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Investigation of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Feeding Humpback Whale Behavior

June 1985

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INVESTIGATION OF THE POTENTIAL EFFECTS OF UNDERWATER NOISE FROM PETROLEUM INDUSTRY ACTIVITIES ON FEEDING HUMPBACK WHALE BEHAVIOR

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The National Marine Fisheries Service extended the required permit for performing the acoustic stimulus research.

The single air gun used during the field work was leased from Western Geophysical and was operated from a geophysical survey air compressor loaned at no cost to the project by Price Compressor, Inc. The equipment was mounted onboard M.V. NANCY-H owned and operated by Latitude 60°N Enterprises, Inc. and chartered by BBN. The availability of these major elements to the project was essential to resolving an answer to the question regarding humpback whale response to air guns.

The enthusiastic support of Mr. Russell Nilson and Ms. Cynthia D'Vincent, owners and operators of R.V. VARUA, the acoustic research vessel, and their skill in operating the vessel in highly variable sea conditions is particularly appreciated.

There were several scientists who provided needed advice and support at various times and at various levels of effort. They are:

Mr. Donald Croll; field observer

Ms. Linda Guinee; field observer and data analysis

Ms. Victoria Rowntree; field observer and data analysis.

Their contributions to the project were essential to the successful completion of the work.

Within BBN, the dedication and skills of Mr. Rafal Mlawski in the installation, maintenance, and operation of the acoustic systems on board R.V. VARUA were very important to the project. Dr. Robert Pyle provided dedicated use of his talents in applying BBN computer facilities to the detailed development and analysis of whale position and behavioral data. His valuable contributions were essential to the completion of the analysis of the field data. Mr. Creighton Gogos, also of BBN, and Mr. Mac Warren of Marine Specialty were the key individuals in the assembly, test, installation, and operation of the air gun system on board the air gun charter vessel. Their skills were essential to the successful completion of the air gun experiments.

The word processing talents and patience which Ms. Judy Russo applied to the typing of this complex report are especially appreciated.

Finally, the authors of this report had the following project responsibilities:

Mr. Charles I. Malme	Chief Project Scientist and Principal Investigator for Acoustics
Mr. Paul R. Miles	Project Coordination and acoustics

Consultants to BBN:

Dr. Peter Tyack	Co-Principal Investigator for whale behavioral research
Dr. Christopher W. Clark	Co-Principal Investigator for whale behavioral research
Mr. James E. Bird	Literature Survey and assistant regarding whale behavioral research.

All of these staff members contributed to various aspects of the required data analysis, interpretation, and reporting.

ABSTRACT

An investigation was made of the potential effects of underwater noise from petroleum industry activities on the behavior of feeding humpback whales. The investigation was conducted in Frederick Sound and Stephens Passage in southeast Alaska in August, 1984, using a 100 cu. in. air gun source and playback of representative recorded sequences of drillship, drilling platform, production platform, semi-submersible drill rig, and helicopter fly-over noise. Sound source levels and acoustic propagation losses were measured to permit estimation of sound exposure levels at whale sighting positions. The movement patterns of whales were determined by observations of whale surfacing positions. A computer-implemented analysis was conducted to determine the distribution of ranges from the sound source to the whale sighting locations under pre-exposure, exposure, and post-exposure conditions. No clear evidence of whale avoidance of the area near the active sound source was obtained. Whales were observed at ranges corresponding to sound exposure levels of up to 172 dB effective pulse pressure level (re 1 μPa) for the air gun source and up to 116 dB (re 1 μPa) for continuous sound from industrial noise playback. In the test areas, a 172 dB effective pulse pressure level was obtained at ranges of 140 to 260 m from the air gun. Scaling the playback sound levels to levels reported for the original industrial sources showed that a 116 dB sound exposure level would generally be obtained at ranges less than 100 m from the source, except for the drillship where the level would occur at a range of about 1 km.

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1. SUMMARY

This report presents the results of an investigation of the potential effects of underwater noise from petroleum industry activities on the behavior of feeding humpback whales (Megaptera novaeangliae). The objective of the study was to determine the nature and degree of any observed behavioral response to controlled sound exposure levels from industrial noise sources. The noise sources used were a single 100 cu. in. air gun and playback of sounds from selected petroleum industry activities. The playback sounds were obtained from tape recordings of drillship, drilling platform, production platform, semi-submersible drilling rig, and helicopter overflight noise. The work was performed in Frederick Sound and Stephens Passage in southeast Alaska during August 18-29, 1984.

Experimental Procedure

To start an experiment, observers and the sound source vessel were positioned in a concentration of whales. The time and location of observed surfacings were then recorded during a nominally 30 min pre-experiment control period, a 60 min. experimental period, and a 30 min. post-experiment control period.

Horizontal azimuths and vertical elevation angles were used to locate whales if a suitable land site was available near whale concentrations. When whales were not near a land site, a new procedure was developed to locate whales using triangulation of azimuths from two vessels. The large number of whales present, their variable movement patterns, and the continual interchange between whale groups made it difficult to follow individual whales from surfacing to surfacing. We therefore concentrated on determining the location of whale sightings relative to the sound source position as one quantitative response measure and did not

collect respiration data or detailed observations of individual behavior.

Acoustic propagation loss was measured to obtain information for estimating the sound exposure levels at sighted whale positions. The output source levels of the air gun and playback sounds were measured. These measurements allow calculation of received sound level for each whale sighting. Ambient noise levels in the test region were measured and found to be generally low, except when influenced by nearby ship traffic.

Whale Movement Analysis

A computer-implemented whale movement analysis program was developed to combine the results of triangulation and theodolite range measurements and to produce a set of whale position data for each test condition. The data were organized into cumulative distributions showing the number of sightings versus range for both control and experimental conditions. Sighting density distributions were then obtained from the cumulative distributions to determine if a general shift occurred in the whale positions relative to the source during the presentation of the industrial noise sequence.

The hypothesis being tested was that the cumulative distributions during experimental conditions would be different than the distributions during their adjacent control periods. Specifically, if the distribution of sightings during playback showed whales sighted at ranges farther from the source than during control periods, this would give evidence of avoidance of the source. By comparing the ranges and calculated received levels at which this avoidance was most significant, one could scale avoidance to received level.

Results

Comparison of the distribution of sightings under control and stimulus conditions showed no clear avoidance response of whales. Of the 13 air gun and playback experiments, seven yielded significant ($p < 0.05$) differences, but three of these seven showed an apparent approach response while only four showed apparent avoidance. None of the significant differences in control and experimental distributions appeared to be a direct response to the sound source for they were not stronger at closer range to the source. Results from one air gun experiment did show an avoidance response that was stronger at closer range. This was the first air gun test at close range. Subsequent tests in the same area during the same day did not show similar results, suggesting possible habituation.

Results from all of the airgun experiments and all of the playback experiments were pooled in order to test whether the apparent lack of an avoidance response might result from the relatively small sample sizes of individual experiments.

Both merged airgun and merged playback experiments showed highly significant differences when either pre-experiment or post-experiment control distributions were compared to experimental distributions, but this difference was much less significant for combined pre- and post-experiment control vs experiment. This effect was due to the slow increase in range of pre-experiment, experimental, and post-experiment distributions. This increase in range was not necessarily a response of whales to the sound stimulus, because a comparison of the first and last halves of the pre-playback control periods showed a similar effect. Since we started each experiment by motoring into a concentration of whales, boat drift and undirected movements of whales are enough to explain the steady increase in range.

If whales were avoiding the stimulus source, the effect should be greater at closer range where whales are exposed to higher sound levels. To test for this effect, a probability of avoidance was calculated scaled to received level. There was no steady increase in avoidance with increasing level except for the highest exposure levels in the merged playbacks. Here, there was some weak evidence for an effect similar to that seen for migrating gray whales (Malme et al. 1984), but the otherwise nonsystematic fluctuations in this measure cast doubt on the significance of this effect.

While the quantitative analysis of sightings showed no persistant avoidance response, for three airgun experiments (Air Gun 1, 4, and 5), we observed short duration movements or "startle responses" of humpbacks as soon as the air gun was turned on. These startle responses were evoked at received sound levels ranging from 150 to 169 dB (re 1 μPa). This suggests that the startle responses were related more to the novelty of the air gun sound rather than to its intensity.

Discussion

Our methods were designed to detect an avoidance response within a group of whales. While observers paid attention to any possible response, our methods were not sensitive indicators of all potential responses. For example, if whales stopped feeding but did not move away from the playback source, we would not necessarily have detected it. Since we were unable to follow individual whales, we were also unable to test whether a small fraction of the population was particularly sensitive to playback. In a study of migratory gray whales exposed to seismic and other industrial signals, Malme et al (1983, 1984), showed avoidance responses to all of the sound stimuli used in this study. In that study the whales were on well-directed migratory tracks and, hence, the track analysis scores were very sensitive to slight deflections in the whales' swimming patterns. The movement patterns of undisturbed feeding humpbacks in this study were much more variable than those of migrating gray whales, so avoidance analysis may be a less sensitive response measure. However, since no avoidance response was seen in feeding humpbacks that were exposed to sound levels sufficiently loud to evoke significant avoidance in gray whales, the avoidance criteria derived from the gray whale study should provide a conservative guide for maximum industrial noise exposure for feeding humpback whales.

Conclusions

The results of this study of feeding humpback whales show no overall pattern of avoidance for air gun sound or for any of the industrial noise playback sounds. Comparison of the exposure levels of feeding humpbacks, where no strong avoidance response was detected, to migrating gray whales, where avoidance responses were systematically scaled with received level, shows roughly equivalent patterns of sound exposure. For air gun tests, humpbacks were observed to be exposed to effective pulse levels up to 172 dB (re 1 μPa). For continuous playback of industrial noise, sightings were obtained in estimated sound exposure levels up to 116 dB (re 1 μPa).

In the absence of data at sound levels high enough to produce statistically significant avoidance behavior in feeding humpback whales, application of the maximum sound level criteria determined for the various test noise sources in the gray whale study would seem to be a conservative approach. The criteria were determined by the avoidance reaction observed for gray whales travelling near the surface during migration.

Recommendations

Further work is recommended using a seismic array to obtain levels high enough to quantify any observed avoidance behavior by humpback whales. Detailed observations using radio tagging to determine depth of dive and dive intervals would be useful to quantify behavioral measures other than avoidance. A long-term study using a controlled noise source in an established humpback feeding area would be useful to establish whether or not the daily and seasonal feeding patterns in the area are disturbed by the sound source. Again, individual tracking procedures should be used in addition to general observations to determine if habituation occurs during a feeding season.

2. BACKGROUND

This report presents the results of research on the behavioral response of feeding humpback whales to various underwater noise stimuli representative of oil and gas exploration and development activities. The work was performed by Bolt Beranek and Newman Inc. and a whale behavioral consultant staff under Minerals Management Service Contract No. 14-12-0001-29033. Previous work performed under MMS sponsorship concerning the behavioral response of migrating gray whales to the same set of industrial noise stimuli has been reported in BBN Report No. 5366 (Malme, Miles, Clark, Tyack and Bird 1983) and BBN Report No. 5586 (Malme, Miles, Clark, Tyack and Bird 1984).

Two major summer feeding areas for humpback whales were considered in selecting the site for this study. The Gulf of the Farallones about 48 km west of San Francisco has been attracting an increasing number of humpback whales. This area is near the site used for the previous gray whale studies. The second area considered was Frederick Sound and Stephens Passage in southeast Alaska about 130 km south of Juneau. This area is frequented by large numbers of humpback whales in June through September.

After an evaluation of the advantages of the two sites, the Alaska location was selected because it was in protected water permitting the use of small craft as secondary observation vessels. A number of potentially useful land sites for theodolite observations were also available. The ongoing studies of the feeding ecology of humpback whales in the Frederick Sound area (Krieger and Wing 1983, Dolphin and McSweeney 1983) were seen as a potential source of additional information on the behavior and feeding patterns of the whales in this area. This area also had the advantage of having acoustic environmental data available from a previous study (Malme, Miles and McElroy 1981). The cost of operating in an area more remote than the Gulf of the

Farallones was offset by eliminating the need for a second large observation vessel and extensive aircraft observations, which would have been required if the study was conducted in the Farallon Island area.

Based on whale sighting data reported by previous studies, particularly the work conducted by Baker, Herman, and co-workers (Baker et al. 1982), it was determined that the field work should be conducted in August to obtain the highest probable whale densities during a limited time schedule.

The work was performed under Permit No. 451 issued by the National Marine Fisheries Service.

The experimental procedure used in performing the work is described in Sec. 3. Section 4 contains a description of field environmental conditions and a chronology of the observations. The acoustic measurements and results are presented in Sec. 5, with behavioral observations and analysis given in Sec. 6. Sections 7 and 8 contain an interpretation of the results, conclusions, and recommendations.

The earlier reports contained a literature review on whale responses to acoustic stimuli (Malme et al. 1983, Appendix A) and a review of the seismic survey history with respect to gray whale migration off the California Coast (Malme et al. 1984, Appendix A). An updating of the information presented in these two previous reports is included here in Appendix A as a review of the effect of seismic operations on marine mammals. Appendix B presents a series of charts showing all of the whale position sightings during control and experimental conditions. Appendix C presents the one-third octave spectra of the playback sounds used in the study. Appendix D is an error analysis of the whale position determination procedure.

3. EXPERIMENTAL PROCEDURE

3.1 Overall

The general area where the field work was performed is shown in Fig. 3.1. The specific sites where playback or air gun experiments were performed are indicated. Land-based observations, using a theodolite for whale position data, were made from Round Rock, Entrance Island in Hobart Bay, and from the helicopter pad at the Five Finger Light Station. At the other locations, an azimuth triangulation method, using two vessels, was used to obtain whale position data.

To start our experiment, we would find a concentration of whales and position the observers and the source vessel. We would then locate all whale surfacings during a nominal 30 min. pre-experimental control period. After this, a nominal 60 min. experiment (source on) would be performed, followed by a 30 min. post-experimental control period. In order to test whether whales avoided the sound source during the experiment, we statistically compared the distributions of sightings as a function of range for control and experimental conditions. Two control conditions were used - the pre-experimental control alone or pooled pre- and post-experimental control periods.

The following discussion covers the procedures used for behavior monitoring, acoustic measurements, and data analysis.

3.2 Behavior Monitoring

3.2.1 Introduction

During all of our sound exposure experiments, observers searched for any changes in whale behavior that might be associated with sound exposure. But in our experimental design, we focused primarily on gathering data that could be used to

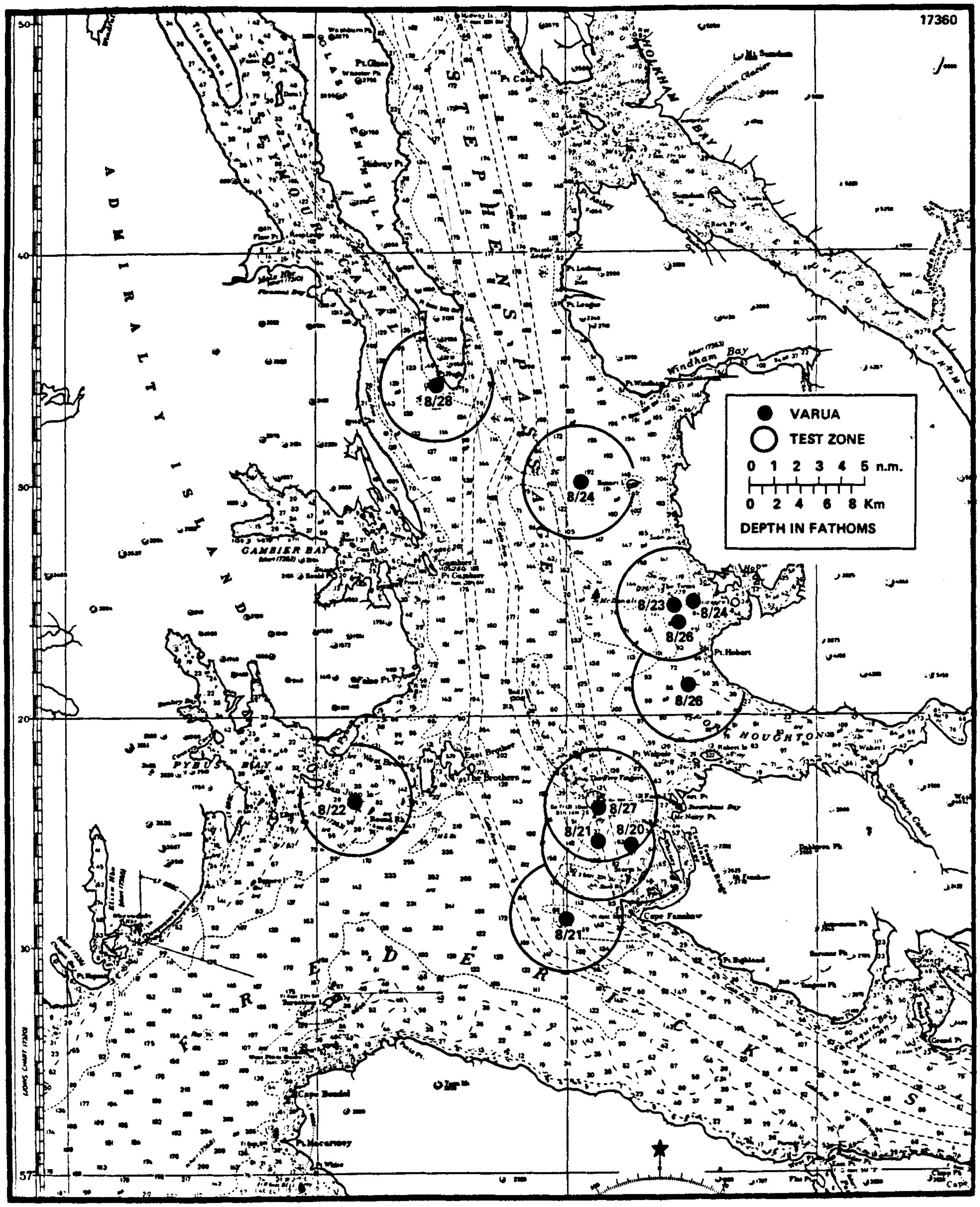


FIG. 3.1. WHALE OBSERVATION SITES IN FREDERICK SOUND AND STEPHENS PASSAGE.

assess the approach or avoidance of whales with respect to the sound source. Secondarily, we were prepared to gather respiratory data on whales similar to that used by Richardson et al. 1982, and Baker et al. 1983, to demonstrate responses of whales to vessel traffic. We subsequently found that this was not feasible.

Initially we had prepared to follow individual whales or groups of whales to obtain movement tracks and respiratory data. In the field we found that it was not possible to follow individual whales with any confidence. We intentionally conducted our experiments near aggregations of many whales. The movement patterns of these whales were not predictable, thus we could not follow whales from surfacing to surfacing.

For these reasons, we did not attempt to keep track of individual whales or groups of whales except under a few exceptional circumstances when this was possible for short periods of time (10 to 30 min.). This occurred in the rare cases where an animal had a very distinctive marking or there were only a few groups that were widely separate.

3.2.2 Whale position observations

The primary objective of the behavioral monitoring effort was to acquire bearings to whale groups under normal conditions and a variety of experimental conditions simulating industrial noise types. There were three basic methods for obtaining these data. The first method was nearly identical to that used in previous theodolite tracking studies (Malme et al. 1983, 1984); a single land-based theodolite station of known altitude was established and theodolite bearings were used to compute the locations of whale groups and vessels. The second method required two observation sites, one on land and one on board the VARUA. The third method used two observation vessels; the VARUA and a

"Boston Whaler." In these latter two methods, observers at both sites obtained synchronous horizontal bearings to a group (see Fig. 3.2), and the distance between the two sites was obtained throughout the observation period from radar (Raytheon 3400) on the VARUA. In order to maintain precision (±10 m) in the radar measurement of this baseline distance, the separation between the Whaler and the VARUA was kept between 100 and 450 m. These techniques enabled us to obtain data showing the location of most whale surfacings out to a range of approximately 5 km.

Each platform was manned by three observers, not including VARUA or BBN personnel. The responsibilities of the three observers were as follows: 1) theodolite (Topcon TC-20 or Lietz TM-1) or binocular compass (Fuji 7 x 50 MTRC) operator, 2) data recorder, and 3) observer and inter-station coordinator. In practice, the theodolite operator, and to a lesser extent, the data recorder served as second and third observers. Positions were rotated periodically so that all personnel were involved in all phases of data collection. Communication between platforms was conducted by CB radio.

The following information was recorded by personnel on the Whaler: 1) type of entry (i.e., whale, boat, comment), 2) time of day (hr., min., sec), 3) sequence or identification number of whale, 4) compass heading to the whale, 5) compass heading to the VARUA, 6) group size, and 7) whale behavior or general comments (i.e., weather conditions). Personnel on the VARUA recorded most of the above information, except that items 4 and 5 were replaced with the angle between the whale and the Whaler, the radar distance to the Whaler and, at times, the distance to the NANCY H. Radar distances to various points of land were also taken so that the VARUA position could be determined.

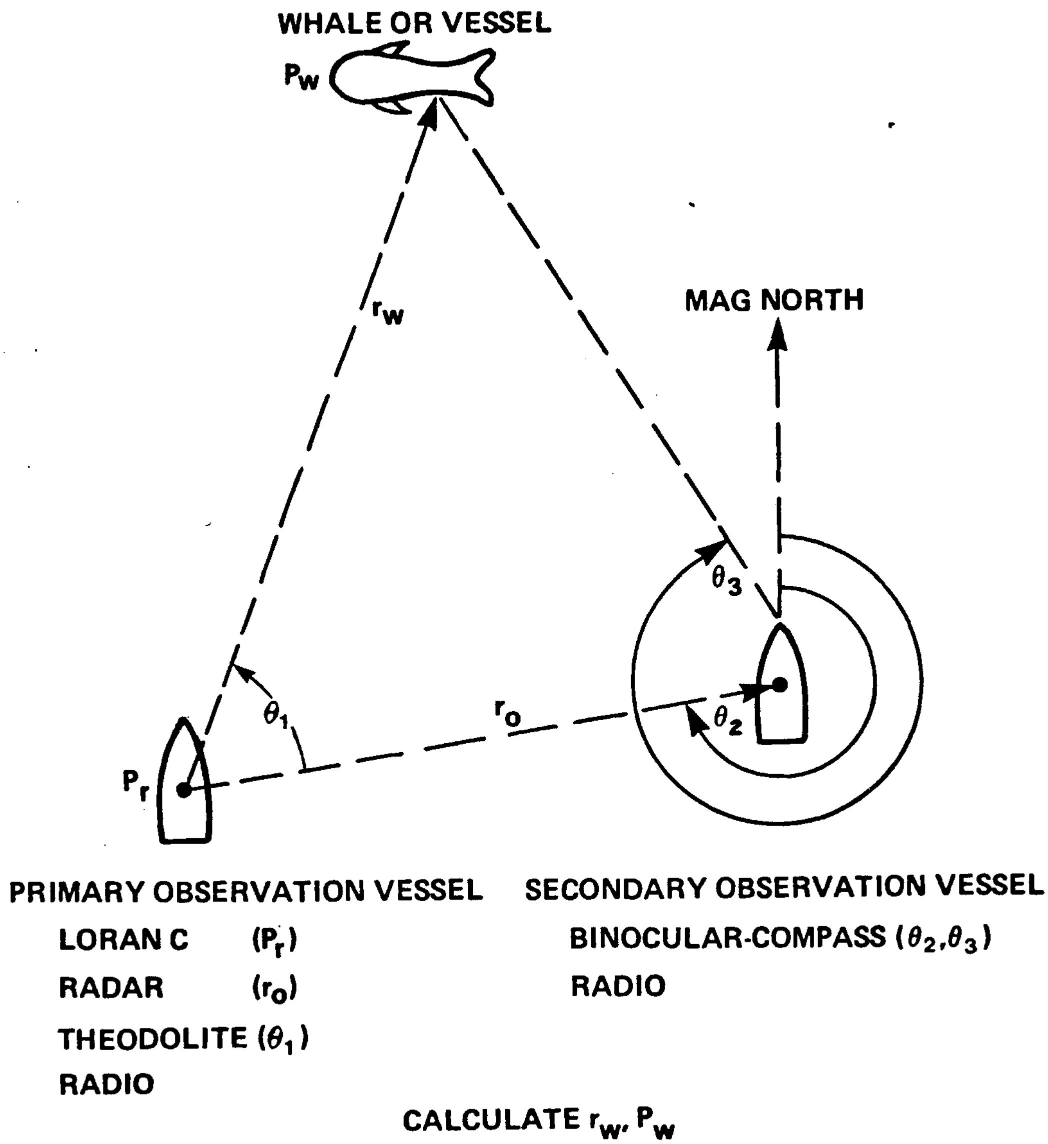


FIG. 3.2. WHALE TRACKING USING OBSERVATIONS FROM TWO VESSELS.

Each observation entry was given a specific numerical code rather than a group identification. During the few occasions when groups could be followed for some time, a series of sightings were linked by a common group identifier. In conjunction with a sighting entry number, each observation record contained the following information: type of entry (whale, boat or comment), time, sighting number, magnetic bearing to the second sighting station, magnetic bearing to whale group, estimate of group size, estimate of direction of movement, changes in conditions and general behavior. Radar range readings to the Whaler were taken approximately every five minutes.

3.3 Acoustic Instrumentation, Measurement, and Analysis Procedures

The instrumentation for the principal measurements was installed on the VARUA, a 73-ft (93-ft OA) brigantine. The air gun source was handled from the NANCY H., an 80-ft cargo/supply vessel normally chartered by the oil industry.

3.3.1 Acoustic environmental measurements

Navigation

A Furuno, Model LC-80, Loran-C on the NANCY H. was used to obtain absolute position references for the whale sighting data. The Loran-C was calibrated to minimize local terrain effects by inputing a correction based on observations using local charted landmarks. When the NANCY H. was not present, the radar on the VARUA was used for determining the location of the observation vessels using charted topographic features. Radar was also used to determine ranges to the air gun vessel and ranges to passing ships which were contributing to the local ambient noise level. A Rangematic optical rangefinder was used for range measurements under 100 m when radar readings became imprecise.

A recording fathometer was used for determining the water depth.

Oceanographic Measurements

The variation of water temperature and salinity with depth was measured with a Beckman Model RS5-3 conductivity, temperature, and salinity probe. This instrument provided a salinity measurement based on the temperature and conductivity data. Measurements were made at selected depths down to 50 m. The measured data were then used to calculate the sound velocity profile.

Wave height was estimated visually.

Ambient Noise Measurements

A standard hydrophone system that combined an ITC Type 6050C hydrophone with a low-noise preamplifier and tape-recorder was used to obtain ambient noise data. The hydrophone sensitivity and electrical noise-floor characteristics are shown in Fig. 3.3. The acoustic noise measurement system block diagram is shown in Fig. 3.4. Overall frequency response of the measurement system was generally flat from 20 Hz to 15 kHz. All components of the system were battery operated during ambient noise measurement. Cable fairings and a support float system were used to minimize strumming and surge noise effects on the ambient measurement hydrophone.

Sonobuoy Measurements

AN/SSQ-57A pre-calibrated sonobuoys were used to obtain ambient noise data and sound level data during some of the playback experiments. These buoys were released from the VARUA

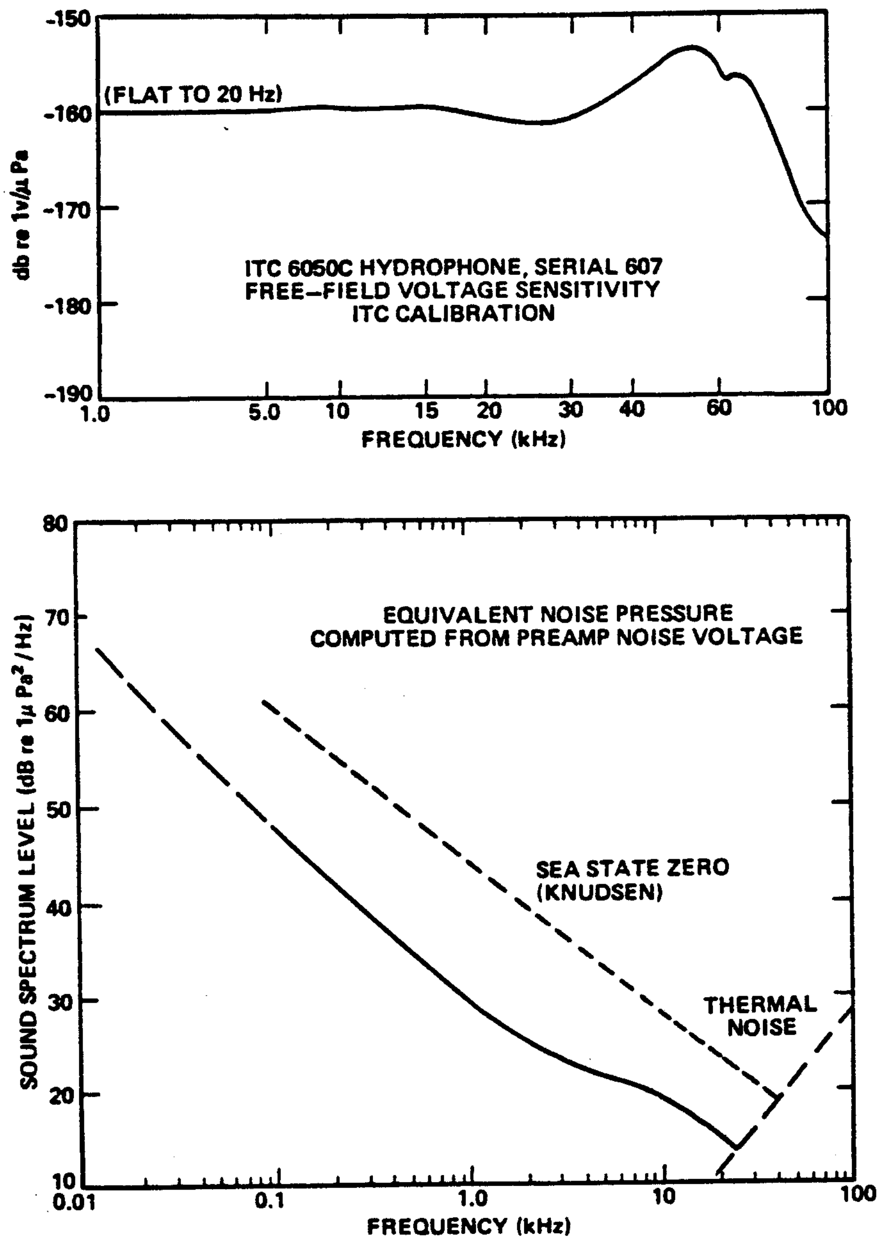


FIG. 3.3. MEASUREMENT HYDROPHONE CHARACTERISTICS.

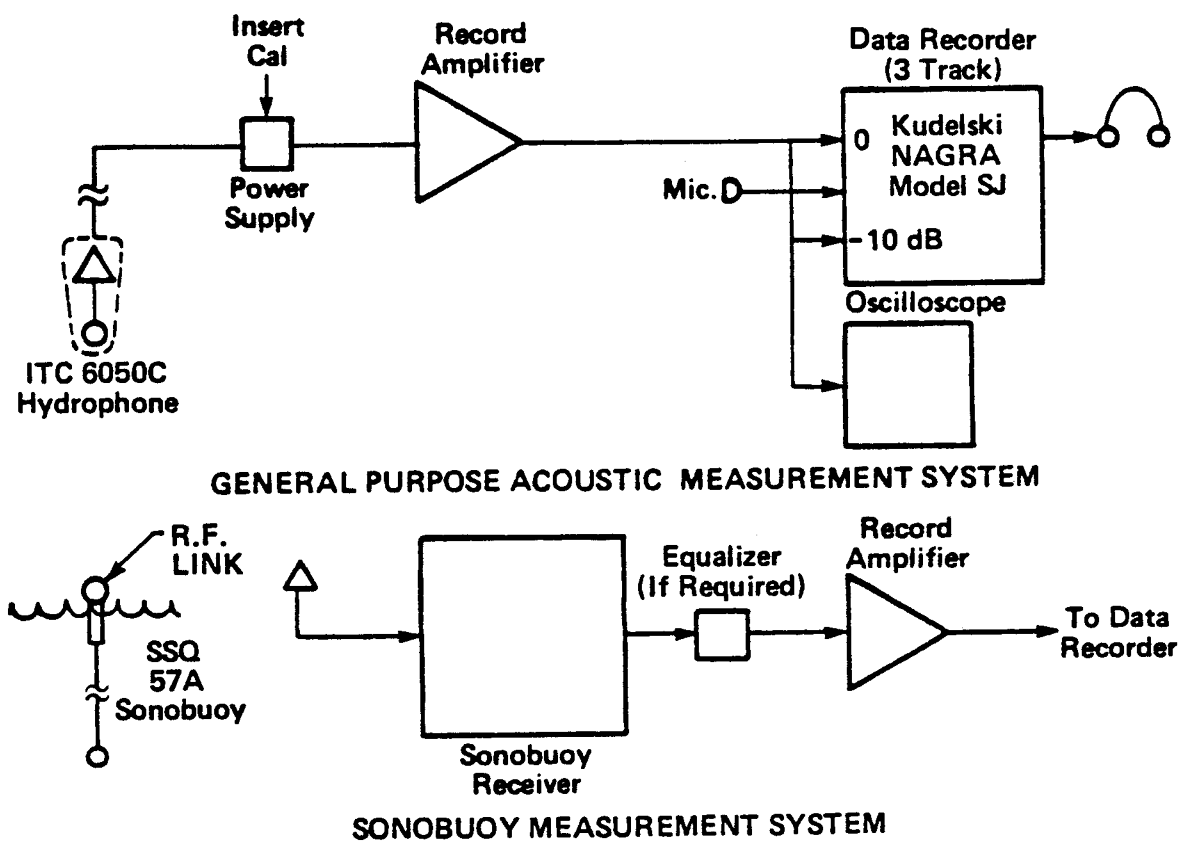


FIG. 3.4. ACOUSTIC MEASUREMENT SYSTEMS.

and allowed to drift with the tidal current, to obtain data at some distance from the VARUA.

An equalizer circuit was used to correct the low-frequency de-emphasis of the sonobuoy as shown in Fig. 3.4. The resulting receiver channel response was flat within ±1 dB from 10 Hz to 20 kHz with a sensitivity of -115 dB re 1v/μPa.

Transmission Loss Measurements

Transmission loss information was obtained by measurements using the air gun source. Data were obtained for several ranges extending from 25 m to 7.5 km. When the air gun vessel was not present, transmission loss was measured using the playback projector system. The source levels of both the air gun and projector system were established by measurement of the direct signal at close, measured ranges using a calibrated reference hydrophone. Transmission loss was then determined as the difference between the received sound level and the previously determined source level as the range from the source to the receiving hydrophone was increased.

3.3.2 Acoustic playback procedure

Projector System

The acoustic playback system was designed to provide sound levels and frequency response capable of realistically simulating the designated range of petroleum industry activities. In order to keep the system within the required operational constraints, a compromise was necessary to boost the low frequency response of the projector system. Two USN/USRD Type J-13 projectors were used to provide response down to 32 Hz. While some industrial noise sources have spectra extending below this frequency, playback sources for reproduction of ultra-low frequencies are very heavy and require special mechanical and electrical support equipment.

Because of the required broad frequency range needed to reproduce the industrial noise spectra, three sound projectors were used. In addition to the two low frequency projectors, a USN/USRD Type F-40 projector was used to provide high frequency sound above 2 kHz. Electrical equalization and cross-over networks were used to enable all of the projectors to be driven from a Crown 300-watt power amplifier. As a result of the use of two low frequency projectors and the electronic equalization network, the useful response of the system extended from 32 Hz to 20 kHz. The playback system and its response curve are shown in Fig. 3.5.

The three projectors were mounted vertically in a support frame to maintain correct acoustic alignment of the radiating surfaces and to facilitate handling. The spacing between acoustic centers was 26 cm. The assembly was lowered to a depth of 12 m with the cargo boom on the VARUA. A vane was mounted on the projector assembly to keep the J-13 projectors pointed away from the current. This facilitated operation during high tidal current conditions by minimizing drag forces on the projector pistons which could cause signal distortion.

A reference monitor hydrophone (ITC Type 6050C) was mounted at a distance of 6 m from the projector system to monitor the calibration of the projected sound levels.

During a playback sequence, a pre-recorded industrial noise stimulus on a cassette tape was used to generate a test signal. Two cassette recorders coupled to a fader control (previously shown in Fig. 3.5) permitted uninterrupted continuous sound for as long as desired. Playback periods of 30 min to 1 hr were generally used.

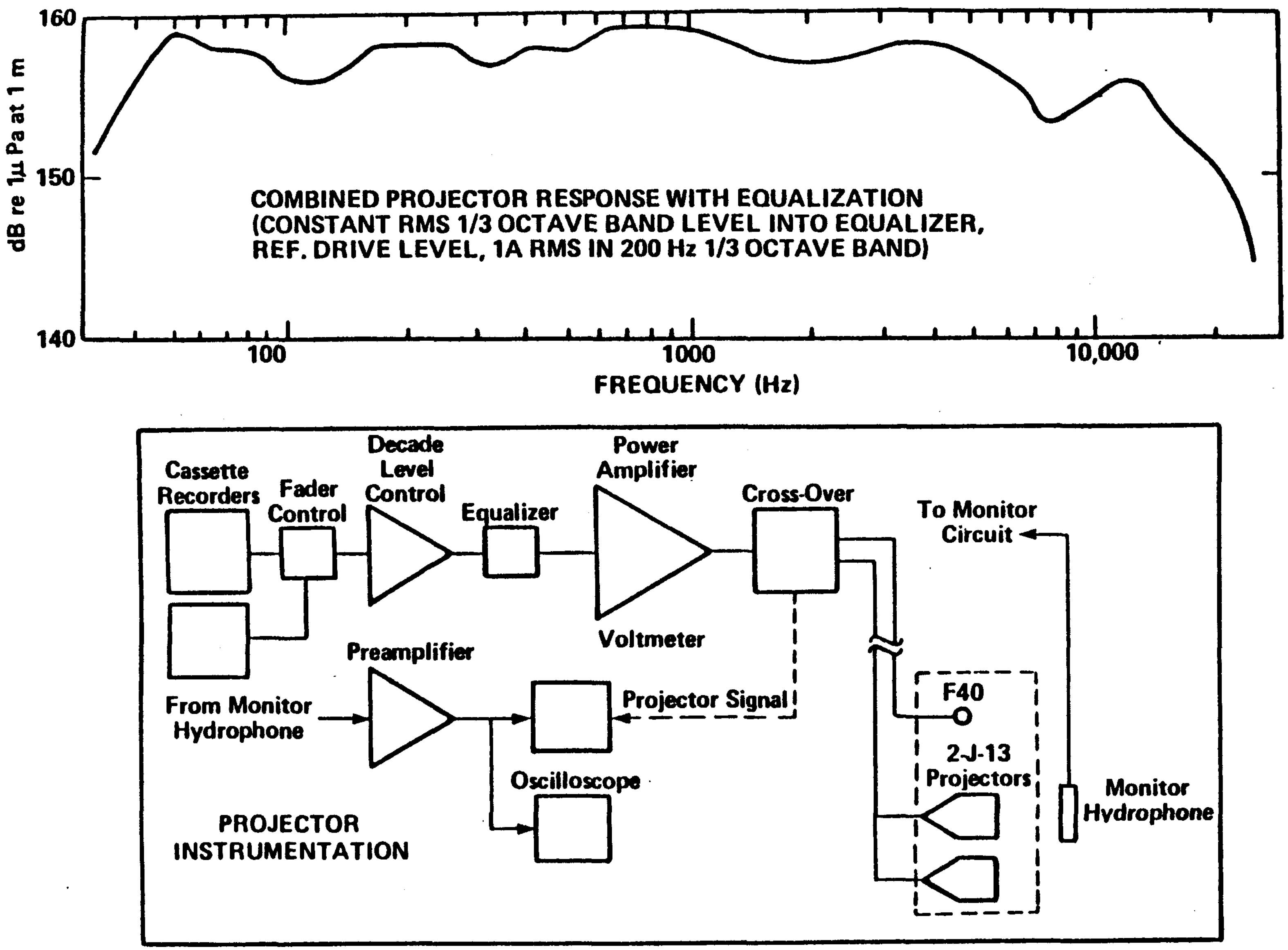


FIG. 3.5. PLAYBACK INSTRUMENTATION.

Stimuli Projection and Monitoring

The acoustic levels reported for the original sources of the playback stimuli varied over a wide range. Playback at source levels designed to reproduce the original signal levels was not feasible for some stimuli because of the high acoustic power required. For other stimuli, the original sound levels were low enough so that reproduction of the original level could limit whale behavioral reaction to areas in close proximity of the VARUA. The presence of the VARUA would be a potential confounding factor in interpreting the results for the lower level stimuli.

Thus, to provide a potential behavioral reaction zone at some distance from the VARUA for all of the playback sequences, the output level of the projector system was set to provide a source level which was 60 to 70 dB above the measured ambient noise level in the dominant bandwidth of the stimulus. An effective range of 2 to 5 km was maintained to the zone where the playback level became approximately equal to the ambient noise level in the dominant band of the stimulus. This procedure produced an acoustic test zone where any behavioral reaction of the nearby whales would probably occur within visual range of the observation vessels but also at some distance from the VARUA.

The sound levels used were subsequently scaled to levels reported for the actual sources and range corrections were derived by using the transmission loss characteristics measured at the test site. This procedure is described in detail in Sec. 5.

Selection and Level Calibration

Five petroleum industry development and production noise examples were used for the playback stimuli. Descriptive information for these test examples is contained in Table 3.1.

TABLE 3.1. PLAYBACK STIMULI INFORMATION.

Stimulus (Code)	Original Recording Dist. Meters	Dominant Frequencies Hz	Reported Level dB//µPa	Est. 100 m Level dB//µPa	Playback 100 m Level dB//µPa	Difference (PB-Orig) dB	Data Ref.
Drilling Platform (HOLLY)	30	5 (t)	119	109	-	-	Gales
		13 (t)	107	97	-	-	p. 66
		80-315 (st)	99	89	125	36	
DRILLSHIP (DS)	185	278 (t)	123	126	122	-4	Greene
(EXPLORER II)		50-315 (bb)	133	136	127	-9	p. 322
Production Platform (PP)	9	20 (t)	134	118	93	25	Gales
(SPARK)		63-250 (st)	125	109	123	14	p. 64
Helicopter (H)	152	20 (t)	114	118*	99	-19	Greene
(Bell 212)	(altitude)	32 (t)	99	103*	113	10	P. 311
		50-200 (st)	99	103*	116	13	
Semisubmersible Rig (SS)	12	28 (t)	129	111	105	-6	Gales
(OCEAN VICTORY)		63-250 (st)	119	101	123	22	p. 65

Key:

(t) tonal, (bb) broadband, (st) summed tonals.

*These values are for a flyover at 100 m altitude. Estimate based on relationships developed for aircraft-underwater sound transmission in deep water. In shallow water, levels would be higher, depending on the acoustic properties of the bottom material. Values assume a receiver position near the surface. (Urick, 1972)

As shown in the table, the acoustic recording used for each of the test stimuli was obtained at various ranges from the respective source. Hence, to standardize the playback comparison process, we corrected the reported acoustic level data to an equivalent 100 m range from the source. Since the water depth and sound propagation characteristics differed for the various sources, we considered that correction to a 100 m range represented a smaller potential error than correction to the usual 1 m range. In each case measured transmission loss data were used, if available, or the best estimate of transmission loss was used based on stated range and water depth values. In deriving the appropriate comparison with the projected playback level, a 100 m sound level estimate was also used. Thus, we were able to derive a scaling factor for the playback level which allowed us to compensate for local transmission loss characteristics and for differences between acoustic levels from the actual sources and the achievable levels from the playback projector. Table 3.1 shows the differences in levels between the playback stimuli and the reported values as corrected to an equivalent 100 m range. We wished to operate at a relatively constant signal-to-noise ratio (S/N) at the source and therefore have a uniform exposure region for all test stimuli. Thus, as shown in the table, the projected level was louder than the actual source for some stimuli, and quieter than the actual source for others.

Table 3.1 lists the maximum measured levels for the stimuli when they were originally recorded. These sound levels are based on the reported data for the actual tape dubs used. The reference cited was used as the basis for establishing the original sound field level because of the difficulty in recovering and preserving a calibration chain through the dubbing and playback process. The original data were used to determine the dominant spectrum components of the original sound field and the frequency region of the principal output. Because of the low frequency limitation of the J-13 projectors below 32 Hz, it was not possible to reproduce the required levels for sources with very low dominant frequencies. In this case, the degree to which the frequency response above 32 Hz matched the original source was examined independently by comparison of this part of the playback spectrum with the comparable part of the reported original source spectrum. This is shown as the "summed tonal level" value in Table 3.1.

The sound level output produced during playback is compared with the original sound source values in the last column of the table. The comparison shows that while low frequency components are often appreciably reduced on playback, the components above 32 Hz are generally greater than their original levels. The exception to this is the drillship stimulus where the achievable level is below that of the actual source at all frequencies. The procedure for scaling level differences between playback and actual sources will be discussed in Sec. 5 using the measured TL and ambient noise data for the observation site.

3.4 Analysis Procedures

3.4.1 Statistical analysis of sighting data

A computer program was written to compare the distribution of ranges from whale sightings to the sound source under stimulus and control conditions. This program first tallied the cumulative distributions under the two conditions and calculated the likelihood that these two distributions were drawn from different populations using the Kolmogorov-Smirnov and Cramer-von Mises two-sample statistical tests.

3.4.2 Development of an approximate sighting density function

In order to facilitate visual comparison of the sighting distributions under control and stimulus conditions, the program also plotted the density of sightings as a function of range.

If the cumulative sighting distributions were continuous functions of the range from the source then differentiation of these functions would yield sighting probability density functions. Comparison of these functions would provide a more direct measure of a shift in sighting density due to avoidance than comparison of the cumulative distribution functions. Unfortunately, the sighting distributions have discrete increments so direct differentiation or slope analysis is difficult.

An approximation to the probability density function was derived by the procedure illustrated in Fig. 3.6. The number of sighting increments contained in a finite "window" along the y direction is proportional to the slope of the cumulative sighting distribution at the window location. The window must be wide enough so that a relatively smooth averaged output is obtained. If the window is made too wide, resolution of small scale density changes is lost. It can be shown that resolution of density changes of a scale equal to one-half of the window width is possible. A 200 m window was used since the average range error in the sighting data was estimated to be about 100 m within 1 km of the source. The density of sightings was calculated by moving a window across the range axis and tallying the number of sightings within the window. In order to create a smooth distribution, a raised cosine (hanning) window was used with an area equal to a 200 m rectangular window of unit height. Each sighting within the window was multiplied by the value of the window function at that range.

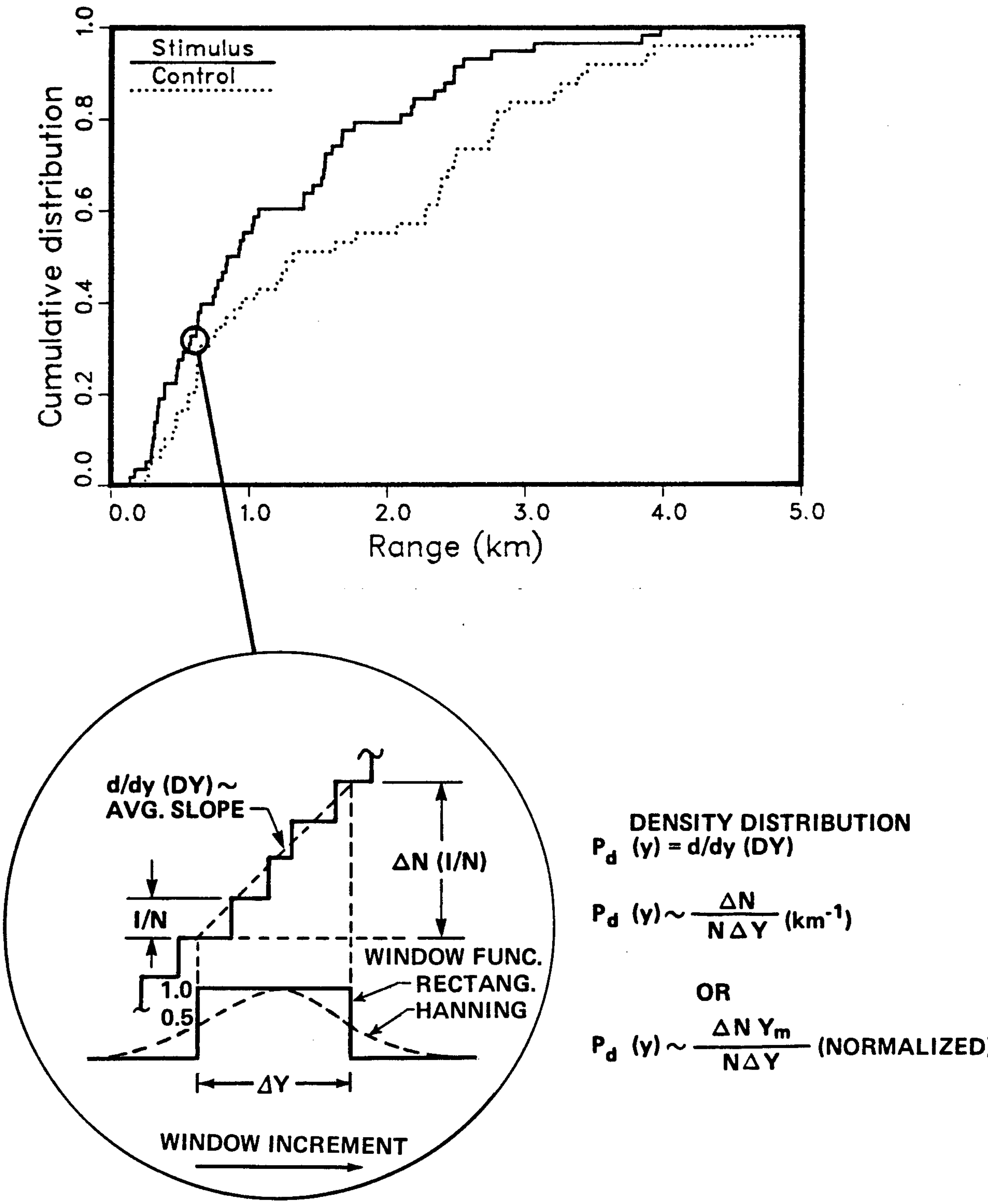


FIG. 3.6. PROCEDURE FOR OBTAINING AN APPROXIMATE SIGHTING DENSITY DISTRIBUTION FROM THE CUMULATIVE DISTRIBUTION.

The density of sightings was normalized so that it represents the fraction of the total number of sightings per kilometer seen within the window. Since the window has an area equivalent to a 0.2 km rectangle, if all the sightings fell within one window, the value could be as high as 5, (100% of sightings/km in 0.2 km = 1/0.2 = 5). If none of the sightings fell within the window, the sighting density would obviously be 0.

3.4.3 Temporal analysis of surfacing data

Richardson et al. (1982) and Baker et al. (1983), reported significant changes in respiration of whales in response to the approach of vessels. One of the strongest effects was that whales tended to blow more frequently just after the start of exposure. We tested whether whales were surfacing more frequently at the start of our playback experiments in two ways. We plotted all sightings vs range and time after the onset of stimulus to look for an effect by inspection. We also used a rank-order statistic* as a distribution free test of the probability that the median time of sighting lies in the first half of the time period. We calculated these probabilities both for control and experimental periods for comparison.

*Equation 32-22 from Kendall and Stuart, "The Advanced Theory of Statistics, Vol. 2, p. 547.

4. DESCRIPTION OF THE FIELD ENVIRONMENT AND OBSERVATION CHRONOLOGY

Field observations of humpback whales during presumably undisturbed periods and during periods of acoustic playback and controlled air gun operations are summarized below. A summary of weather conditions for each period of observation is also provided.

4.1 Test Schedules

Playback Schedule Considerations

The playback schedule was designed to present the five sound stimuli in relatively short playback periods. This was necessary because a whale group or concentration could not be expected to remain in a given area for a long period of time. A typical playback sequence consisted of a 30 min. pre-experiment control period, a 60-min. stimulus period, and a 30-min. post-experiment control period.

Because of drift of the vessel and changes in whale grouping, it was often necessary to move the VARUA to a new location following a playback sequence in order to increase the number of whales in the useful acoustic test zone for the next playback sequence.

Since the VARUA was used as an observation vessel in addition to being the source vessel, it was not possible to use a blind test method where the observers did not know the playback schedule. However, this is not expected to cause significant bias in the sighting data.

One complete block of all five stimuli was completed with one additional drillship playback during the test period.

Air Gun Source Schedule

Five days of observations were made with an air gun source vessel present. The results obtained during the 1984 air gun measurements with gray whales showed that behavioral changes were not observed at ranges greater than 1 to 2 km. Thus, a preliminary set of measurements were performed for this study where the air gun range was gradually decreased from about 3 km to a position near the center of the feeding zone. Following this test, two days of whale behavior observations were made with the air gun vessel operating at slow speed near the VARUA. These tests provided measurement geometry very similar to that used for the playback observations and permitted use of the same statistical testing procedures for both playback and air gun data. Two tests were performed with the air gun vessel moving at 2 to 3 kts.

A chronological list of the control, playback and air gun sequences obtained during the field period is shown in Table 4.1.

4.2 Field Observations in August 1984

Table 4.2 presents a summary of observations by date and experimental period. Observation periods generally lasted between 2 to 3 hrs. Our daily starting time depended on the length of time it took us to locate a concentration of whales and the observation conditions. Overall, we had generally good to excellent observation conditions (see Table 4.3). We did, however, lose one full day, 25 August, and parts of two other days, 22 and 23 August, to adverse weather conditions. We achieved a total of 39.7 hrs. of field observation during the season. This figure was determined by counting a 2 hr experimental period using two platforms as 2 total hours of field observation. During the entire field season, approximately 375 whales were observed. However, because individual identification

TABLE 4.1. TEST SUMMARY FOR HUMPBACK WHALE STUDY, 18 THROUGH 29 AUGUST 1984.

Date/Time		Stimulus	Stimulus/ Duration
8/19	1600-1800	Control[1]	120 min.
8/20	1044-1244	Control	120 min.
	1645-1826	Control	101 min.
	1826-1920	Drillship	54 min.
	1920-1932	Control	12 min.
8/21	0929-1205	Control	156 min.
	1205-1307	Drilling Platform	62 min.
	1307-1340	Control	33 min.
	1509-1621	Control	72 min.
	1621-1724	Helicopter	63 min.
	1724-1809	Control	43 min.
8/22	1143-1153	Control	10 min.
	1153-1242	Air Gun	49 min.
	1242-1258	Control	16 min.
	1509-1540	Control	31 min.
	1540-1647	Air Gun	67 min.
	1647-1715	Control	28 min.
	1748-1820	Control	32 min.
	1820-1922	Air Gun	62 min.
	1922-1953	Control	31 min.
8/23	1817-1853	Control	36 min.
	1853-1928	Air Gun	35 min.
	1928-2000	Control	32 min.
8/24	0943-1015	Control	32 min.
	1015-1109	Air Gun	54 min.
	1109-1146	Control	37 min.
	1426-1500	Control	34 min.
	1500-1601	Air Gun	61 min.
	1601-1639	Control	38 min.
	1818-1950	Control	92 min.
8/26	0922-1017	Control	55 min.
	1017-1115	Air Gun	58 min.
	1115-1149	Control	34 min.
	1413-1439	Control	26 min.
	1439-1607	Air Gun	88 min.
	1607-1709	Control	62 min.

Date/Time		Stimulus	Stimulus/ Duration
8/26	1804-1825	Control	21 min.
	1825-1910	Semi-Submersible Rig	45 min.
	1910-1920	Control	10 min.
8/27	1202-1232	Control	30 min.
	1232-1308	Production Platform	36 min.
	1308-1418	Control	70 min.
8/28	1803-1835	Control	32 min.
	1835-1913	Drillship	38 min.
	1913-1943	Control	30 min.

Total Acoustic Test Time

Stimulus	Time	Test Periods
Drillship	1 hr, 32 min.	2
Drilling Platform	1 hr, 2 min.	1
Production Platform	36 min.	1
Semi-Submersible Rig	45 min.	1
Helicopter	1 hr, 3 min.	1
Air Gun	7 hrs, 54 min.	7

NOTE 1: All control periods were performed with source and observation vessels present. The auxiliary equipment on the NANCY H. (air compressor and diesel generator) was running. No auxiliary equipment was running on the VARUA during either playback or observation periods.

TABLE 4.2. DATA SUMMARY FOR HUMPBACK WHALE - STUDY 18-29 AUGUST 1984
Part I - Estimated Number of Whales versus Test Conditions

Date	Time	#Sightings	#Whales	Stimulus	Location
19 Aug.	1600-1800	112	20	Control	Land & Boat: Lighthouse & VARUA
		Realize difficulty of tracking groups. Whale concentrations continually moving, making land-based observation difficult.			
20 Aug.	1044-1244	67	25-30	Control	2 Land Stations: Whitney Island, Bill Pt. & Bartlett Pt.
		Reinforced our opinion of the day before. Concentrations originally near shore remained there, but groups constantly joining and splitting making tracking impossible.			
20 Aug.	1645-1932	209	30-40	Drillship 1	2 Boat Stations: VARUA & Whaler
		New approach: start numbering sightings to coordinate data rather than keeping track of groups. Whales moved away, came back near end. Used two boats.			
21 Aug.	0929-1340	208	20-30	Drilling Platform 1	2 Boat Stations: VARUA & Whaler
		Number of sightings decreased throughout the experiment.			
21 Aug.	1509-1809	69	10	Helicopter 1	2 Boat Stations: VARUA & Whaler
		Number of sightings decreased throughout the experiment. All distant.			

TABLE 4.2. (Cont.) DATA SUMMARY FOR HUMPBACK WHALE - STUDY 18-29 AUGUST 1984
Part I - Estimated Number of Whales versus Test Conditions

Date	Time	#Sightings	#Whales	Stimulus	Location
22 Aug.	1143-1258	106	30-40	Air Gun	Land & Boat: Round Rock & VARUA
		Very close whales. Saw probable startle when air gun started. Whales moved south then return. Terminated early due to heavy fog. Whales were feeding.			
22 Aug.	1509-1715	145	20	Air Gun	Two Boat: Round Rock
		Distant whales. No obvious reaction.			
22 Aug.	1748-1953	126	15	Air Gun	Two Boat: Round Rock
		Mostly distant whales. Some close. No obvious reaction. One group passed close to NANCY H. when air gun was operating.			
23 Aug.	1817-2000	62	10	Air Gun	Two Boat: VARUA & NANCY H., Hobart Bay
		Bad weather. Tried using NANCY H. and VARUA. Only distant whales. Whales moved off during experiment.			
24 Aug.	0943-1146	120	20	Air Gun	Two Boat: VARUA & Whaler, Hobart Bay
		Some obvious response to air gun start. Close, discrete groups. We were able to track groups.			

TABLE 4.2. (Cont.) DATA SUMMARY FOR HUMPBACK WHALE - STUDY 18-29 AUGUST 1984
Part I - Estimated Number of Whales versus Test Conditions

Date	Time	#Sightings	#Whales	Stimulus	Location
24 Aug.	1426-1639	187	20-25	Air Gun	2 Boats: VARUA & Whaler, Sunset I
		Whales generally moved away throughout. Obvious startle response.			
24 Aug.	1818-1950	84	20-25	Control	2 Boat: VARUA & Whaler, Sunset I.
		Whales moved away but returned very close to NANCY H.			
26 Aug.	0922-1149	83	15-20	Air Gun (moving)	3 boat stations: NANCY H.,* VARUA, WHALER. Hobart Bay
		Whales seemed to move to the south, southeast, and southwest as the NANCY H. came through area. Some whales moved back into our area during the post-playback control period. *One observer on NANCY H. getting orientations and distances.			
26 Aug.	1431-1709*	76	20-30	Air Gun (moving)	Land & Boat: Entrance Island & NANCY H., Hobart Bay
		No obvious reaction noted. One group clearly stayed in same place as NANCY H. moved through. Overall - no flight response observed. *Observations from Entrance Island were continuous from 1413-1920			

TABLE 4.2. (Cont.) DATA SUMMARY FOR HUMPBACK WHALE - STUDY 18-29 AUGUST 1984
Part I - Estimated Number of Whales versus Test Conditions

Date	Time	#Sightings	#Whales	Stimulus	Location
26 Aug.	1804-1920	68	20-30	Semi-Submersible 1	Land & Boat: Entrance Island & VARUA, Hobart Bay
		No obvious reaction noted. Several groups approached close to VARUA with one group of 3 whales passing VARUA within 50 m.			
27 Aug.	1202-1418	76	10-20	Production Platform 1	Land & Boat: Lighthouse & VARUA
		No obvious reaction noted. VARUA in current eddies and then drifted rapidly to the south. Whales appeared to be feeding underwater - staying down for long periods.			
28 Aug.	1300-1415 (approximate)				Airflight.
		We could not find a concentration of whales so an airflight was called. A major concentration of whales was found near Pt. Hugh at the entrance to the Seymour Canal so we motored north for approximately 33 km.			
28 Aug.	1803-1943	105	30-40	Drillship 2	Two Boats: VARUA & Whaler. Pt. Hugh
		After an aborted control period (1732-1748) we did a playback. No obvious reaction noted with many of the whales moving generally in a southerly direction. Some whales (6-8) passed within 200 m of the VARUA.			

TABLE 4.3. WEATHER SUMMARY.

19 August:	1542-1755 -	Lighthouse: & VARUA	Seas choppy with some white caps. Wind 8-12 kts (no direction noted). 100% cloud cover.
20 August:	1045-1244 -	Land Stations:	Intermittent rain. Wind SW 0-5 kts. 100% cloud cover.
	1645-1933 -	VARUA & Whaler	Seas calm. Light rain up to 1844. Wind S 0-5 kts by 1921. Visibility very good to excellent. 100% cloud cover.
21 August:	0929-1340 -	VARUA & Whaler	Seas calm. No wind. Some fog 2-3 km away at start. Visibility excellent. Cloud cover 100% down to 35% by end.
	1509-1809 -	VARUA & Whaler	Seas calm. No wind. Visibility excellent. Cloud cover 60-75%.
22 August:	1143-1258 -	VARUA & Round Rock	Fog making visibility fair at start. By 1216, thick fog making viewing from VARUA impossible - slightly better at Round Rock.
	1509-1715 -	VARUA & Whaler	Seas calm. No wind. Visibility excellent. Cloud cover 40%.
	1748-1953 -	VARUA & Whaler	Seas calm. No wind. Visibility excellent. Cloud cover 60-90%
23 August:	1817-2000 -	NANCY H. & VARUA	Seas choppy, swells at start - calmer by end. Wind SE 5-15 kts at start down to 5 kts at end. Visibility fair. Light rain at end. Cloud cover 100%.

24 August:	0943-1146 -	VARUA & Whaler	Visibility good at start deteriorating as time went on because of fog - improving at end. Cloud cover 100%.
	1426-1639 -	VARUA & Whaler	Seas calm. Visibility excellent to good at end. Cloud cover 100%.
	1818-1950 -	VARUA & Whaler	Seas calm. Wind up from SE by end. Visibility excellent at start deteriorating as rain and fog came in by 1910. Cloud cover 100%.
26 August:	0921-1150 -	VARUA & Whaler & NANCY H.	Seas choppy, swells at start - calmer at end. Wind up to 15 kts at start (no direction noted) down to 3-5 kts (variable) at end. Visibility good with rain at start. Cloud cover 90% down to 60% at end.
	1414-1920 -	Entrance Island & NANCY H. & VARUA	Seas calm. 1530-1700 - wind line with rain (no direction noted). Visibility excellent except 1530-1700 when good to fair.
27 August:	1201-1418 -	Lighthouse and VARUA	Seas calm. Current/eddies causing VARUA to drift south. Light variable wind. Visibility excellent. Cloud cover 30%.
28 August:	1732-1943 -	VARUA & Whaler	Seas calm. Light variable wind. Visibility excellent, fair to east. Cloud cover 30-40%.

identification was not critical to our experimental design, it should be presumed that some of these whales were resightings.

During our observations we saw three other species of marine mammals: Dall porpoise (Phocoenoides dallii), harbor seal (Phoca vitulina), and the northern or Steller's sea lion (Eumetopias jubatus). On 22 August, we observed a group of northern sea lions breaching very close to 4 or 5 surface active humpback whales. We also observed associations between humpback whales and northern phalaropes (Lobipes lobatus). The phalaropes were presumably taking advantage of the disturbed water surface to feed on prey items brought to the surface (MacIvor 1984).

5. ACOUSTIC MEASUREMENTS AND RESULTS

This section contains a description of the acoustic measurements made during the August 1984 field season and a summary of the results obtained. The analytical background for many of the procedures used was developed during previous studies with gray whales (Malme et al. 1983). Some of that discussion will be included here to facilitate understanding of the results and minimize refererence to the earlier report.

The test procedure requires establishment of a controlled sound field in a region where humpback whales are present. To accomplish this, a calibrated source of sound must be used and knowledge of the attenuation rate of the sound with propagation distance must be obtained. This permits estimation of the signal levels at the observed positions of whales without requiring specific measurements at each position. The following discussion describes source calibration procedures, transmission loss measurements, ambient noise measurements, and procedures for estimation of noise exposure levels.

5.1 Acoustic Source Characteristics

The air gun and playback projector system were identical to those used in the January 1984 study, (Malme et al. 1984). A description of these sources was given previously in Sec. 3.3.

5.1.1 Air gun source characteristics

The previous measurements of a single 100 cu. in. air gun (Malme et al. 1983, Sec. 5.1.2) showed that the effective pulse pressure level was a useful measure of the received level of the transient signals from an air gun. This quantity is a measure of the effective energy of a noise pulse in terms of an average pressure level defined as (Urick 1983, Sec. 4.4)

$$E = \frac{1}{\rho c} \int_0^\infty p^2(t)dt = \frac{\overline{P}^2 T}{2\rho c} \text{ (Joules)} \tag{1}$$

where

ρc = the specific acoustic impedance of water

$p(t)$ = the original pulse pressure waveform

$\overline{P}$ = the effective pulse pressure

T = the effective pulse duration (the time required for $p^2(t)$ to decay to less than 10% of the initial value).

The instrumentation used to analyze air gun signals to obtain the effective pulse pressure incorporated a squaring and integrating circuit to provide a voltage output proportional to the integrated acoustic energy of the pulse. The time duration of the signals was determined by visual inspection of the pulse envelope on a digital transient recording of the waveform. Figure 5.1 illustrates a typical air gun signature and the analysis procedure. Generally it is more convenient to express acoustic pressure in logarithmic terms. Consequently, the effective pulse pressure level is defined as

$$L_{\overline{P}} = 20 \text{ Log}_{10}(\overline{P}/P_{ref}) \text{ dB} \tag{2}$$

where

P_{ref} = 1μPascal.

Air gun signature analysis

A narrowband analyzer was used to analyze air gun signatures for various ranges. The time waveforms of the pulses were also recorded to obtain peak pressure data and examine time duration

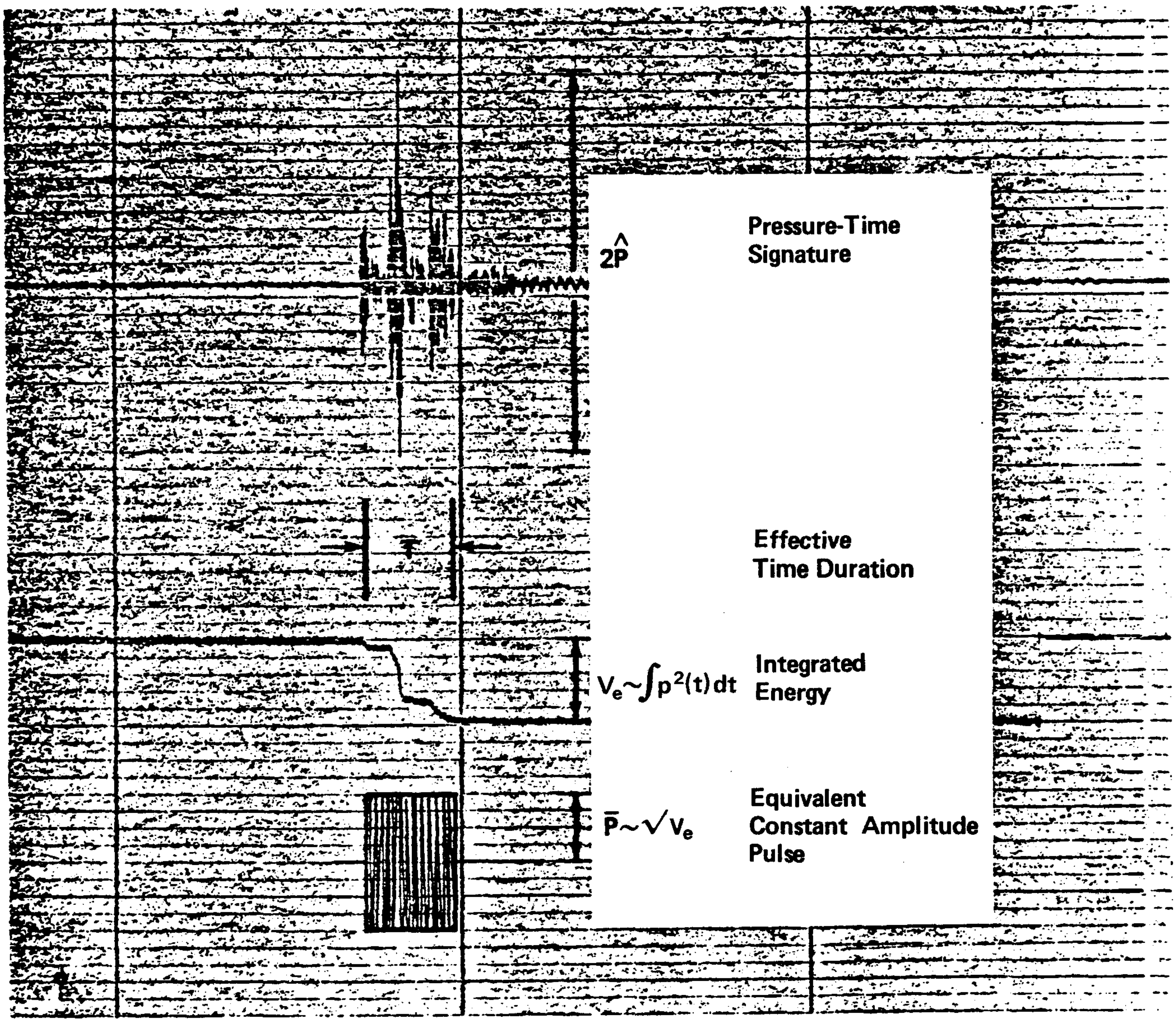


FIG. 5.1. CHART RECORD SHOWING PULSE SIGNATURE AND PULSE ENERGY INTEGRATOR OUTPUT.

as a function of range. Because of multipath transmission, peak pressure values were found to be quite variable. The time duration of the signals was observed to generally increase with range due to reverberation. Separate discrete multipath pulses were often received, especially in areas where the water depth was greater than 100 m.

The air gun was operated at ranges of 6 km (3.2 nm) to 20 m at a firing rate of 6 pulses/min. The pressure signature observed at close range was found to agree quite well with the data obtained during the previous work with gray whales, also using a 100 cu. in. gun.

5.1.2 Playback system response measurement

As described previously in Sec. 3.3, the low frequency response of the playback system was improved by adding a second low-frequency projector. In addition, an equalization network was used to provide a smooth frequency response in the mid-band and high-frequency regions. The accuracy of the playback system was examined by recording the output of the source monitor hydrophone and comparing the spectrum of the reproduced signal with the relative spectrum of the original tape recording. An example of this comparison is shown in Fig. 5.2 for the drillship stimulus. A complete set of comparison spectra is contained in Appendix C for all of the industrial noise stimuli.

5.2 Transmission Loss Measurements

5.2.1 Shallow water sound propagation characteristics

Acoustic transmission loss in shallow water is highly dependent on the acoustic properties of the bottom material since, in most areas, sound energy is transmitted mainly by paths that are multiply reflected from the bottom and surface. The

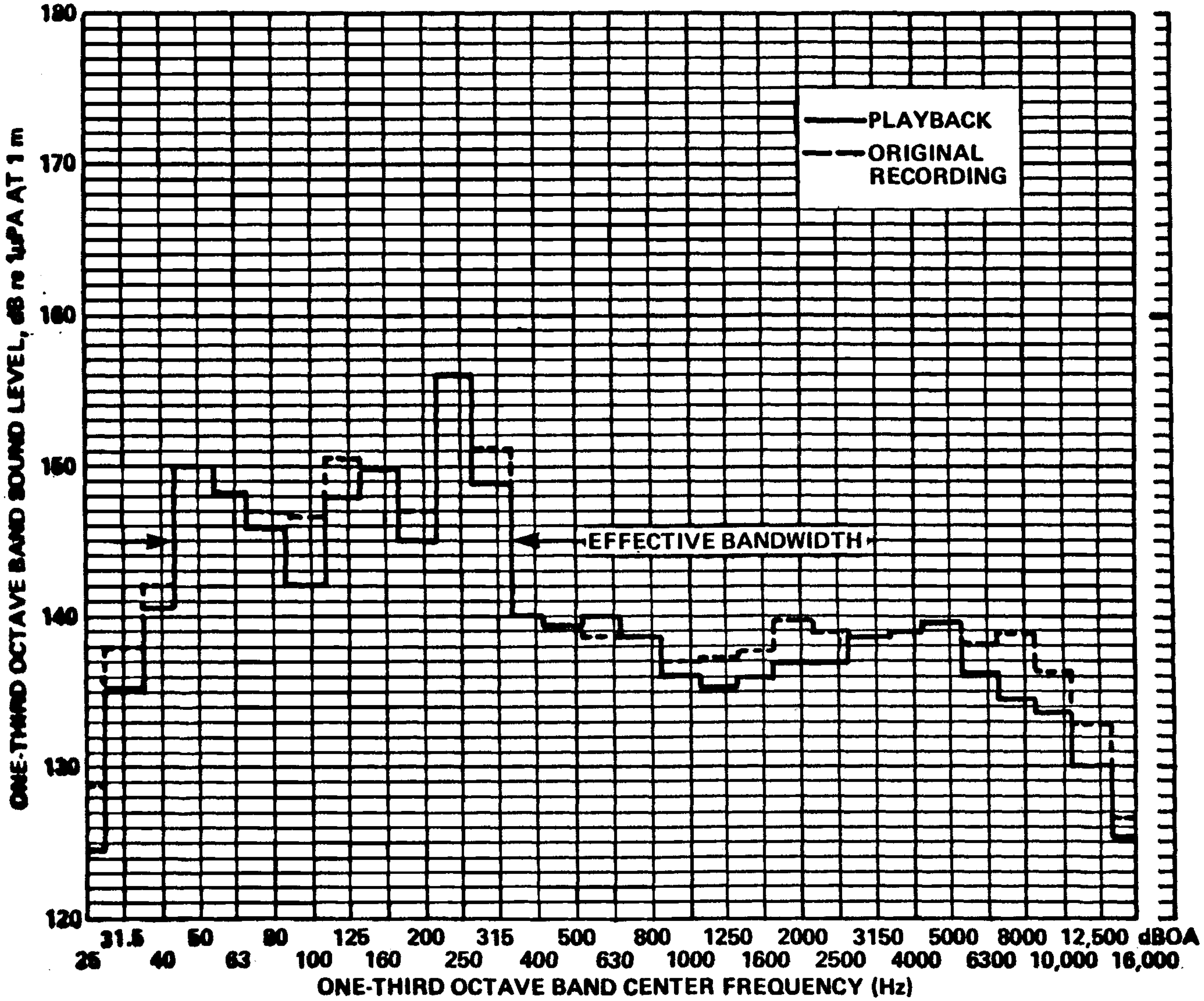


FIG. 5.2. DRILLSHIP ONE-THIRD OCTAVE SPECTRA.

average number of reflections (or "bounces") depends on the water depth, bottom slope, acoustic properties of the water column (sound velocity gradient), acoustic properties of the bottom, and any directional properties of the source and receiver. In most shallow water areas, the relationship between acoustic pressure and distance from the source (range) has been found to be modeled quite well by considering a spreading loss which is midway between that of unbounded deep water (spherical spreading or 20 log range) and that of ducted horizontal spreading (cylindrical spreading or 10 log range) (Urick 1983, Sec. 6.6). To the spreading loss must be added a loss due to molecular absorption in the water, a loss due to the scattering and absorption at the surface and bottom, and an energy increase due to the surface and bottom "image" sources. The resulting sound propagation model can be expressed in equation form as:

$$L_r = L_s - 15\ \mathrm{Log}(r) - A_v(r) - A_r(r) + I\ (\mathrm{dB}//1\mu\mathrm{Pa}) \qquad (3)$$

where

L_r = Received level at range r (dB//1μPa)

L_s = Source level (dB//1μPa at 1 m)

r = Range in meters

A_v = Molecular (volumetric) absorption (dB per meter)

A_r = Reflection loss at surface and bottom (dB per meter)

I = Change in effective source level due to proximity of surface and/or bottom (dB).

For the previous gray whale studies off the California coast, a version of this sound propagation model was developed which incorporated an experimentally derived reflection loss coefficient. Transmission loss data were obtained using both the air gun and the projector sources. Regression analysis of the data provided a best fit value for the reflection loss in terms of an average "loss per bounce." Fortunately, the bottom characteristics in the test area were uniform and the sound velocity gradients were neutral so a single propagation loss equation was found to be applicable to all of the data.

This is not the case for the test area in Frederick Sound/Stephens Passage. Bottom reflection characteristics were found to be quite variable in previous measurements in this area (Malme, Miles and McElroy 1982). Moreover, appreciable sound velocity gradients were found to exist as a result of the lower salinity and higher temperature of the water near the surface. These gradients can cause variable sound shadowing or sound focusing effects which make transmission loss depth dependent as well as range dependent. Since the depth at which whales were spending most of their time was not determined, it was not feasible to measure the transmission loss versus range at an appropriate depth. A compromise procedure was followed in which transmission loss data measured at a depth of 10 m were used together with a computer implemented transmission loss model based on an augmented version of Eq. (3) to predict the transmission loss at the estimated feeding depth of the whales. Depth values of 50 to 100 m were used based on data reported by Krieger and Wing (1983). Measured sound velocity profile (SVP) data were incorporated into the computer model as well as an estimate of the bottom loss characteristics. The transmission loss data measured at 10 m were compared with computer model predictions for the same receiver depth. If a good comparison was obtained, the computed transmission loss at the estimated feeding depth of the whales was then used to derive the sound exposure level estimate for the specific test area. The following subsections describe this process in more detail.

5.2.2 Water temperature, salinity, and sound velocity profiles

Variations in the speed of sound with depth in the water column (gradients) can impose important variations on the transfer of acoustic energy from one point to another. Depending upon the average gradient of the sound velocity profile, acoustic energy can be refracted downward (negative gradient conditions - decreasing sound speed with depth), upward (positive gradient conditions - increasing sound speed with depth), or have little path curvature under neutral (mixed water column) conditions. Sound channeling occurs at the depths of local minima in the sound velocity profile, when acoustic energy becomes trapped (propagates without boundary reflections). An understanding of the variability of the sound velocity profile in various regions of the test area is particularly important, since the average profile will dictate the degree to which sound energy will interact with the ocean bottom and surface. Bottom and surface losses imposed on the incident acoustic energy can vary considerably with bottom material and roughness, and sea surface roughness.

Sound velocity in water varies directly with temperature, salinity, and pressure. One algorithm that defines this relationship was derived by Wilson and is used in many underwater sound texts such as Urick (1983). Wilson's equation states:

$$c = 1449.2 + 4.623T - 0.0546T^2 + 1.391(S-35), \text{ (m/sec)} \quad (4)$$

where c is the speed of sound, T is the temperature (°C), and S is the salinity in parts per thousand. Wilson's equation also contains a term which depends on pressure. Because the depths of interest here are 50 m or less, the pressure term contribution is negligible and has been ignored in Eq. (4).

Temperature and conductivity were measured and salinity calculated at discrete depth increments to a maximum depth of 50 m. It was found, by comparing the acquired data with data reported by Krieger and Wing (1983), that temperature and salinity become quite stable and predictable at depths beyond about 40 m. Sound velocity profiles were computed from the resulting temperature and salinity profiles with a hand-held calculator that was preprogrammed with Wilson's equation.

Figures 5.3 and 5.4 give typical sound velocity, temperature and salinity profiles in the test area. The data are representative of measurements taken in the inlets of southeast Alaska where cold water, having a low salinity, is often present in a surface layer. Measurements taken at stations further away from tidal glaciers and snow/ice melt run-off generally show a clear trend of warming and increased salinity near the surface. In areas where there is strong mixing due to tidal currents and/or high wind speeds, the temperature and salinity profiles are nearly constant with depth. The ebb and flow of the tide has some second-order influence on the temperature and salinity profiles in slow current areas at some distance from the ocean.

Near the surface, lower salinity and warmer temperature conditions produce opposing effects on the speed of sound. The sound velocity profiles shown in Fig. 5.3 result when the temperature is high enough near the surface to offset the effect of low salinity. The profiles shown produce downward refraction which results in the loss of the direct sound path at a relatively short range between a source and receiver shallower than 15 m. Bottom reflected sound is dominant in determining acoustic transmission loss for shallow source-receiver geometry. The sound velocity profile for 8/26 shows the result of surface layer mixing due to a 15 kt wind. Here, the surface layer extends down to a depth of 30 m rather than to the 8 to 10 m

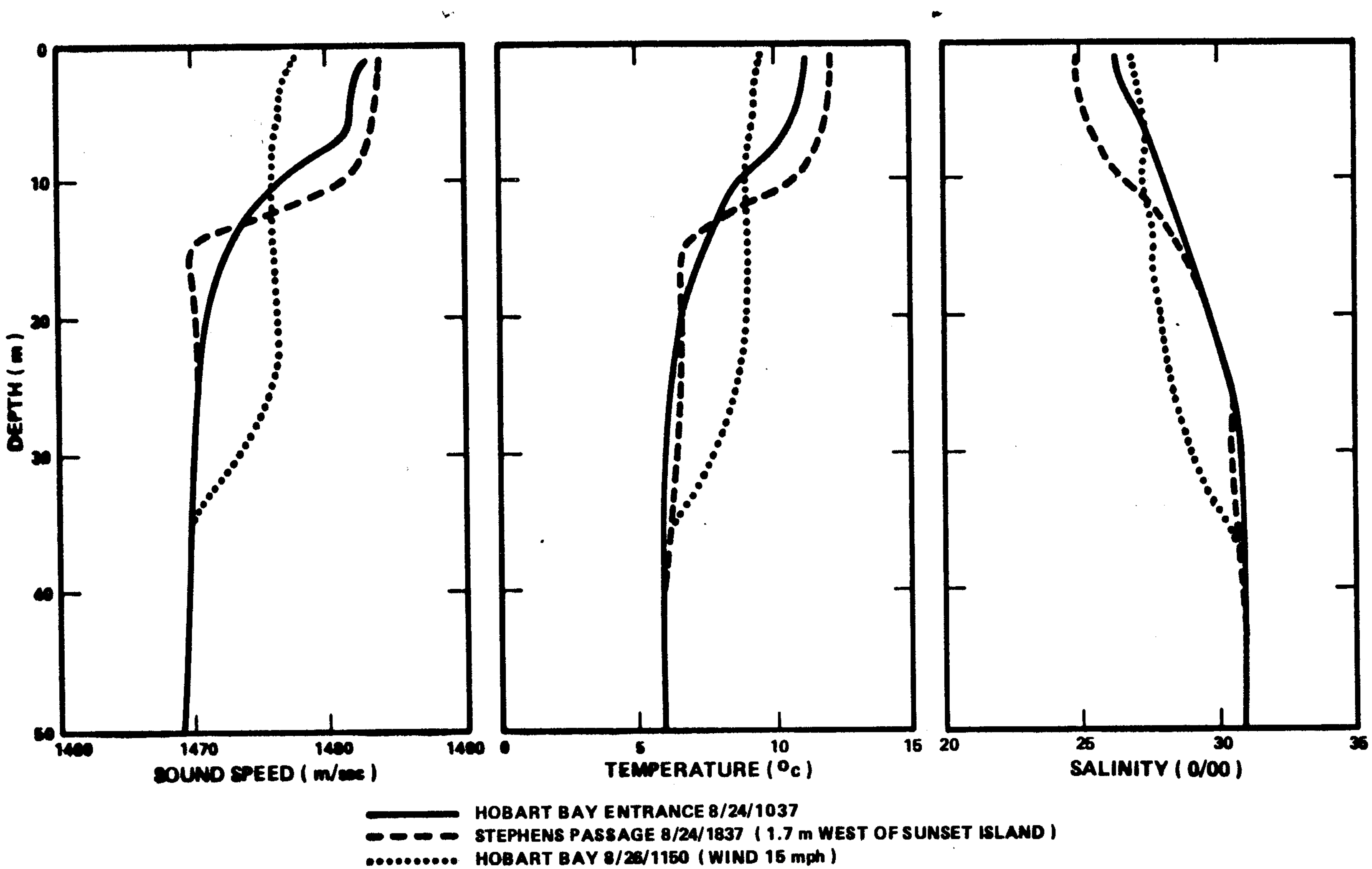


FIG. 5.3. SOUND VELOCITY, TEMPERATURE, AND SALINITY PROFILES (EXAMPLES OF DOWNWARD REFRACTING CONDITIONS).

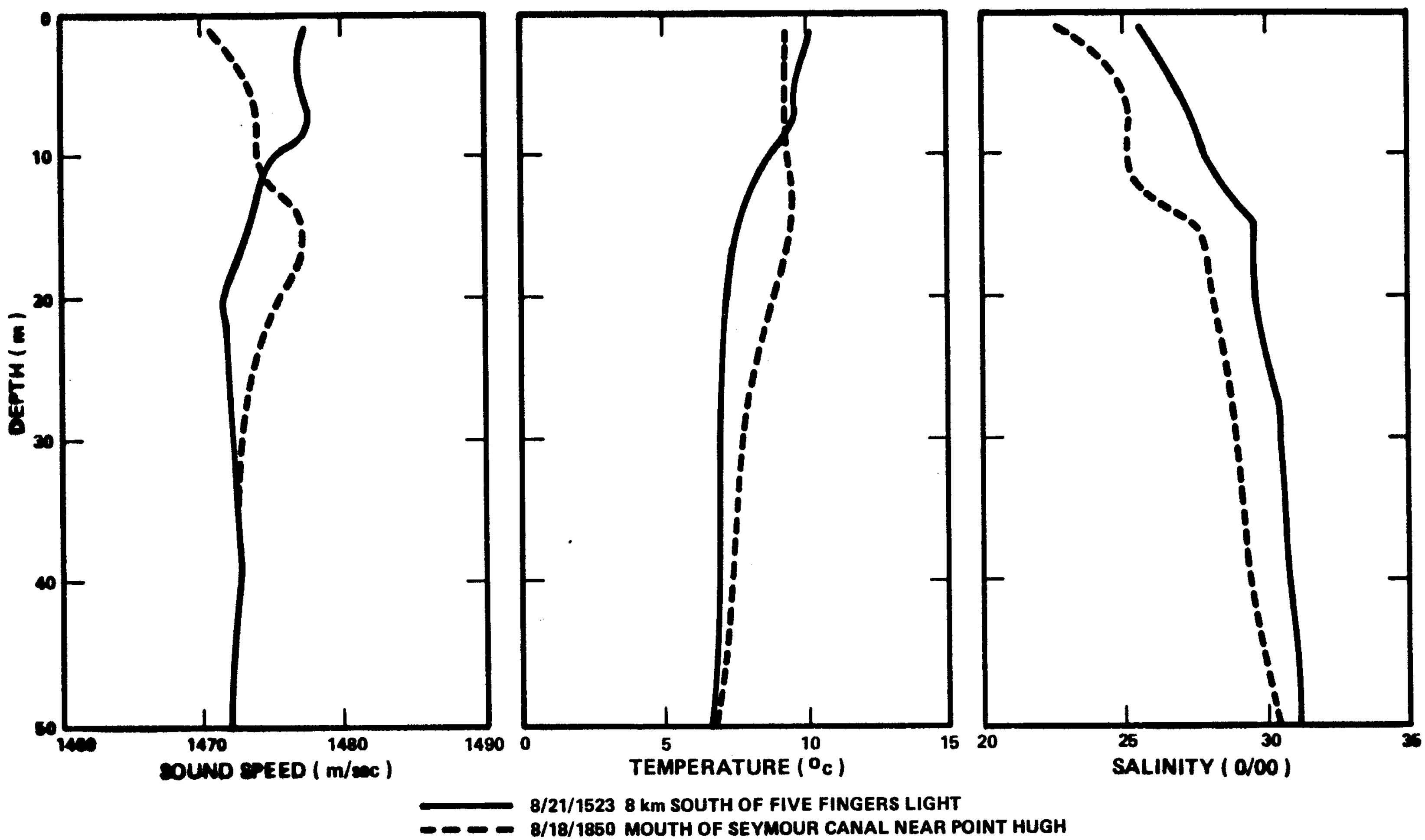


FIG. 5.4. SOUND VELOCITY, TEMPERATURE, AND SALINITY PROFILES (EXAMPLES OF SURFACE DUCT CONDITIONS).

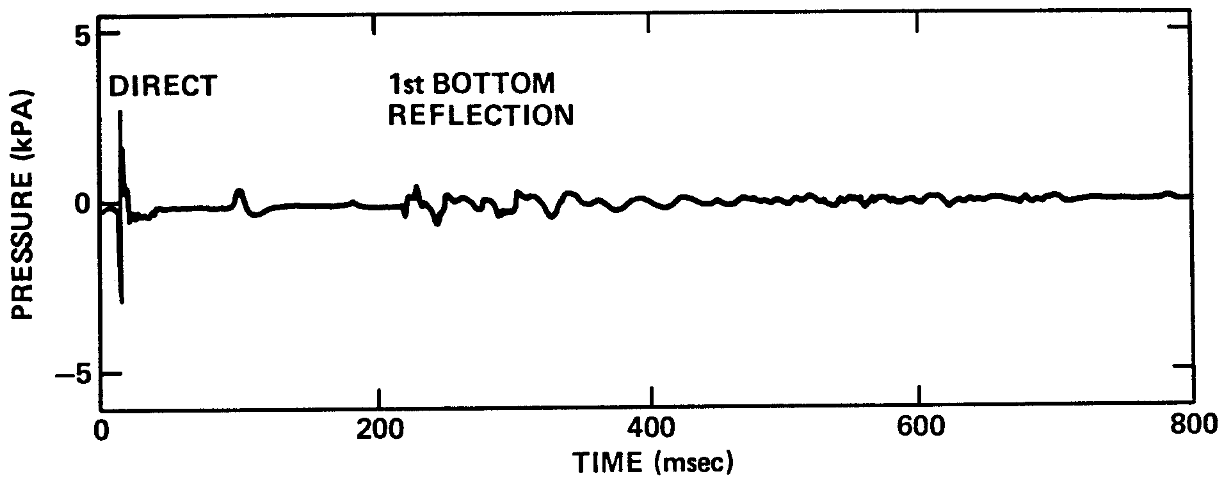
depth seen to be typical of calm conditions. For a shallow source - deep receiver geometry, the direct sound path as well as reflected paths are important in determining transmission loss. This consideration is applicable for the general test conditions where the air gun or projector was at a depth of 8 to 12 m with whales feeding at depths estimated to be 50 to 100 meters.

Sound velocity profiles showing the possible existance of a surface sound channel were obtained at the entrance of the Seymour Canal. These conditions are shown in Fig. 5.4. The data obtained south of Five Fingers Light also show the presence of a possible shallow surface sound channel. In this case, the effect is not very pronounced and may not be significant compared to the general downward refraction trend caused by the negative gradient below 8 m.

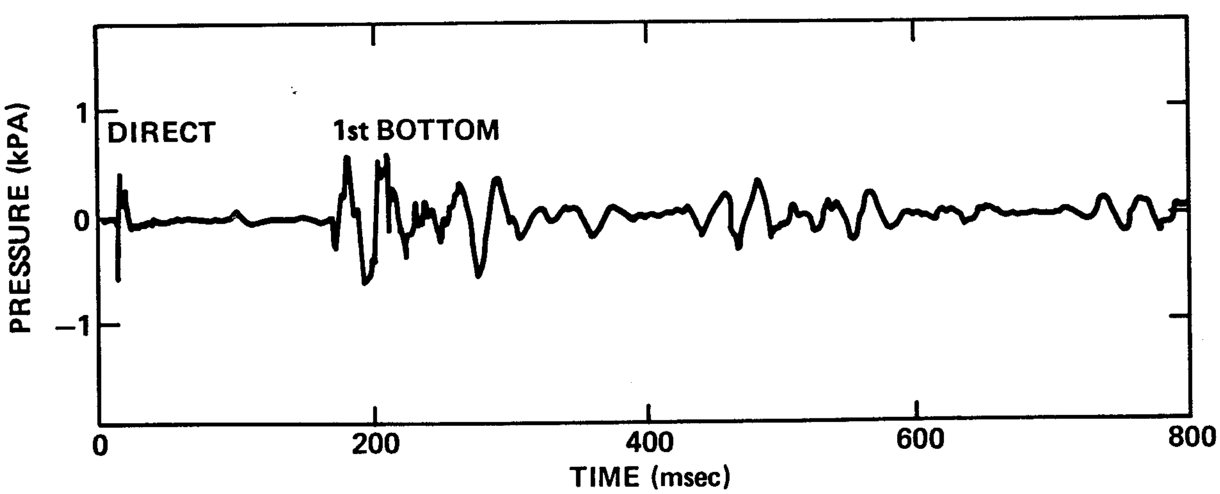
5.2.3 Sound propagation measurements and predictions

The air gun source was used for most of the transmission loss measurements. Figure 5.5 shows the effect of downward refraction on the direct signal at relatively short ranges. Figure 5.5A shows the air gun signature at a range of 125 m. Here, the direct signal is dominant and the first bottom reflection considerably weaker. At a range of 250 m (Fig. 5.5B), refraction causes the direct signal level to drop much more rapidly than would be caused by spreading loss alone. Here, the first bottom signal becomes the dominant component. Later, bottom-surface multipath returns can also be seen.

The effect of different water depths and different bottom properties is illustrated in Fig. 5.6. Figure 5.6A shows the air gun signature and its spectrum for propagation in an area with an average depth of 180 m. Figure 5.6B shows the results of air gun signal propagation to about the same range, but in a region with

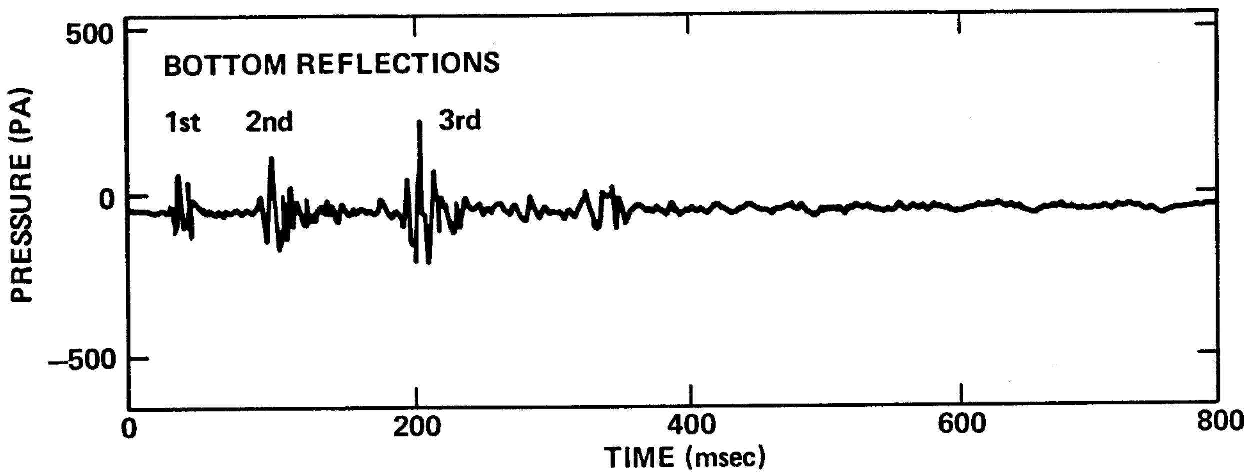


A. RANGE–125 M

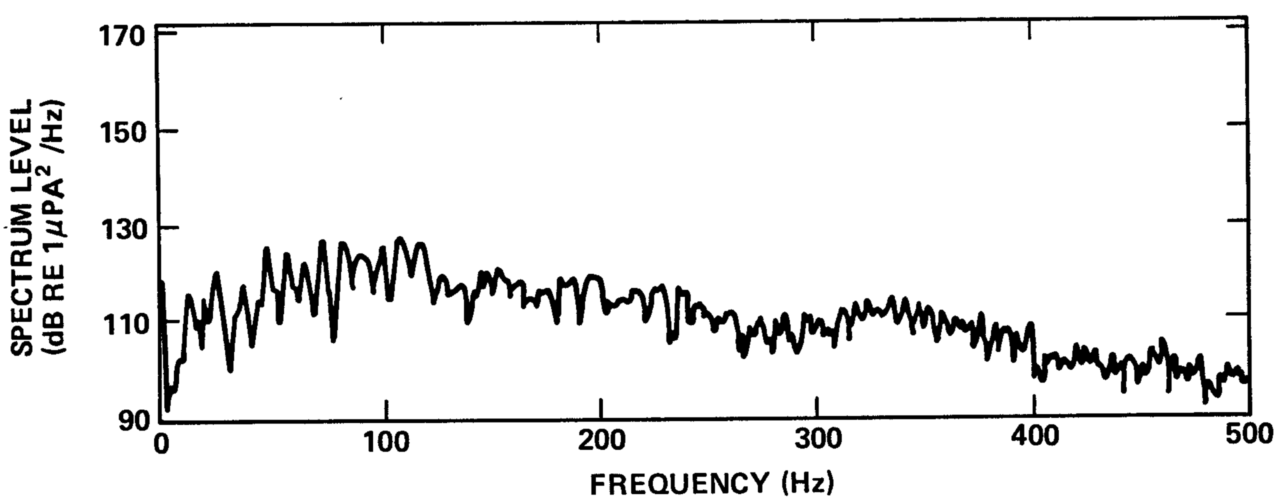


B. RANGE–250 M

FIG. 5.5. AIRGUN SIGNAL AND MULTIPATH EFFECTS (AVERAGE DEPTH – 150 m).

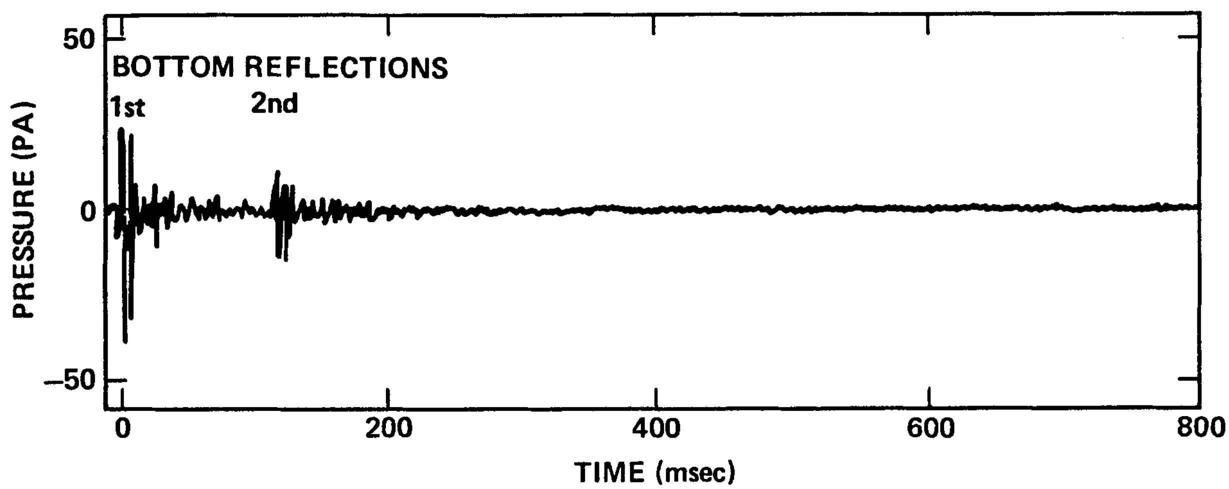


A. SIGNAL

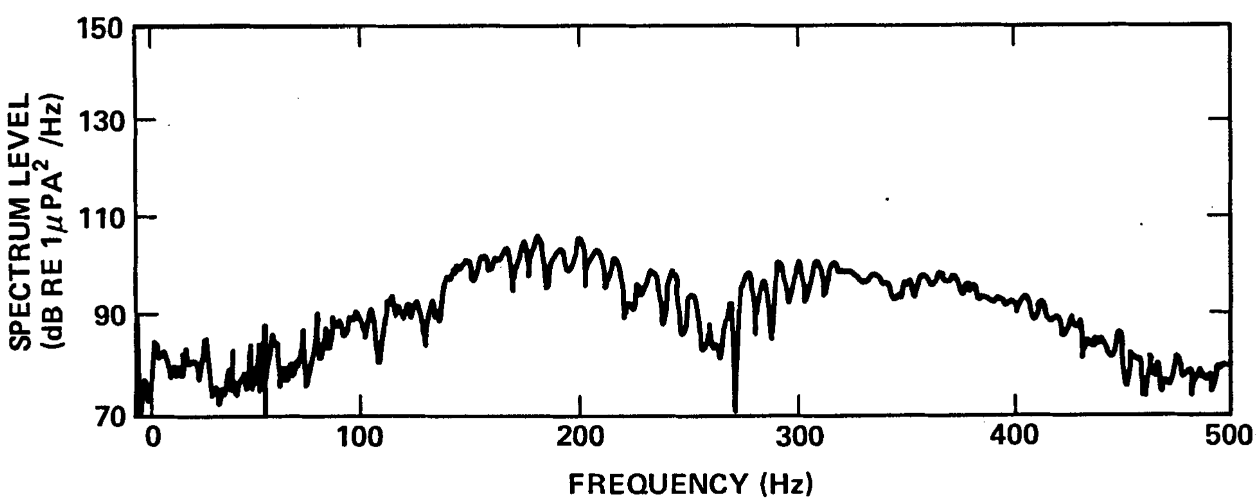


B. PRESSURE SPECTRUM

FIG. 5.6A. AIRGUN SIGNAL AND PRESSURE SPECTRUM (AVERAGE DEPTH - 180 m).



A. SIGNAL



B. PRESSURE SPECTRUM

FIG. 5.6B. AIRGUN SIGNAL AND PRESSURE SPECTRUM (AVERAGE DEPTH - 130 m).

region with an average depth of 130 m and with more absorptive bottom material. Note that frequencies below 200 Hz are highly attenuated.

A representative set of measured values of effective pulse pressure versus range is shown in Fig. 5.7. These data were obtained in Hobart Bay for conditions where the SVP data shown for 8/26/1150 in Fig. 5.3 are appropriate. Estimated sound levels at 100 Hz from the RAYMODE algorithm of the Generic Sonar Model (Weinberg 1981) developed for sonar research, are also shown in this figure. The computer output was obtained for both the depth used for the data (10 m) a well as for the estimated feeding depth for the whales in the area (100 m). The levels for the shallow receiving depth can be seen to drop off rapidly near the source as a result of the downward refraction, whereas the computer estimated values for 100 m do not show this trend. A simplified best-fit exposure prediction model based on Eq. (3) was also developed to facilitate sound exposure level estimates for whales at a depth of 100 m. The values predicted by this model are also shown in the figure.

The effective variation of sound exposure levels with depth and range can be visualized by using a ray trace diagram. This is a diagram showing the path of sound rays transmitted from the source at selected initial angles with respect to horizontal. A ray trace diagram was developed using the SVP conditions pertaining to Fig. 5.7. The results are shown in Fig. 5.8. This figure shows the paths followed by rays projected from an omnidirectional source at 5° increments over a sector of ± 40° where 0° is horizontal. Note that most of the rays near the source are bent sharply downward (the horizontal scale is greatly compressed compared with the vertical scale). The sound exposure variation with depth can be estimated by observing the density of the ray paths. Note that the density near the surface is low compared with that at depth but that, for depths greater than 30 m, the

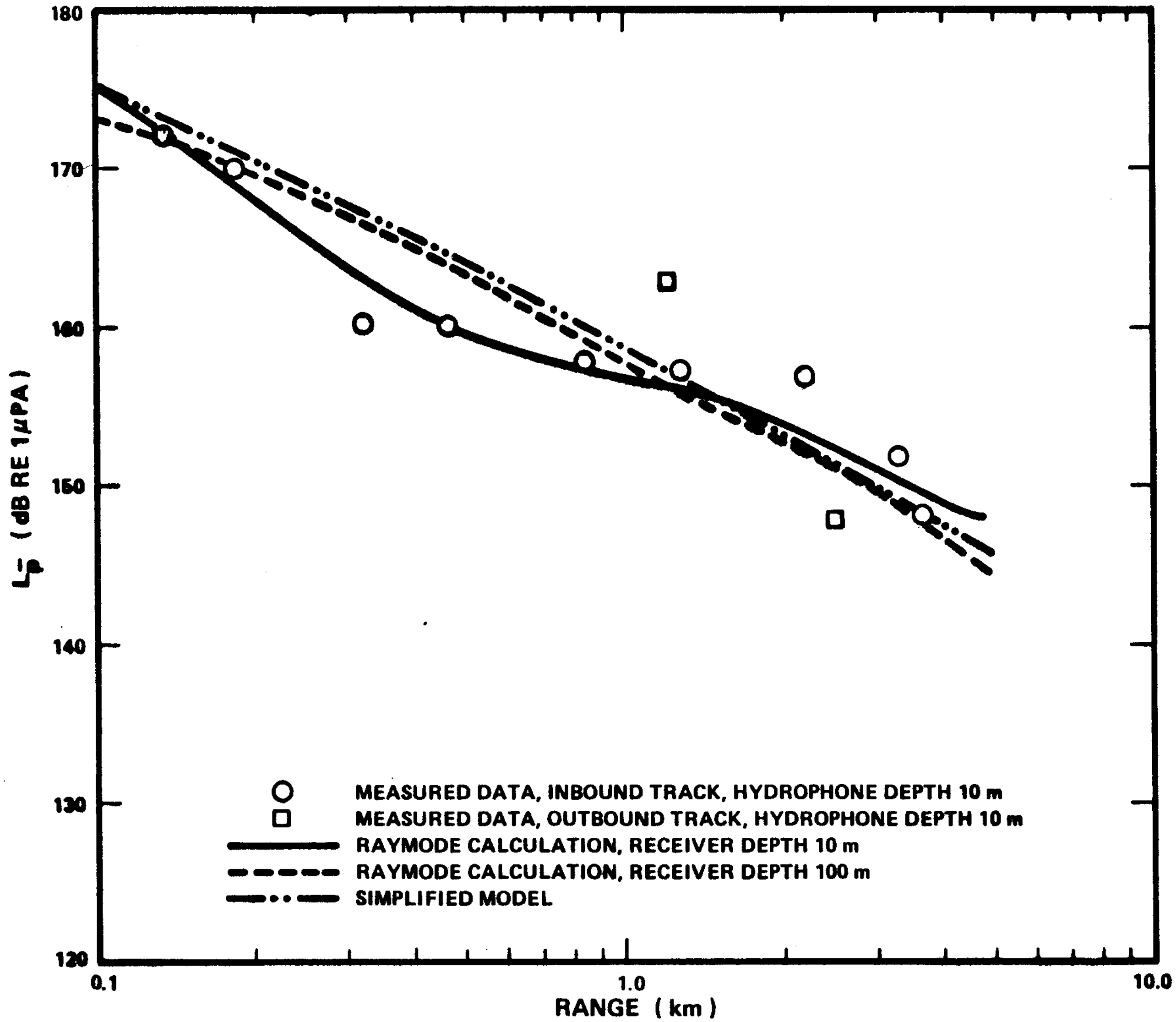


FIG. 5.7. AVERAGE PULSE PRESSURE DATA COMPARED WITH PROPAGATION MODEL PREDICTIONS.

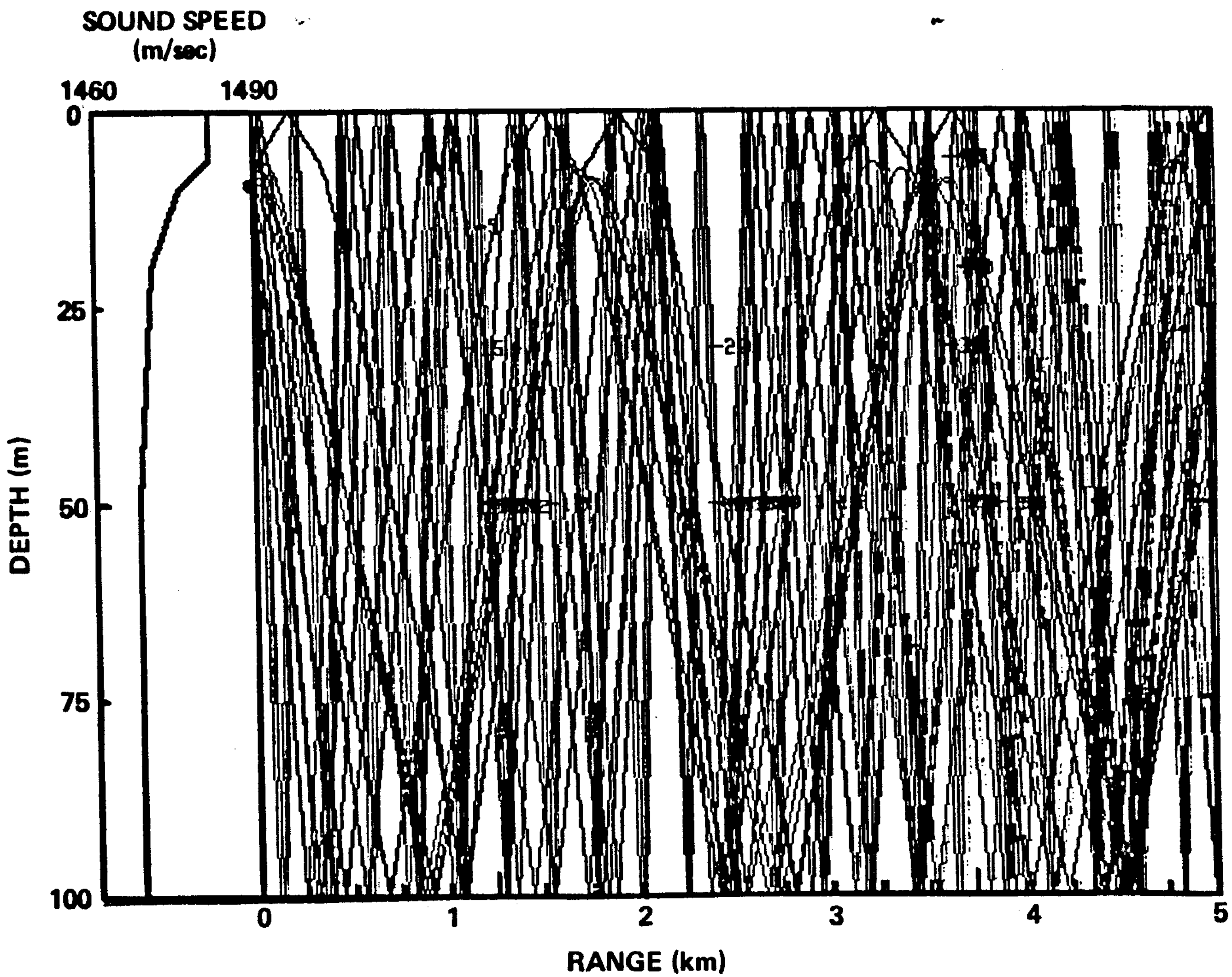


FIG. 5.8. RAY TRACE DIAGRAM, DOWNWARD REFRACTING CONDITIONS (SOURCE DEPTH - 8 m).

ray density is fairly uniform. Thus, the sound exposure levels would not be expected to vary greatly with depth below 30 m and knowledge of the exact feeding depth of whales is not critical below this value when predicting their sound exposure levels due to a source near the surface.

A ray trace diagram for the potential surface duct conditions represented by the SVP for 8/28/1850 previously shown in Fig. 5.4 is presented in Fig. 5.9. This diagram illustrates that some rays are indeed trapped near the surface and that a region of low ray density exists beneath the surface layer. However, at depths below 50 m, the ray density becomes more uniform. Since the whales were not observed to be feeding at the surface in this area, it is probable that they were feeding on prey layers below 80 m (Kreiger and Wing, 1983) and that sound exposure estimates based on predicted levels at these depths are more appropriate than the levels existing in the surface duct.

5.3 Ambient Noise Measurements

Ambient noise levels in the Frederick Sound/Stephens Passage are quite low compared with normal ocean ambient levels. Wind speeds were generally low or zero during the test period. As a result, the dominant contributions to the ambient noise was from vessel traffic and from humpback whale vocalizations. The traffic consisted of fishing vessels, pleasure craft, tugs with tow, and cruise ships. The whale vocalizations consisted of grunts, squeaks, moans, and possible song fragments.

Ambient spectra for two quiet conditions are shown in Fig. 5.10. The data were obtained in relatively shallow water in Hobart Bay and in deeper water near Five Fingers Light. The deeper water data are influenced by distant traffic noise.

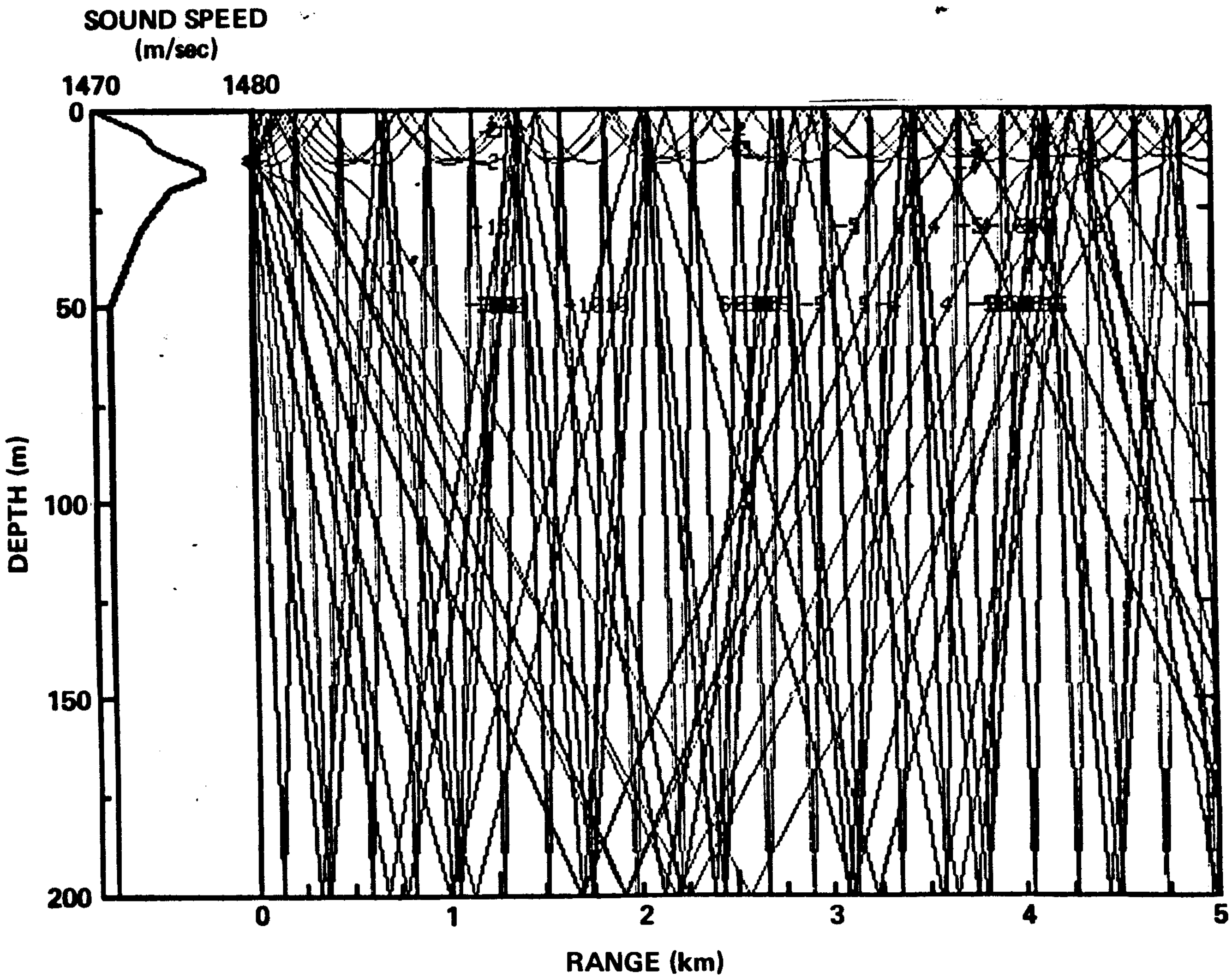


FIG. 5.9. RAY TRACE DIAGRAM, SURFACE DUCT CONDITIONS (SOURCE DEPTH - 8 m).

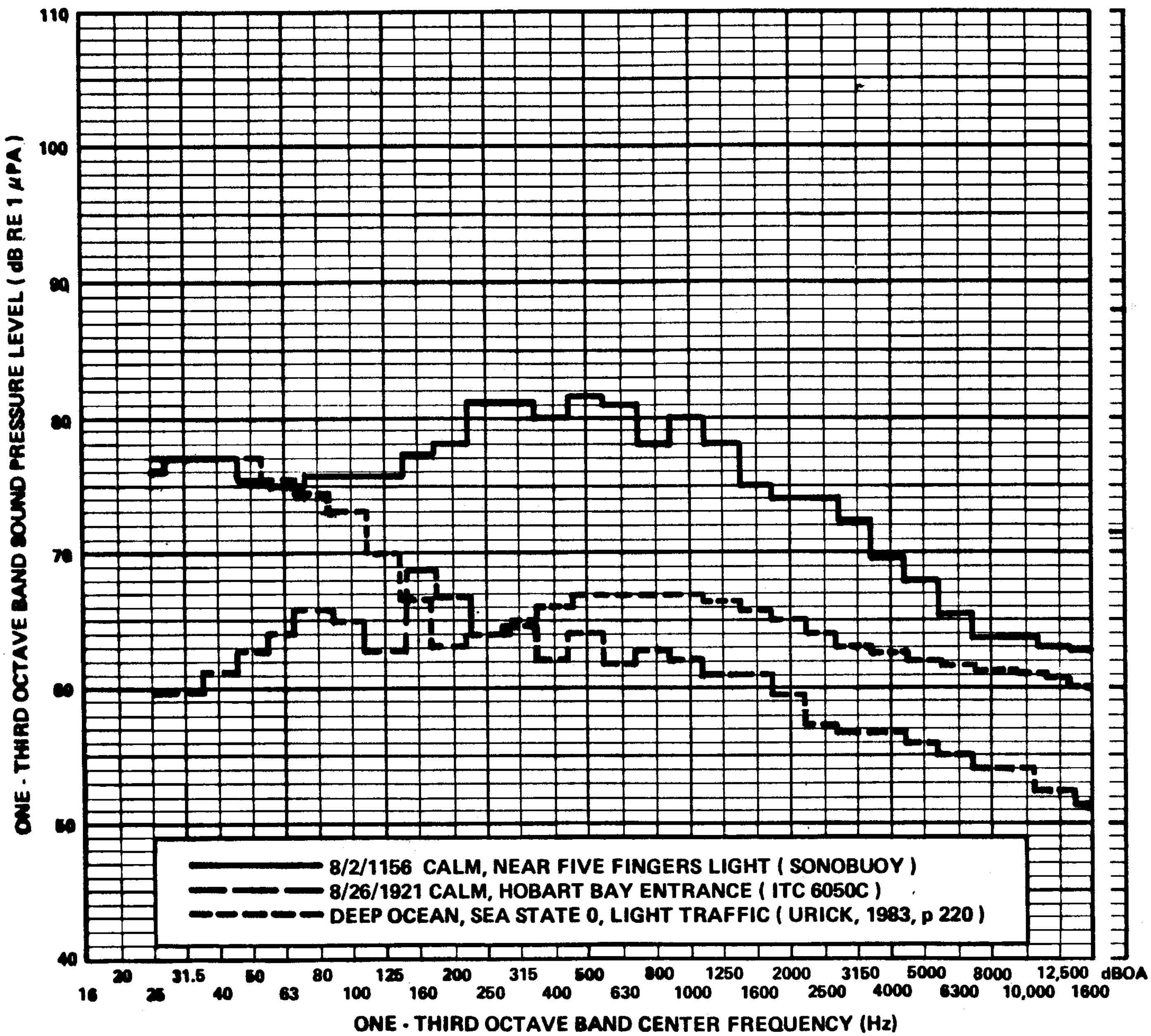


FIG. 5.10. AMBIENT NOISE SPECTRA IN TEST AREA.

The range of ambient conditions is illustrated in Fig. 5.11 which shows the contrast between quiet conditions and the effect of a nearby tug with tow. An ambient noise spectra for relatively "quiet" conditions at the gray whale test site off the California coast is also shown. Fortunately, the shrimp noise contribution peaking at 5 kHz is not present in Frederick Sound.

5.4 Acoustic Exposure Estimation

The procedure using a combination of transmission loss measurements and computer model estimation outlined previously in Sec. 5.2.3 was carried out for all of the test areas shown previously in Fig. 2.1. It was found that sound propagation characteristics for some of the areas were similar so that a combined characteristic could be used. Where significant differences were obtained, specific sound level characteristics were developed and used to predict sound exposure levels from range observations at that test area.

5.4.1 Air gun exposure estimate

The simplified sound exposure level equations for predicting the levels in the various test areas are shown in Table 5.1. These equations were derived using an average value for the bottom depth in each test area. The actual depth varied appreciably in some test areas. It was not possible to incorporate depth variation in the computer model for prediction of exposure level at depth. Hence, the computer exposure level predictions would be expected to be higher or lower than the actual value depending on the difference between the actual average depth along the transmission path and the value used in the computer model. The estimated standard deviation of this error is ±2 dB.

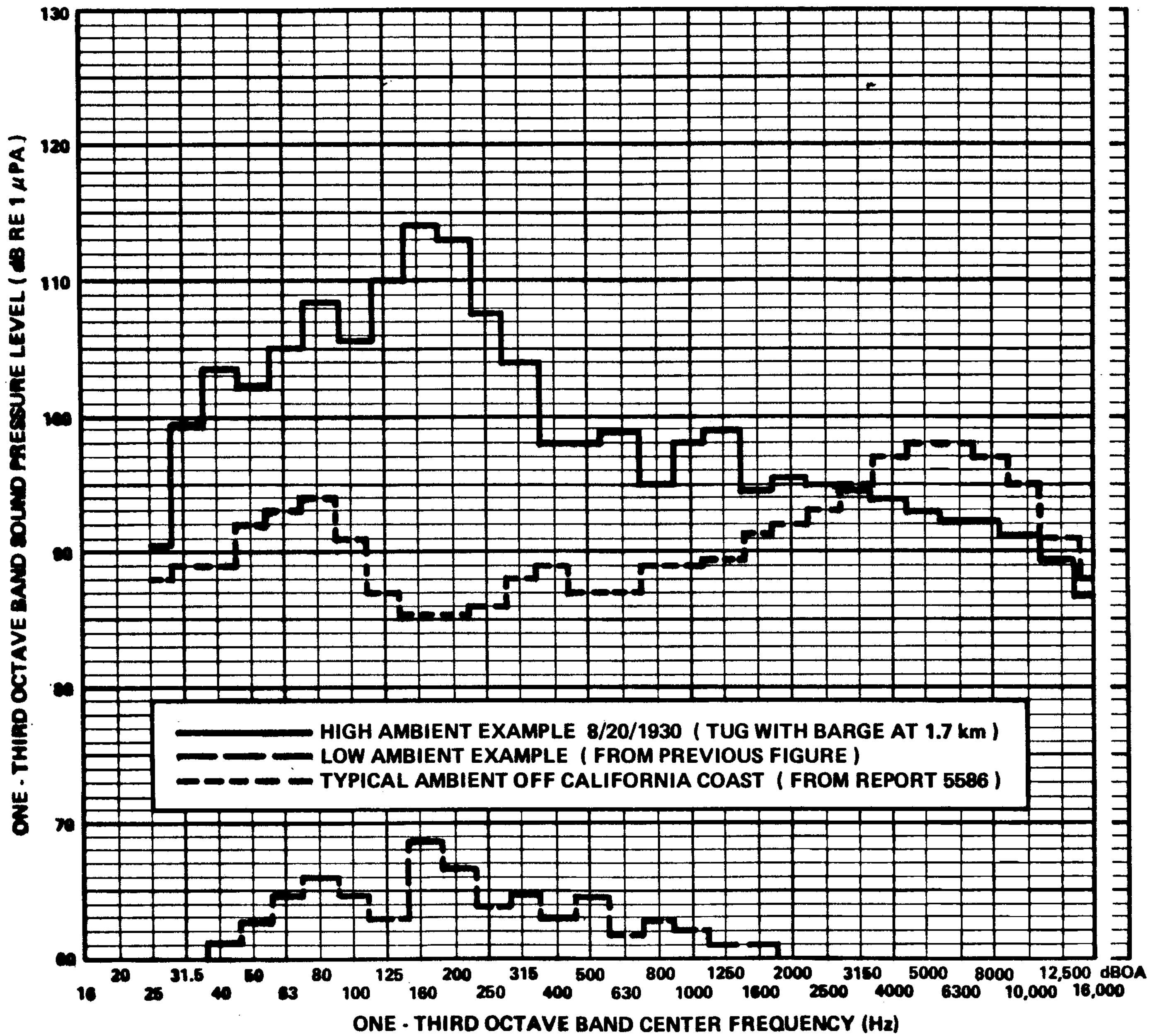


FIG. 5.11. RANGE OF AMBIENT NOISE SPECTRA IN TEST AREA.

TABLE 5.1. RELATIONSHIPS FOR ESTIMATION OF EFFECTIVE PEAK PRESSURE VERSUS RANGE FOR AIR GUN OBSERVATIONS.

Observation	Effective Peak Pressure	Equation
Date/Time	$R > 0.1$ km	
8/22-all periods 8/23/1853-1926 8/24/1015-1109 8/26/1017-1115	$L_{\overline{P}} = 163 - 15 \log R - 1.1R$ dB re 1μPa	(5)
8/24/1500-1601	$L_{\overline{P}} = 161 - 15 \log R - 0.5R$ dB re 1μPa	(6)
8/26/1439-1607	$L_{\overline{P}} = 159 - 15 \log R - 0.5R$ dB re 1μPa	(7)
	$r < 500$ m	
all observations	$L_{\overline{P}} = 223 - 20 \log r$ dB re 1μPa	(8)

where R is the range in km, and
r is the range in m

5.4.2 Playback exposure level and signal-to-noise ratio

The results of the playback experiments with migrating gray whales (Malme et al. 1983, Malme et al. 1984) showed that two types of behavioral reactions occurred. An initial "detection" reaction occurred at ranges where the loudest portion of the playback spectrum approached the ambient noise level in the same frequency band (0 dB S/N). This reaction was generally observed as a change in swimming speed and often a slight change in heading. As a result of this change in swimming pattern, the whales would pass the region of the source at a greater distance than would be the case under control (no playback) conditions. A second type of behavioral reaction observed for some playback tests was a change in swimming direction occurring at a relatively close range to the source. In either case, the reaction could be considered as an "avoidance" of the region with loud sound levels. Accordingly, we have analyzed the playback data to provide information not only on the absolute level and spectrum of the reproduced signals but also on their relative level in relation to local ambient noise conditions.

The sound exposure levels versus range for the playback tests were estimated using the equations derived for the air gun tests in the areas where they were relevant. In other areas, transmission loss was measured using the playback projector as a source. The exposure level versus range at the estimated feeding depth of the whales was then derived using the same techniques developed for the air gun data.

The "available S/N ratio" was estimated for each playback stimulus using the following procedure. The effective signal level for the playback signal was determined by calculating the RMS signal level for the "dominant" bandwidth. Referring back to Fig. 5.2, the dominant signal bandwidth was determined by observing the highest 1/3 octave band level in the signal as measured by the monitor hydrophone, and then including the total number of 1/3 octave bands which had levels within 10 dB of the maximum. The ambient noise spectra measured before and after the playback sequence were averaged and the RMS noise signal for the same dominant bandwidth was calculated. The available S/N ratio was obtained by subtracting the effective masking noise level (dB). Thus, in developing our estimated signal-to-noise (S/N) ratios for the playback stimuli, we have considered that the dominant masking of the playback signal is produced by ambient noise in the same frequency range.

Table 5.2 lists the results of analyzing the playback stimuli and the ambient noise levels at the time of projection according to the procedure discussed in the preceding section. The results are presented in terms of available S/N ratio, 1 m from the projector, and the estimated range for an effective S/N ratio of 0 dB or 10 dB. These ranges are presented both for the entire dominant bandwidth as well as for the highest 1/3 octave band in the respective stimulus. The last measure is appropriate for determining if observed response changes are the result of stimulus detection at low levels.

The transmission loss relationships pertaining to the various test areas are also listed in Table 5.2. These equations were used to obtain the range values given in the table.

TABLE 5.2. PLAYBACK SIGNAL/NOISE DATA AND EFFECTIVE RANGE.

Date/Time		Stim Code	BW_{eff} Hz	L_s* dB/1µPa	L_N dB/1µPa	S/N dB	R_o km	R_{10} km	B_M Hz	S/N dB	R_o km	R_{10} km	L_N Var dB	TL Eq.
8/20	1826-1920	DS-1	50-315	160	97	63	2.6	0.7	250	68	4.5	1.3	13	9
8/21	1205-1307	DP-1	80-1.6K	158	87	71	5.9	2.3	100	74	7.3	3.2	6	10
8/21	1621-1724	H-1	31.5-315	150	110	40	0.1	22m	50	57	1.2	0.3	10	9
8/26	1825-1910	SS-1	50-1K	156	76	80	16	7.0	250	85	22	11	2	11
8/27	1232-1308	PP-1	63-500	153	84	69	5.0	1.6	125	73	7.3	2.6	7	9
8/28	1835-1913	DS-2	50-315	157	86	71	6.1	2.1	125	75	8.5	3.3	2	9

*Referred to 1 m.

TL Relationships for $R > 0.1$ km — Eq.

$TL = 55 + 15 \log_{10}R + 0.7R$ dB re 1 m $R \sim$ km (9)

$TL = 53 + 15 \log_{10}R + 1.1R$ dB re 1 m $R \sim$ km (10)

$TL = 54 + 15 \log_{10}R + 0.5R$ dB re 1 m $R \sim$ km (11)

TL Relationships for $r < 50$ m, $TL \approx 20 \log_{10}r$ $r \sim$ m (12)

Exposure Level = $L_S - TL$ (13)

B_M = highest 1/3 octave band

L_N var = variation observed in ambient noise level between start and finish of playback

6. BEHAVIORAL OBSERVATION AND ANALYSIS

A total of 18 experiments were conducted between 20-28 August (see Data Summary Table 4.2). Of these, five were judged to be unacceptable due to inclement weather (n = 2) or a poor data set (n = 3). All data from the remaining 13 experiments were reduced to scatter plots of sightings and a set of ranges relative to the experimental source location. These range data were then used to construct cumulative distribution and density of sighting plots for each experimental period and two control periods. One control was the pre-experimental period only, while the second control was the sum of the pre- and post-experimental periods. These data were then analyzed statistically using the Kolmogorov-Smirnov (KS) test (Siegel 1956) and the Cramer-von Mises (CVM) test (Anderson and Darling 1952). These analytical and statistical procedures are similar to those used previously by Malme et al. (1983, 1984).

The hypothesis being tested was that the cumulative distributions during experimental conditions would be different from the distributions during their adjacent control periods. Specifically, if the distribution of sightings during playback showed whales sighted at ranges farther from the source than during control periods, this would give evidence of avoidance of the source. By comparing the ranges and calculated received levels at which this avoidance was most significant, one could scale avoidance to received level.

6.1 Sighting Data Analysis

The following is a brief presentation of the statistical results for each of the 13 experiments. A tabulation of the experimental periods, condition, sample sizes, and statistical results is given in Table 6.1.

TABLE 6.1. SUMMARY OF 13 EXPERIMENTS. p VALUES GREATER THAN 0.05 ARE LISTED AS N.S. (NOT SIGNIFICANT).

					Pre vs Experimental		Pre & Post vs Experimental	
#	Date	Start-End Time	Condition	Sample Size	KS	CVM	KS	CVM
1	20 Aug 84	1645-1826	Pre Control	103				
		1826-1920	Drillship	54	p<0.001	p<0.001	p<0.001	p<0.001
		1920-1932	Post Control	7				
2	21 Aug 84	0929-1205	Pre Control	119				
		1205-1307	Drilling Platform	46	N.S.	N.S.	N.S.	N.S.
		1307-1340	Post Control	10				
3	21 Aug 84	1509-1621	Pre Control	28				
		1621-1724	Helicopter	16	N.S.	N.S.	N.S.	N.S.
		1724-1809	Post Control	23				
4	22 Aug 84	1143-1153	Pre Control	20				
		1153-1242	Air Gun #1	60	N.S.	N.S.	N.S.	N.S.
		1242-1256	Post Control	5				
5	22 Aug 84	1509-1540	Pre Control	34				
		1540-1647	Air Gun #2	78	p<0.001	p<0.001	p<0.001	p<0.001
		1647-1715	Post Control	16				
6	22 Aug 84	1748-1820	Pre Control	31				
		1820-1922	Air Gun #3	58	N.S.	N.S.	N.S.	0.01<p<0.05
		1922-1953	Post Control	18				
7	24 Aug 84	0943-1015	Pre Control	38				
		1015-1109	Air Gun #4	52	p<0.001	0.001<p<0.01	N.S.	N.S.
		1109-1146	Post Control	20				
8	24 Aug 84	1426-1500	Pre Control	42				
		1500-1601	Air Gun #5	57	N.S.	N.S.	N.S.	N.S.
		1601-1639	Post Control	20				
9	26 Aug 84	0922-1017	Pre Control	20				
		1017-1115	Air Gun #6	23	N.S.	N.S.	N.S.	N.S.
		1115-1149	Post Control	10				
10	26 Aug 84	1413-1439	Pre Control	7				
		1439-1607	Air Gun #7	35	0.005<p<0.010	0.001<p<0.01	0.025 p<0.050	0.01 p<0.05
		1607-1709	Post Control	35				
11	26 Aug 84	1804-1825	Pre Control	16				
		1825-1910	Semi Submersible Rig	42	N.S.	N.S.	N.S.	N.S.
		1910-1920	Post Control	10				
12	27 Aug 84	1202-1232	Pre Control	28				
		1232-1308	Production Platform	20	0.025<p<0.05	0.01<p<0.05	N.S.	N.S.
		1308-1418	Post Control	31				
13	28 Aug 84	1803-1835	Pre Control	27				
		1835-1913	Drillship	31	0.025<p<0.05*	N.S.	0.025<p<0.050	N.S.
		1913-1943	Post Control	25				

Drillship, 20 August

Figure 6.1 shows the cumulative distributions and density of sighting plots using the combined pre- and postplayback period. These results are very similar to those using the pre-playback control only. The difference between experimental and either preplayback or pre- and post-playback control distribution is significant to the $p < 0.001$ level using either the KS or CVM tests.

Inspection of Fig. 6.1 reveals that the distribution of whales shifted away from the experimental sound source during playback. One might interpret this to demonstrate a statistically significant avoidance response to this playback. But before reaching this conclusion, one must examine the scatter plot of whale sightings and sound source track in Fig. B.1 of Appendix B for pre-playback control, experimental, and post-playback control periods. In Fig. B.1.a, one can see that the sound source vessel had positioned itself in the middle of a tight clump of apparently feeding whales at the start of the pre-playback control. By the end of the pre-playback control, the source vessel had drifted S to SW and some of the whales were dispersing from the group and drifting in the same direction. During the playback period, part of the group of whales moved west of its original location, while the other whales continued to disperse in a generally southwest direction. The drift of the source vessel during the 54 minute playback was approximately 0.76 km, a large amount compared to the approximately 0.5 km average difference between the cumulative distributions under experimental and control conditions. It thus appears that most of the apparent avoidance response in this experiment may well have been due to drift of the source vessel away from the whales rather than vice versa.

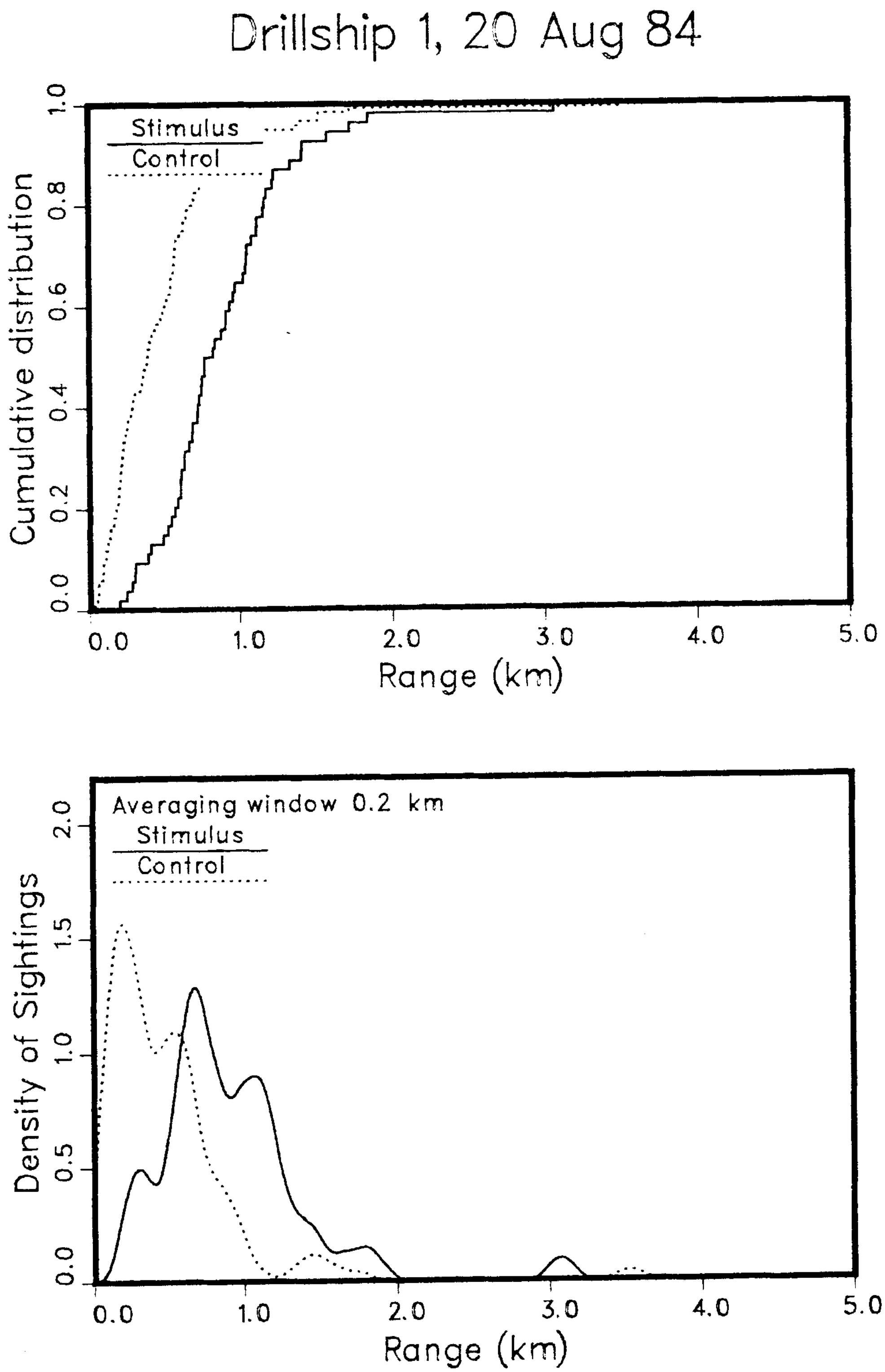


FIG. 6.1. DRILLSHIP PLAYBACK SIGHTING DISTRIBUTIONS 8/20/84 DATA.

Drilling Platform, 21 August

Figure 6.2 shows the cumulative distributions and density of sighting plots using the combined pre- and post-experimental period. Figure B.2 in Appendix B shows a scatter plot of the sighting locations during the experimental and combined control periods. There were no significant differences between the experimental and control distributions using either the pre-playback or combined control periods (see Table 6.1).

Helicopter, 21 August

Figure 6.3 shows the cumulative distribution and density of sighting plots using the combined pre- and post-experimental period. Figure B.3 in Appendix B shows a scatter plot of the sighting locations during the experimental and combined control periods. There were no significant differences between the experimental and control distributions using either the pre-playback or combined control periods (see Table 6.1).

Air Gun #1, 22 August

Figure 6.4 shows the cumulative distribution and density of sighting plots using the combined pre- and post-experimental control period. Figure B.4 shows a scatter plot of the sighting locations during the experimental and combined control periods. There were no significant differences between the experimental and control distributions using either the pre-control or combined control periods (see Table 6.1). Since this was the first air gun experiment performed with humpbacks, we did not work at a very close range but started with the nearest concentration of whales 3 to 4 km away, in case there was a dramatic response at this long range. This is why there were few sightings at ranges of < 3.0 km.

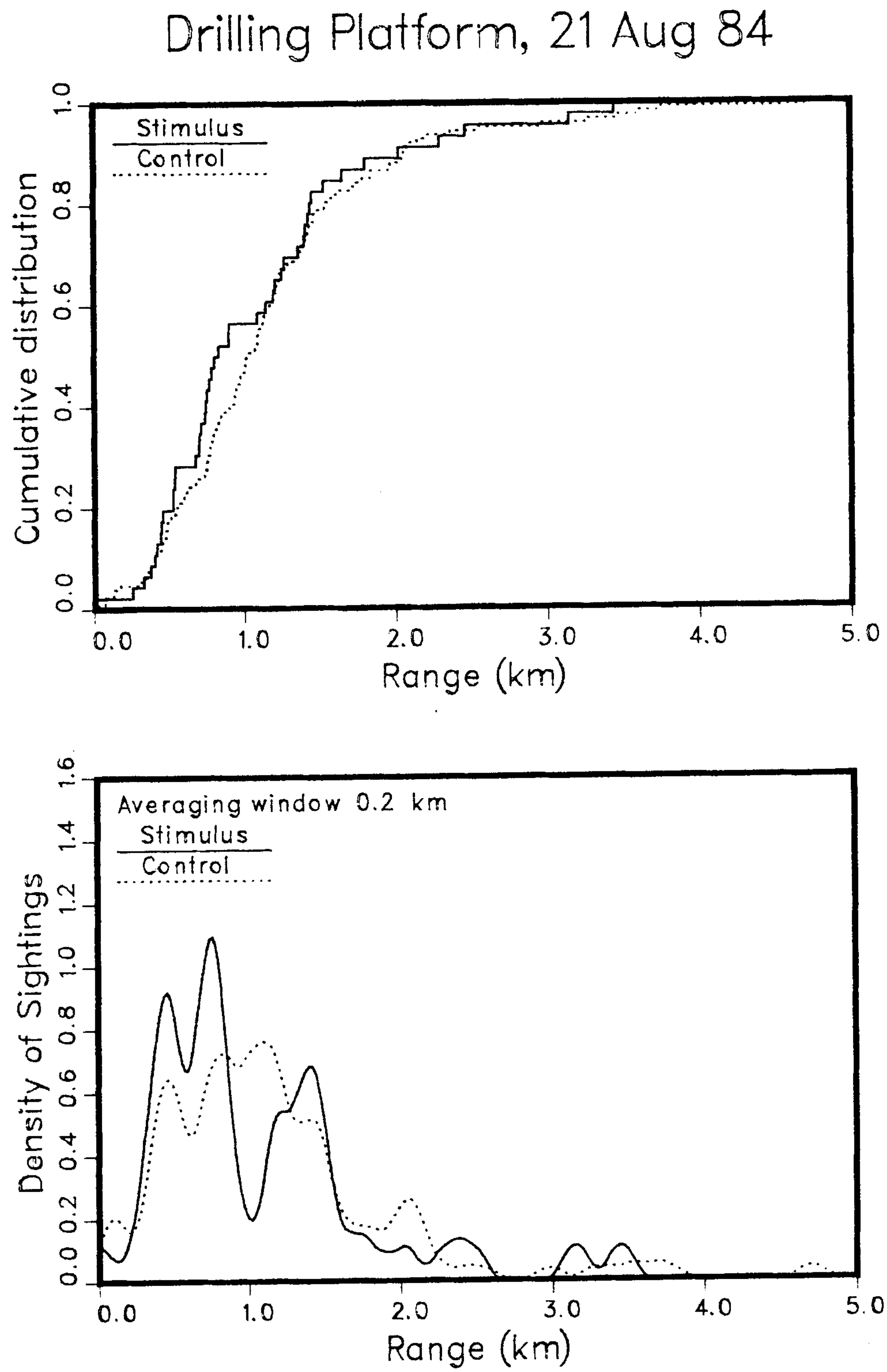


FIG. 6.2. DRILLING PLATFORM PLAYBACK SIGHTING DISTRIBUTIONS.

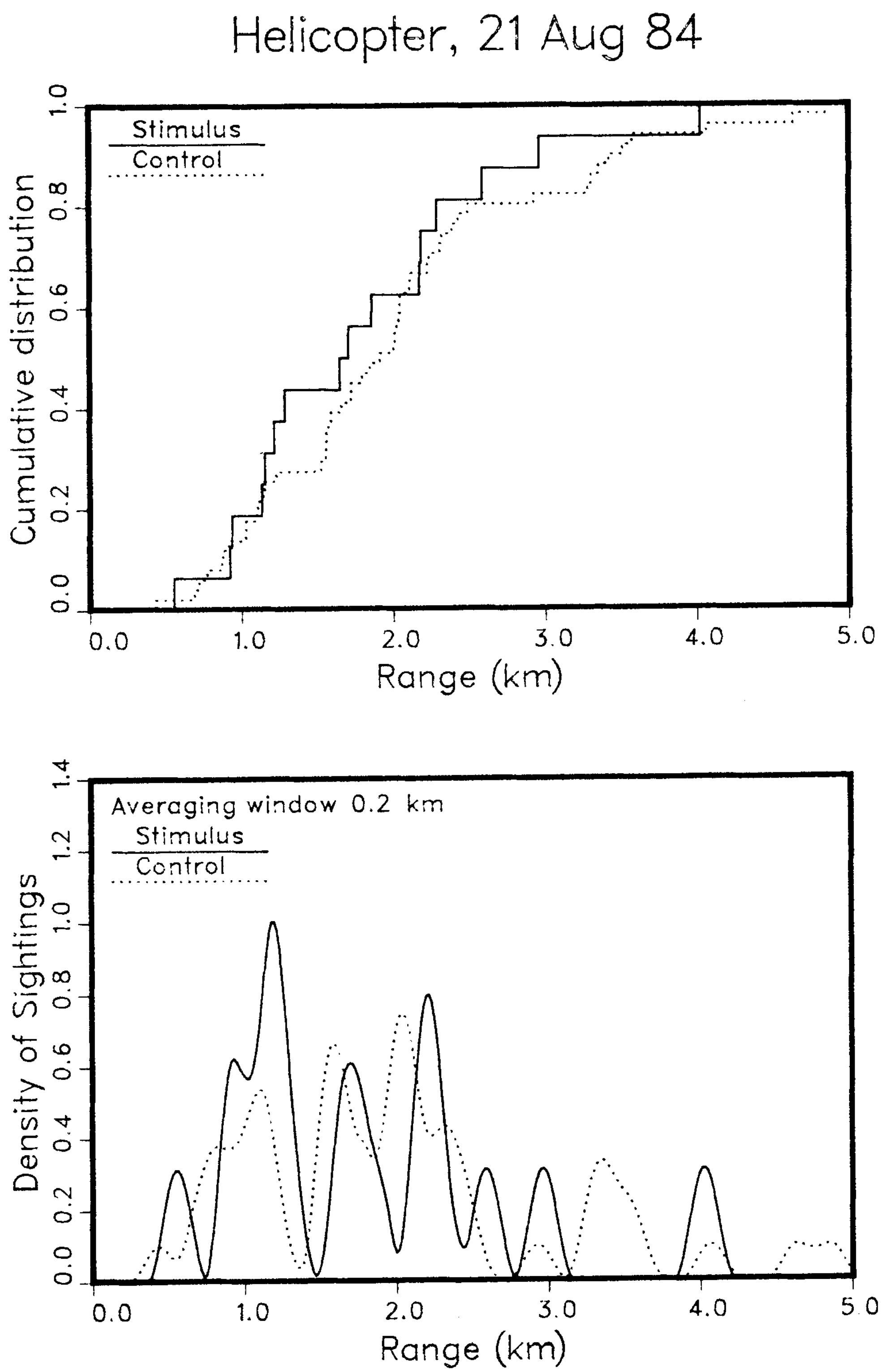


FIG. 6.3. HELICOPTER PLAYBACK SIGHTING DISTRIBUTIONS.

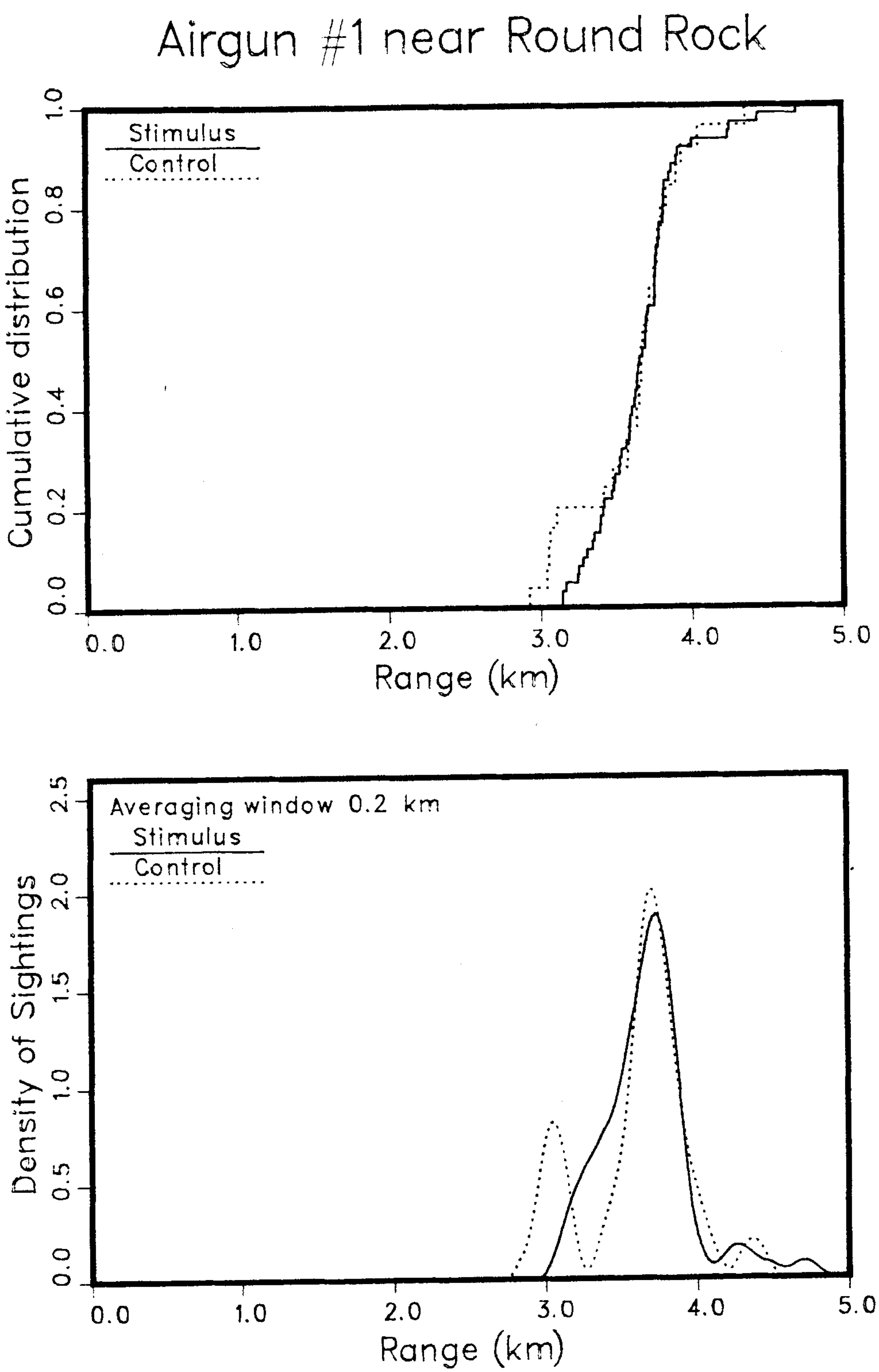


FIG. 6.4. AIR GUN 1 SIGHTING DISTRIBUTIONS.

During the pre-exposure control period of this playback, a group of approximately 30 humpbacks were feeding within a few hundred meters of Round Rock. Within 10 min. of the start of the air gun firing, most animals were moving south away from where they had been feeding (see Sec. 6.5). Most whales seemed to move no more than 500 m to the south where they milled. This effect can be seen on the sighting density graph of Fig. 6.4. The large cluster of sightings centered at 3 km in the control distribution shifted right to greater ranges in the stimulus distribution.

While this movement pattern is consistent with our avoidance model of increasing response at closer range, the movement was not pronounced enough to yield a significant difference in our statistical tests.

Air Gun #2, 22 August

Figure 6.5 shows the cumulative distribution and density of sighting plots using the combined pre- and post-experimental control periods. Figure B.5 shows a scatter plot of the sighting locations during the experimental and combined control periods. All of the differences between the experimental and control distributions using either the pre-experimental or the combined control periods were significant at the $p < 0.001$ level (see Table 6.1).

The sighting density plot on Fig. 6.5 shows a large cluster of sightings at ranges of 1.0 to 1.5 km from the source. During air gun operation, this cluster spread out, with sightings tending to occur at increased range. This same effect is obvious in Fig. B.5. During the pre-playback period shown in Fig. B.5.a, whales were clumped along a line between Round Rock and the San Juan Islands. During the stimulus period, shown in Fig. B.5.b, the distribution of sightings was much more dispersed, with most apparent motion to the southwest away from the sound source. The

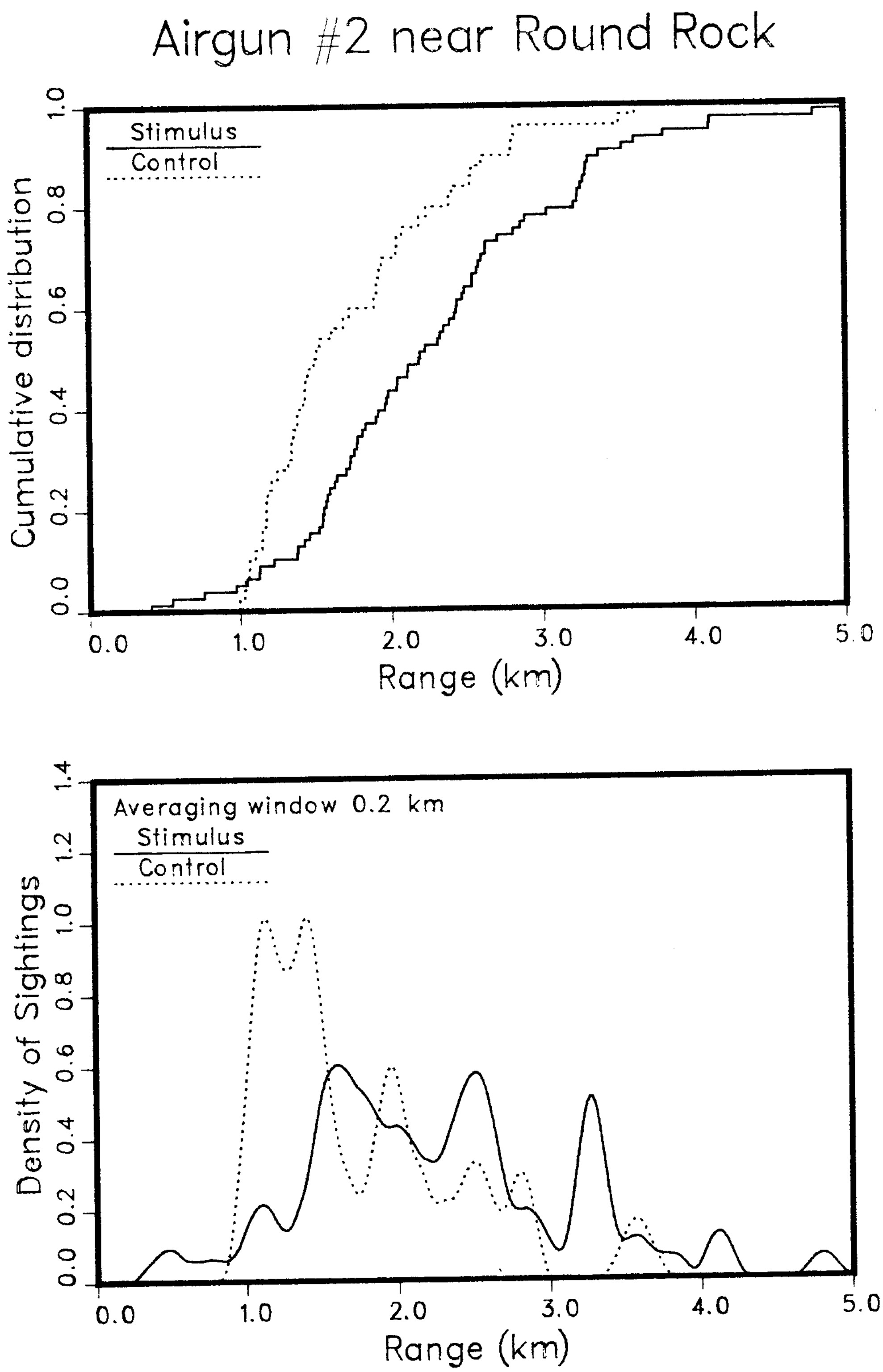


FIG. 6.5. AIR GUN 2 SIGHTING DISTRIBUTIONS.

source vessel moved very little during this experiment, and so should not have contributed significantly to the apparent movement of whales. There appears to have been a significant avoidance response during this experiment.

Air Gun #3, 22 August

Figure 6.6 shows the cumulative distributions and density of sighting plots using the combined pre- and post-experiment control period. Figure B.6 shows a scatter plot of the sighting locations during the experimental and combined control periods. There was no significant difference between the experimental and pre-experimental control distributions but there was one significant difference between the experimental and the combined control periods using the Cramer-von Mises Test (see Table 6.1). Inspection of Figs. 6.6 and B.6 shows that this difference is a result of the same groups being further away during control periods compared to the experimental period. However, there is very little difference in the sighting distributions for the 0 to 1 km range where whales are exposed to the highest sound levels.

Air Gun #4, 24 August

Figure 6.7 shows the cumulative distributions and density of sighting plots using the combined pre- and post-experiment control period. Figure B.7 shows a scatter plot of the sighting locations during the experimental and combined control periods. There was a significant difference between experimental and pre-experiment control distributions, while there was no significant difference between the experimental and the combined control periods (see Table 6.1). Inspection of Figs. 6.7 and B.7 indicates that the primary difference in pre-experiment control and experimental distributions was a large clump of sightings just under 2 km in the control condition that moved to ranges greater

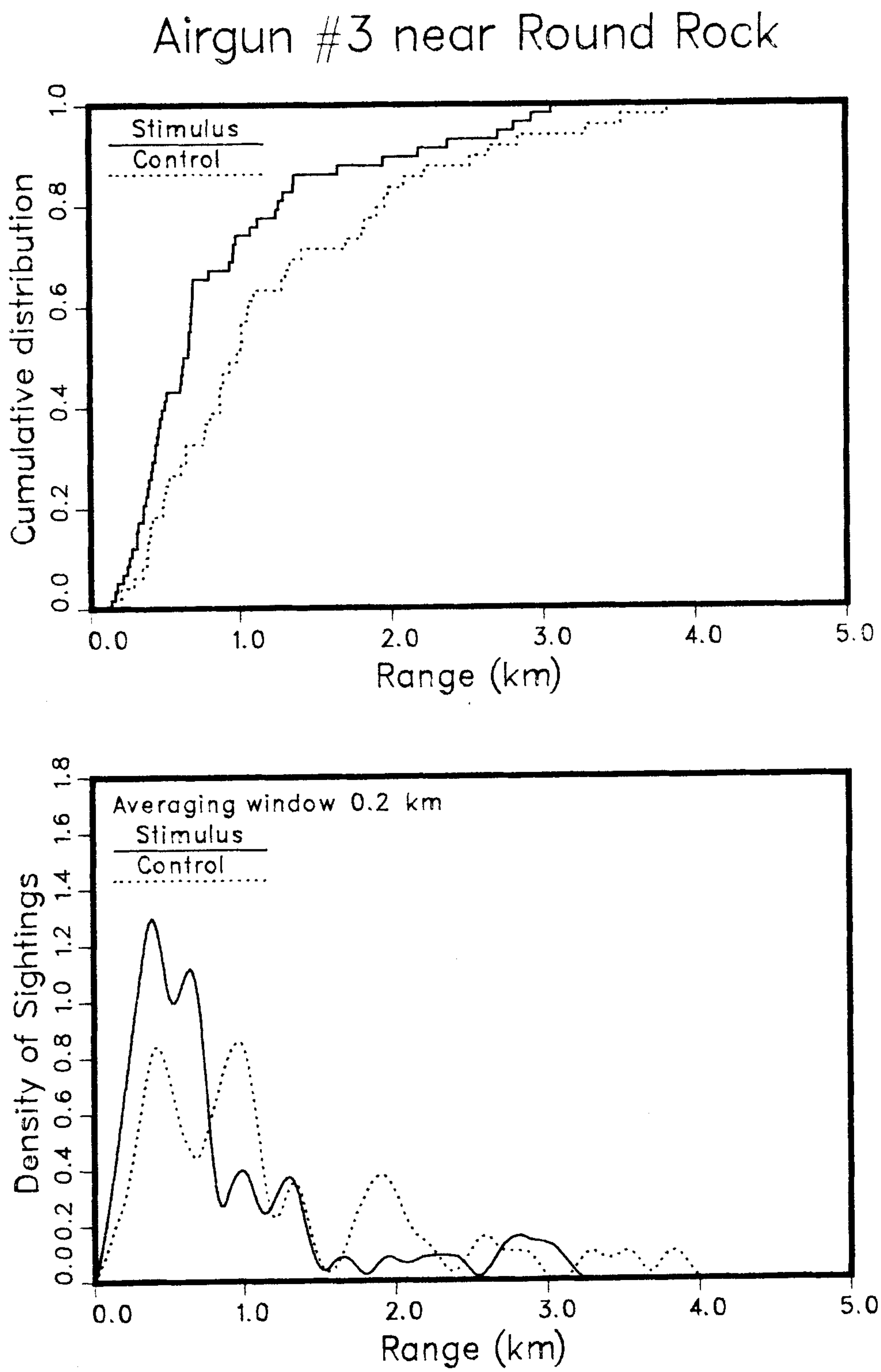


FIG. 6.6. AIR GUN 3 SIGHTING DISTRIBUTIONS.

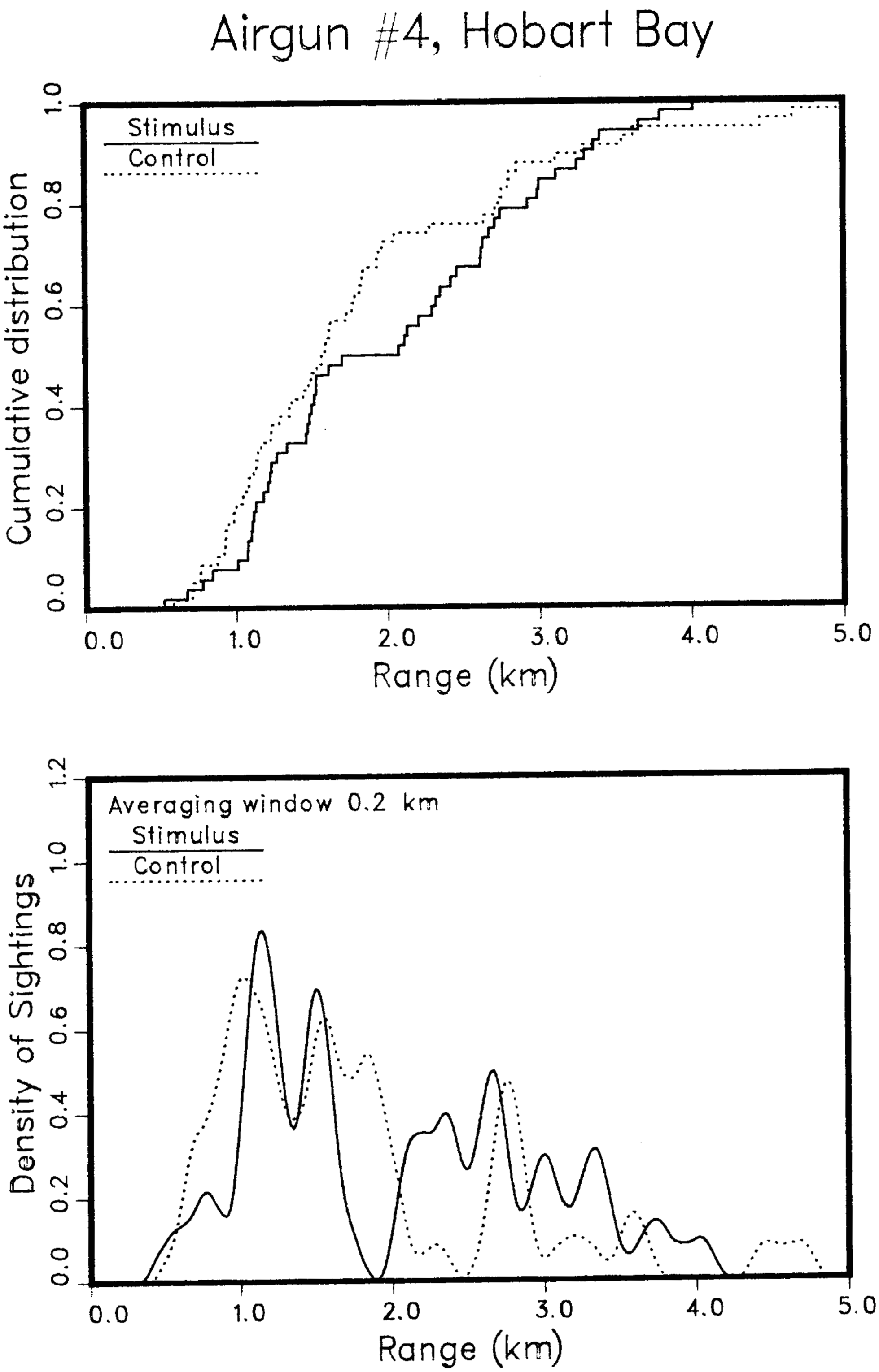


FIG. 6.7. AIR GUN 4 SIGHTING DISTRIBUTIONS.

than 2 km in the experiment. This apparent response does not fit our avoidance model of response increasing at decreasing range.

Air Gun #5, 24 August

Figure 6.8 shows the cumulative distributions and density of sighting plots using the combined pre- and post-experiment control periods. Figure B.8 shows a scatter plot of the sighting locations during the experimental and combined control periods. There were no significant differences between the experimental and control distributions using either the pre- or combined control periods (see Table 6.1).

Air Gun #6, 26 August

Figure 6.9 shows the cumulative distribution and density of sighting plots using the combined pre- and post-experiment control period. Figure B.9 shows a scatter plot of the sighting locations during the experimental and combined control periods. There were no significant differences between the experimental and control distributions using either the pre- or combined control periods (see Table 6.1).

Air Gun #7, 26 August

Figure 6.10 shows the cumulative distribution and density of sighting plots using pre- and post-experimental control period. Figure B.10 shows a scatter plot of the sighting locations during the experimental and combined control period. There were significant differences between the experimental and control distributions using both the pre- and combined control periods (see Table 6.1). Inspection of Figs. 6.10 and B.10 reveals that groups were further away during control periods than they were during the experimental period; a result similar to the previous

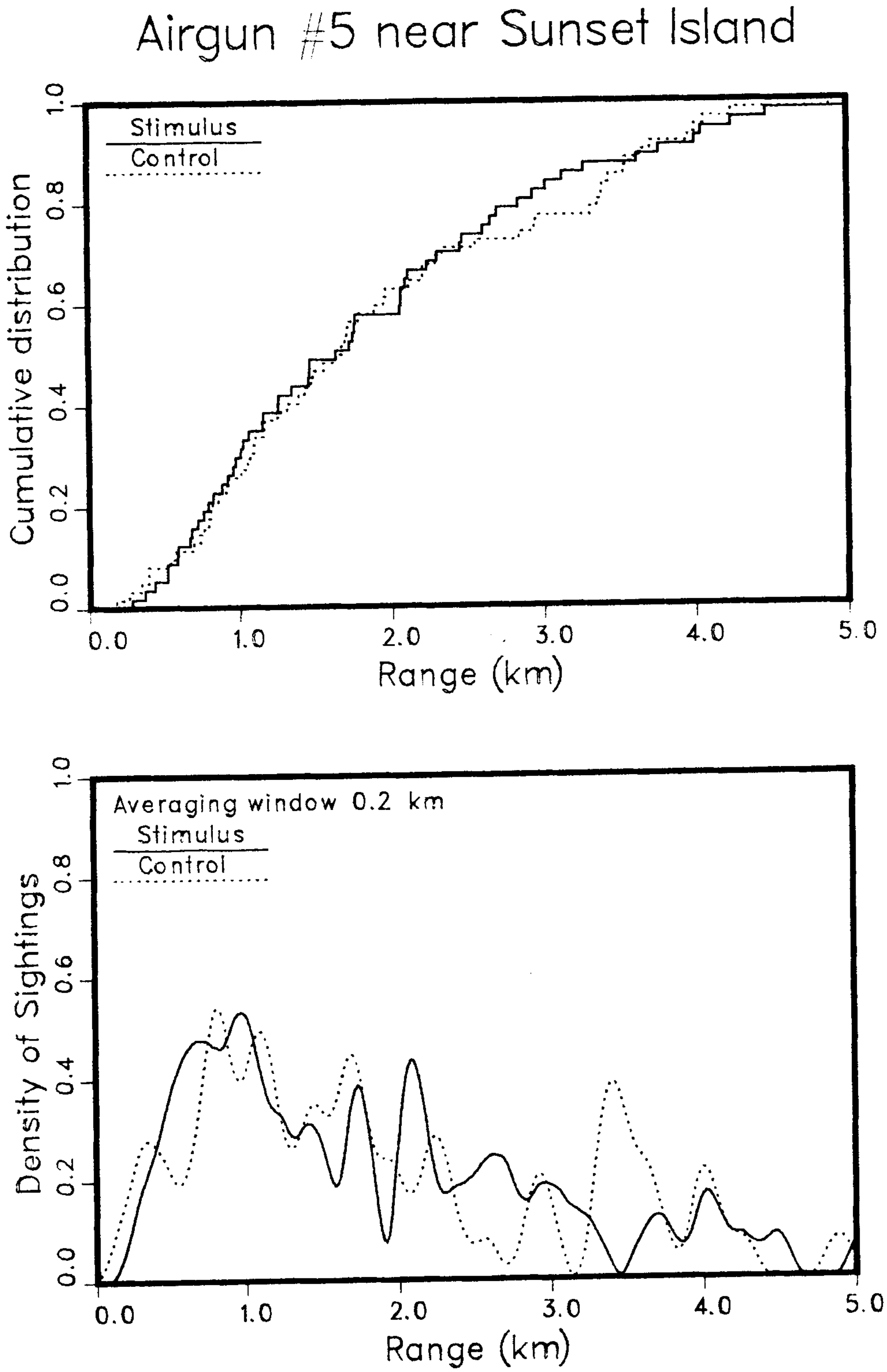


FIG. 6.8. AIR GUN 5 SIGHTING DISTRIBUTIONS.

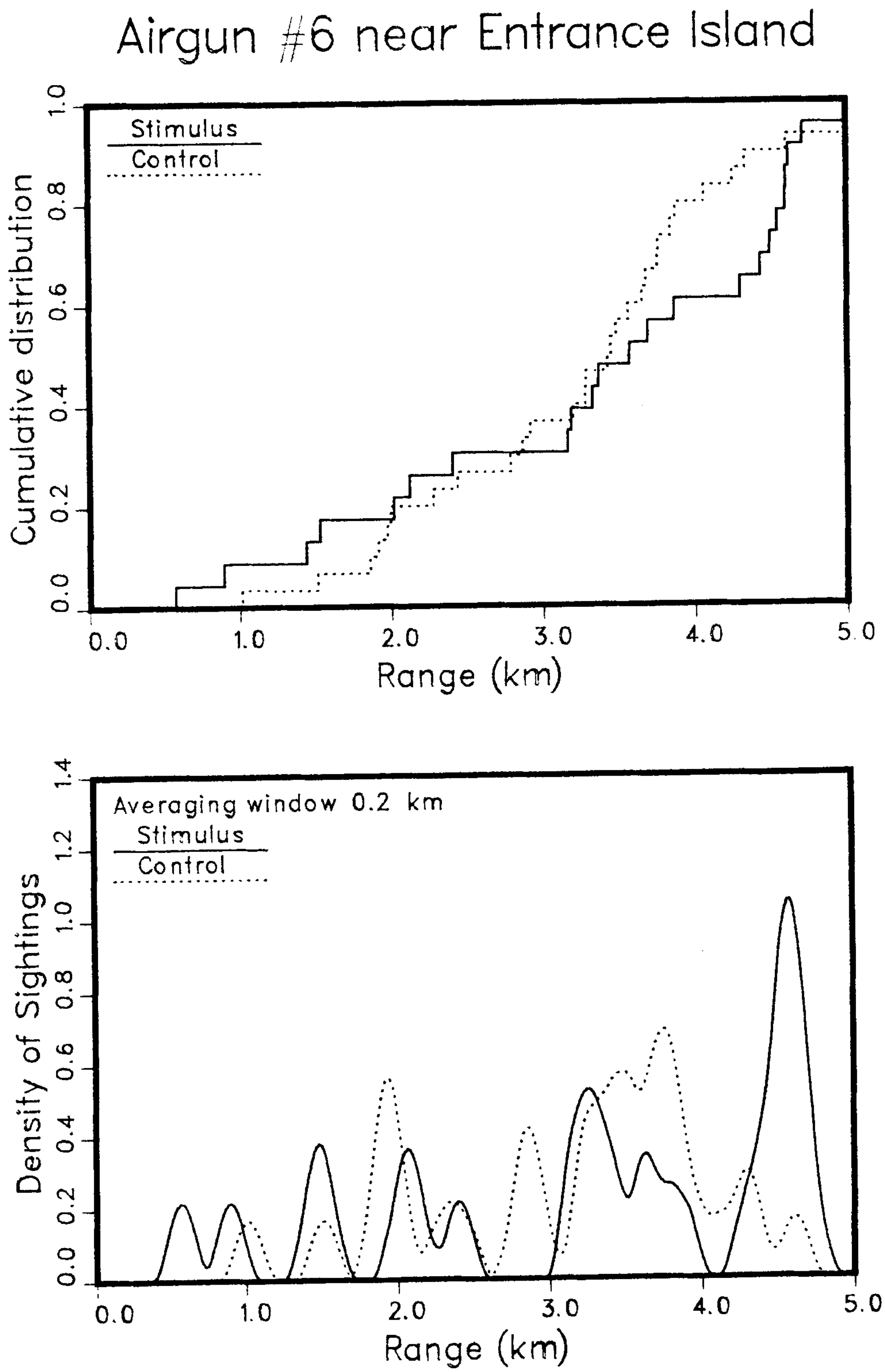


FIG. 6.9. AIR GUN 6 SIGHTING DISTRIBUTIONS.

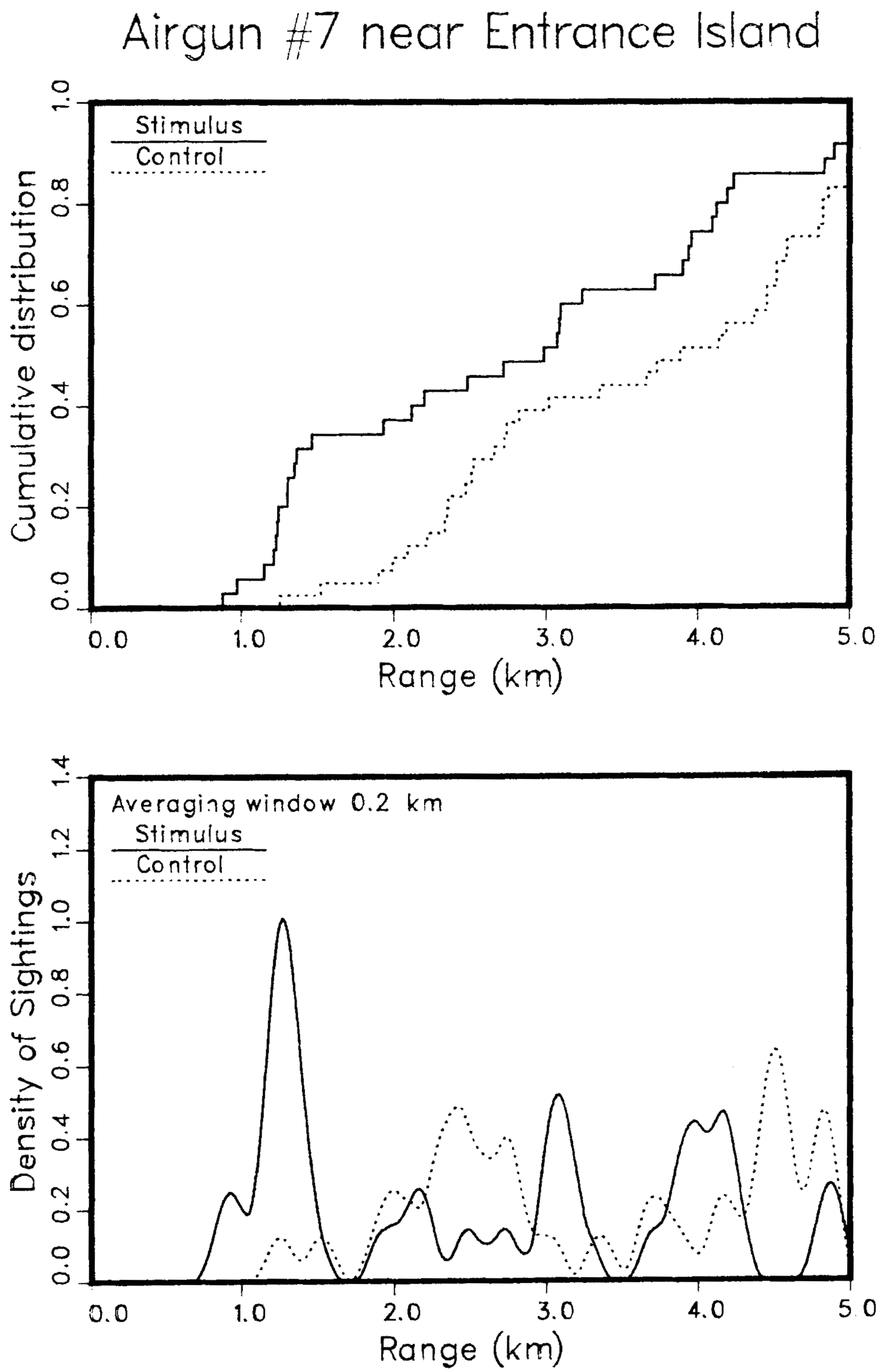


FIG. 6.10. AIR GUN 7 SIGHTING DISTRIBUTIONS.

air gun experiment, indicating a possible approach by whales during the experimental period.

Semi-Submersible Rig, 26 August

Figure 6.11 shows the cumulative distribution and density of sighting plots using the combined pre- and post-playback control period. Figure B.11 shows a scatter plot of the sighting locations during the experimental and combined control periods. There were no significant differences between the experimental and control distributions using either the pre-control and combined control periods (see Table 6.1).

Production Platform, 27 August

Figure 6.12 shows the cumulative distributions and density of sighting plots using the combined pre- and post-playback control period. Figure B.12 shows a scatter plot of the sighting locations during the experimental and combined control periods. There was a significant difference between experimental and pre-control distributions, while there was no significant difference between experimental and the combined control period (see Table 6.1). Inspection of Figs. 6.12 and B.12 reveals that more groups were sighted between 0 to 1 km during the pre-control period than during the subsequent experiment. However, the placement of the peaks in the density of sighting plot below the 1 km range indicates that some whales in the pre-playback control period actually moved closer to the air gun during the experiment. Thus, while there is some indication of avoidance from 0.0 to 0.5 km, there is also an indication of approach from 0.5 to 1.0 km.

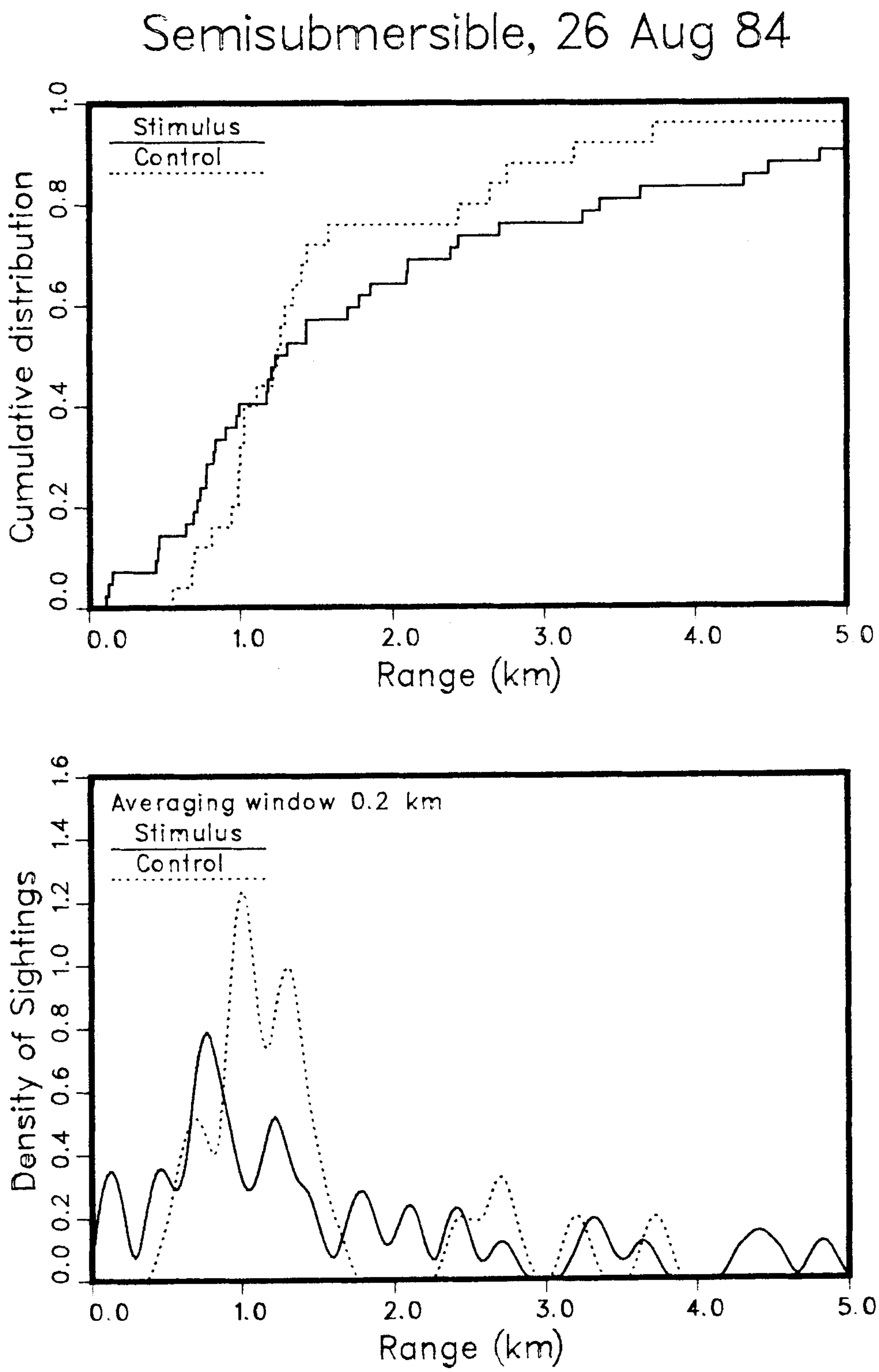


FIG. 6.11. SEMI-SUBMERSIBLE RIG PLAYBACK SIGHTING DISTRIBUTIONS.

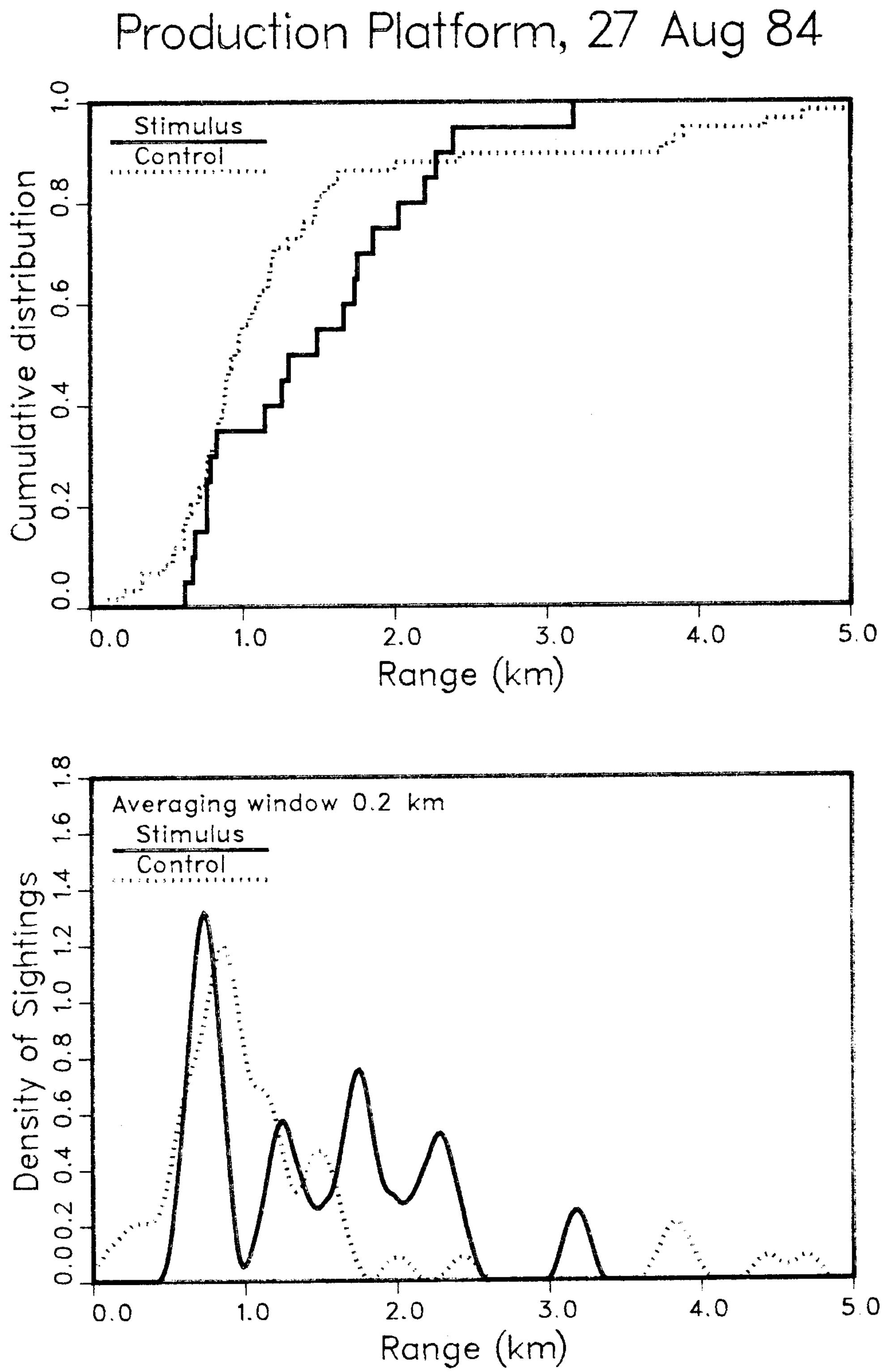


FIG. 6.12. PRODUCTION PLATFORM PLAYBACK SIGHTING DISTRIBUTIONS.

Drillship, 28 August

Figure 6.13 shows the cumulative distribution and density of sighting plots using the combined pre- and post-playback control period. The Kolmogorov-Smirnov tests showed significant differences between both the experimental and pre-playback control distributions and the experimental and the combined control period (see Table 6.1). Inspection of Fig. 6.13 reveals that more groups were sighted closer to the source during the experiment than during the control periods.

6.2 Summary of Sighting Analysis Results

A summary of the behavioral analysis indicates that 19 of the 52 tests were significant. However, inspection of the control and experimental distributions revealed that in 7 of those 19 cases, control sightings were distributed further away from the source than experimental sightings, indicating approach toward the stimulus. Since four statistical tests were performed on each playback, a better comparison would count each playback only once. Table 6.2 lists all playbacks that showed significant differences between control and experimental distributions of sightings. Of the seven playbacks, three showed apparent approach and four showed apparent avoidance. The strongest response was observed with Air Gun Experiment #2, the first air gun test at close range. If the same whales remained in our study area, the later lack of response may reflect habituation to the air gun stimulus.

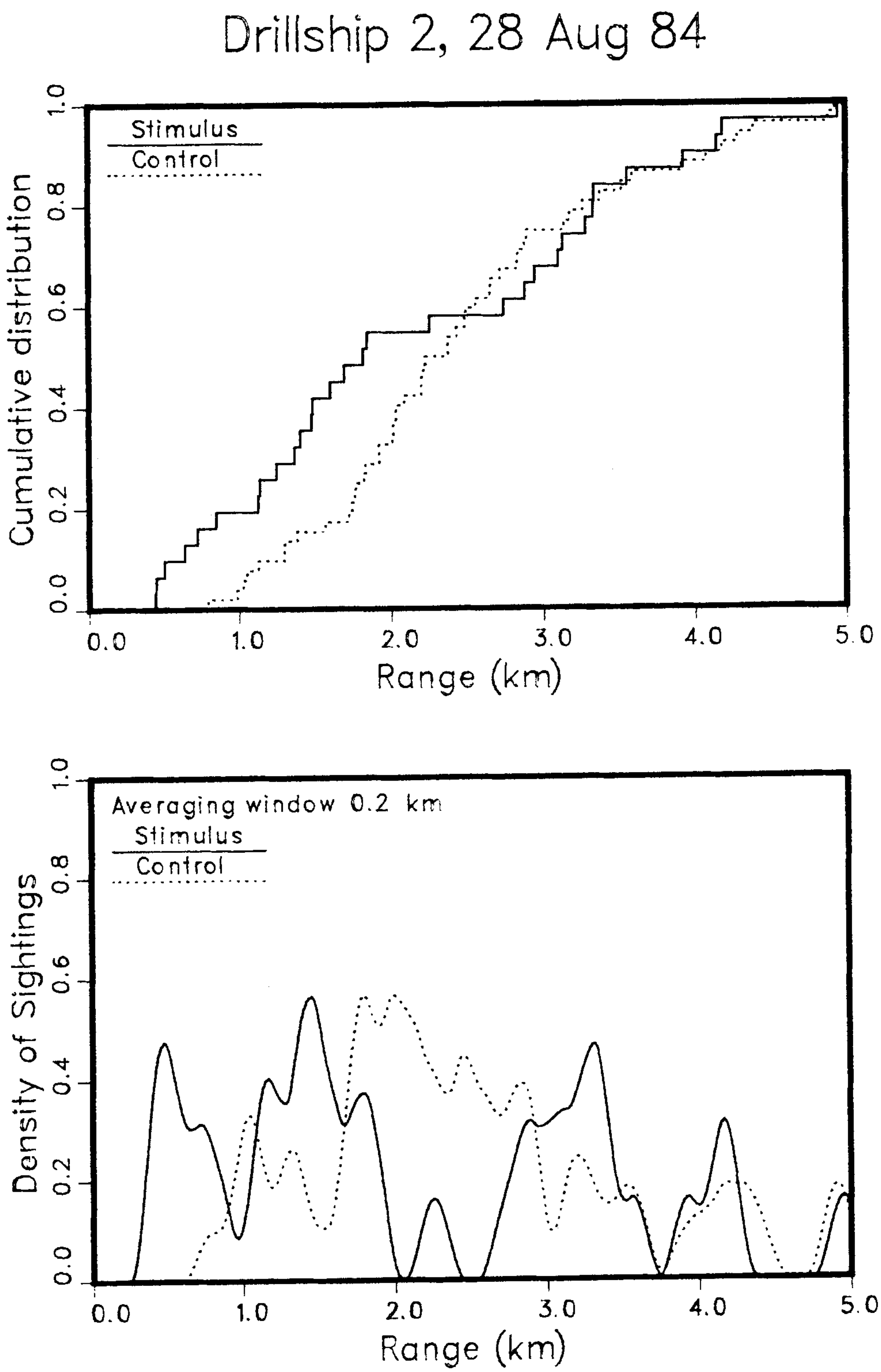


FIG. 6.13. DRILLSHIP PLAYBACK SIGHTING DISTRIBUTIONS, DATA OF 8/28/84.

TABLE 6.2. LIST OF EXPERIMENTS SHOWING SIGNIFICANT DIFFERENCES BETWEEN EXPERIMENTAL AND PRE- OR PRE- AND POST-EXPERIMENTAL CONTROL PERIODS. THE RESPONSE OF WHALES IS EVALUATED AS APPROACH OR AVOIDANCE DEPENDING ON WHETHER THE CUMULATIVE DISTRIBUTION OF WHALE SIGHTINGS DURING STIMULUS PRESENTATION IS AT CLOSER OR FARTHER RANGE THAN THE CONTROL DISTRIBUTION.

Date	Stimulus	Response
20 August 1984	Drillship	Avoidance*
22 August 1984	Air Gun #2	Avoidance
22 August 1984	Air Gun #3	Approach
24 August 1984	Air Gun #4	Avoidance**
26 August 1984	Air Gun #7	Approach
27 August 1984	Production Platform	Avoidance
28 August 1984	Drillship	Approach 0 to 2 km

*Primarily caused by drift of source vessel away from whales.

**Insignificant in range 0 to 1 km.

6.3 Pooled Air Gun Results

Two factors make pooling of different experiments difficult to interpret. First, experiments were performed in different sites with different characteristics of sound propagation. This means that the same stimulus sensed at the same range in two different sites may yield different received sound levels. For this reason, we scaled the pooled results against received level as well as range. Second, the whales' behavior and movements changed from day to day and site to site, so each experiment can most appropriately be compared only with a control from an adjacent time period.

With recognition of these problems, we pooled results from all of the air gun experiments in order to test whether the apparent lack of avoidance response might result from relatively small sample sizes. Figure 6.14 shows the cumulative distributions and density of sightings as a function of range from these merged air gun experiments.

Figure 6.15 shows the cumulative distribution and density of sightings as a function of received level for the merged air gun experiments. Received levels were calculated using the transmission loss characteristics for each experiment. Received levels calculated for control periods were the levels that whales would have experienced had the source been on. Most sightings were exposed to levels of 150 to 160 dB.

There were no significant differences between experimental and combined pre- and post-experimental control distributions in spite of sample sizes of > 300 in both distributions.

However, as Table 6.3A demonstrates, there were highly significant differences between experimental and either pre-

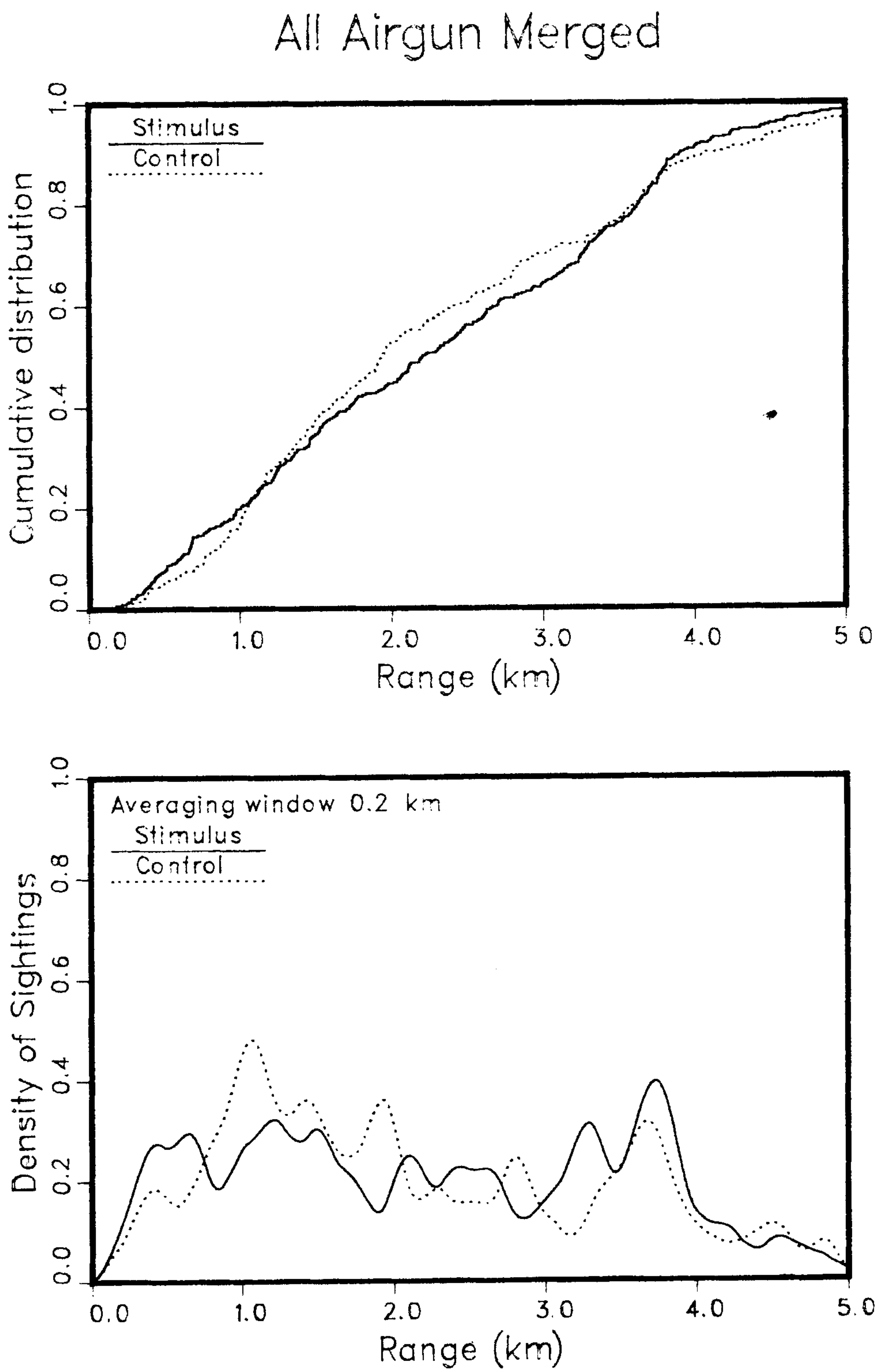


FIG. 6.14. POOLED AIR GUN SIGHTING DISTRIBUTIONS VS RANGE FROM SOURCE.

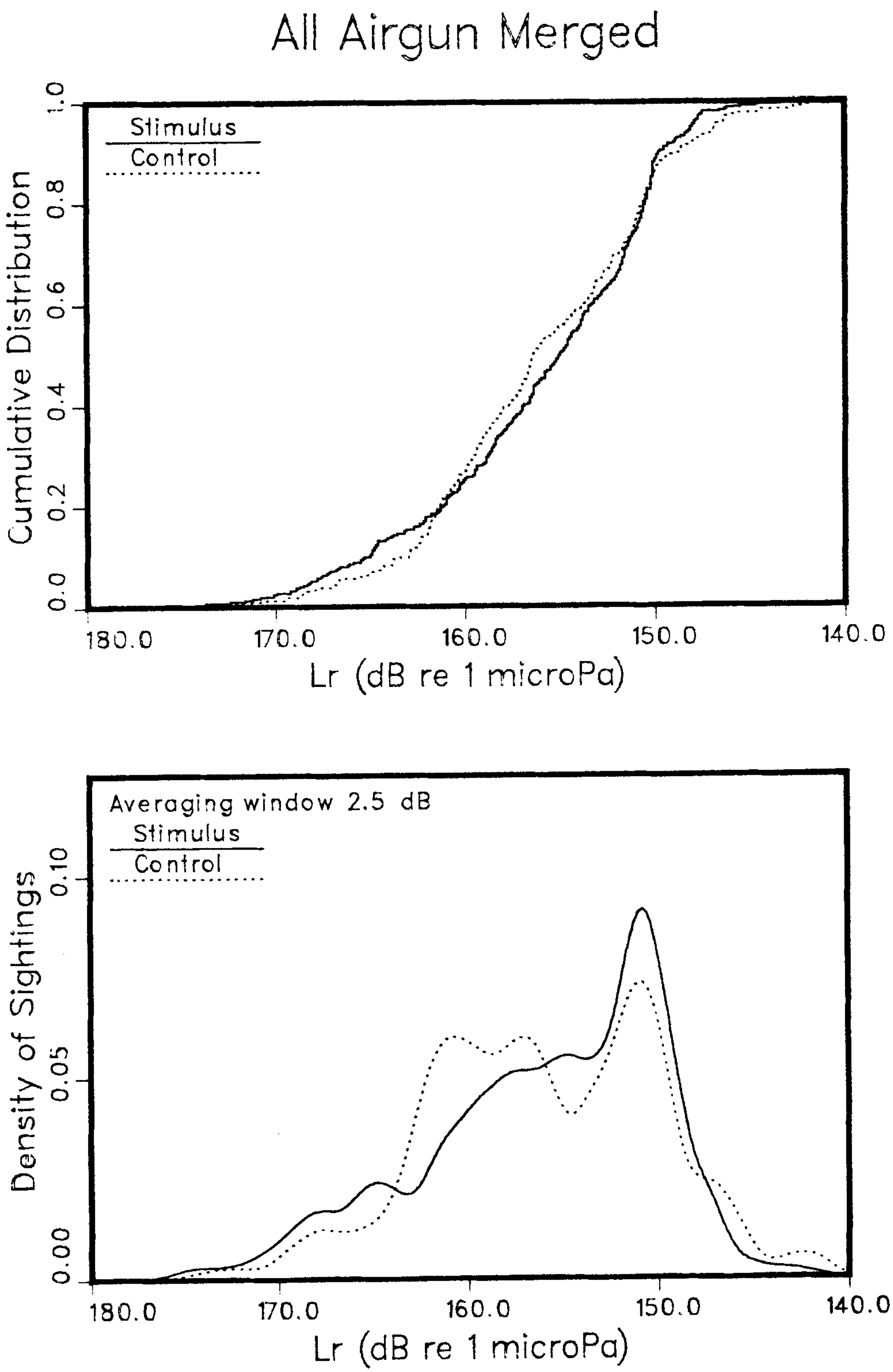


FIG. 6.15. POOLED AIR GUN SIGHTING DISTRIBUTIONS VS SOUND EXPOSURE LEVEL.

TABLE 6.3. STATISTICAL RESULTS FROM MERGING ALL AIR GUN EXPERIMENTS OR ALL PLAYBACK EXPERIMENTS. RESPONSES ARE SCALED AGAINST RECEIVED LEVEL. p VALUES GREATER THAN 0.05 ARE LISTED AS N.S. (NOT SIGNIFICANT).

A. Merged Air Gun Experiments

Condition	Number of Sightings
Pre Control	192
Air Gun	363
Post Control	123

	KS	CVM
Pre Control vs Exp.	$p < 0.001$	$0.001 < p < 0.010$
Pre and Post Control vs Exp.	N.S.	N.S.
Post Control vs Exp.	$0.01 < p < 0.025$	$0.001 < p < 0.010$

B. Merged Playback Experiments

Condition	Number of Sightings
Pre Control	276
Playback	147
Post Control	83

	KS	CVM
Pre Control vs Exp.	$p < 0.001$	$p < 0.001$
Pre and Post Control vs Exp.	$0.005 < p < 0.01$	N.S.
Post Control vs Exp.	$p < 0.001$	$p < 0.001$

experimental or post-experimental control conditions. Figure 6.16 shows why each half of the control yielded such a significant difference while combined controls showed no effect. During the pre-experimental control condition, whales were significantly closer to the source than during experimental conditions, while during the post-experimental control condition, whales were significantly farther from the source than during experimental conditions.

These results could indicate one of two possibilities. When we started an experiment we would position the observation vessels in the middle of a group of feeding whales, as close to the center of concentration as possible, and we would position the air gun source vessel also close to the whales. Once we started the pre-experimental control, the source vessel either ran a pre-established course, or slowly drifted away from the whales. These results could simply result from the drift of the source vessel, or random movement of whales away from the center of concentration where we started the experiment. On the other hand, these results are consistent with a potential response where whales started moving away from the source during the period of exposure and continued to move away during the post-experimental control period.

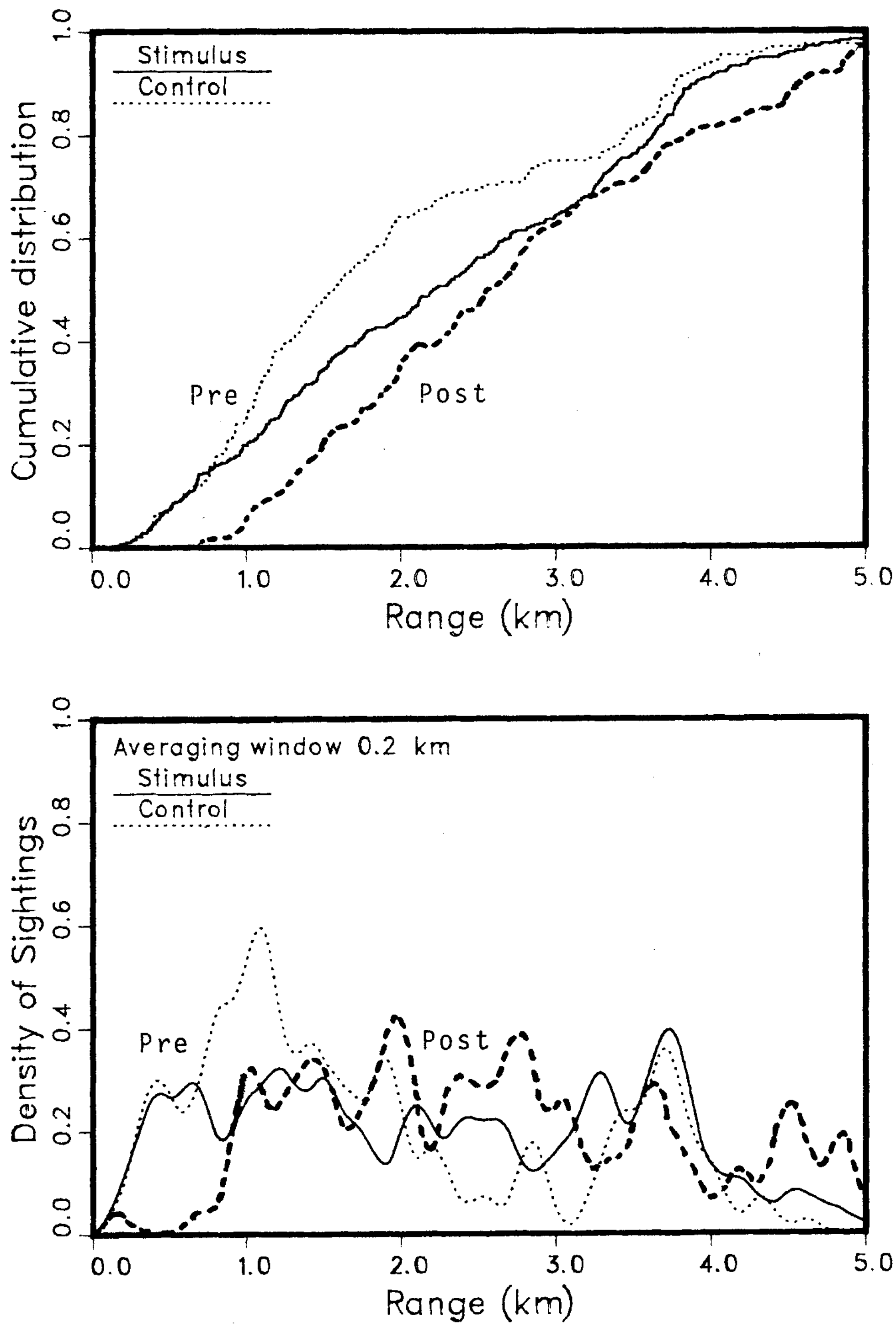


FIG. 6.16. POOLED AIR GUN, COMPARISON OF PRE- AND POST-EXPERIMENTAL CONTROL DISTRIBUTIONS WITH STIMULUS DISTRIBUTION.

A separate test was performed to discriminate between the boat drift and continued whale avoidance interpretations. This test assumed that whales would not show any motion away from the sound source during the pre-experimental control. In order to perform the test, each pre-experimental control period was divided into two equal time periods. Whale sightings from the first half of each period was accumulated in a nominal "Control" distribution while sightings from the latter half were accumulated in a nominal "Experimental" distribution. Figure 6.17 shows the results for the merged air gun experiments. Since whales were closer to the source during the first half of the pre-experimental control period, this test supports the boat drift interpretation. The difference between the two distributions scaled to received level is significant to $p < 0.010$ (KS statistic).

It was not possible to make one scatter plot of the merged whale sighting positions since the data were obtained at different sites. Instead, plots of range vs time after onset of stimulus during merged pre-experimental periods (Fig. 6.18) and merged air gun experimental periods (Fig. 6.19) were produced to allow inspection for avoidance at any combination of range and duration. In this figure sightings from different air gun test periods are represented by different symbols.

These plots are designed to show if the presence of the NANCY H. resulted in avoidance of the region near the vessel during the pre-experimental control periods and further show if the air gun pulses during the experimental periods produced avoidance behavior. Since time information is retained in this type of presentation, any transient reactions of the whales to either the presence of the vessel, or to the start of the air gun source would be shown as general movement in the sighting positions as a function of time after the start of the control or stimulus periods.

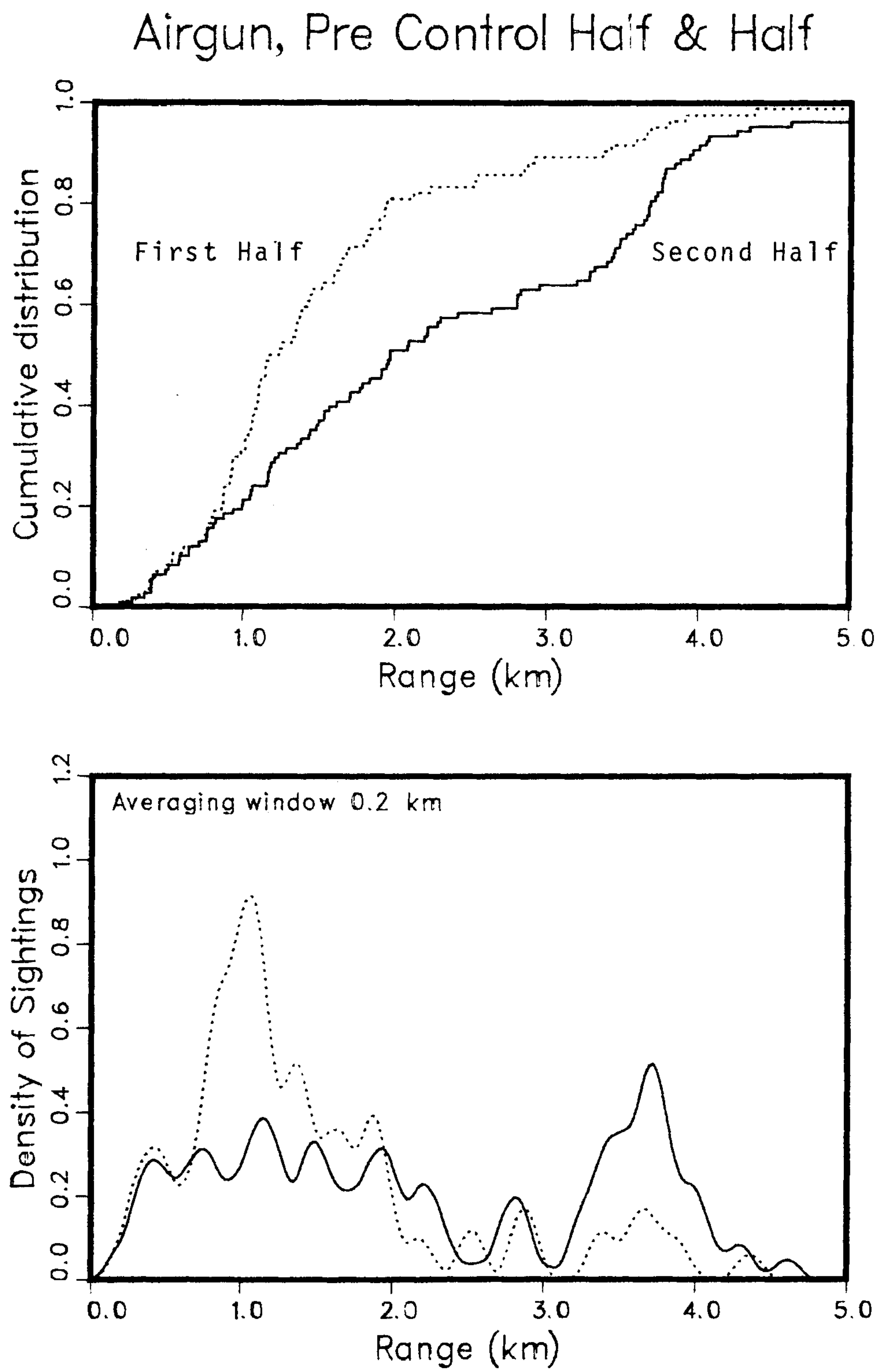


FIG. 6.17. POOLED AIR GUN, COMPARISON OF PRE-CONTROL SIGHTING DISTRIBUTIONS, FIRST HALF VS LAST HALF.

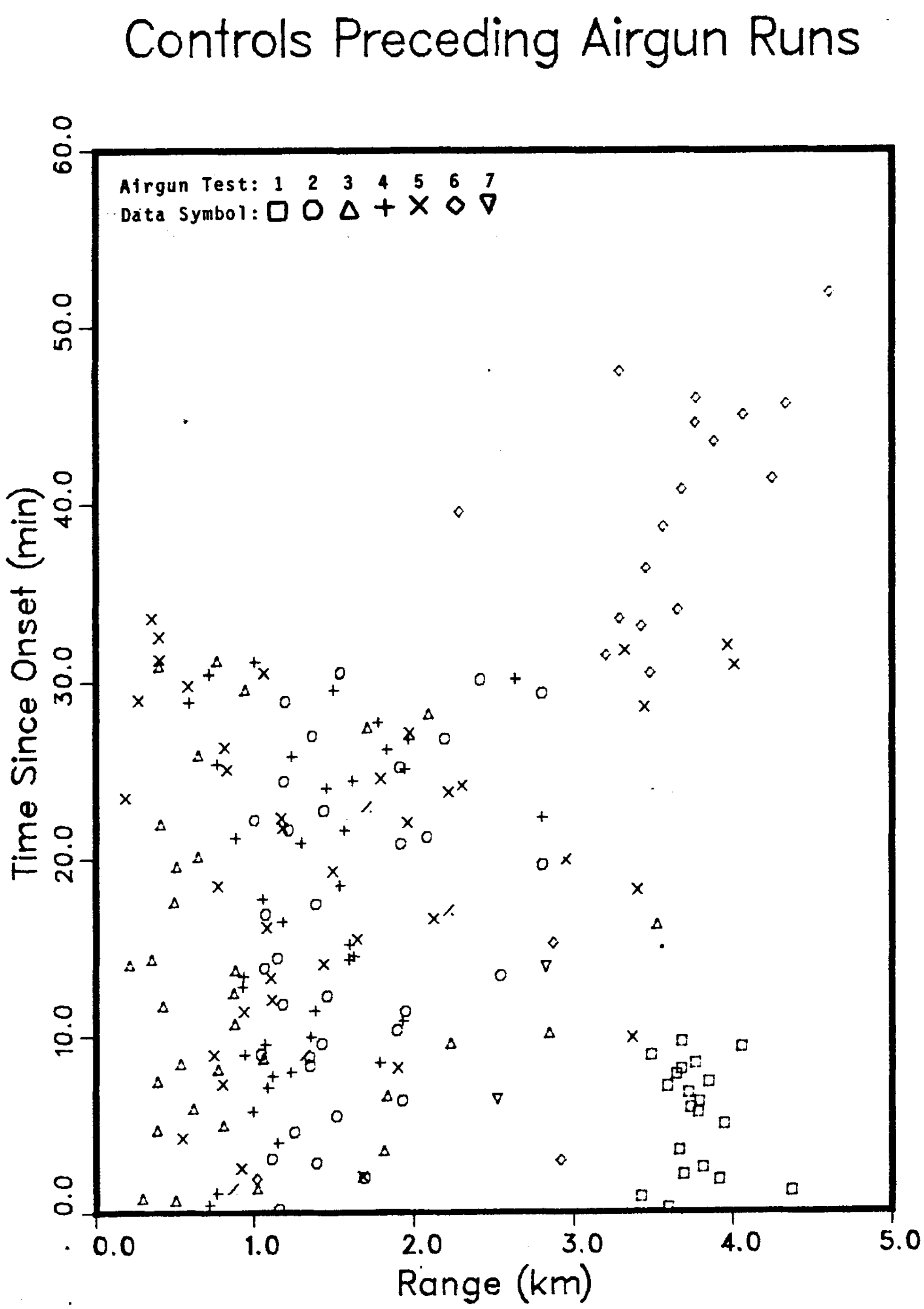


FIG. 6.18. POOLED AIR GUN CONTROL, SIGHTINGS VS TIME AFTER START OF TEST, RANGE FROM SOURCE.

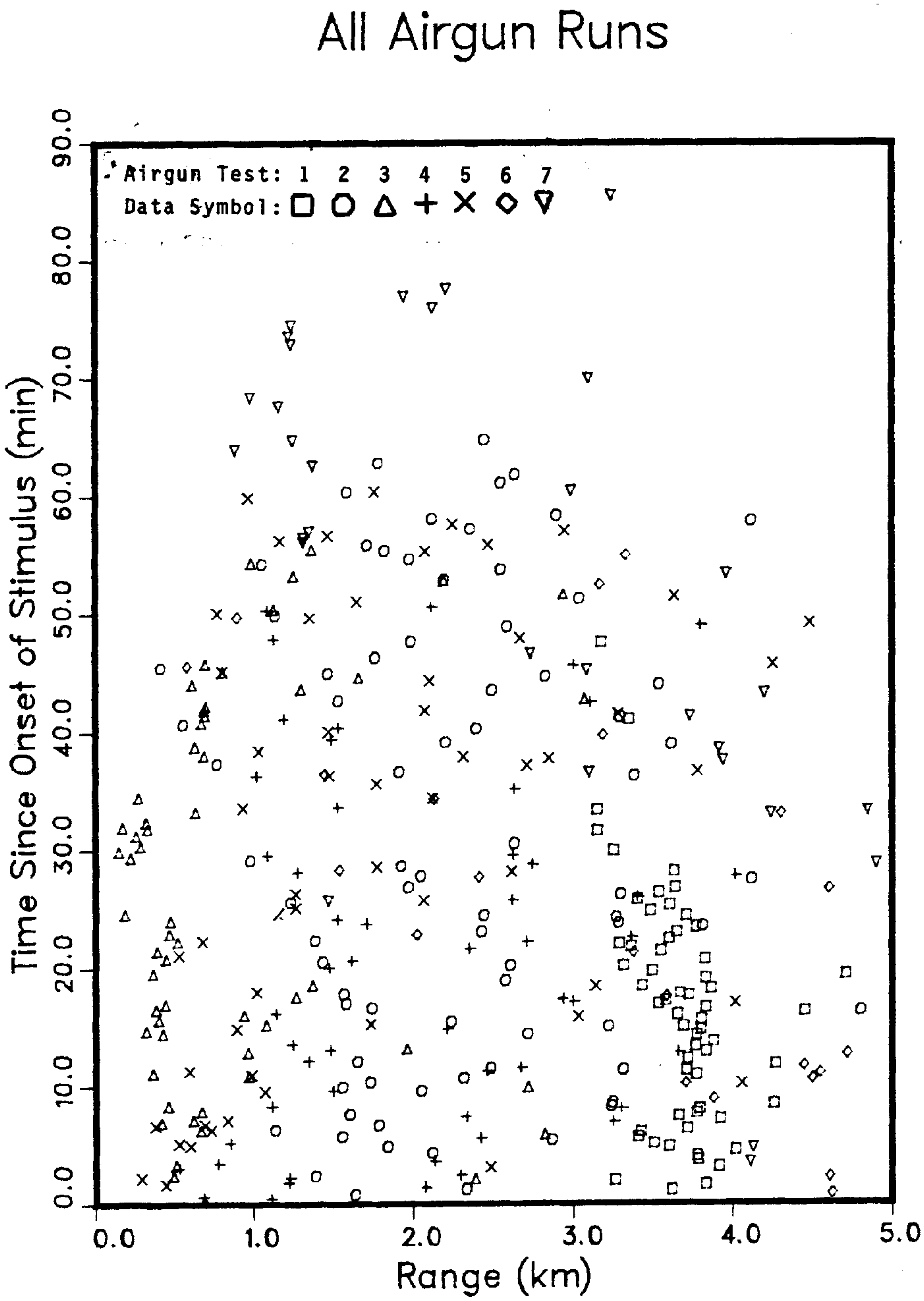


FIG. 6.19. POOLED AIR GUN, SIGHTINGS VS TIME AFTER START OF STIMULUS, RANGE FROM SOURCE.

No obvious movement patterns can be seen in either the control or the experimental data.

Because the various test areas had different acoustic propagation conditions, the scatter plots in Fig. 6.20 and Fig. 6.21 were also developed to show the sighting data as a function of received level. As seen in Fig. 6.21, the data for Air Gun Test 3 had whale sightings in the highest sound exposure range with the sightings at the highest levels occurring about 30 min. into the test. No clear avoidance pattern can be seen in the sighting data for any of the tests.

6.4 Pooled Playback Results

As in the case of the air gun experiments, there are problems with pooling different playback experiments. The different playback stimuli might elicit different patterns of response as was observed for migrating gray whales (Malme et al. 1984). Whales on different days might be engaged in different activities with different patterns of response to noise.

Not only did the sound propagation conditions vary from playback to playback, but the different playback stimuli had different source levels. It is thus meaningless to scale pooled playback sighting distributions to range from the source.

With these caveats, we pooled playback results as a function of received level to test whether the apparent lack of an avoidance response might result from the relatively small sample sizes associated with each individual playback. Figure 6.22 shows the cumulative distribution and sighting density for stimulus and combined pre- and post-playback control conditions.

As the results of Table 6.3B indicate, there were highly significant differences in either the pre- <u>or</u> the post-playback

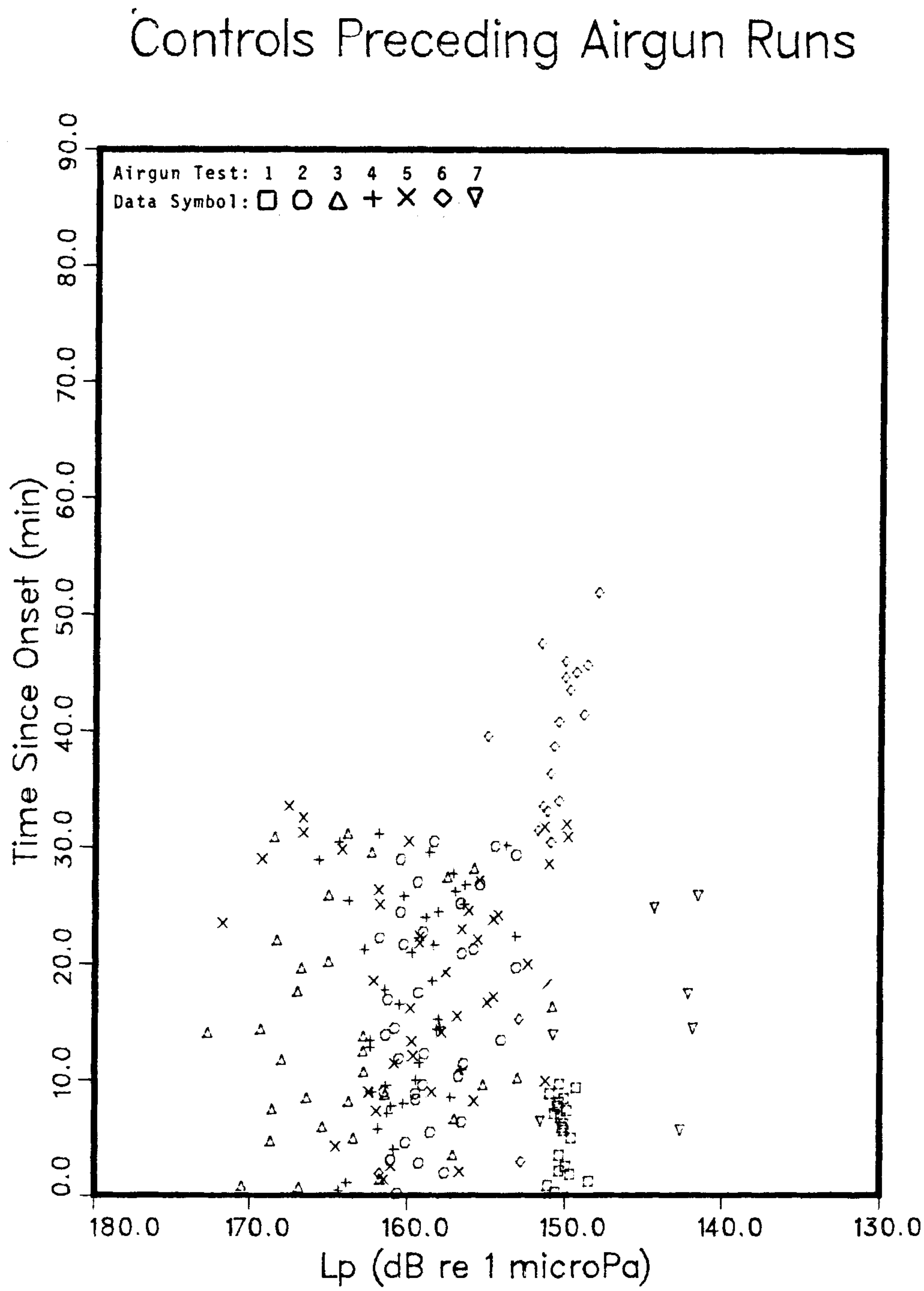


FIG. 6.20. POOLED AIR GUN CONTROL, SIGHTINGS VS TIME AFTER START OF TEST, SOUND EXPOSURE LEVEL.

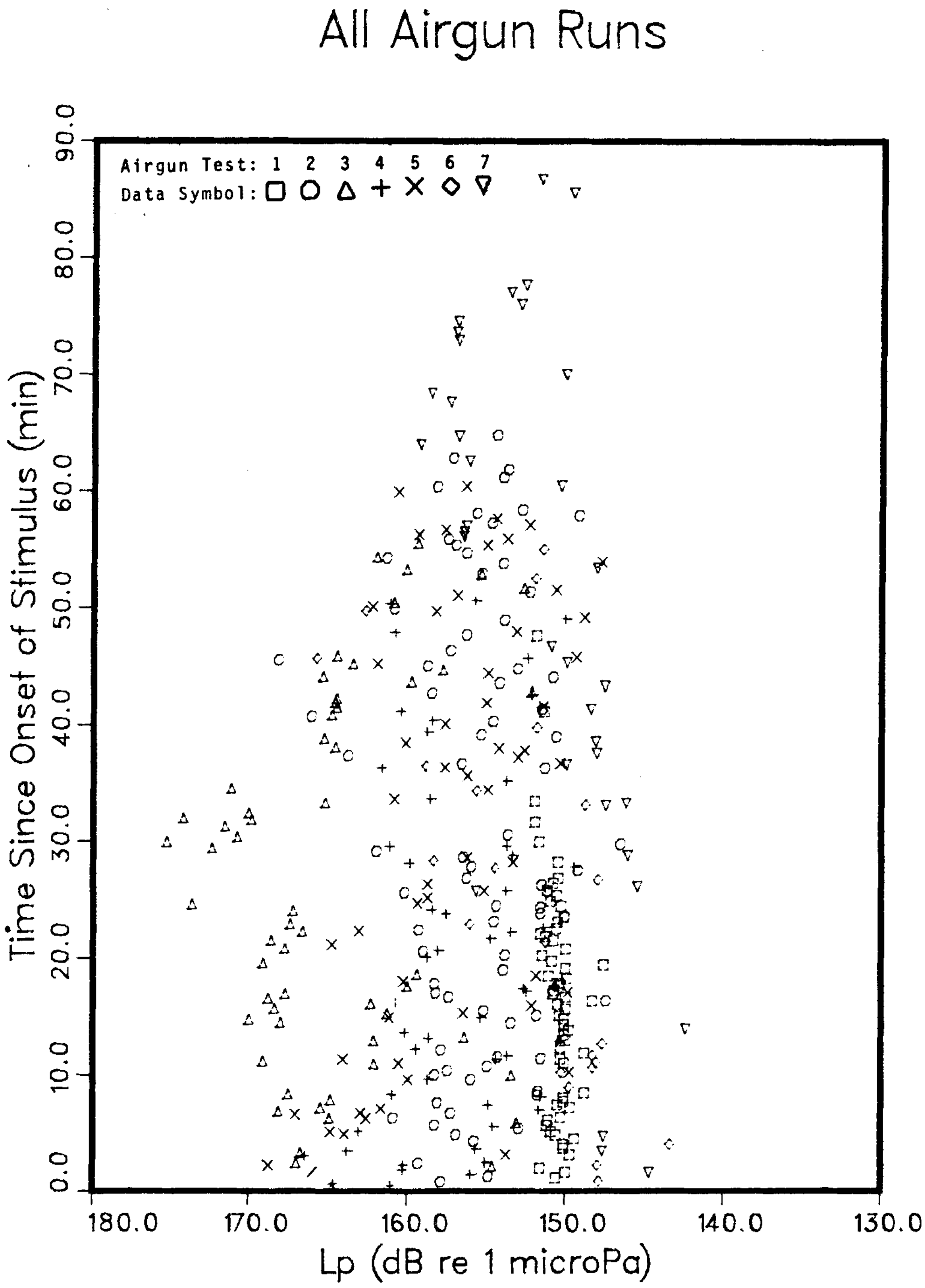


FIG. 6.21. POOLED AIR GUN, SIGHTINGS VS TIME AFTER START OF STIMULUS, SOUND EXPOSURE LEVEL.

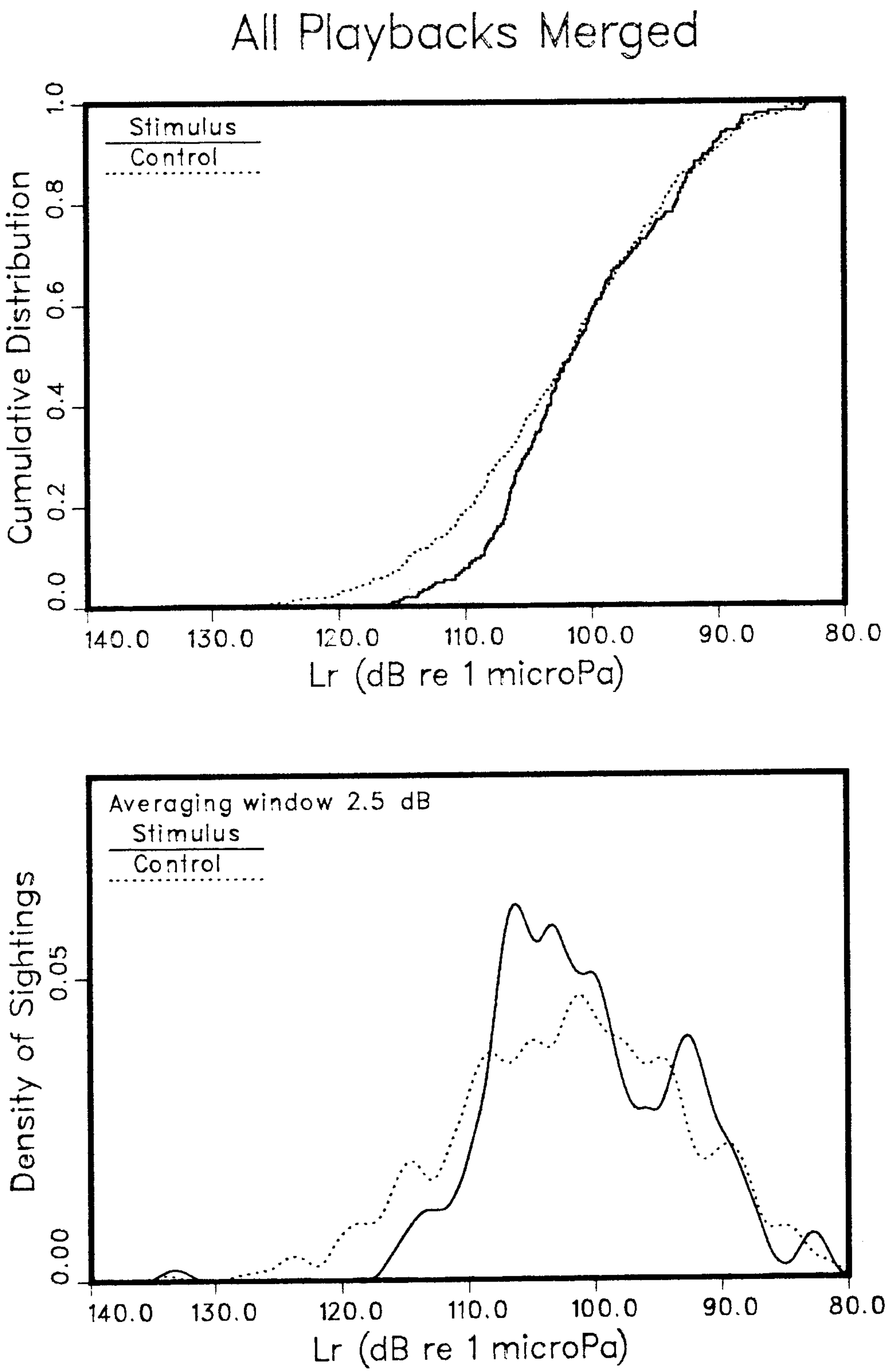


FIG. 6.22. POOLED PLAYBACK, SIGHTING DISTRIBUTIONS VS SOUND EXPOSURE LEVEL.

control distributions compared with the experimental distribution, but this effect is much less significant comparing the combined pre- and post-playback distributions to the experimental distribution.

This result is similar to those from the pooled air gun experiments, and it stems from the same reason. Inspection of Fig. 6.23 shows that the distribution of whale sightings shifted progressively farther from the source in the pre-playback control, experimental, and post-playback control distributions. As with the air gun experiments, the pre-playback control periods were divided in half and these two distributions were compared to test if this progressive increase was due to boat drift or to whale response to sound. The two distributions scaled to received level were significantly different ($p < 0.001$ ks test). The distributions are plotted in Fig. 6.24 which shows that whales were already farther from the source during the second half of the pre-playback control, a result consistent with the boat drift interpretation.

The significant difference between the combined pre- and post-playback distributions is probably due to the dominance of pre-playback control sightings compared to post-playback sightings. As Table 6.3 shows, the number of sightings was relatively balanced for the merged air gun control periods, which showed no significant differences in experiment vs combined controls. In these experiments, the effects of boat drift evidently cancelled out because of the well balanced controls, but the merged playbacks had extremely unbalanced samples in pre- and post-playback controls, 276 vs 83. Here, the combined pre- and post-playback distributions were heavily weighted by the large closer pre-playback sample.

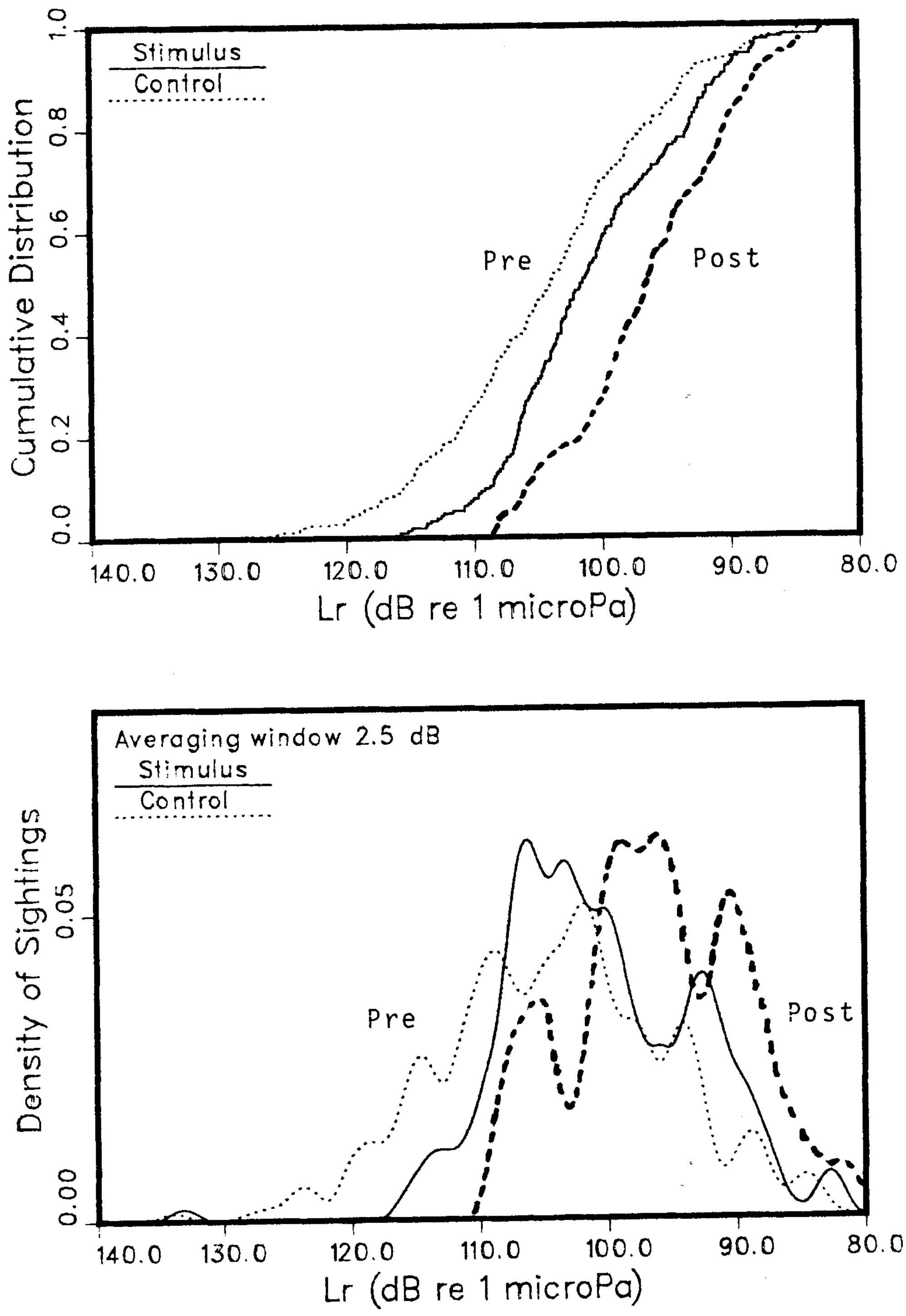


FIG. 6.23. POOLED PLAYBACK, COMPARISON OF PRE- AND POST-PLAYBACK CONTROL DISTRIBUTIONS.

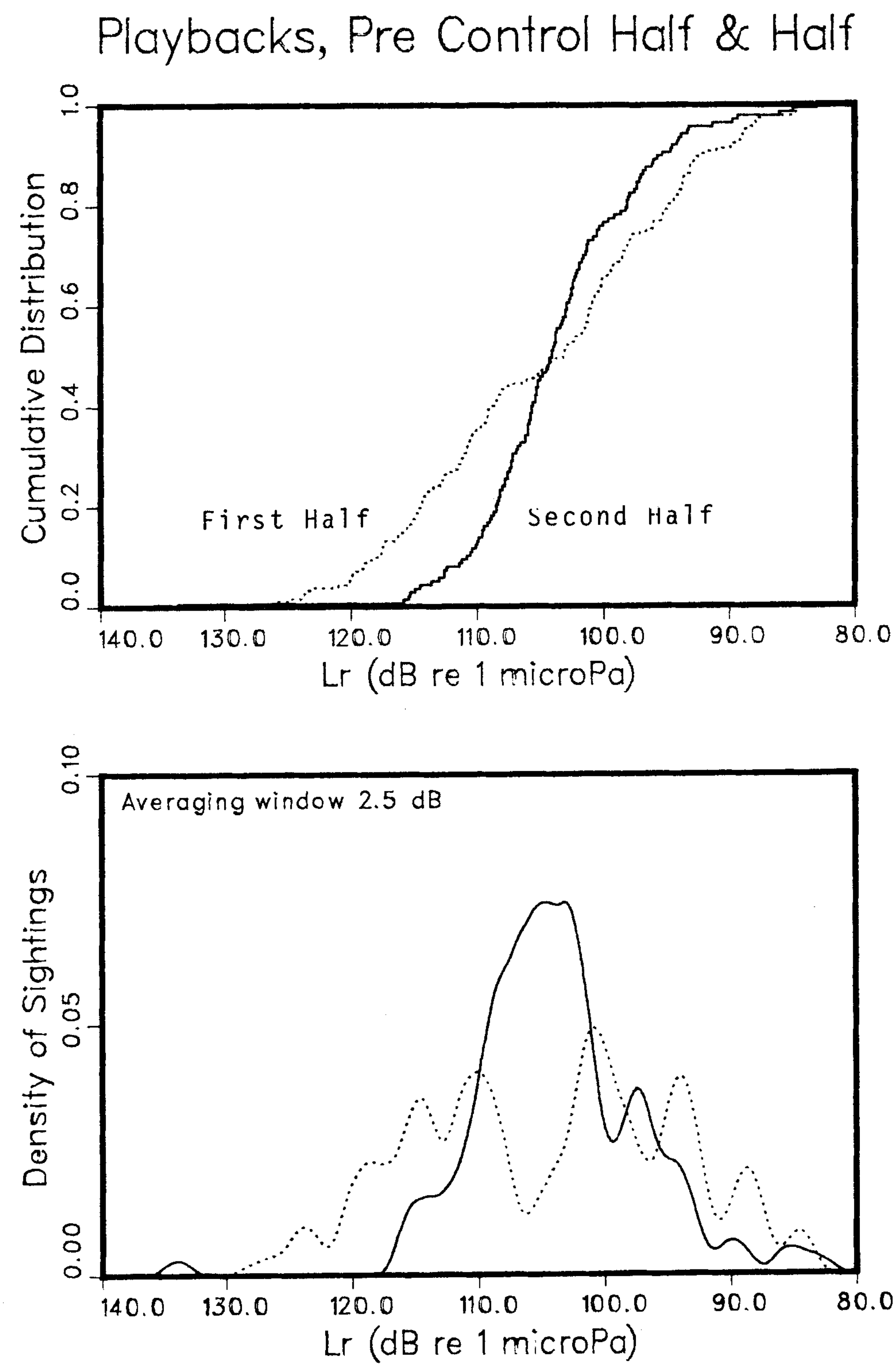


FIG. 6.24. POOLED PLAYBACK, COMPARISON OF PRE-CONTROL SIGHTING DISTRIBUTION, FIRST HALF VS LAST HALF.

Figures 6.25 and 6.26 show all whale sightings made during the merged playbacks scaled for time since stimulus onset as a function of received level. These show no obvious pattern of avoidance at any combination of levels and times.

6.5 Analysis of the Temporal Distribution of Sighting Data

Some researchers have reported increased blow rates after the onset of a disturbing stimulus. We were unable to gather blow rate or down time data on individual whales. But since we were able to record almost every whale surfacing within an approximately 5 km range, our data should show an increase in sightings just after stimulus onset if individual whales are surfacing more frequently.

Investigation of plots of range vs. time after stimulus onset showed no obvious pattern of increased sightings following onset of playback. We developed a statistical test for the hypothesis that our sighting rates were higher in the first part of our playback periods. Since we did not have any expectations as to the exact timing or range dependence of a possible response, we used as assumption free a statistical test as possible. We used a distribution-free rank-order statistical test to measure the probability that the median sighting occured in the first half of the exposure period, as predicted by the increased blow rate model, or in the second half. In two out of eleven playbacks, the probability that the median sighting occurred in the first half of the period was greater than 0.95, indicating a significant validation of the hypothesis. However, in 3 of the 22 pre- or post-experiment control periods, the probability was also > 0.95 even though there was no stimulus onset. There were also 3 out of 22 control periods when the probability was less than 0 to 0.05. This indicates a large degree of variability in the sighting conditions and range to

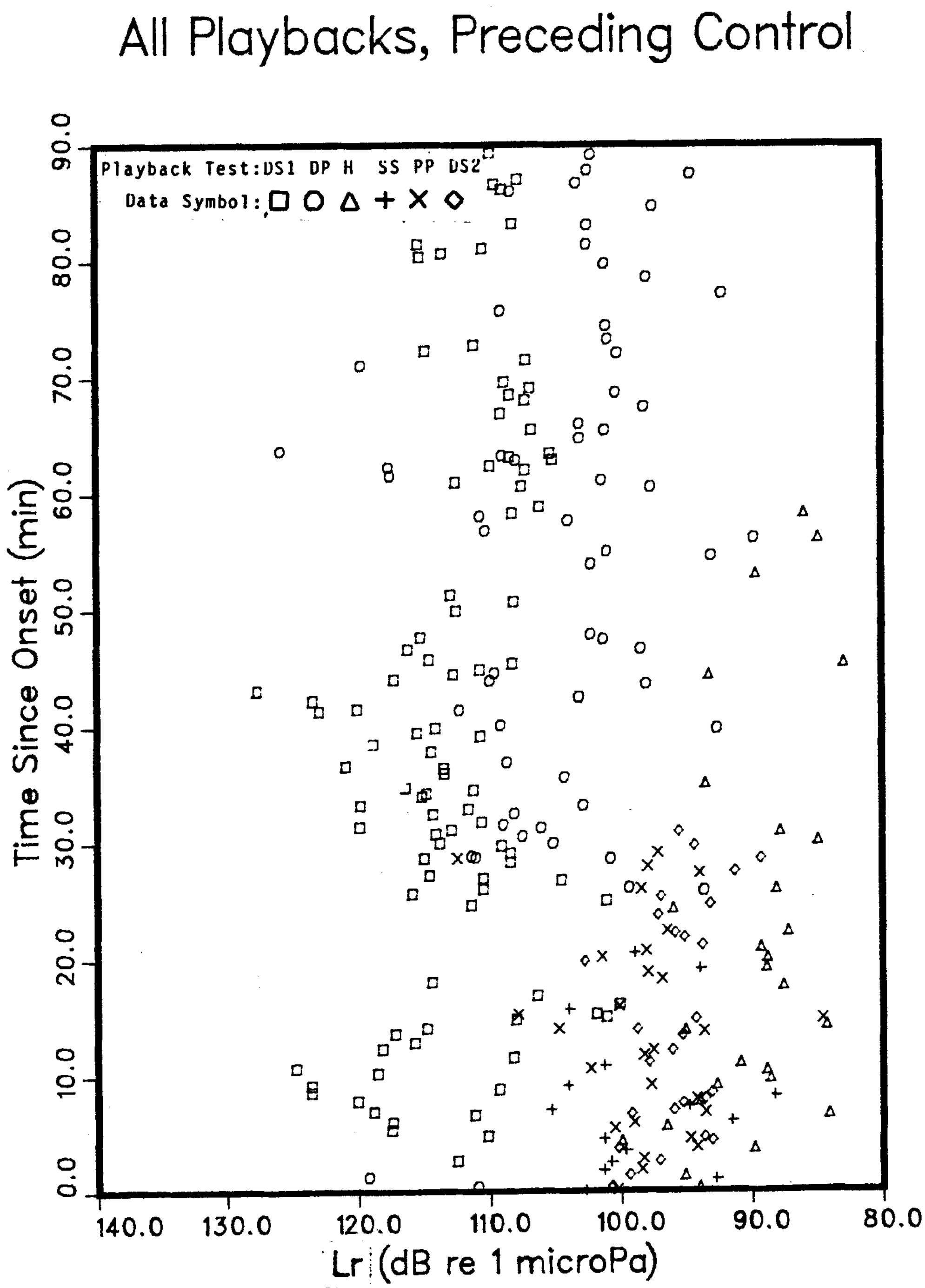


FIG. 6.25. POOLED PLAYBACK CONTROL, SIGHTINGS VS TIME AFTER START OF TEST, SOUND EXPOSURE LEVEL.

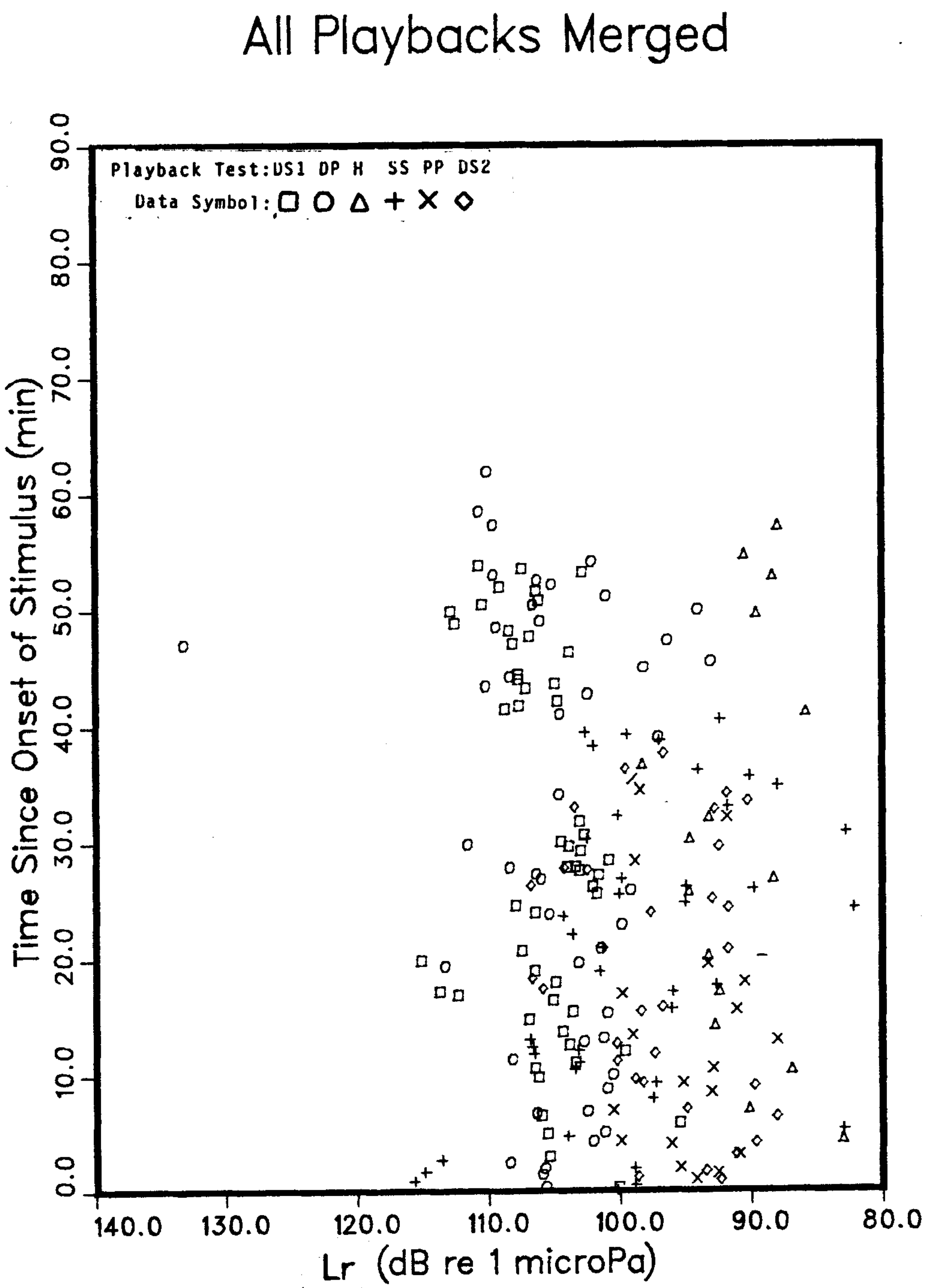


FIG. 6.26. POOLED PLAYBACK, SIGHTINGS VS TIME AFTER START OF STIMULUS, SOUND EXPOSURE LEVEL.

to whales. Thus, this temporal analysis of sightings gives some support to the hypothesis that sightings increase after the onset of playback, but the result is weak.

6.6 Specific Behavioral Observations

On three occasions during air gun experiments, we observed what we believed were startle responses by individual whales under observation prior to the onset of air gun firing. We also observed what may have been the use of a sound shadow by a group of two whales.

These three incidents were the only reactions we observed in the field which we could tentatively attribute to experimental conditions. Startle reactions by whales to loud noise have been reported on many occasions in the marine mammal literature (see Malme et al. 1983 and Appendix A of the present report).

On 22 August, the VARUA was located 100 to 200 m west of Round Rock in a concentration of approximately 30 humpback whales that were presumed to be feeding because of their surface behavior and numerous red patches of feces in the water. A single whale, labeled #13 in our field notes, was logging or "resting at the surface" within 200 m west of the VARUA. The air gun began firing at 1153. At that time the experimental boat, the NANCY H., was 3.2 km WSW of the VARUA. At approximately the same time as the air gun was activated, whale #13 was observed to stop logging and move rapidly to the south. Although none of the other whales under observation were seen to exhibit this behavior, it was noted at the time that by 1200 most whales in the area appeared to be moving to the south. By 1230, visibility conditions were very poor because of heavy fog, however, the number of loud, in-air exhalations near the VARUA led us to believe that many whales were now moving north through the area.

The fourth air gun experiment was conducted on 24 August between 0943 and 1146. We were stationed in Hobart Bay. It was noted in our field notes that there were a number of logging whales in the area, however the overall behavior of the whales under observation could not be determined. Two whales, labeled Group B in our field notes, were logging at the surface at least from 1008. Within seconds after the air gun was activated (1015) both whales in Group B blew and surfaced higher out of the water than had been observed previously. Both whales raised their tail flukes and dove, moving rapidly in a SSW direction.

Later in the afternoon of the 24th (1426-1639), we conducted our fifth air gun experiment west of Sunset Island. The behavior of the whales in the area could not be determined. A group of three whales, labeled Group A in our field notes, was moving to the south when the air gun began firing at 1500. In the next 11 minutes, this group made a number of direction changes. By 1501 the group was observed moving to the east. At 1507, personnel aboard the VARUA observed the group heading in a northerly direction. The group was then seen moving to the northwest at 1509. By 1511, Group A was moving south, their original heading. this group was still heading in a southerly direction until at least 1521. At the start of our observations, Group A was within 1 km of the NANCY H. and was estimated to be experiencing stimulus levels around 160 dB (re 1μPa).

During the first air gun experiment on 22 August, we observed what may have been the use of a sound shadow by a pair of whales. Approximately 30 minutes after the onset of seismic noise a group of two whales was observed to move south then around to the east side of Round Rock. This movement placed

Round Rock between the whales and the experimental vessel, the NANCY H. The interpretation that this group was using Round Rock to effectively lower the sound level that they were receiving remains speculative. However, similar incidents involving the possible use of a sound shadow by humpback whales were reported by Jurasz and Palmer (1981) and Malme et al. (1984), reported that gray whales may, on occasion, exhibit similar behavior.

7. INTERPRETATION AND APPLICATION OF RESULTS

7.1 Interpretation of Results

The locations of whale sightings during these controlled noise exposure experiments were measured in order to test whether whales avoid an area surrounding an active sound source. A statistically significant difference in sightings from control and experimental distributions could be interpreted as an avoidance response if there were more sightings at close ranges in the control distribution than in the experimental one. The shift in distributions would have to start only after the onset of playback. If the response scaled with range from the source, showing a greater avoidance at higher sound levels, this would provide even stronger evidence that the whales avoided the sounds.

The results of the merged air gun and merged playback experiments both show highly significant differences in sighting distributions from pre-playback, experimental, and post-playback periods with whales progressively being sighted farther from the sound source. But an equally significant difference is obtained if one compares the first halves of the merged pre-experiment control periods to their second halves (Figs. 6.17 and 6.24). Since this continual steady increase in the distance between whale sightings and the sound source occurred even before the sound started, it can be interpreted as a consequence of drift of the sound source vessel and whales. Since we started all experiments by positioning the sound source close to the whales, even random whale motions would tend to increase the ranges of sightings.

Our response measures were thus sensitive enough to find a significant effect from boat drift but do any of the responses scale with sound level in a way consistent with our avoidance model? A probability of avoidance measure was developed in our previous study of migrating gray whales (Sec. 8.2, Malme et al. 1984) to quantify avoidance as a function of received sound level. For the gray whale study, we were able to follow the tracks of most groups of whales, and the response measure used for the probability of avoidance analysis was track density at the closest point of approach to the sound source.

Since we were unable to follow individual humpbacks or groups of humpbacks in the present study, the only measure we could use for probability of avoidance analysis is the density of sightings calculated as described in Sec. 3.4.2 of this report.

The probability of avoidance P_a at a particular exposure level is calculated as:

$$P_a(L_R) = \frac{\left(P_c(L_R) - P_s(L_R)\right)}{P_c(L_R)} \qquad (7\text{-}1)$$

where P_c is the density of sightings under control conditions,

and

P_s is the density of sightings under stimulus conditions.

This index becomes 1 if no sightings are found under stimulus conditions, 0 if equal sightings are found under stimulus and control conditions, and negative if more sightings are found under stimulus conditions than under control conditions.* Where sample sizes are very small, this index shows large swings even for insignificant differences so P_a was only calculated for received levels where more than 2 sightings occurred within a

*If $P_s(L_R) > P_c(L_R)$, the denominator in Eq. (7-1) should be $P_s(L_R)$ to obtain the correct normalization. This case is really approach rather than avoidance.

2.5 dB increment. Increments of 2.5 dB were selected as appropriate for the measurement precision in range observation and in sound level calibration.

Figure 7.1 shows the result of probability of avoidance analysis for the merged air gun experiments and Fig. 7.2 shows the result for merged playbacks. The equivalent results from the gray whale study are indicated with a dotted line. For the gray whale study, migrating gray whales exposed to air gun pulses or each of the five playback stimuli showed a generally monotonic increase in probability of avoidance as a function of received level.

For the merged air gun experiments, not only does the probability of avoidance not increase with increasing sound level, but at the received levels where avoidance was observed, the humpbacks showed negative P_a or apparent approach. The merged playback experiments also show highly variable probability of avoidance, but at the highest levels (> 110 dB) there does appear to be an increase in P_a slightly greater than, but paralleling the increase for the gray whale track data.

Given the amount of apparently random fluctuation of P_a at lower received levels, this apparent avoidance between 110 and 115 dB should be retested in an experiment preferably including exposure to higher levels as well. Overall, the random fluctuations of P_a as a function of L_R give no strong evidence of a systematic avoidance response of feeding humpbacks comparable to the obvious responses of migrating gray whales.

While the probability of avoidance analysis provides a powerful method to quantify systematic avoidance responses, it does not incorporate a measure of the significance of each P_a estimate. This varies as a function of the sample size for each

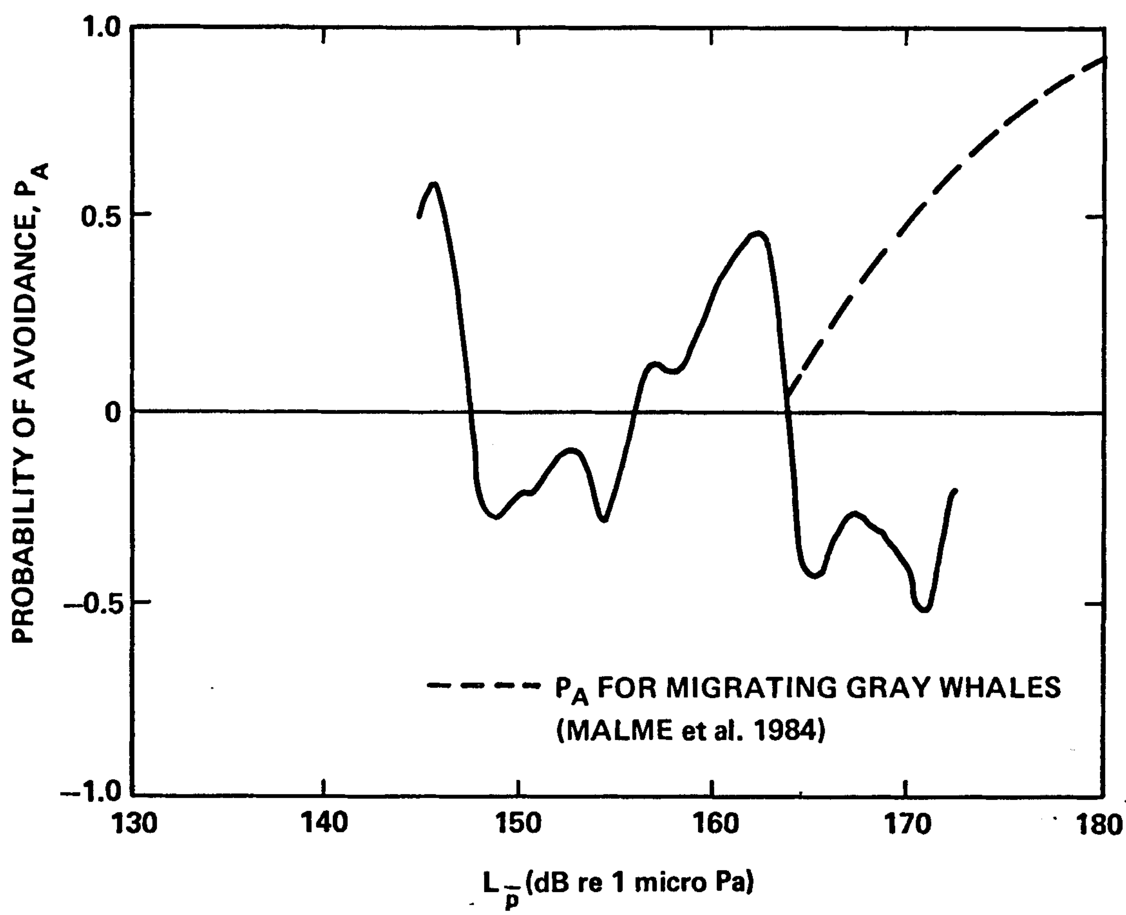


FIG. 7.1. PROBABILITY OF AVOIDANCE CURVES FOR FEEDING HUMPBACK WHALES, MERGED AIR GUN EXPERIMENTS.

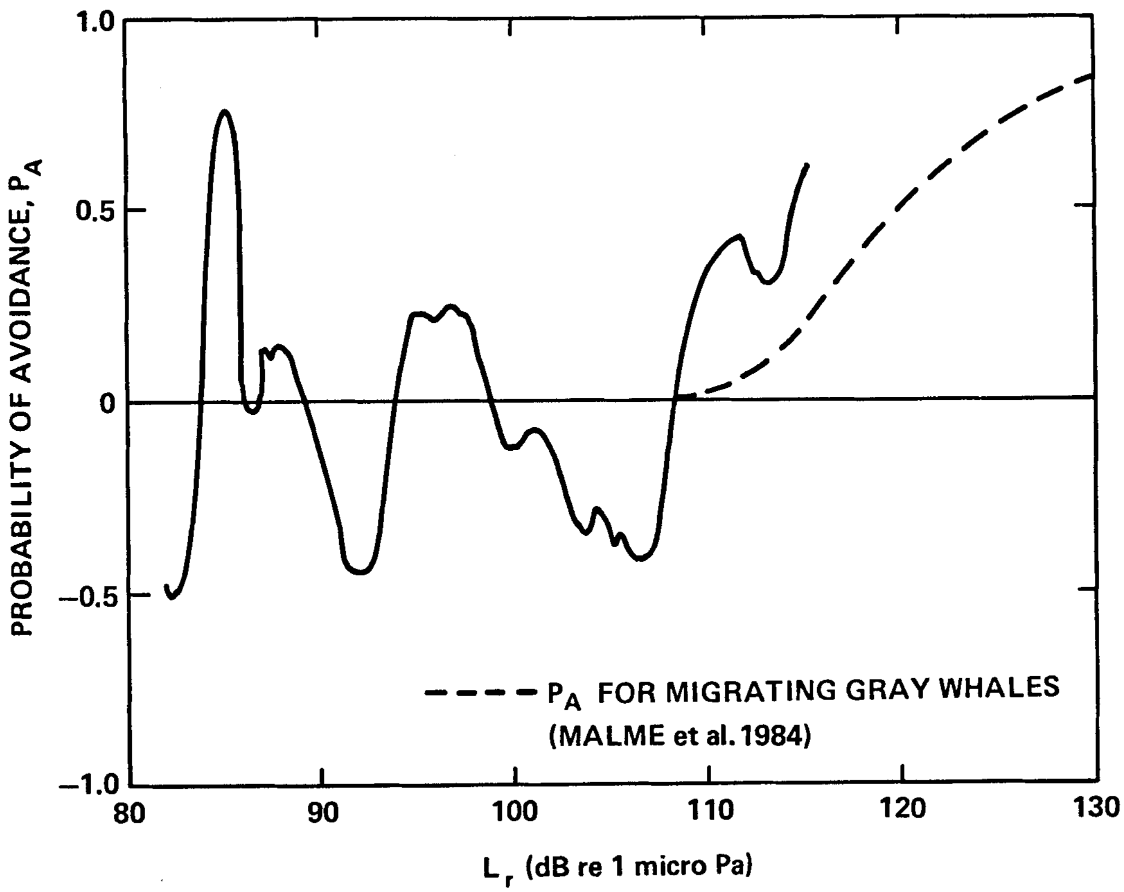


FIG. 7.2. PROBABILITY OF AVOIDANCE CURVES FOR FEEDING HUMPBACK WHALES, PLAYBACK EXPERIMENTS.

L_R increment. How do the sample sizes of the humpback and gray whale studies compare?

Figures 7.3 and 7.4 show the sample sizes of merged air gun experiments for feeding humpbacks and migrating gray whales, respectively. These samples are not directly comparable because each gray whale track was made up of many sightings, but they both served as measures for the probability of avoidance calculations. The important area to compare these distributions is for received levels above 165 dB where gray whales showed a significant response. A total of 36 humpback sightings and 34 gray whale tracks were counted above this level under stimulus conditions, while 22 humpback sightings and 23 gray whale tracks were counted in control conditions at ranges at which they would have been exposed to levels above 165 dB had the source been on. Thus, the sample sizes for both sets of experiments are quite similar, so low sample size seems an unlikely explanation for the lack of humpback avoidance, unless tracks are much more sensitive measures than individual sightings.

7.2 Application of Results

As shown in Figs. 7.3 and 7.4, a comparable number of humpback whales were exposed to sound levels which produced an avoidance reaction in migrating gray whales. Thus, in the absence of evidence showing that humpback whales are adversely affected by short-term exposure to the noise levels achieved in the study, it seems that the avoidance criteria derived from the gray whale study could be used as a conservative interim guide for the maximum industrial noise exposure for feeding humpback whales.

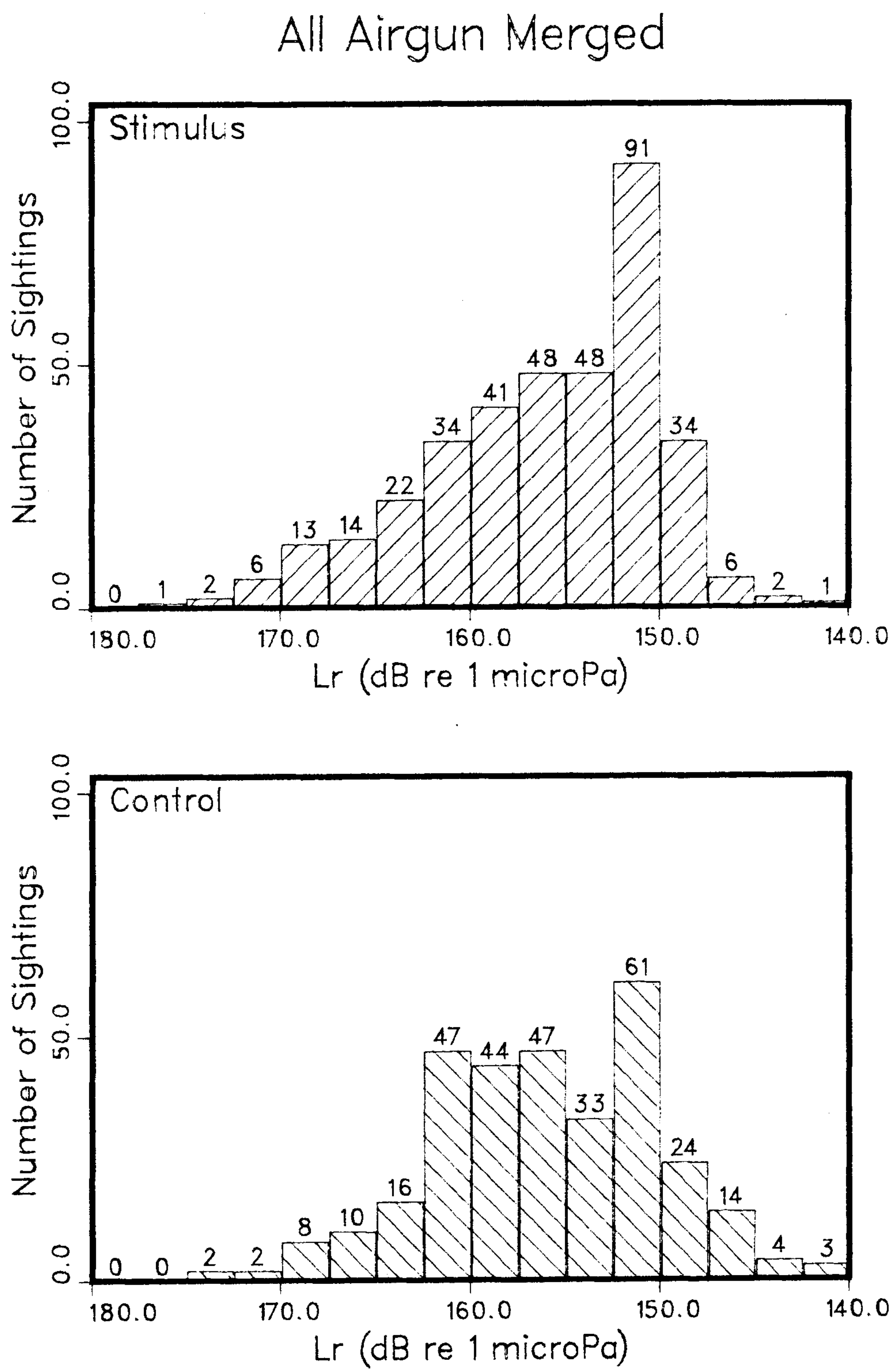


FIG. 7.3. NUMBER OF SIGHTINGS VS SOUND EXPOSURE LEVEL FOR MERGED AIR GUN TESTS.

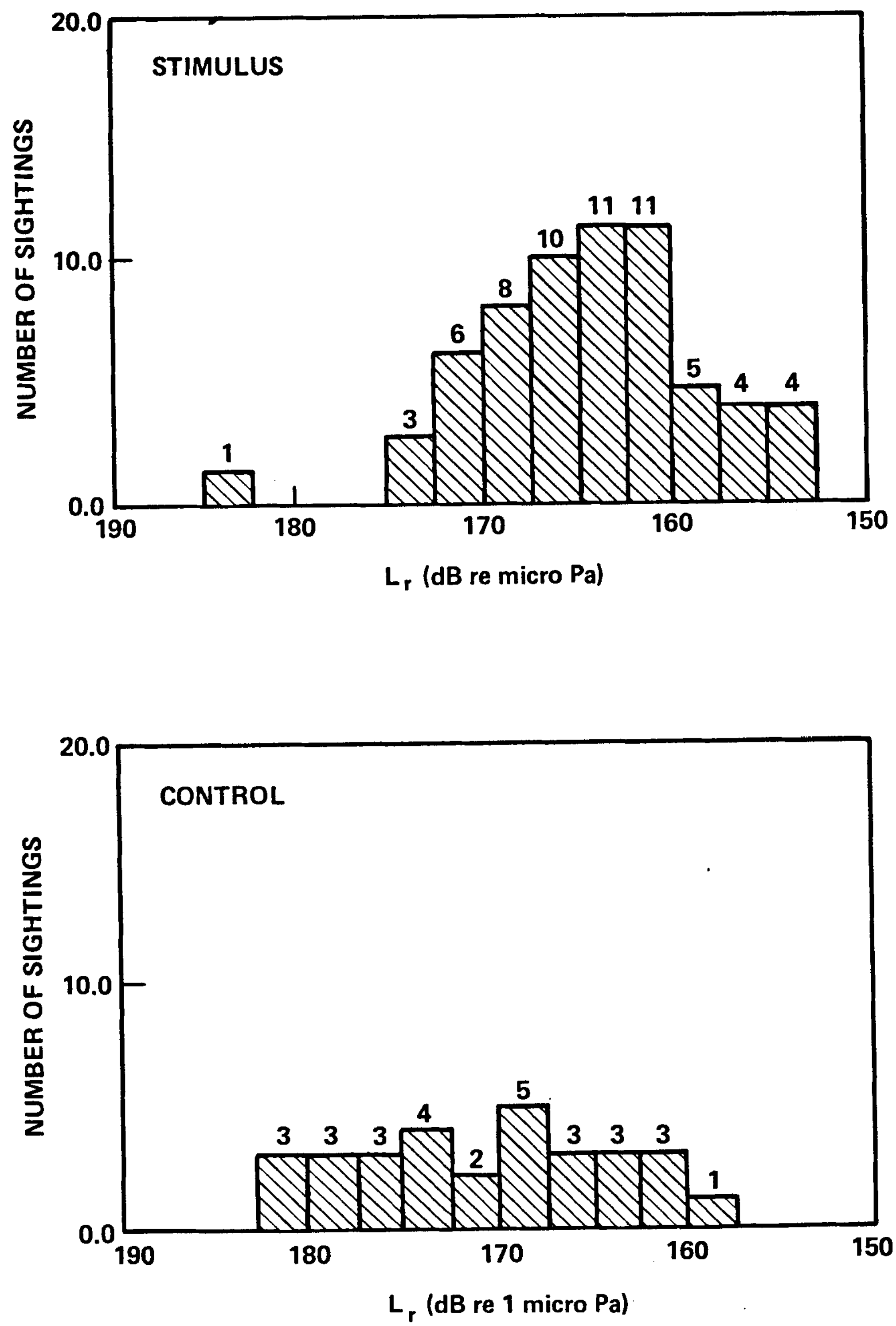


FIG. 7.4. NUMBER OF TRACKS VS SOUND EXPOSURE LEVEL, DATA FOR MERGED AIR GUN TESTS WITH MIGRATING GRAY WHALES (MALME ET AL. 1984).

Tables 7.1 and 7.2 summarizing the gray whale results, obtained from Malme et al. (1984), are repeated here for convenience. The effective range values given in Table 7.2 are based on sound propagation conditions off the California coast. No attempt at correction for application to the southeast Alaska test area has been made since that would be applying conjecture to conjecture in view of the observed highly-variable sound propagation conditions. Application of site-specific sound propagation measurements or estimates is most important for determining the minimum range for a seismic array. The other sources have a much shorter minimum range and hence are less affected by sound propagation variability.

TABLE 7.1. COMPARISON OF PROBABILITY OF AVOIDANCE LEVELS FOR THE TEST STIMULI. (Malme et al. 1984)

Stimulus Level, dB re 1μ Pa

P_a	Drillship	Drilling Platform	Production Platform	Helicopter	Semi-submersible	Avg. Playback	Air Gun (Seismic Array)
0.1	110	114	120	115	115	115	164
0.5	117	117	123	120	120	119	170
0.9	122	>128	>129	>127	>128	>127	>180

TABLE 7.2. EFFECTIVE RANGE IN TEST AREA FOR $P_a = 0.5$. (Malme et al. 1984)

	Drillship	Drilling Platform	Production Platform	Helicopter	Semi-submersible	Air Gun	Seismic Array[5]
Sound Level at 100 m	136[1]	89 (109)[2]	109 (118)	103[3] (118)	101 (111)	180	212 (dB re 1μPa)
Sound Level for P_a=0.5	117	117	123	120	120	170	170 (dB re 1μPa)
Required TL Change	19	-28 (-8)	-14 (-5)	-17 (-2)	-19 (-9)	10	42 (dB re 1 m)
Est. Range for P_a=0.5	1.1 km	4 m (40 m)	20 m (56 m)	14 m[4] (79 m)	11 m (35 m)	400 m	2.5 km

Notes:

(1) Estimated sound level at 100 m for broadband or summed tonal components of original source included with good fidelity in playback (from Table 3.1).

(2) Estimated sound level at 100 m of loudest low frequency tonal components of original source not reproduced adequately by playback (from Table 3.1).

(3) These levels are estimated for a direct flyover at an altitude of 100 m.

(4) These values are altitude predictions for producing 120 dB in the water at a point just below the surface for a direct flyover.

(5) Data from Report Malme et al. 1983, array orientation-broadside.

(6) Referred to transmission loss at 100 m.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Comparison of the distribution of whale sightings under control and stimulus conditions showed no clear avoidance response of whales. Of the 13 air gun and playback experiments, seven yielded significant ($p < 0.05$) differences, but three of these seven showed an apparent approach response while only four showed apparent avoidance. Of these four "avoidance" responses, one is more a result of boat drift than whale movements.

One might interpret the significant approach or avoidance responses as differential responses to the different playback stimuli, but this is unlikely for several reasons. The only stimulus to yield more than one significant response was the air gun, and this stimulus evoked both approach and avoidance responses. The significant responses did not appear to scale with range, and were not stronger closer to the stimulus as one would predict if they were responses to the received level of the stimulus. When these same stimuli were played back to migrating gray whales (Malme et al. 1984), they all evoked statistically significant avoidance responses. There was no suggestion that gray whales approached any of these stimuli.

It appears more likely that the significant movements of the humpbacks were either a response to some stimulus other than our playbacks or were due to the effect of drift of the sound source vessel. During many of these playbacks, whales were apparently feeding. In some cases, they worked against currents to remain in one location, while in others they showed highly variable but coordinated movement patterns. Both kinds of movement could have yielded significant apparent responses, but were more likely a result of feeding patterns than of the influence of our sound source.

The method for localizing whales from two boats developed for this study worked successfully in our application although it was not as easy nor as precise as land-based theodolite localization. We were unable to track individual whales for useful periods of time, but were able to localize most whale surfacings sighted within approximately 5 km of the sound playback source. The sighting range error was estimated to be less than 10% within 1 km.

8.2 Recommendations

We recommend that the sound exposure levels which were found to produce observable avoidance for migrating gray whales be considered as interim exposure level criteria for humpback whales. A given avoidance probability level, such as 50%, can be selected and the associated exposure levels for the various industrial sources, as given previously in Table 7.2, can be used as guidelines. These exposure levels together with source level information for a given industrial source and site-specific transmission loss data can be used to estimate the zone of influence for an existing or planned industrial activity which may impact feeding humpback whales. These interim exposure level criteria can be modified as data from further experiments with feeding humpback whales become available. Recommendations for these experiments are presented in the following discussion.

Our methods were designed to detect an avoidance response within a group of whales. While observers paid attention to any possible response, our methods were not sensitive indicators of all potential responses. For example, if whales stopped feeding but did not move away from the playback source, we would not necessarily have detected it. Since we were unable to follow individual whales, we were also unable to test whether a small fraction of the population was particularly sensitive to playback.

These questions would be better addressed by concentrating on responses of focal animals which are kept under close observation. This might be best performed with the implantation of radio tags equipped to telemeter depth of dive or heart rate. Data from such a study on movements, surface time, dive time, depth of dive, and physiological responses, would be a useful supplement to the overall approach/avoidance responses which were the focus of this study.

We were unable to expose feeding humpbacks to sound levels of our experimental stimuli loud enough to evoke unequivocal avoidance responses. It would be very difficult to expose feeding humpbacks to higher sound levels without either boosting source level, approaching whales during playback, or eliminating the pre-exposure control period. In the present study, we positioned the source in the middle of a group of humpbacks at the start of an experiment. But by the start of playback, the whale concentration often had changed and moved beyond the source range of a few hundred meters which was found to be required to evoke a response in gray whales. This drift is unavoidable given our experimental design. Even if the sound source were moored during each experiment, the often erratic movements of feeding whales would be likely to produce the same effect.

One approach to alleviate the problem for the air gun source, which is usually moving for seismic surveying, would be to plan a series of passes near feeding whales with a randomized schedule of source on or source off. For playback tests simulating sources which are usually in a fixed location, long-term studies should be made wherein a controlled industrial noise source is located in a previously established humpback whale feeding area. This would permit observation of day-to-day feeding patterns to determine if any general avoidance of the area near the source occurred over the course of a season.

This type of study should be coupled with a study of focal animals so that any habituation which occurred for resident animals could also be detected.

A study of the response of humpback whales to a full-scale seismic array would provide information on their behavior in the presence of the loudest industrial noise source. This type of source would expose humpbacks to sound levels loud enough to elicit an avoidance response if they respond similarly to migrating gray whales.

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APPENDIX A

THE EFFECT OF SEISMIC OPERATIONS ON MARINE MAMMALS; A LITERATURE REVIEW UPDATE

James E. Bird

APPENDIX A: THE EFFECT OF SEISMIC OPERATIONS ON MARINE MAMMALS; A LITERATURE REVIEW UPDATE

In 1983, we reviewed the literature on the effects of offshore oil and gas exploration and development on baleen whales under contract #AA851-CT2-39 for the Minerals Management Service, Anchorage (see Malme et al. 1983, Appendix A). This review was undertaken in order to better understand past research in this area and to put our own experimental work on migrating gray whales (Eschrichtius robustus) in proper perspective. The results of this literature review revealed that there has been little experimental work done to assess the acoustic effects of offshore industrial development and related activity (i.e., boat traffic, helicopter transport, etc.) on baleen whales. Many of the reports of responses of whales to acoustic stimuli are anecdotal in nature and ancillary to other work which was conducted (i.e., censusing, survey work, etc.). However, a few recent studies have been dedicated to determining, experimentally, the possible effects of these sounds on marine mammals. Some of these studies were reviewed by Malme et al. (1983). These studies include work on the bowhead whale (Balaena mysticetus) in the eastern Beaufort Sea, the humpback whale (Megaptera novaeangliae) in southeast Alaska (Baker et al. 1982, 1983), the gray whale in the lagoons of Baja California, Mexico (Swartz and Jones 1978, 1980, 1981, 1983, and recent work by Dahlheim) and our own work on migrating gray whales along the central California coast (Malme et al. 1983, 1984).

One of the major acoustic sources associated with offshore industrial development is seismic profiling. Since completion of our literature review in 1983, several new and relevant publications have been released that present the results of studies on the effects of seismic activity on baleen whales. It is the purpose of this brief literature review to update our 1983 report with regard to these studies. As this present report is an extension of our above mentioned contract covering our gray whale work (see Malme et al. 1983, 1984), we will not review the results of our seismic experiments here, but refer the reader to these two reports for review. Also, in Malme et al. (1984), a history of offshore seismic surveying in California is presented investigating potential relationships with the migration characteristics of gray whales in that region.

Richardson et al. (1983) completed a report entitled: "Effects of offshore petroleum operations on cold water marine mammals: A literature review." This report was prepared for the American Petroleum Institute, Washington, DC. In this extensive review, the authors address a variety of topics that are of interest to those working in this subject area. Among the topics covered include general background information on underwater acoustics, sources of noise associated with offshore exploration and development, sound propagation in water, sound production capabilities of both toothed and baleen whales and also pinnipeds, a review of the status of knowledge on hearing in marine mammals, zones of influence, and the documented response of marine mammals to noise - including a section on reactions to seismic profiling and shock waves. This is an excellent literature review of available (October 1983) knowledge on the subject.

Reeves et al. (1983) reported on their work monitoring the behavior of bowhead whales in the presence of seismic operations in the Alaskan Beaufort Sea. Observations were made from a Grumman Goose (G21C), twin-turbine, high-wing configuration aircraft flying at altitudes of between 411 to 457 m (above sea level - a.s.l.). Behavioral observations were made on six days during the period from 14 September to 2 October, 1982. On 14 September, a possible response to the onset of seismic activity was observed. A spread out assemblage of approximately 18 bowheads were noted. These whales were in groups ranging in size from 1 to 6-7 individuals, with group separation between 0.25 to 1 km. Orientation of individuals was termed random and both synchronous and asynchronous surfacing patterns were observed. A "quiet" seismic vessel was within 3 km of the whales. The vessel began shooting at 1502 and by 1530, the observers noted a complete change in the behavior of the whales. Most of the group had come together into one assemblage with a few single whales within 1 km of the coalesced group. The members of this close-together group of 12 to 14 individuals were synchronized in their surfacings and in close proximity, orienting towards each other. A similar incident was noted on 15 September. On this occasion, the whales were 9 km from the seismic vessel. Reeves et al, speculate that the onset of seismic sound may have caused this behavior, however they state that without experimental control, this interpretation remains speculative. They also observed, on 24 September, a group of 6-7 bowheads exhibiting a similar behavior, however in this incident no seismic sounds were detected over the sonobuoy.

This same type of behavior, termed "huddling," was also reported by Ljungblad et al. (1984a) during aerial survey work in the Beaufort Sea. This response was noted as possibly being caused by the approach of the survey aircraft (Grumman Turbo Goose-G21G) flying at an unspecified altitude of between 305 to 460 m (a.s.l.). On two different occasions, single concentrations of 5 bowheads, with each whale in the group separated from the others by 100 to 500 m, were seen to come together "...with their heads nearly touching either lateraly or rostrum to rostrum" (p. 66). The whales coalesced within 5 minutes of the aircraft's approach. This response may have resulted from the onset of loud noise, however, as Ljungblad et al. note, this interpretation is speculative.

On 23 September, two individually identifiable bowheads were observed by Reeves et al, in an assemblage of approximately 13 whales, 38 km away from a seismic vessel. Observations were made during and after seismic blasts. The altitude of the aircraft was 457 m (a.s.l.). No close contact was noted and the group of whales was catagorized as resting or moving slowly throughout. Respiration data was taken on the individually marked bowheads during the observations. However, the data set was not sufficiently large enough to test for significance.

A group of 20 bowheads was observed on 24 September under pre-seismic and seismic conditions. This group of whales included 6 to 7 whales exhibiting the "huddling" behavior noted earlier. The altitude of the aircraft was 457 m (a.s.l.). The number of blows per surfacing and the surface time of individual whales was found to be significantly greater just after the seismic impulses started than before them. At the time of the observations, the seismic vessel was 135 km from the whales. Again, on 25 September, the authors had the opportunity to observe whales under both conditions (altitude of aircraft - 457 a.s.l.), however, on this occasion the whales, two individually identifiable bowheads, were seen under seismic and post-seismic conditions. This time the number of blows per surfacing and the surface time were greater right after the seismic vessel stopped shooting, however, the results were not statistically significant. Based on available data, the seismic vessel was determined to be 154 km from the whales.

In summarizing, Reeves et al. (1983) stressed that the behavioral changes noted above may have been the result of variety of factors, including, but not limited to, water depth, group size and composition, or the various behaviors in which the whales were engaged at the time of the observation. They comment on the need for experimental control when assessing the effects of seismic profiling on marine mammals.

Ljundblad et al. (1984b) attempted to conduct controlled experiments on the effects of seismic profiling on bowhead whales in the Beaufort Sea during the fall of 1983, however, severe ice conditions in the study area precluded any experiments. Observations were carried out using a deHavilland Series 300 Twin Otter with two turbo-prop engines and high wing configuration. Behavioral observations were conducted at an altitude of approximately 460 m (a.s.l.). The following criteria were used in categorizing undisturbed whales: 1) altitude of aircraft not below 457 m (a.s.l.), 2) "...no moving vessel within 5.0 km of the whales, and 3) no underwater industrial activity noise could be heard via sonobuoys monitored in the aircraft" (p. 24). Although no controlled experiments could be conducted, a limited amount of respiration data was collected on whales exposed to seismic noise and whales that were presumably undisturbed. On the three days when useable data was collected on whales exposed to seismic activity, the operating vessels were 42 to 57 km from the whales. Results of the analysis found that: 1) the number of blows per surfacing was significantly lower for whales that were exposed to seismic operations, 2) blow intervals were longer for potentially disturbed whales, however, not significantly, and 3) the length of surfacing and length of dive were not significantly different when the two conditions were compared, but showed a tendency to increase during potentially disturbed periods. Ljungblad et al. (1984) then compared their findings with those of Reeves et al. (1983). They note that in 1982, the whales under study were characterized as milling and possibly feeding as opposed to the whales in 1983 which were characterized as travelling. Comparisons were also made with observations made during the summer. Based on the outcome of their field season, Ljungblad et al. (1984) delineated two conditions which should be met in the future, in order "...to successfully conduct seismic/ bowhead behavior studies..." (p. 72): 1) light ice conditions should prevail to allow for arranged movement of seismic vessels, and 2) the whales under study "...should be non-travelling, e.g., whales feeding or milling in an area for extended periods of time, to facilitate resighting of individuals and the documentation of any progressive changes in their behavior during an experiment" (p. 72).

Richardson et al. (1984), in their fourth report on the effects of offshore industrial noise on bowhead whales in the eastern Beaufort Sea, observed whales near operating seismic vessels on four days, two in early August and two in late August, early September, 1983. The vessels were 26 to 99 km from the whales. It was estimated that the received sound levels to the whales were at least 107 to 135 dB. They note that there was a possible overload in their receiving equipment because of strong pulses which would have made their received level estimates conservative. Observations were carried out using two types of aircraft: from 1 to 12 August, a deHavilland Series 300 Twin Otter, with two turbo-prop engines, high-wing configuration was used; and from 13 August on, a Britten-Normal Islander, with twin piston engines, high-wing configuration was used. Behavioral observations were conducted at altitutdes of 457 m or 610 m (a.s.l.). Richardson et al, found that in 1983 no observed response was noted to either the start-up or shut-down of seismic operations. The values for the four surfacing and dive parameters used to access possible effects (mean number of blows per surfacing, mean blow interval, mean surface time, mean dive time) were not inconsistent with the range of values for presumably undisturbed whales. They note that:

> "The mean values of behavioral variables sometimes did differ in the presence and absence of seismic noise. However, when all available data from 1980-83 were considered, the directions of the apparent effects were not consistent, and the overall trends were not statistically significant." (p. 159)

They also examined several other behavior variables in the presence and absence of seismic operations. Using four rate of movement categories (no movement, slow, medium, or fast), no differences were noted between seismic/no seismic conditions. The rate of turning during surfacings on 31 August and 1 September, when whales were exposed to seismic operations, was found to be significantly less when compared to the presumably undisturbed period, 22 August - 1 September. This difference was not found when data from earlier years were analyzed. Data gathered on 7 and 9 August could not be compared to a control period because of sample size. No difference in the number of predive flexes was noted between seismic/no seismic conditions from 22 August through 1 September.* Again, low sample size precluded comparison of the data from 7 and 9 August. When comparing the incidence of whales raising their flukes above the water's surface when diving, a significant increase was noted during the seismic period, 31 August, 1 September, when compared to the presumably undisturbed period 22 August through 1 September. This increase could possibly be explained by behavioral activity differences between the two periods. Again, low sample size precluded comparisons during the first part of August. A comparison of the rate of bowhead sound production and sound type between seismic/no seismic periods was also made. No statistical difference was detected.

A single air gun experiment was conducted on 28 August. Data collected on the four surface and dive variables during pre-air gun and air gun conditions showed a trend for an increase in mean blow interval and a reduction in mean length of surfacing and mean number of blows per surfacing. Sample sizes during the

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*Predive flex is "...a distinctive concave bending of the back, with the back about 0.5 m to 1 m below the level of the rostrum tip and the tail." (Wursig et al. 1984, p. 40.)

air gun exposure period were low, however. When the results from the three air gun experiments conducted during 1981 and 1983 were pooled there was a trend for the number of blows per surfacing and the mean length of surfacing to be reduced during air gun periods. The mean blow interval showed a significant increase during air gun periods. A comparison of the other behavioral indicators mentioned above showed no significant differences.

Regarding the effects of seismic operations and air guns on the behavior of bowhead whales, the authors conclude:

> "Overall, our results show that behavior of bowheads summering in the Canadian Beaufort Sea is not altered in a conspicuous, consistent manner by noise from seismic vessels 6 km or more away or by a single air gun simulating such a vessel." (p. 170.)

They also stress the need for higher received levels of seismic noise and controlled experiments that can be replicated in order to determine if bowheads are effected by seismic operations.

In summary, these reports add to our knowledge of the effects of seismic operations on marine mammals, particularly the bowhead whale. However, they emphasize the fact that on at least this species, controlled experiments with higher received levels of seismic noise are needed in order to determine the effect of seismic profiling. Again, we would like to refer readers to two main literature reviews on the effects of offshore oil and gas exploration and development on marine mammals: Richardson et al. (1983) and Malme et al. (1983).

I would like to thank the following individuals for sending me copies of reports or for providing information on their availability: Janet T. Clarke, Donald K. Ljungblad, Marilyn Dahlheim, Dr. W. John Richardson, and Dr. Bernd Würsig.

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APPENDIX B

SIGHTING POSITION PLOTS

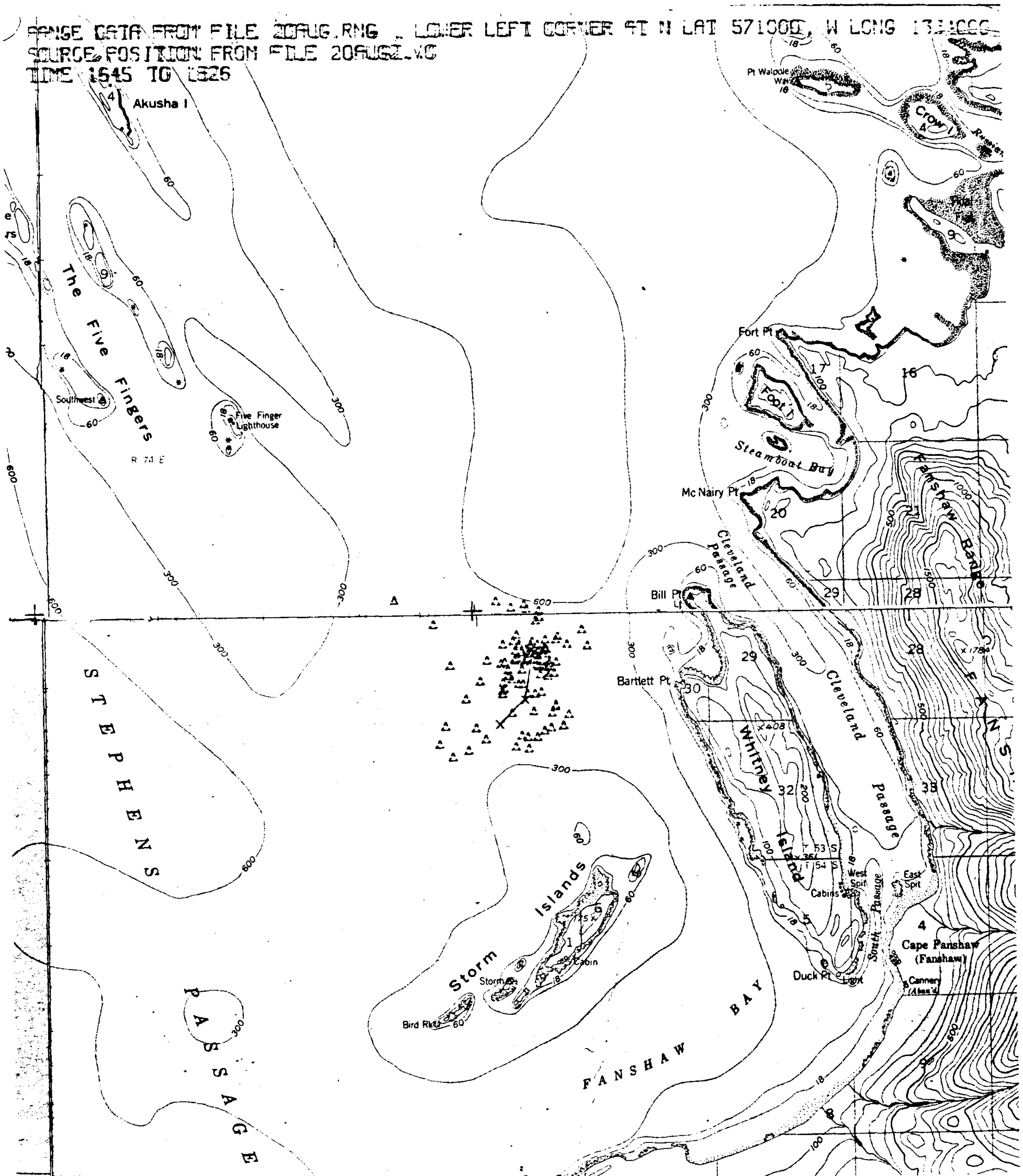
APPENDIX B: SIGHTING POSITION PLOTS

This appendix contains computer-implemented plots of whale sighting positions and sound source vessel positions during control periods (no sound emissions) and during experimental stimulus presentation. These figures have been previously discussed in Sec. 6.

To assist the reader in interpreting the figures, coded symbols have been used to designate the source and whale sighting locations. The symbol for a whale sighting represents either a single whale or a closely-spaced group of whales. For the stimulus periods the whale sightings have been coded to distinguish sightings in successive 15-min. intervals after the start of the stimulus. The track of the source vessel has also been segmented into 15-min. sections if the source was in motion during stimulus presentation. This was done to show the relationships between the source location and the whale positions as a function of time after the start of the stimulus. Source movement direction is indicated by an arrow.

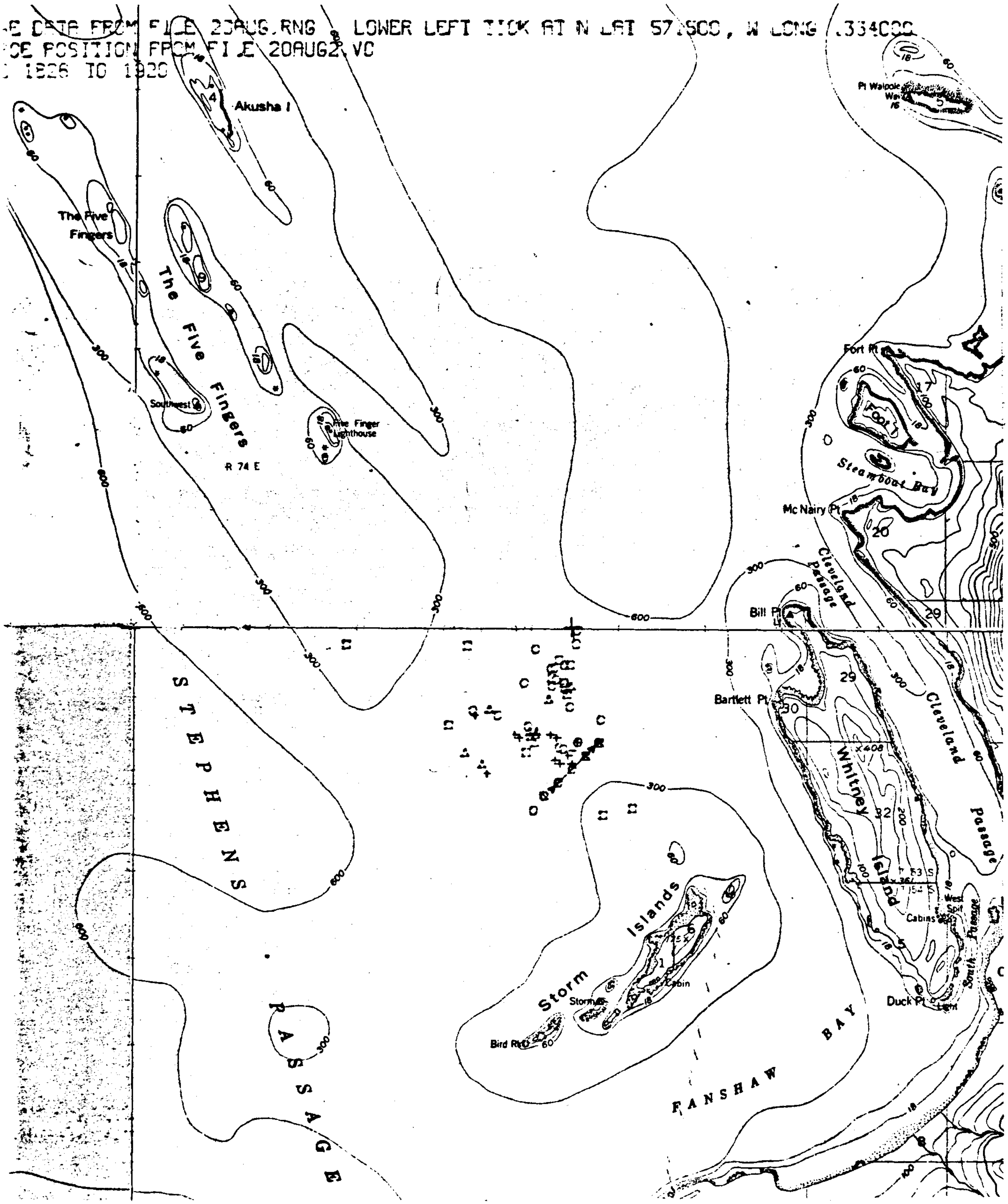
The plots show all whale sightings used in the analysis out to a maximum range of about 5 km. Maximum accuracy in the sighting locations was achieved within a range of 1 km where errors of less than 100 m were estimated, based on the results presented in Appendix D. The findings of this report depend primarily on the data obtained within 1 km of the source. The average error beyond 1 km is estimated to scale proportionally with range.

Table 4.1 in Sec. 4 provides a summary of dates and time periods for control and experimental conditions. The computer header on each plot provides the applicable date, time and location information for the data shown.



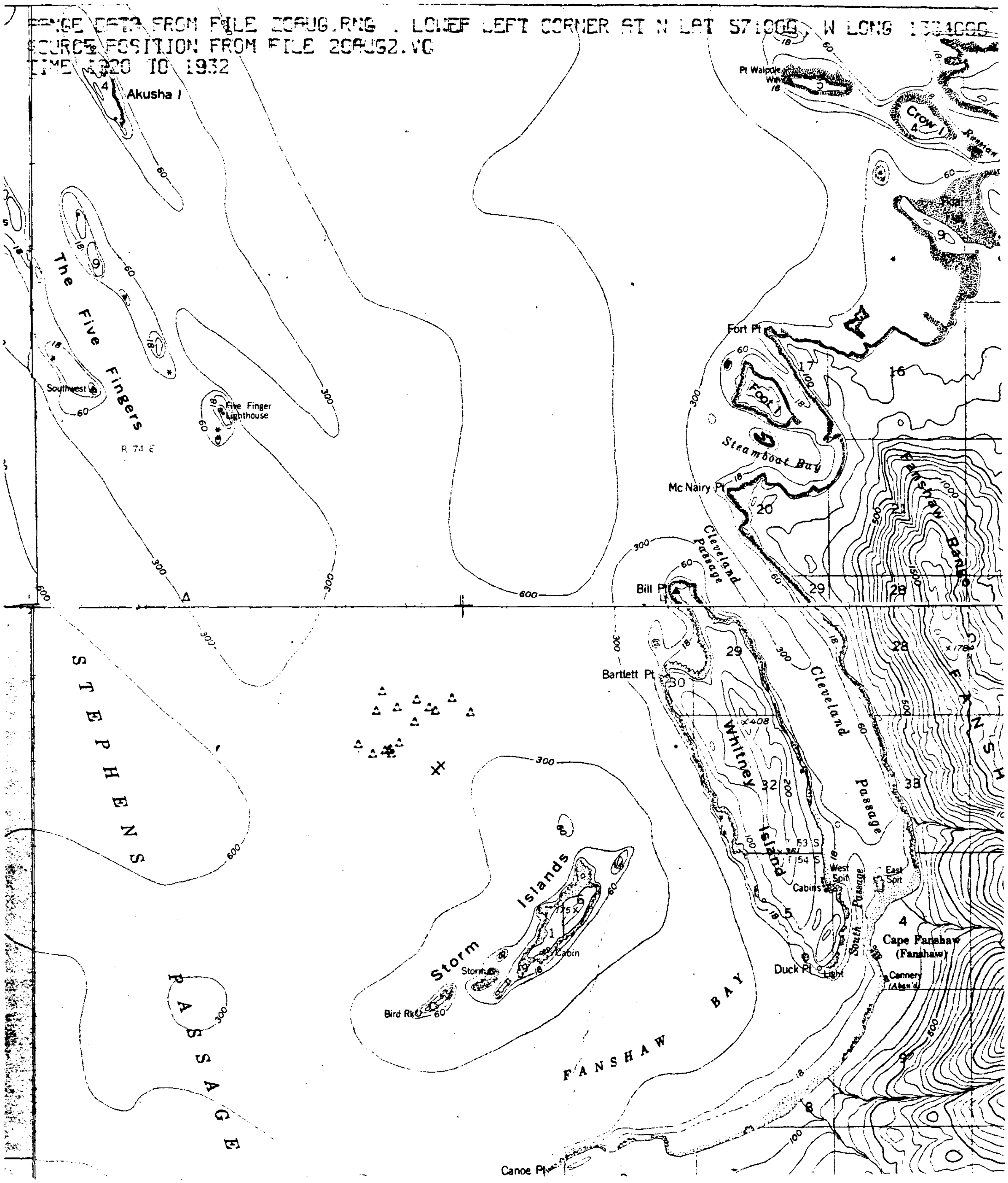
Legend: Δ = whale position x = source vessel position

FIG. B.1.a. SIGHTING POSITION DATA: DRILLSHIP PRE-TEST CONTROL PERIOD (20 AUGUST 1984).



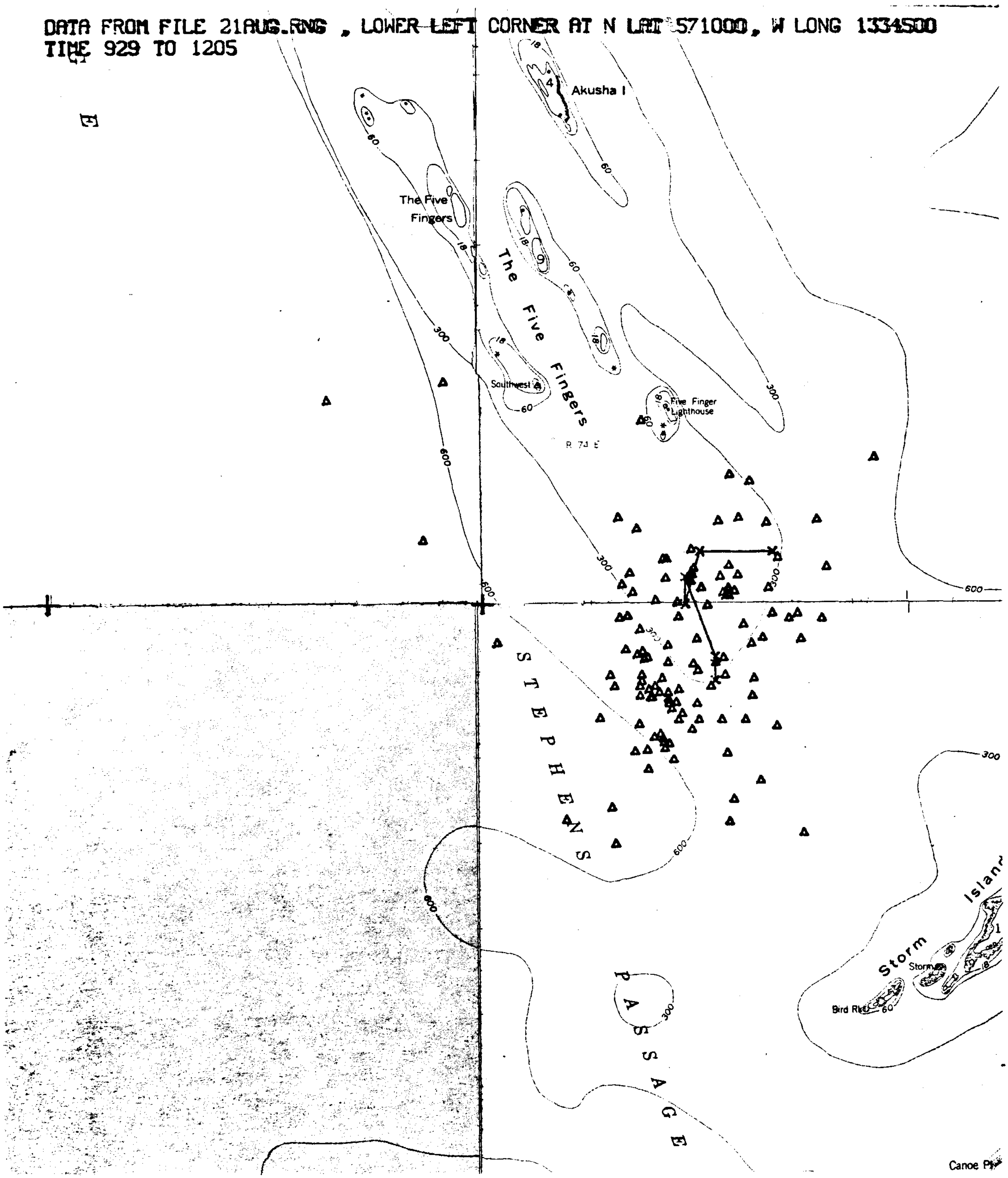
Whale Position	Source Vessel Position
Interval (min) 0-15-30-45-end	
Sighting code □ ○ △ +	⊞

FIG. B.1.b. SIGHTING POSITION DATA: DRILLSHIP PLAYBACK (20 AUGUST 1984)



Legend: Δ = whale position x = source vessel position

FIG. B.1.c. SIGHTING POSITION DATA: DRILLSHIP POST-TEST CONTROL PERIOD (20 AUGUST 1984).



Legend: Δ = whale position x = source vessel position

FIG. B.2.a. SIGHTING POSITION DATA: DRILLING PLATFORM PRE-TEST CONTROL PERIOD (21 AUGUST 1984).

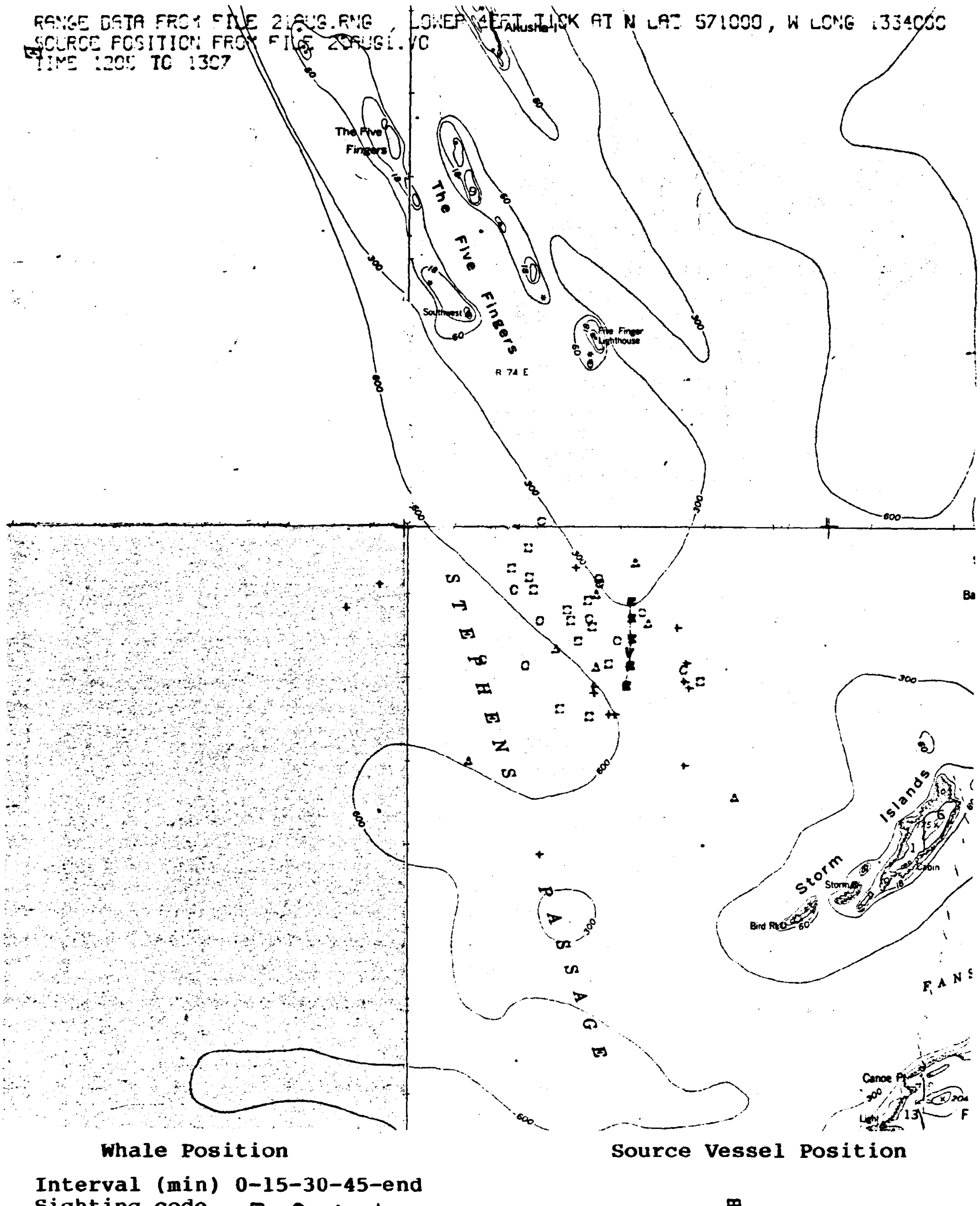
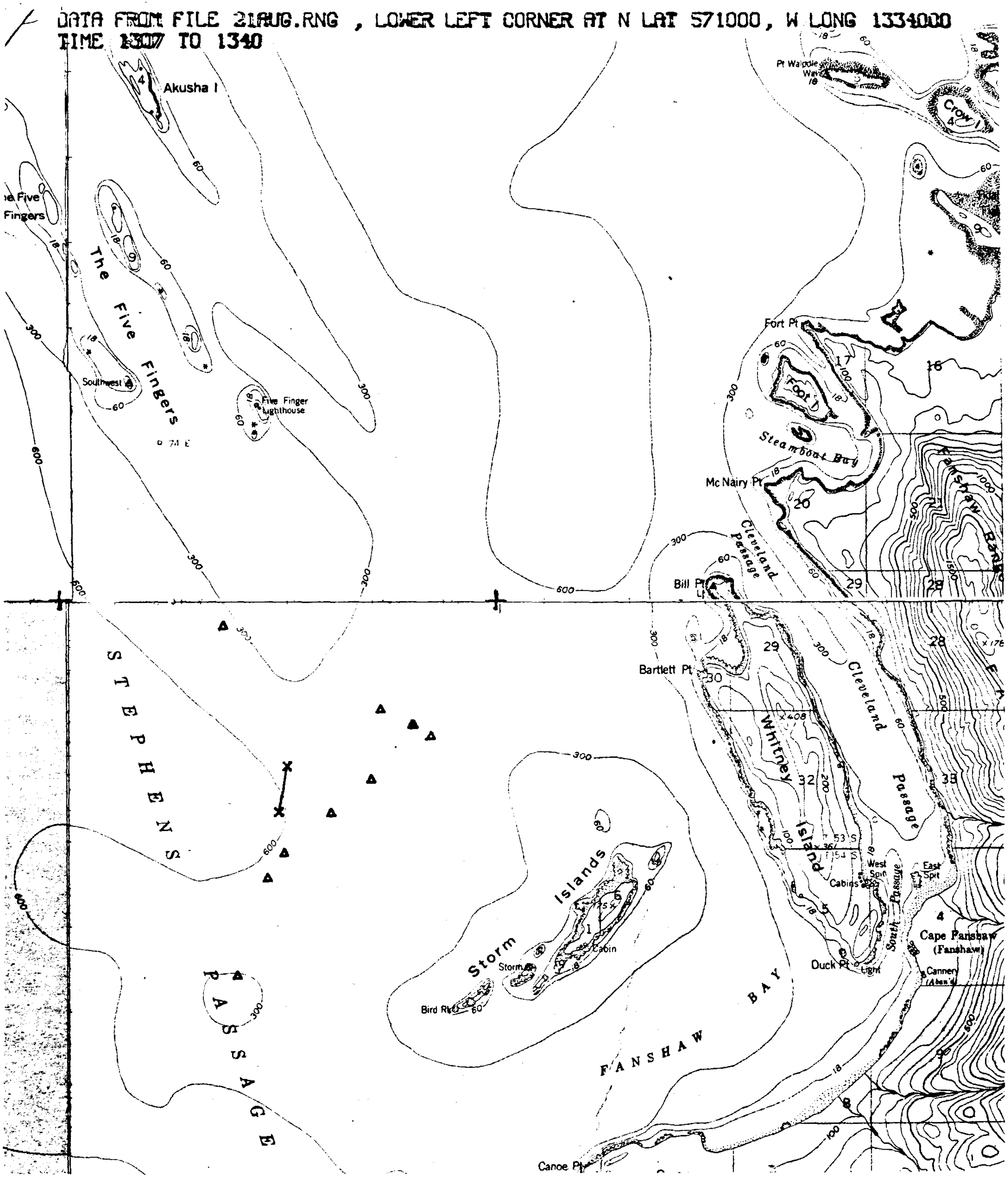
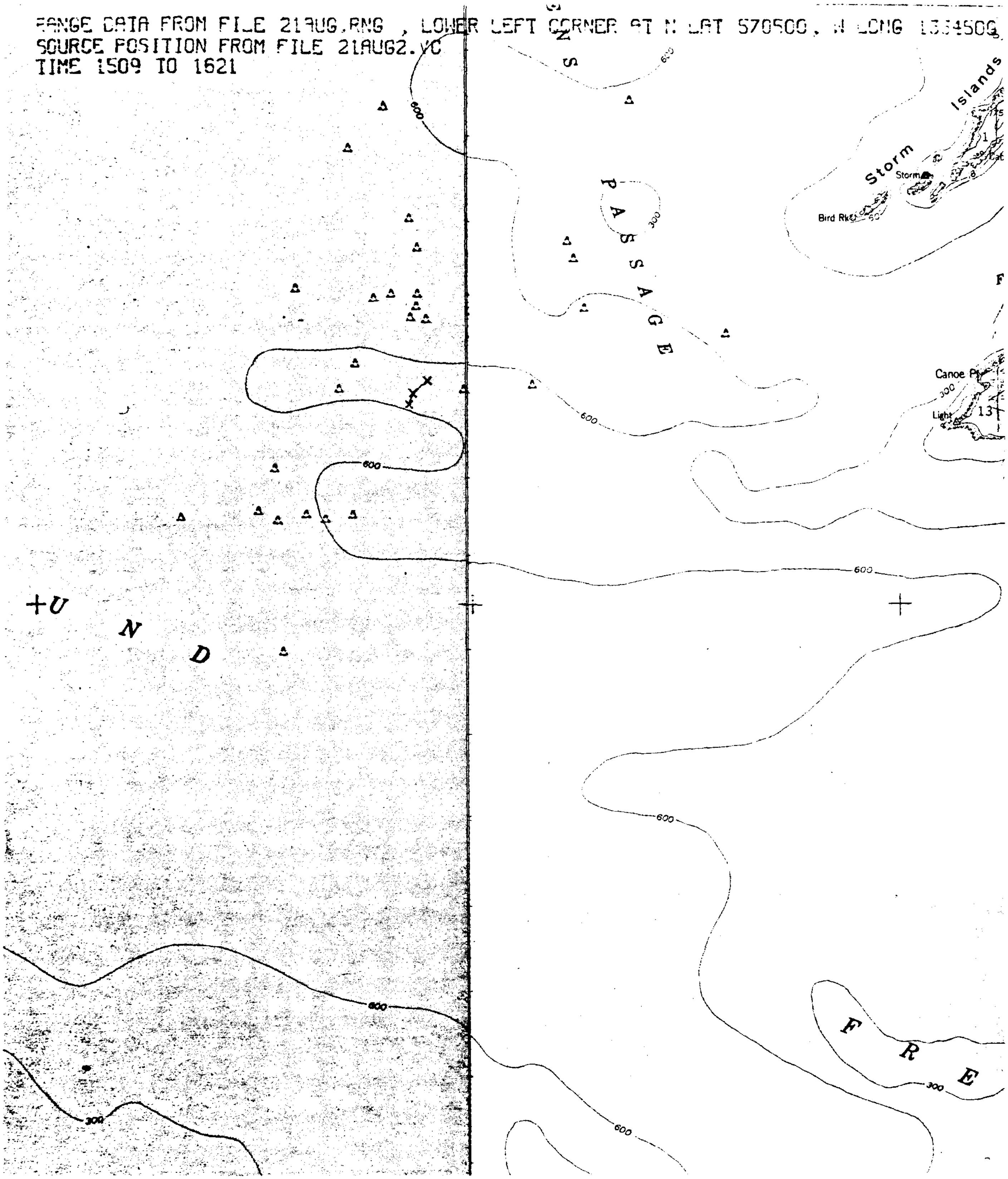


FIG. B.2.b. SIGHTING POSITION DATA: DRILLING PLATFORM PLAYBACK (21 AUGUST 1984).



Legend: Δ = whale position x = source vessel position

FIG. B.2.c. SIGHTING POSITION DATA: DRILLING PLATFORM POST-TEST CONTROL PERIOD (21 AUGUST 1984).



Legend: ▲ = whale position x = source vessel position

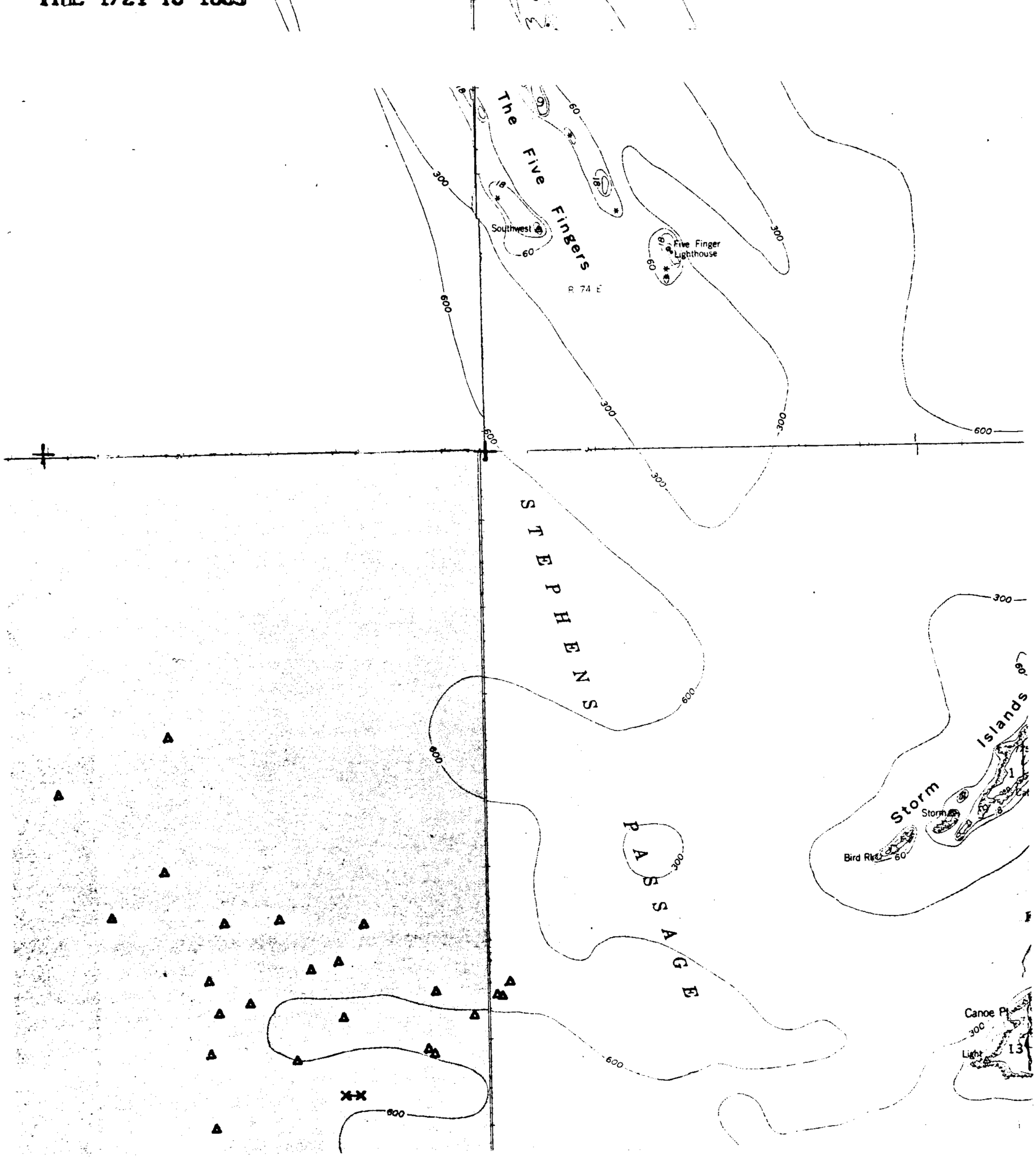
FIG. B.3.a. SIGHTING POSITION DATA: HELICOPTER PRE-TEST CONTROL PERIOD (21 AUGUST 1984).

Whale Position Source Vessel Position

Interval (min) 0-15-30-45-end
Sighting code □ ○ △ + ⊞

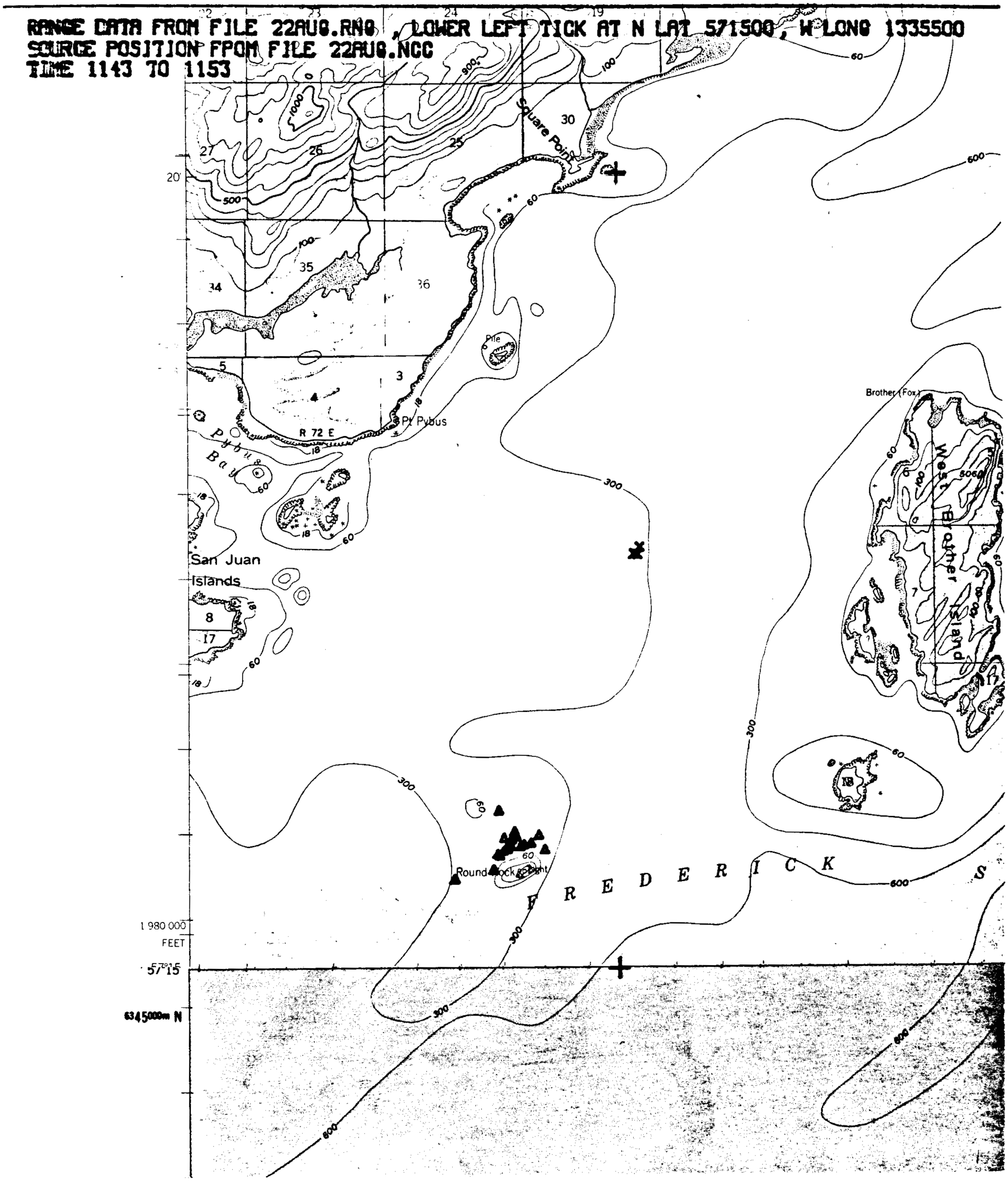
FIG. B.3.b. SIGHTING POSITION DATA: HELICOPTER PLAYBACK (21 AUGUST 1984).

DATA FROM FILE 21AUG.RNG , LOWER LEFT CORNER AT N LAT 571000, W LONG 1334500
TIME 1724 TO 1809



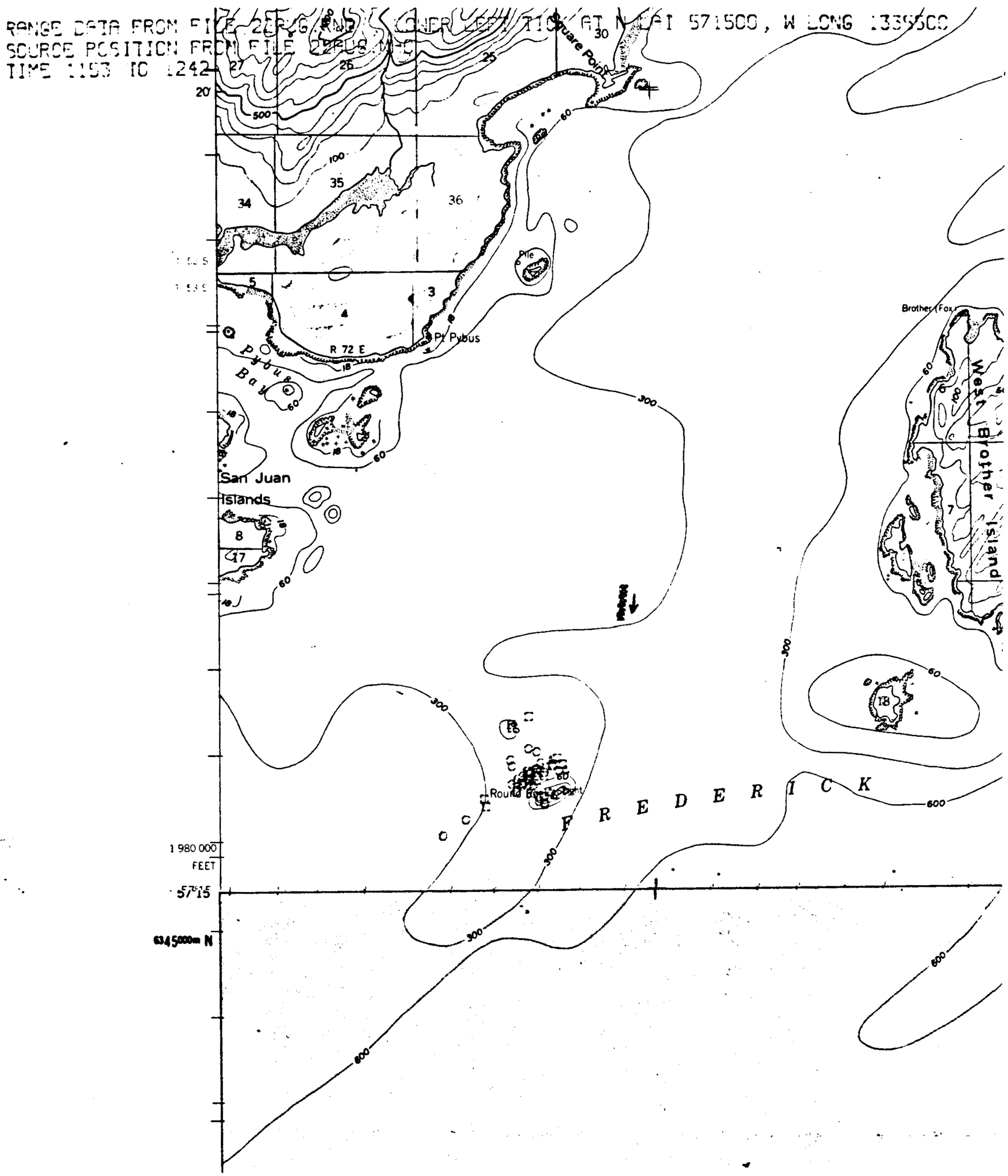
Legend: ▲ = whale position x = source vessel position

FIG. B.3.c. SIGHTING POSITION DATA: HELICOPTER POST-TEST CONTROL PERIOD (21 AUGUST 1984).



Legend: Δ = whale position x = source vessel position

FIG. B.4.a. SIGHTING POSITION DATA: AIR GUN #1 PRE-TEST CONTROL PERIOD (22 AUGUST 1984).



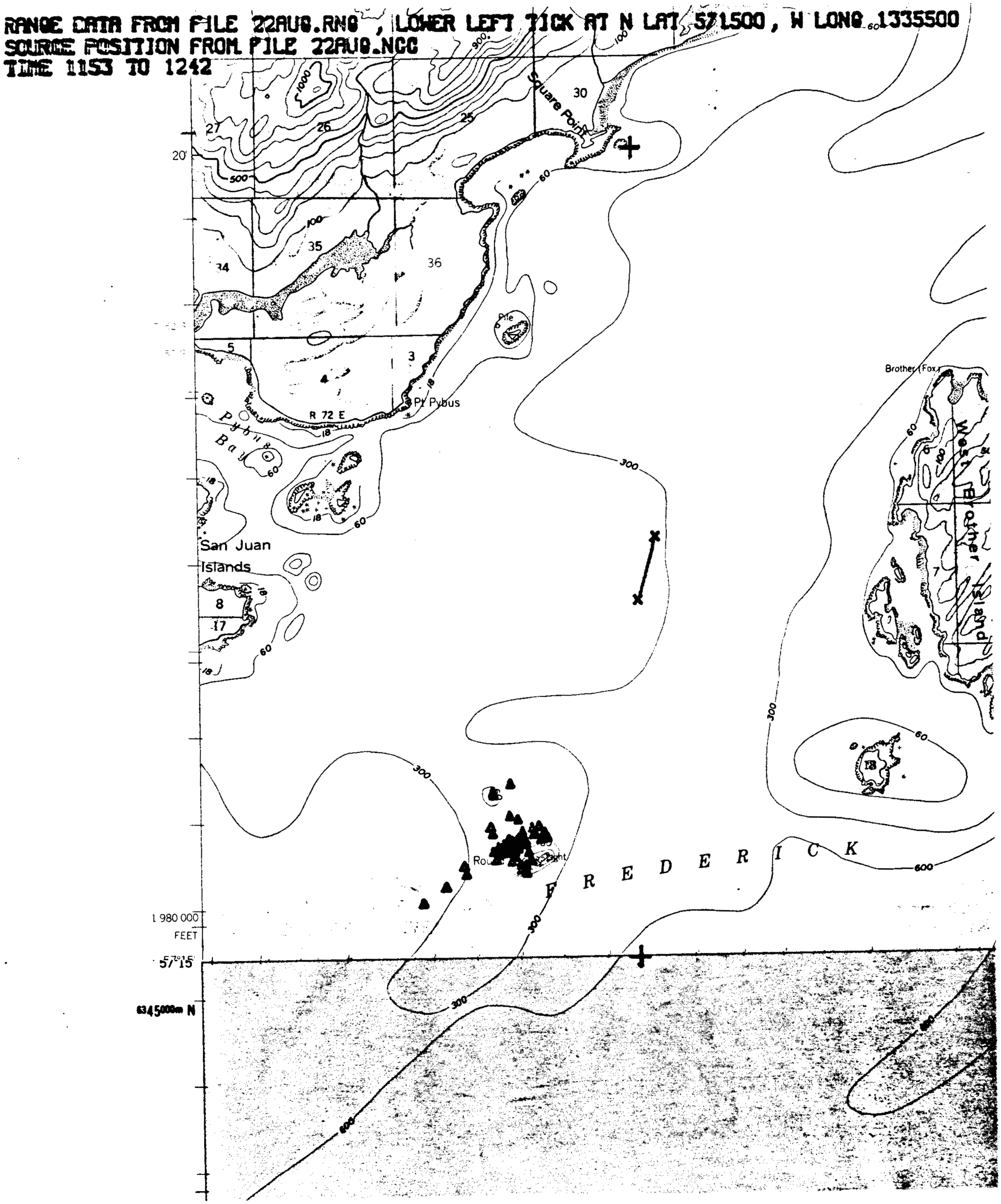
Whale Position

Source Vessel Position

Interval (min) 0-15-30-end

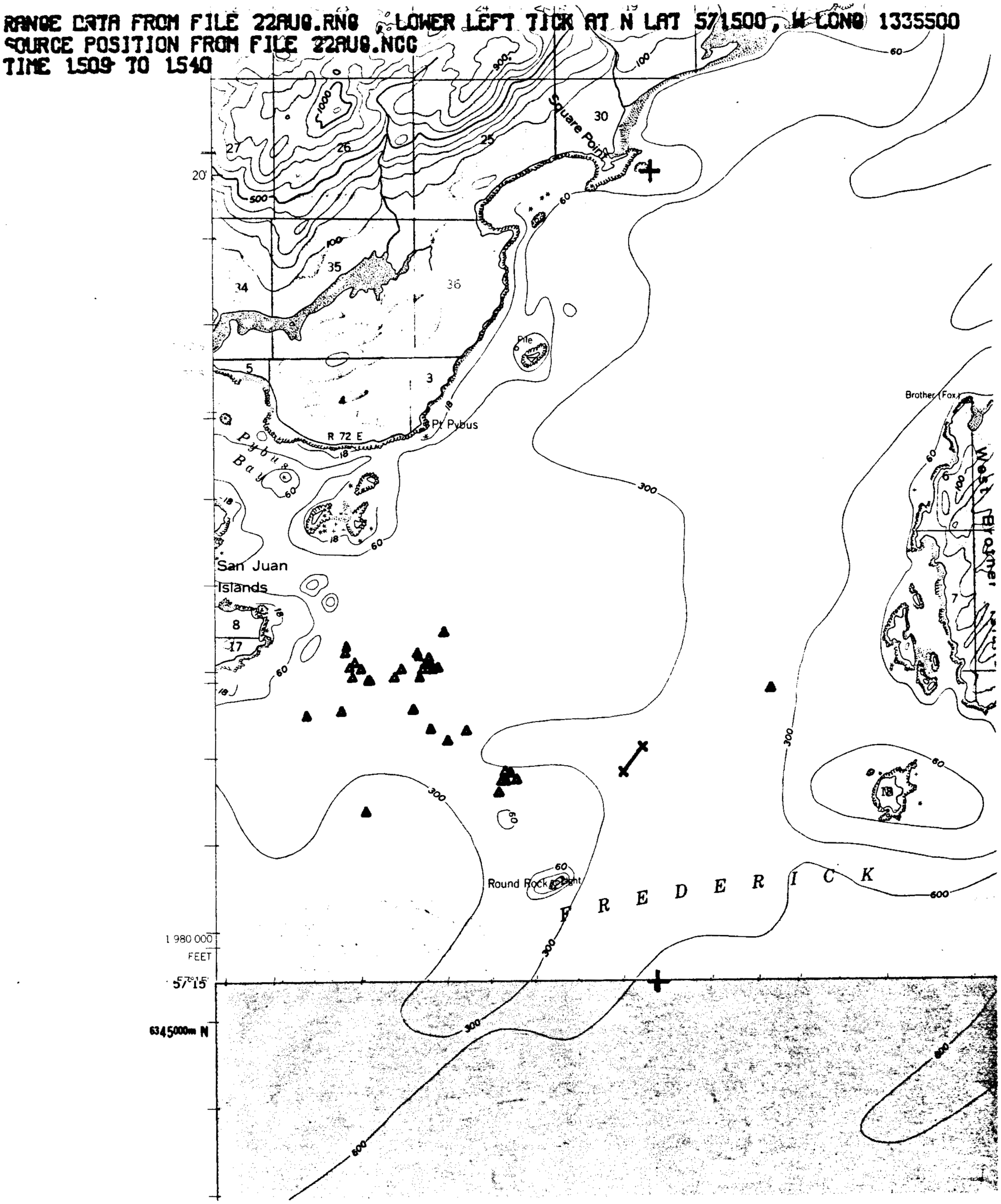
Sighting code □ ○ △ ⊞

FIG. B.4.b. SIGHTING POSITION DATA: AIR GUN #1 OPERATION (22 AUGUST 1984).



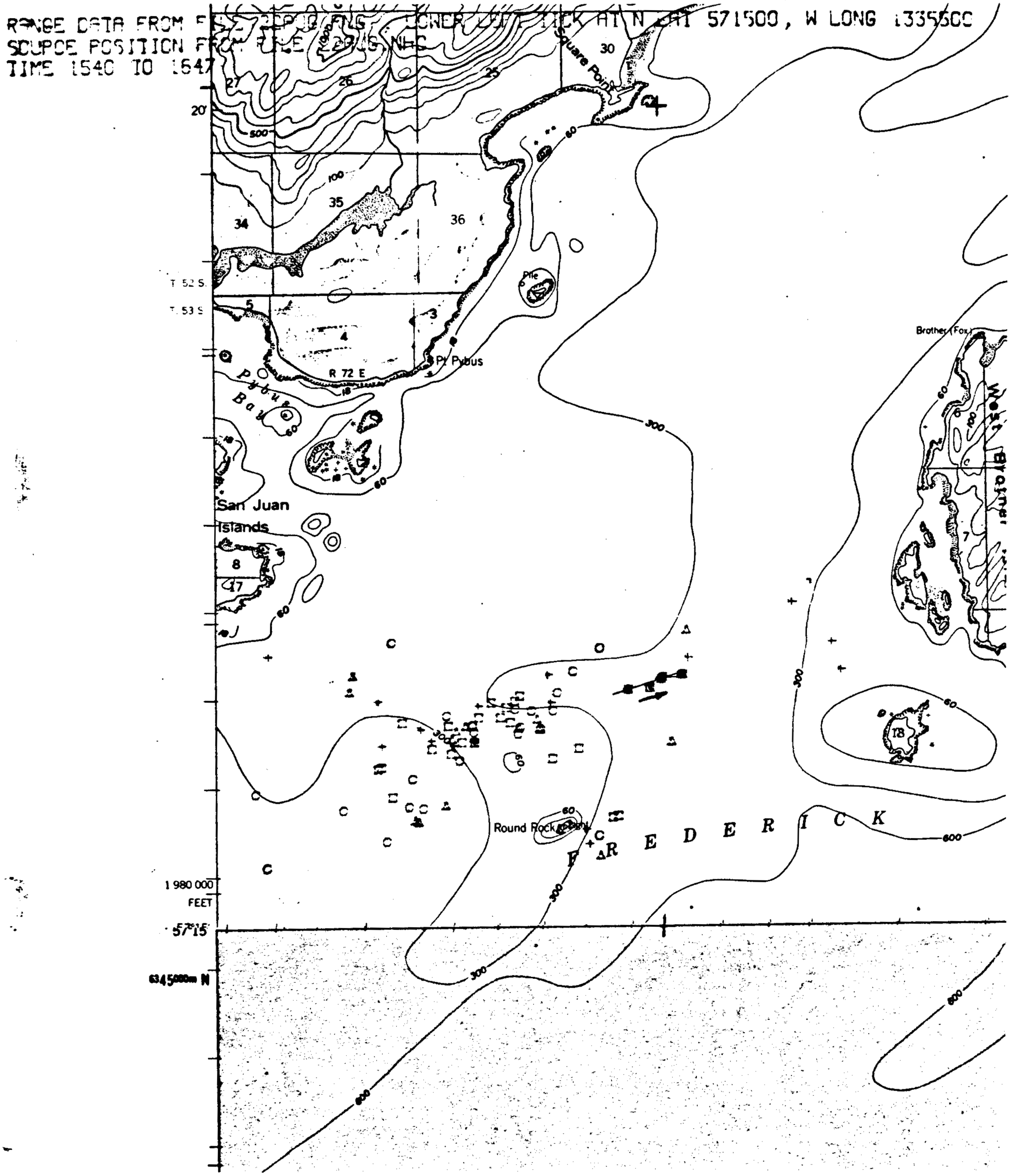
Legend: ▲ = whale position x = source vessel position

FIG. B.4.c. SIGHTING POSITION DATA: AIR GUN #1 POST-TEST CONTROL PERIOD (22 AUGUST 1984).



Legend: ▲ = whale position x = source vessel position

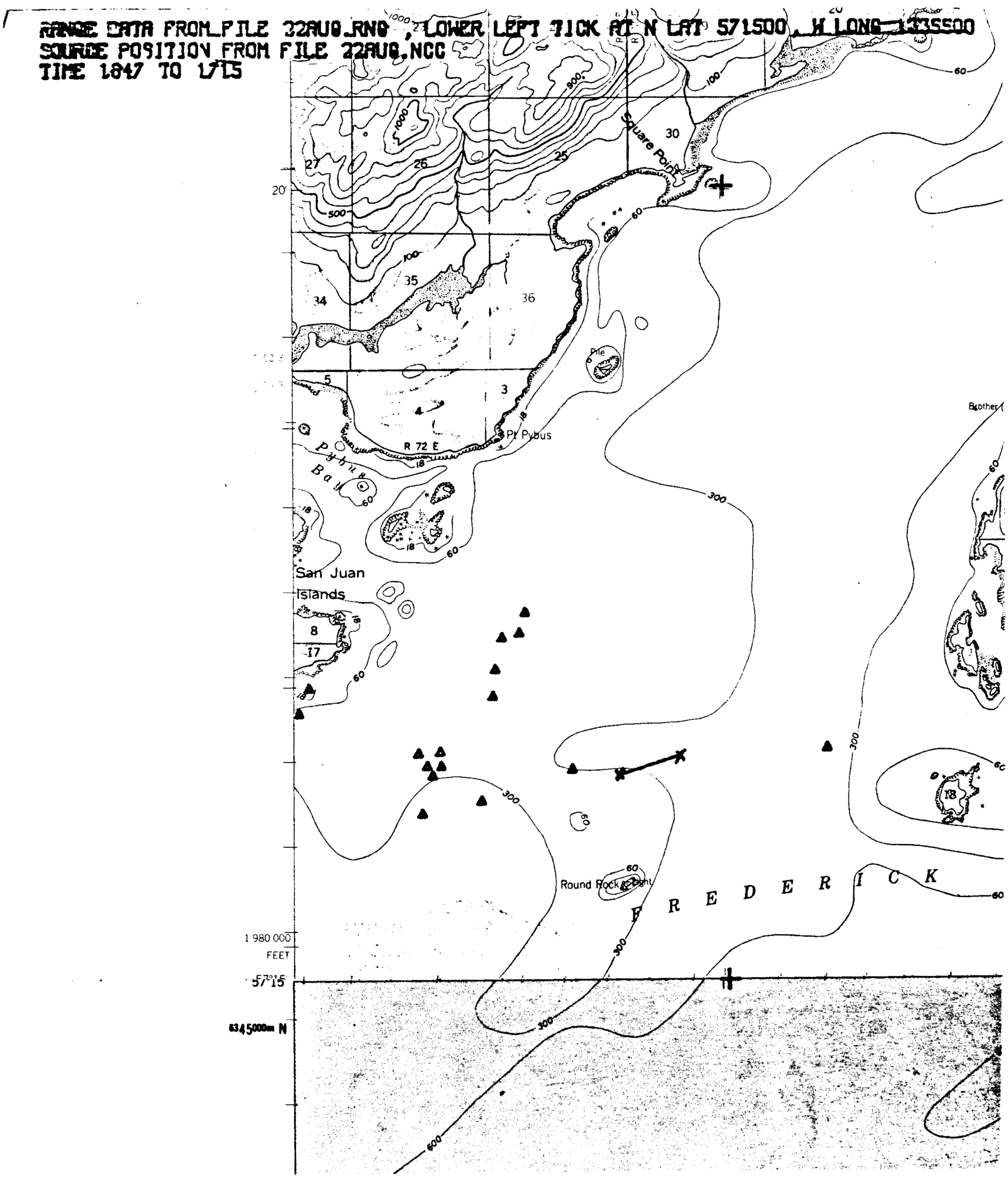
FIG. B.5.a. SIGHTING POSITION DATA: AIR GUN #2 PRE-TEST CONTROL PERIOD (22 AUGUST 1984).



Whale Position **Source Vessel Position**

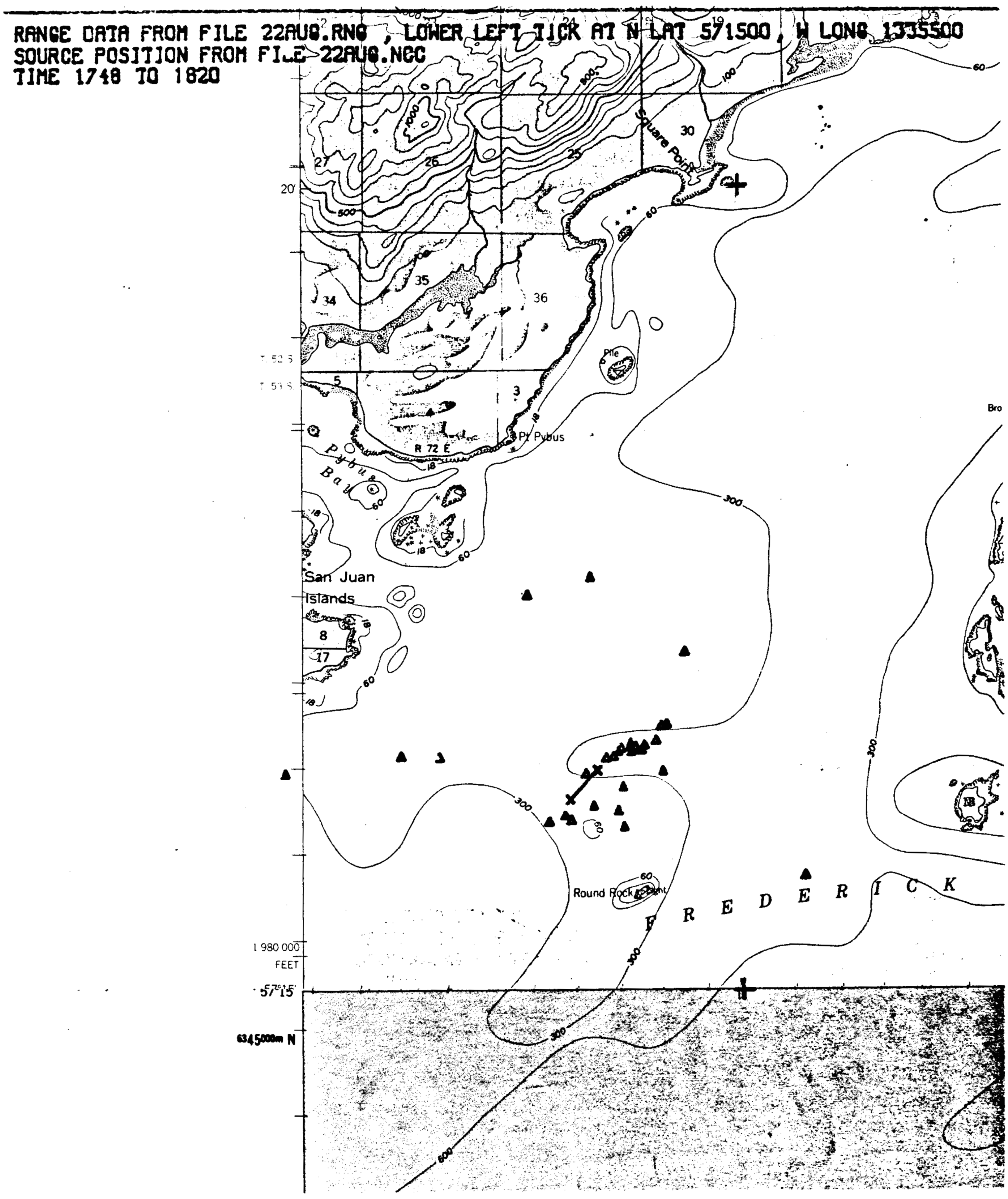
Interval (min) 0-15-30-45-end
Sighting code □ ○ △ + ⊞

FIG. B.5.b. SIGHTING POSITION DATA: AIR GUN #2 OPERATION (22 AUGUST 1984).



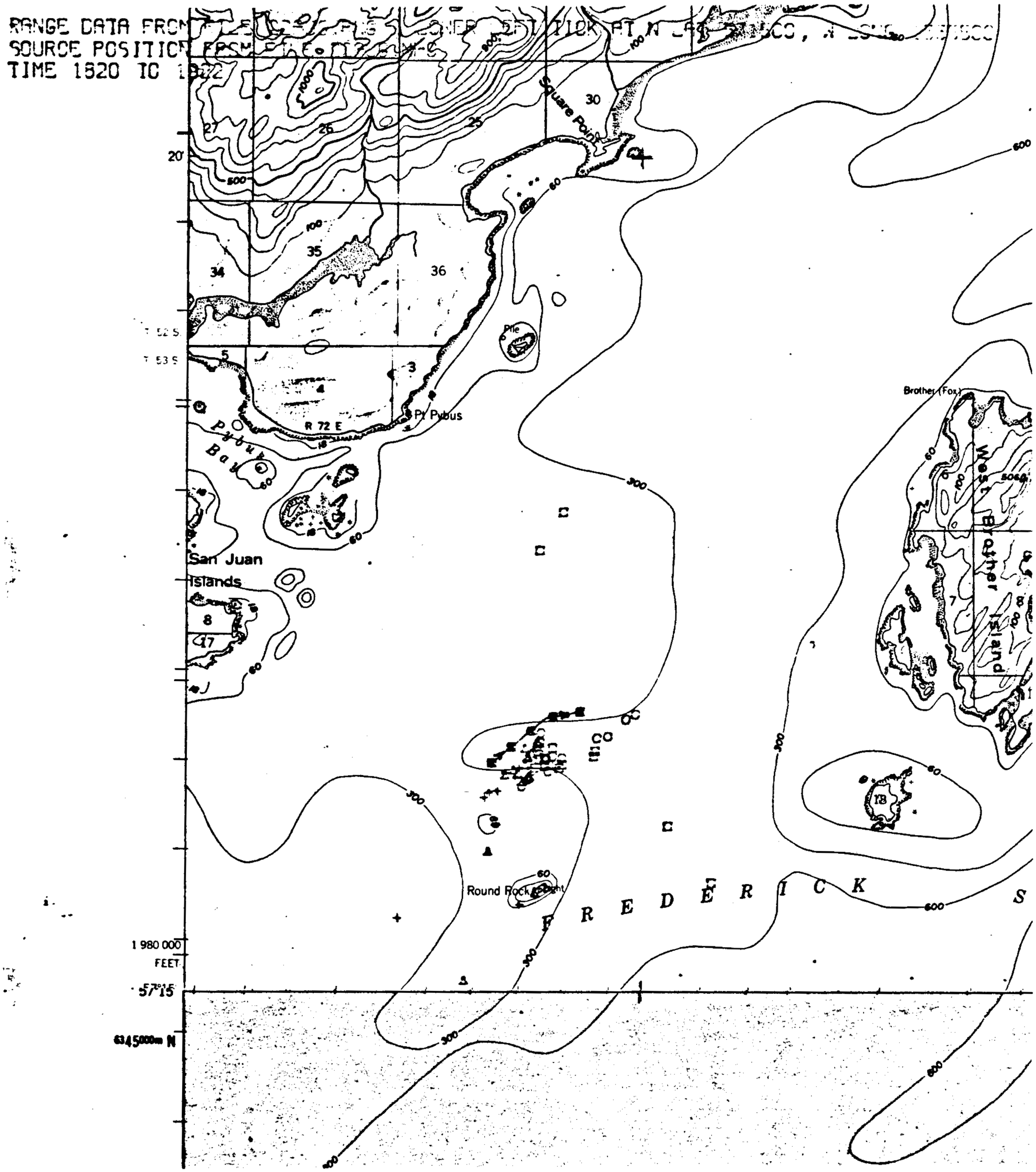
Legend: Δ = whale position x = source vessel position

FIG. B.5.c. SIGHTING POSITION DATA: AIR GUN #2 POST-TEST CONTROL PERIOD (22 AUGUST 1984).



Legend: ▲ = whale position x = source vessel position

FIG. B.6.a. SIGHTING POSITION DATA: AIR GUN #3 PRE-TEST CONTROL PERIOD (22 AUGUST 1984).

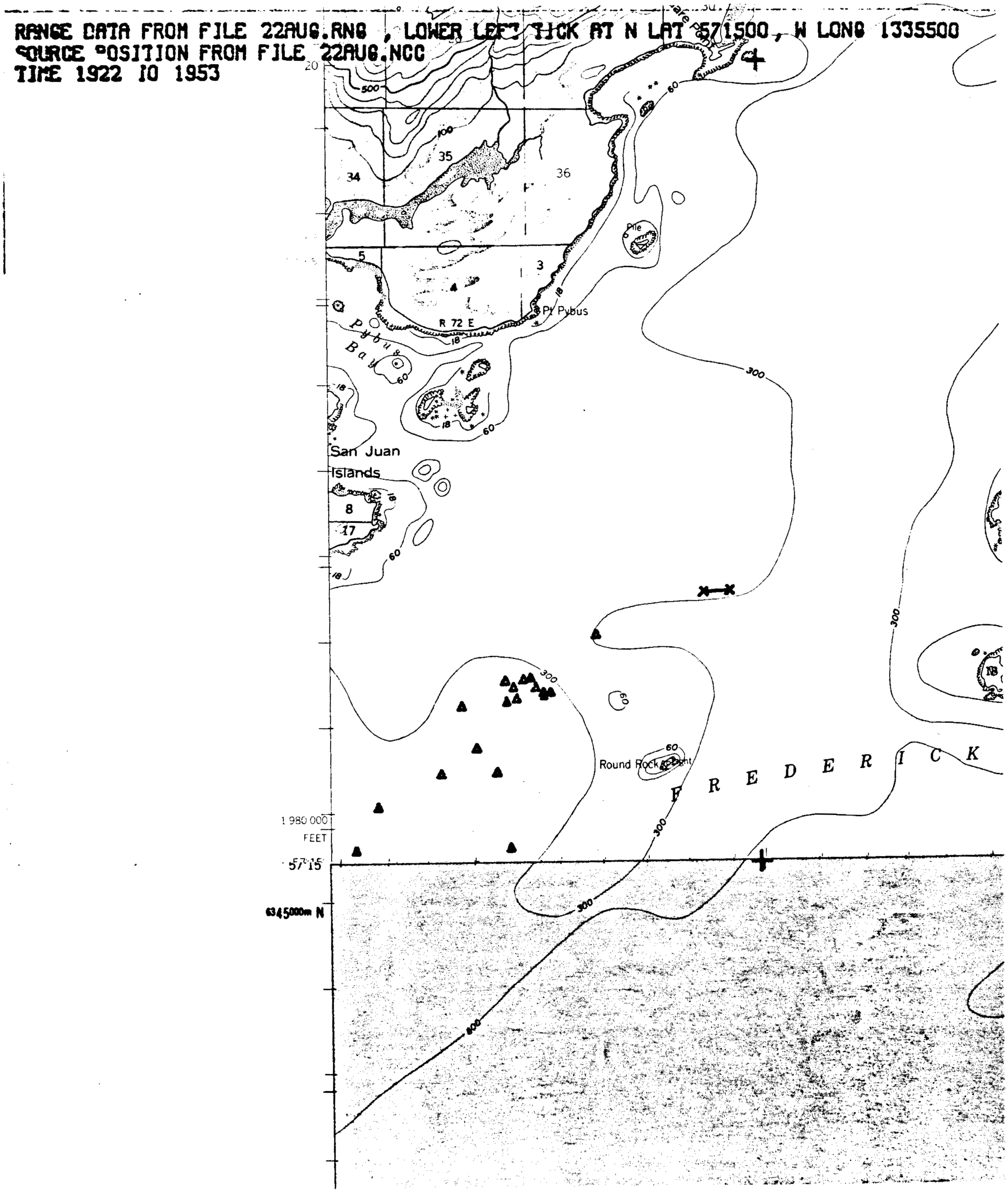


Whale Position **Source Vessel Position**

Interval (min) 0-15-30-45-end
Sighting code □ ○ △ + ⊞

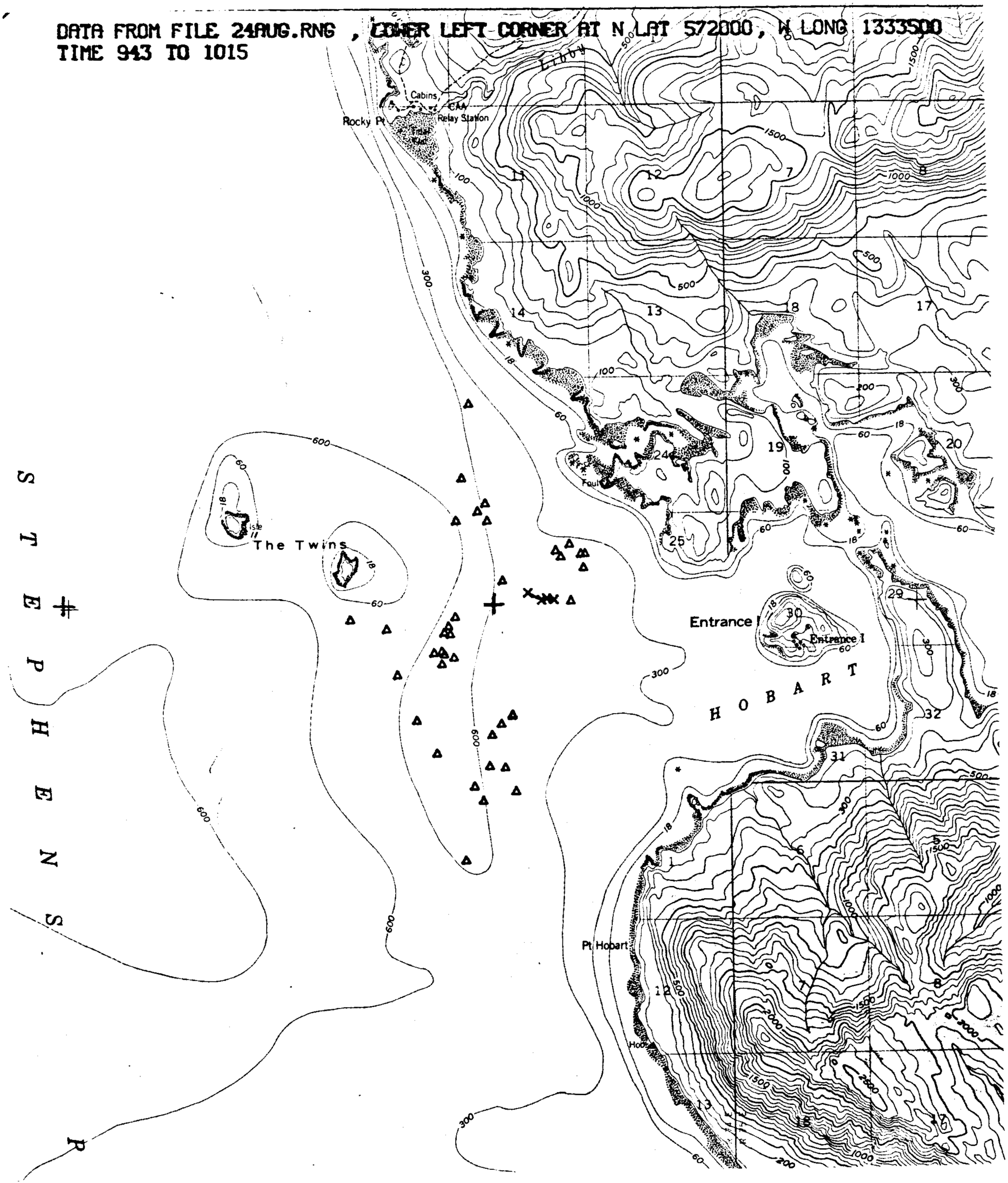
FIG. B.6.b. SIGHTING POSITION DATA: AIR GUN #3 OPERATION (22 AUGUST 1984).

RANGE DATA FROM FILE 22AUG.RNG , LOWER LEFT TICK AT N LAT 571500, W LONG 1335500
SOURCE POSITION FROM FILE 22AUG.NCC
TIME 1922 TO 1953



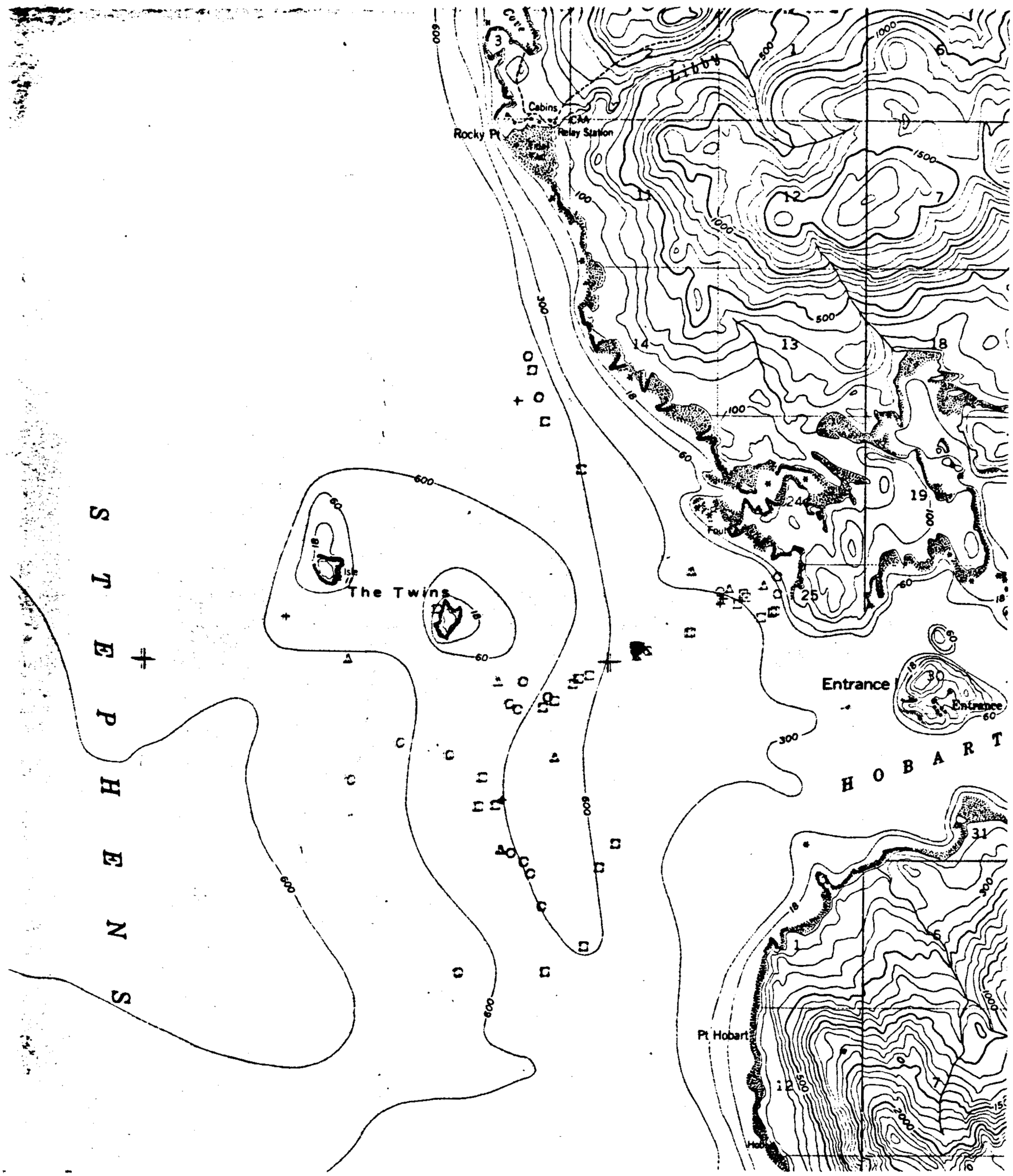
Legend: ▲ = whale position x = source vessel position

FIG. B.6.c. SIGHTING POSITION DATA: AIR GUN #3 POST-TEST CONTROL PERIOD (22 AUGUST 1984).



Legend: Δ = whale position x = source vessel position

FIG. B.7.a. SIGHTING POSITION DATA: AIR GUN #4 PRE-TEST CONTROL PERIOD (24 AUGUST 1984).

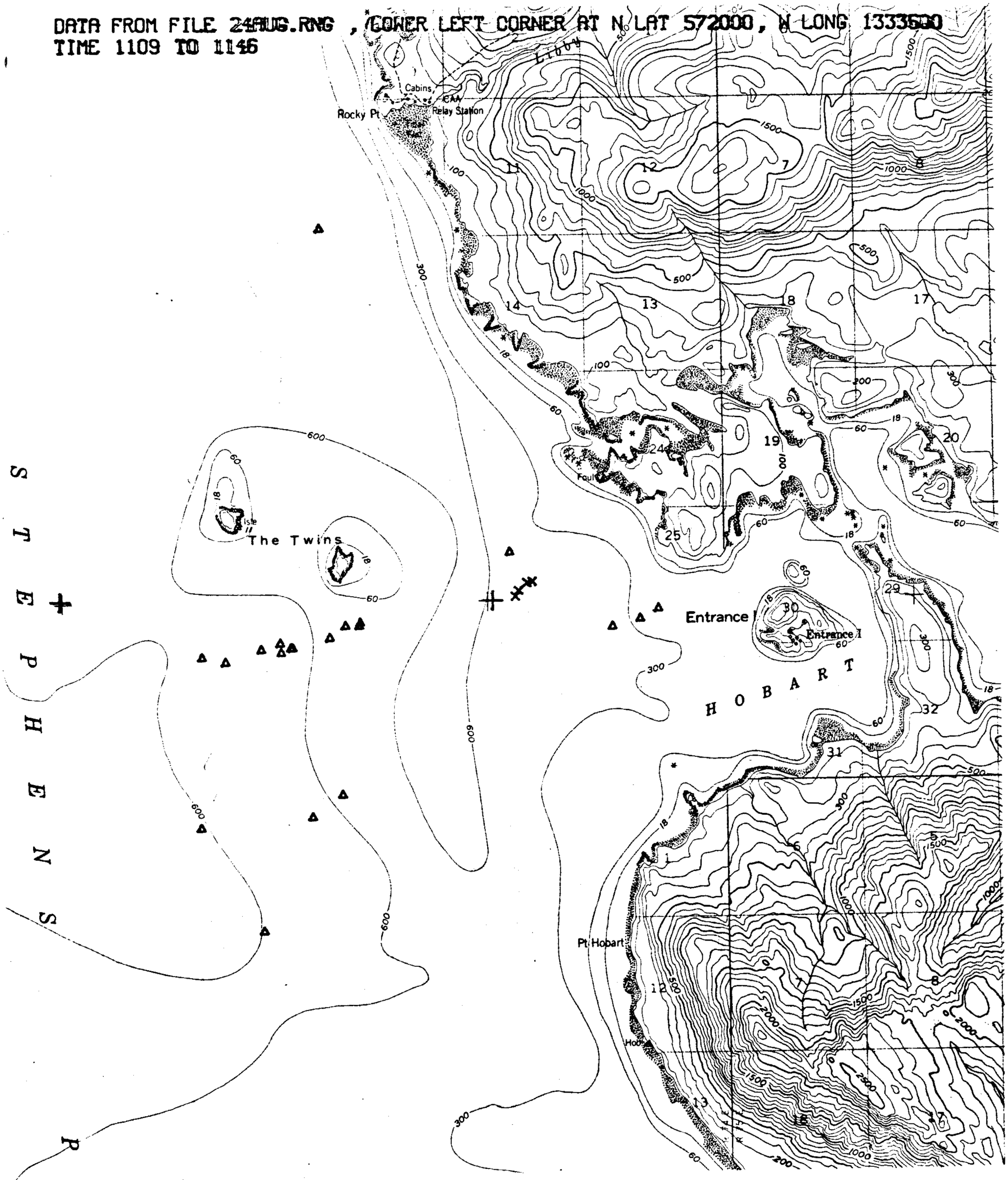


Whale Position **Source Vessel Position**

Interval (min) 0-15-30-45-end
Sighting code □ ○ △ + ⊞

FIG. B.7.b. SIGHTING POSITION DATA: AIR GUN #4 OPERATION (24 AUGUST 1984).

DATA FROM FILE 24AUG.RNG , LOWER LEFT CORNER AT N LAT 572000, W LONG 1333600
TIME 1109 TO 1146

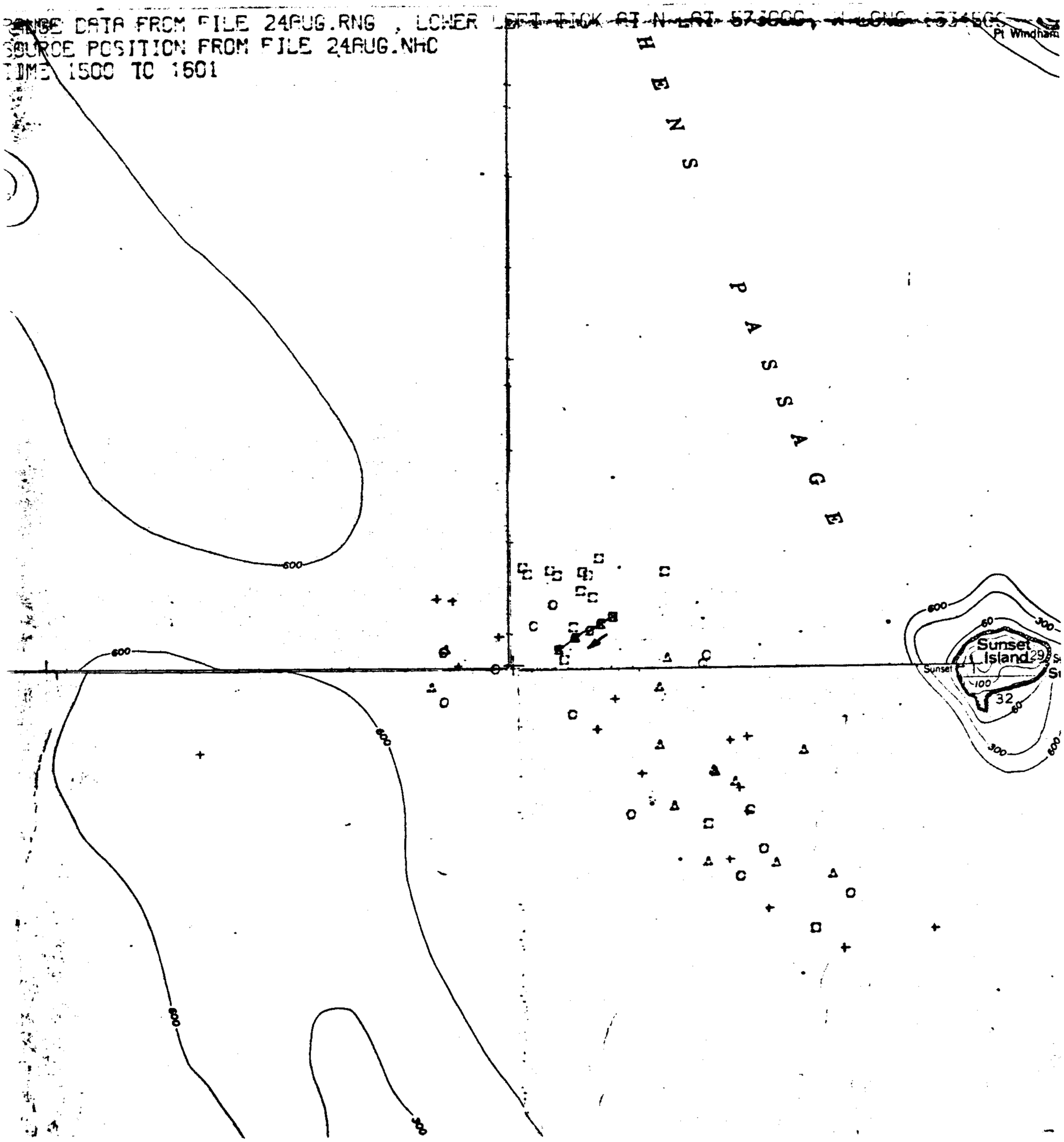


Legend: Δ = whale position x = source vessel position

FIG. B.7.c. SIGHTING POSITION DATA: AIR GUN #4 POST-TEST CONTROL PERIOD (24 AUGUST 1984).

Legend: Δ = whale position x = source vessel position

FIG. B.8.a. SIGHTING POSITION DATA: AIR GUN #5 PRE-TEST CONTROL PERIOD (24 AUGUST 1984).



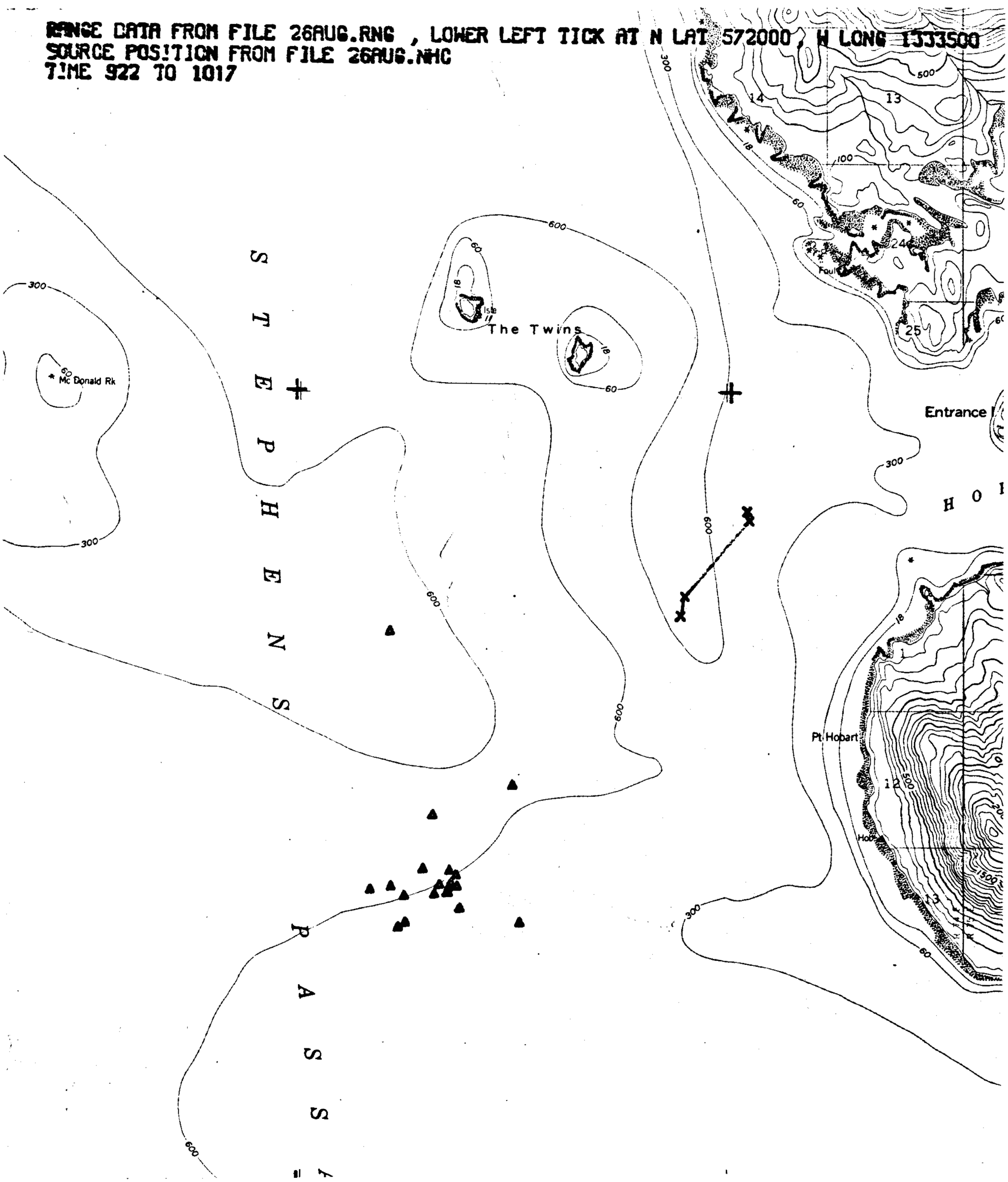
Whale Position **Source Vessel Position**

Interval (min) 0-15-30-45-end
Sighting code □ O △ + ⊞

FIG. B.8.b. SIGHTING POSITION DATA: AIR GUN #5 OPERATION (24 AUGUST 1984).

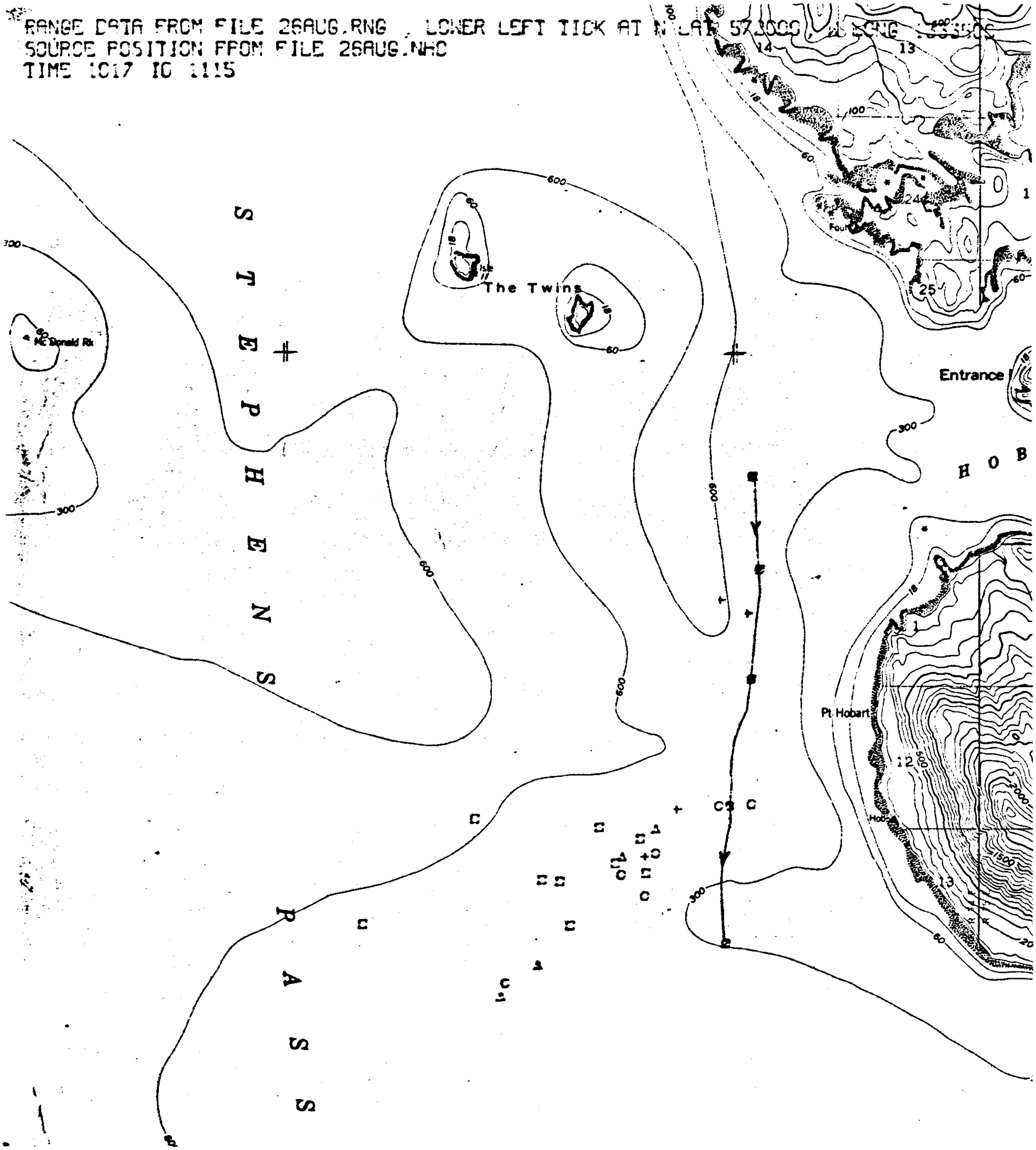
Legend: ▲ = whale position x = source vessel position

FIG. B.8.c. SIGHTING POSITION DATA: AIR GUN #5 POST-TEST CONTROL PERIOD (24 AUGUST 1984).



Legend: ▲ = whale position x = source vessel position

FIG. B.9.a. SIGHTING POSITION DATA: AIR GUN #6 PRE-TEST CONTROL PERIOD (26 AUGUST 1984).

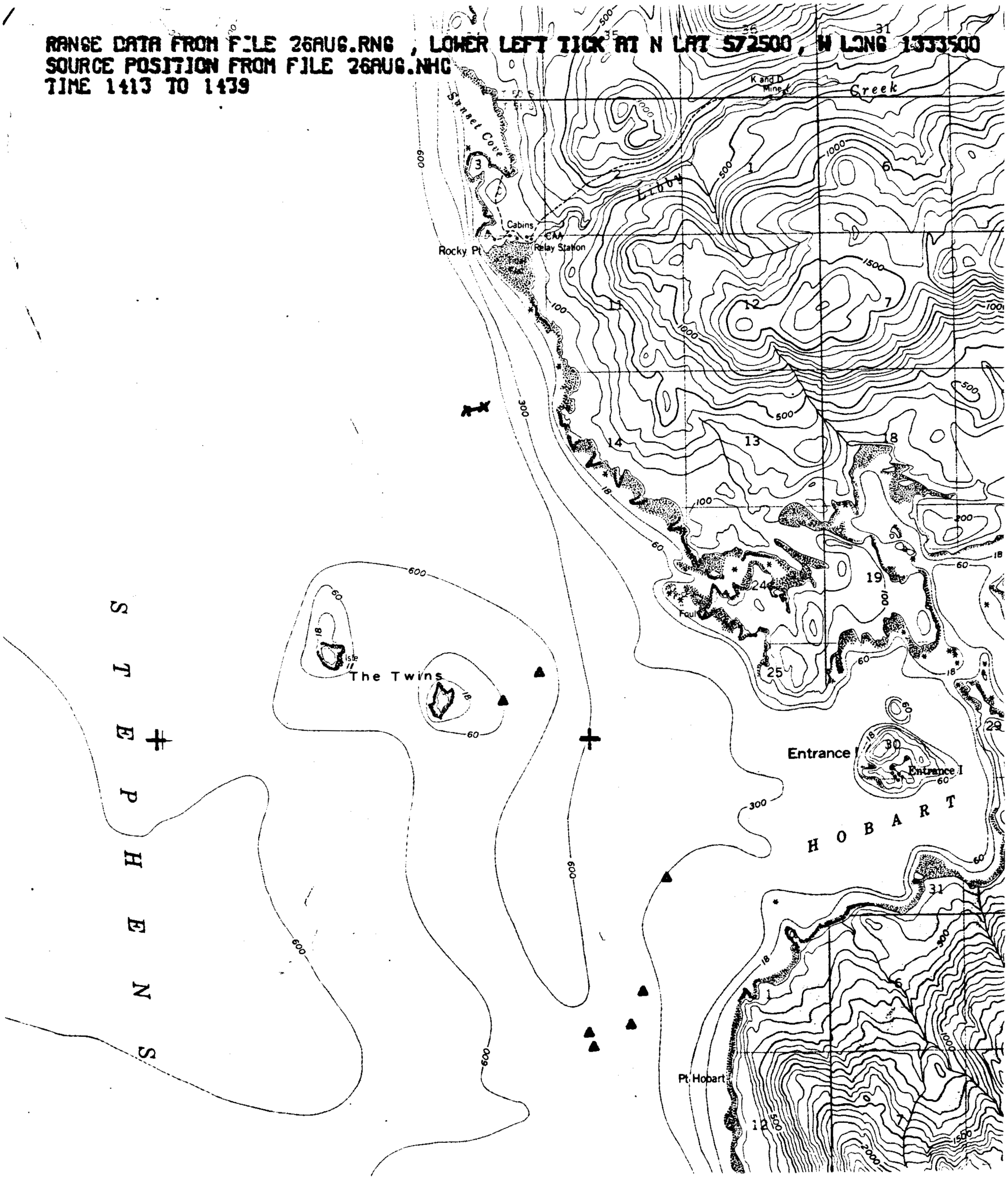


Whale Position

Source Vessel Position

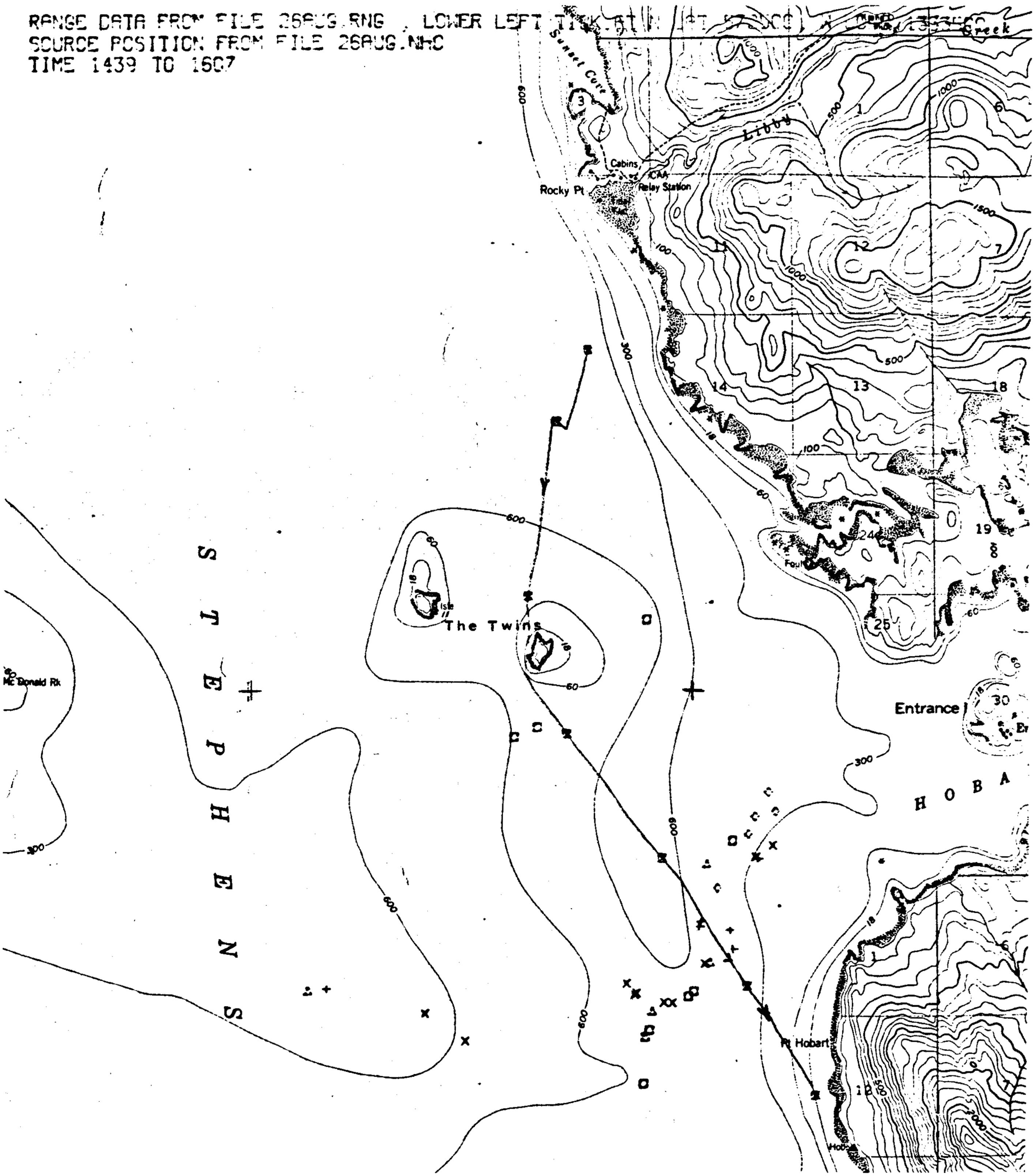
Interval (min) 0-15-30-45-end
Sighting code □ ○ △ + ⊞

FIG. B.9.b. SIGHTING POSITION DATA: AIR GUN #6 OPERATION (26 AUGUST 1984).



Legend: Δ = whale position x = source vessel position

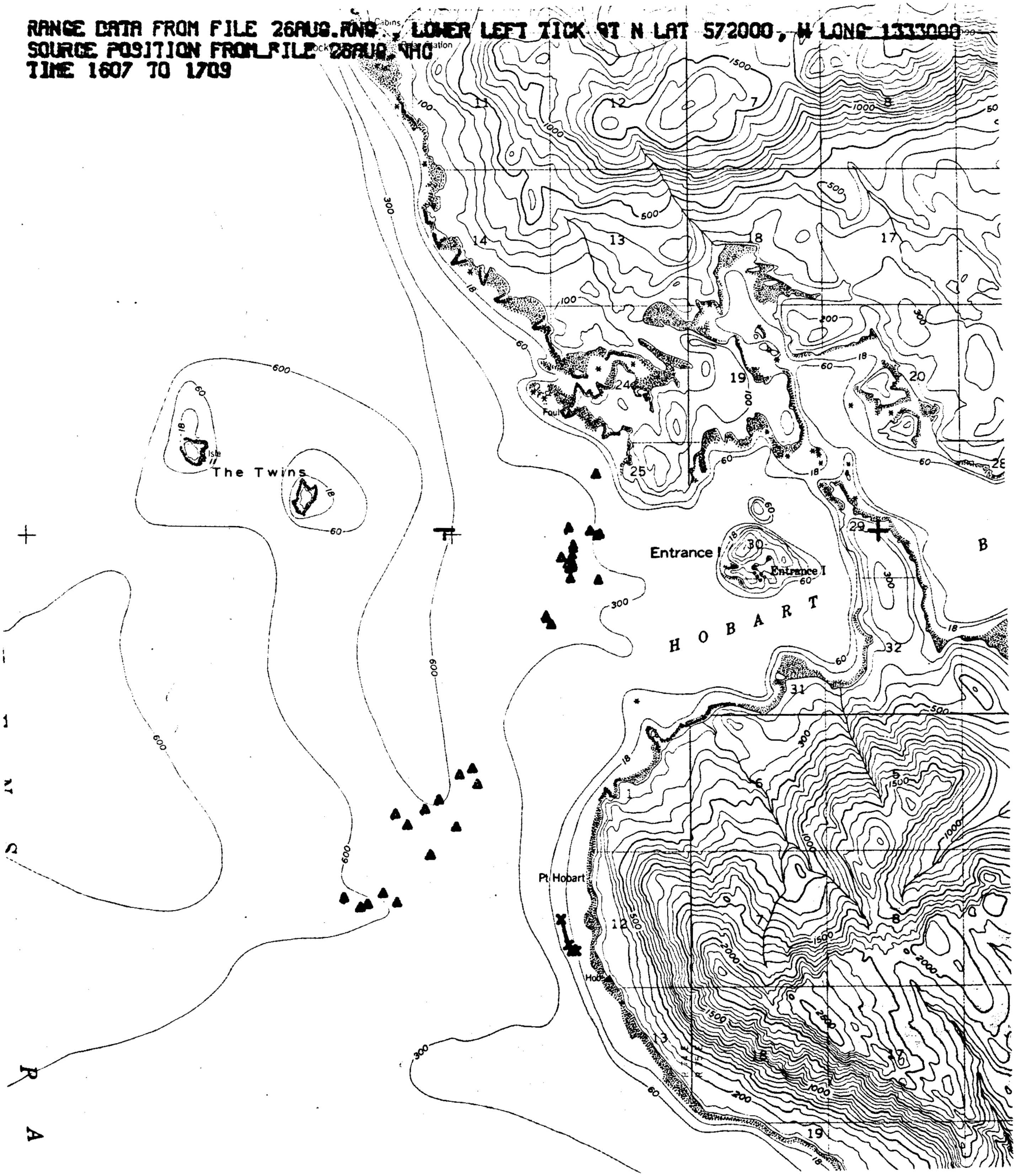
FIG. B.10.a. SIGHTING POSITION DATA: AIR GUN #7 PRE-TEST CONTROL PERIOD (26 AUGUST 1984).



Whale Position Source Vessel Position

Interval (min) 0-15-30-45-60-75-end
Sighting code □ ○ △ + × ◇ ⊞

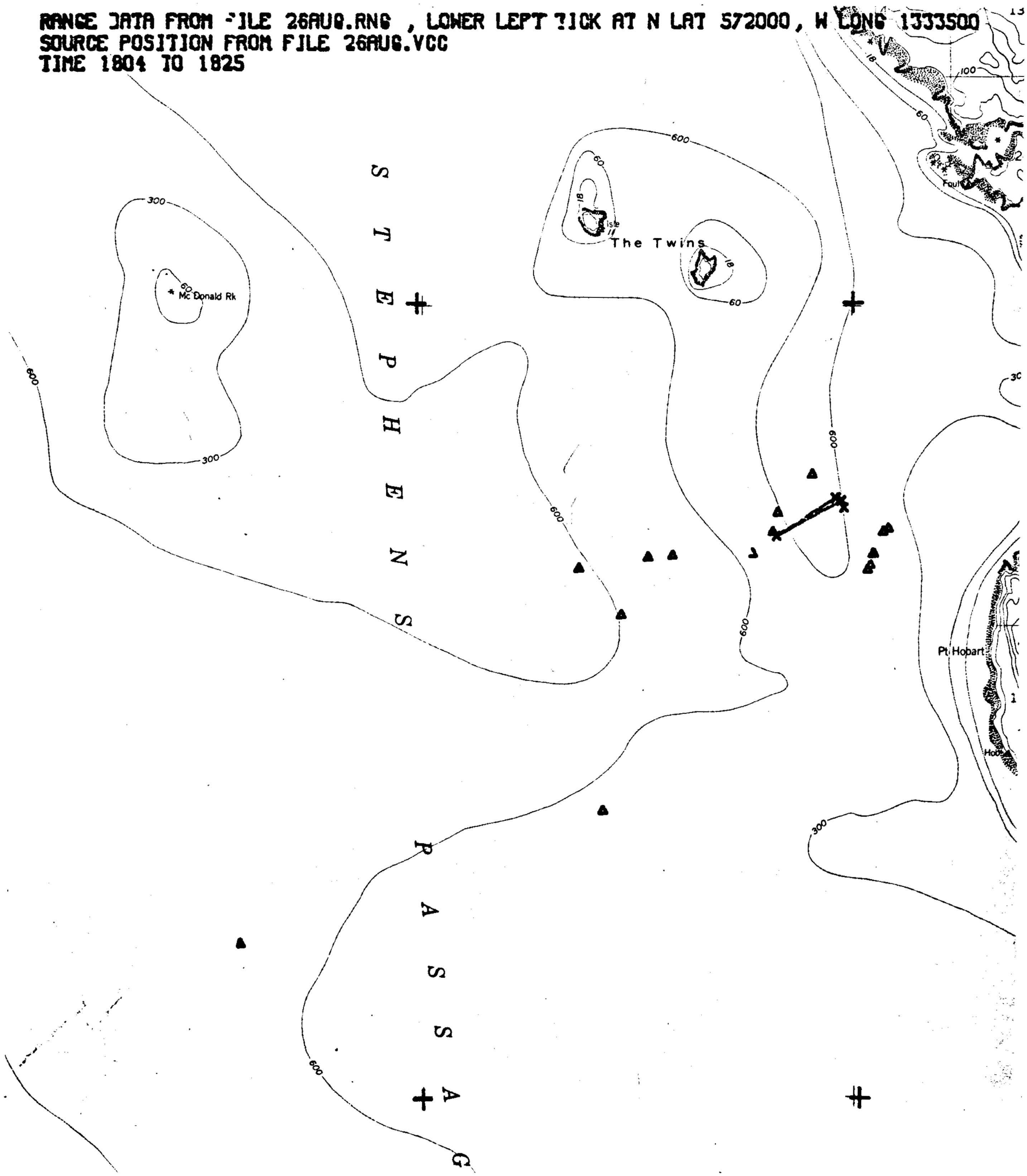
FIG. B.10.b. SIGHTING POSITION DATA: AIR GUN #7 OPERATION (26 AUGUST 1984).



Legend: ▲ = whale position x = source vessel position

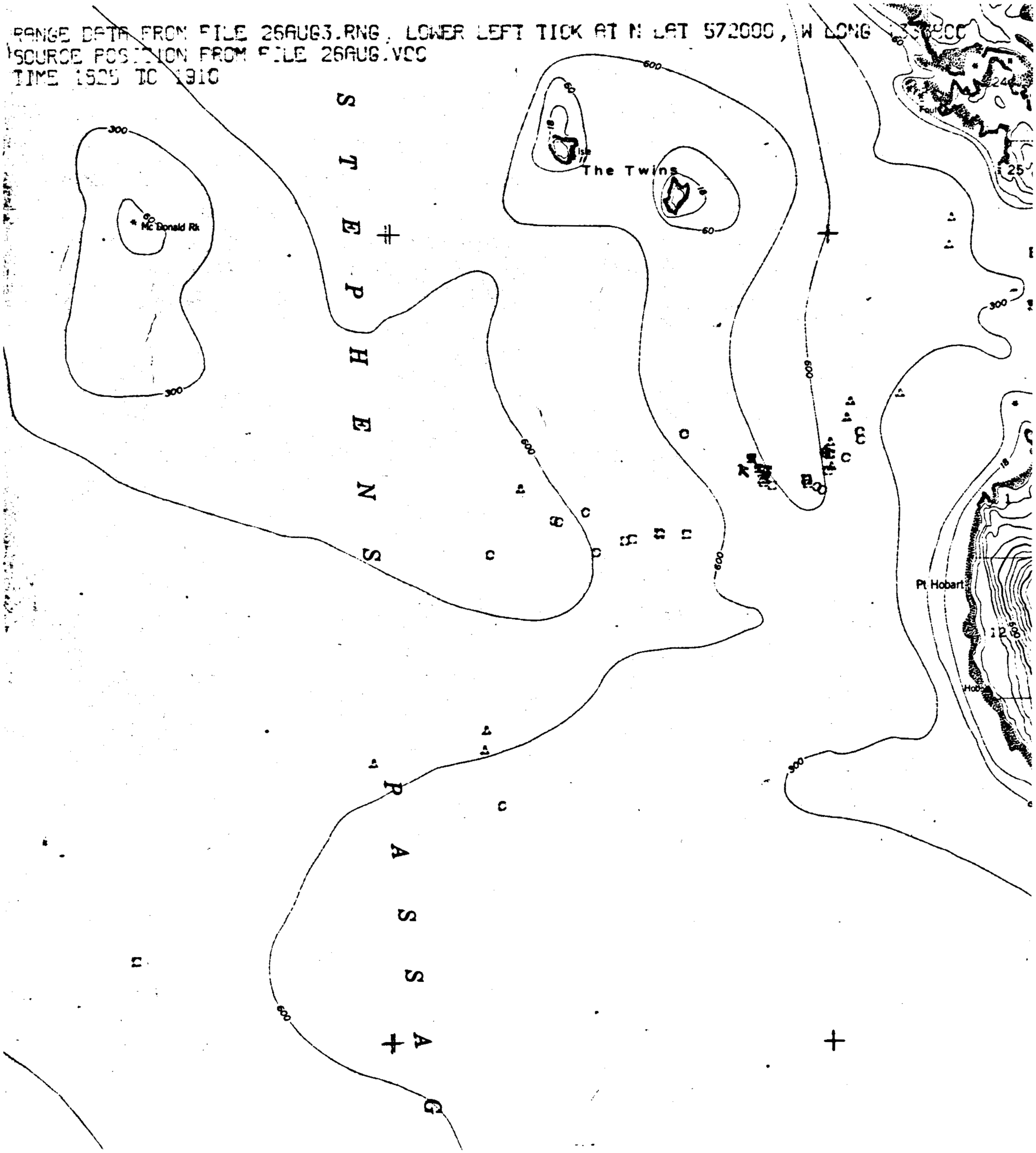
FIG. B.10.c. SIGHTING POSITION DATA: AIR GUN #7 POST-TEST CONTROL PERIOD (26 AUGUST 1984).

RANGE DATA FROM FILE 26AUG.RNG , LOWER LEFT TICK AT N LAT 572000, W LONG 1333500
SOURCE POSITION FROM FILE 26AUG.VCC
TIME 1804 TO 1825



Legend: ▲ = whale position x = source vessel position

FIG. B.11.a. SIGHTING POSITION DATA: SEMI-SUBMERSIBLE RIG PRE-TEST CONTROL PERIOD (26 AUGUST 1984).

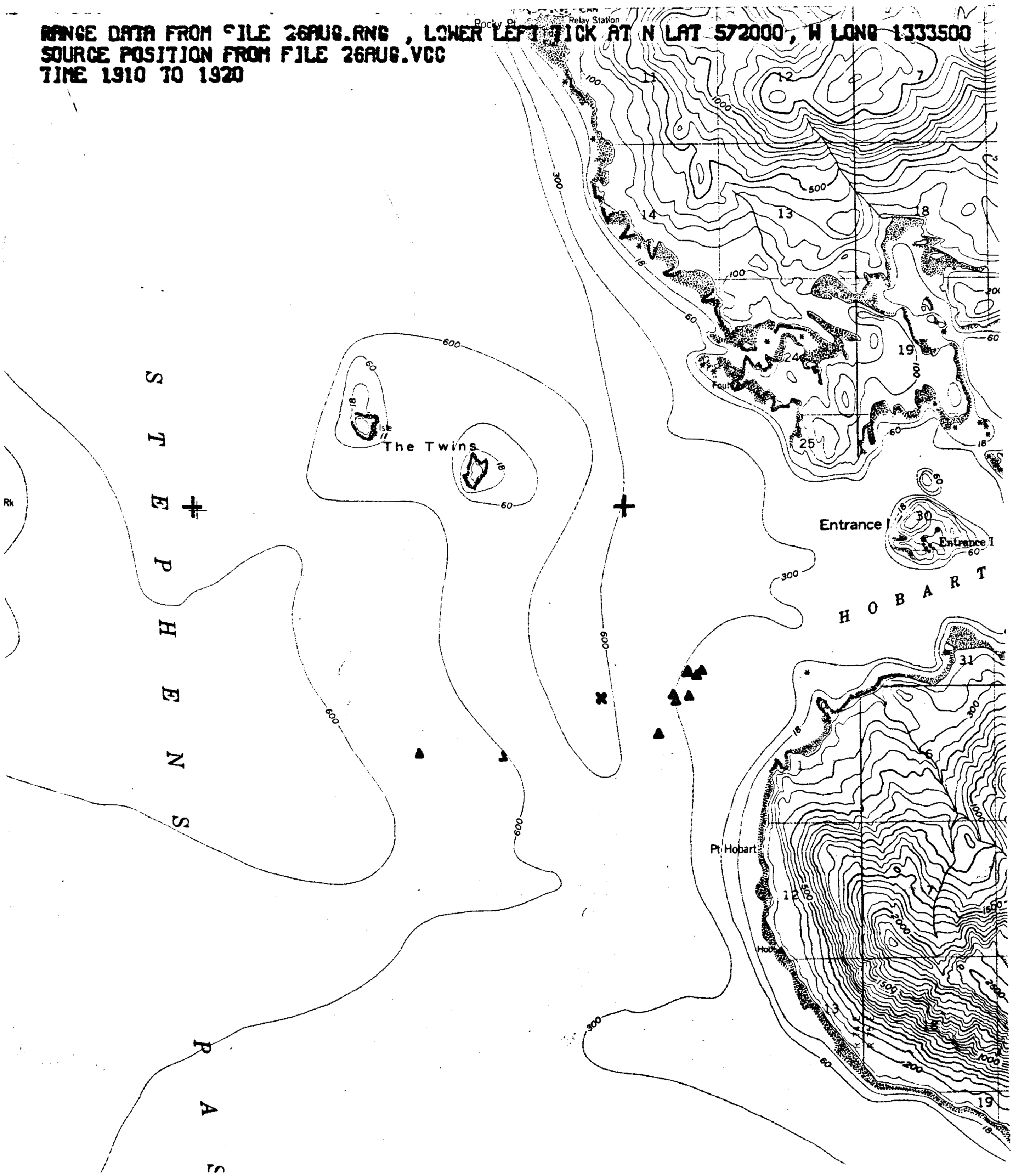


Whale Position

Source Vessel Position

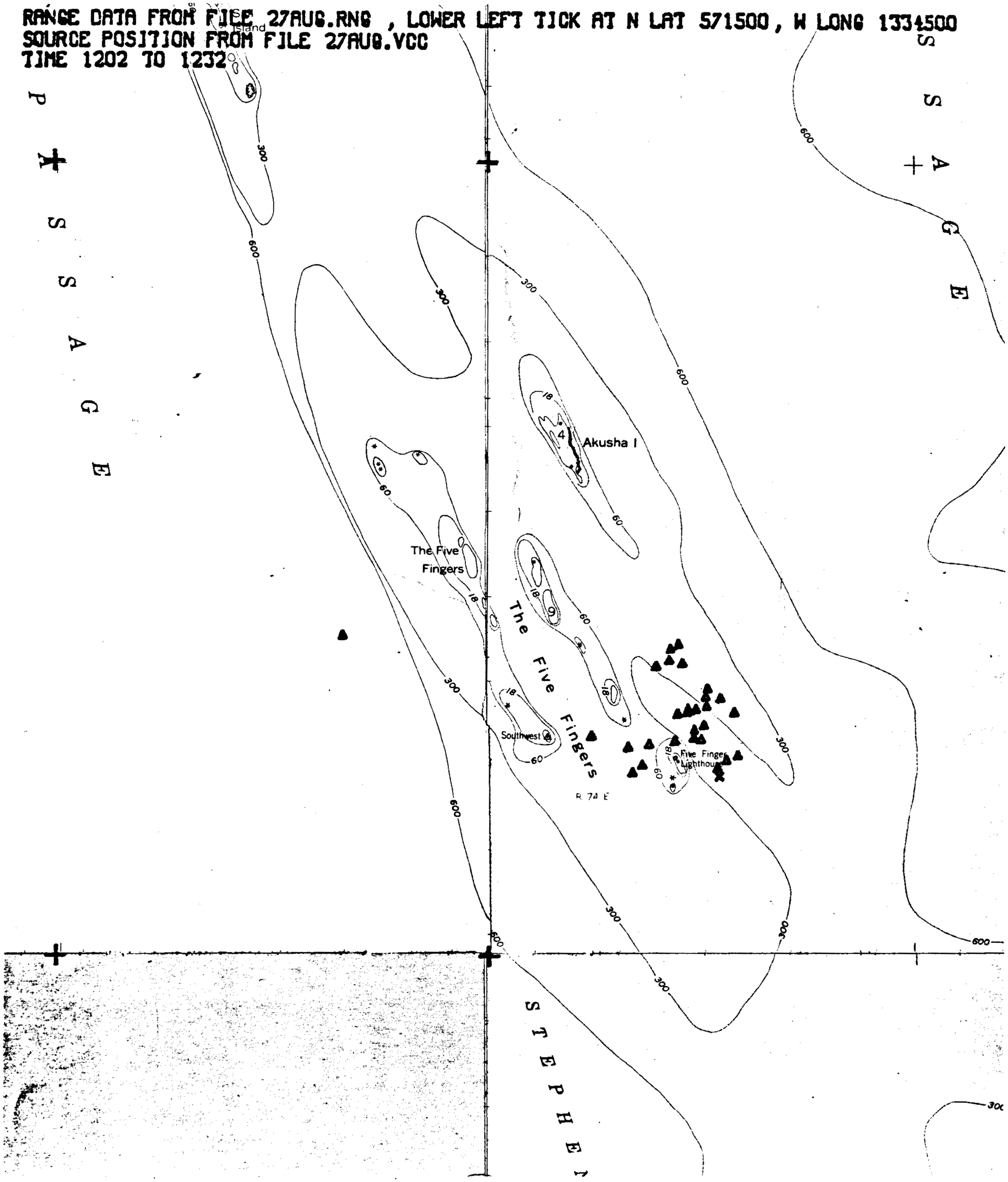
Interval (min) 0-15-30-end
Sighting code □ O Δ ⊞

FIG. B.11.b. SIGHTING POSITION DATA: SEMI-SUBMERSIBLE RIG PLAYBACK (26 AUGUST 1984).



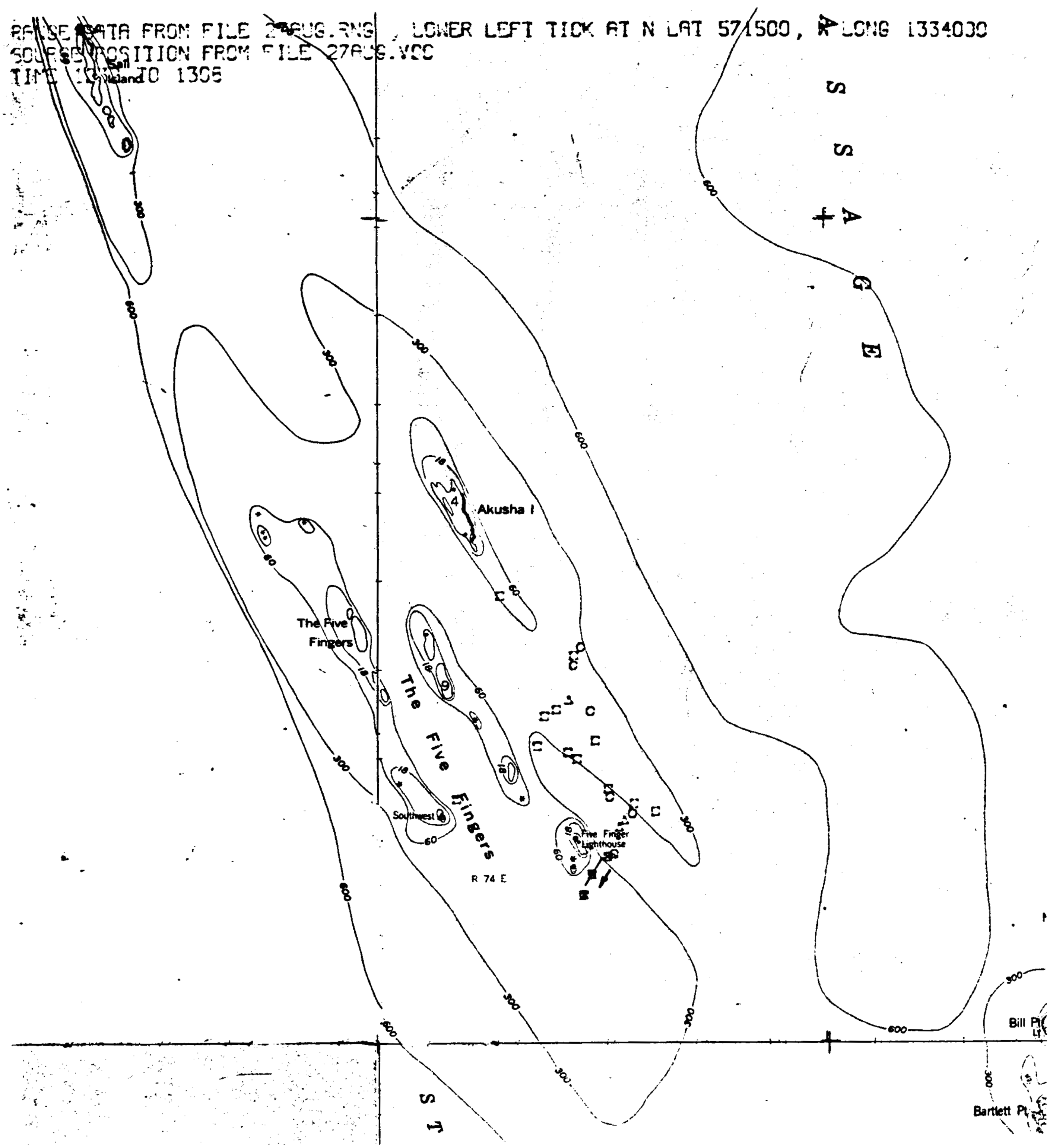
Legend: Δ = whale position x = source vessel position

FIG. B.11.c. SIGHTING POSITION DATA: SEMI-SUBMERSIBLE RIG POST-TEST CONTROL PERIOD (26 AUGUST 1984).



Legend: ▲ = whale position x = source vessel position

FIG. B.12.a. SIGHTING POSITION DATA: PRODUCTION PLATFORM PRE-TEST CONTROL PERIOD (27 AUGUST 1984).



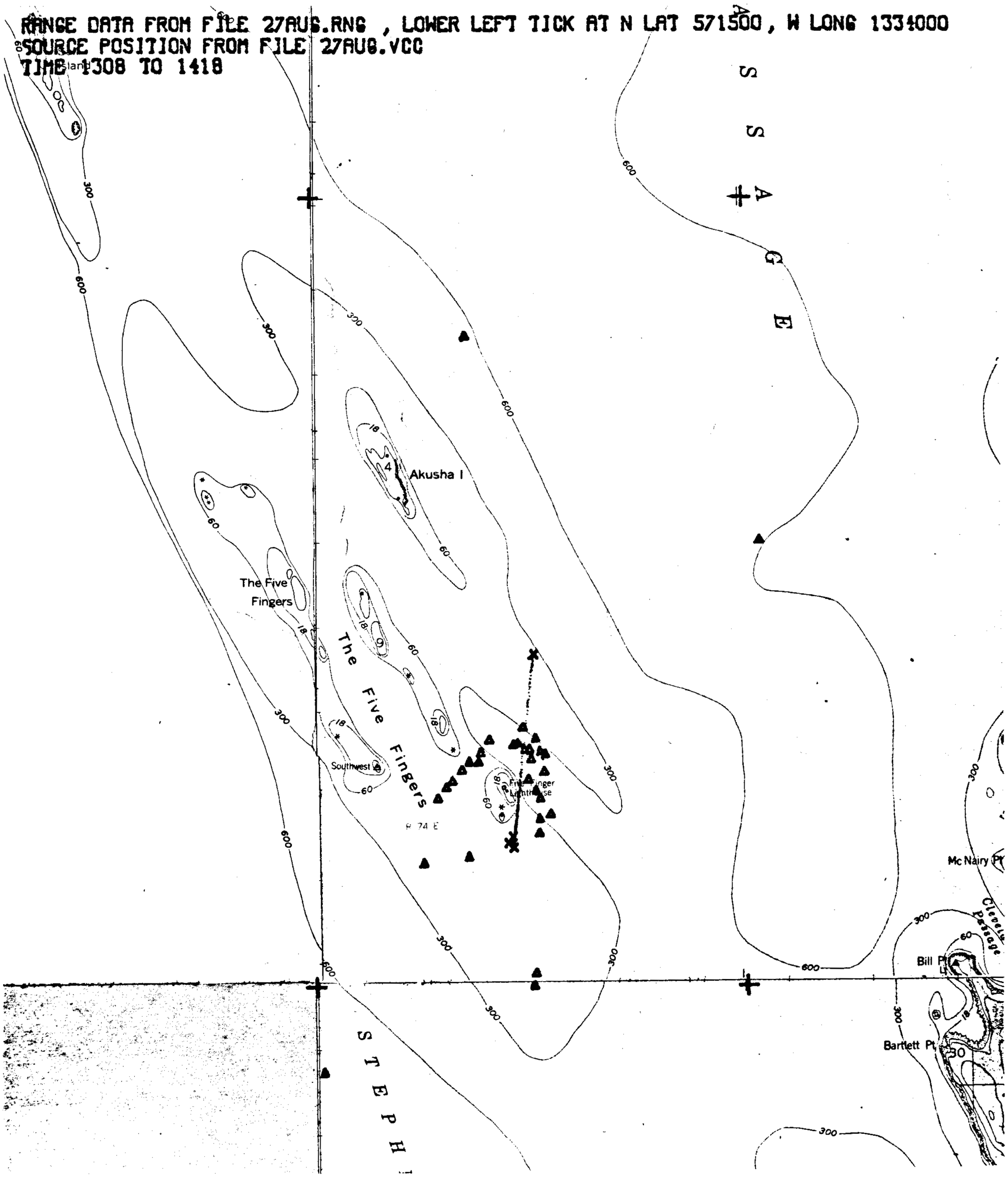
Whale Position

Source Vessel Position

Interval (min) 0-15-30-end
Sighting code □ ○ △

⊞

FIG. B.12.b. SIGHTING POSITION DATA: PRODUCTION PLATFORM PLAY-BACK (27 AUGUST 1984).



Legend: ▲ = whale position x = source vessel position

FIG. B.12.c. SIGHTING POSITION DATA: PRODUCTION PLATFORM POST-TEST CONTROL PERIOD (27 AUGUST 1984).

Whale Position

Source Vessel Position

Interval (min) 0-15-30-end

Sighting code □ ○ △ ⊞

FIG. B.13.a. SIGHTING POSITION DATA: DRILLSHIP PLAYBACK (28 AUGUST 1984).

APPENDIX C

PLAYBACK STIMULI SPECTRA

APPENDIX C: PLAYBACK STIMULI SPECTRA

This appendix contains a set of 1/3 octave band spectra for each of the playback stimuli used in the study. Spectra for both the original recording dub and the playback are included for comparison. The playback spectra were obtained by analyzing the recorded output of the projector monitor hydrophone located 6 m from the projector system. The projector depth for all playbacks was 12 m. Spectra from analysis of the original recording dub are shown with their relative level adjusted to facilitate comparison with the playback spectra. Note that some of the industrial stimula used were obtained from recordings having considerable fluctuation in level and spectrum content. Thus, it was difficult to obtain an exact match of the machinery operating condition for the dub-playback comparison. Hence, some of the figures presented here show spectra differences which may not be due entirely to system response effects.

The response data for drillship, drilling platform, production platform, helicopter, and semisubmersible rig, are presented in Figs. C.1 through C.5 on the following pages.

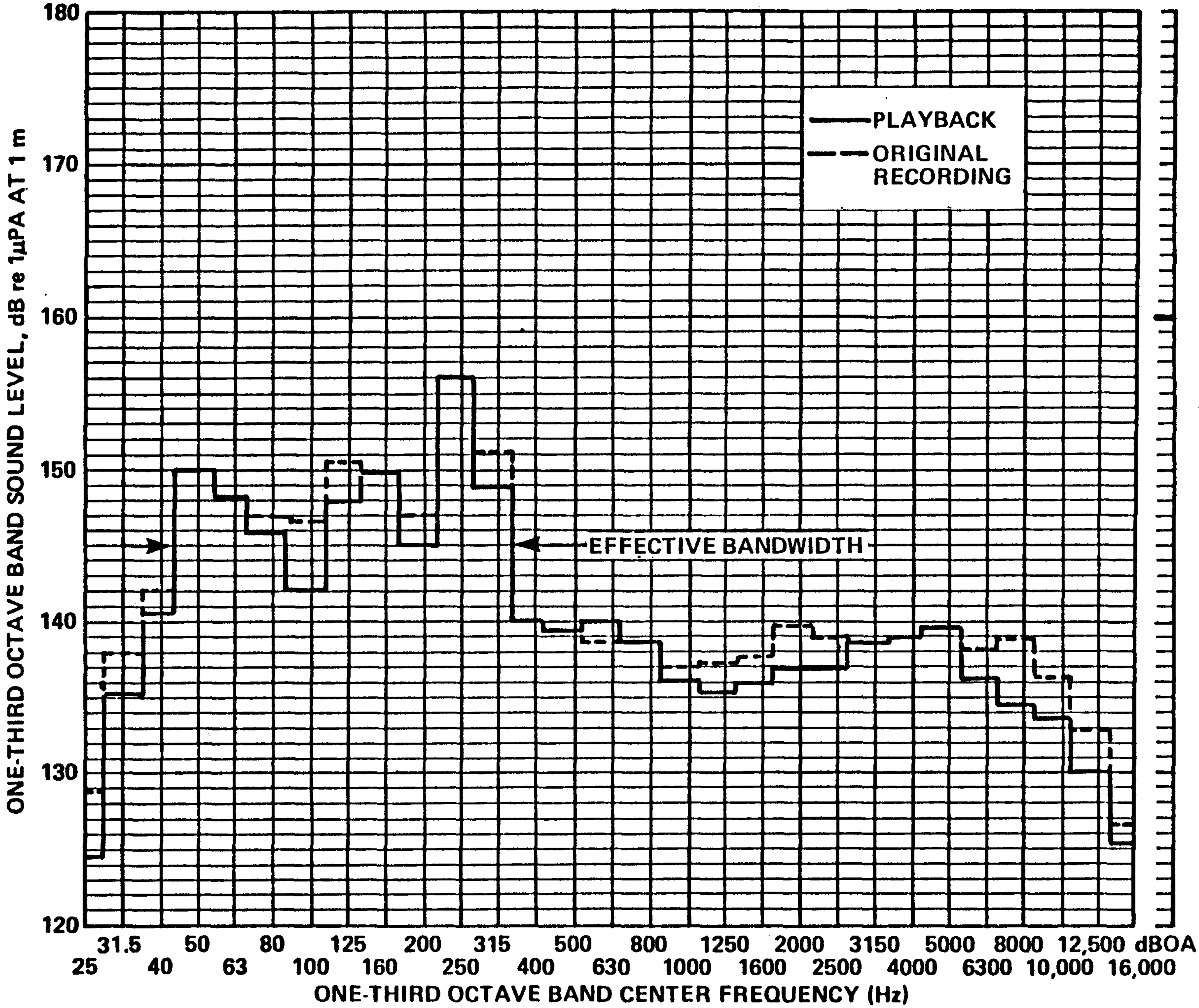


FIG. C.1. DRILLSHIP STIMULUS

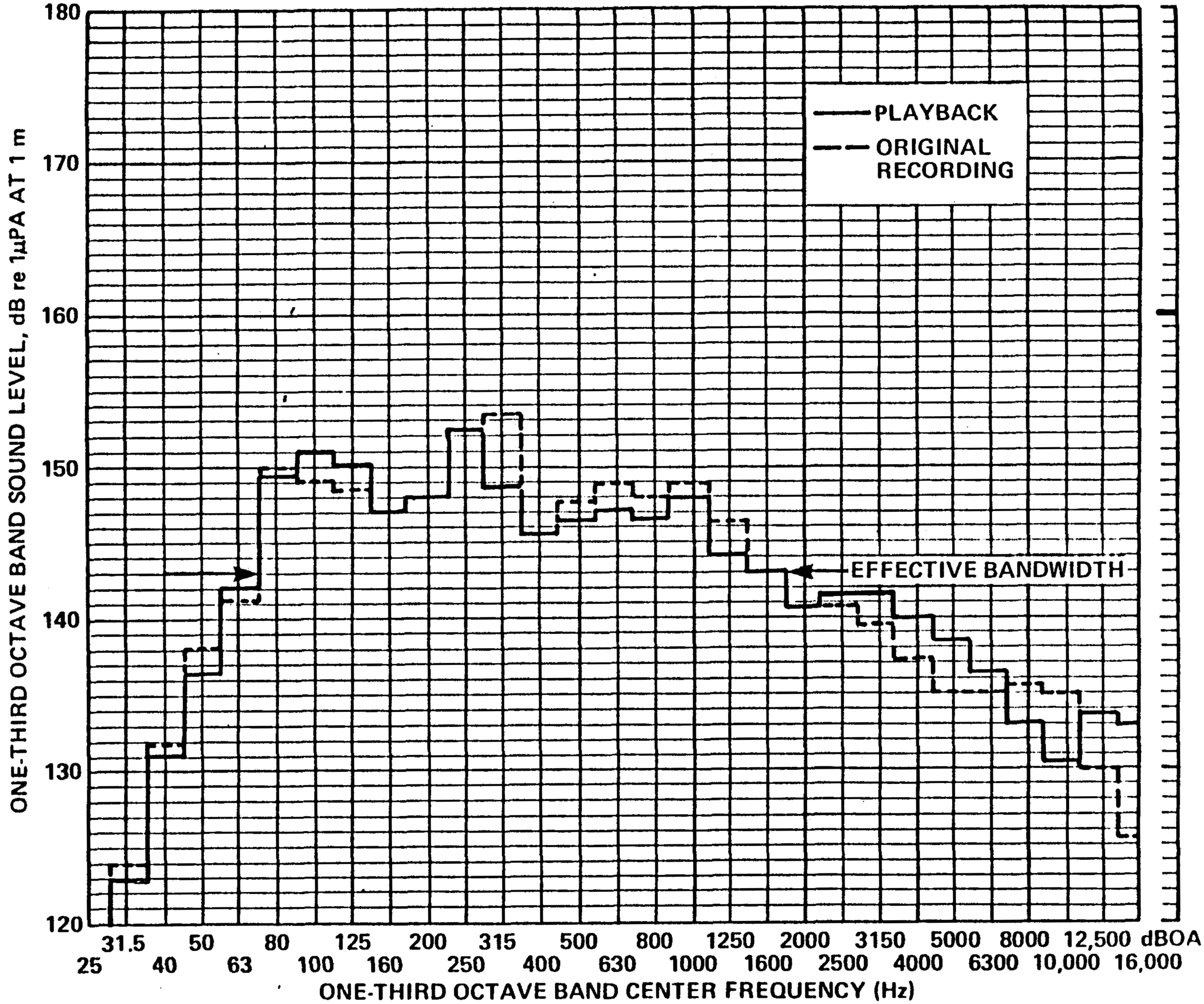


FIG. C.2. DRILLING PLATFORM STIMULUS.

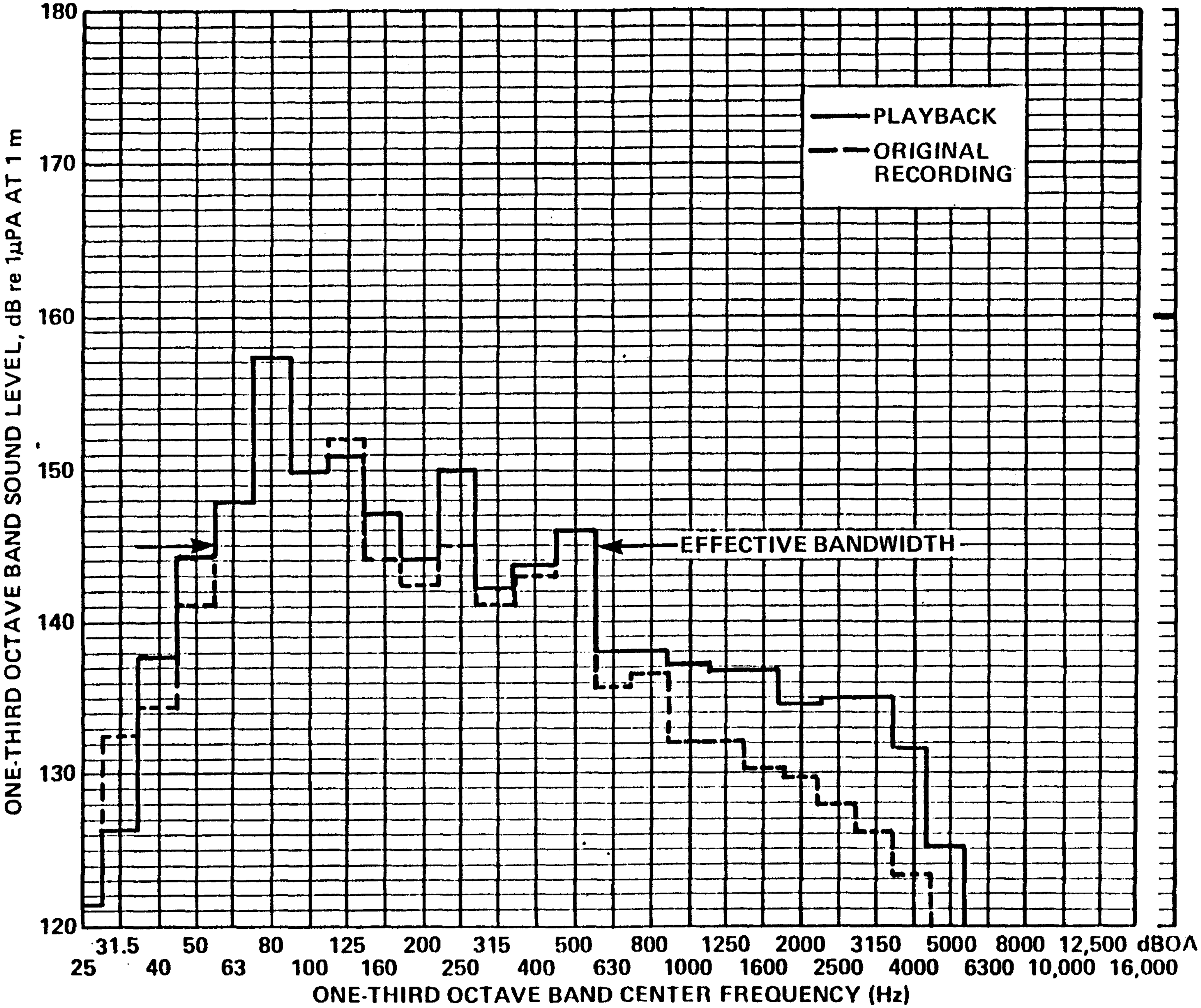


FIG. C.3. PRODUCTION PLATFORM STIMULUS.

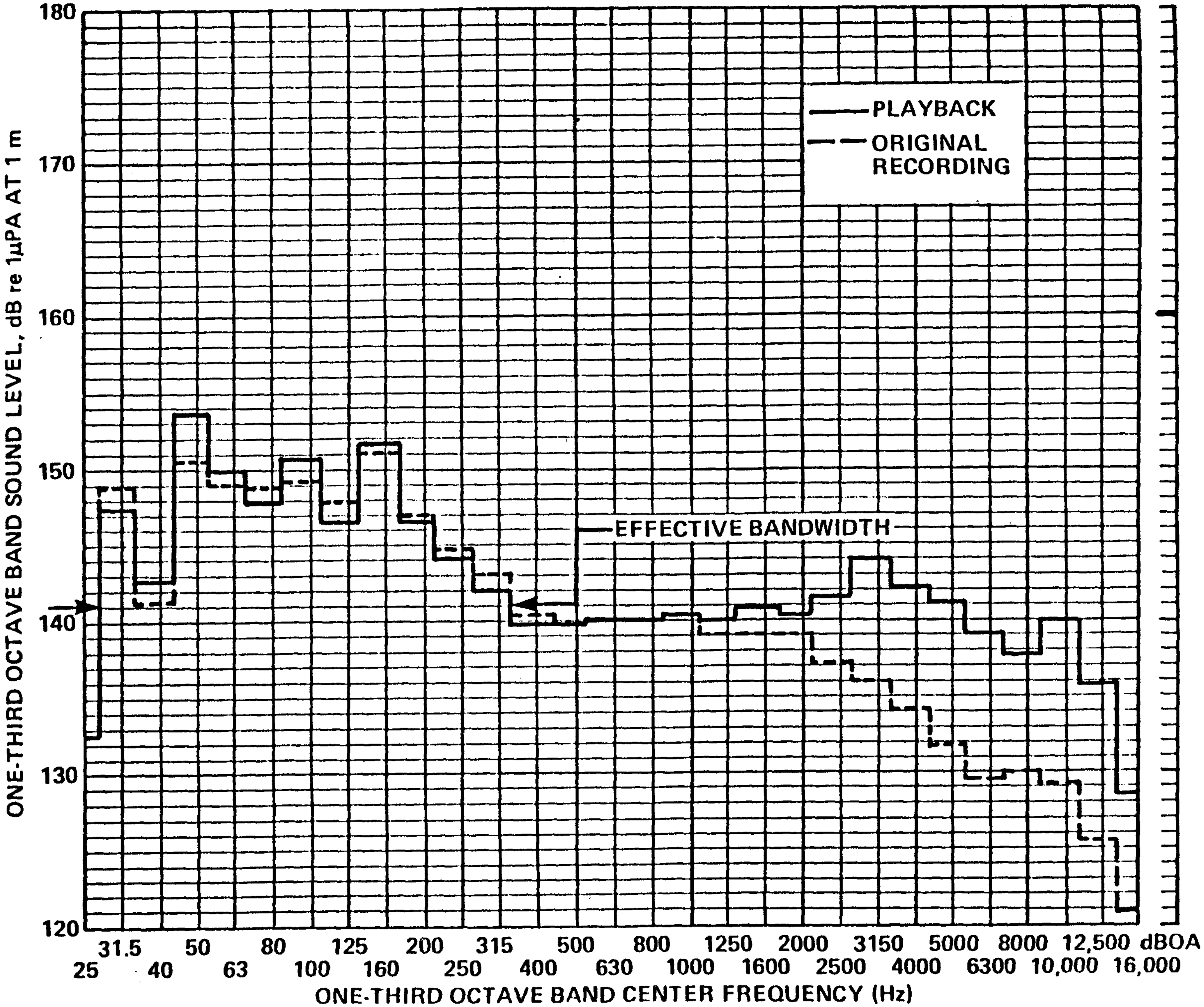


FIG. C.4. HELICOPTER STIMULUS.

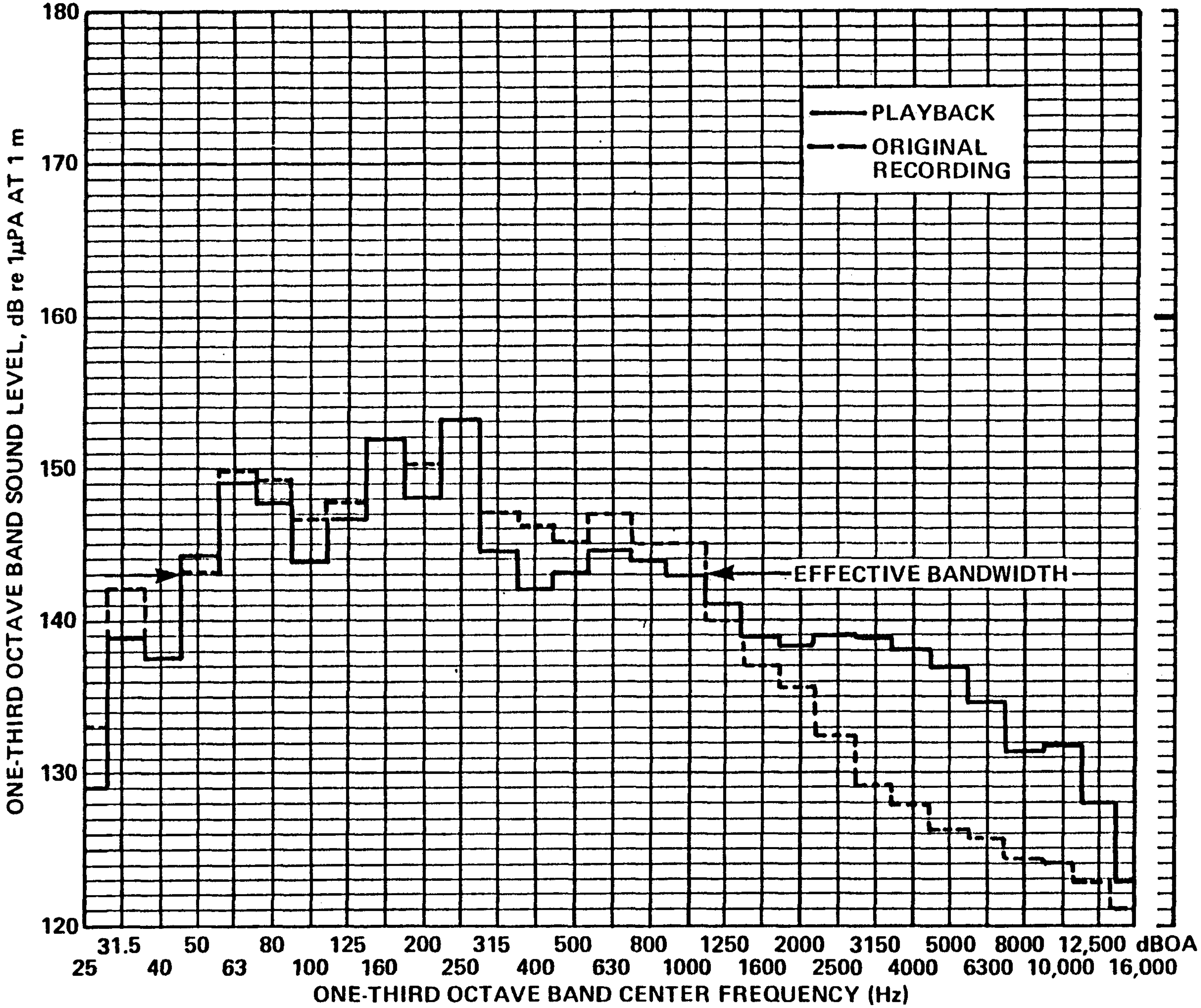


FIG. C.5. SEMI-SUBMERSIBLE DRILLING PLATFORM STIMULUS.

APPENDIX D
SIGHTING ERROR ANALYSIS

Triangulation Errors

The method of triangulating whale sightings using azimuths from two vessels, which was developed for this study, has not to our knowledge been used or tested before. In order to determine its accuracy and precision, we performed an error analysis on sightings of the NANCY H., comparing ranges derived from triangulation to radar ranges measured directly. Figure D.1 shows the error in triangulation ranges as a function of radar ranges to the NANCY H. The 33 triangulation ranges include all cases where triangulation ranges were bracketed by radar ranges of the NANCY H. Where the two ranges were not obtained at the same time, the radar range was interpolated to the time of the triangulation range. The data presented in the figure indicates that the method worked with reasonable precision (± 100 m) at ranges of up to 1 km, but beyond 1 km, errors of several hundred m were common.

Navigational Errors

As mentioned in Sec. 3.3.1, a Loran-C on the NANCY H. provided location of this vessel, which was the sound source during air gun experiments. When the NANCY H. was close to landmarks such as islands, the Loran position indications were checked against the charted position to determine the required rf propagation correction. The correction was found to remain constant throughout the test area.

The VARUA did not have a Loran, so radar navigation was used to fix its location by measuring ranges to 3 landmarks. A full-time observer was not available to record radar positions, hence data were obtained at 15 to 30 min. intervals. The radar position data were used to estimate VARUA position drift during playback experiments. Depending on wind and current conditions, the total drift during an experiment was found to be as high as several hundred meters.

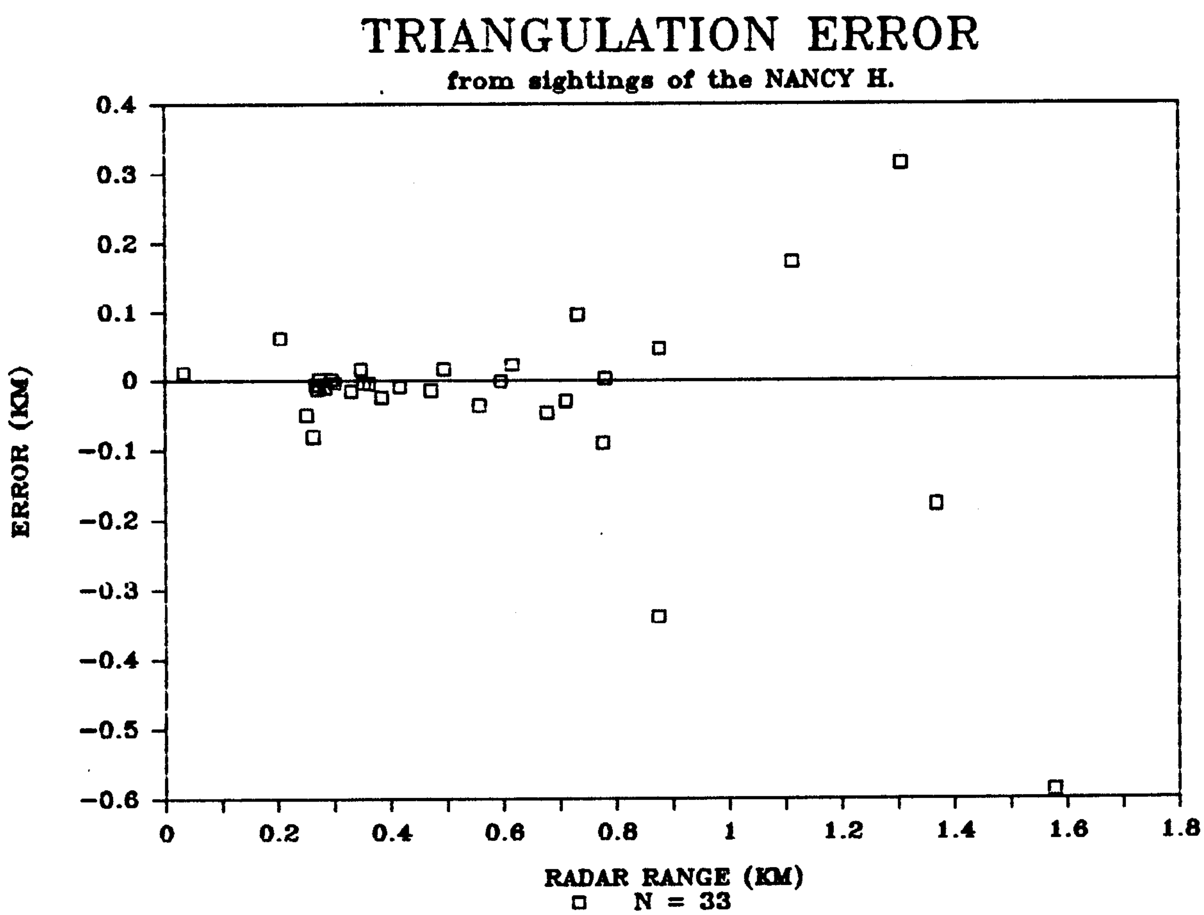


FIG. D.1. TRIANGULATION ERROR VS RANGE FOR TWO VESSEL SIGHTING PROCEDURE.

The accuracy of the radar fixes of the VARUA was tested by comparing sightings of the NANCY H., made using the VARUA - Whaler triangulation technique, with the NANCY H. Loran data. A comparison of 18 sightings from 1020 to 1635 on 24 August reveals an average error of 555 m (range = 342 to 1135 m). This error is more than an order of magnitude greater than that due to the triangulation technique alone, and indicates that the precision of VARUA radar fixes was much lower than all other measurements in this study. Since the complex bathymetry of Frederick Sound made it impossible to incorporate exact bathymetry in our transmission loss calculations (Sec. 5.4.1), this lack of precision in absolute location was not important for our playback experiments where the VARUA was the sound source, for all whale sightings were made relative to the VARUA.

For the air gun experiments where the NANCY H. was the sound source, sightings of the NANCY H. from the VARUA were used in the boat triangulation technique to calculate the positions of the VARUA with respect to the NANCY H. This brought the possible errors of VARUA location into line with possible errors of whale sightings. Since the accuracy of the triangulation was assessed using the sightings of the NANCY H., we know these sightings were accurate to approximately 10% of the range for ranges up to 1 km.