303	11	0.74	0.647	11
MEDIUM															
Undisturbed	12.7***	4.94	256	6.9***	3.58	27	1.57*	1.188	28	6.58	6.586	6	1.70	1.798	5
Disturbed	16.2	7.94	306	3.9	2.96	58	1.03	0.794	63	5.66	7.750	31	1.28	1.000	25
FAST															
Undisturbed	11.6**	2.94	18	3.3	2.75	10	0.57	0.570	10	3.89	6.674	4	1.94	0.297	3
Disturbed	16.5	8.16	42	2.5	2.67	15	0.51	0.694	15	0.46	0.268	12	2.20	0.712	12

a Undisturbed = presumed undisturbed.
b Disturbed = during exposure to seismic noise.

* = p 0.05
** = p 0.01
*** = p 0.001

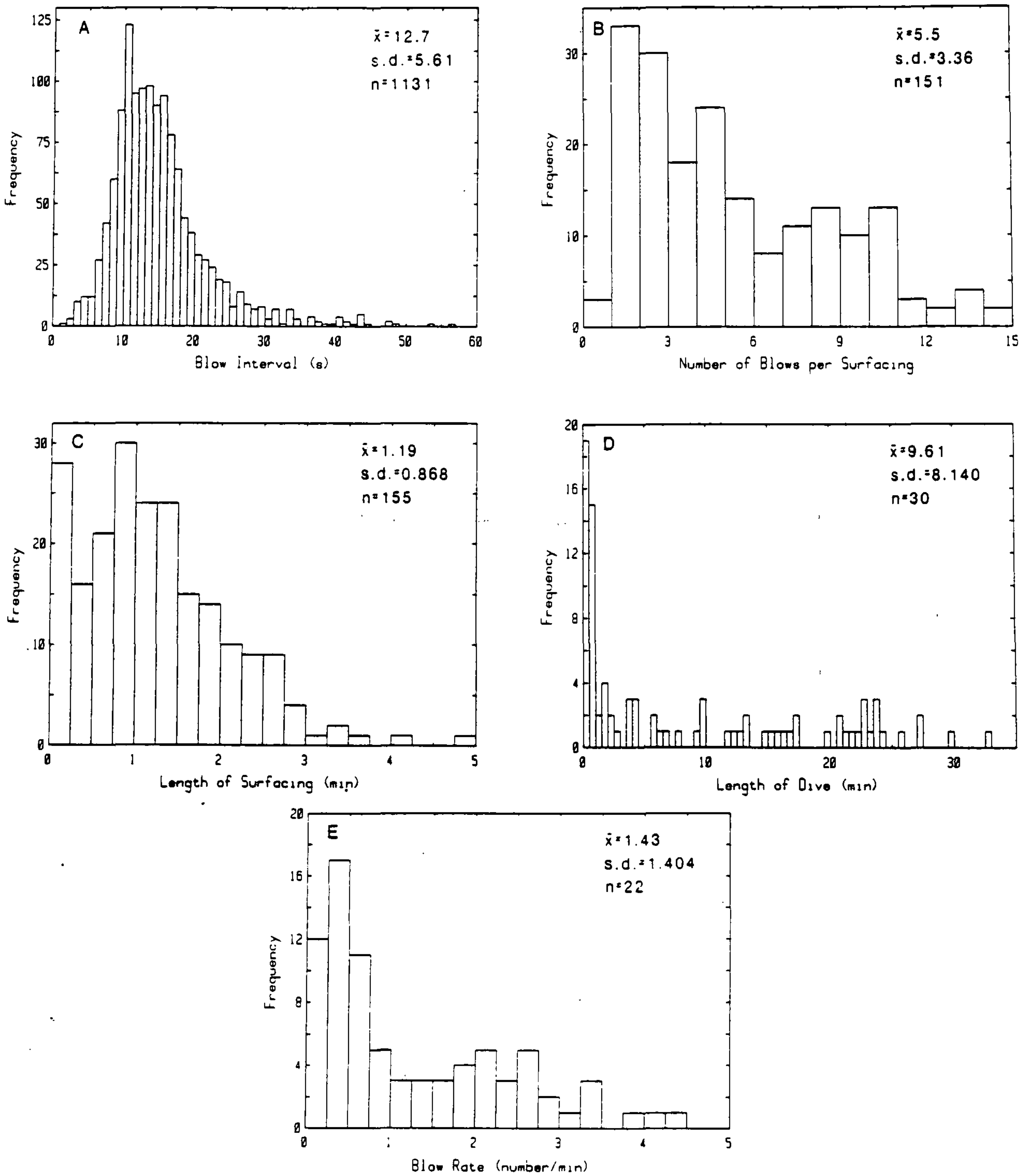

Figure 4. Frequency distributions of surfacing, respiration, and dive characteristics for presumed undisturbed bowhead whales.

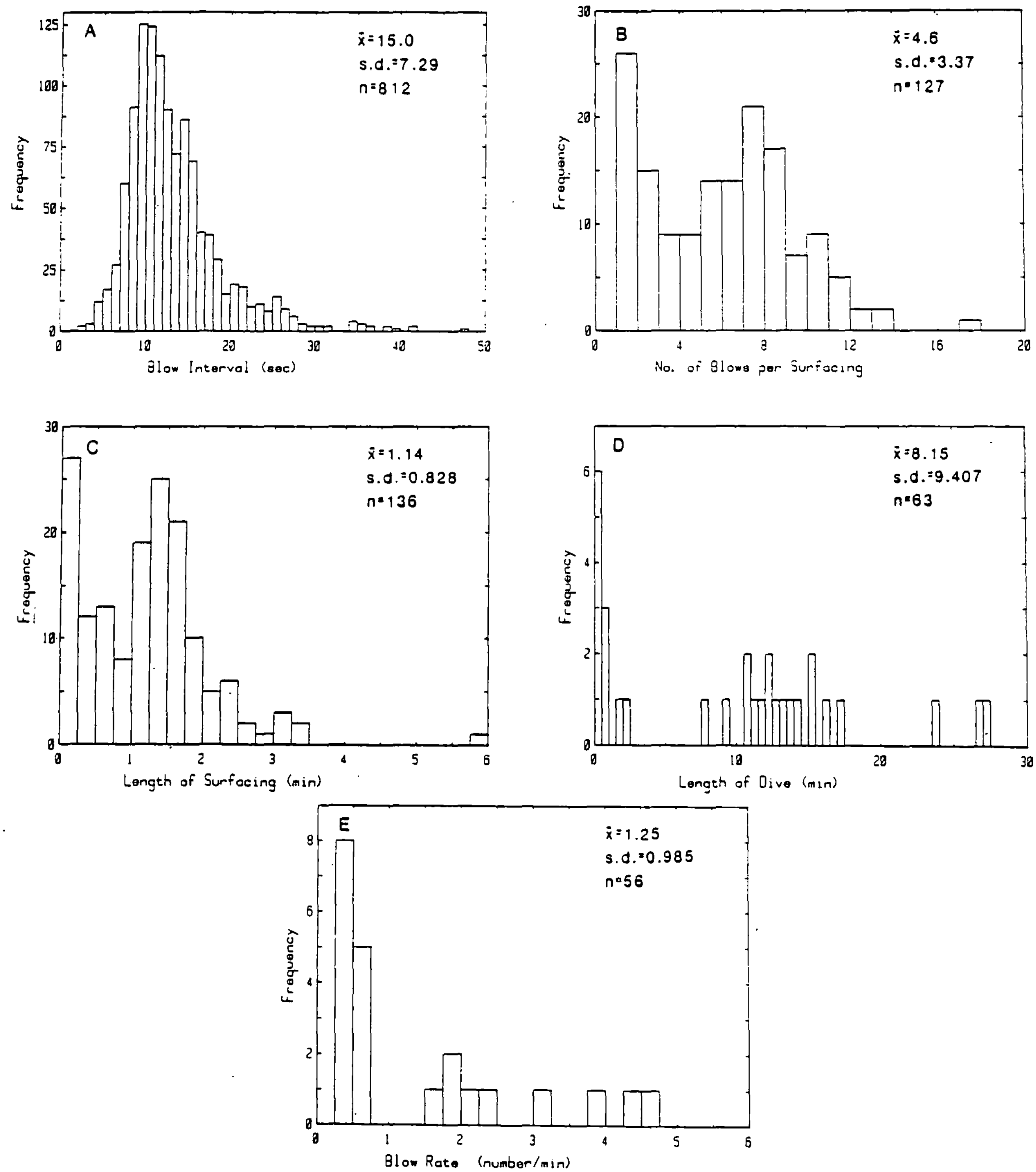

Figure 5. Frequency distributions of surfacing, respiration, and dive characteristics for potentially disturbed bowhead whales.

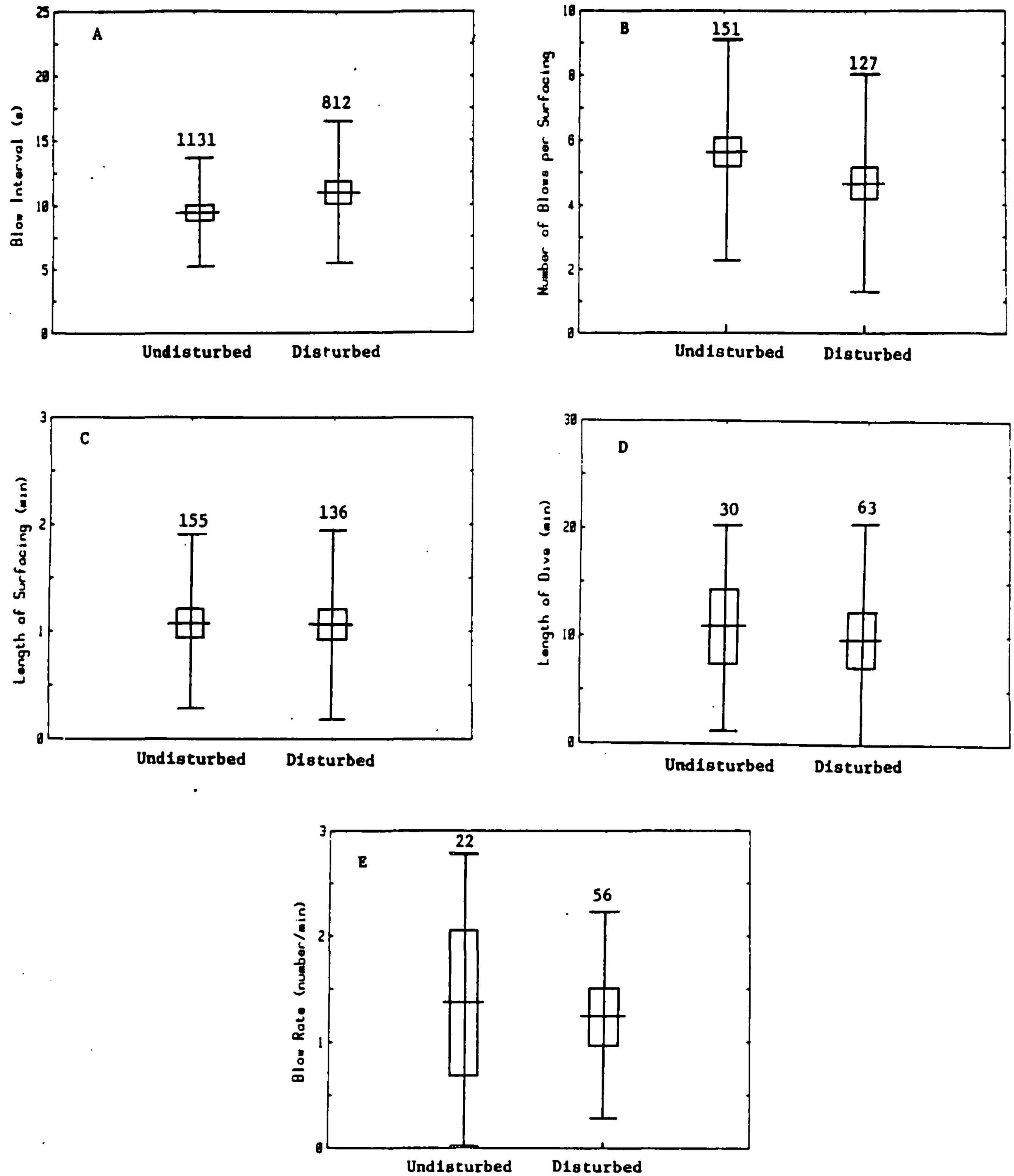

Figure 6. Overall mean values for surfacing, respiration and dive characteristics of presumed undisturbed and disturbed whales. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 95% confidence limits to the mean, and numbers at top of bars are sample sizes.

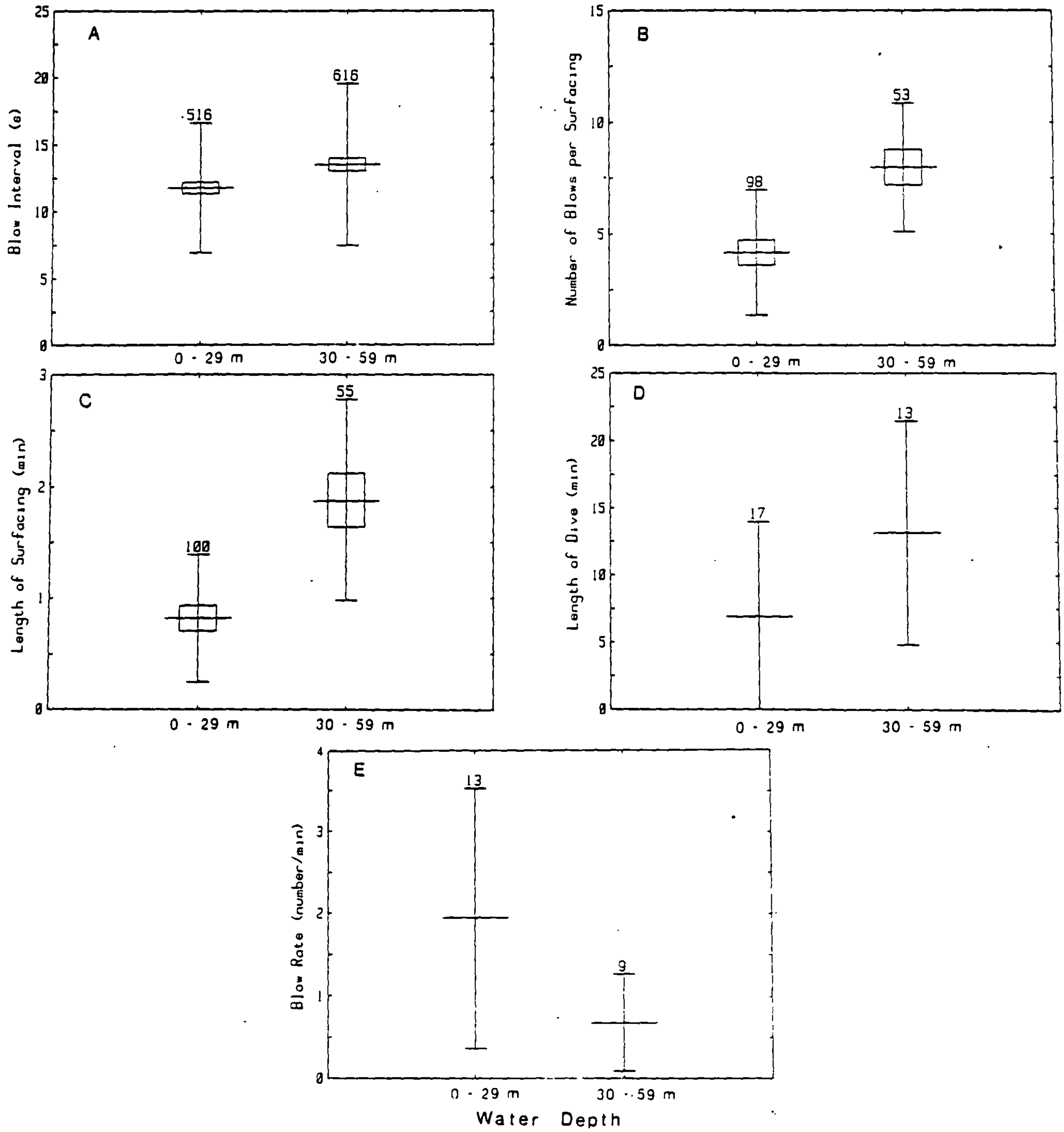

Figure 7. Surfacing, respiration, and dive characteristics for presumed undisturbed bowhead whales in two different water depth ranges. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 95% confidence limits to the mean, and numbers at the top of bars are sample sizes.

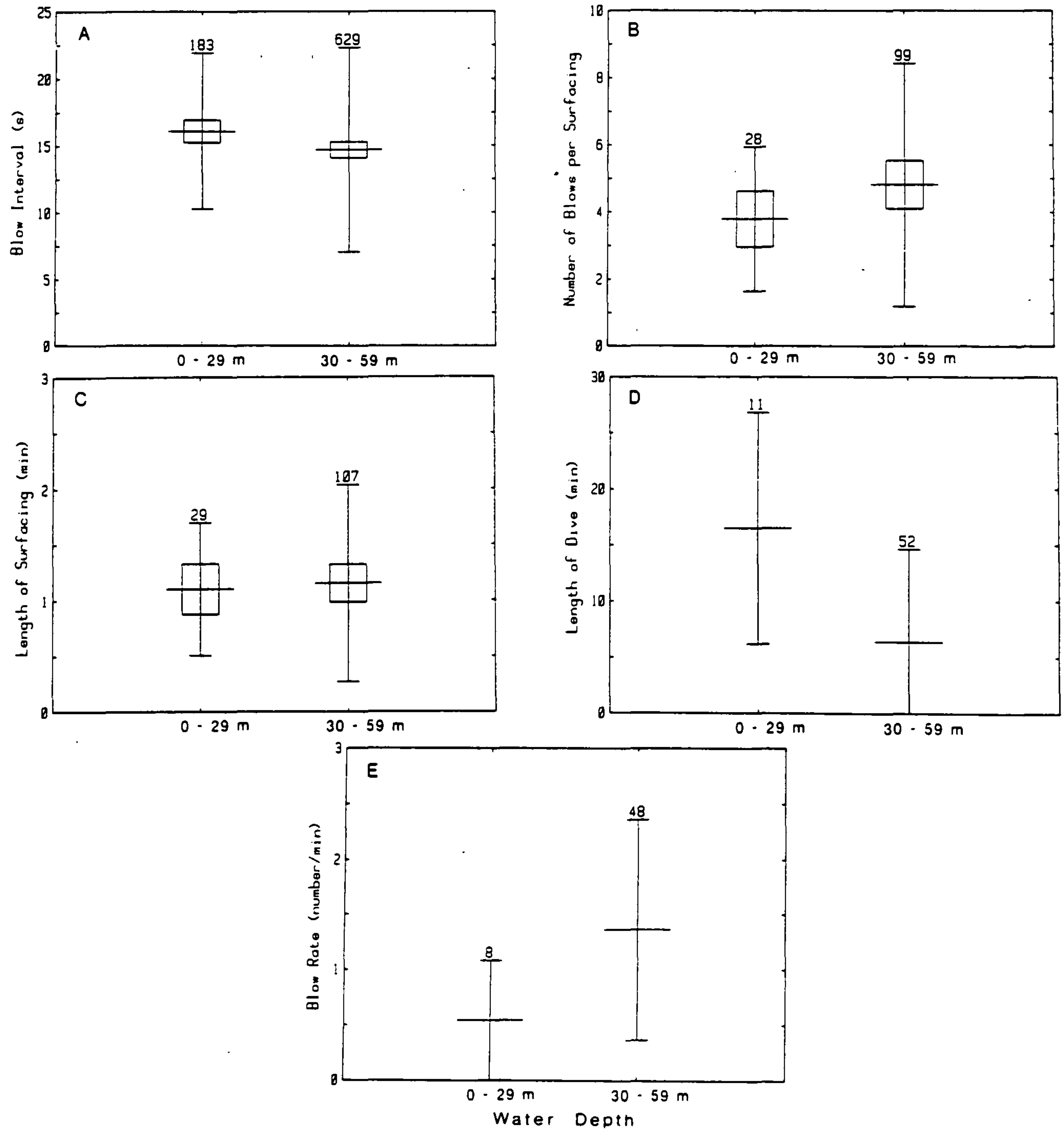

Figure 8. Surfacing, respiration, and dive characteristics for potentially disturbed bowhead whales in two different water depth ranges. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 95% confidence limits to the mean, and numbers at top of bars are sample sizes.

With the exceptions of number of blows per surfacing and length of surfacing, whales disturbed by the presence of seismic sounds demonstrated a curious reversal of behavioral characteristics in relation to depth compared to undisturbed whales. For disturbed whales mean blow interval decreased with increasing depth from 16.1 to 14.7 s ($t' = 2.706$, $p < 0.01$), as did mean length of dive from 16.53 to 6.38 min (Mann-Whitney $Z = 3.124$, $p < 0.002$). Mean blow rate increased in deeper water from 0.54 to 1.36 blows/min (Mann-Whitney $Z = 2.599$, $p < 0.01$). Mean number of blows per surfacing and length of surfacing, although not significantly different between depths, increased slightly in greater depth than for undisturbed whales (Fig. 8A-E).

Statistical comparisons of the behavior characteristics for presumed undisturbed and disturbed whales for both depths also indicated significant differences, but these differences were not consistent between depths. Mean blow interval increased significantly both in shallow water ($t = 7.856$, $p < 0.001$) and in deep water ($t = 3.071$, $p < 0.01$) during exposure to seismic sounds. Mean number of blows per surfacing decreased at both depth categories with exposure to seismic sounds, although only the decrease in deep water from 8.0 to 4.8 blows was significant ($t = 5.559$, $p < 0.001$). Mean length of surfacing during seismic disturbance increased significantly in shallow water from 0.82 to 1.10 min ($t = 2.299$, $p < 0.05$), but decreased from 1.88 to 1.15 min in deep water ($t = 4.956$, $p < 0.001$). Mean length of dive in shallow water increased with exposure to seismic sounds from 6.90 to 16.53 min ($t = 2.935$, $p < 0.01$), but decreased from 13.16 to 6.38 min in deep water ($t = 2.644$, $p < 0.01$). Similarly, mean blow rate decreased during seismic disturbance in shallow water from 1.95 to 0.54 blows/min ($t = 2.414$, $p < 0.05$), but the rate increased from 0.68 to 1.36 blows/min in deep water ($t = 1.974$, $p < 0.05$).

Speed of Movement

Relative speed of movement of whales was subjectively estimated from the aircraft as stationary, moving at slow, medium, or fast speed, Slow speeds produced no wake, medium speeds produced a slight wake, and fast speeds produced a large wake of "white water" behind the swimming whales. To evaluate differences in the behavior characteristics of whales traveling at different speeds, we first tested the data for differences among speed categories for both presumed undisturbed and disturbed conditions separately. We then tested for differences between undisturbed and disturbed conditions within each speed category.

For presumed undisturbed whales, mean blow intervals did not change appreciably with different speeds of movement, but mean number of blows per surfacing, mean length of surfacing, and mean length of dive all decreased as whales moved faster (Table 1). This trend was significant only for mean number of blows per surfacing ($F = 11.699$, $df = 110$, $p < 0.001$) and mean length of surfacing ($F = 8.417$, $df = 109$, $p < 0.001$), and not significant for mean length of dive. Mean blow rate increased significantly during faster movement (Mann-Whitney $U = 64.0$, $n = 18$, $p < 0.05$).

For whales potentially disturbed by seismic activity, mean blow intervals increased slightly but significantly for faster whales ($F = 6.847$, $df = 746$, $p < 0.001$), while mean blow rate also increased greatly as swimming speed increased (Kruskal-Wallace $H_C = 19.673$, df = 3, $p < 0.001$). The mean number of blows per surfacing, mean length of surfacing, and mean length of dive all decreased with increasing speed ($F = 10.017$, df = 110, $p < 0.001$; $F = 8.428$, df = 119, $p < 0.001$; and Mann-Whitney $Z = 4.834$, $p < 0.001$, respectively). Mean length of dive of potentially disturbed whales was the characteristic most changed at different swimming speeds, with a mean length of 17.00 min at slow speed and only 0.46 min at fast speed. Indeed, whales exposed to seismic sounds at close range generally swam fast and only dived for brief times (see experiment narratives).

Overall there were differences in the values for the behavior characteristics of whales traveling at different speeds during presumed undisturbed and disturbed conditions. The only significant changes were, a lengthening of mean blow interval at medium and fast speeds from 12.7 to 16.2 ($t = 6.129$, $p < 0.001$) and 11.6 to 16.5 ($t = 2.469$, $p < 0.01$), repsectively, an increase in the mean number of blows per surfacing of 5.1 to 6.8 for slow swimming whales ($t = 2.533$, $p < 0.05$), a decrease in number of blows per surfacing from 6.9 to 3.9 ($t = 4.065$, $p < 0.05$) for medium swimming whales, a slight but significant increase in the length of surfacing from 1.12 to 1.52 min ($t = 2.421$, $p < 0.05$) for slow whales, and a significant decrease in the mean length of surfacing from 1.57 to 1.03 min ($t = 2.553$, $p < 0.05$) for whales swimming at medium speeds (Table 1).

General trends included lengthening of blow interval at medium and fast speeds during seismic disturbance, and decreasing number of blows per surfacing, length of surfacing, and length of dive with increasing swimming speed. Blow rate increased with increasing speed.

Response Experiments

Experiment No. 1: Western Beaufort

The first experiment began at approximately 12:00 (ADT) hrs on 18 September with our sighting of three bowhead whales in the general area of 70°18.7' N, 143°47.3' W, approximately 28 km (15 nm) northwest of Barter Island (Fig. 2). The geophysical vessel Western Beaufort was actively shooting approximately 12 km (6.5 nm) from the whales' position. The visibility was excellent with sea state Beaufort 1 and high overcast. The Western Beaufort is a "high resolution" geophysical vessel equipped with a single 11,311 cm^3 (80 in^3) which fired every four seconds. The calculated source level for sounds produced by this airgun is approximately 220 dB re 1 uPa at 1 m (Safar, 1984). A sonobuoy dropped near the whales revealed seismic sounds from the Western Beaufort with an estimated received level near the whales of 131.1 dB re 1 uPa at a distance of 12.04 km (6.4 nm) (Fig. 9). Additional seismic sounds from an unknown source firing every 12 to 14 seconds were also received at this time with a measured received level of 133.0 dB re 1 uPa.

While observing the whales for 1.5 hr, we contacted the Western Beaufort and requested her participation in a seismic response experiment. The captain of the vessel indicated that he would participate, and changed course to bring the vessel toward the whales' position. The Western Beaufort continued her active approach toward the whales at a speed of 3.0 kts, and by 15:08 hrs she was 9.6 km (5.2 nm) to the southeast. The measured received seismic levels at this time were 133 dB re 1 uPa from the Western Beaufort and 142.1 dB re 1 uPa from the unknown source. At 16:51 hrs the Western Beaufort had approached to within 3.5 km (1.9 nm) of the whales, and the estimated received sound level from the vessel had increased to 142.0 dB re 1 uPa. The experiment terminated at 17:31 hrs when the Western Beaufort was approximately 1.3 km (0.7 nm) from the whales. Just prior to the shutdown, the measured received sound level was 152.4 dB re 1 uPa. Because the vessel had been shooting prior to the beginning of the experiment, we were unable to obtain pre-disturbance observations, and post-disturbance observations were confounded by other geophysical vessels that had become active in the area.

Intermittently throughout the Western Beaufort's approach to the whales, additional seismic sounds were recorded, although their origin was not determined. The measured received levels of these sounds at times exceeded sound levels produced by the Western Beaufort and ranged from 133.0 dB re 1 uPa at 12:00 hrs to 142.1 dB re 1 uPa at 13:08 hrs. These sounds fluctuated as the vessel producing them (apparently) moved into and out of the experiment area. No overt behavior changes appeared to be associated with these additional seismic sounds.

To evaluate a potential a "zone of influence" that may surround an active seismic vessel, the whale behavior data were divided into three subsets and compared for differences in conspicuous behavior that may be correlated with distance from the vessel, and received sound level. During the approach of the

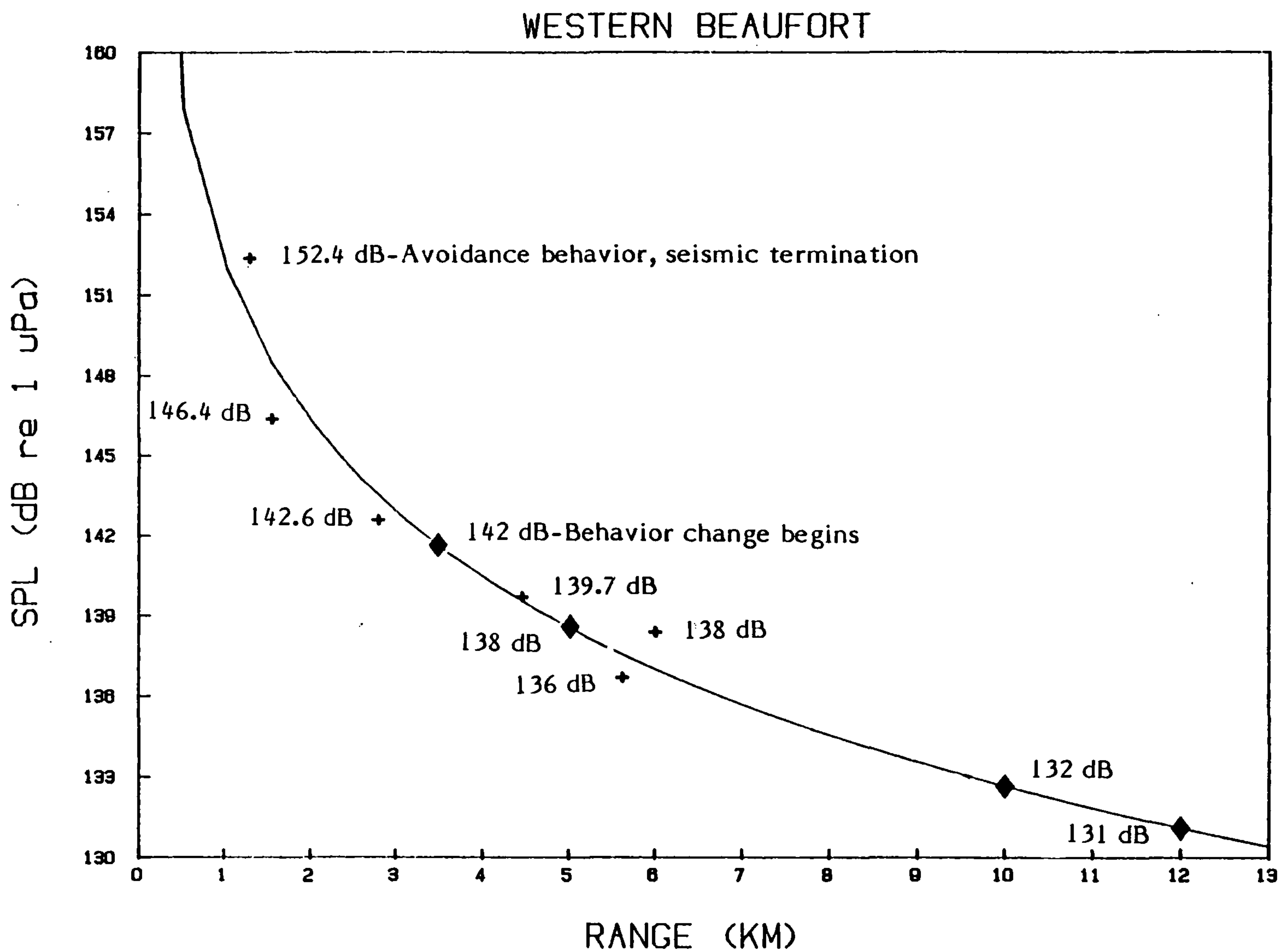

Figure 9. Received seismic sound levels versus range for the Western Beaufort. Line is a least squares regression line fit to the measured sound levels. ◆= Estimated sound level; + = Measured sound level.

Western Beaufort, sound levels ranged from < 131.1 dB re 1 uPa at distances greater than 10 km, 132 to 138 dB re 1 uPa between 5 and 10 km (2.7 and 5.4 nm), and 138 to 152 dB re 1 uPa at ranges between 5 and 1.3 km (2.7 and 0.7 nm) (Fig. 9).

The Western Beaufort was active at a range of > 10 km (>5.4nm) during the first 2:6 hrs of observations between 12:00 and 14:51 hrs. Thirty-one surfacings of individual whales occurred during this period. The general behavior of the whales during those surfacings included milling (13%, n = 4 surfacings), socializing (19%, n = 6 sightings), and traveling (68%, n = 21 sightings (Table 2). The 21 sightings of traveling whales included slow swimming (29%, n = 6 surfacings), swimming at medium speed (71%, n = 15 surfacings), and no whales were swimming at fast speed. The orientations of the whales at the time of surfacing with respect to the position of the approaching vessel, included 7% (n = 2 surfacings) oriented toward the vessel, 17% (n = 5 surfacings) oriented 90° to the left or right away from the vessel, and 76% (n = 22 surfacings) were oriented 180° directly away from the approaching vessel (Fig. 10).

From 14:51 to 16:51 the number of recognizable bowhead whales in the area increased from three to eight individuals; two female-calf pairs and four singles. During these two hours 32 surfacings of individual whales occurred, while the Western Beaufort moved to within 5 km (2.7 nm) of the whales. During this period, milling behavior increased to 17% (n = 5 sightings), socializing increased to 22% (n = 7 sightings), and traveling decreased to 61% (n = 20 sightings) (Table 2). Of those traveling, 29 were swimming slowly (n = 6 sightings), 71% were traveling at medium speed (n = 14 sightings), and again, no whales were judged to be moving at fast speed. Whale orientations included 19% oriented at 90° to the left or right away from the vessel (n = 6 sightings), and 81% were now oriented 180° directly away from the approaching vessel (n = 26 sightings) (Fig. 10).

Change in the whales' behavior occurred between 16:51 and 17:31 hrs as the vessel approached to within 3.5 km (1.9 nm) of the whales. Individual whales that had previously been widely separated surfaced synchronously within a few whale lengths of each other, huddled tightly together orienting away from the vessel, and dived (Fig. 10). All observations at this time were of whales moving in a westerly direction with 75% traveling at medium speed (n = 12 sightings) and 25% traveling at fast speed (n = 4 sightings) away from the approaching vessel (Table 2). At the conclusion of our observations, the whales were dispersing to the west and northwest at medium to fast speed.

The principal surfacing, respiration, and dive variables for non-calf whales all changed significantly when the Western Beaufort approached to within 5 km (2.7 nm) (Fig. 11A-E, Table 3). Mean blow interval was relatively unchanged at ranges greater than 5 km (2.7 nm), but increased significantly from 12.33 to 20.39 s when the vessel was < 5 km (2.7 nm) away ($F = 18.087$, $df = 254$, $p < 0.001$). Concomitantly, the mean number of blows per surfacing declined significantly from 9.2 to 2.0 blows per surfacing when the vessel was >10 km (5.4 nm) to < 5 km (<2.7 nm) ($F = 45.665$, $df = 39$, $p < 0.001$).

Mean length of surfacing declined from 1.82 min to 1.25 min when the vessel was between 5-10 km (2.7-5.4 nm) away ($F = 11.774$, $df = 42$, $p < 0.001$). This decline continued to 0.59 min as the vessel closed to within 1 km (.53 nm).

Table 2. General Surface Behavior of Non-Calves

SEISMIC EXPERIMENT	Number of Surfacings	Milling	Socializing	Travelling
	BEHAVIOR AS % OF SIGHTING			
No. 1: Western Beaufort				
Disturb. 10 km	31	13	19	68
Disturb. 5-10 km	32	17	22	61
Disturb. 5 km	16	0	0	100
No. 2: Western Aleutian				
Pre-Disturb.	9	22	56	22
Disturb. 3.5-6.6 km	8	0	0	100
Post-Disturb. 30 min.	9	0	0	100
Post-Disturb. 30 min.	7	14	0	86
No. 3: Arctic Star				
Disturb. 10 km	39	18	13	69
Post-Disturb. 30 min.	13	14	0	86
Disturb. 5-12 km	15	0	0	100
Disturb. 5 km	15	0	0	100
No. 4: Western Polaris				
Pre-Disturb.	84	37	56	7
Disturb. 5-10 km	18	0	0	100
Disturb. 5 km	25	0	0	100
Post-Disturb. 30 min.	18	28	0	72
Post-Disturb. 30 min.	21	28	20	52

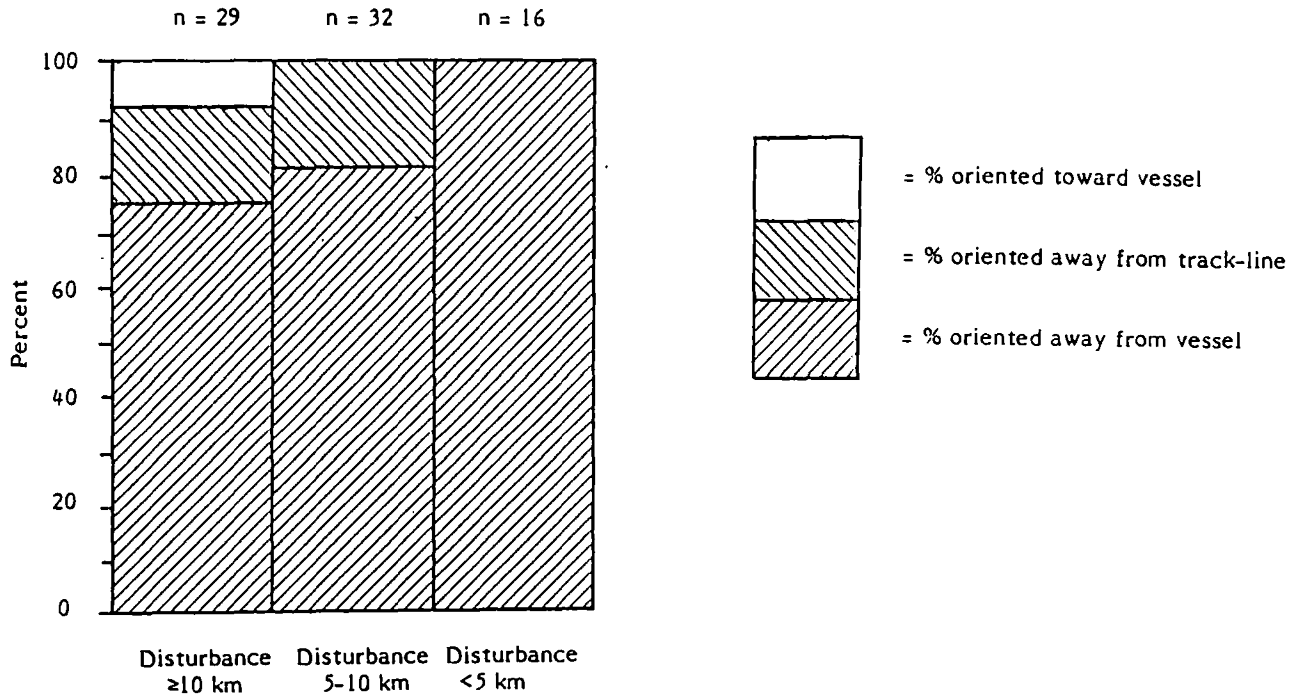

Figure 10. Orientations of surfacing bowhead whales as percent of sightings during a seismic response experiement with the geophysical vessel, the Western Beaufort. Numbers at top of bars are sample sizes.

Mean length of dive showed a pronounced and significant decrease at all ranges as the vessel approached: it declined from 17.9 to 1.12 min ($H_C = 21.677$, df = 2, $p < 0.001$). Mean blow rate increased significantly from 0.38 to 1.81 blows per min, suggesting that the shortening of dives was accompanied by more rapid breathing as the vessel approached ($H_C = 15.223$, df = 2, $p < 0.001$).

In summary, as the active Western Beaufort approached to within 3.5 km (1.9 nm) of the whales, and the concomitant levels of received seismic sound increased to 142 dB re 1 uPa, milling and social behavior ceased. There followed a brief period of huddling, and then all whales in the area began traveling away from the vessel at medium and fast speeds. Blow interval, number of blows per surfacing, length of surfacing, length of dive and blow rate all changed significantly and were accompanied with avoidance behaviors as the vessel approached to within 1.3 km (0.9 nm) and the measured sound level was 152 dB re 1 uPa. During the 5.5 hours of this experiment, the net movement of the whales was 5.4 km (2.9 nm) to the west.

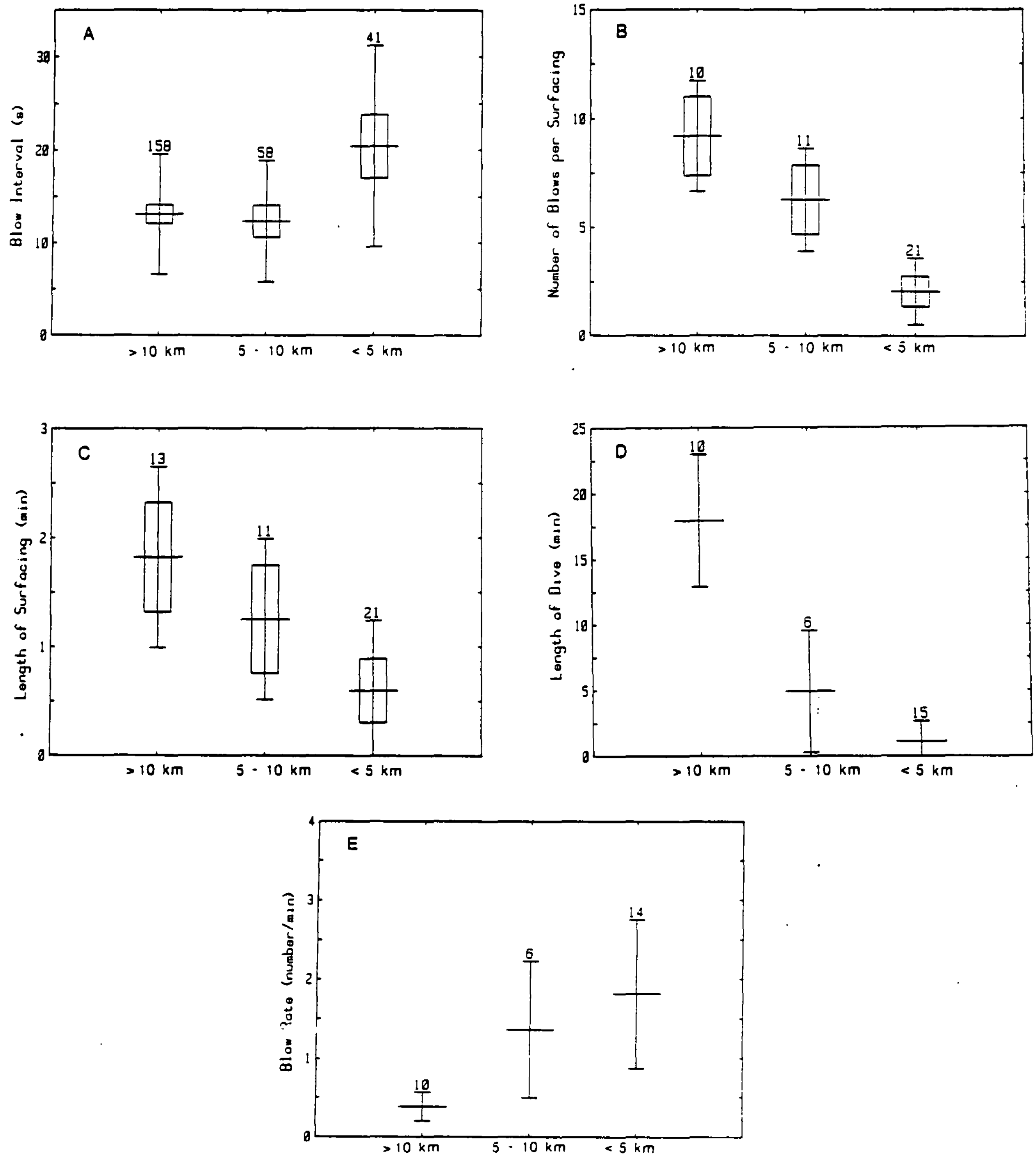

Figure 11. Surfacing, respiration, and dive characteristics of bowhead whales at different distances from an active geophysical vessel, the Western Beaufort. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 95% confidence limits to the mean, and numbers at the top of bars are sample sizes.

Table 3. Summary statistics of the Principal Surfacing, Respiration and Dive Characteristics During Four Seismic Experiments. All Categories are for Non-Calves.

SEISMIC EXPERIMENT	BLOW INTERVAL (S)				NO. BLOWS/SURFACING				LENGTH OF SURFACING (MIN)				LENGTH OF DIVE (MIN)				BLOW RATE (NO./MIN)			
	$\bar{x}$	Rank[a]	S.D.	n	$\bar{x}$	Rank	S.D.	n	$\bar{x}$	Rank	S.D	n	$\bar{x}$	Rank	S.D.	n	$\bar{x}$	Rank	S.D.	n
Western Beaufort, Sept. 18																				
1. Disturb. 10 km	13.12	2	6.49	158	9.2	3	2.53	10	1.82	3	0.829	13	17.9	3	5.04	10	0.38	1	0.180	1
2. Disturb. 5-10 km	12.33	1	6.54	58	6.3	2	2.37	11	1.25	2	0.737	11	4.93	2	4.64	6	1.36	2	0.868	6
3. Disturb. 5 km	20.39	3	10.81	41	2.0	1	1.53	21	0.59	1	0.643	21	1.12	1	1.55	15	1.81	3	0.937	14
	F = 18.087				F = 45.665				F = 11.774				H(c)[d] = 21.077				H(c)[d] = 15.323			
	p 0.001				p 0.001				p 0.001				p 0.001				p 0.001			
	df_e = 254				df_e = 39				df_e = 42				df = 2				df = 2			
	MRT[b] 1 2 3				MRT 1 2 3				MRT 1 2 3				MRT 1 2 3				MRT 1 2 3			
Western Aleutian, Sept. 20																				
Pre Disturb.	13.0	1	3.78	49	8.5	4	2.33	8	1.81	4	0.593	8	17.80	4	11.703	4	1.46		1.788	5
Disturb. 5-10 km	16.6	2	6.51	25	3.0	2	2.52	7	0.73	1	0.823	7	3.11	1	2.103	6	0.78		0.899	4
Post Disturb. 30 Min.	22.2	4	10.11	13	2.0	1	0.00	2	0.87	2	0.174	3	7.15	2	2.257	4	0.43		0.230	3
Post Disturb. 30 Min	17.4	3	4.56	27	5.5	3	2.65	4	1.77	3	0.354	2	15.64	3	9.683	3	0.46		--	1
	F = 10.342				t = 4.217[c]				t = 3.761[c]				U[e] = 59.5[c]				No Tests			
	p 0.001				p 0.001				p = 0.001				0.01 p 0.02							
	df_e = 110				df = 20				df = 18				1 2 3 4							
	MRT 1 2 3 4				1 2 3 4				1 2 3 4											
Arctic Star, Sept. 23																				
Disturb. 10 km.	15.3	1	6.14	132	3.8		1.98	19	1.07		0.578	21	14.15		10.520	6	--		--	--
Post Disturb. 30 min.	15.9	2	6.10	22	4.5		1.73	4	1.35		0.225	4	--		--	--	--		--	--
Disturb. 5-12 km	17.2	3	4.24	17	3.3		2.08	3	1.18		0.436	2	24.27		2.334	2	--		--	--
Disturb. 5 km	19.4	4	3.97	30	3.8		2.99	6	1.19		0.773	6	16.13		13.289	3	--		--	--
	F = 4.428				No Tests				No Tests				No Tests				No Tests			
	p 0.001																			
	df_e = 197																			
	MRT 1 2 3 4																			
Western Polaris, Sept. 26																				
Pre Disturb.	14.8	2	7.10	246	8.0	4	2.05	24	1.97	4	0.638	25	16.17	5	11.471	4	0.78	1	0.933	4
Disturb. 5-10 km	16.8	5	8.64	182	4.6	3	3.95	29	1.26	3	0.984	31	1.91	2	4.255	9	1.81	2	0.981	8
Disturb. 5 km	15.3	3	9.05	23	3.8	2	2.82	8	0.78	1	0.643	8	0.56	1	0.365	2	2.84	5	0.623	2
Post-Disturb. 30 min.	16.2	4	5.08	30	3.6	1	2.30	7	0.93	2	0.442	7	8.44	3	16.353	4	2.01	3	1.127	4
Post-Disturb. 30 min.	14.3	1	6.38	160	8.1	5	4.25	16	2.09	5	1.164	18	12.56	4	14.053	4	2.06	4	1.987	4
	F = 3.039				F = 6.806				F = 6.275				U[e] = 96.0[c]				H(c)[d] = 5.122			
	p 0.05				p 0.001				p 0.001				p = 0.02				p = 0.27			
	df_e = 636				df_e = 79				df_e = 84				1 2 3 4 5				df = 4			
	MRT 1 2 3 4 5				MRT 1 2 3 4 5				MRT 1 2 3 4 5								1 2 3 4 5			

a Rank = rank of means from smallest to largest
b MRT = multiple rank test
c Groups pooled to give adequate sample sizes
d Kruskal-Wallace test
e Mann-Whitney test

Experiment No. 2: Western Aleutian

On 20 September at 10:23 hrs we began observations of three bowhead whales that were lying on the surface, socializing, and traveling slowly to the southwest in the general area of 70°41.4' N, 147°30.9' W, approximately 83 km (45 nm) northeast of Deadhorse, Alaska (Fig. 2). Visibility was excellent with calm water (Beaufort 1) and overcast. A sonobuoy dropped at this position revealed some distant low level seismic sound (<120 db re 1 uPa) from an unknown source. The geophysical vessel Western Aleutian was inactive (airguns not operating) approximately 12.4 km (6.7 nm) to the northeast of the whales. This vessel is equipped with a multiple airgun array, of which 20 guns are activated and fire synchronously every 12 to 14 seconds. The estimated source level of sound produced by this array is between 230 and 240 dB re 1 uPa at 1 m (Western Geophysical, pers. comm.).

During the initial 3.34 hrs of observations, we contacted the Western Aleutian and requested her participation in a seismic response experiment. The captain acknowledged our request and began to approach toward our position at a speed of 4.5 kts with the airguns inactive. We asked the vessel to activate her airguns at 14:21 hrs when she was 7.2 km (3.8 nm) from the whales. The measured sound level at the whales' position was 164.6 dB re 1 uPa (Fig. 12). At approximately 14:57 hrs, when the Western Aleutian was within 3.5 km (1.9 nm) of the whales, our observations were briefly interrputed by low fog that restricted our ability to reliably identify each whale surfacing. At this time, the estimated received sound level at the whales' position was 169.6 dB re 1 uPa. We requested termination of the seismic sounds at 15:00 hrs when the whale-to-vessel range was 3.5 km (1.9 nm). The now inactive Western Aleutian broke off her approach towards the whales and turned to the north to resume her original position. Post-disturbance observations continued until 16:20 hrs when the experiment was terminated.

As with the first experiment, the whale behavior data were divided into subsets and compared for differences in conspicuous behavior that may be correlated with distance from the approaching vessel and corresponding sound level. For the Western Aleutian experiment we divided the data into a pre-disturbance period when the vessel was inactive, a period of exposure to seismic sounds at ranges from 7.2 to 5 km (3.8 to 2.7 nm) with measured received sound levels between 164.6 and 16.73 dB re 1 uPa, a period of close exposure between 5 and 3.5 km (2.7 and 1.9 nm) when received levels were 167.3 (estimated) and 169.6 db re 1 uPa (estimated), and post-disturbance periods 0-30 min and 30-60 min following the cessation of seismic sound production (Fig. 12).

The three bowhead whales initially encountered at 10:18 hrs remained under continuous observation until 14:57, when fog intermittently obscured the whales' surfacings. While the vessel was making its approach with its airguns inactive, nine surfacings of these whales were observed. The general behavior for the whales during these surfacings included milling (22% n = 2 sightings), socializing (56% n = 5 sightings), and whales traveling (22% n = 2 sightings) (Table 2). The two traveling observations were of the same individual swimming slowly south. The orientations of the whales as they surfaced, with respect to the position of

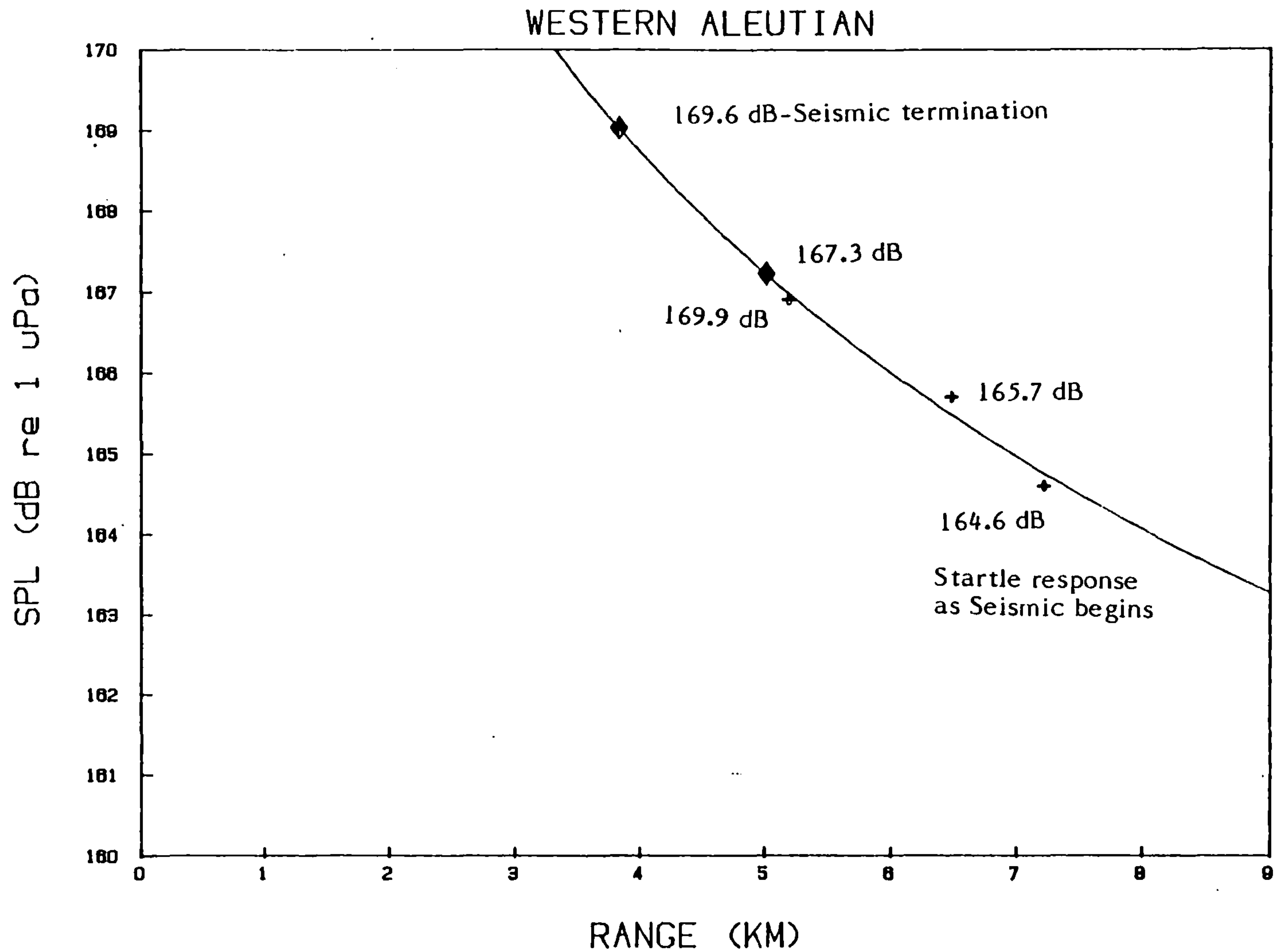

Figure 12. Received seismic sound levels versus range for the Western Aleutian. Line is a least squares regression line fit to the measured sound levels. ◆ = Estimated sound level; + = Measured sound level.

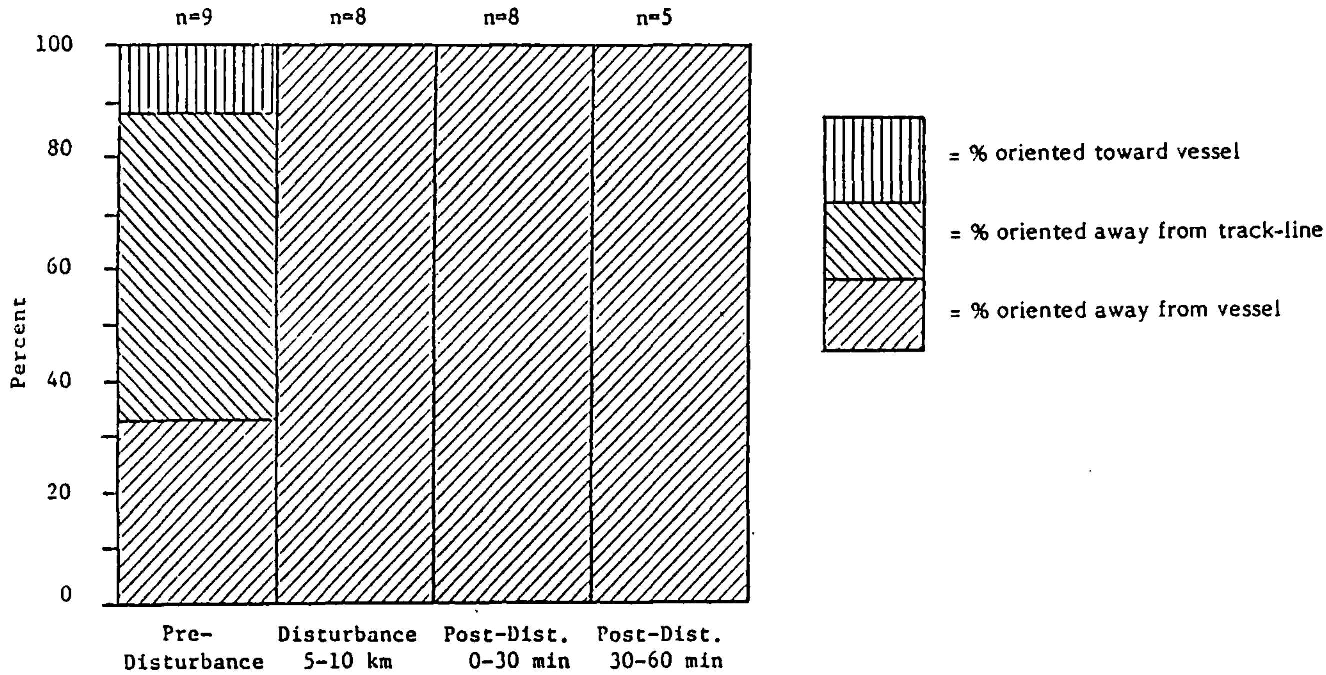

Figure 13. Orientations of surfacing bowhead whales as percent of sightings during a seismic response experiment with the geophysical vessel, the Western Aleutian. Numbers at top of bars are sample sizes.

the approaching vessel, included 11% toward the vessel (n = 1 sighting), 56% oriented (90% to the left or right) away from the vessel (n = 5 sightings), and 33% surfacings were of whales pointed 180° directly away from the vessel (n = 3 sightings) (Fig. 13).

All three whales were at the surface in close proximity to each other when the Western Aleutian activated its airguns at 14:21 hrs; two whales were within one-whale length of each other, and the third was 3-5 whale lengths from the pair. The whales' behavior changed abruptly with the commencement of seismic sounds: they exhibited what we termed a "startle" response (the type of response elicited from humans when a door slams in an otherwise quiet room), which included considerable water disturbance, tail-slaps on the water surface, traveling at moderate to fast speed away from the approaching vessel, and diving together (Fig. 13, Table 2). The whales continued to move in a westerly direction away from the approaching vessel until the termination of the experiment.

Following the termination of seismic sound at 15:00 hrs, the number of recognizable bowhead whales under observation had increased from three to two female-calf pairs and 6 adults. Nine surfacings of these whales were recorded during the first 30 minutes of post-seismic observations. The whales were traveling at slow to medium speed away from the now inactive Western Aleutian. The behavior of the whales seen during seven surfacings in the second 30 minute period following the cessation of the seismic sounds, included milling (14% n = 1 surfacing), and traveling at slow to medium speed to the west (86% n = 6 sightings) (Fig. 13, Table 2). Additional behaviors seen at this time included cow-calf nursing bouts and play.

All of the principal surfacing, respiration, and dive characteristics changed significantly with exposure to seismic sounds following an inactive approach by the Western Aleutian. During the vessel's active approach, the measured and estimated received sound levels changed from 164.6 to 169.9 dB re 1 uPa at ranges from 7.2 to 3.5 km (3.8 to 2.2 nm) respectively (Fig. 14A-D, Table 3).

Mean blow interval increased significantly from 13.0 s during the pre-disturbance approach to 16.6 s during exposure to seismic sounds, and continued to increase to 22.2 s during the first 30 minutes. By the second 30 minute post-seismic period the interval declined to 17.4 s, approaching the pre-seismic value. ($F = 10.342$, $df = 110$, $p < 0.001$). The mean number of blows per surfacing declined significantly from a high value of 8.5 during the pre-seismic period to a low of 2.0 during the first half-hour of post-seismic observations. Like blow interval, number of blows per surfacing began to recover during the second 30 min period of post-seismic observations, and at that time averaged 5.5 blows per surfacing. Number of blows per surfacing during the pre-seismic and second post-seismic periods combined were significantly higher than during the period of active seismic noise and the first post-seismic period combined ($t = 4.217$, $df = 20$, $p < 0.001$).

Mean length of surfacing declined from 1.81 to 0.73 min shortly after the onset of seismic sounds. Following the cessation of seismic sound, this parameter increased from 0.87 to 1.77 min, showing a recovery to the pre-seismic condition. The length of surfacing during exposure to seismic sounds and during the first 30 min of post-seismic observations combined were significantly different from lengths of surfacing during the pre-seismic and second 30 min of post-seismic observations combined ($t = 3.761$, $df = 18$, $p < 0.001$).

The presence of seismic sounds was accompanied by changes in mean length of dive which were similar to changes that occurred in the number of blows per surfacing and length of surfacing. This change showed a significant decline from 17.8 to 3.1 min. After seismic sounds were terminated, the dive duration increased from 7.15 to 15.64 min, thus approaching the pre-seismic dive duration. As with these other characteristics, the length of dive during seismic disturbance and immediately following the termination of the sound was significantly shorter than during the pre-seismic and second post-seismic periods combined ($U = 59.5$, $p < 0.02$). There were insufficient data to determine whether blow rate changed during this experiment.

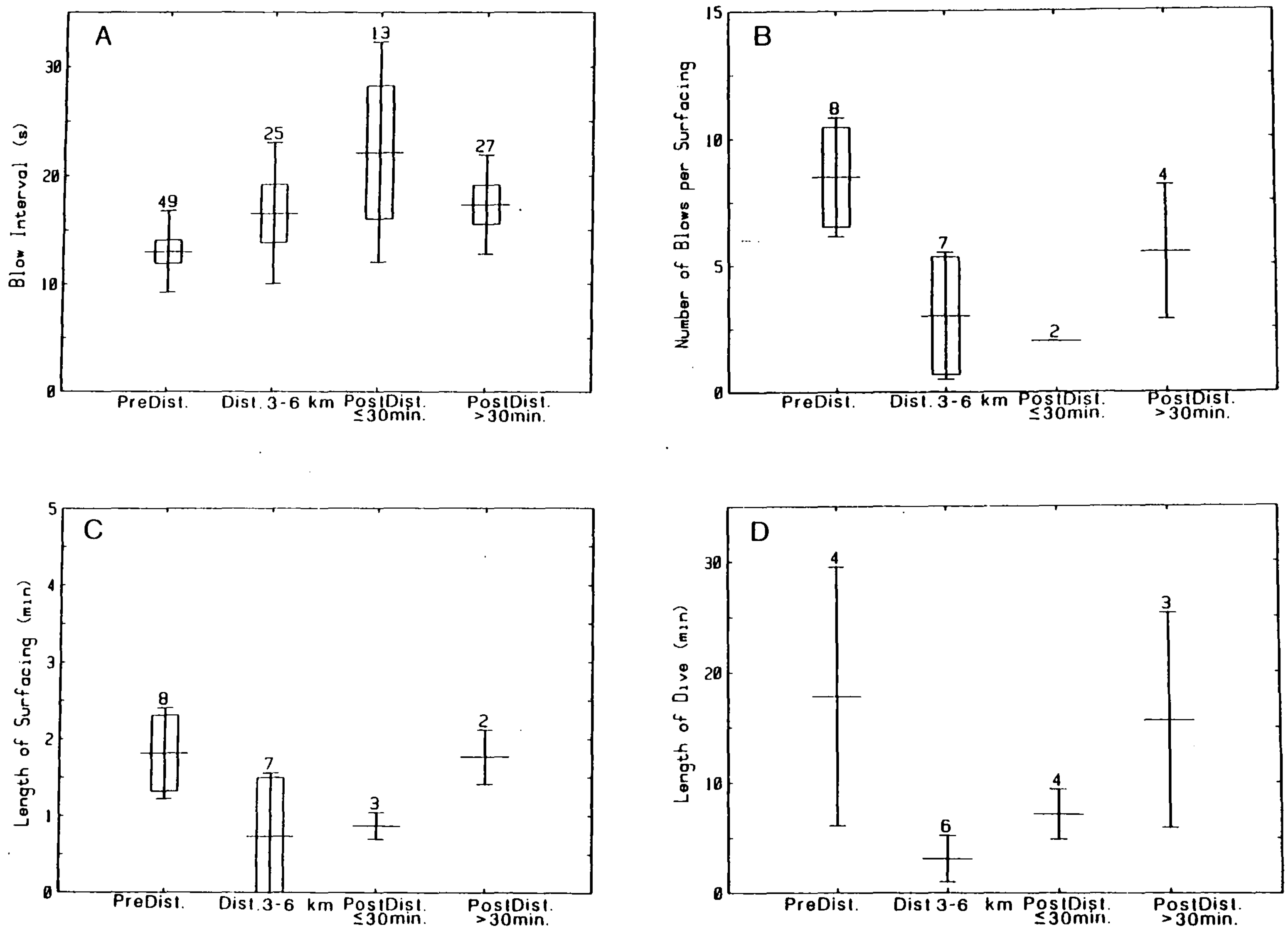

Figure 14. Surfacing, respiration, and dive characteristics for bowhead whales during different categories of exposure to seismic noise from a geophysical vessel, the Western Aleutian. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 95% confidence limits to the mean, and numbers at top of bars are sample sizes.

In summary, the surfacing behaviors and responses to the sudden seismic startup at a range of 7.2 km (3.8 nm) with a received sound level of 164.6 dB re 1 uPa confirmed that bowhead whales do hear and respond to sudden changes in their acoustic environment, at least within the low frequency ranges produced by this geophysical vessel. The surfacing, respiration and dive characteristics all declined significantly when whales were exposed to close seismic sounds at a range of 3.5 km (1.9 nm). These parameters continued to decline during the first 30 minutes of post-seismic observations, however, this decline then reversed during the second 30 minute post-seismic period, and values for the behavioral characteristics indicated a return to pre-seismic conditions. During the 6.0 hours of this experiment the net movement of the whales was 6.5 km (3.5 nm) to the west.

Experiment No. 3: Arctic Star

At 12:01 hrs on 23 September we sighted a minimum of seven bowhead whales, three of which were re-identifiable due to their distinctive markings. The whales were located near 71°07.5' N, 152°14.1' W, approximately 28 km (15 nm) north of Lonely on the shallow shelf area to the northwest side of Harrison Bay (Fig. 2). The visibility was excellent with clear skys and sea state of Beaufort 1. The seismic vessel Arctic Star was located approximately 15.5 km (8.2 nm) south of these whales and was actively shooting. A sonobuoy dropped near the whales revealed seismic sounds with a measured received level of 148.4 dB re 1 uPa (Fig. 15). Radio contact with the Arctic Star confirmed that she was active, that she would complete her survey within 40 min, and that afterward would particpate in a seismic response experiment. At 14:25 hrs the vessel had completed the line, and was requested to remain on standby with its airguns shut down. At 14:30 under experimental direction the Arctic Star changed course to begin an approach toward the whales position with her airguns inactive.

At 15:30 hrs we requested the Arctic Star to become active. The vessel activated 18 of her 24 guns, which fired once every 12 to 14 s, and produced an estimated sound source level of 246 dB re 1 uPa at 1 m (Ljungblad et al. 1984). The distance between the Arctic Star and the whales was 11.6 km (6.2 nm), and at this time the measured received sound level at the whales' position was 154.9 dB re 1 uPa. By 16:30 hrs the active vessel had closed to within 9.04 km (4.7 nm) of the whales and the received sound level measured was 159.1 dB re 1 uPa (Fig. 15). The Arctic Star continued her approach and at 17:30 hrs was within 6.7 km (2.5 nm) of the whales. At this time the measured received sound level near the whales was 165.4 dB re 1 uPa.

The experiment was terminated at 18:10 hrs with only two of the original distinctively marked whales still under observation. Just prior to shutdown, the estimated received sound level was 178.0 dB re 1 uPa at a range of 3.5 km (1.9 nm). The sonobuoy overloaded at this close range, and therefore received levels were estimated from the levels measured at ranges greater than 6.7 km (2.5 nm). The 178.0 dB re 1 uPa may be unrealistically high for this range because estimated received sound levels from geophysical vessels with similar seismic equipment produced lower received sound levels at similar ranges (Figs. 11 and 17). These sound levels may have been the result of unique propagation characteristics of the shallower water or oceanographic conditions at the time of the experiment (Urick, 1967).

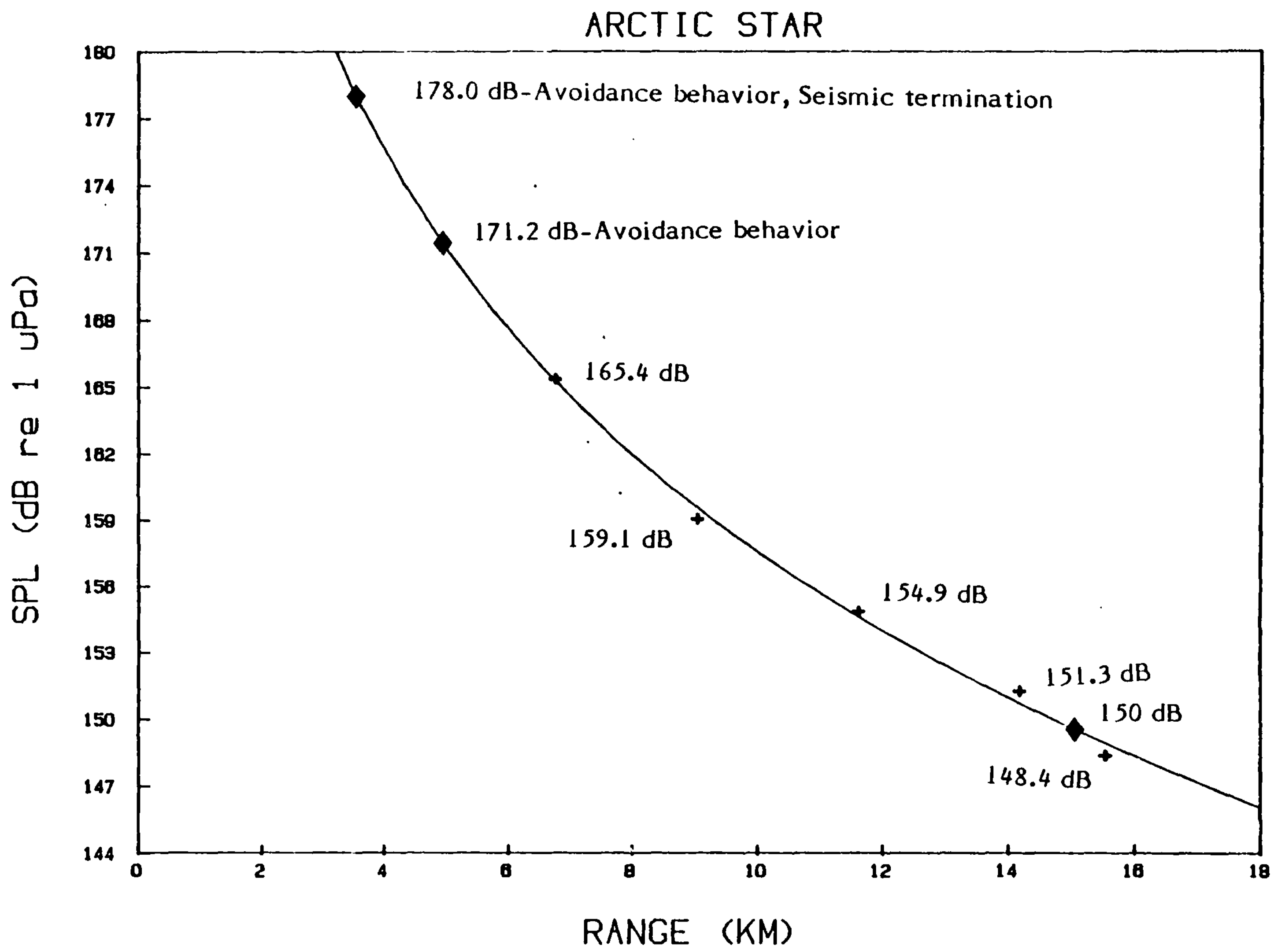

Figure 15. Received seismic sound levels versus range for the Arctic Star. Line is a least squares regression line to fit to the measured sound levels. ◆ = Estimated sound level; + = Measured sound level.

The Arctic Star had been active prior the the initiation of the experiment, and we were therefore unable to obtain pre-disturbance observations at the beginning of the experiment, and post-disturbance observations were not possible due to other geophysical vessels that had become active in the area.

To analyze the Arctic Star response experiment we divided the behavior data into four sub-sets: a period of exposure to seismic sounds of approximately 150 dB re 1 uPa at a range of >12 km (6.4 nm) a post-seismic period between 14:25 and 15:30 hrs when the Arctic Star was inactive at a distance of 12 km (6.4 nm) from the whales, then a second period of seismic disturbance when the vessel was closing from approximately 12 to 5 km (6.4 to 2.7 nm) with sound levels ranging between 154.9 dB re 1 uPa (measured) and 171.2 dB re 1 uPa (estimated), and finally a period of close approach by the vessel when its range to the whales was between 5 and 3.5 km (2.7 and 1.9 nm) with estimated sound increasing to levels between 171.2 and 178.2 dB re 1 uPa (Table 3).

During the initial period of exposure to seismic disturbance at a range greater than 10 km (5.4 nm) we recorded 43 surfacings of at least seven individual whales. General behavior during these surfacings included milling (18% n = 8 surfacings), socializing (13% n = 6 surfacing), and traveling (69% n = 29 surfacings). Of the 29 surfacings of traveling whales, 80% were swimming at medium speed (n = 23 surfacings), and 20% were traveling at slow speed (n = 6 surfacings) (Table 2). The orientations of the whales, with respect to the position of the Arctic Star as they surfaced, included 20% oriented 90° to the left or right away from the vessel (n = 8 surfacings), and 80% were oriented 180° directly away from the approaching vessel (n = 32 surfacings) (Fig. 16).

From 14:30 to 15:30 hrs the Arctic Star ceased seismic activity while remaining on standby, giving us the opportuntity to observe 13 whale surfacings without seismic sounds. General behavior during these surfacings included milling (14% n = 2 surfacings) and traveling (86% n = 11 surfacings) (Table 2). Of those traveling, 60% were swimming slowly (n = 7 surfacings) and 40% traveled at medium speed (n = 4 surfacings). The orientations of the whales as they surfaced were similar to orientations during the previous period of seismic activity: 16% were oriented away from the vessel trackline (n = 2 surfacings), and 84% were facing oriented to the west, away from the approaching inactive vessel (n = 11 surfacings). (Fig. 16).

The Arctic Star became active at 15:30 hrs. All but two whales continued to travel to the west as the active vessel made its approach: 37% moved at slow speed (n = 3 surfacings), and 62% now moved at medium speed (n = 5 sightings). When the vessel had closed to within 3.5 km (1.9 nm), the three animals that had been under constant observation exhibited avoidance behaviors and turned away from the approaching vessel and began swimming to the north.

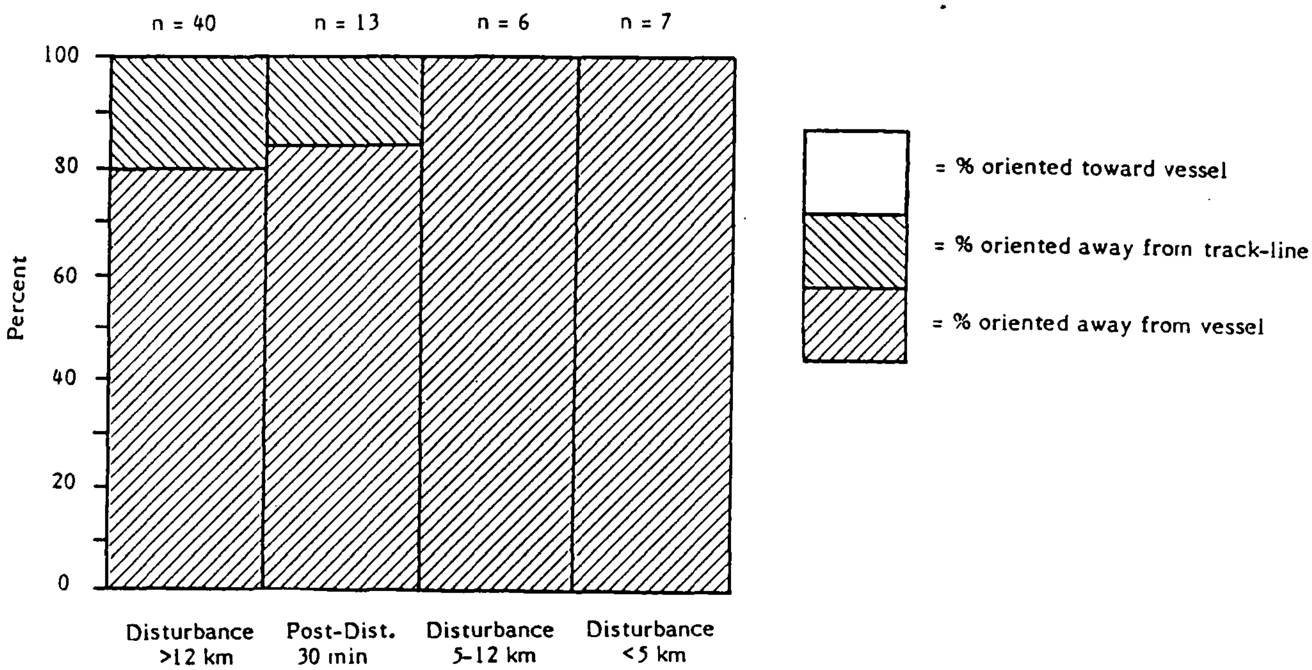

Figure 16. Orientations of surfacing bowhead whales as percent of sightings during a seismic response experiment with the geophysical vessel, the Arctic Star. Numbers on top of bars are sample sizes.

The response experiment with the Arctic Star differed from the other experiments in that a period of post-seismic disturbance occurred during the middle of the experiment rather than at the end. Notably, however, the trends of the surfacing, respiration, and dive characteristics in this experiment were consistent with trends in other experiments (Fig. 17A-D, Table 3).

Mean blow interval during the post-disturbance period were 15.9 s. During the vessel's active approach this interval increased to 17.2 s at a range of greater than 5 km (2.7 nm) and continued increasing as the vessel approached to less than 5 km (2.7 nm). The post-disturbance value for the blow interval of 19.9 s was lower than during exposure to close disturbance but slightly greater than the 15.3 s during exposure to seismic sound at a distance of > 10 km (5.4 nm) ($F = 4.428$, $df = 197$, $p < 0.001$). Blow interval during the closest approach of the active seismic vessel was significantly longer than during any other point during the experiment.

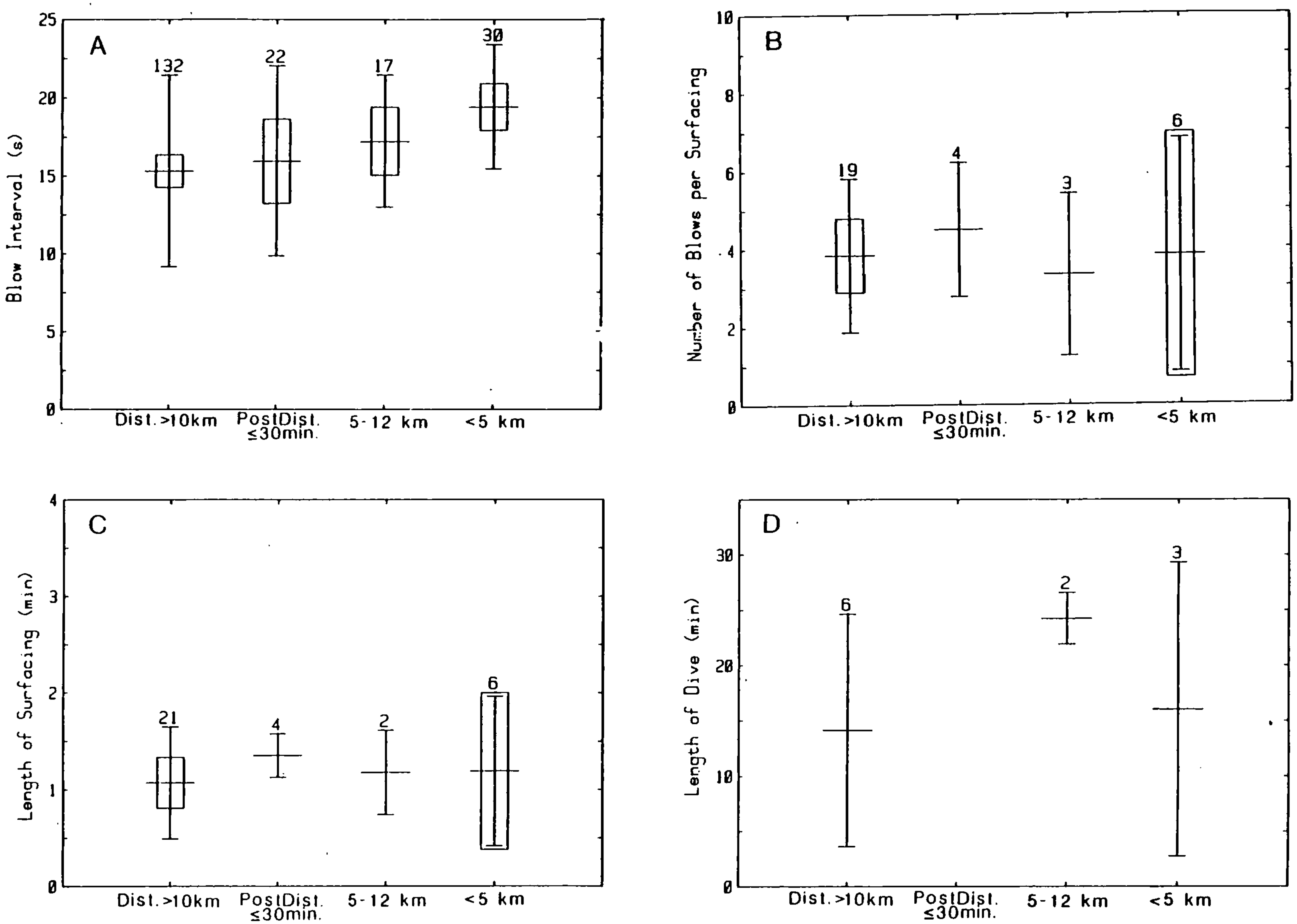

Figure 17. Surfacing, respiration, and dive characteristics for bowhead whales during different categories of exposure to seismic noise from a geophysical vessel, the Arctic Star. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 95% confidence limits to the mean, and numbers on top of bars are sample sizes.

Sample sizes for the number of blows per surfacing, length of surfacing, length of dive, and blow rate were insufficient for meaningful statistical analysis; thus, their values without measures of significance are presented below.

Mean number of blows per surfacing increased from 3.3 to 3.8 during exposure to seismic disturbance between 12 and 5 km (6.5 to 2.7 nm), and from 3.8 to 4.5 blows per surfacing during the post-seismic period. The mean length of surfacing increased slightly from 1.18 to 1.19 min during exposure to seismic noise between 12 and 5 km (6.5 to 2.7 nm), and also increased from 1.07 to 1.35 min during the post-seismic period.

No complete dive cycles for individual whales were observed during the post-seismic period, but mean length of dive decreased from 24.47 to 16.13 min during the close approach by the active seismic vessel. No data on blow rate were obtained during this experiment.

In summary, blow interval, number of blows per surfacing and length of surfacing all increased during progressively closer approaches from 12 to 5 km (6.5 to 2.7 nm) by the active Arctic Star, while length of dive decreased during the same period. This change in blow interval differs from the results of other experiments, in that, as length of surfacing and number of blows per surfacing increased, blow interval decreased. This unexpected result may be, however, the consequence of very small sample size relative to the other experiments. During the post-disturbance period, blow interval, number of blows per surfacing, and length of surfacing all increased.

The observations in this experiment were somewhat difficult to interprete because the majority of the whales were moving slowly through the observation area, and stopped only to feed. Although numerous whales were observed moving slowly past our observation point, only two recognizable animals remained in the area throughout the experiment. The two whales that remained in the area eventually reacted to the approaching vessel at a range of 3.5 km (1.9 nm) by swimming directly from it to the north. The total distance the whales moved during this experiment was 15.8 km (8.8 nm). Although the magnitude of the changes in behavior observed were less than seen in previous experiments, the responses to the onset of seismic sounds were consistent with our observations.

Experiment No. 4: Western Polaris

At 10:30 hrs on 26 September we encountered 25 to 35 bowhead whales within an area centered near 70°28.6' N, 143°14.0' W, approximately 55 km (30 nm) northeast of Barter Island (Fig. 2). Environmental conditions at this time were excellent; weather was clear and sunny with unlimited visibility, and sea-state of Beaufort 0-1. Surface disturbances and blows from additional whales were seen in all directions, bringing our estimate to at least 50 whales within a 25 km^2 (7.25 nm^2) area. By 11:30 hrs we had identified by their distinctive markings two female-calf pairs and four single whales within a 5 km (2.7 nm) diameter circle. The seismic vessel Mariner was actively shooting approximately 28 km (15 nm) to the west of the whales. The received sound levels from this vessel was measured at 120 dB re 1 uPa.

A second inactive seismic vessel, the Western Polaris, was on standby approximately 30 km (18 nm) to the south. We requested the Western Polaris to participate in a response experiment. Her captain indicated that he would participate, and changed the vessel's heading to intercept our position. We requested that the Western Polaris remain inactive during a period of pre-exposure data collection, until she had closed to within approximately 10 km (5.4 nm) from the whales position. At 13:48 hrs the Western Polaris activated 18 of her 24 airguns while the whales were on the surface. The airgun array produced an estimated sound source level of 250 dB re 1 uPa at 1 m (Ljungblad et al. 1984). The received sound level measured at the whale's position 11.7 km (6.2 nm) from the vessel was 154 dB re 1 uPa (Fig. 18).

The active vessel maintained a course directly toward the whales' position. At 14:20 hrs the Western Polaris had closed to 7.02 km (3.72 nm) and measured received sound levels were 158.1 dB re 1 uPa. At 1500 hrs the vessel was requested to terminate their seismic activities, at a distance of 1.8 km (1.0 nm) from the whales. The estimated received level of seismic sounds just prior to shut down was 169 dB re 1 uPa (Fig. 18). At the conclusion of the vessel's participation, the Western Polaris turned westward and passed to the south abeam and within 1.3 km (0.72 nm) of the whales' position. Post-disturbance observations were continued until 16:00 hrs when the experiment was terminated.

To evaluate the response of the whales to the approaching and active Western Polaris, we divided the whale behavior data into five subsets corresponding to different distances between the vessel and whales, and their exposure to seismic sounds. These were: a period of pre-disturbance between 11:30 and 13:48 hrs when the Western Polaris was inactive at a range of >10 km (>5.4 nm), a period of exposure to seismic sound between 13:48 and 14:20 while the vessel approached from a range of 10 to 5 km (5.4 to 2.7 nm) and estimated sound levels were 155.3 to 160.8 dB re 1 uPa, a period of close approach at ranges of 5 km to 1.8 km (2.7 to 1.0 nm) with estimated sound levels ranging from 160.8 to 169 dB re 1 uPa, and two consecutive 30 min periods of post-disturbance observations (Fig. 18).

Pre-disturbance observations of two female-calf pairs, four single whales, and two groups of 7 and 9 whales respectively took place between 11:30 and 13:48 hrs. These observations accounted for 84 whale surfacings while the inactive Western Polaris approached from 30 km to approximately 12 km (16 to 5.4 nm). Whales surfaced individually, in pairs, and in two groups. Behaviors included milling (37% n = 31 surfacings), socializing (56% n = 47 surfacings), and traveling (7% n = 6 surfacings). Of those traveling, 66% were swimming slowly (n = 4 surfacings), and 33% swam at medium speed (n = 2 surfacings.) Cow-calf interactions and synchronous group diving were also seen during this period.

The orientations of the surfacing whales, with respect to the position of the Western Polaris, changed with each surfacing and included 32% (n = 27 surfacings) facing toward the vessel, 47% (n = 39 surfacings) 90° orientedto the left and right away from the Western Polaris; and 21% (n = 19 surfacings) surfaced facing 180° away from the approaching vessel (Fig. 19).

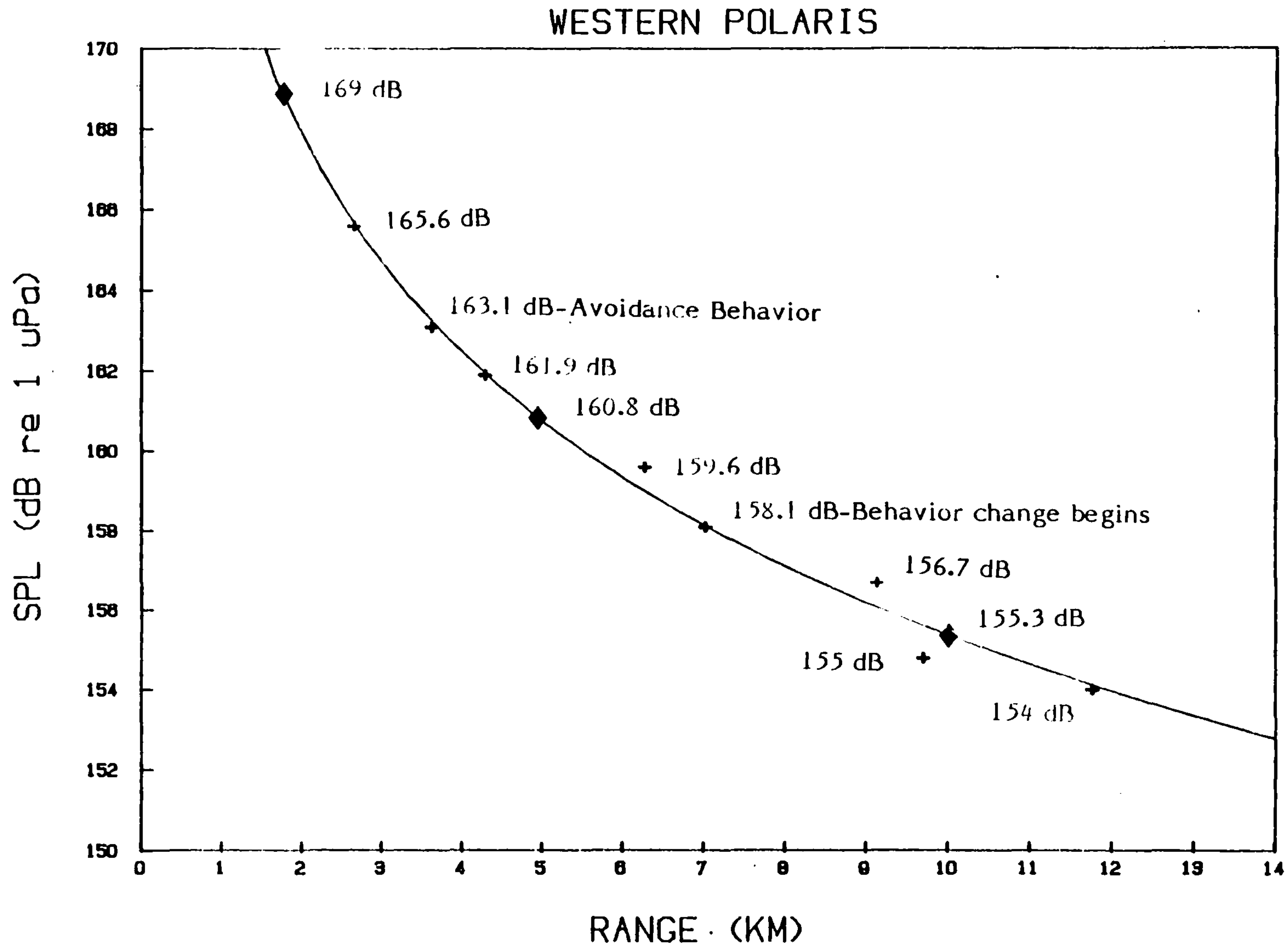

Figure 18. Received seismic sound levels versus range for the Western Polaris. Line is a least squares regression line fit to the measured sound levels. ◆= Estimated sound level; + = Measured sound level.

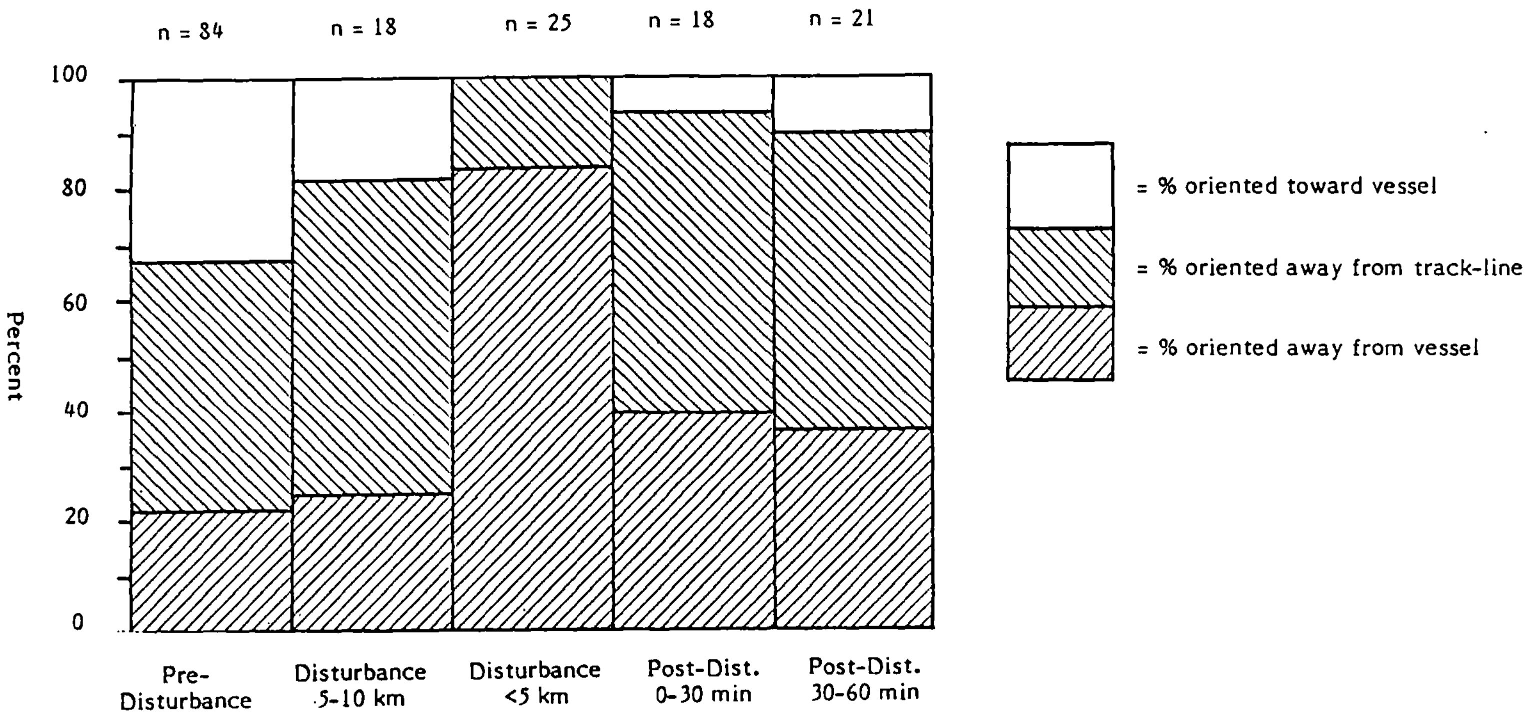

Figure 19. Orientations of surfacing bowhead whales as percent of sightings during a seismic response experiment with the geophysical vessel, the Western Polaris. Numbers at top of bars are sample sizes.

Seismic sound production was initiated at 13:48 hrs when several whales were in view at the surface at a range of 11.87 km, and a measured received sound level of 154 dB re 1 uPa. The whales gave no obvious indication of any startle responses or overt reactions to the seismic sound. Within 15 minutes after the initiation of seismic activity, surface behaviors began to change (Table 3). Prior to the seismic stimulus, calves were closely associated with their mothers but not with each other, and members of groups were loosely associated and socializing. Changes in surface behaviors included close calf-to-calf association, less socializing among the larger groups, and whales drawing closer together on the surface. These surface behaviors finally led to "huddling" (Reeves et al. 1983) of the whales into tight groups while at the surface just prior to swimming away from the approaching vessel.

In another example, shortly before the initiation of the airgun activity, two calves surfaced without their mothers. They remained seven to ten "calf" lengths apart apparently resting or waiting for their mothers. Shortly after the Western Polaris began to fire its airguns, both calves moved toward each other and huddled closely within one calf length, touching, rolling, and slapping their flippers on the water surface. After approximately six minutes of exposure to seismic sounds the calves were joined by three adults, two of which were presumed to be their mothers. All five animals socialized together for a few minutes before moving off away from the approaching vessel.

Eighteen whale surfacings were observed between 13:48 and 14:40 hrs: 12% swam slowly (n = 2 surfacings), 44% traveled at medium speed (n = 8 surfacings), and 44% were judged to be moving at fast speed (n = 8 surfacings) (Table 2). The orientations of the surfacing whales during this period included 17% (n = 3 surfacings) facing toward the vessel, 61% (n = 11 surfacings) pointed away from the trackline, and 22% (n = 4 surfacings) oriented directly away from the approaching vessel.

From 14:20 to 15:00 hrs all whales continued to travel as the active Western Polaris approached from 5 to 1.8 km (2.7 to 1.0 nm) 25 surfacings were observed: 16% (n = 3 surfacings) were of whales traveling slowly, 72% (n = 18 surfacings) swam at medium speed and 12% (n = 2 surfacings) were swimming fast as they surfaced. At each surfacing, whales were moving away from the oncoming vessel during this close approach; no whales were oriented toward the vessel, 16% surfaced facing away from the vessel's trackline (n = 4 surfacings), and 84% were oriented directly away from the vessel (n = 21 surfacings).

The Western Polaris ceased seismic activity at 15:00 hrs. Within minutes some whales ceased traveling and began to mill at the surface. Of 18 whale surfacings observed during the first 30 min post-seismic period, 28% (n = 5 surfacings), were of whales milling and 72% (n = 13 surfacings) continued to travel at slow, (38%, n = 5 surfacings) and medium (62%, n = 8 surfacings) speeds. All fast swimming ceased with the termination of seismic sounds. Orienations of the surfacing whales now included 5% (n = 1 surfacing) toward the inactive vessel, 55% (n = 10 surfacings) surfaced away from the trackline, and 40% (n = 7 surfacings) faced away from the Western Polaris (Fig. 19).

Twenty-one whale surfacings were observed during the second 30 min period of post-disturbance observations. During this time nearly 50% of the whales ceased traveling and surfaced synchronously in groups. Twenty-eight percent of the surfacing whales were judged to be milling (n = 6 surfacings), 20% were socializing (n = 4 surfacings), and 52% continued to travel (n = 11 surfacings). No whales were traveling fast, 61% (n = 7 surfacings) were swimming at medium speed, and 39% (n = 4 surfacings) swam slowly (Table 2). Orientations of the whales upon surfacing were similar to those during the first 30 min of post-seismic observations and included 10% (n = 2 surfacings) oriented toward the vessel, 52% (n = 11 surfacings) faced away from the trackline, and 38% (n = 8 surfacings) were oriented away from the inactive vessel.

The principal surfacing, respiration, and dive characteristics all showed significant changes as the whales were exposed to increasing levels of seismic sounds at a range of about 7 km (4.2 nm). Avoidance behavior while traveling included shallow dives when whales could be seen swimming a few meters below the surface, and whales swimming nose-to-nose in single file directly away from the approaching vessel. Within 30 min after seismic sounds ceased, surfacing, respiration and dive characteristics were similar to those for the pre-exposure period, suggesting a period of recovery of between 30 and 60 min for most whales (Fig. 20A-E, Table 2).

Mean blow interval increased significantly from 14.8 to 16.8 s during exposure to seismic noise, but decreased from 16.2 to 14.3 s during the second 30 min post-seismic period ($F = 3.039$, $df = 636$, $p < 0.05$). The mean blow interval at the end of the experiment was not significantly different from that during the pre-exposure period.

The mean number of blows per surfacing showed similar significant changes during exposure to seismic sounds, decreasing from 8.0 to 3.8 blows when the disturbance was the greatest ($F = 6.806$, $df = 79$, $p < 0.001$). Like blow interval, by the second 30 min post-seismic period, the number of blows per surfacing had returned to values similar to those recorded during the pre-exposure period (Table 3).

Mean length of surfacing decreased significantly from 1.97 to 0.78 min as whales began to travel and make repeated shallow dives, as the vessel drew closer ($F = 6.275$, $df = 84$, $p < 0.001$). The length of surfacing returned to 2.09 min during the second post-seismic period, nearly approaching the pre-seismic condition (Table 3). Length of surfacing during exposure to seismic sound and during the first 30 min following the disturbance was significantly shorter than during the pre-disturbance and second 30 min of post-disturbance observations (Table 3).

Mean length of dive showed the greatest change of all the behavior characteristics, decreasing from 16.17 min during the pre-exposure period to 0.56 min during the vessel approach of less than 5 km (2.7 nm) ($U = 96.0$, $p < 0.02$). At this time the whales were generally traveling away from the vessel at or just below the surface, often in groups. Like the other characteristics, length of dive increased again when seismic sound ceased. During the second 30 min post-disturbance period the mean of 12.56 min was not significantly different from the pre-exposure values (Table 3).

Notably, blow rate ranged from 0.78 blows per min during the pre-exposure period, to 2.84 blows per min when the vessel was less than 5 km (2.7 nm) away, increasing to 2.06 blows per min during the post-disturbance period. However, these changes were not significant ($H = 5.122$, $df = 4$, $p = 0.27$) (Table 3).

In summary, every aspect of the experiment with the Western Polaris approached ideal conditions for a "controlled" field situation. The weather was clear, visibility unlimited, sea state calm and glassy, numerous whales were in the area, and several well marked individuals were easily re-identified. Communications with the vessel were problem free, as were all audio and electronic systems onboard the aircraft. The vessel's intitial 30 km (18 nm) distance from the whales was an advantage because it allowed the documentation

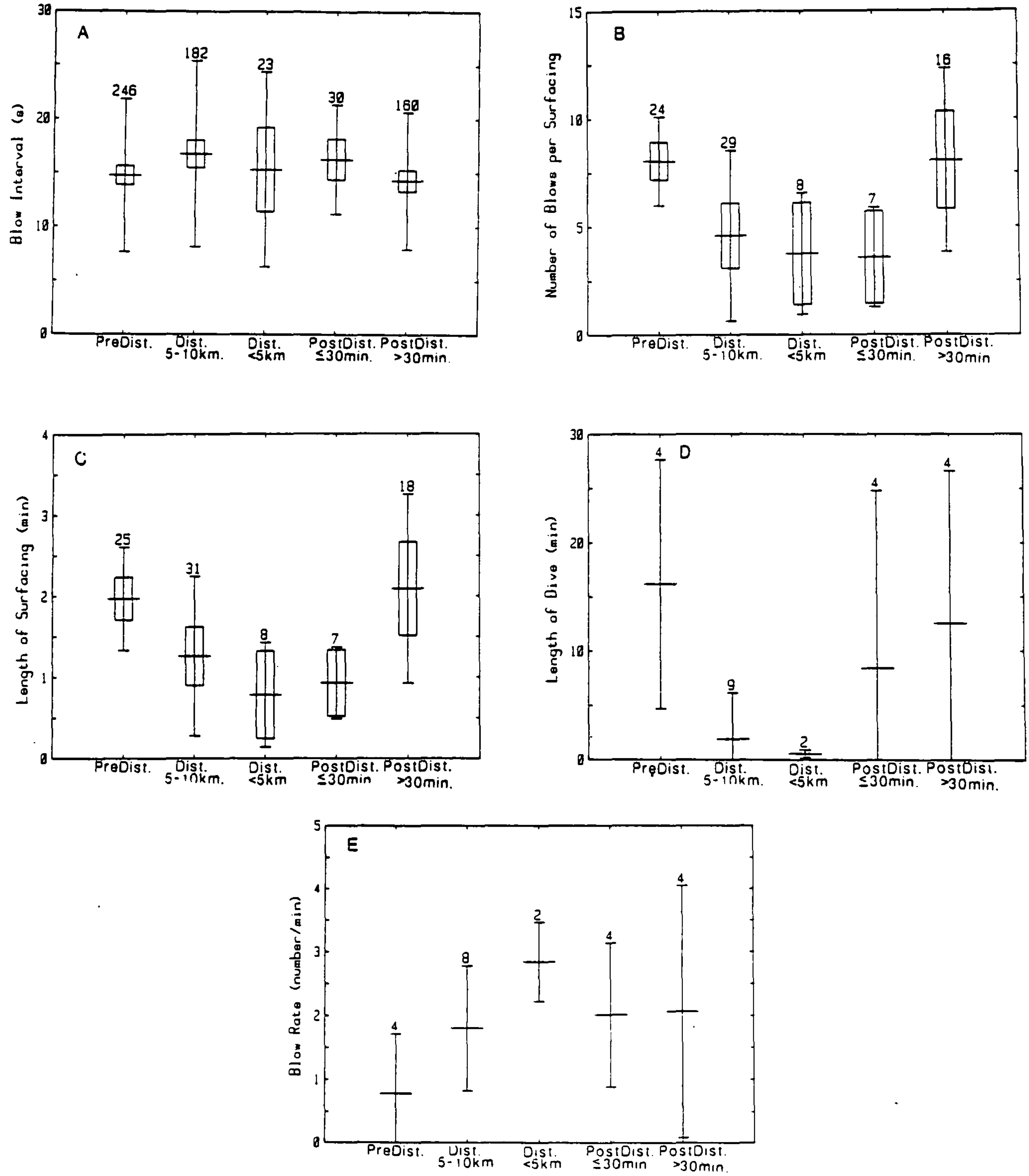

Figure 20. Surfacing, respiration and dive characteristics for bowhead whales during different categories of exposure to seismic noise from a geophysical vessel, the Western Polaris. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 95% confidence limits to the mean, and numbers at top of bars are sample sizes.

of substantial pre-exposure or undisturbed behavior. In addition, there was adequate time prior to the initiation of the experiment to communicate with the vessel and set up the experimental procedure. Following the completion of the seismic approach, the post seismic observations were conducted without interruption from other vessels.

The initiation of seismic sounds and the approach of the active vessel from 11.8 km (6.25 nm) produced a measured seismic level of 154 dB re 1 uPa. The start up did not elicit any startle response or sudden behavior change as in experiment No. 2. Changes in surface associations or respiration, surface and dive characteristics began to occur approximately 15 minutes into the actual approach, at a range of 7 km (4.2 nm) with a measured received sound level of 158.1 dB re 1 uPa. At 3.5 km (2.0 nm) partial avoidance behaviors began with a measured received level of 163.1 dB. When the Western Polaris was 1.8 km (1.0 nm) from the whales and the estimated received sound level was 169 dB re 1 uPa, complete vessel avoidance reactions were exhibited by all whales, with all swimming directly away from the approaching vessel. During the 6.0 hrs of this experiment the net movement of the whales was 4.6 km (2.5 nm) to the west. The final post-seismic observations of the surface behaviors and associated respiration, surface and dive characteristics provide strong evidence that the whales' behavior had returned to near undisturbed pre-seismic condition.

Combined Experimental Results

Whale behavior during all four of the response experiments changed with exposure to seismic sounds, and with the termination of seismic sounds the whales began to exhibit behavior similar to that seen prior to exposure to seismic sounds. The trend for surfacing, respiration and dive characteristics to first change and then recover becomes very apparent when the data from all experiments are pooled into the five disturbance exposure categories; pre-disturbance, disturbance at 5-10 km (2.7 to 5.4 nm), disturbance at less than 5 km (2.7 nm), 0-30 min post-disturbance, and 30-60 min post-disturbance (Fig. 21A-E).

Values for blow interval increased with exposure to seismic sounds at progressively closer ranges, and began to decline once seismic sounds ceased. The number of blows per surfacing, length of surfacing, and length of dive all decreased with the onset of seismic sounds with the lowest values obtained when the sound source was <5 km (2.7 nm) away. When the disturbance ceased, values for these parameters continued to decrease during the first 30 min post period then began to increase to values equivalent to those before the seismic sounds began. Values for blow rate followed a similar trend, except that we obtained very few post-exposure observations and subsequently the return to pre-seismic conditions was not as clear as with the other parameters.

These trends clearly indicate that the whales responded to seismic sounds at ranges of less than 10 km (5.4 nm), with the strongest responses occurring when the whales were within 5 km (2.7 nm) of the sound source. Whale behavior began to recover to pre-seismic conditions within 30 min of the termination of seismic sounds, with definite reversals of the seismic response seen within one hour of the last seismic activity.

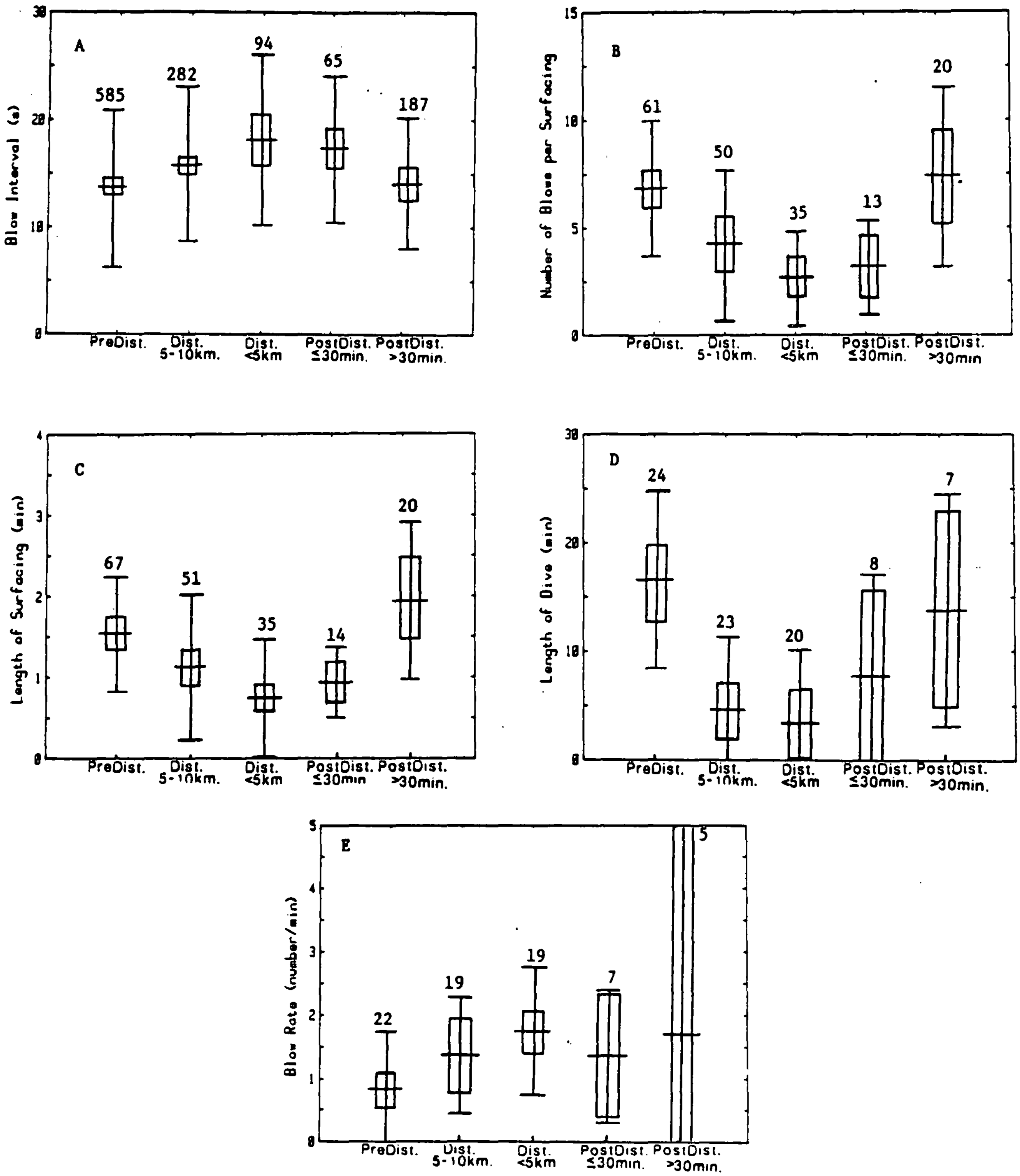

Figure 21. Overall changes in the behavior characteristics for bowhead whales during different categories of exposure to seismic sounds. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 95% confidence limits to the mean, and numbers at top of bars are sample sizes.

DISCUSSION

The experimental paradigm utilized in the bowhead whale seismic reponse experiments gave us the unique opportuntity to address the question of short-term seismic effects in reasonably "controlled" field situations. The exposure of bowhead whales to seismic exploration signals resulted in some significant short-term changes in their surfacing, respiration and dive characteristics, particularly during close approaches by active geophysical vessels. The four experiments presented in this report do provide strong evidence that there exists a predictable "zone of influence" for seismic sounds and vessel noise surrounding an approaching active geophysical vessel that can affect bowhead whale behavior at close ranges.

No discernable behavioral changes occurred during exposure to seismic sound at ranges of greater than 10 km (5.4 nm), with pronounced changes occurring once an active vessel approached to within 5 km (2.7 nm) of the whales. However, Malme et al (1983), point out that airgun arrays are designed to optimize the vertical propagation of low frequencies, and as a result the dominant frequencies on the horizontal beam axis have considerable directivity. Their analysis of the horizontal directivity pattern of a 4,000 cu in. airgun array indicated a lobed propagation pattern rather than uniform spherical attenuation from the source; the measured sound levels were greater directly abeam the geophysical vessel and lowest directly ahead and behind. It is possible, therefore, that bowhead whales directly abeam of an active geophysical vessel could be exposed to greater levels of seismic sounds than if they were directly in front or behind the vessel at the same distance, and that the behavior changes observed in our experiments at ranges less than 5 km (when the active vessels approached directly toward the whales) might also be elicited at ranges greater than 5 km to either side of an active geophysical vessel.

The reactions of the whales exposed to seismic sounds varied somewhat between experiments, but the general trends in the behavioral changes between "undisturbed" and "disturbed" whales were consistent in all instances. With the exception of the Arctic Star experiment, significant behavior changes were noted when the received levels of seismic sounds reached 142 to 164 dB re 1 uPa at ranges from 5 to 7 km (2.7 to 3.7 nm). Avoidance responses to full-scale seismic operations, including orientation away from the approaching vessel and "flight", occurred at ranges of 3.5 to 5 km (1.9 to 2.7 nm) with received sound levels ranging from 160 to 170 dB re 1 uPa. These results are comparable to behavior changes of migrating gray whales (Eschrichtius robustus) in response to exposure to seismic sounds with average pulse pressure levels of 160 dB re 1 uPa (Malme et al. 1983). Malme et al. further indicated that some behavior changes did occur at sound pressure levels between 140 and 160 dB, but that limited observations precluded definite quantification of the responses.

Previous studies of bowhead whales suggest that in general, little change occurs in behavioral parameters between undisturbed and disturbed conditions when whales are exposed to sounds from vessels further than 10 km (5.4 nm) away (Reeves, et al. 1983; Ljungblad, et al. 1984). Richardson (1985) found little evidence that bowhead whales changed their behavior or oriented away from seismic sound sources at ranges between 6 and 99 km, or during three experiments with a single airgun that produced received sound levels of 113-118 dB re 1 uPa at ranges of 3-5 km. Richardson (1985) did observe bowhead whales orienting away from the single airgun when exposed to received sound levels of at least 124-134 dB re 1 uPa at ranges of 0.2-4.5 km, and during an experiment with a full-scale seismic vessel at ranges between 1.5-7.5 km. These observations are consistent with our findings that significant changes in bowhead whale behavior occurred at ranges of less than 10 km (5.4 nm), and that avoidance responses occurred when the seismic sound source was within 5 km (2.7 nm) or less.

The Western Beaufort experiment resulted in behavioral responses that were consistent with responses observed during experiments with full-scale seismic vessels. However, the Western Beaufort differed somewhat by operating only a single airgun, which fires every four seconds instead of once every 12 to 14 seconds which is typical for a full scale seismic vessel. Additional effects from seismic sounds generated from another vessel were also present during the experiment, and at times exceeded sound levels produced by the Western Beaufort. Interestingly, the response of the whales to the seismic sounds became apparent only when the Western Beaufort moved to within 3.5 km (1.9 nm) of the whales despite the presence of additional intermittent seismic disturbance. From this result, we suspect that under some circumstances whales may not respond to seismic sounds alone, and that seismic sounds and ship noise may act together to elicit avoidance behavior, particularly at close ranges. For example, it has been demonstrated that bowhead whales react to ship noise alone at distances of up to 4 km (2.1 nm) (Fraker et al. 1982 and Richardson et al. 1983 and 1984). We were unable to conduct experiments to determine the response of bowhead whales to approaches by inactive geophysical vessels, however, such experiments would contribute valuable information on the significance of seismic sounds in concert with ship noise and their individual and combined affects on bowhead whale behavior.

The conclusion that the influence of seismic sounds on bowhead whale behavior is short-term is supported by the "post-disturbance" reversal of the changes in the whales' surface, respiration and dive characteristics that occurred after the sound disturbance ceased. The trend for these parameters to return to values approaching those prior to the onset of close seismic sounds suggests that a period of between 30 and 60 minutes is required before the whales "recover" from the effects of the close disturbance.

It is significant that conspicuous behavior changes occurred consistently as the seismic vessels approached ranges of < 5 km (2.7 nm), and that bowhead whales appeared to tolerate continuous full-scale seismic sounds at distances greater than 10 km (5.4 nm). Richardson et al. (1984) point out that bowhead whales must routinely experience loud low-frequency calls from conspecifics which may reach source levels of 180 dB re 1 uPa, and that short duration loud seismic pulses may be equally tolerated. Although similar in intensity, whale calls and seismic sounds are very different types of sounds, each with different fundamental components and tonal qualities, and we cannot assume that whales would respond to each in a similar manner. Another major distinction between the responses to whale calls and seismic sounds, particularly at close ranges, may be the added ship-noise component that may cue avoidance reactions.

All experiments, except the Arctic Star, were conducted in water ≥40m deep. The Artic Star experiment was conducted in shallow water ≤29.9m. In this shallow water experiment whales were exposed to seismic sound levels which were greater than sound levels experienced by whales in the deeper water experiments at similar ranges. The received sound levels for the shallow water experiment at ranges of less than 5 km (2.7 nm) were greater by approximately 10 dB re 1 uPa than levels from similar ranges and airgun arrays operating in deeper water. Sound propagation characteristics are highly dependent on bottom loss components for shallow water transmission paths, and are not directly comparable with sounds traveling through deep water (Urick, 1967). We found that the responses of bowhead whales to seismic sounds were not consistent in deep and shallow water, and different propagation properties of sound in shallow and deep water could contribute to the observed reversal of whales' responses to seismic sound. The frequency components and levels of seismic sounds received by the whales (and our sonobuoys) varied with distance from the source and depth, and these progressively changed as the active vessels made their approaches (Appendix A). Whales in deeper water may have been subjected to sounds with similar acoustic qualities in the three deep (40 m) water experiments, thus accounting for the similarity of the trends seen in the deep water. We suspect the accuracy of the close range estimates of 178 dB re 1 uPa, and do not believe that the whale avoidance responses to specific seismic levels in the Artic Star experiment are directly comparable to the responses that occurred during the deep water experiments.

In addition to possible differences in sound propagation properties between shallow and deep water, differences in site specific whale behavior could also have contributed to the trend reversals apparent in the analysis. The Arctic Star experiment occurred in relatively shallow water along the shelf break of Harrison Bay. Whales in this area historically are seen feeding less and more often traveling than whales seen further to the east (Ljungblad et al, 1985). We suspect that in this experiment site specific behavior (i.e., feeding coupled to traveling) may have influenced the whale's response to the seismic sounds, with the exception of direct avoidance, and subsequently confounded the analysis of behavior in deep versus shallow water in this area. Our analysis of whale responses showing reversals of behavioral trends to seismic sounds for the two depth categories (0-29.9 and 30-59 m) support this contention.

The tendency for bowhead whales to dive for shorter periods during exposure to close seismic sounds may also be related to the transmission characteristics of the sounds in water and, thus the levels and frequencies of sound received by the whales at and below the surface. Greene (1984) reported that received levels of seismic sound are reduced near the surface, and, if seismic sound is irritating to the whales, one would expect the animals to spend more time where the sound is the least intense. Our results suggest that whales respond to close approaches by active seismic vessels with shorter surface and dive times. The Western Polaris experiment demonstrated this trend well, as when exposed to loud seismic sound at close range, whales surfaced frequently as they moved out of the area and their dives were short and shallow, often so shallow that whales could be seen swimming just below the surface. Presumably, the region near the surface may expose the whales to the lowest level of sound and resulted in this characteristic flight response.

In summary, the data from the four seismic response experiments provides a consistent picture of short-term disturbance effects elicited by active seismic vessels at close ranges. Initial overt behavioral changes seen during 3 of the 4 experiments occurred at 3.5 km Western Beaufort, 7.2 km Western Aleutian, 7.0 km Western Polaris, with seismic intensities or levels ranging from 142 dB, 164 dB, and 158 dB respectively. Total avoidance responses occurred at 1.25 km Western Beaufort, 7.2 km Western Aleutian, 3.5 km Arctic Star, and 3.5 km Western Polaris with seismic intensities or levels ranging from 152 dB, 164 dB, 178 dB and 163 dB respectively. These effects are both visually apparent and discernable by noting avoidance responses, changes in the length of surfacing, dive times, and respiration characteristics. We feel these data may be used to evaluate bowhead whale responses to seismic sounds in the absence of direct acoustic monitoring. That is, the measured behavior responses to seismic sounds observed in this study could be used to identify, with reasonable limits, whales that are responding to geophysical activities at close ranges, and to predict at what ranges from active geophysical vessels bowhead whales would be likely to respond to and avoid seismic activities.

The information gathered in this study is valuable in the prediction and assessment of short-term disturbance effects to bowhead whales as elicited by seismic operations in the Beaufort Sea, and perhaps it may provide insights into interpreting the behavioral responses for this and other species of cetaceans.

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LITERATURE CITED

Davis, R.A., Koski, W.R. and Miller, G.W. 1983. Prelimnary assessment of length-frequency distribution and gross annual reproductive rate of the western arctic bowhead whale as determined with low-level aerial photography, with comments on life history. Unpub. Rep. from LGL Ltd., Toronto and Anchorage, for Nat. Mar. Mamm. Lab., Seattle, WA. 91 pp.

Fraker, M.A., Ljungblad, D.K., Richardson, W.J. and Van Schoik, D.R. 1985. Bowhead whale behavior in relation to seismic exploraton, Alaskan Beaufort Sea, Autumn 1981. Upubl. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Bureau of Land Management and Minerals Management Service, 37 pp.

Fraker, M.A., Richardson, W.J. and Würsig, B. 1982. Disturbance responses of bowheads. p. 145-248 In: W. J. Richardson (ed.) 1982. Behavior, disturbance responses and feeding of bowhead whales Balaena mysticetus in the Beaufort Sea, 1980-1981. Upubl. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Bureau of Land Management, Washington, D.C. 456 p.

Greene, C.R. 1984. Characteristics of waterborne industrial noise, 1983. p. 217-308 In: W.J. Richardson (ed.) 1984. Behavior, disturbance responses and distribution of bowhead whales Balaena mysticetus in the eastern Beaufort Sea, 1983. Unpubl. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Management Service, Reston, VA. 361 pp.

Ljungblad, D.K. 1981. Aerial surveys of endangered whales in the Beaufort Sea, Chukchi Sea, and Northern Bering Sea. Final Report: Fall 1980. Rep. to Minerals Management Service, Alaska OCS Region. Naval Ocean Systems Center (San Diego), Technical Document No. 449.

Ljungblad, D.K., Würsig, B., Reeves, R.R., Clark, J.T. and Green, C.R. Jr. 1984. Fall 1983 Beaufort Sea seismic monitoring and bowhead whale behavior studies. Rep. to Minerals Management Service, Alaska OCS Region, under Interagency Agreement No. 14-12-0001-29064. 77 pp.

Ljungblad, D.K., Moore, S.E. and Clarke, J.T. 1985. Assessment of bowhead whale (Balaena mysticetus) feeding patterns in the Alaskan Beaufort and northeastern Chukchi Seas via aerial surveys, fall 1979-1984. Rep. Intl. Whal. Comm. SC/37/PS1.

Malme, C.I., Miles, P.R., Clark, C.W., Tyack, P. and Bird, J.E. 1983. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior. Unpubl. Rep. from Bolt Beranek and Newman, Inc., Cambridge, MA, for U.S. Minerals Management Service, Alaska OCS Region, Contract No. AA851-CT2-39.

Reeves, R.R., Ljungblad, D.K., and Clarke, J.T. 1983. Report on studies to monitor the interaction between offhsore geophysical exploration activity and bowhead whales in the Alaskan Beaufort Sea, Fall 1982. Report to Minerals Management Service, Alaska OCS Region under Interagency Agreement No. 41-12-0001-29064. 38 pp.

Richardson, W.J., Davis, R.A., Evans, C.R. and Norton, P. 1983. Distribution of bowheads and industrial activity, 1980-1982. p. 269-357. In: Richardson, W.J. (ed.) Behavior, disturbance responses and distribution of bowhead whales Balaena mysticetus in the eastern Beaufort Sea, 1982. Unpubl. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Management Service, Reston, VA. 357 pp.

Richardson, W.J., Wells, R.S. and WUrsig, B. 1984. Disturbance responses of bowheads, 1983. p. 101-215. In: Richardson, W.J. (ed.) 1984. Behavior, disturbance responses and distribution of bowhead whales Balaena mysticetus in the eastern Beaufort Sea, 1983. Unpubl. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX, for U.S. Minerals Management Service, Reston, VA. 361 pp.

Richardson, W.J. (ed.) 1985. Behavior, disturbance responses and distribution of bowhead whales Balaena mysticetus in the eastern Beaufort Sea, 1980-84. Unpubl. Rep. from LGL Ecol. Res. Assoc., Inc. Bryan, TX, for U.S. Minerals Management Service, Reston, VA 305 pp.

Safar, M.H. 1984. First break I.S.S.N. 0263-5046 QUAERE. ET. INVENIES. 2(2):20-24. 24.

Sokal, R.R. and Rohlf, F.J. 1981. Biometry; the principles and practice of statistics in biological research, 2nd Ed. W.H. Freeman, San Francisco. 859 pp.

Urick, R.J. 1967. Principles of underwater sound for engineers. McGraw-Hill, New York, 341 pp.

WUrsig, B., Dorsey, E.M., Richardson, W.J., Clark, C.W., Payne, R.S. and Wells, R.S. 1984a. Normal behavior of bowheads, 1983. p. 23-99 In: Richardson, W.J. (ed.) Behavior, disturbance responses and distribution of bowhead whales Balaena mysticetus in the eastern Beaufort Sea, 1983. Unpubl. Rep. from LGL Ecol. Res. Assoc., Inc., Bryan, TX to U.S. Minerals Management Service, Reston, VA. 361 pp.

WUrsig, Dorsey, E.M., Fraker, M.A., Payne, R.S., Richardson, W.J. and Wells, R.S. 1984b. Behavior of bowhead whales, Balaena mysticetus, summering in the Beaufort Sea: surfacing, respiration and dive characteristics. Can. J. Zool. 62(10):1910-1921.

Zar, S.H. 1984. Biostatistical analysis. 2nd Ed. Prentice-Hall, Inc., Englewood Cliffs, NJ. 718 pp.

APPENDIX A

MODIFICATION DETAILS AND ANALYSIS OF RESULTS FROM SSQ-41A SONOBUOYS USED TO MONITOR SEISMIC AIR GUN SOUNDS IN THE ALASKAN BEAUFORT SEA

INTRODUCTION

It has become increasingly important to gather quantitative acoustic data during the study of bowhead whale behavioral response to geophysical seismic sounds to support the conclusions reached through traditional observational methods. To this end, a sonobuoy-based sound acquisition system was designed to provide a definitive measure of the sound pressure level in the vicinity of the whales. The analysis of these signals and levels provide the predictive qualities necessary to make prudent policy decisions regarding the impact of industrial activity on endangered whales in the Alaskan Beaufort Sea.

METHODS

Equipment and Modifications

The instrument chosen for this effort was the AN/SSQ-41A, which is an expendable sonobuoy that is dropped into the sea from an aircraft. It detects and amplifies underwater sounds that modulate a self-contained FM transmitter. The FM signals are then transmitted to an associated sonobuoy receiver in the aircraft. This sonobuoy was chosen over other models for several reasons, including ease of modification, reliability, and general availability to our research group. The standard buoy consists of a four-element hydrophone arranged in a shaded-line array, a preamplifier, 300 feet of connecting cable, a primary amplifier, and an FM transmitter. A functional block diagram of the 41A appears in Figure 1. The hydrophone/preamp operational depth can be adjusted for 50 or 300 feet, and the unit can be set to scuttle in 1 or 3 hours. Onboard the aircraft, the signals were received on a modified USQ-42 FM receiver and recorded on a Nagra IV-SJ analog tape recorder.

The choice of the 41A buoy was not without its liabilities, however. The standard sonobuoy is designed for anti-submarine applications and as such proved to be too sensitive for sounds of the level emitted by seismic air guns. Near field seismic sounds will cause the system to go into an overload condition, rendering the resulting sound recordings useless. In addition, the frequency response of the system is designed to be the complement of the typical ambient noise spectrum; that is, with the low frequencies somewhat attenuated. Although the uneven response can be corrected with some post-processing compensation, it was desired to have all frequencies of interest amplified equally at the sonobuoy level. Finally, the presence of an Automatic Gain Control (AGC) in the electronics makes the system unable to determine absolute sound level measurements because the AGC automatically compensates for increased levels. Therefore, to make the buoy suitable for our application, electrical modifications to the AGC and detetion circuits were necessary.

The overall design goal of the modification project was to provide a buoy that could be confidently used to monitor and record seismic signals, with its performance limitations carefully defined. This included attention to frequency response, system gain stability, conditions indicating overload, and reliability of deployment.

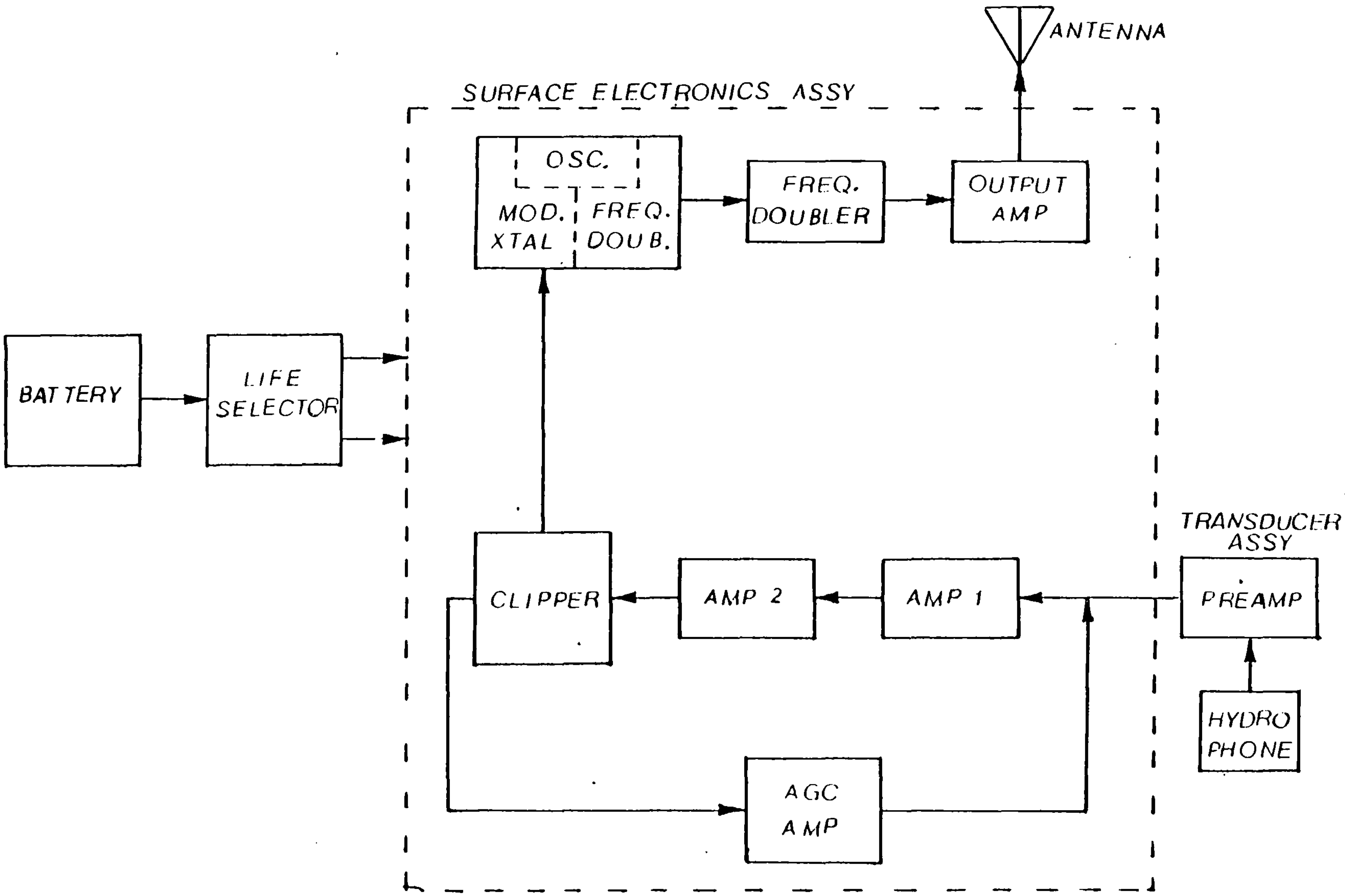


FIGURE 1. Unmodified 41A sonobuoy functional block diagram

It was decided that the 41A system should be modified such that a seismic pulse equivalent to a sound pressure level of 165 dB re 1 uPa would pass through the buoy electronics without significant distortion. In addition, to keep the modification costs low and insure that the buoy's proven deployment reliability was not threatened, it was decided to concentrate the effort on the main electronics board rather than on the less accessable hydrophone/preamp module.

A schematic diagram (Fig. 2) accompanies the following tutorial. First, it was desirable to disable the 41A's AGC, which was originally designed to provide a constant output with an input signal change of $\pm$ 6dB. The AGC action was eliminated by cutting the printed circuit trace connecting the emitter of transistor Q201 with the primary signal path between C202 and C204, thus preventing the gain correction voltage from entering the system. Next, tests were run on the buoy to determine its overall frequency response between 10 and 100 Hz (Fig. 3). By removing capacitors C211 and C216, the low frequency response was flattened to $\pm$ 1dB over the desired frequency range (Fig. 4). The other performance characteristics of the circuit were not affected by these changes.

The bulk of the modification effort was centered on the de-sensitization of the buoy electronics. Preliminary tests were run to determine where signal saturation occurred as a function of input. It was found that, with a gain reduction, the hydrophone and its associated preamplifier were capable of passing a 250 Hz sine wave equivalent to a maximum sound pressure level of approximately 190 dB (re 1 uPa) without significant distortion. The unmodified main amplifier board distorted the same signal at approximately 140 dB. It was clear that to meet the design goal of 165 dB, changes had to be made to the main amplifier electronics. The gain of the preamplifier was permanently reduced from +14 dB to -2 dB by removing R201, the 27 K Ω($\pm$ 5%) preamp gain resistor, and replacing it with a more stable 1800 Ω($\pm$ 1%) metal film resistor. In addition, a 200 KΩ resistor, acting as an attenuator in this case, was inserted into the main signal path between C202 and C204 to further reduce the amplitude of the incoming pulse. Readjustment of the main amplifier gain potentiometer was also necessary, but this procedure will be described in more detail later.

Sonobuoy Calibration

To insure that the data quality was absolutely consistent regardless of the buoy used, a careful calibration was performed on each sonobuoy prior to the field season. This approach was considered feasible because only forty units were required to supply the investigators with enough buoys to complete the study. The calibration phase was approached on two levels. An electronic calibration was performed on each unit, consisting of a known electronic signal injected into the hydrophone amplifier, which allowed precise adjustment of system gain. In addition, random buoys were selected to undergo a complete system calibration, performed in a water tank with a variable sound source and a calibrated hydrophone. Each of the calibration methods are described in detail below.

The instrumentation for the electronic calibration consisted of a Wavetek Model 132 VCG/Noise Generator, two Hewlett Packard Model 355C and 355D VHF attenuators, Tektronix Type 453 oscilloscope, a Global Specialties "Max 100"

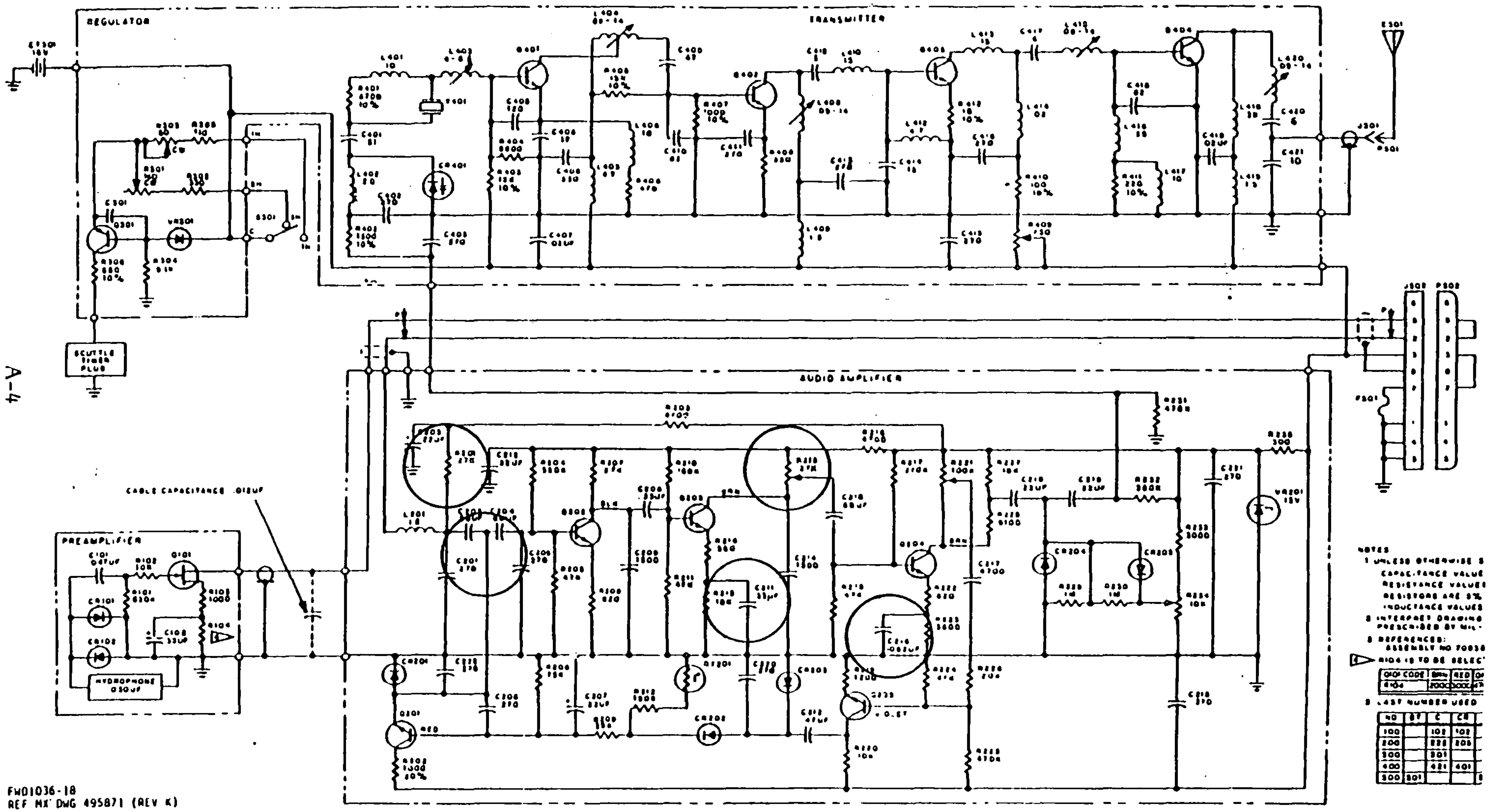
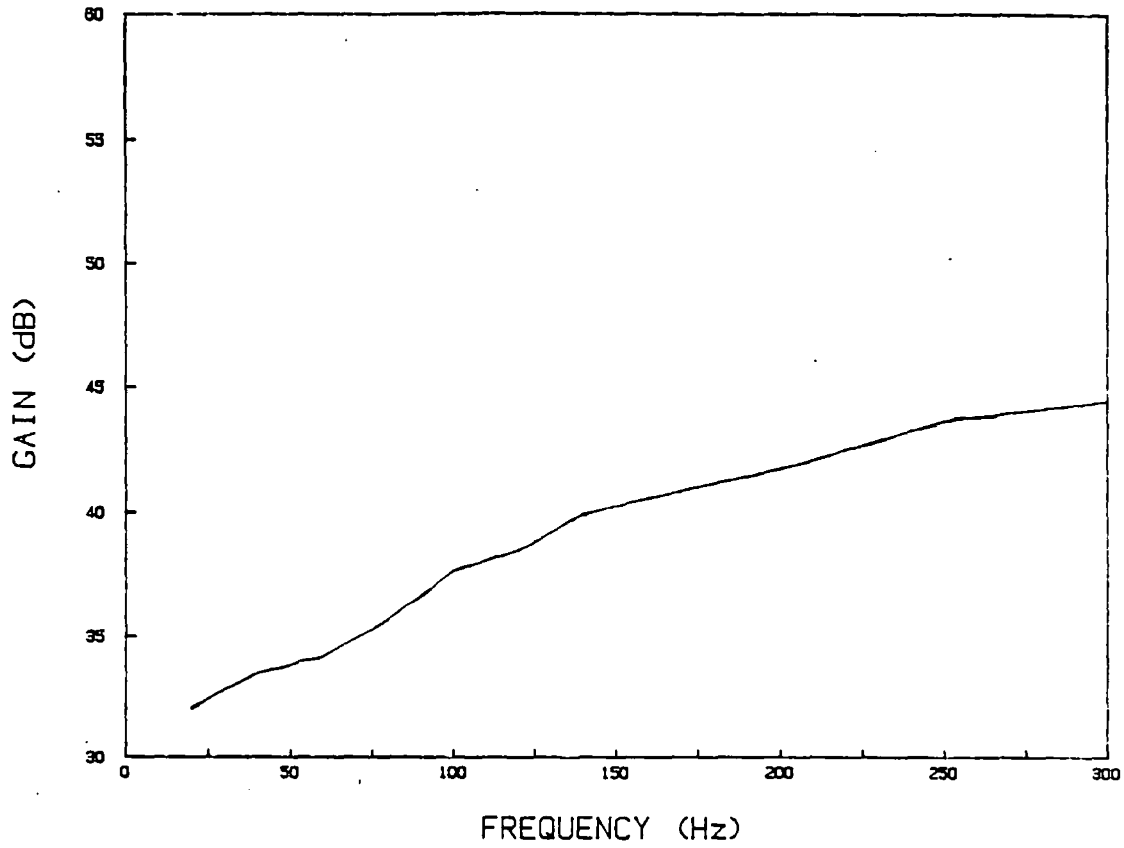


FIGURE 2. Unmodified 41A sonobuoy schematic (circles denote points of modification)



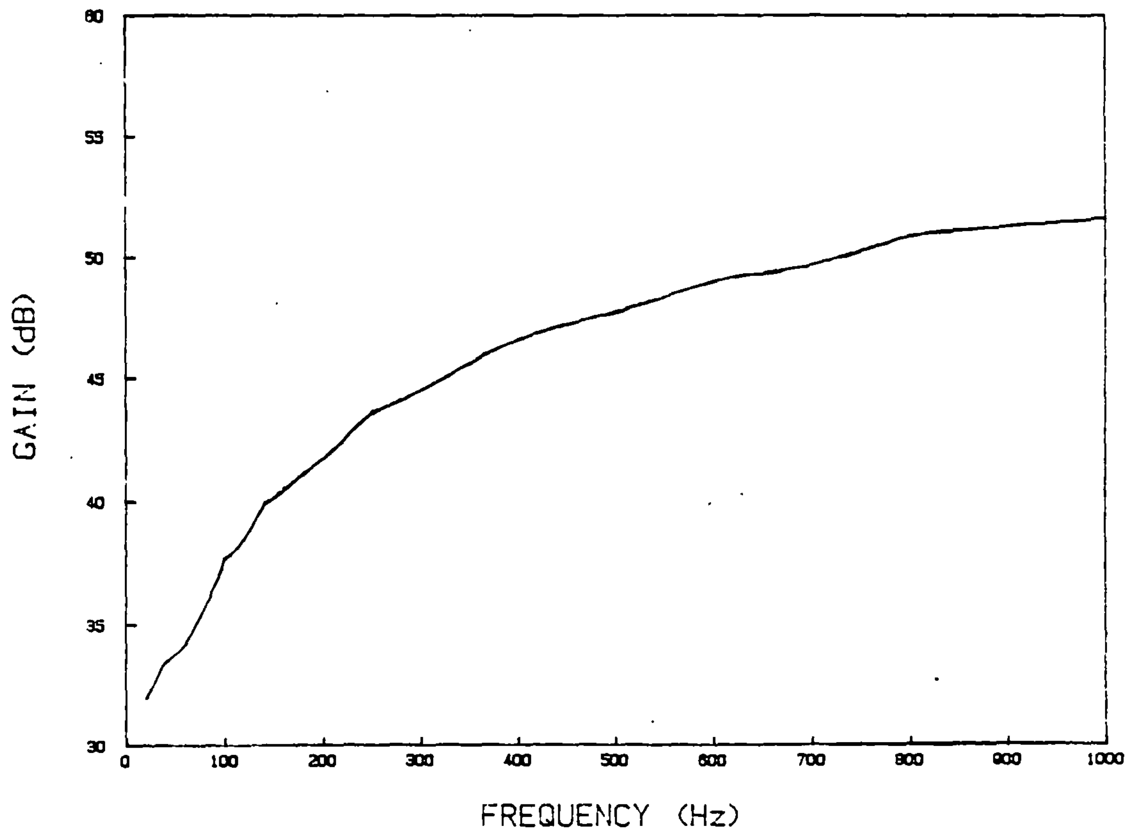


FIGURE 3. Unmodified 41A sonobuoy frequency response, 0-300 Hz (top), 0-1000 Hz (bottom)

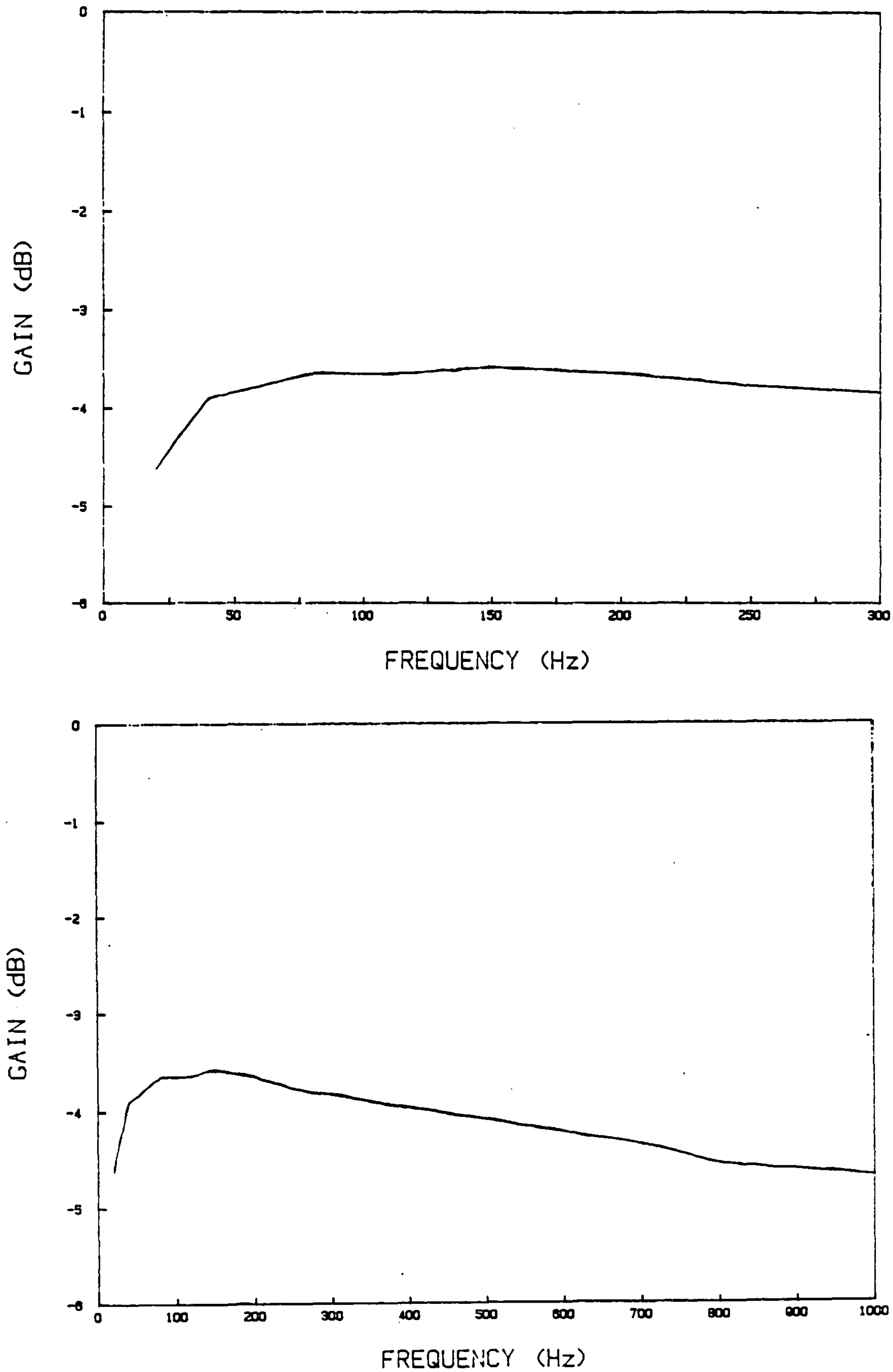


FIGURE 4. Modified 41A sonobuoy frequency response, 0-300 Hz (top), 0-1000 Hz (bottom)

frequency counter, a Hitachi VR-3525 digital multimeter, a Model USQ-42 receiver, and the sonobuoy under test (Fig. 5). Preliminarily, a 100-1000 Hz frequency response check was made to insure that the modified buoy electronics demonstrated the expected flatness. A 250 Hz sine wave, of a magnitude chosen according to the stamped sensitivity on the hydrophone, was then injected at L201 on the main amplifier board. The voltage at the receiver output was adjusted using the system gain potentiometer (R213) to .090 Vrms, which represented the minimum gain achievable without degrading performance. The output signal was also observed on the oscilloscope for evidence of distortion under maximum input signal conditions. The frequency response was then tested again after the gain adjustment, in a stepwise fashion, over the 10-100 Hz frequency range. A computer program, written on a Radio Shack Model 100, was used to facilitate entry of the data and the computation of system gain.

The sonobuoy hydrophone could not be calibrated by the electronic means described above, so a water tank calibration was conducted to test the system's response to actual underwater sounds. A circular pool of 20 ft. diameter and 4 ft. depth was filled with fresh water and rigged to accept a type J9 underwater transducer, a calibrated LC-10 hydrophone, and the sonobuoy to be tested. In addition to the test equipment previously described, the support instrumentation included a Pioneer SA-608 power amplifier (for the sound source) and a Princeton Applied Research differential amplifier (for the LC-10). The equipment was configured as shown in Figure 6. A stepwise sweep of frequencies between 20 Hz and 1000 Hz was applied to the J9 and the resulting signals were analyzed using a computer program designed for this purpose.

The use of a continuous-wave sound source in a small tank should be approached with caution due to the superposition of various reflected components on the primary signal of interest. To this end, no effort was made to use the J9 transducer as a calibrated sound source; rather, a calibrated LC-10 was tightly coupled to the test sonobuoy hydrophone as an indicator of the sound level received at that point, regardless of its origin. The driver frequency was adjusted slightly at each step such that the signals from both the test hydrophone and the calibrated LC-10 resembled sinusoids as much as possible. The sound pressure level could then be determined with the RMS voltmeter and the computer.

The tank tests generally yielded expected results when compared to values mathematically derived using the electronic CAL and the known hydrophone sensitivity (to ± 2dB). Because complete disassembly of the buoy was necessary for these tests, the tank calibration was performed on only five of the forty buoys chosen for modification. In computations involving hydrophone sensitivity, the stamped value assigned by the manufacturer was assumed to be accurate. This assumption is supported by Fish (1977), who reported that fourteen 41A hydrophone arrays calibrated at NOSC's transducer evaluation center (TRANSDEC) matched stamped sensitivity values to ± 1dB from 20 Hz to 500 Hz.

In addition to the buoys described above, a group of ten were specially modified so that their hydrophone arrays deployed to a depth of 3 meters rather than the standard 20 meters. These were included to test for the variability of sound level and spectral character with depth. The depth modification required disassembly of the hydrophone/preamp/cable module and mechanically restraining the cable at the

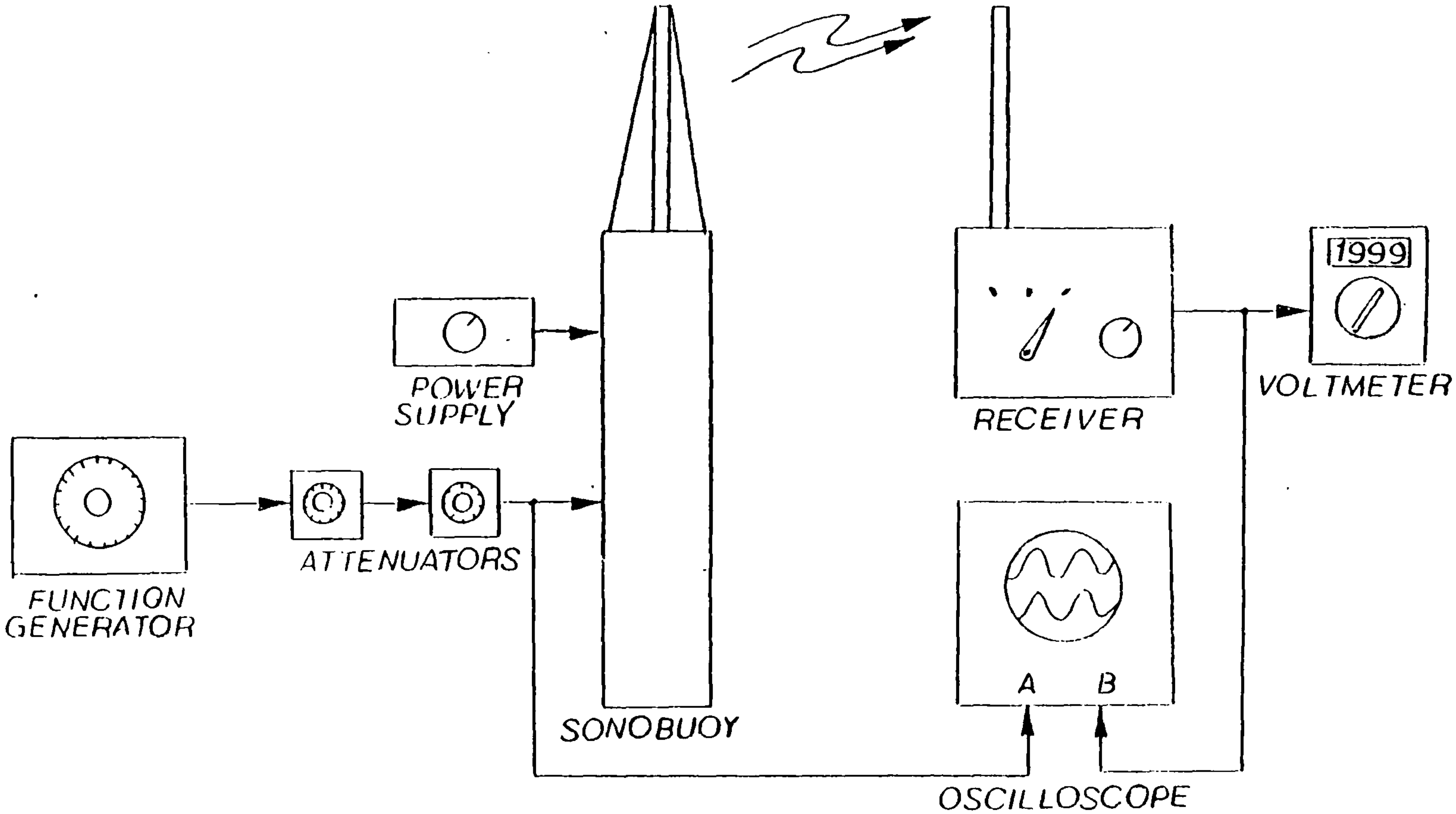


FIGURE 5. Electronic calibration test equipment

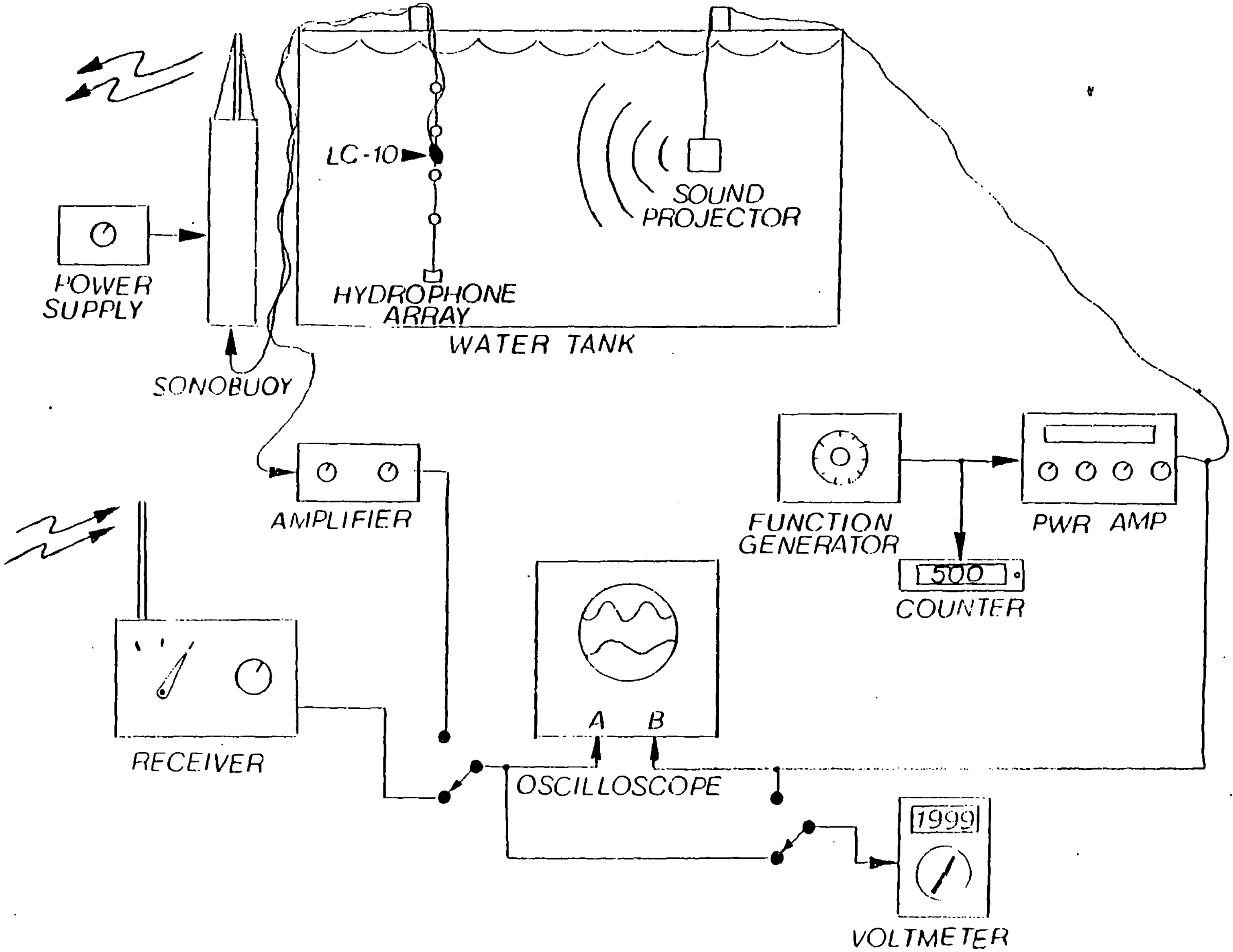


FIGURE 6. System calibration test equipment

desired length. Special care was taken to insure that the modification did not interfere with the normal deployment sequence of the buoy. The integral damping action of the cable was disrupted somewhat, so this group of buoys were considered for experimental use only and data taken are not included in the analysis portion of this appendix.

Field Procedures

The acoustic monitoring procedures were essentially the same for each of the four bowhead/seismic response experiments. When a group of whales was located, a type SSQ-57A sonobuoy was dropped first to detect seismic activity in the area, as well as whale sounds. The use of this buoy was necessary because the modified 41A had a dynamic range down to about 120 dB re 1uPa, and could not pick up whale sounds unless they were fairly loud and close by. If an experiment was to take place, a modified buoy was then dropped in the study area. Each buoy type transmitted on an exclusive frequency and was monitored continuously through one of two available FM receivers onboard the aircraft. The seismic sounds were collected on one channel of a Nagra IV-SJ instrumentation-quality tape recorder, with whale sounds and voice commentary (including behavioral data and sonobuoy system parameters) recorded on the other channel.

During the course of an experiment, the overall seismic sound level was indicated on the Nagra input meter. Although this could not be used as a definitive measure of the level at a particular frequency, it served as a general indicator that the sonobuoy was operating as designed and was not overloading. Sound levels were continuously monitored throughout the experiment, even if system overload was indicated, because quite often the seismic vessel would pass by the monitoring buoy and the level would have dropped to the point that the buoy was once again in its linear operating region.

ANALYSIS

The analog tape recordings were analyzed in the laboratory in both the time and frequency domains, using the transient-capture mode of a Spectral Dynamics Model 375 spectrum analyzer. With an analysis bandwith set to 500 Hz, the SD375 digitizes the input signal at a rate of 1280 samples/second. The memory period, or time width of the time-domain signal, is 0.8 sec, which allows for a total of 1024 samples for each sesmic pulse analyzed. To achieve a frequency-distributed set of voltage levels, the SD375 performs a Fast Fourier Transform (FFT) on the time data. The transformed data, combined with a weighting function (which prevents spurious frequency components from appearing due to discontinuities at the ends of the time sample) is presented as a spectrum of 400 cells, with a cell bandwidth of 1.25 Hz.

The analysis of the data collected from the experiments had to be approached carefully due to the configuration of the modified 41A's transducers. Frequency-dependent vertical directionality is introduced into the system when a linear array of hydrophones is used, causing a rejection of spurious noise due to reflections from the ocean floor and surface. This is a distinct advantage in submarine detection, but potentially causes difficulties in interpretation of the data in our application.

However, the hydrophone is specified to operate omnidirectionally in the vertical plane to ± 3dB between 10 and 300 Hz, and undergoes a "soft" transition to full directionality between 300 and 1540 Hz, so data collected to 300 Hz can be considered valid for this analysis.

The seismic impulse waveform was stored and plotted in the time-domain with linear scaling appropriate to the size of the signal. In keeping with the analysis procedures adopted by Greene (1984), the effective (rms) sound pressure level with respect to 1 volt was determined by measuring and squaring the peak value of the highest amplitude component of the pulse , dividing by 2, and computing 10 times the logarithm (base 10) of the result. This was equated to a known calibration sine wave, and the sound pressure level in decibels with respect to 1 micropascal was determined (noted on each plot). In computing the rms value of a pulsive signal in the manner described, it is necessary to make the assumption that the largest peak in the waveform is essentially sinusoidal in nature, which is generally the case with seismic-type signals. It is obvious that the effective pressure reported did not exist for the entire duration of the blast, but it may be reasonable to suggest that the animals react (at least in the short term) to the highest amplitude component of the signal, if the frequencies lie within the sensitive range of their hearing.

The stored seismic waveform was analyzed for frequency content using the SD375 Spectrum Analyzer and plotted over a range of 0 to 500 Hz. As noted before, only data to about 300 Hz should be considered valid because of directivity effects imposed by the use of hydrophone arrays in our application. The amplitudes are reported as spectrum levels (dB re $1uPa^2/Hz$), which relate the relative energy of the pulse in a 1 hertz frequency band. Since the analyzer's resolvable bandwidth is 1.25 Hz/line, the spectrum level had to be reduced to 1 Hz by applying a correction to the data of -.97 dB across the entire band.

RESULTS AND DISCUSSION

Typical time and frequency-domain plots, arranged together by vessel and range, are presented in Figures 7-13. The characterizations of the Western Beaufort (Figs.7-8) show features that made it distinct from the other vessels. The Western Beaufort is normally contracted to perform single-gun, "high resolution" work; that is, shallow penetration studies of areas already profiled by vessels equipped with multiple gun arrays. Examination of the plots shows that the single gun produced an output that is lower in overall level, and had a relatively wide band of near-equal energy from approximately 50 to 300 Hz (especially apparent at the 1.29 km range). The recorded pulses also had a "crisper" sound, without the frequency sweeps that are sometimes identified with the larger arrays (Greene, 1984). In comparison to the other vessels, the Western Beaufort signals were also more frequent (approximately 1 pulse every 4 seconds) and were relatively short, with a duration of about 0.25 seconds at the 1.29 km range.

The spectra for the full array vessels show features generally common to all multiple-gun seismic sources: concentration of energy in the low frequencies (primarily in a band around 100 Hz), and a swept frequency quality, with higher frequencies appearing first, followed by lower frequencies. More specifically, there was a slight downward frequency shift seen in the Western Polaris spectra (Figs. 9-10) as the range decreased, and the energy peak around 250 Hz at 6.27 km is absent

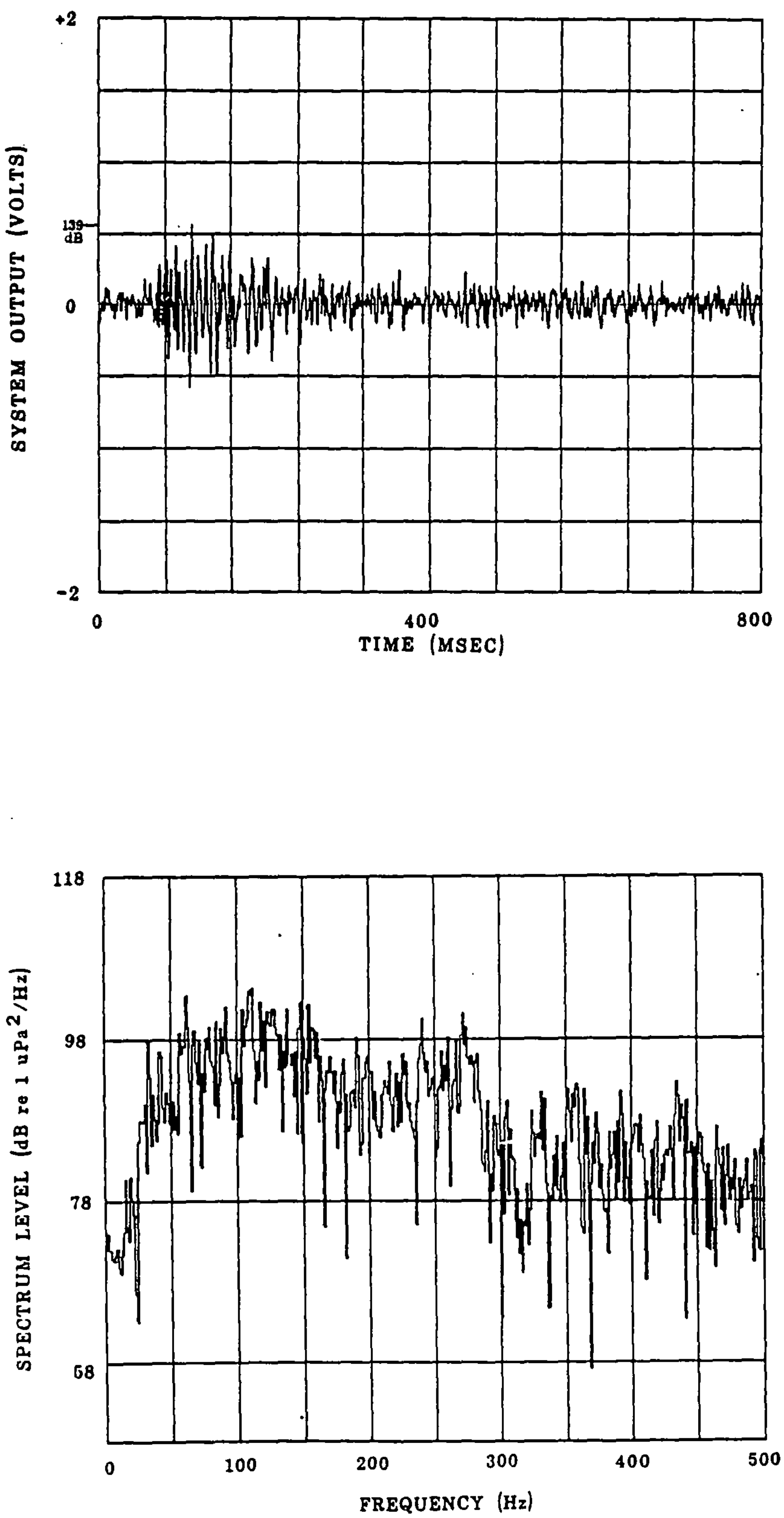


FIGURE 7. Western Beaufort seismic pulse, 6.01 km range, time-domain (top) and frequency-domain (bottom)

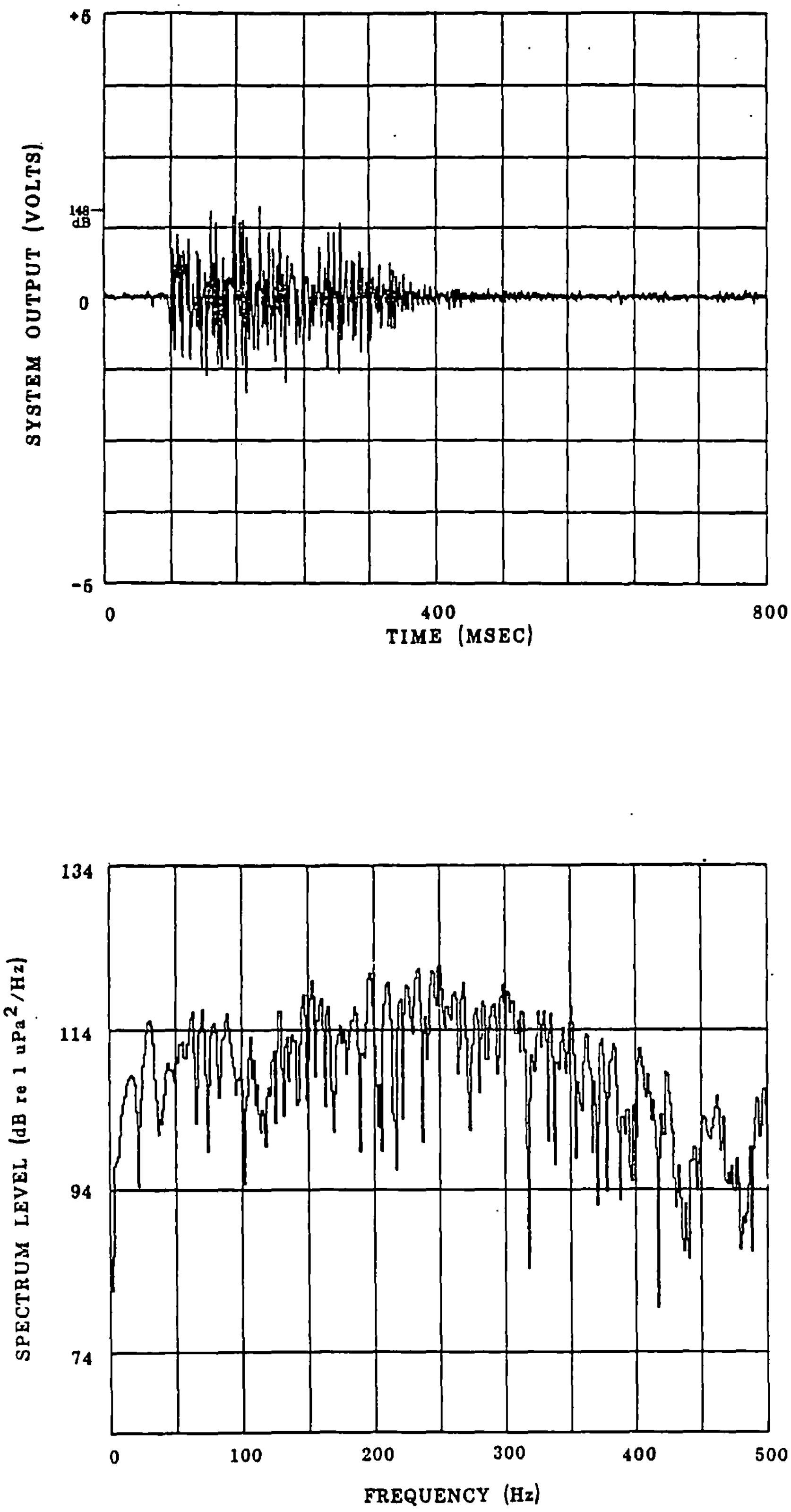
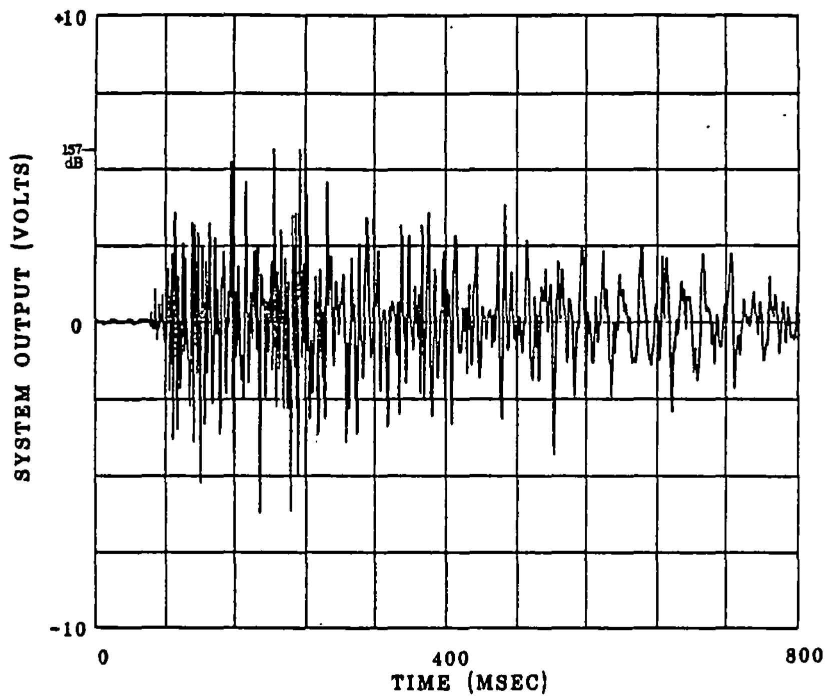


FIGURE 8. Western Beaufort seismic pulse, 1.29 km range, time-domain (top) and frequency domain (bottom)



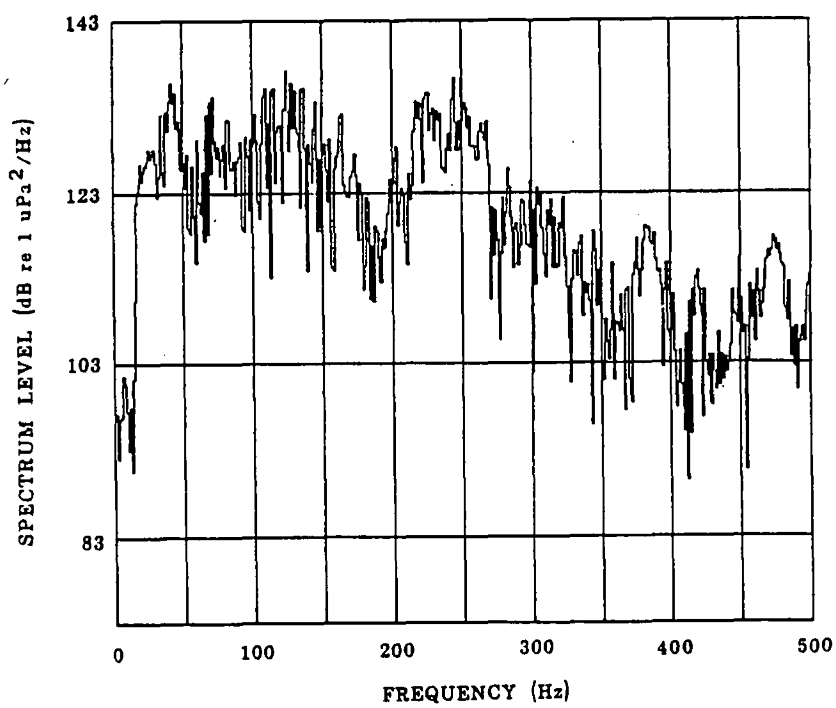


FIGURE 9. Western Polaris seismic pulse, 6.27 km range, time-domain (top) and frequency-domain (bottom)

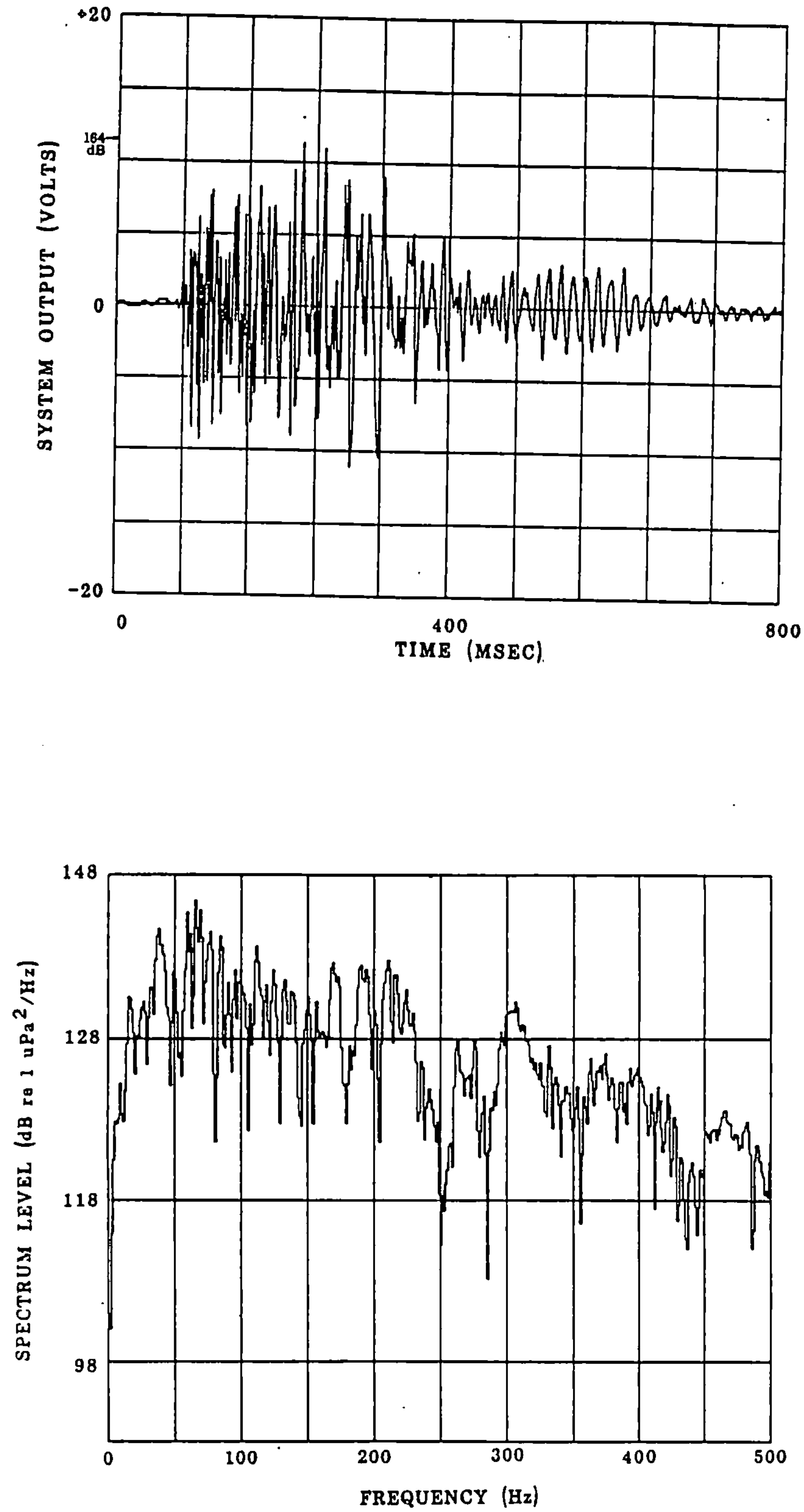


FIGURE 10. Western Polaris seismic pulse, 2.66 km range, time-domain (top) and frequency-domain (bottom)

at 2.66 km. The pulse also persisted longer at the latter range, probably due to multiple reflections off the surface and bottom. The Western Aleutian (Fig. 11) displayed an unusual high-low-high pattern of frequencies with time and showed a slight dip in energy at about 100 Hz. The 11.62 km measurement of the Arctic Star (Fig. 12) clearly demonstrated the reported high-low frequency sweep and the concentration of waveform energy into a band bracketing 100 Hz. In keeping with the trend noted for the Western Polaris, the Arctic Star 6.76 km time waveform was shorter in duration than the 11.62 km pulse by approximately 0.1 seconds, but maintained similar characteristic frequency features.

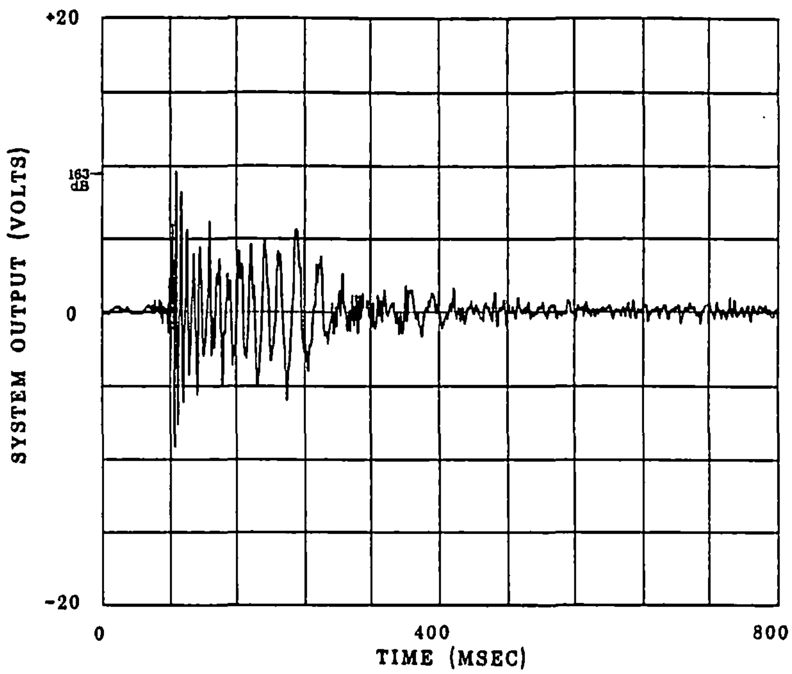
The measured and estimated received sound levels generated to supplement the accounts of the experiments in this report require some qualification. First, due to the movement of animals away from the initial study area (and thus, the sonobuoy drop area), sound levels reported may not have been directly measured at the location of the whales. Instead, values were extrapolated using measured levels and range from each data set as required. No corrections were made for differences in local oceanographical conditions (assumed to be negligible over a small geographical area) or changes in the aspect of the source to the receiver with time. The latter change could cause considerable differences in reported levels due to a strong horizontal directivity effect exhibited by seismic air gun arrays (Malme et al, 1983,p. 5-23). To minimize this possible error, only "vessel approach" data were used in the extrapolations; that is, data collected when the buoy was directly in front of the vessel. This is representative of a seismic vessel approaching directly toward a group of whales, which closely reflects the actual experimental condition.

The second qualification involves the way in which the data were processed. Variability of pulses at a given range (probably due to propagation anomalies) necessitated the use of a four-pulse average in the determination of sound pressure level. These averaged values, along with their associated ranges, were entered into a computer program that fit the data to a logrithmic curve of the form:

$$RL=a-b \log(R)$$

where RL is the received level in decibels, R is the range in kilometers, and a and b are the regression coefficients. The plotted data and the resulting curves for each vessel are shown in Figures 14-17. The program also performs an analysis of variance, generating the coefficient of determination (r^2) as an indicator of the quality of fit achieved by the regression. Values of r^2 close to 1.00 indicate a better fit than those close to zero. The resulting equations and their coefficients of determination appear on each plot. The plots are not an attempt at modeling; they represent a best-fit curve to a data set which may be quite small. The development of a theoretical model to describe shallow-water sound propagation would require knowledge of local surface and bottom properties, sound velocity profiles, and other parameters not easily measured from an aircraft. Therefore, extrapolation much beyond the limits of the data will yield misleading results and is not recommmended, especially at close ranges.

Examination of the received sound pressure levels reveals the variability that existed among the four vessels tested. The Western Beaufort (Fig. 14), with its single gun, had the lowest overall seismic level as expected, and showed the steepest



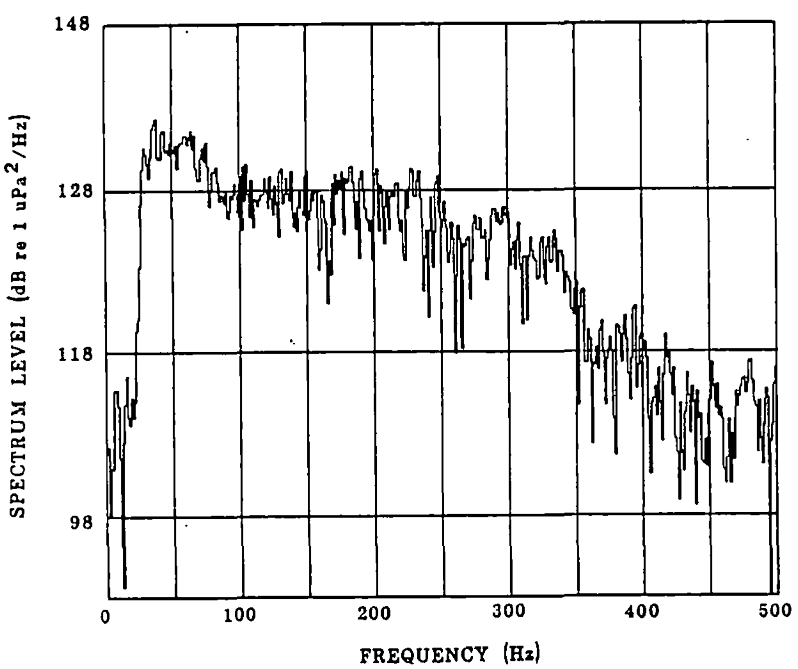
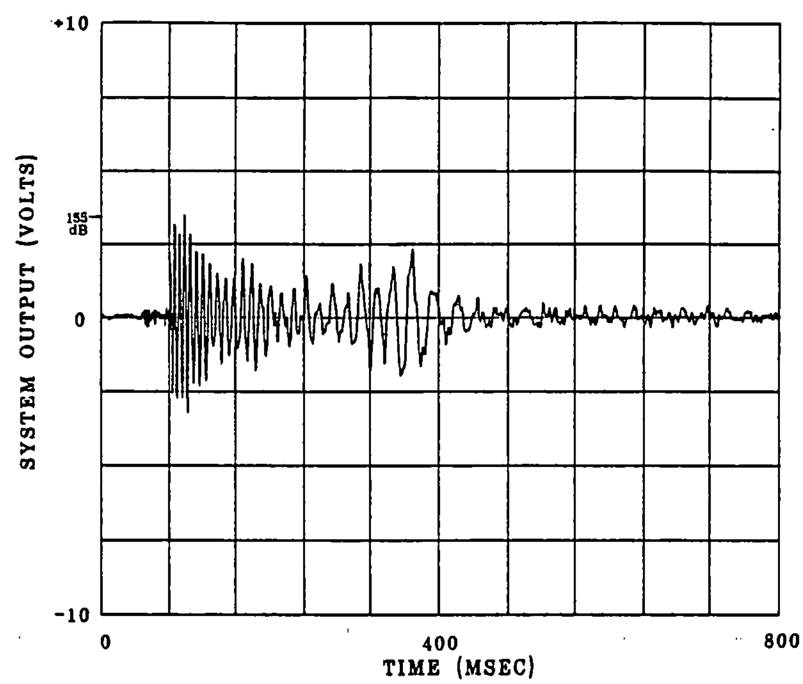


FIGURE 11. Western Aleutian seismic pulse, 5.84 km range, time-domain (top) and frequency-domain (bottom)



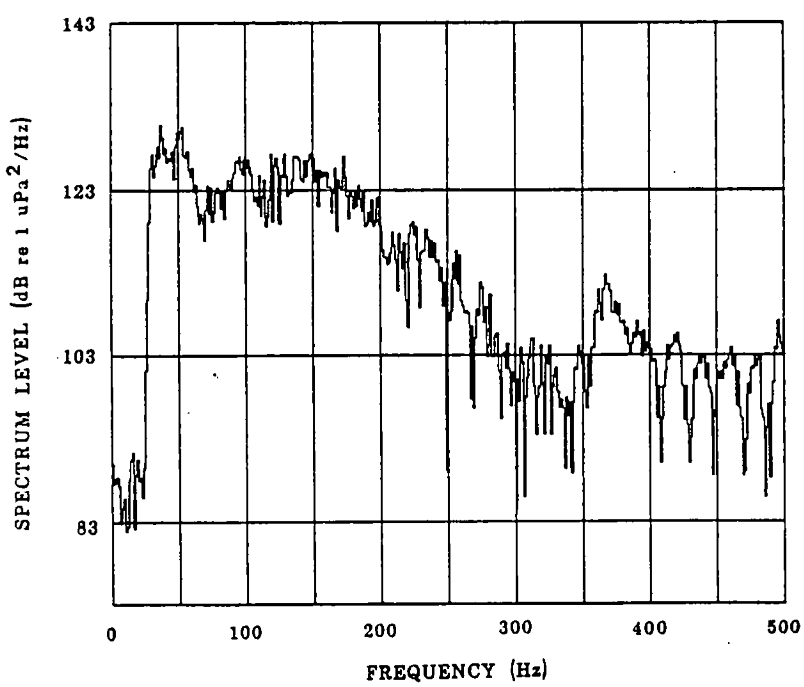


FIGURE 12. Arctic Star seismic pulse, 11.62 km range, time-domain (top) and frequency-domain (bottom)

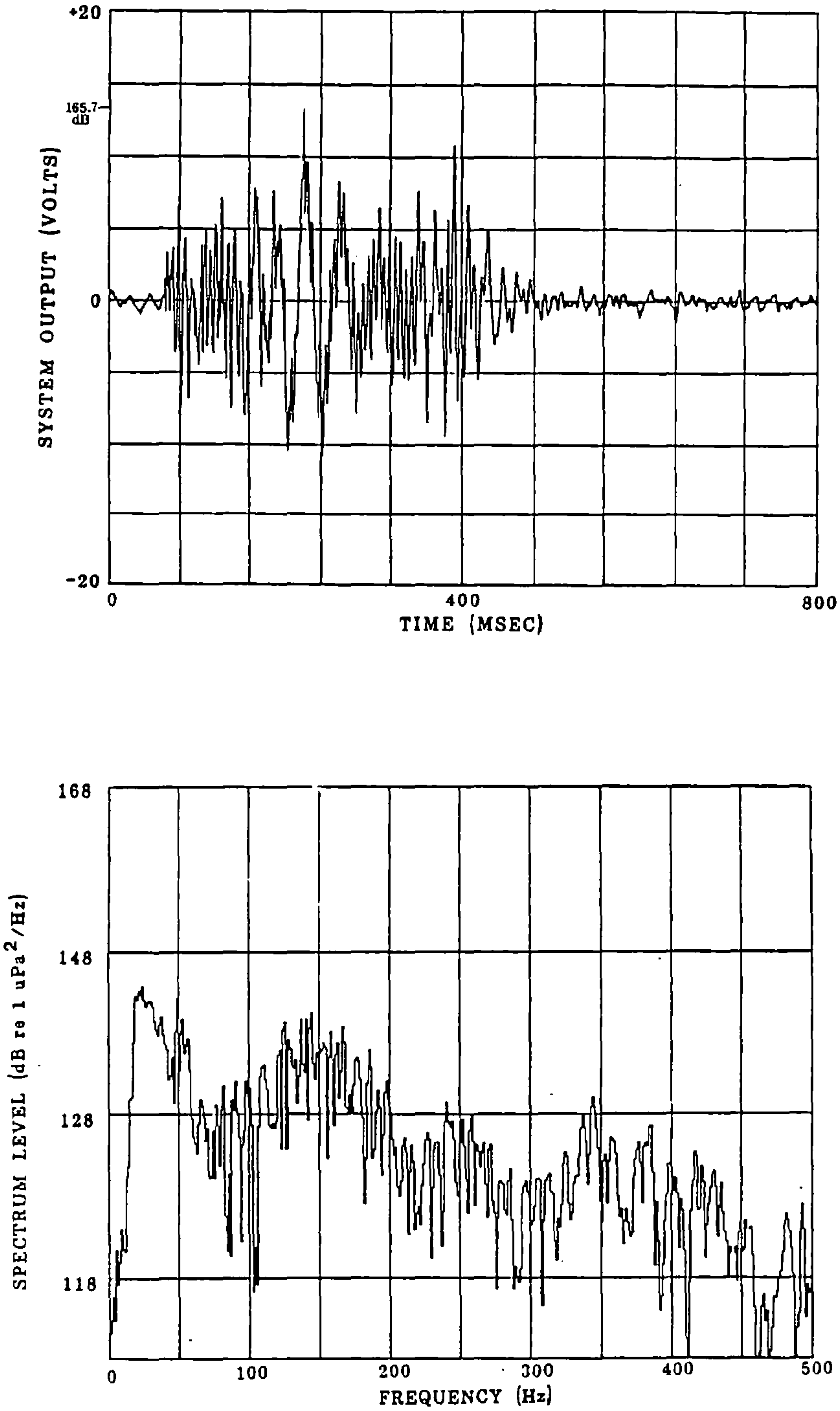


FIGURE 13. Arctic Star seismic pulse, 6.76 km range, time-domain (top) and frequency-domain (bottom)

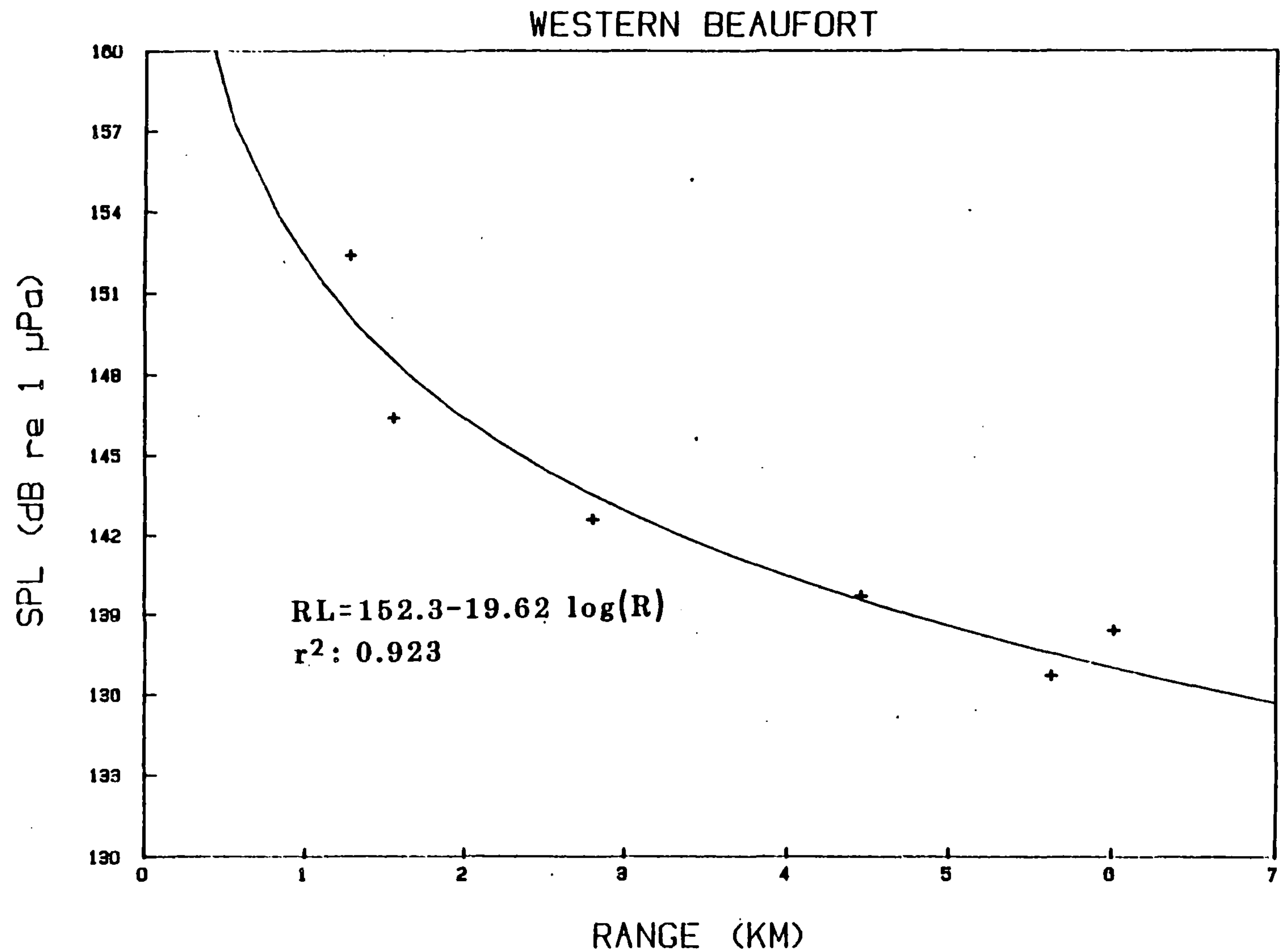


FIGURE 14. Western Beaufort seismic level vs. range (logarithmic curve fit: RL = receive level, R = range in kilometers, r^2 = coefficient of determination).

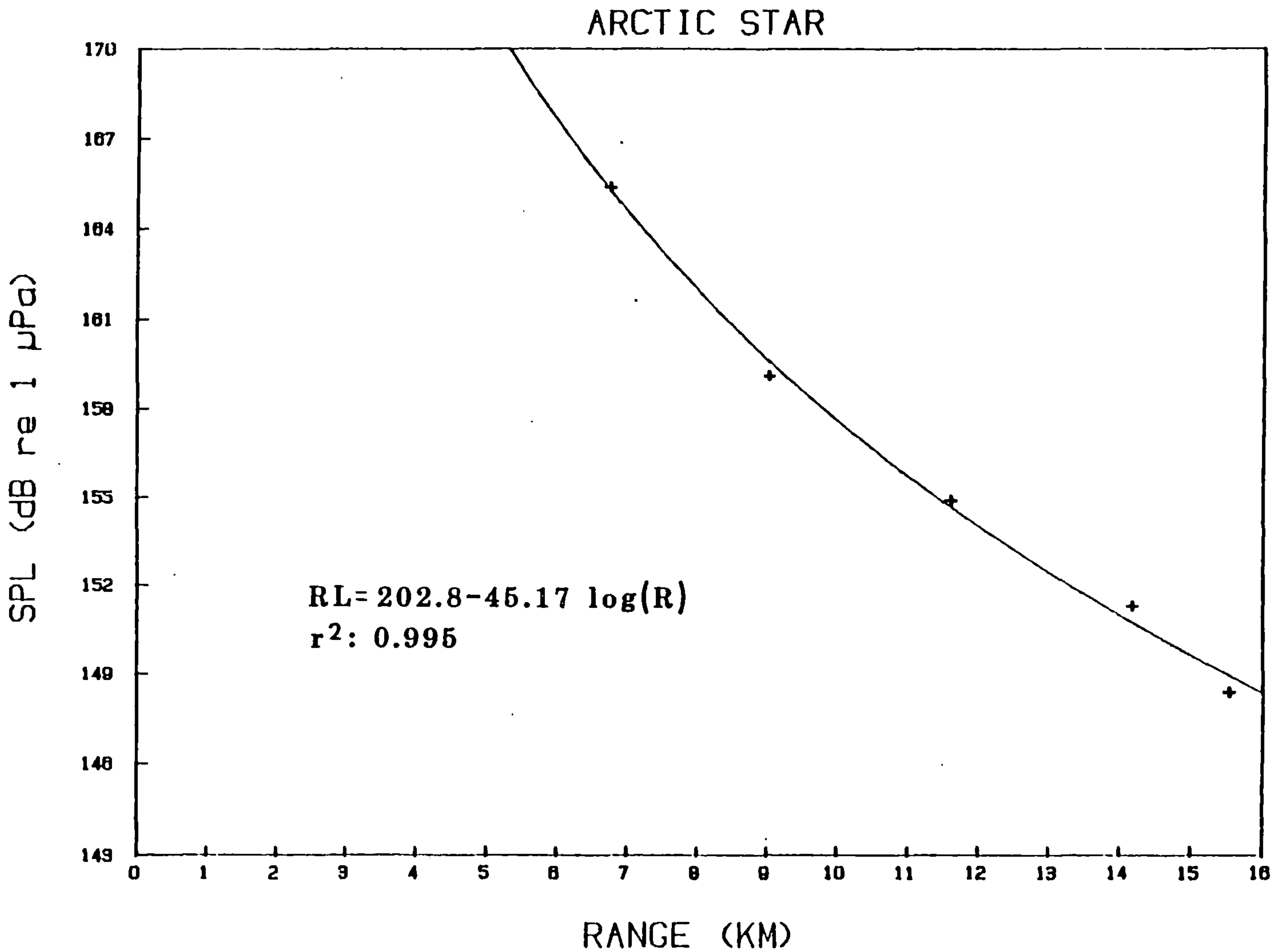


FIGURE 15. Arctic Star seismic level vs. range (logarithmic curve fit: RL = receive level, R = range in kilometers, r^2 = coefficient of determination).

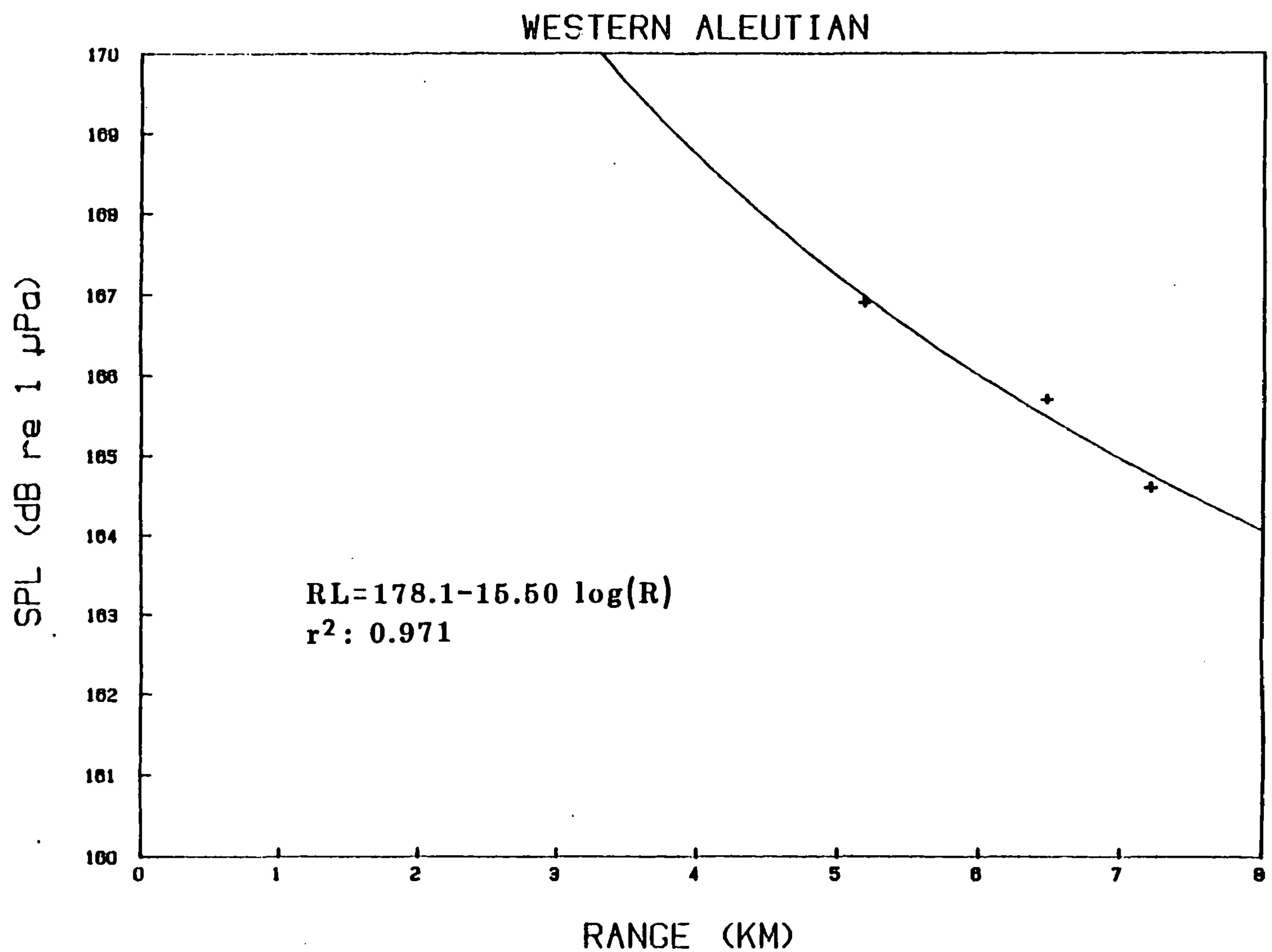


FIGURE 16. Western Aleutian seismic level vs. range (logarithmic curve fit: RL = receive level, R = range in kilometers, r^2 = coefficient of determination).

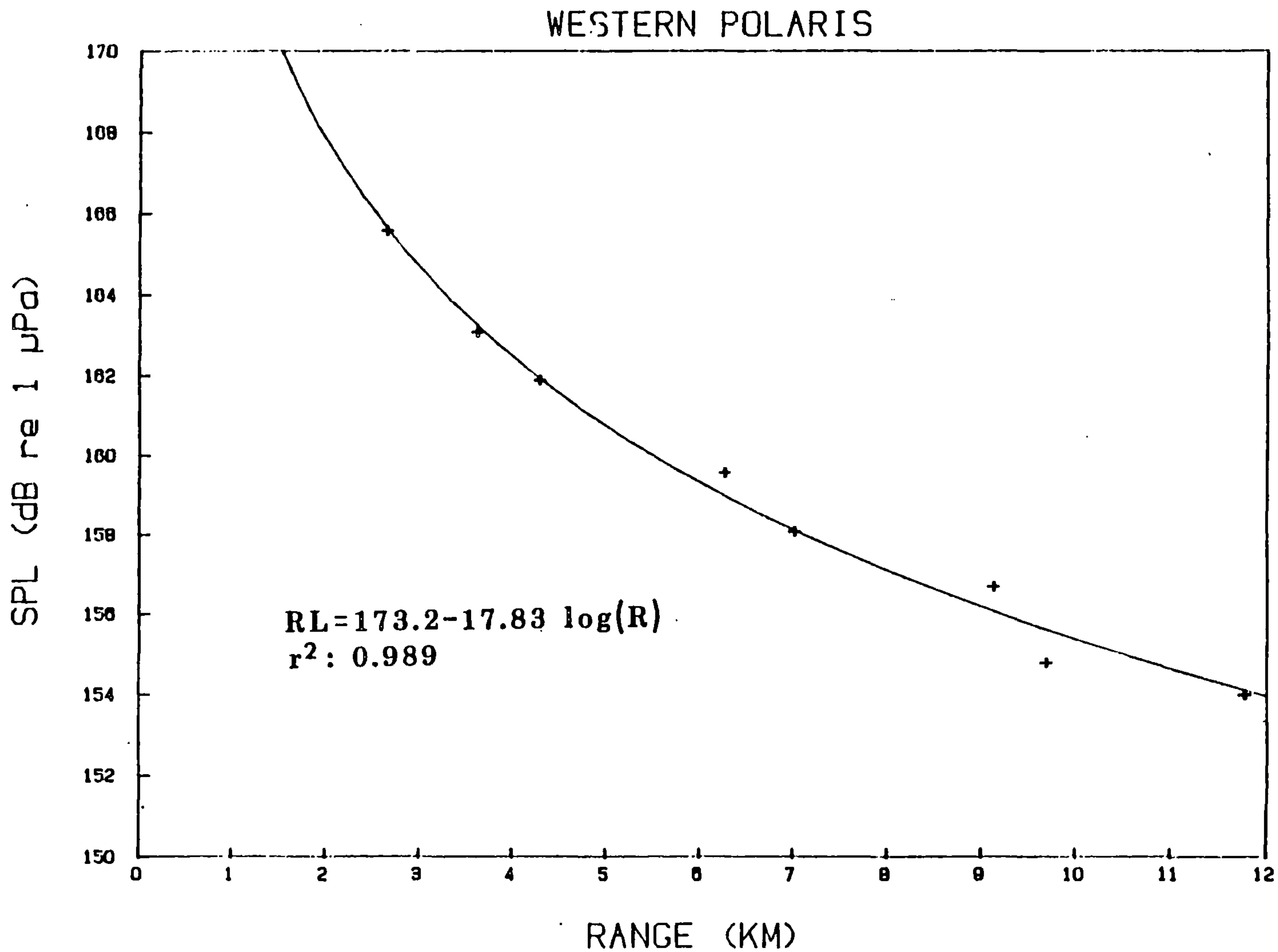


FIGURE 17. Western Polaris seismic level vs. range (logarithmic curve fit: RL = receive level, R = range in kilometers, r^2 = coefficient of determination).

rise in relative level with decreasing range. The Arctic Star (Fig. 15), while producing a level comparable to the Western Aleutian (Fig. 16) at 7 km and the Western Polaris (Fig. 17) at 12 km, showed a much steeper slope at all other ranges. The Western Aleutian and the Western Polaris had similar curve shapes (converging somewhat at close ranges), but were offset with respect to each other by approximately 8 decibels. These differences were not totally surprising when one considers that each experiment was geographically separate, and local oceanographic conditions undoubtedly affected sound propagation and thus the levels received. In addition, the configuration of the air gun arrays in terms of the number of guns, depth, and firing sequence varied somewhat with each vessel and would have had a marked effect on its acoustic output.

As a final comment on the overall effort, the use of modified SSQ-41A sonobuoys is a viable approach to seismic air gun sound measurements which permits the determination of absolute sound pressure levels in the vicinity of whales. They are easily deployed as needed from the aircraft and have proved to be very reliable in service. The required modifications are reasonably simple, although the expense of adding electronic circuitry and performing individual calibrations on sealed buoys may preclude their use in larger volume applications.

LITERATURE CITED

Fish, J.F., C.W. Turl, R.W. Skipton, and B.B. Strachan, 1977. Calibrated Sonobuoys for Acoustic Sound Pressure Level Measurements. NOSC TD 166.

Greene, C.R. 1982. Characteristics of waterborne industrial noise. In: W.J. Richardson (ed.), Behavior disturbance responses and feeding of bowhead whales (Balaena mysticetus) in the Beaufort Sea, 1980-81. Final Report, to: the Bureau of Land Management, prepared by: LGL Ecological Research Associates, Inc., 445 p.

Greene, C.R. 1983. Characteristics of waterborne industrial noise, 1982. In: W.J. Richardson (ed.), Behavior, disturbance responses and distribution of bowhead whales (Balaena mysticetus) in the eastern Beaufort Sea, 1982. Final Report to: U.S. Minerals Management Service, prepared by: LGL Ecological Research Associates, Inc., 357 p.

Greene, C.R. 1984. Seismic Survey Signals in the Shallow Beaufort Sea. In: Ljungblad, D.K., B. Würsig, R.R. Reeves, J.T. Clarke, C.R. Greene, Jr. Fall 1983 Beaufort Sea Seismic Monitoring and Bowhead Whale Behavior Studies. Report prepared for: U.S. Minerals Management Service, Alaska OCS Region, 180 p.

Malme, C.I., P.R. Miles, C.W. Clark, P. Tyack and J.E. Bird. 1983. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior. Final Report to: U.S. Minerals Management Service, prepared by: Bolt Beranek and Newman, Inc., 376 p.

Richardson, W.J., C.R. Greene, J.P. Hickie and R.A. Davis. 1983. Effects of offshore petroleum operations on cold water marine mammals. Final Report to: American Petroleum Institute, prepared by: LGL Limited, 247 p.