BEHAVIORAL RESPONSES OF GRAY WHALES TO INDUSTRIAL NOISE:
FEEDING OBSERVATIONS AND PREDICTIVE MODELING

by

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ABSTRACT

An investigation was made of the potential effects of underwater noise from petroleum industry activities on feeding gray whales. The investigation consisted of two components, a field study and an acoustic model study. The field study was performed near Southeast Cape, St. Lawrence Island in August, 1985, using a 100 cu. in. air gun source and playback of drillship noise. Sound source levels and acoustic propagation losses were measured to permit estimation of sound exposure levels at whale sighting positions. The surface-dive patterns and blow rates of whales were determined by observation of focal groups. A computer-aided analysis of whale sighting data was performed to determine swimming patterns under pre-exposure, exposure, and post-exposure conditions. For the air gun source there was a 0.5 probability that the whales would stop feeding and move away from the area when the average pulse levels reached 173 dB (re 1 μPa). The 0.1 probability of feeding interruption was estimated to occur at 163 dB, but whale responses were highly variable. Most whales returned and resumed feeding after the air gun vessel had moved on. Playback of drillship noise did not produce clear evidence of disturbance or avoidance behavior for levels below 110 dB. Possible avoidance occurred for exposure levels approaching 119 dB. Until more playback data are available, 120 dB is recommended as the level for which a 0.5 probability of avoidance might be expected for continuous industrial noise sources near feeding areas. These behavioral response levels were used as criteria in the sound propagation modeling part of the study to obtain range estimates for the zone of influence for a specific source. For a large air gun array with a peak source level of 250 dB (re 1 μPa at 1 m) operating in the Chirikof Basin, an average pulse pressure level of 173 dB would be produced at a range of 2.6 km. For the Explorer II drillship (source level =

165 dB), a received level of 120 dB would be produced at a range of 300 m. Near Unimak Pass, for sources operating in uniform water depths of 30 m, the large array would produce an average pulse pressure of 173 dB at a range of 2.8 km, and the drillship would produce a received level of 120 dB at 500 m. For sources located offshore in deeper water with sound propagation upslope to whale locations nearer shore, the resulting ranges are 3 km and 700 m for the array and drillship, respectively.

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Our dedicated team of field observers are responsible for obtaining the data needed for this report under sometimes very adverse conditions. In addition to two of the authors (Würsig and Bird), this team included:

Mr. Don Croll, field observer

Ms. Jo Guerrero, field observer, data analysis

Ms. Linda Guinee, field observer, data entry

Mr. Guy Oliver, field observer, project representative to St. Lawrence Island

Ms. Victoria Rowntree, field observer.

The air gun was leased from Western Geophysical and was operated using an air compressor leased from Price Compressor, Inc. The equipment was mounted on board NANCY-H owned and operated by Latitude 60°N Enterprises/ Inc., and chartered by BBN . The observation and playback source vessel was the BIG VALLEY owned and operated by Mr. Ralph Botkin. The ship handling skills of Mr. Botkin and Mr. Wolfgang Mikat of the NANCY-H were greatly appreciated - especially during the gale that terminated the observation period.

Within BBN Laboratories staff, the sound transmission analysis and model development of Dr. Preston Smith, Jr., were a major contribution to the zone-of-influence predictions. The expertise of Mr. Rafal Mlawski in the installation, maintenance, and operation of the acoustic equipment on board the BIG VALLEY was essential to the project. Mr. Creighton Gogos of BBN and Mr. Mac Warren of Marine Specialty were essential for the installation and operation of the air gun system on the NANCY-H. Mr. Paul Miles was the key expediter in getting all of the

equipment ordered, shipped, and coordinated so that the field work could begin on time. Ms. Judy Russo's work in processing all of these words in a timely and patient manner is greatly appreciated.

The project and report responsibilities of the authors were:

Mr. Charles I. Malme - Project Manager and Principal Investigator for Acoustics, Acoustic data analysis

Consultants to BBN Laboratories

Dr. Bernd Würsig - Principal Investigator for Whale Behavior, Dive-surfacing and blow rate analysis

Mr. James E. Bird - Observation data analysis

Mr. Peter Tyack - Sighting data and track analysis

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 gray whales (Eschrichtius robustus). The objectives of the study were to determine the character and degree of response of feeding gray whales to playbacks of industrial noise or actual seismic sound sources and to develop predictive models of the potential zones of influence of various types of industrial noise sources for important gray whale habitats such as Chirikof Basin and Unimak Pass. The noise sources used were playback of drillship sound and a single 100 cu. in, air gun. The work was performed in the Bering Sea near Southeast Cape, St. Lawrence Island, during August 17-28, 1985.

Experimental Procedure

The acoustic environment of the test area was measured by determining the propagation loss and ambient noise levels. The output source levels of the playback source and the air gun were calibrated. These measurements permitted calculation of the test stimulus level at sighted whale positions. Ambient noise in the "test area was generally low and controlled by wind-generated sea noise. Sound transmission was found to be more efficient than is usual for shallow water areas with a sand/silt bottom because of the probable presence of a sub-bottom rock layer.

Whale behavior data were obtained by close observation of focal whale groups, recording surfacing-dive and blow information. In addition, tracking of the focal groups was performed using a two-vessel triangulation procedure or a land-based theodolite when weather permitted. The experimental procedure involved location of feeding whales, observation of behavior during a control period with the support vessels present,

observation of behavior during an experiment period with the sound stimulus on, and observation of behavior during a post-experiment control period. Generally, several of these sequences were performed each day.

Surfacing-Dive and Blow Rate Analysis

The four basic characteristics used to describe the surfacing-dive behavior of gray whales were (1) respiration or blow interval, (2) length of surfacing, (3) length of dive, and (4) number of blows per surfacing. Blow rate was calculated from these data. For drillship sounds, blow intervals decreased and length of surfacing, length of dive, and number of blows per surfacing increased. Blow rate changed little. Recovery back to a pre-disturbance level occurred in about 30 min. after the stimulus was turned off. For air gun sounds, the characteristics changed in a reverse order. Blow intervals were increased, but length of surfacing, length of dive, and number of blows per surfacing all decreased. Blow rate did not change significantly except for high exposure levels when it increased - usually accompanied by cessation of feeding and movement away from the air gun vessel. Recovery to “normal” levels after exposure was less rapid than that for drillship sounds, requiring about one hour.

Whale Movement Analysis

Because of visibility conditions and the distance of feeding areas from shore, it was not feasible to use land-based theodolite tracking procedures except for one day. A two-vessel tracking procedure using a theodolite and binocular-compass provided sighting data which were analyzed using a computer-implemented triangulation program to determine whale distances from the sound source. The absolute position of the test geometry was determined using Loran C.

Limited data obtained for drillship playback sequences did not show any consistent pattern of feeding disturbance or avoidance of the sound source for levels up to 110 dB re 1 μPa; however, some whales were observed to leave the test area during an experiment when levels reached about 119 dB. The behavioral response of feeding gray whales to air, gun sound was highly varied. At high exposure levels up to 176 dB (average pulse pressure level), some whales would continue feeding while others would stop feeding and move away from the sound source area. One whale was observed to leave a feeding area for an exposure level of about 150 dB. Most whales returned and resumed feeding after the air gun vessel had moved on.

Sound Transmission Modeling

The results of the sound propagation modeling were used for prediction of zones of influence for air gun array, air gun, and drillship sounds in the Chirikof Basin and Unimak Pass areas. The modeling procedure used both analytic and semi-empirical techniques assisted by measured data and data obtained from the literature. The whale migration corridor near Unimak Island is in shallow water near shore so it was necessary for the model to predict upslope sound propagation characteristics as well as characteristics for sound propagation in water of constant depth.

Conclusions

The data base obtained from the field study will not support the detailed statistical analysis required to obtain behavioral measures highly quantitized in terms of noise exposure level. However, it is possible to assign at least two general response levels to the stimuli used in the study.

For the drillship stimulus we recommend that 110 dB be considered as the lowest level which may possibly cause disturbance of feeding activity. This was the level that was observed to cause an onset of avoidance behavior for migrating gray whales. Until more data are available, we recommend that 120 dB be considered as the level which will probably cause avoidance of a potential feeding area near an industrial site by more than 50% of the local gray whale population. A level of 119 dB resulted in a 0.5 probability of avoidance for the average of all the playback stimuli tested with migrating gray whales.

Because of the wide range of responses of feeding gray whales to air gun noise, we recommend that an average pulse pressure level of 163 dB be considered the level at which the disturbance of feeding activity is possible. We also recommend that 173 dB be considered the level at which cessation of feeding activity and temporary movement away from the feeding area are probable for at least 50% of the whales exposed.

By using the sound level criteria given above together with the sound propagation model, it is possible to predict zones of influence for specific source types. For an air gun array with a peak beam pressure level of 250 dB, an average pulse pressure level of 173 dB will occur at a range of 2.6 km in the Chirikof Basin and at 2.8 km offshore of Unimak Island. For the EXPLORER II drillship, a level of 120 dB will occur at a range of 300 m in the Chirikof Basin, and at a range of 500 m offshore of Unimak Island.

Recommendations

Augmentation of the available data is necessary to have a better statistical basis for establishing sound exposure criteria for feeding gray whales.

An extended field study should be performed early in the season when the whale population is larger and weather conditions better. The St. Lawrence Island site would be desirable for this study because of the available high ground for a theodolite station. Potentially, this would eliminate the need for a second large support vessel and reduce the cost for the project.

2. BACKGROUND

The work described in this report was performed by BBN Laboratories Incorporated under NOAA Contract No. 85-ABC-00141. The study was funded by the Minerals Management Service through an interagency agreement with NOAA, as part of the Outer Continental Shelf Environmental Assessment Program. The contract officer's technical representative was Mr. Laurie Jarvela at NOAA, National Ocean Service, OMA, OAD, Anchorage.

The work was performed under Permit No. 511 issued by the National Marine Fisheries Service.

Previous work, under MMS sponsorship, concerning the behavioral response of migrating gray whales to petroleum industry noise has been described in BBN Report No. 5366 (Malme, Miles, Clark, Tyack, and Bird, 1983) and BBN Report No. 5586 (Malme, Miles, Clark, Tyack, and Bird, 1984). Many of the experimental procedures used in this study have evolved from this previous work. The two-vessel tracking procedure employed in this study was developed for a related study of feeding humpback whales and described in BBN Laboratories Report No. 5851 (Malme, Miles, Tyack, Clark, and Bird, 1985).

The acoustic modeling procedure used for the zone-of-influence estimation has been developed in conjunction with several ongoing projects concerning marine environmental acoustics. The reports for these projects, now in preparation, will provide information and technical discussions related to the material covered here. These reports are BBN Laboratories Report No. 6185 (Beaufort Sea) (Miles, Malme, Shepard, Richardson, and Bird, 1986) and BBN Laboratories Report No. 6125 (Pacific Ocean near Central California) (Malme, Smith, and Miles, 1986).

The region near Southeast Cape, St. Lawrence Island, selected for the test site, was also used in a previous study of feeding gray whale behavior by one of the authors (Würsig, Wells, and Croll, 1983, 1986). Thus, many of its advantages as a good observation area for gray whales were known. It also had the advantage of providing shelter from rough weather without requiring a long transit and resulting in lost field time.

The experimental procedure for the behavioral study, data analysis methods, and the results are described in Sec. 3. Section 4 describes the acoustic transmission modeling procedure and the results of the zone-of-influence estimates. Conclusions and recommendations are presented in Sec. 5. An error analysis for the whale position tracking procedures is provided in Appendix A.

3. STUDY OF BEHAVIORAL RESPONSE DURING FEEDING ACTIVITY

3.1 Field Environment and Observation Chronology

In this section we discuss the considerations that determined our selection of the test site. We also present a summary and chronology of observations, including viewing conditions, during the 17-26 August 1985 field season near Southeast Cape, St. Lawrence Island, Alaska.

3.1.1 Test site selection considerations

Gray whales migrate to the waters of the northern Bering and southern Chukchi Seas to feed during summer months (Pike 1962, Bogoslovskaya, Votrogov, and Semenova 1981, Oliver et al. 1983, Braham 1984, and Nerini 1984). The area of the northern Bering Sea has been characterized as a major feeding area (Oliver et al. 1983) with small aggregations of whales known to inhabit the southeastern Bering Sea along the Alaskan Peninsula (Gill and Hall 1983, Braham 1984), as well as other locations south of the Bering Sea (Hatler and Darling 1974, Patten and Samaras 1977, and Sumich 1984).

Based on a review of recent literature and discussions with researchers working on feeding gray whales in the northern Bering Sea (Würsig, Wells, and Croll 1983, 1986; Thomson 1984), we decided to conduct our studies in the nearshore waters off Southeast Cape, St. Lawrence Island, Alaska. The project was conducted in the latter half of August.

Nome, Alaska served as the project's staging area, In order to determine if gray whales were present and feeding in the proposed study area, an aerial survey was conducted on 16 August from 0920-1630 (Alaska Daylight Savings Time) using a twin engine Cessna 402 low-wing aircraft, with a pilot and three observers.

The survey concentrated on the area around St. Lawrence Island, especially near Southeast Cape, and King Island. Gray whales, apparently feeding as evidenced by mud plumes, were located in the area of Kialegak Point, Southeast Cape, in the same location where Würsig, Wells, and Croll (1983, 1986) conducted a study on the behavior of feeding gray whales in 1982.

3.1.2 Field observation summary

Project personnel, including seven whale behavior observers and two acousticians, left Nome on 17 August on board the BIG VALLEY, arriving at the study area on the morning of 18 August. The study area near St. Lawrence island is shown in Fig. 3.1. Data collection began on this date and ended on 26 August, during which time a total of 88.5 hr of observation was achieved. Table 3.1 summarizes our observations by date, hour of day, and location.

The number of whales present for study during the test period was expected to be considerably less than those available for the previous work with migrating gray whales (Malme et al. 1983, 1984). We therefore limited our playback test stimuli to one of the five industrial sounds used previously. Drillship sound was used because it had been observed to produce avoidance of migrating whales at a greater range than other test sounds. Other sounds were of drilling platform, production platform, semi-submersible rig, and helicopter. The test sound was produced by playing back a recorded sequence through the broadband underwater projector system used in the previous gray whale studies (Malme et al. 1983, 1984).

The second test signal employed in our study was the sound produced by a single 100 cu. in. air gun operated at 4500 psi,

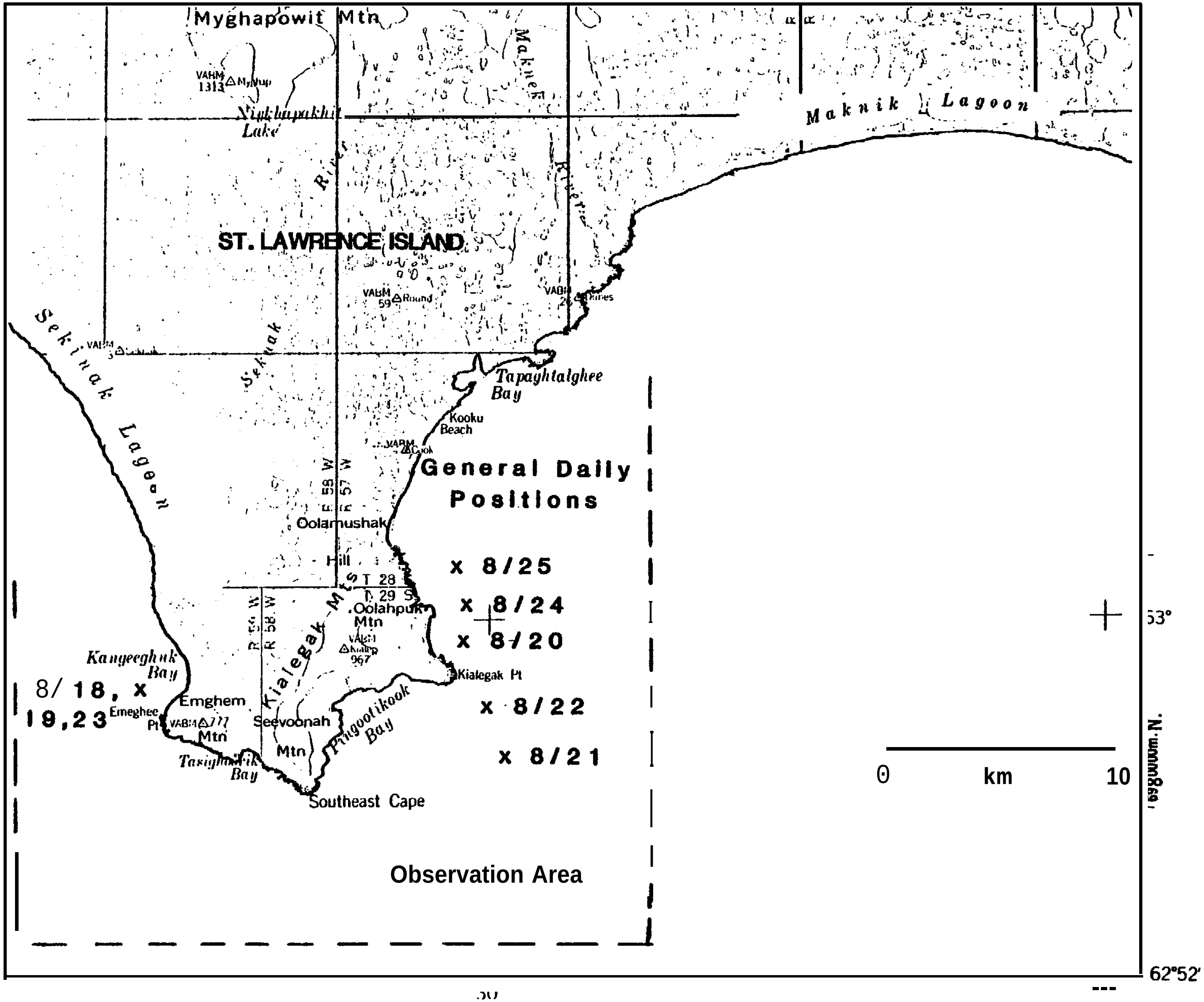


FIG. 3.1. STUDY AREA NEAR ST. LAWRENCE ISLAND.

TABLE 3.1. DATA SUMMARY FOR GRAY WHALE - STUDY 17-27 AUGUST 1985.

Date	Time	Stimulus	No. of Whales Sighted	No. of Whales Sur/Resp Data	Tracking Data	Observation Location	General Observations
8/17	1400-2300 (1)	--	0	--	--	Nome to St. Lawrence	No gray whales seen on Nome-St, Lawrence Island transit.
8/18	0935-1016	C	6	6	--	Kialegak Point	Sea conditions prevented observers from determining whether whales were feeding or not.
	1306-2253	C	25	22	--	West of Southeast Cape	Most of the whales were between 100-400 m from "Big Valley". Observers were able to take data on one whale for 1.5 hr.
8/19	0709-0908	C	9	6	--	Kangeeghuk Bay	Observers took limited data on a mother/calf pair.
	1518-2108	C	26	16	--	Kangeeghuk Bay	Sea conditions and distance of whales from "Big Valley" prevented observers from determining whether whales were feeding or not.
	2100-2129	DS 1	1		--	Kangeeghuk Bay	The whale which observers were following was within 200 m of "Dig Valley". It was last seen at 211128.

(1) All times given in Alaska Daylight Savings Time.

(2) These numbers represent number of simultaneous readings on whales. As explained in the table, we did not try to track individual whales during these two periods.

Stimulus abbreviations: C = Control Period; DS = Drillship Playback; AG = Air Gun Experiment.

TABLE 3.1. (Cont.) DATA SUMMARY FOR GRAY WHALE - STUDY 17-27 AUGUST 1985.

Date	Time	Stimulus	No. of Whales Sighted	No. of Whales Sur/Resp Data	Tracking Data	Observation Location	General Observations
8/19	2129-2239	C	14	5	--	Kangeeghuk Bay	Observers did not note another whale within 600 m of "Big Valley" until 2151. The five whales under observation during this control period were between 200-500 m from "Big Valley".
8/20	0730-0851	C	2	2	--	Kangeeghuk Bay	Observers took approximately 40 min. of data on one whale which may have been feeding for a limited time.
	1216-1713	C	2	1	--	Kialegak Point	From 1425 to 1552, four observers in the Zodiac searched for whales to the north but none were observed.
	1915-2330	C	5	1	--	Kialegak Point	Data was taken on a single whale for approximately 20 min. This was a small whale, possibly a first year calf.
8/21	0724-1142	C	9	5	2	NE of Kialegak Point	This was the first day that triangulation data was taken. Although mud and/or birds (2 indications of feeding) were not noted, one of the whales was moving slowly and staying in the same general area, a possible indication of feeding.
	1142-1212	DS 2	4	3	3	NE of Kialegak Point	One of the whales under observation was noted surfacing with mud present.

TABLE 3.1. (Cont. DATA SUMMARY FOR GRAY WHALE STUDY 17-27 AUGUST 1985.

Date	Time	St mu us	No. of Whales Sighted	Sur/Resp Data	Tracking Data	Observation Location	General Observations
8/21	12 2- 448	C	11	6	2	NE of Kialegak Point	The presence of mud was noted with four of the whales under observation. At one point, two whales were very close together (< 15 m) and a variety of behaviors were observed including underwater blows, a pectoral slap, and a vertical fluke. No indication of feeding was observed at this time, however when the whales separated the presence of mud was noted when both whales surfaced. One of the whales had been surfacing with mud visible before this interaction.
	1'48- 542	DS 3	4	3	2	NE of Kialegak Point	Observers continued to take data on Whale W, which had been under continuous observation since 1258.
	1542-1650	<	5	5	--	NE of Kialegak Point	Observations continued on Whale W, which continued to feed.
	1800-1858	<	8	4	-	NE of Kialegak Point	No mud was noted with the four whales under observation; however, birds were noted with one whale. One of the focal whales passed under the bow of "Big Valley".
	1924- 35°	=	5	5	2	NE o≤ Kialegak Poi⊂	The Zodiac observers took surfacing/respiration data on f ve whales. Because of the close proximity of the whales to one another and their lack of individually distinctive features. it was not possible to track individual whales.

TABLE 3.1. (Cont.) DATA SUMMARY FOR GRAY WHALE - STUDY 17-27 AUGUST 1985.

Date	Time	Stimulus	No. of Whales Sighted	No. of Whales Sur/Resp Data	No. of Whales Tracking Data	Observation Location	General Observations
8/21	1950-2057	DS 4	26	1	22(2)	NE of Kialegak Point	Observers onboard the "Big Valley" noted a shift in movement of whales. Whales that had been to the west and inshore of "Big Valley" moved to the northeast.
	2057-2149	C	5	--	4(2)	NE of Kialegak Point	Very limited data taken. Most of the whales in the area had moved away. There were two whales 3-5 km to the northeast of 'Big Valley" and a few to the north of the Zodiac and "Big Valley".
8/22	0730-1440	C	20	11	5	Kialegak Point	Surfacing/respiration data were taken on Whale E from 1141 to 1832. The presence of mud was noted during surfacings towards the end of observations, but not earlier presumably because over-cast conditions in the late AM and early PM prevented its detection.
	1440-1600	AG 3	15	3	4	Kialegak Point	Observers continued to take data on Whale E. The Zodiac observers noted that the whales in the area (including Whale E) moved offshore and that apparent feeding stopped. This offshore movement appeared to continue until "Nancy H." was abeam of "Big Valley". During this period, "Big Valley" had to make two moves to stay in the same area as the whales and the Zodiac.

TABLE 3.1. (Cont.) DATA SUMMARY FOR GRAY WHALE STUDY 17-27 AUGUST 1985.

Oate	Time	"Stimulus	No. of Whales Sighted	Sur/Resp Data	Tracking Data	Observation Location	General Observations
0/22	1600-1710	c	6	3	3	Kialegak Point	Observations on Whale E continued with mud noted for many surfacings. The control period ended when "Big Valley" was forced to start engines and move offshore because it was drifting Into shallow water.
	1731-1758	AG 2		1	2	Kialegak Point	Observations on Whale E continued. Observers onboard the Zodiac noted that Whale E did not exhibit the same behavior (moving offshore) as seen during the first AG run.
	1758-1851	C	8	3	2	Kialegak Point	Observations on Whale E continued, with mud still being noted.
8/23	0730-1201	C	5	--	--	Kialegak Point	Weather conditions and poor visibility prevented taking surfacing/respiration data.
	1446-1851	C	3-4	1	--	Kangeeghuk Bay	Limited surfacing/respiration data taken.
	1851-2240	C	3	1	--	Kangeeghuk Bay	Limited surface/respiration data taken.
8/24	0735-1203	C	1	--	--	Pingootikook Bay	Very limited visibility
	1606-1715	C	6	1	6	Theodolite station N of Kialegak Point and nearshore waters	Whales were tracked from shore by theodolite while Zodiac observers monitored surfacing/respiration. Four of the six whales tracked were feeding, as evidenced by the presence of mud and birds.

TABLE 3.1. (Cont.) DATA SUMMARY FOR GRAY WHALE - STUDY 17-27 AUGUST 1985.

Date	Time	Stimulus	No. of Whales Sighted	Sur/Resp Data	Tracking Data	Observation Location	General Observations
8/24	1715-1758	AG 3	5	--	5	Theodolite station N of Kialegak Point	Theodolite tracking continued. The Zodiac observers stopped taking surface/respiration data at 1710 because of sea conditions and lack of individually identifiable whales.
	1758-1929	C	4	--	4	Theodolite station N of Kialegak Point	Theodolite tracking continues.
	1929-2026	AG 4	3	--	2	Theodolite station N of Kialegak Point	The "Nancy H" came within < 200 m of Whale B. Shore observers noted that this whale turned and moved to the southeast and offshore slightly. A fluke out was noted (the only time one was seen associated with Whale B). This whale continued to feed in same general area.
	2026-2050	C	1	--	1	Theodolite station N of Kialegak Point	Poor visibility prevented observation of mud at the surfacings of whales. Whale B had been followed almost continuously from 1609 to 2042.
8/25	0805-0857	C	4-5	--	--	N of Kialegak Point	Thick fog prevented taking surfacing/respiration data from "Big Valley".
	1020-1220	C	2	2	2	N of Kialegak Point	Surfacing/respiration data taken on one whale for over 1.5 hr and on the other whale for 1 hr. Triangulation data taken at the end of control period.

TABLE 3... (Cont. DATA SUMMARY FOR GRAY WHALE - STUDY 17-27 AUGUST 1985.

Date	Time	Stimulus	No. of Whales Sighted	Sur/Resp Data	Tracking Data	Observation Location	General Observations
8/25	1600-1706	AG 6	2	2	-	N of Kialegak Point	Thick fog prevented taking of triangulation data. Whale N continued feeding until ~1605 when it began traveling. It crossed within 100 m directly in front of the "Nancy H " at 1654; slowed down its traveling speed at 1704.
	1706-1901	C	1	1	1	N of Kialegak Point	Whale N returned to original location and resumed feeding.
8/26	0720-1031	C	2	2	--	Kialegak Point	Both whales feeding until 1021 when they began traveling, possibly in reaction to the presence of the Zodiac.
8-27							Because of worsening weather/sea conditions, observations were terminated at 1017 and we began preparations to leave St. Lawrence Island area.

the same type of air gun source used as in the previous studies. The tests were performed with the air gun vessel moving slowly to simulate the slowly changing level that a whale would experience when a seismic array passed by at some distance.

A chronological summary of the acoustic test periods and control periods used in the study is shown in Table 3.2.

Table 3.3 summarizes observation conditions during the field season. Viewing conditions were generally fair during the period; however, fog, ocean swell, and relatively high sea states hampered observations on several occasions. Very little surfacing and respiration data were collected on 20, 23, 24, and 26 August because of adverse weather and the project ended one day earlier than scheduled, on the morning of 27 August, because of a developing gale.

3.2 Experimental Procedure

This section contains a discussion of the whale behavioral observation techniques together with a summary of the procedures used to measure the acoustic environment and calculate sound stimulus exposure levels where whales were observed.

3.2.1 Overall

The experimental procedure was based on the techniques developed in previous studies of gray whale responses to acoustic stimuli. Both whale movement and respiration data were obtained to determine if behavioral changes occur in response to varying levels of industrial noise. Two research vessels were used. The BIG VALLEY, a 90 ft fishing/utility vessel, served as the primary observation and acoustic measurement vessel. The NANCY H, a 75 ft fishing/utility vessel, was the air gun handling vessel. A 16 ft Zodiac inflatable boat served as a secondary observation vessel when observations close to whales were required.

TABLE 3.2. TEST PERIOD SUMMARY, GRAY WHALE STUDY.

Date/Time		Stimulus	Control Duration	Stimulus Duration
8/18	0935-1016	C	41 m	
	1306-2253	C	9 h 47 m	
8/19	0709-0908	C	1 h 59 m	
	1518-2108	C	5 h 50 m	
	2108-2129	DS-1		21 m
	2129-2239	C	1 h 10 m	
8/20	0730-0851	C	1 h 21 m	
	1216-1713	C	4 h 57 m	
	1915-2330	C	4 h 15 m	
8/21	0724-1142	C	4 h 18 m	
	1142-1212	DS-2		30 m
	1212-1448	C	2 h 36 m	
	1448-1542	DS-3		54 m
	1542-1650	C	1 h 08 m	
	1800-1858	C	58 m	
	1924-1950	C	26 m	
	1950-2057	DS-4		1 h 07 m
	2057-2149	C	52 m	
8/22	0730-1440	C	7 h 10 m	
	1440-1600	AG-1		1 h 20 m
	1600-1710	C	1 h 10 m	
	1731-1758	AG-2		27 m
	1758-1851	C	53 m	
8/23	0730-1201	C	4 h 31 m	
	1446-1851	C	4 h 05 m	
	1851-2240	C	3 h 49 m	
8/24	0735-1203	C	4 h 28 m	
	1606-1715	C	1 h 09 m	
	1715-1758	AG-3		43 m
	1758-1929	C	1 h 31 m	
	1929-2026	AG-4		57 m
	2026-2050	C	24 m	

TABLE 3.2. (Cont.) TEST PERIOD SUMMARY, GRAY WHALE STUDY.

Date/Time		Stimulus	Control Duration	Stimulus Duration
8/25	0805-0857	c	52 m	
	1020-1220	c	2 h 00 m	
	1220-1323	AG- 5		1 h 03 m
	1323-1600	c	2 h 3 7 m	
	1600-1706	AG-6		1 h 06 m
	1706-1901	c	1 h 55 m	
8/26	0720-1031	c	3 h 11 m	

Total Time: Control (C) 80 h 03 m, Drillship (DS) 2 h 52 m, Air Gun (AG) 5 h 36 m

TABLE 3.3. SUMMARY OF OBSERVATION CONDITIONS, 17-27 AUGUST, 1985, ST. LAWRENCE ISLAND, ALASKA.

17 August	Fair visibility early p.m. with BF* = 0, but 95% cloud cover causing glare. Wind increasing WSW 10-15 kts by late p.m. with BF = 1-2, visibility good with 100% cloud cover. Fair visibility with low light at end of observations.
18 August	Fair to good visibility in a.m. with winds increasing out of the ESE to 20 kts. BF 1-2 at start increasing to 4-5 with 100% cloud cover. Winds shift to WNW early p.m. then to NNE increasing to 40-45 kts by 1900. Cloud cover 50-100% during p.m. BF = 4-5 in p.m. with fair to poor visibility.
19 August	Fair to poor visibility early a.m. with wind N at 15-20 kts. Seas BF = 3-4 with 95-80% cloud cover. Winds up to 30 kts out of the NE by late a.m. with slight drizzle, BF = 6 with 100% cloud cover. Winds down to 15-20 kts out of the NE by mid-day. Visibility poor to fair rest of day with varying amounts of rain and winds out of the N,NE at 15-25 kts. 100% cloud cover.
20 August	Limited visibility with some fog/drizzle with wind increasing out of the SW to 8 kts by mid-day and some swell. 100% cloud cover with BF = 1. SW winds building to 15-20 kts by 1600 with BF up to 3-4 and rain. Winds decrease but by late p.m. shifted to NW up to 25 kts. Rain, poor visibility with 100% cloud cover.
21 August	Good visibility in a.m. with winds out of the NNW at 5-8 kts. Cloud cover 20% with fog to east. Early p.m. seas BF = 2-3 with wind NW at 10 kts shifting to SW at 10 kts and then back to NW at 7-9 kts at 1512. Visibility fair to good in p.m. with seas BF = 3 decreasing to BF = 1. Cloud cover 20-60% in p.m.

*Based on a 12 point Beaufort scale (Couper 1983).

TABLE 3.3. (Cont.) SUMMARY OF OBSERVATION CONDITIONS, 17-27 AUGUST, 1985, ST. LAWRENCE ISLAND, ALASKA.

22 August	Fair visibility in a.m. with low contrast, 95% cloud cover. Light E,NE wind early in a.m. increasing to N 3-5 kts by mid a.m. Good visibility by mid-day (low contrast/fog to NE and NW made viewing fair in those directions) continuing throughout rest of observations. BF = 0-1 entire day with 100-90% cloud cover. Limited time period in mid p.m. when glare affected visibility.
23 August	Fair to poor visibility most of a.m. with wind out of the W,SW at 8-12 kts. Strong 1 m swell by mid a.m. with steady rain. Early p.m. fair visibility with BF = 2. Winds shifted throughout rest of observations, usually staying between 5 to 8 kts. Visibility increased to good but by late p.m. mist/fog and rain made viewing poor. Cloud cover 100% all day.
24 August	Poor visibility much of a.m. with fog/low contrast. Wind out of the SE at 4-6 kts with large swell. By late a.m. BF = 3 with a 1 m swell. Viewing from shore was good out to 1-2 km with low light decreasing visibility by end of observations. Conditions on the water were good inshore but rough water/wind prevented effective offshore observations.
25 August	Poor visibility in early a.m. with mist/fog and low contrast. BF = 2 with wind out of the W at 5-7 kts. Increasing visibility out to 300 m by mid-day. During p.m. visibility stayed generally fair with wind out of the S, increasing to SW 10 kts by end of observations. Seas up to BF = 3-4 by mid p.m. Cloud cover 100% all day with drizzle during a.m. and early p.m.
26 August	Visibility conditions decreased throughout the day with seas reaching BF = 5-6 by mid p.m. and wind out of the S at 15+ kts. Cloud cover 100% all day with mist.
27 August	Visibility poor with seas BF = 4-5 and wind out of the S at 25 kts.

Daily observations usually began between 0730 and 0800 with two observers stationed on the flying bridge of the BIG VALLEY (height above water approximately 7 m) noting whale distribution in the general area. Observations ended at varying times between 1901 and 2330 (see Table 3.1). During some days it was necessary to actively search for gray whales over a large area. This usually required an approximate 4 hr transit between Kialegak Point and Kangeeghuk Bay, the two areas where most of our observations took place. At times, observers used the Zodiac to locate whale concentrations. Personnel on board the NANCY H, the air gun support vessel which arrived in the study area on 22 August, also assisted in locating whale groups.

During the first three days of the field season, observations were conducted from the BIG VALLEY. The following data were recorded:

Location of whales relative to BIG VALLEY

Surfacing, respiration (or blow), and dive times of whales (see Section 3.2.2 for definitions)

General heading of whales

Behavior, including presumed feeding (presence of mud, birds, and/or surfacing and diving in same general location), milling, active travel, and surface active behaviors (see Section 3.2.2. for definitions)

Individual identifying characteristics (e.g., scars and coloration pattern)

Loran position of BIG VALLEY and depth of water

The number of whales in the general area and observation conditions were recorded on an hourly basis or when a change occurred.

We refer to individual whales as "focal" whales when, during the two-boat experiments, both Zodiac and BIG VALLEY observers were tracking the whale (or whales), were noting all behaviors including surfacing, respiration, and dive times, and observed the whale (or whales) over a time period encompassing all or part of a control period and an experimental period. We borrow the term "focal" from Altmann (1974), however, the selection of focal whales was not random nor did we use set sampling periods (i.e., focal-animal sampling, Altmann 1974, p. 242).

Observation personnel consisted of 3-4 observers at any one time, with 2-3 observers surveying the area for whales, noting the surfacing, blow, and dive times of from 1-3 focal whales, and one person recording the data in real time. One of the whale observers was responsible for noting the water depth and the position of the BIG VALLEY. Visual observations were made with binoculars (various powers) and by unaided eye.

From 21-23 August and 25 August during which time the two-boat experiments were conducted, observers worked from both the BIG VALLEY and the Zodiac.

Four observers were stationed on the BIG VALLEY with the following responsibilities: theodolite (Topcon DT-20) operator, data recorder; whale observer/communications coordinator, and one person noting, at two minute intervals, Loran position and magnetic heading of the BIG VALLEY, radar range and bearing to the Zodiac and the NANCY H, and water depth. In practice, the theodolite operator and to a lesser extent the data recorder served as second and third observers. Personnel were rotated periodically. It was often difficult to determine if the whales were feeding because of observer height above water and distance to whales. Observers attempted to scan the entire area around the BIG VALLEY to assess whale distribution during control and experimental conditions, however this was not always feasible.

The Zodiac crew consisted of three individuals with the following responsibilities: boat operator/communications coordinator/observer, binocular compass (Fujinon model 7 x 50 MTRC)/ observer, and data recorder, who would assist in observations as time permitted. The Zodiac personnel attempted to note all surfacing, blow, and dive times of focal whales as well as their behavior, heading, and distance from boat. Observers also took depth readings (Lowrance X-15 depth sounder, 100 kHz) at periodic intervals near whales presumed to be feeding.

Previous studies have shown that gray whales can be individually identified by various morphological characteristics (Hatler and Darling 1974, Swartz and Jones 1978, 1980, and Darling 1984). Noting distinguishing features of whales proved useful and enabled observers on board the Zodiac to follow some individuals for relatively long periods of time; in one case for 7.2 hr (Whale E on 22 August). Two whales were seen in the same general area for periods longer than one day, thereby indicating at least short term site fidelity (Würsig, Wells, and Croll 1983, 1986). One whale observed on 22 August was noted again on 26 August and another whale observed on 21 August was again seen on 22 August.

We observed two mother/calf pairs (possibly the same) on 19 August, and a whale on 20 August was a small possible yearling. All other whales observed were judged to be adults (see Table 3.1 for number of whales sighted each day). Würsig, Wells, and Croll (1983, 1986) observed no calves during their work in the same area in July and September 1982.

During the course of the field season we observed a number of other marine mammal species, most notably spotted seals (*Phoca largha*) and up to ten minke whales (*Balaenoptera acutorostrata*), with five seen during a 1 hr period on 22 August near Kialegak Point. We did not observe any interactions between gray whales and these species. Seabirds were also prevalent during the study, with numerous black-legged kittiwakes (Rissa tridactyla), red-necked phalaropes (Phalaropus lobatus), and several immature Sabine's gulls (Xema sabini) associated with presumably feeding gray whales. These birds tended to follow gray whales, landing on the water's surface near surfacing whales, presumably taking advantage of food items brought to the surface. Both black-legged kittiwakes and red-necked phalaropes have been observed with feeding gray whales in the northern Bering and southern Chukchi Seas (Harrison 1979, Wilke and Fiscus 1961). However, Sabine's gulls have only been reported with one feeding gray whale sighted on 24 August 1980 in the Canadian Beaufort Sea (Rugh and Fraker 1981).

3.2.2 Behavior observation measures

Measurements of the surfacing, respiration, and dive cycles have proven useful in quantifying the behavior of large baleen whales (Harvey and Mate 1984, Würsig et al. 1984, Würsig, Wells, and Croll 1986) and have provided one means of assessing the effect of underwater noise from industrial and related activities on bowhead whales (Richardson et al, 1985; Richardson, Würsig, and Greene 1986) and humpback whales (Baker et al. 1983, Dean et al. 1985).

To assess the possible effects of air gun and drillship operations on the behavior of gray whales on the feeding grounds, we measured the following surfacing, respiration, and dive cycle variables (after Würsig et al. 1984, 1986) under control and experimental conditions: 1) Blow Interval - time between respirations while the whale is at the surface; 2) Length of Surfacing - time that the whale is at the surface discounting shallow submergence between respirations; 3) Length of Dive - time that the whale is below the surface between surfacings; 4) Number of Blows per Surfacing; and 5) Blow Rate - the number of blows per minute calculated from length of surfacing, length of dive, and number of blows per surfacing.

As outlined in Section 3.1.2, we also noted if whales were engaged in the following activities: 1) Feeding - the presence of mud, birds, and/or regular surfacing and diving in the same location; 2) Travelling - concerted movement in a particular direction; 3) Milling - movement at or near the surface accompanied by many direction changes; 4) Socializing - two or more whales within 1/2 body length (7-8 m) of each other and interacting in some way; and 5) Surface Active Behavior - breaching, pectoral slapping, etc. Because of small sample sizes, we were unable to compare statistically the frequency of these behaviors during control and experimental conditions. In Section 3.4.1, we mention these various behaviors in our narrative descriptions of the results of specific drillship and air gun experiments.

3.2.3 Measurement of whale positions and whale movement patterns

Most whale positions were ascertained by triangulating with a shipboard theodolite and binocular compasses, a technique developed by Malme et al. (1985) to study feeding humpback whales in Frederick Sound, Alaska. This procedure is shown in Fig. 3.2. On 24 August, when whale location and observation conditions were optimal, we were able to track feeding gray whales with a theodolite from a land-based station, 81.38 m high, approximately 2 km north of Kialegak Point (see Wursig 1978 and Tyack 1981 for a description of this technique). A total of six whale groups were tracked, with one whale followed for 4.7 hr. Observers using the Zodiac collected very limited surfacing and respiration data on two of these groups because of rough seas and problems with identifying individual whales.

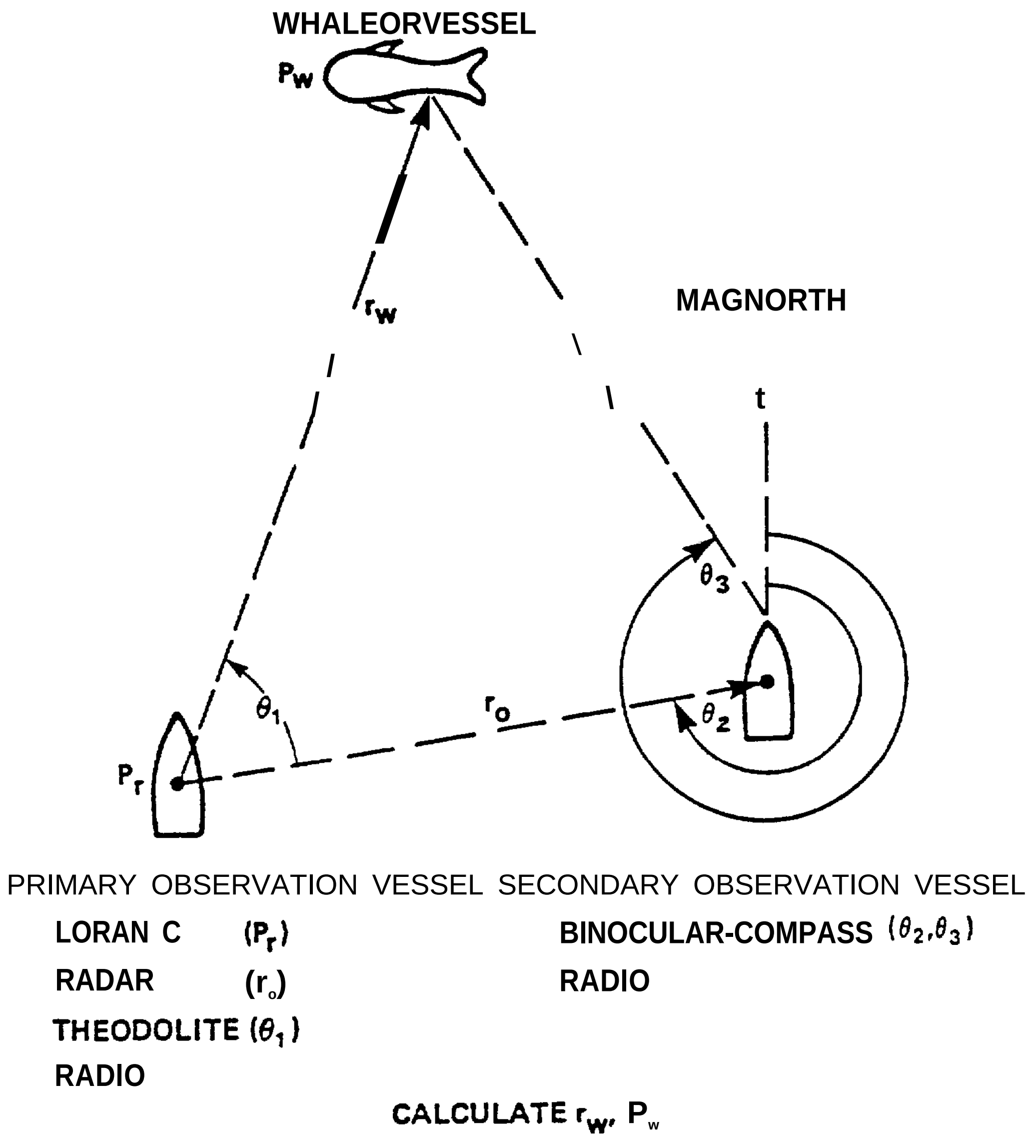


FIG. 3.2. WHALE TRACKING USING OBSERVATIONS FROM TWO VESSELS.

3.2.4 Acoustic environmental measurements

Navigation

A Northstar Model 6000, Loran-C on the BIG VALLEY was used to obtain absolute position references for the whale sighting data. A Furuno Model LC-80, Loran-C on the NANCY H provided position information for the air gun vessel. The radars on both vessels were used to coordinate the Loran track data and obtain position information on the whale observation vessel (Zodiac).

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 a position just off the bottom. The measured data were then used to calculate the sound velocity profile using Wilson's equation (discussed in Sec. 3.3.2).

Wave height was estimated visually.

Ambient Noise Measurements

A standard hydrophore system that combined an ITC Type 6050C hydrophore with a low-noise preamplifier and tape-recorder was used to obtain ambient noise data. The hydrophore 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 flat from 20 Hz to 15 kHz. All components of the system were

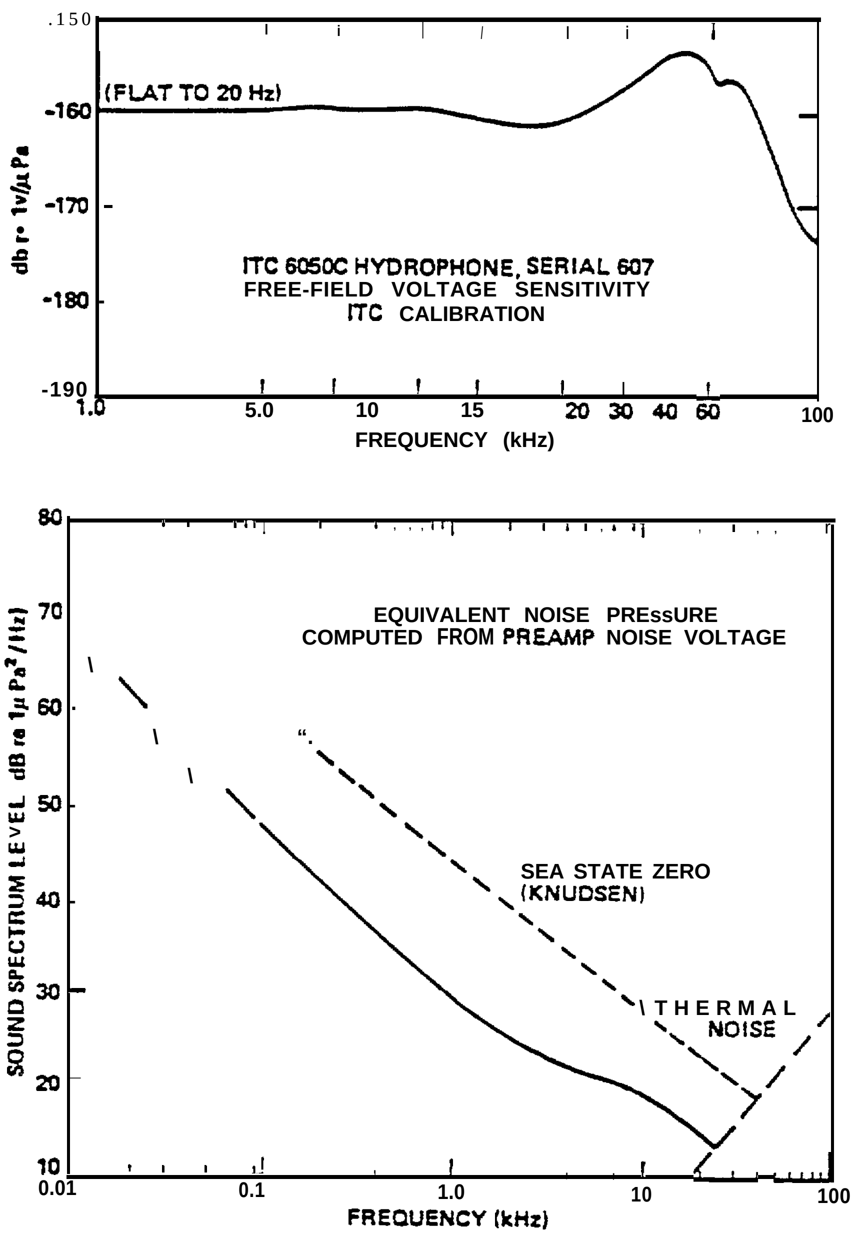


FIG. 3.3. MEASUREMENT HYDROPHORE CHARACTERISTICS.

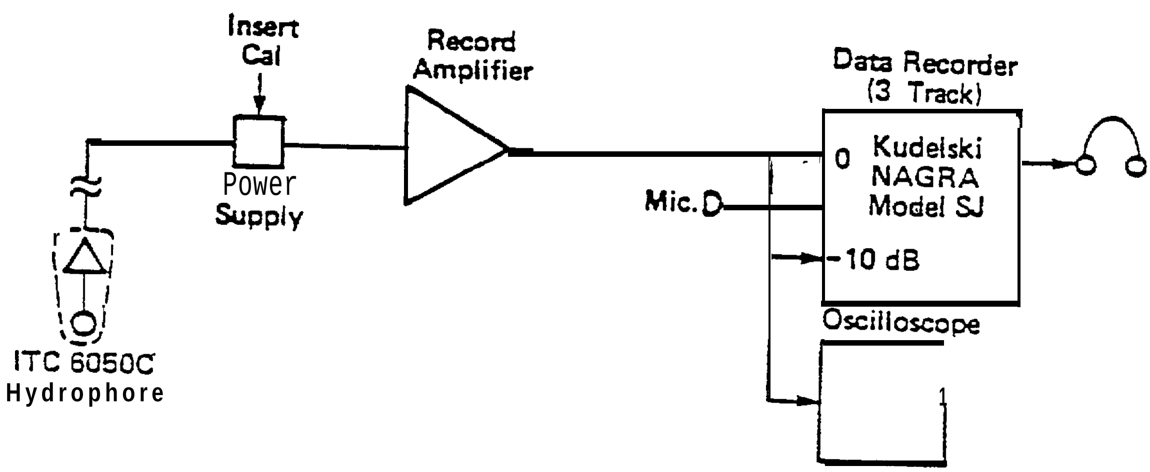


FIG. 3.4. ACOUSTIC MEASUREMENT SYSTEM

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 hydrophore.

Transmission Loss Measurements

Transmission loss (TL) information was obtained by measurements using the air gun source. Data were obtained for several ranges extending from 0.15 km to 4 km. 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 hydrophore. Transmission loss was then determined as the difference between the received sound energy level and the previously determined source energy level as the range from the source to the receiving hydrophore was increased.

3.2.5 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 a boom on the BIG VALLEY. 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 hydrophore (Celesco LC-10) was mounted at a distance of 1 m from the projector system to monitor the calibration of the projected sound levels.

During a playback sequence, a pre-recorded, 15-min. duration, 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.

Stimuli Projection and Monitoring

The drillship playback stimulus used in this study was the same recording used for the previous gray whale studies. Playback at a source level comparable to the original drillship output was not feasible because of projector power limitation. However, the playback levels used were high enough to insure a signal level of 111 to 117 dB re 1 μPa was obtained at a range of

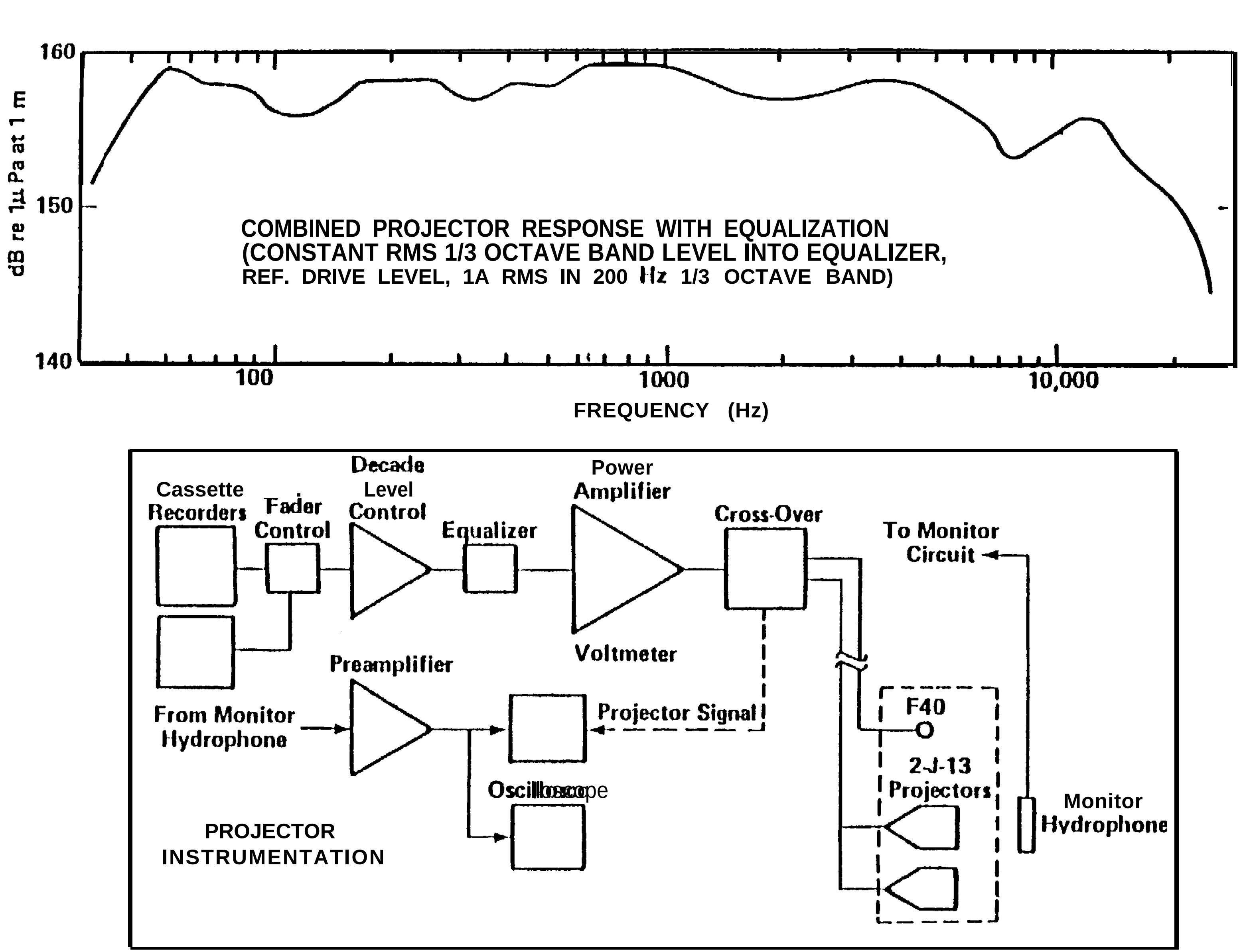


FIG. 3.5. PLAYBACK INSTRUMENTATION.

1 km. A level of 117 dB was observed to produce a 0.5 probability of avoidance for migrating whales (Malme et al, 1984). Because of the relatively low ambient noise level, an effective range of 6 to 8 km was obtained to the zone where the playback level became approximately equal to the ambient noise level. A comparison between the playback level and the original source level is shown in Table 3.4. The playback sound levels were subsequently scaled to the level reported for the actual source and range corrections were derived by using the measured transmission loss at the test site. This procedure is described in detail in Sec. 3.3.5.

Table 3.4 lists the maximum measured level for the stimulus as originally recorded. This sound level is based on the reported data for the actual tape dub 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.

The sound level output produced during playback is compared with the original sound source values in the last column of the table. The drillship stimulus 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

TABLE 3.4. PLAYBACK STIMULI INFORMATION.

Stimulus (Code)	Original Recording Dist. Meters	Dominant Frequencies Hz	Reported Level dB/µPa	Est. 100 m Level dB//µ Pa	Playback 100 m Level dB//µ Pa	Difference (PB-Orig) dB	Data Ref.
DRILLSHIP (DS)	185	278 (t)	123	126	122	-4	Greene 1982
(EXPLORER II)		50-315 (bb)	133	136	127	-9	(P. 322)

Key:

(t) tonal, (bb) broadband

in Sec. 3.3.5 using the measured TL and ambient noise data for the observation site.

3.3 Acoustic Measurements and Results

This section contains a description of the acoustic measurements made during the August 1985 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 and humpback whales (Malme et al. 1983, 1984, 1985). Some of the discussion in these previous reports will be included here to facilitate understanding of the results and minimize the need to refer to the earlier reports.

The test procedure requires establishment of a controlled sound field in a region where feeding gray 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.

3.3.1 Acoustic source characteristics

The air gun and playback projector system were identical to those used in the August 1984 study, (Malme et al. 1985). A description of these sources was given previously in Sec. 3.2.5.

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 average 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)

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

where

ρc = the specific acoustic impedance of water

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

$\bar{P}$ = the average pulse pressure

T = the average pulse duration (the time required for $p^2(t)$ to decay to less than 13.5% of the initial value) .

Generally it is more convenient to express acoustic pressure in logarithmic terms. Consequently, the average pulse pressure level is defined as

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

where

P_{ref} = 1μPascal.

A Hewlett Packard Model 3562A signal analyzer was used to analyze air gun signals to obtain the average pulse pressure. This instrument performed signal capture, squaring and integrating functions to determine the total acoustic energy of the pulse. The time duration of the signals was determined by measurement of the integrated signal envelope on the analyzer display, Figure 3.6 illustrates a typical air gun signature and the analysis procedure.

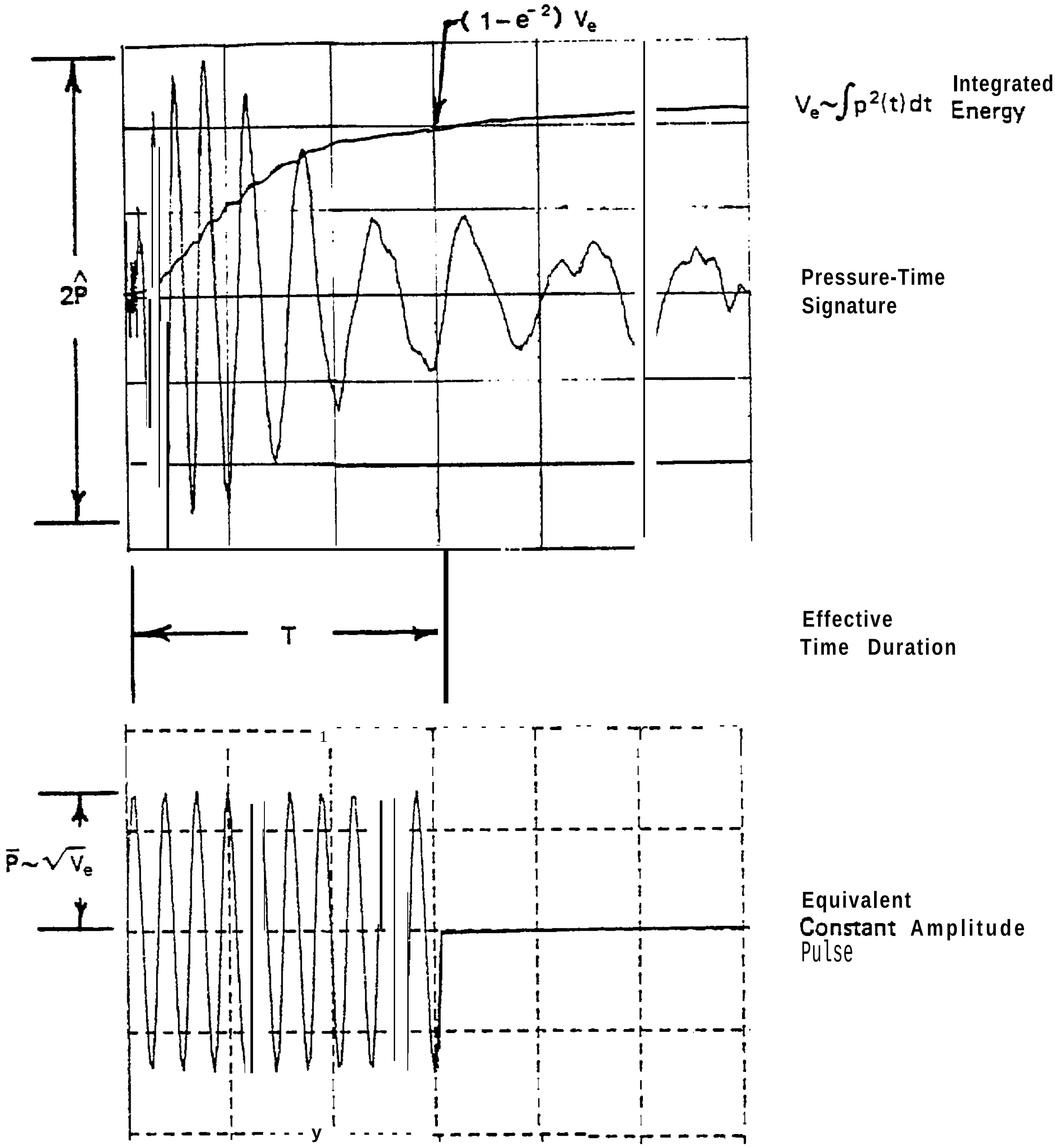


FIG. 3.6. ANALYZER RECORD SHOWING PULSE SIGNATURE AND INTEGRATED PULSE ENERGY .

Air Gun Signature Analysis

The Model 3562A analyzer was also used to analyze the energy spectrum of the air gun signatures at various ranges. The time waveforms of the pulses were also recorded to obtain peak pressure data and examine time duration as a function of range. For bottom conditions where multipath and high reverberation conditions occur, the time duration of a transient signal increases with increase in range. This was observed to occur at the California test site (Malme et al. 1983). However, at the St. Lawrence Island sites, the signal reverberation was much less, even though the bottom loss factors were appreciably smaller than those measured off California. For the relatively short transmission ranges used, the pulse time duration was observed to remain nearly constant, or even decrease with increasing range. A comparison of acoustic transmission parameters for the St. Lawrence Island test area is presented in Table 3.5.

The air gun was operated at ranges to the hydrophore of 4 km to 130 m at a firing rate of 6 pulses/rein. 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.

Playback System Response Measurement

As described previously in Sec. 3.2.5, 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. 3.7 for the drillship stimulus.

TABLE 3.5. AIR GUN PULSE PARAMETERS VS RANGE FOR REPRESENTATIVE TRANSMISSION DATA NEAR ST. LAWRENCE ISLAND.*

Range (km)	L_E (dB re 1μPa²sec)	T (sec.)	$L_{\bar{p}}$ (dB re 1μPa)	$L_{\hat{p}}$ (dB re 1μPa)	$L_{\hat{p}} - L_E$ (dB)	$L_{\hat{p}} - L_{\bar{p}}$ (dB)
.37	160.6	.02	180.6	183.2	22.6	2.6
.41	158.2	.031	176.2			
.65	155.8	.03	174.0	176.9	21.1	2.9
.93	152.5	.065	167.4			
1.3	148.6	.03	166.8	170.6	22.0	3.8
1.6	146.0	.03	164.2	167.6	21.6	3.4
2.2	143.6	.033	161.4			
2.6	139.5	.036	159.9	161.1	21.6	1.2
				Mean	21.8	2.8

Key: L_E = Total Pulse Energy Level

T = Effective Pulse Duration

$L_{\bar{p}}$ = *Average* Pulse Pressure Level

$L_{\hat{p}}$ = Peak Pulse Pressure Level

*Data for 8/25/1221-1254

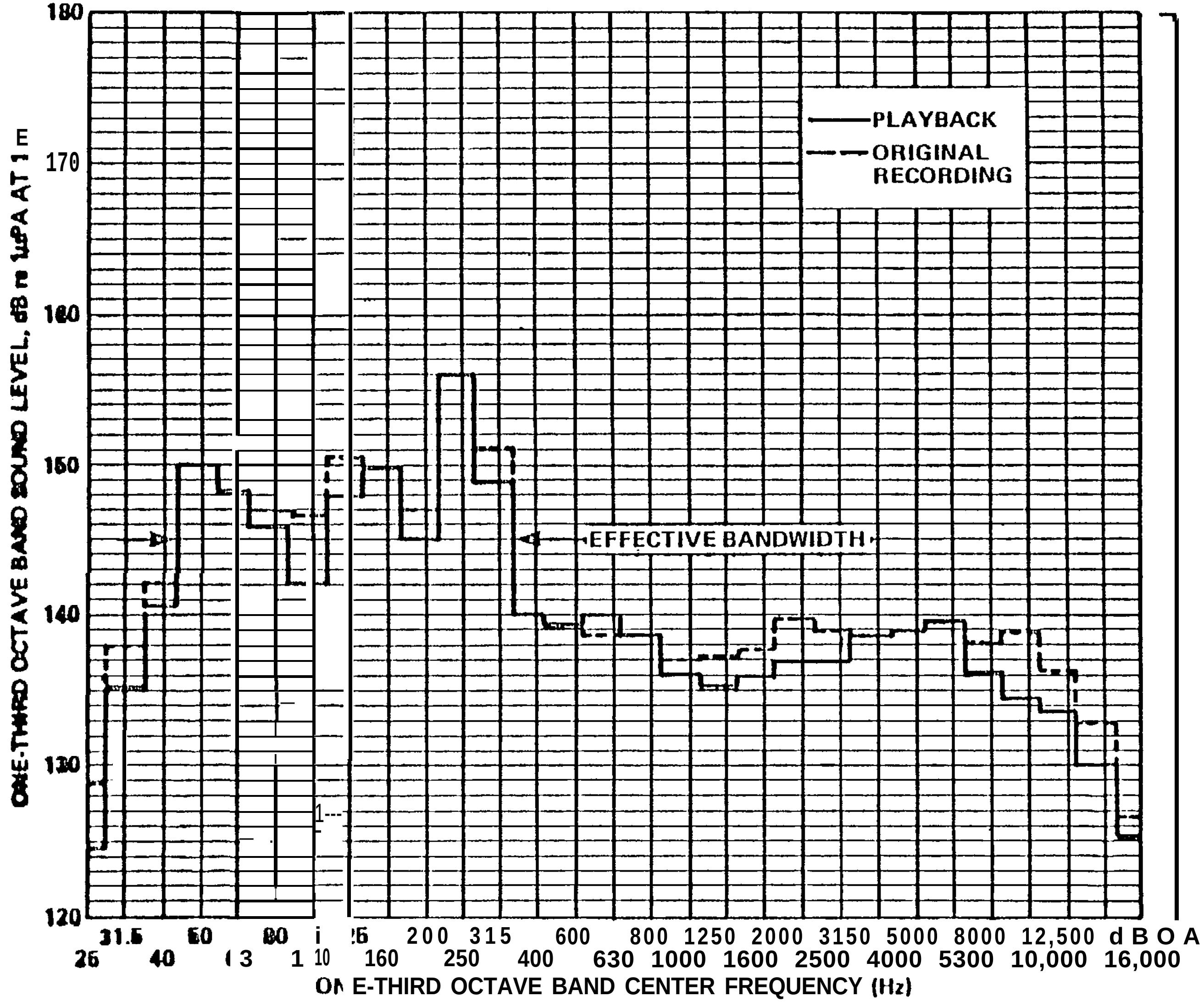


FIG. 3.7 DRILLSHIP ONE-THIRD OCTAVE SPECTRA.

3.3.2 Transmission Loss Measurements

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 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:

$$RSL = L_s + A_n - 5 \log H_{av} - 15 \log R - A_vR - A_rR/H_{av} - 41 \text{ (dB re 1}\mu\text{Pa)} \quad (3)$$

where

RSL = Received sound level at range R (dB re 1μPa)

L_s = Source level (dB re 1 μPa at 1 m)

R = Range in km

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

A_r = Reflection loss at surface and bottom (dB - meters per km)

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

-41 = Conversion constant (5 log $2\pi - 15$ log m/km)

$H_{av} = (H_s + H_r)/2$ where H_s = depth at source (m) and H_r = depth at receiver (m).

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 was not the case for the test area near St. Lawrence Island. Bottom reflection characteristics were found to be somewhat variable in this area. 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.

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:

$$c = 1449.2 + 4.623T - 0.0546T^2 + 1.39(S-35), \text{ (m/See)} \qquad (4)$$

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 25 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 20 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 3.8 through 3.10 give typical sound velocity, temperature and salinity profiles in the test area. Most of the data are similar to measurements taken in the inlets of southeast Alaska where water with lower salinity, is often present in a surface layer. Near the surface, lower salinity and warmer temperature conditions produce opposing effects on the speed of sound. The sound velocity profiles shown in Fig. 3.8 result when the temperature is high enough near the surface to offset the effect of lower 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 lower salinity layer near the surface may be the result of the outflow from the Yukon River and other large streams which flow into the Bering Sea. Tidal mixing effects cause considerable variation in the observed temperature and salinity gradients in the area. Figure 3.9 shows a set of data taken in approximately the same area as that shown in Fig. 3.8, but one day later. Here the extreme gradients shown in Fig. 3.8 have been considerably reduced in magnitude. Temperature and salinity data were also taken in Kangeeghuk Bay (see Fig. 3.1), which is on the west side of Southeast Cape. Figure 3.10 shows the results for two sets of measurements taken five days apart. The water column can be seen to be very well mixed in this area with only the salinity data showing slight gradient effects. The reason for the dramatic differences in the temperature and salinity gradients between the east side and west side of Southeast Cape may be a result of turbulence in the tidal flow around the point. Kangeeghuk Bay is sheltered from the general tidal flow into the Chirikof Basin by the shoal area extending south from the cape.

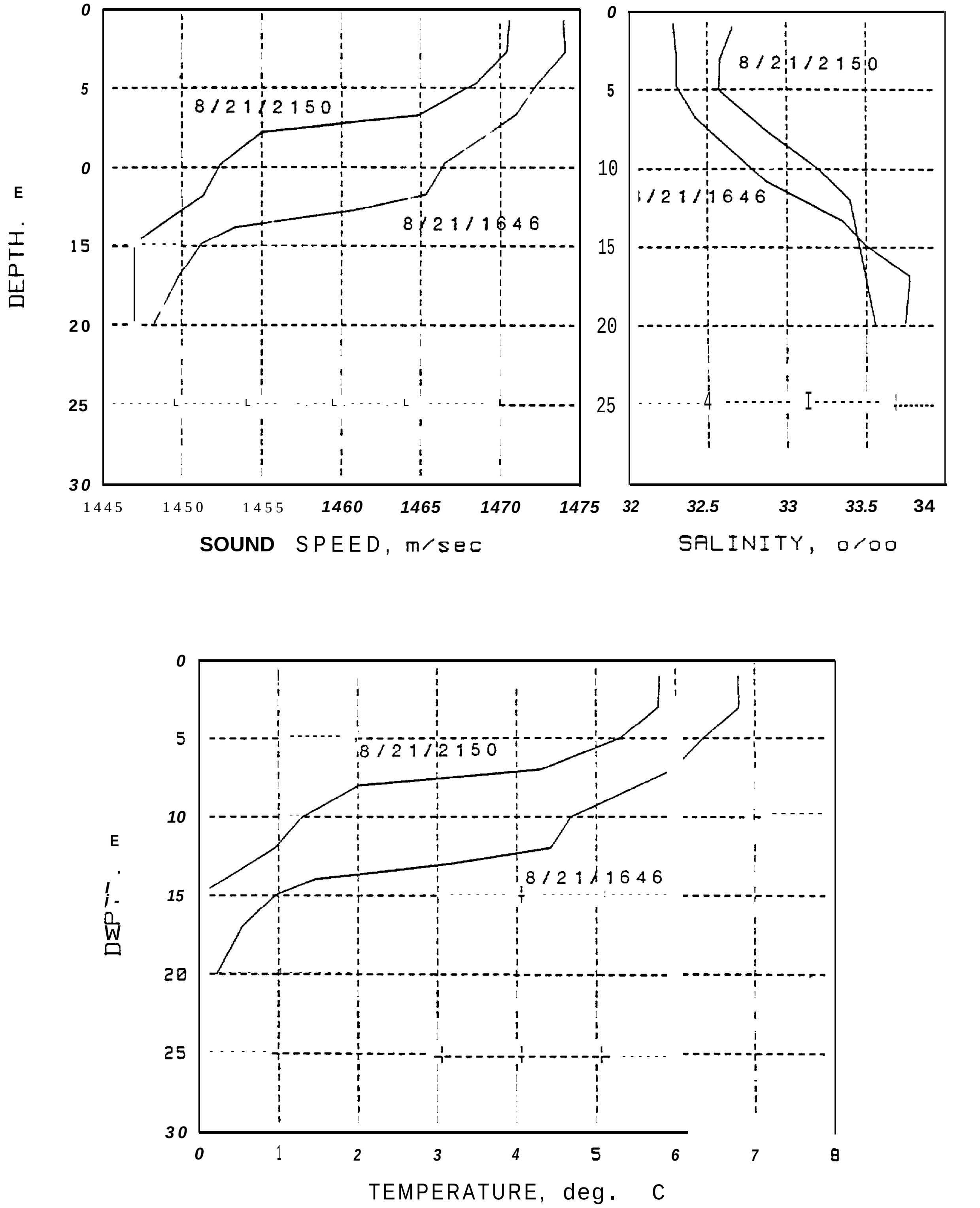


FIG. 3.8. SOUND SPEED, SALINITY, AND TEMPERATURE PROFILES FOR ST. LAWRENCE ISLAND AREA, 8/21/1646, 2150.

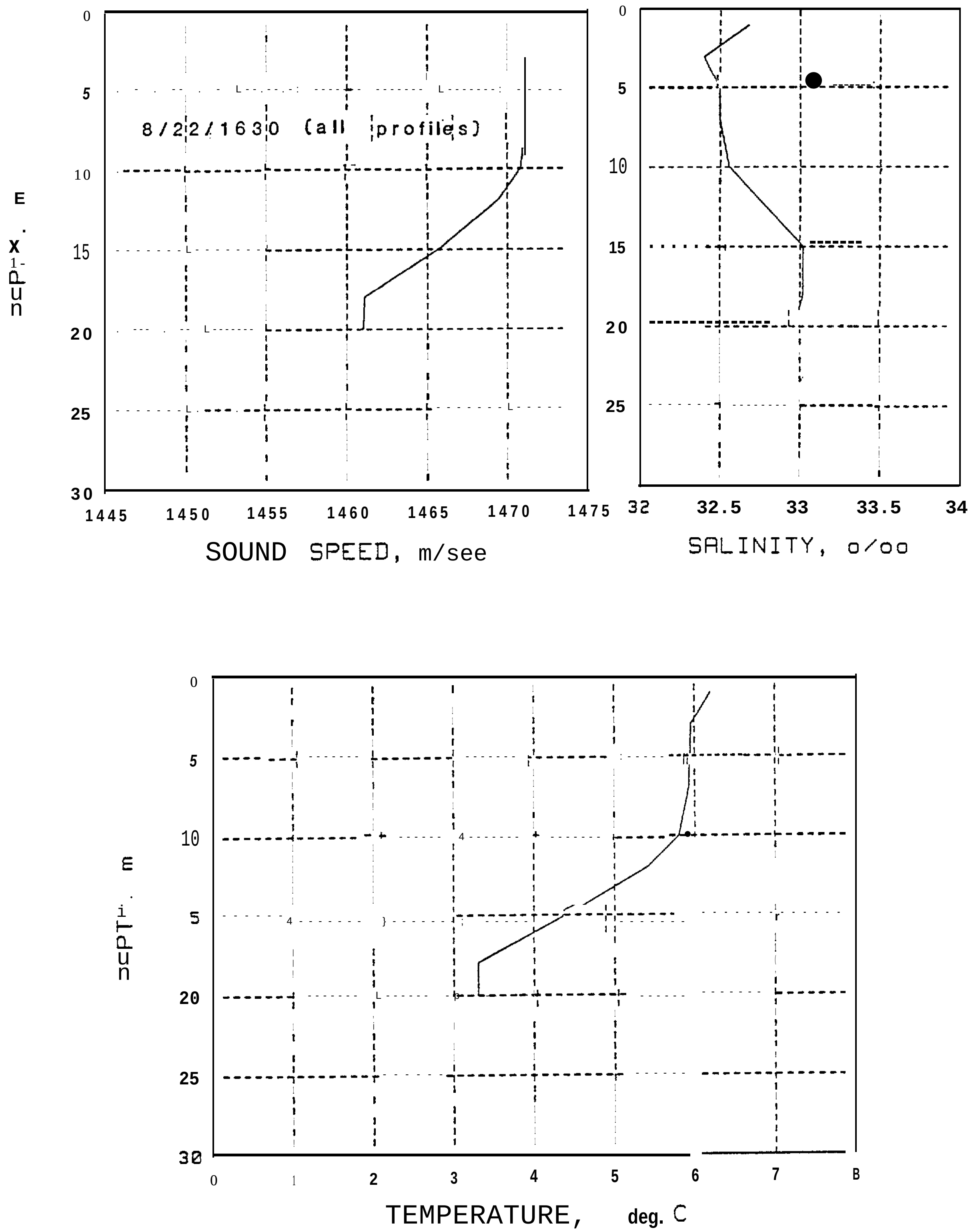


FIG. 3.9. SOUND SPEED, SALINITY, AND TEMPERATURE PROFILES FOR ST. LAWRENCE ISLAND AREA, 8/22/1630.

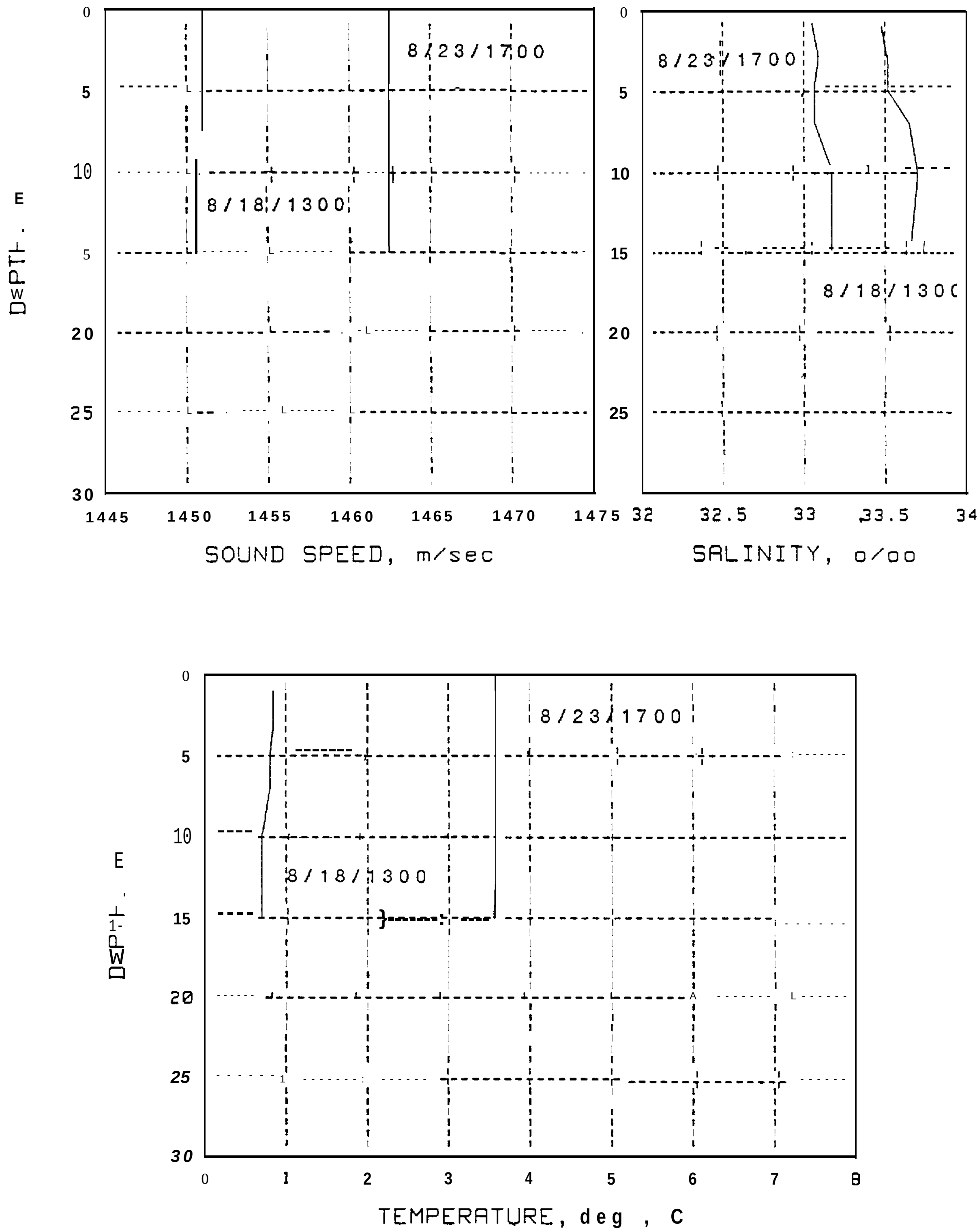


FIG. 3.10. SOUND SPEED, SALINITY, AND TEMPERATURE PROFILES FOR ST. LAWRENCE ISLAND AREA, 8/18/1300, 8/23/1700.

Sound Propagation Measurement Results

Transmission loss measurements were performed concurrently with the whale behavior tests. The air gun was operated at a depth of 10 m which was generally below or near the bottom of the surface layer of warmer, less saline water. Measurements of received level at several depths and ranges did not show the depth dependence expected to be produced by the observed strong downward refracting gradients such as those shown previously in Fig. 3.8. This was probably a result of the shallow water which ranged from 15 to 25 m in depth. Reflections and general scattering from the bottom and probable sub-bottom layers produced generally reverberant received signals.

Figures 3.11 and 3.12 show typical signal waveforms and pressure spectra for two different propagation ranges. The data shown in Fig. 3.11 are for short range propagation where the direct signal and probable sub-bottom reflections can be separated in the observed waveform. The spectrum can be seen to have an effective bandwidth extending from 30 Hz to 500 Hz. Figure 3.12A shows the effect of increased propagation range. Here, the waveform is generally higher frequency in character and has a shorter duration than that seen in Fig. 3.11A. The signal spectrum in Fig. 3.12B shows attenuation of both the low frequency and high frequency portions of the spectrum when compared to the short range spectrum shown in Fig. 3.11B. This demonstrates that sound propagation in shallow water has the effect of a bandpass filter. Low frequencies are attenuated because they often involve propagation through a portion of the bottom sediments with high energy absorption. High frequencies are attenuated as a result of volume absorption, boundary absorption? and boundary scattering. As a result there remains an optimum pass band, from about 100 to 350 Hz in this case, which suffers the lowest absorption losses (Smith 1986).

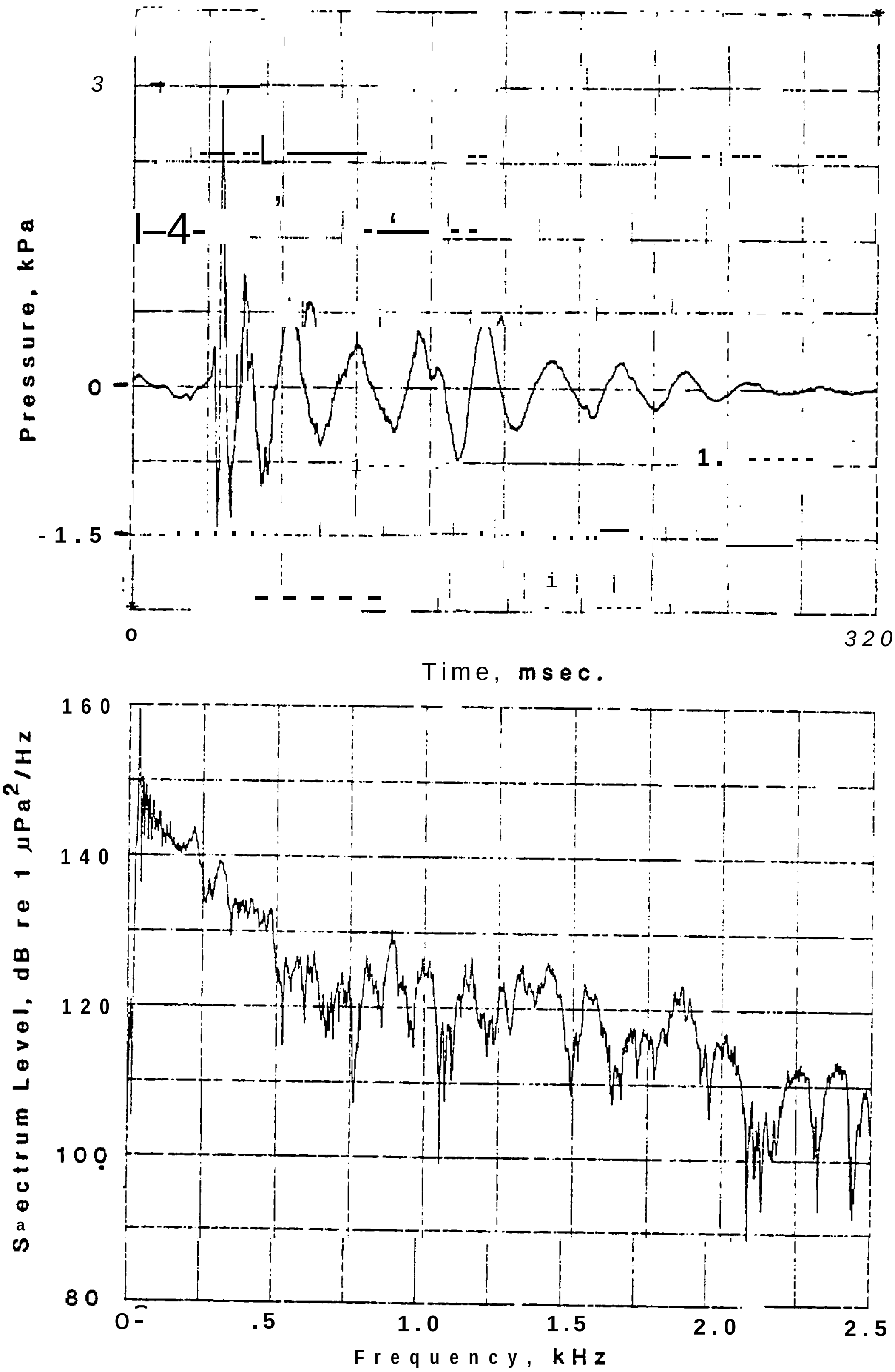


FIG. 3.11. AIR GUN SIGNATURE AND SPECTRUM, 100 in.³, 4500 psi, RANGE 200 m, DEPTH 10 m.

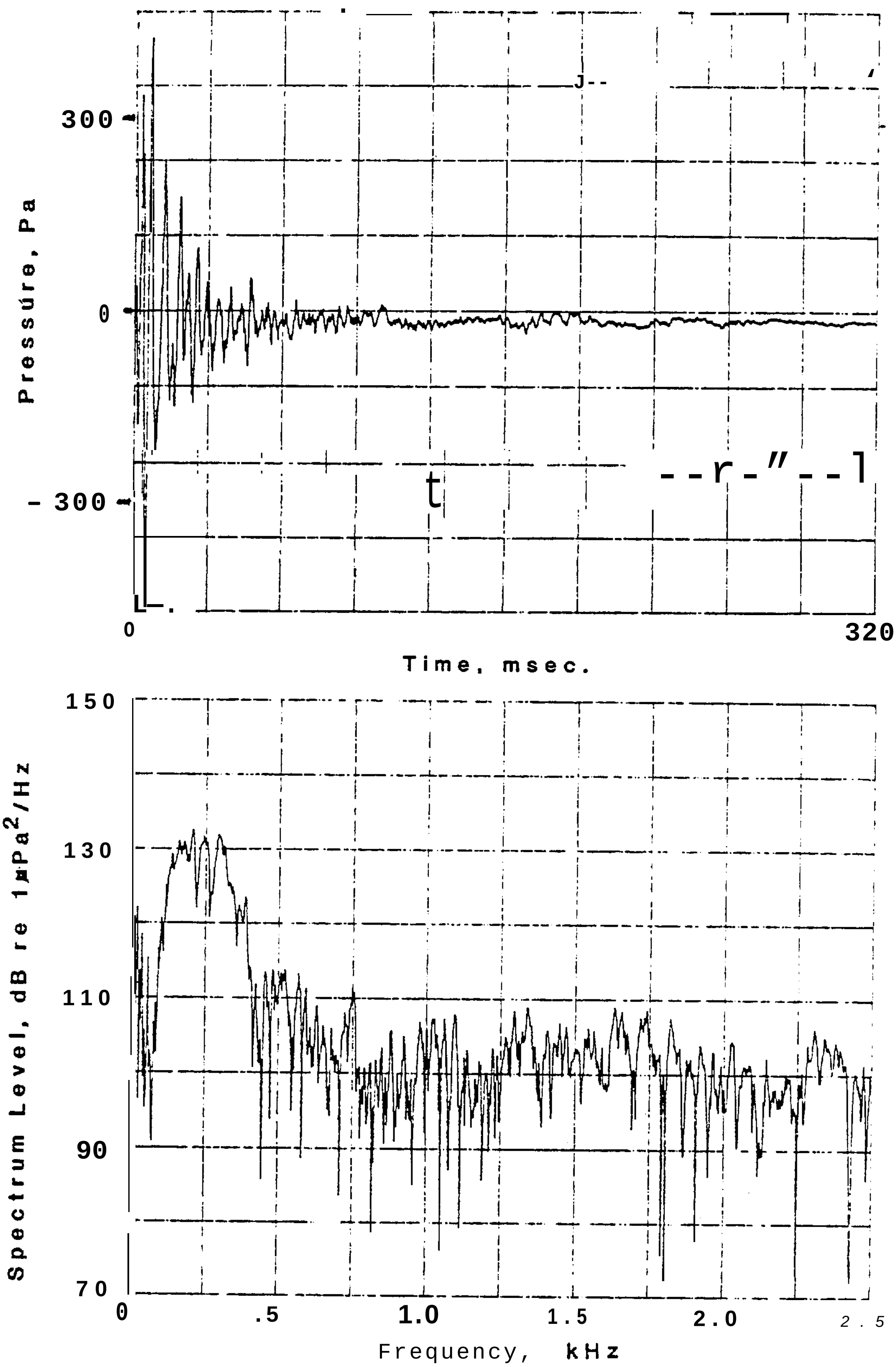


FIG. 3.12. AIR GUN SIGNATURE AND SPECTRUM, 100 in.[3], 4500 psi, RANGE 650 m, DEPTH 10 m.

The transmission loss measured in the St. Lawrence Island area was lower than that measured off the California coast during the migrating gray whale study (Malme et al. 1983, 1984). A comparison of the characteristics of the two areas for average pulse pressure propagation is shown in Fig. 3,13. A shallow sub-bottom layer of rock probably causes the considerably better sound propagation conditions observed off St. Lawrence Island since the bottom composition according to chart information is sand/silt for both areas. While no specific sub-bottom information has been obtained for the St. Lawrence test area, MacKensie (1973) reported underlying layers of granitic and basaltic rock at depths of 3 to 10 m for an area lying to the east of the island.

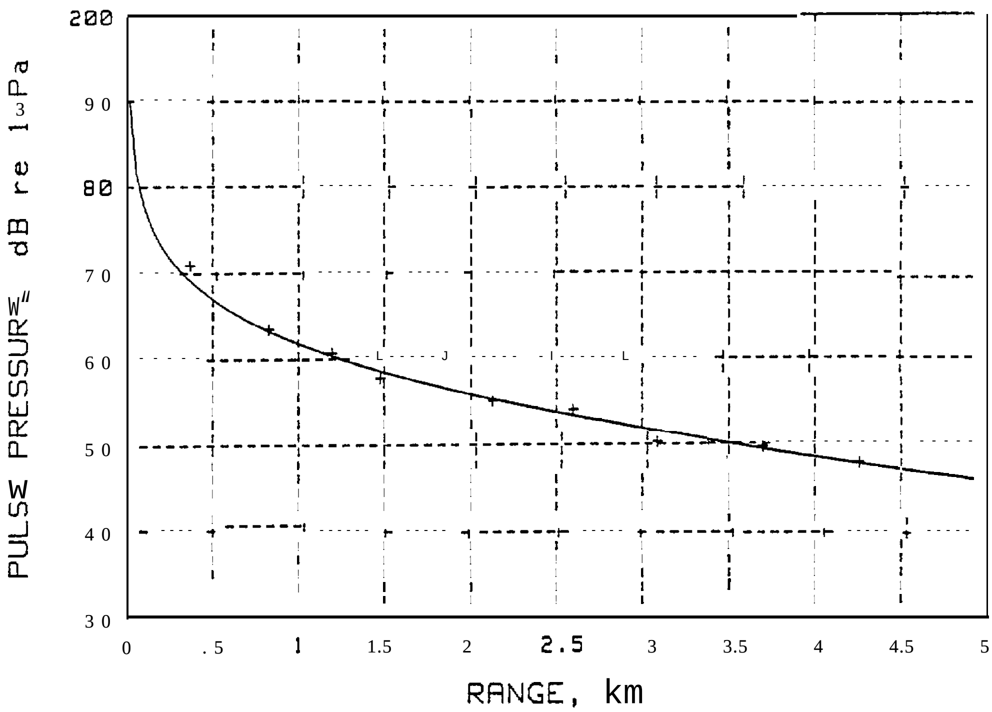
The average pulse pressure level incorporates measures of both pulse amplitude and time duration and is related to the total pulse energy level by the following relationship:

$$L_{\bar{p}} = L_e - 10 \log T \text{ (dB re 1 } \mu\text{Pa)} \quad (5)$$

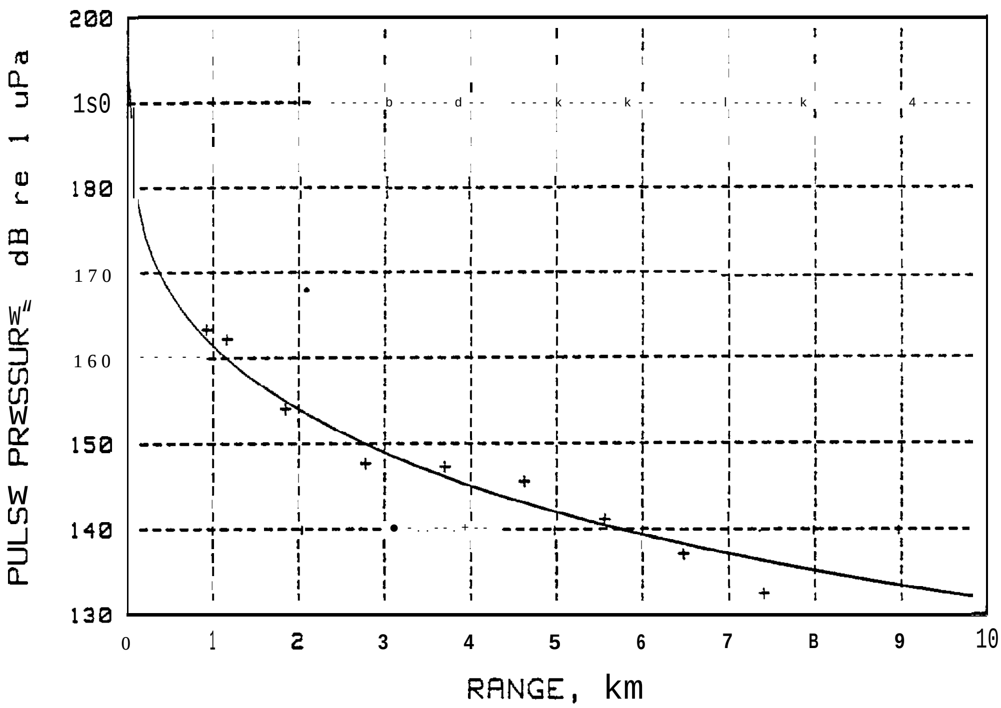
where the total pulse energy level,

$$L_e = 10 \log \bar{P}^2 T/2 - 10 \log \rho c \text{ (dB re 1 Joule)} \quad (6)$$

from Eq. (1). If L_e is referenced to 1 μPa^2-second, the correction term, 10 log ρc can be omitted. The pulse duration is influenced by bottom attenuation, surface roughness, and by multi-path propagation and, as a result, often changes with increasing range. A comparison of the air gun pulse duration characteristics of the California and St. Lawrence test sites is shown in Fig. 3.14A. The transmission loss characteristics as determined using the total pulse energy level from air gun tests

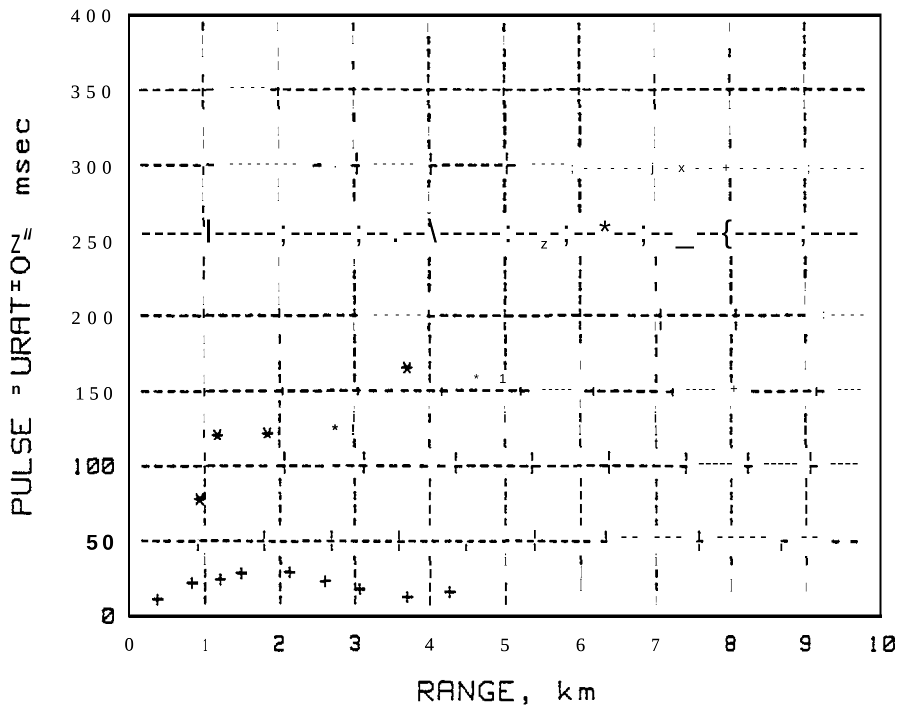


A. St. Lawrence Island Site, Depth 14 m, 0 Slope

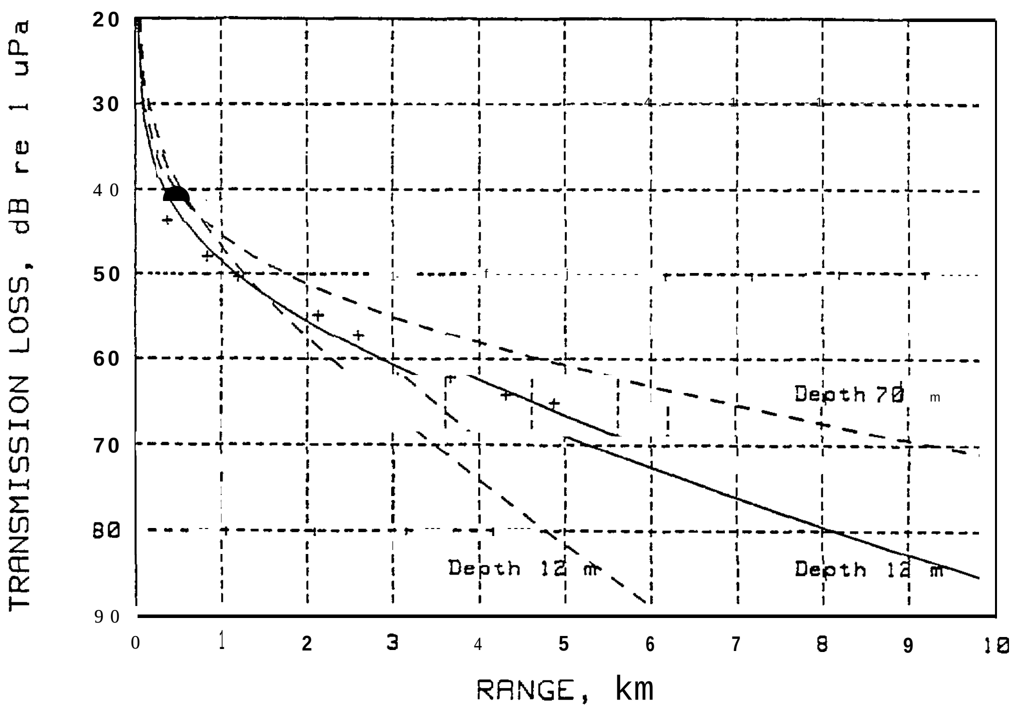


B. California Site, Avg. Depth 70 m, Slope .015

FIG. 3.13. COMPARISON OF AVERAGE PULSE PRESSURE DATA WITH PREDICTIONS OF EMPIRICAL PROPAGATION MODEL. (SOURCE - 100 CU. IN. AIR GUN AT 4,500 PSI.)



A. Pulse Duration, St. Lawrence Is. (+), California (*)



B. Transmission Loss, St. Lawrence Is.(+) ——, California ----

FIG. 3.14. COMPARISON OF PULSE DURATION TIME SPREADING AND TRANSMISSION LOSS CHARACTERISTICS OF ST. LAWRENCE ISLAND AND CALIFORNIA TEST AREAS.

at the California and the St. Lawrence test sites are shown in Fig. 3.14B.

3.3.3 Ambient noise measurements

The ambient noise levels near St. Lawrence Island were determined by the local wind conditions and by the radiated noise from the vessels used in the study. No contributions from biological sources were measured. No definite gray whale vocalizations were heard during the ambient noise monitoring periods. The vessel noise was primarily caused by auxiliary generator operation since all maneuvering during test conditions was done at low speed.

The sea conditions during the acoustic study periods ranged from sea state 1/2 to sea state 2. During periods of higher sea states it was not possible to observe whales properly so testing was suspended. Figure 3.15 shows the one-third octave spectrum for representative ambient conditions. This spectrum is compared with data reported by Urick (1983) for other shallow water areas. The radiated noise source level for the BIG VALLEY is shown in Fig. 3.16. This noise spectrum is primarily caused by auxiliary generator operation and is also typical of that produced by the NANCY H generator. By referring to the transmission loss characteristic for the area, it is possible to estimate that the levels of the highest one-third octave bands will approximately equal ambient noise levels at a range of 3 to 4 km for the conditions existing for Fig. 3.15. The playback spectrum shown previously in Fig. 3.7 is louder than the radiated noise in all one-third octave bands. Thus, the generator operation during playback was not expected to influence the simulated drillship stimulus.

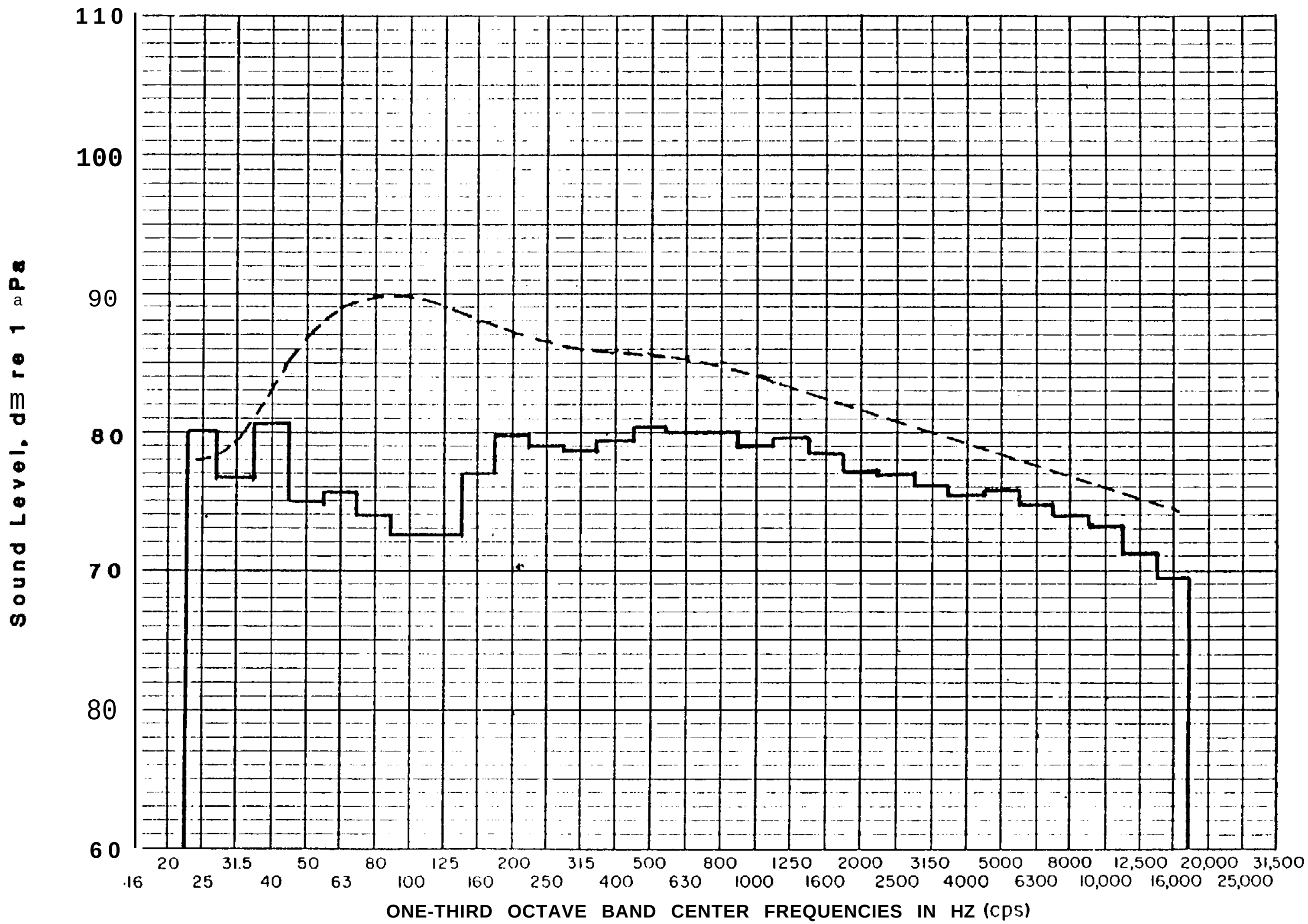


FIG. 3.15. AMBIENT NOISE SPECTRUM FOR ST. LAWRENCE ISLAND TEST AREA. WIND SPEED 10 KTS, DEPTH 12 m. DASHED CURVE FROM WENZ (1962) FOR SHALLOW WATER, 10 KT WIND, MODERATE SHIPPING TRAFFIC.

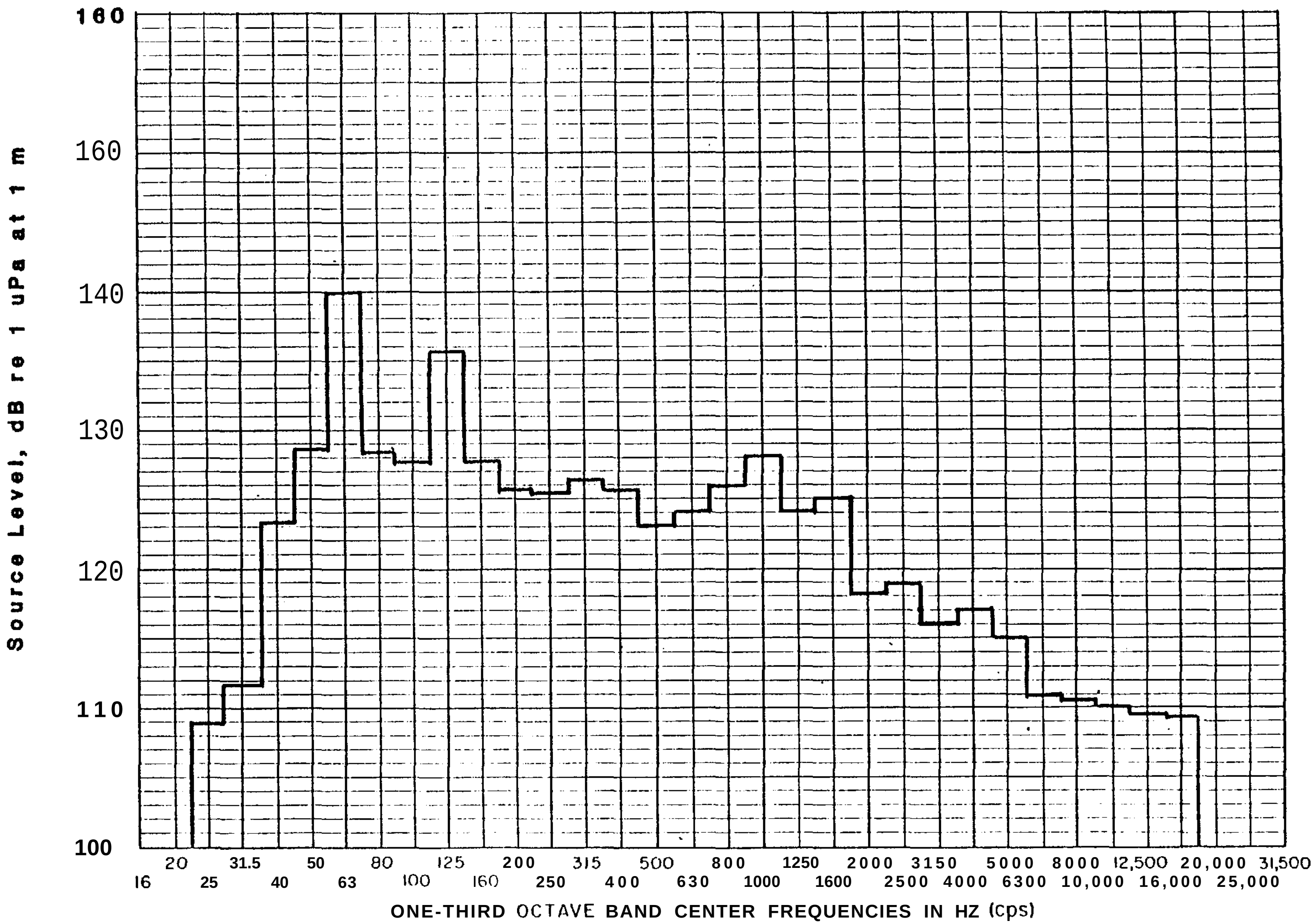


FIG. 3.16. RADIATED NOISE SOURCE LEVEL FOR AUXILIARY MACHINERY ON M.V. BIG VALLEY.

The control periods for the playback and air gun tests were performed with normal auxiliary machinery operating conditions on both the BIG VALLEY and the NANCY H. The air compressor for operating the air gun on the NANCY H was not running during control conditions to conserve fuel. This compressor was mounted on rubber tires and was not expected to contribute significantly to underwater radiated noise.

3.3.4 Acoustic exposure estimation

Since some variation in sound transmission was observed for the several test areas used, specific data from each test area were used in prediction of the sound exposure levels for whale sightings.

Air Gun Average Pulse Pressure

As described previously in Section 3.2.5, the data were analyzed using a computer-implemented least-squares technique which determines the best-fit values for two parameters in the received level equation presented previously as Eq. (3). The values of Ls′ and A_r are determined by the computer using measured data. When the source level is calibrated, the effect of the local bottom and surface conditions on sound propagation can be determined as a local “anomaly” where:

$$Ls' = Ls + An \text{ (dB)} \qquad (7)$$

Here, Ls is the pressure level measured at 1 m from the source and An is the local anomaly resulting from bottom and surface reflection effects.

The results of analysis of the transmission loss measurements are summarized in Table 3.6. The values of An and A_r

TABLE 3.6. SOUND TRANSMISSION PARAMETERS FOR ST. LAWRENCE ISLAND AIR GUN TESTS.

SOUND TRANSMISSION EQUATION

$$L_{p} = L_s + An - 5 \log H_{av} - 15 \log R - A_r(R/H_{av}) - 41 \text{ (dB re } 1\mu\text{Pa)}$$

$$L_s = 213 \text{ dB re } 1\mu\text{Pa at 1 m}$$

Date/Time	An* (dB)	A=* dB-m/km	H_{av} (m)
8/22/1443-1600	-4	17	20
8/22/1731-1745	2	144	20
8/24/1722-1754	-3	20	10
8/24/2015-2024	0	30	12
8/25/1221-1254	7	54	14

*Determined from data using the method of least-squares.

shown in the table were used together with Eq. (3) to estimate the exposure levels at the whale sighting positions for the air gun experiments. An example of the received average pulse pressure level versus range characteristic was shown previously in Fig. 3.13A.

Playback Exposure Level and Signal-to-Noise Ratio

The results of the playback experiments with migrating gray whales (Malme et al. 1983- 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 (O 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 resulted in varying degrees of “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 levels in relation to local ambient noise conditions.

The sound transmission characteristics for the playback tests were estimated using the equations derived for the air gun tests in the areas where they were relevant. The exposure level versus range to 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. 3.7, the dominant signal bandwidth was determined by observing the highest 1/3 octave band level in the signal as measured by the monitor hydrophore, 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, in the absence of specific hearing response measurements for gray whales, we have considered that the dominant masking of the playback signal is produced by ambient noise in the same frequency range.

Table 3.7 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 O, 10, 20, and 30 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. This was not possible in the St. Lawrence Island tests because the detection response, if any occurred, would have been well beyond the range of observation.

The transmission loss relationship pertaining to the playback test areas is also listed in Table 3.7. This equation was used to obtain the range values given in the table.

TABLE 3.7. PLAYBACK SIGNAL/NOISE DATA AND ESTIMATED EFFECTIVE RANGE.

Date/Time	Stimulus Code	BW_{eff} Hz	L_S* dB**	L_N dB**	S/N dB	R_0 km	R_{10} km	R_{20} km	R_{30} km	B_M Hz	S/N dB	R_0 km	R_{10} km	R_{20} km	R_{30} km
8/21/1142	DS 2	50-315	162	86	76	8.4	4.8	2.2	0.7	250	80	10.2	6.3	3.2	1.2
8/21/1448	DS 1	50-315	156	86	70	6.3	3.2	1.2	0.32	250	74	7.7	14.2	1.8	0.53
8/21/1950	DS 4	50-315	159	86	73	7.3	3.8	1.6	0.45	250	77	8.8	5.2	2.3	0.79

*Referred to 1 m.

**Referred to 1 μPa.

Key: B_M = 1/3 octave band with highest S/N

R_0 = range at which S/N = 0 dB, etc.

Propagation Characteristic for Playback Tests

$$RSL = L_S - 5 \log H_{av} - 15 \log R - 20\ R/H_{av} - 41 \text{ (dB re } 1\mu Pa)$$

where

$H_{av} = (H_S + H_r)/2$, H_S = depth at source (m), H_r = depth at receiver (whale) (m)

R = range (km)

3.4 Behavioral Observations and Analysis

In this section we provide qualitative descriptions of gray whale movement patterns during control and experimental conditions as well as analyses of surface, respiration, and dive time variables and sighting data. These results are compared with other studies conducted on non-migrating baleen whales.

3.4.1 Gray whale movement patterns

The following behavioral descriptions are based on field notes, summaries written at the end of each observation day, estimated received sound levels (RSL) at whales observed under experimental conditions, and track plots of whale movement patterns. We have included only brief descriptions of overall whale movement patterns for Drillship experiments 1 and 4 (DS 1, DS 4) on 19 and 21 August, respectively. During DS 1, observations were made from only one vessel. Therefore no whale position or RSL data are available for this experiment. Low light conditions and inability to follow individual whales prevented detailed observations during DS 4.

The number of whales observed under experimental conditions was low throughout the field season. This was due mainly to the late starting date of the project, which resulted in a low number of whales present in the study area and adverse viewing conditions (see Section 3.1.2). The primary behavioral objective of this study was two-fold: to obtain surfacing, respiration, and dive data on individual whales during control and experimental conditions, as well as to track the movements of these same whales. Because many whale groups were so far offshore during much of the field season, it was not possible to use land-based theodolite tracking of individual whales in combination with small boat observations as was accomplished by Würsig, Wells, and Croll (1983, 1986). The use of this method would have increased the number of whale groups tracked, since land-based observers could have concentrated on 3 to 4 groups simultaneously, whereas the two-boat method most often employed required BIG VALLEY observers to focus only on the one to two groups under observation by Zodiac personnel in order to obtain whale movement data. During Air gun 1 and 2 (AG 1, AG 2) experiments on 22 August, for example, we have prolonged detailed observations, including both surfacing/respiration data and track plots, on one whale. What follows, then, with the two exceptions noted above, are descriptions of whale groups for which overall behavioral patterns are fairly complete. We have presented all times to the nearest minute.

Drillship Playback Experiments

DS 1,* 19 August, 2108-2129

Prior to the onset of DS 1, observers on board the BIG VALLEY took surfacing, respiration, and dive times on a number of whale groups within 600 m of the vessel, at times recording data on two whales simultaneously. Viewing conditions were fair to poor during this period; however, observers were able to take useful data. It could not be determined if the whales in the area were feeding.

In the first 3+ minutes after the onset of DS 1, only one whale was sighted in the vicinity of the BIG VALLEY. After 2111, no whales were observed within 600 m of the vessel until 2151, approximately 21 minutes after DS 1 had ended. Although observation conditions remained the same as they had been during the" pre-DS 1 control period, it was our impression that the

*This was a preliminary experiment to check and adjust the projector system.

whales moved out of the immediate area of the BIG VALLEY after 2111, with whales returning to the area during the post-DS 1 control period. Individual identification of whales was not possible because of their distance from the observation vessel, so it is not known whether the whales in the vicinity of the BIG VALLEY before DS 1 were the same whales present after the experiment.

DS 2, 21 August, 1142-1212

Several whales were under observation prior to DS 2, most notably focal whale Q. Surfacing/respiration and movement data on one whale, Whale Q, were collected by Zodiac personnel from 1129-1203. There were no indications that Whale Q was feeding during this period.

During pre-DS 2 control period, observers noted that Whale Q increased its speed of movement at approximately 1134, moving away from the BIG VALLEY, which was motoring from north to south through the area. This time coincides with the closest recorded approach of the BIG VALLEY to Whale Q, 0.95 km. Other whales were under observation in the same general area and there is some indication that these whales, too, were moving away from the vessel between 1131-1134. Whale M exhibited similar behavior, moving away from the vessel at 1124-1125, a time coinciding with the closest recorded approach of the BIG VALLEY, 0.48 km. There is some indication, based on its movement pattern, that Whale M had been feeding prior to this time. Based on these limited observations, it is possible that the movement patterns observed during the pre-DS 2 control period were the result of BIG VALLEY’s transecting through the area. Whale M was joined by two other whales at 1139, and the observed movement may also have been at least in part due to social activity, After this time, observations on Whale M were terminated because this whale could no longer be individually identified.

During DS 2 playback, Whale Q was exposed to peak RSL of 110 dB at 1150, with the BIG VALLEY 1.45 km distant. Subsequent levels decreased to 105 dB. No unusual behavior was noted.

DS 3, 21 August, 1448-1542

Focal whale W was first observed by Zodiac personnel at 1258 and was followed until 1617, a period encompassing both pre- and post-DS 3 controls. Movement data on this whale are only available for the pre-DS 3 control and DS 3 playback periods. Figures 3.17 and 3.18 present track plots of Whale W relative to the BIG VALLEY during the pre-DS 3 control and DS 3 playback, respectively.

From 1302-1313 during the pre-DS 3 control, Zodiac observers noted one of the few interactions between whales seen during the entire field season. This occurred before we started gathering triangulation data, so there is no figure for this. Whales W and Y joined, resulting in a number of underwater blows and two pectoral fin slaps. Prior to this time, Whale W had been feeding and after this interaction the whale resumed feeding, with mud observed on several occasions from 1322-1455. An examination of the track of Whale W on both figures shows that it stayed in the same general area throughout the time it was followed by both Zodiac and BIG VALLEY observers (1358-1536). At approximately 1403, the BIG VALLEY was 0.5 km distant from Whale W (see Figure 3.17). No unusual behavior was observed at that close distance. See Section 3.4.2 for a description of the surfacing/dive characteristics of Whale W related to experiment #2 of the day.

During the period from 1448, the start of DS 3, and 1455, RSL at Whale W peaked at 106 dB, with the BIG VALLEY 1.12 km distant. Subsequent levels decreased to approximately 103 dB near the end of the playback. These decreasing levels were the result of BIG VALLEY drifting northwest, away from Whale W,

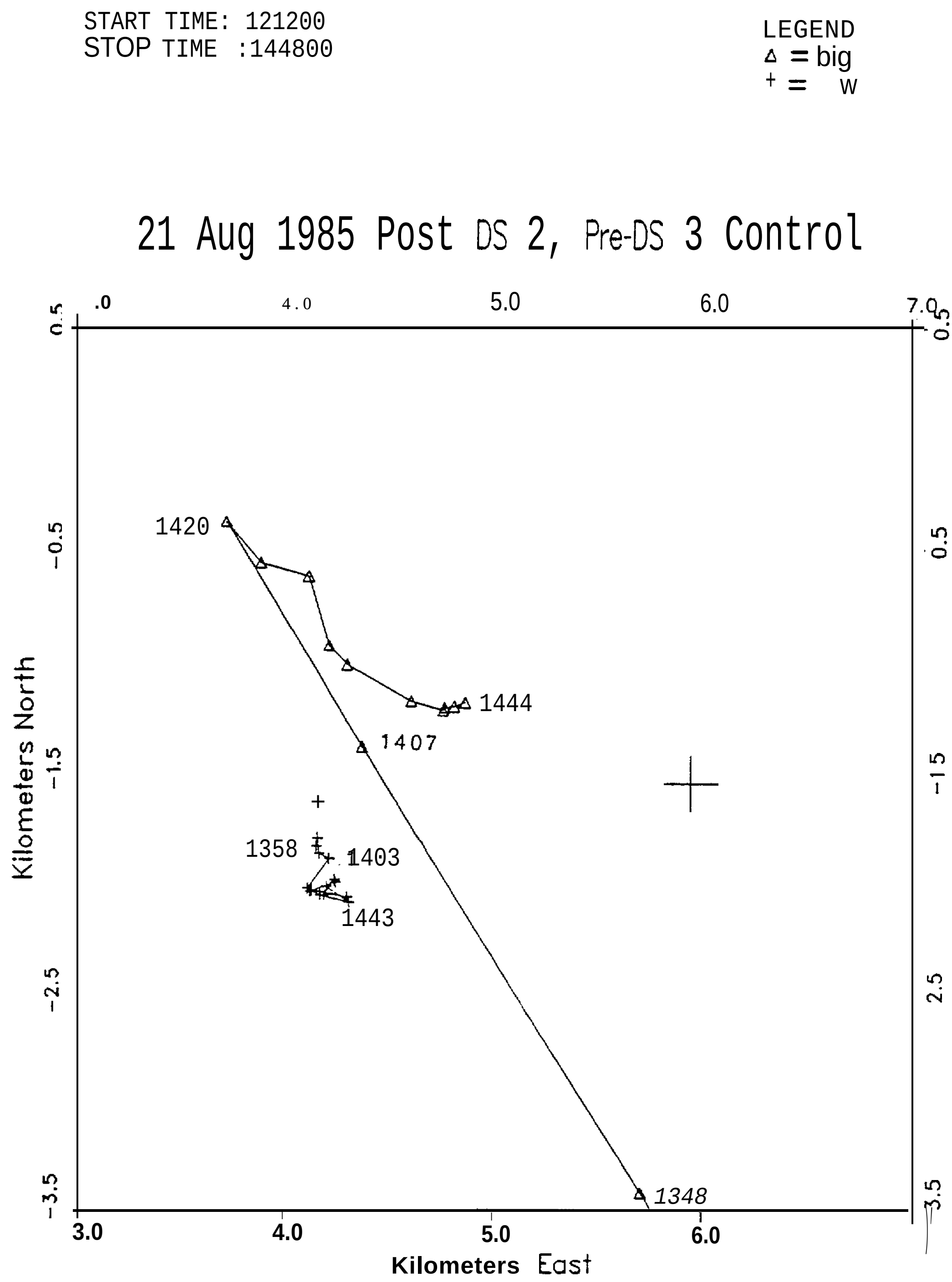


FIG. 3.17. TRACK PLOT OF WHALE W DURING PRE-DS 3 PLAYBACK CONTROL ON 21 AUGUST.

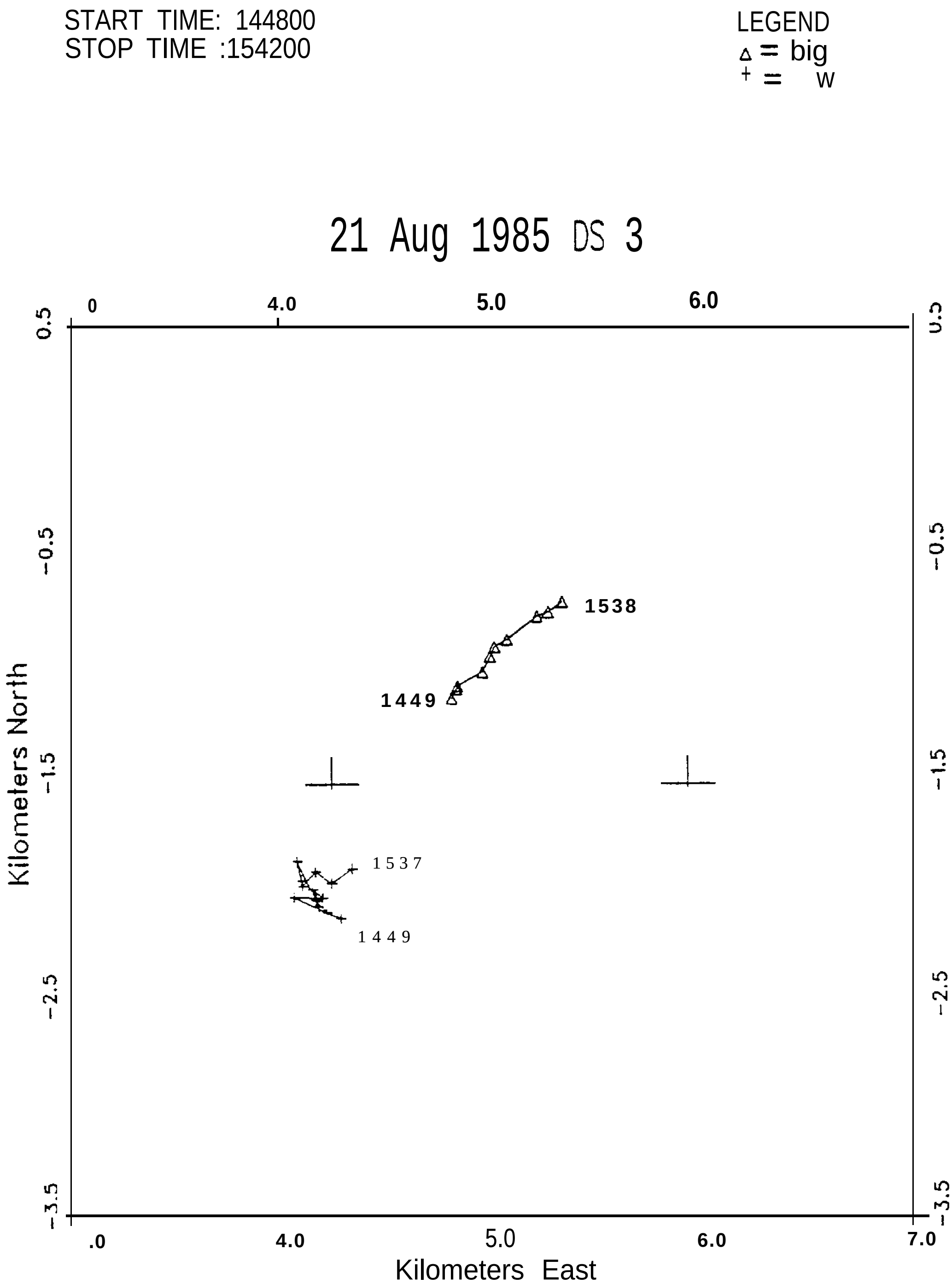


FIG. 3.18. TRACK PLOT OF WHALE W DURING DS 3 PLAYBACK ON 21 AUGUST.

during the playback (see Figure 3.18). Whale W was not observed to feed from 1456 until 1543, 1 minute after the end of DS 3. However, we believe that Whale W was feeding during this period because its pattern of changing direction and remaining in one area were typical of feeding behavior. Whale W continued to feed (as evidenced by mud plumes) until the end of observations at 1617.

DS 4, 21 August, 1950-2057

Difficulty in identifying and following individual whales and low light conditions hampered collection of data for DS 4. However, observers on BIG VALLEY qualitatively noted a shift in whale distribution within 10 minutes after the onset of the playback at 1950, with all whales under observation moving to the northeast. RSL at whales under observation during DS 4 varied from 108 to 119 dB. We took 27 position readings on approximately 15 whales. We were unable to determine if the whales were feeding.

Air gun Experiments

AG 1 and 2, 22 August, 1440-1600, 1731-1758

We combine the discussion of these two AG experiments because much of the data collected concerns a single focal whale followed for an extended period encompassing both experiments.

Whale E was followed by Zodiac personnel from 1141-1852, a total of 7.2 hr, the longest period that a whale was kept under continuous observation during the field season. Movement data were collected on this whale from 1327-1832. Figure 3.19 shows the movement of Whale E during pre-AG 1 control. Although mud was only observed associated with Whale E once during this control period, (observance of mud was hampered by poor visibility between approximately 1400-1632), the many direction

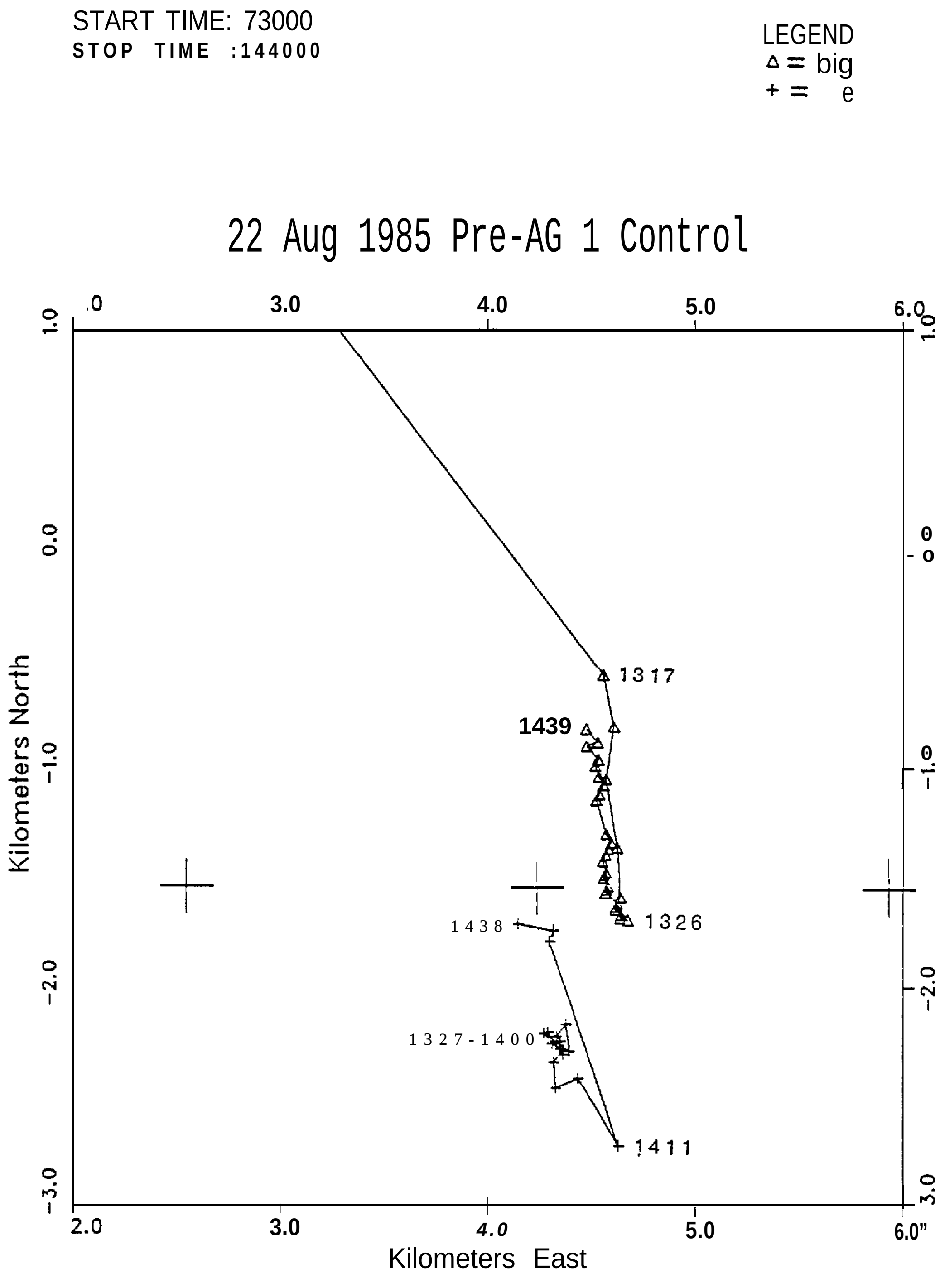


FIG. 3.19. TRACK PLOT OF WHALE E DURING PRE-AG 1 CONTROL ON 22 AUGUST.

changes and the fact that the whale stayed in the same general location during much of the time, led observers to conclude that this whale was feeding. We cannot explain the northward movement pattern between 1411-1438 as shown in Fig. 3.19. At 1446, 6 minutes after the onset of AG 1, personnel on the BIG VALLEY noted that the 5 to 7 whales under observation, including Whale E, were moving offshore. RSL at the whales was approximately 149 dB, with the NANCY H 3.9 km distant. The Zodiac personnel also noted the whales moving offshore at 1503, at which time the NANCY H was 3.63 km distant from Whale E and RSL was 150 dB. Throughout both control and experimental periods, Whale E was the only whale under continuous observation. Figures 3.20A and 3.20B show the movement pattern of Whale E in relation to the NANCY H, which was moving south towards the general area of the whale. At 1504, Whale E was joined by 1 or 2 whales, and the whales moved south, then southeast and offshore. RSL increased at Whale E throughout AG 1, with a peak level of 172 dB reached at 1559, with NANCY H 0.19 km distant. No indications of feeding by Whale E or by other whales in the area were noted during the experiment.

Examination of the track plot of Whale E in relation to the southward-moving NANCY H indicates that this whale was actively moving away from the vessel, possibly attempting to move offshore. However, the last three readings on Whale E during AG 1 indicate that it did not continue to move southeast, but stayed in the same area as the NANCY H approached its position. During this period (1549-1558), RSL at Whale E increased from 160 dB to 172 dB.

Our next reading of Whale E (see Figure 3.21) at 1606, almost 6 minutes after the end of AG 1, shows that between 1558 and this time, the whale moved back to the north and by 1633 was feeding, as evidenced by mud plumes. (Time 1633 coincides with

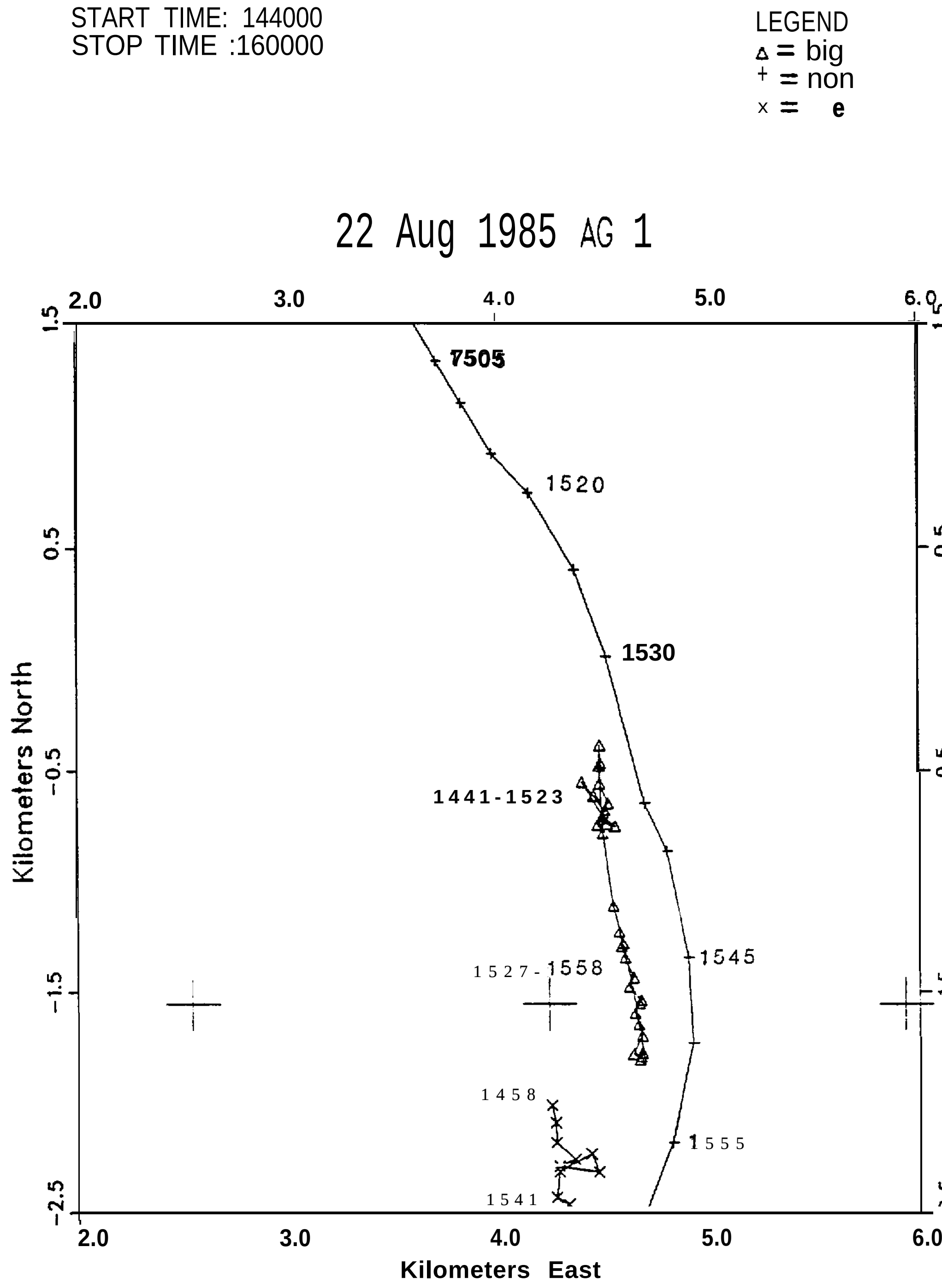


FIG. 3.20A. TRACK PLOT OF WHALE E DURING AG 1 ON 22 AUGUST. TWO FIGURES ARE PRESENTED TO SHOW THE SOUTHWARD PROGRESSION OF THE NANCY H.

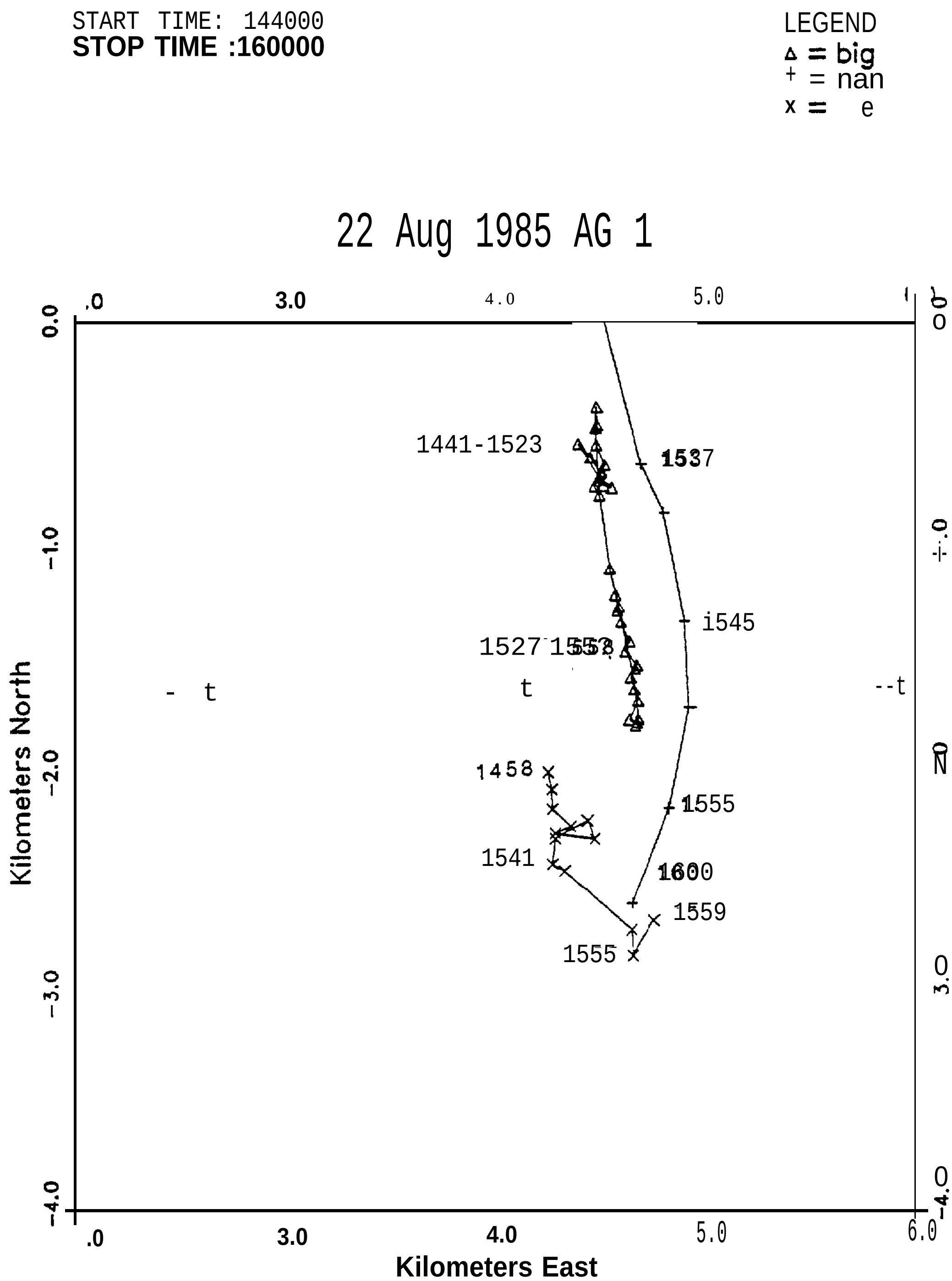


FIG. **3.20B.** TRACK PLOT OF WHALE E DURING AG 1 ON 22 AUGUST. TWO FIGURES ARE PRESENTED TO SHOW THE SOUTHWARD PROGRESSION OF THE NANCY H.

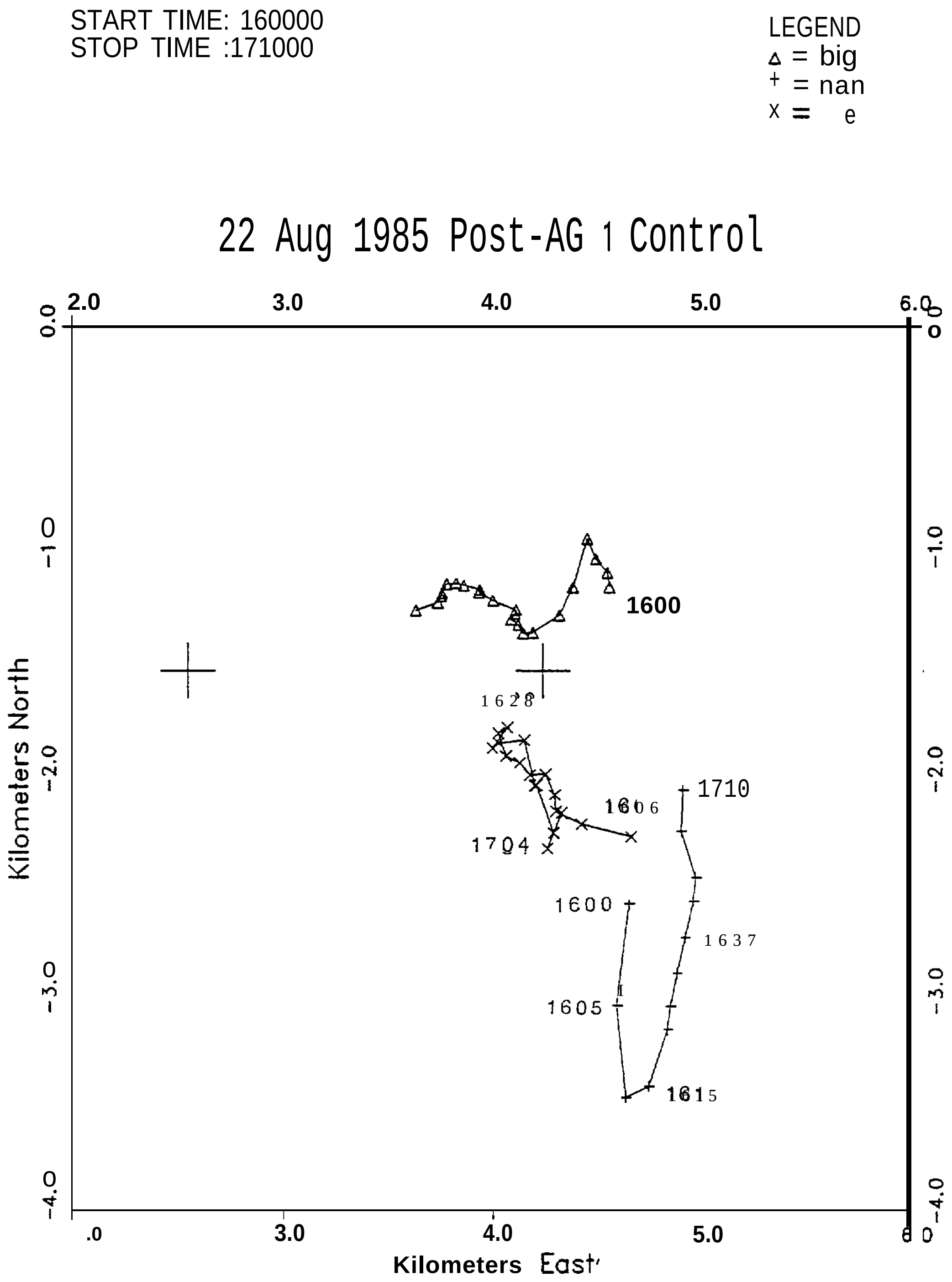


FIG. 3.21. TRACK PLOT OF WHALE E DURING POST-AG 1 CONTROL ON 22 AUGUST.

the first appearance of the sun all day, thereby making mud at the water's surface more easily visible to observers). At this time, the whale was approximately 0.5 km northeast of its pre-AG 1 control position. The whale stayed in this same general area, feeding, through the post-AG 1 control period. Zodiac personnel noted that after the end of AG 1, other whales were also moving inshore to the general area of Whale E. However, we do not have track information on these whales.

Prior to the onset of AG 2, Whale E was observed to be feeding in the same general area that it had returned to after the completion of AG 1. During AG 2, RSL reached a peak of 172 dB at 1742 with the NANCY H 0.47 km distant, moving to the northeast (see Figure 3.22). At 1739, roughly coinciding with peak RSL, observers on board the Zodiac as well as on BIG VALLEY noted Whale E "abruptly" change direction, turn approximately 135° from NW to ENE, and orient towards the NANCY H. Whale E moved toward the general location of the NANCY H until approximately 1746 when the whale turned to the southeast and continued south until at least 1754, at which time RSL at the whale was 163 dB. Mud was not seen associated with Whale E between the time of the abrupt change in direction and 1749; however, this whale was feeding both before and after these times. Figure 3.22 shows that the BIG VALLEY was within 0.5 km of Whale E during AG 2. This movement of the BIG VALLEY is the result of drift. It is unclear whether Whale E's movements during AG 2 were a response to the playback or were associated with feeding behavior.

Figure 3.23 shows that during the post AG 2 control period, Whale E moved SSE until approximately 1825 when it headed to the east. The whale continued to feed throughout this period. Unfortunately, the BIG VALLEY, which had been drifting into shallow water, was forced to start engines and move offshore at

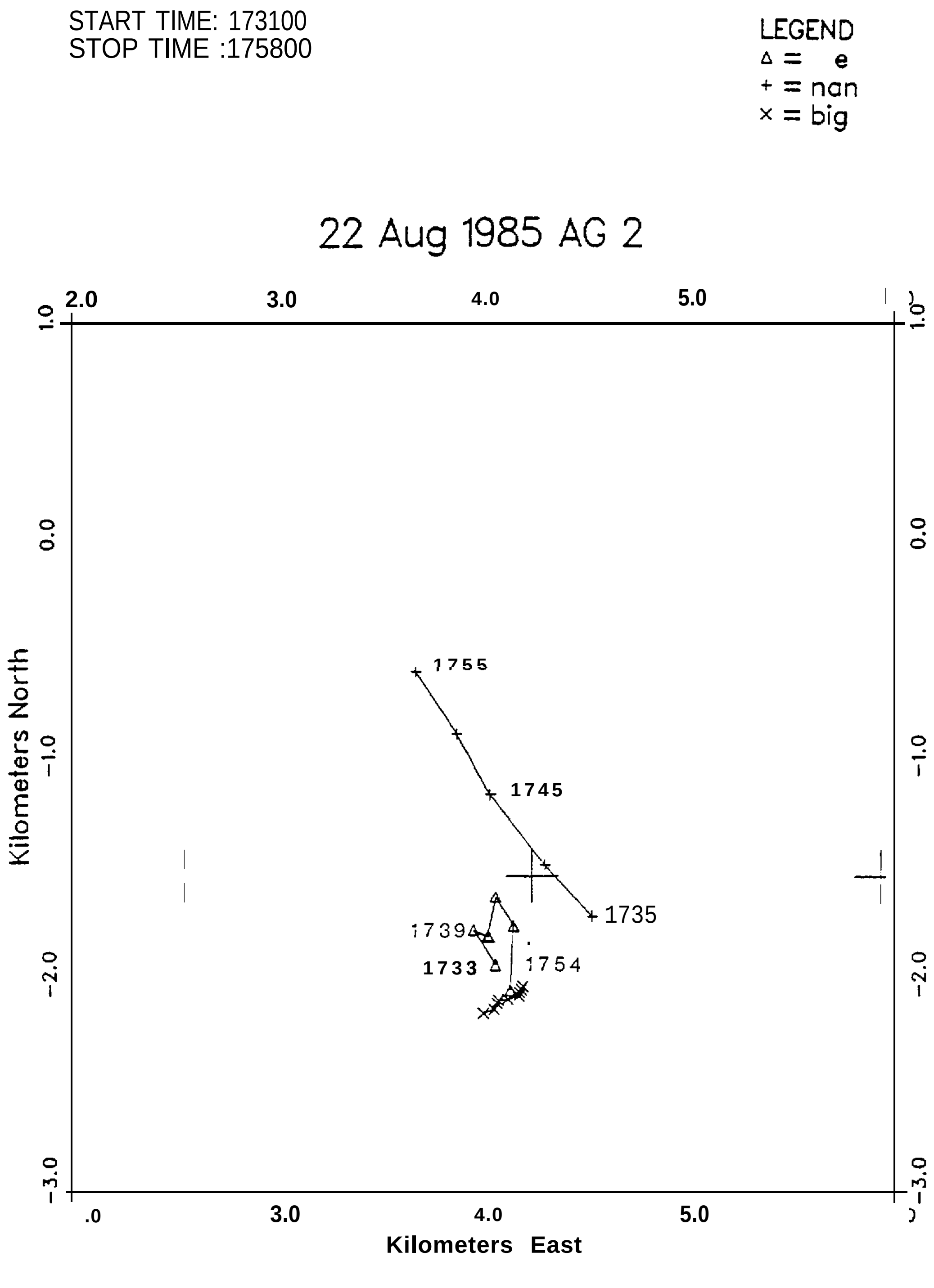


FIG. 3.22. TRACK PLOT OF WHALE E DURING AG 2 ON 22 AUGUST.

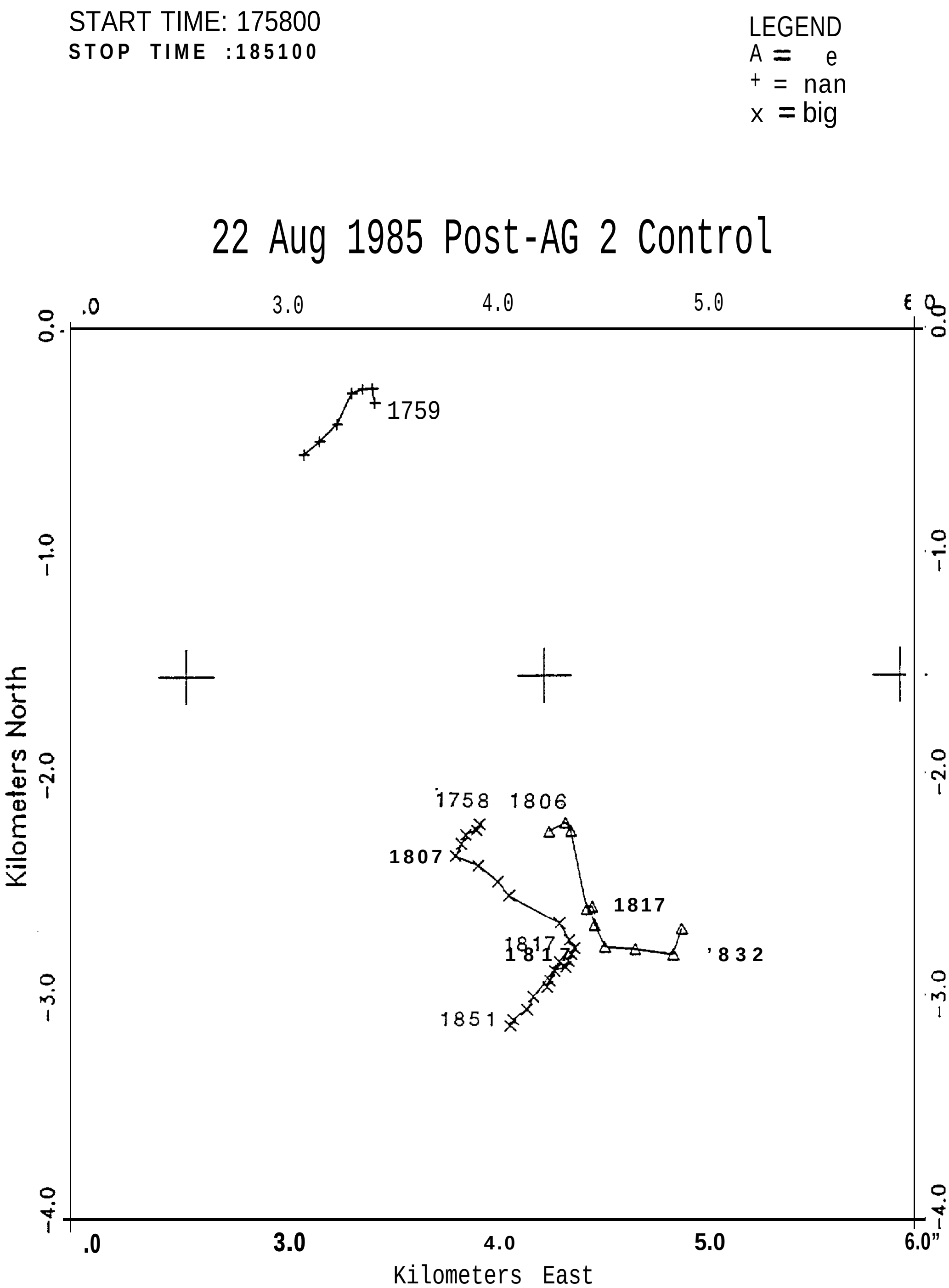


FIG. 3.23. TRACK PLOT OF WHALE E DURING POST-AG 2 CONTROL ON 22 AUGUST.

approximately 1807 during the post-AG 2 control. By approximately 1817, the BIG VALLEY was within 0.2 km of Whale E (Fig. 3.23). This close approach may have been responsible for the eastward movement of Whale E.

AG 3, 24 August, 1715-1758

As noted in Section 3.1.2, 24 August was the only day during the field season that viewing conditions and inshore whale locations allowed land-based transiting of whale group movement. We were able to track six whale groups; however, most of our data come from the two focal whales, A and B.

Whale A was first observed by shore-based personnel at 1606. The whale was feeding at this time and continued to feed throughout the pre-AG 3 control period. Whale A and Whale B, another feeding whale in the same general area, were noted moving toward each other at 1632, but they did not join. At 1649, Whale A and Whale E, which had been under observation since 1636 and also feeding, joined. Group A+E continued to feed together, generally moving northward.

Figure 3.24 shows the movement pattern of both Whales A and E during the pre-AG 3 control. At 1715, group A+E separated. Time 1715 coincides with the onset of AG 3, when RSL at the whales was approximately 154 dB, with the NANCY H 2.4 km to the Ssw. Figure 3.25A shows the position of both the NANCY H and the BIG VALLEY at the start of AG 3. An examination of Figure 3.25B (extending 4 km N of the northern limit of 3.25A) shows that Whale A started to move to the northeast after separating from Whale E; however, it continued to feed until at least 1731, at which time RSL was 157 dB with the NANCY H 1.74 km distant. Whale E was only sighted and transited once after the group separated, at 1719. At this point, Whale E was still in close proximity to Whale A, indicating that it also was moving in a

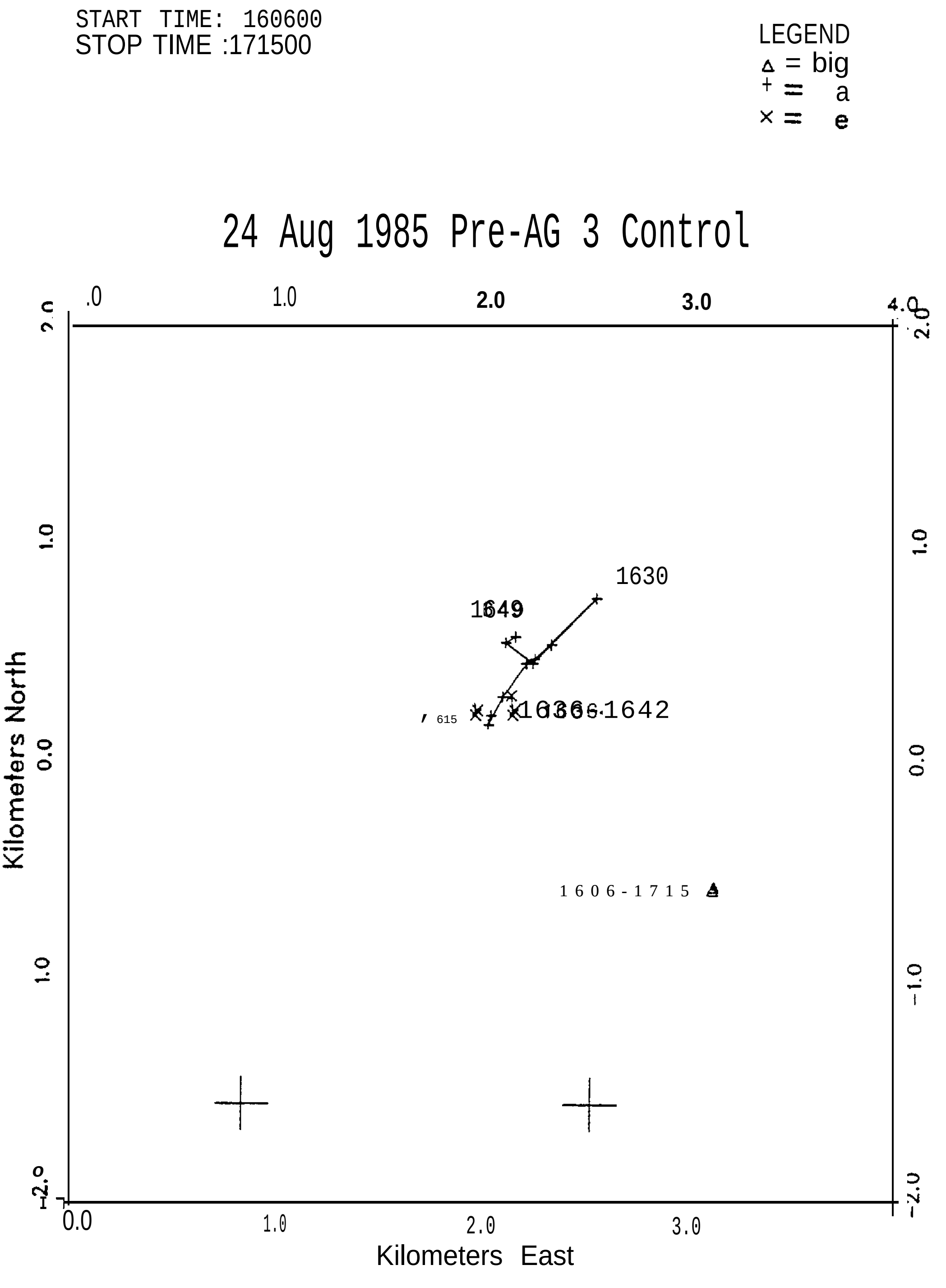
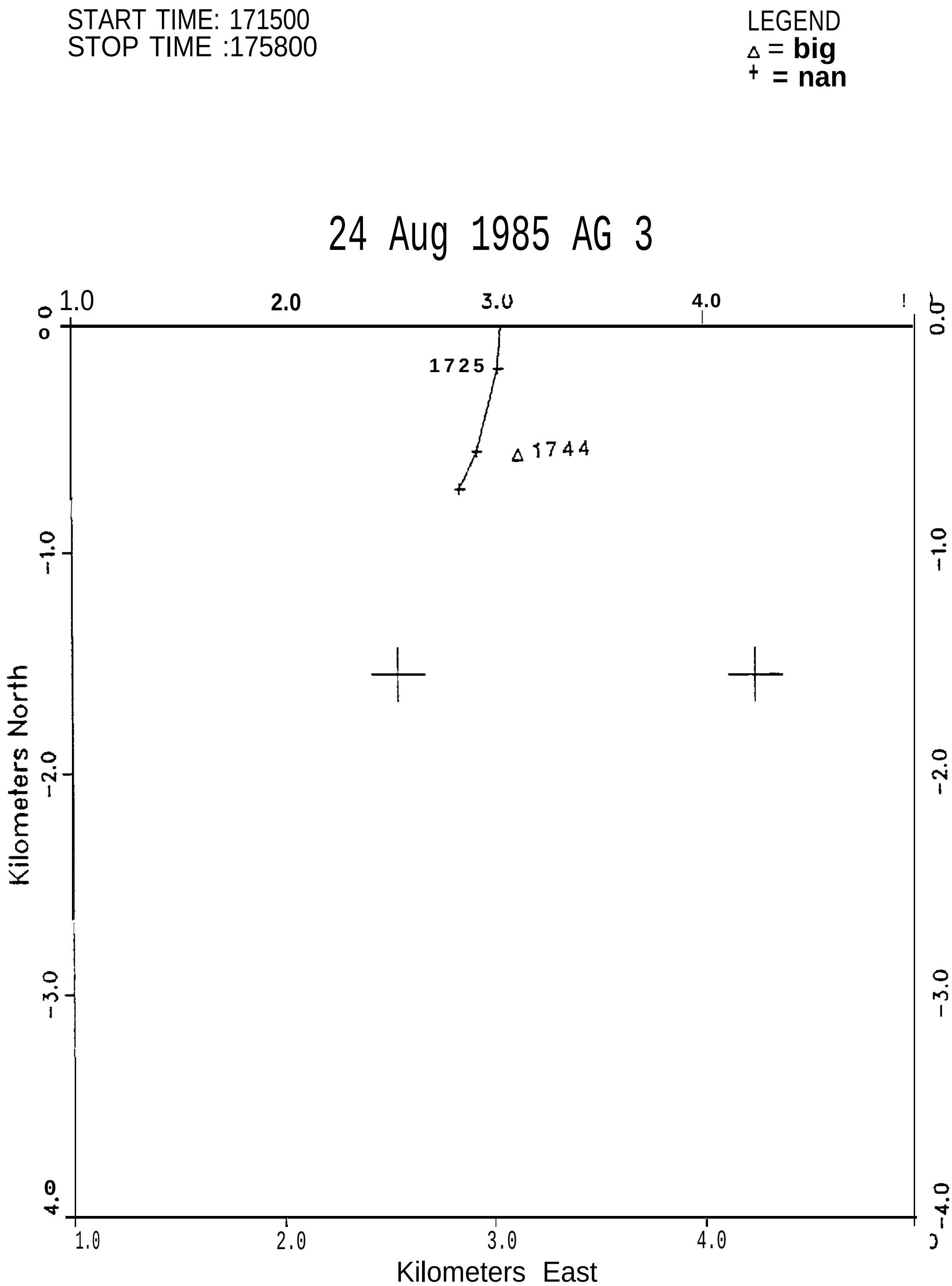


FIG. 3.24. TRACK PLOT OF WHALES A AND E DURING PRE-AG 3 CONTROL ON 24 AUGUST. THE MOVEMENT OF GROUP A+E IS NOT SHOWN AS NO POSITION DATA ARE AVAILABLE. HOWEVER, THE LAST LOCATION OF WHALE A AT 1649 IS THE POSITION WHERE THE JOINING OCCURRED.



FIGS. 3.25A. FIGURE 3.25A SHOWS THE POSITION OF THE M/V NANCY H. AND THE M/V BIG VALLEY AT THE START OF AG 3 ON 24 AUGUST.

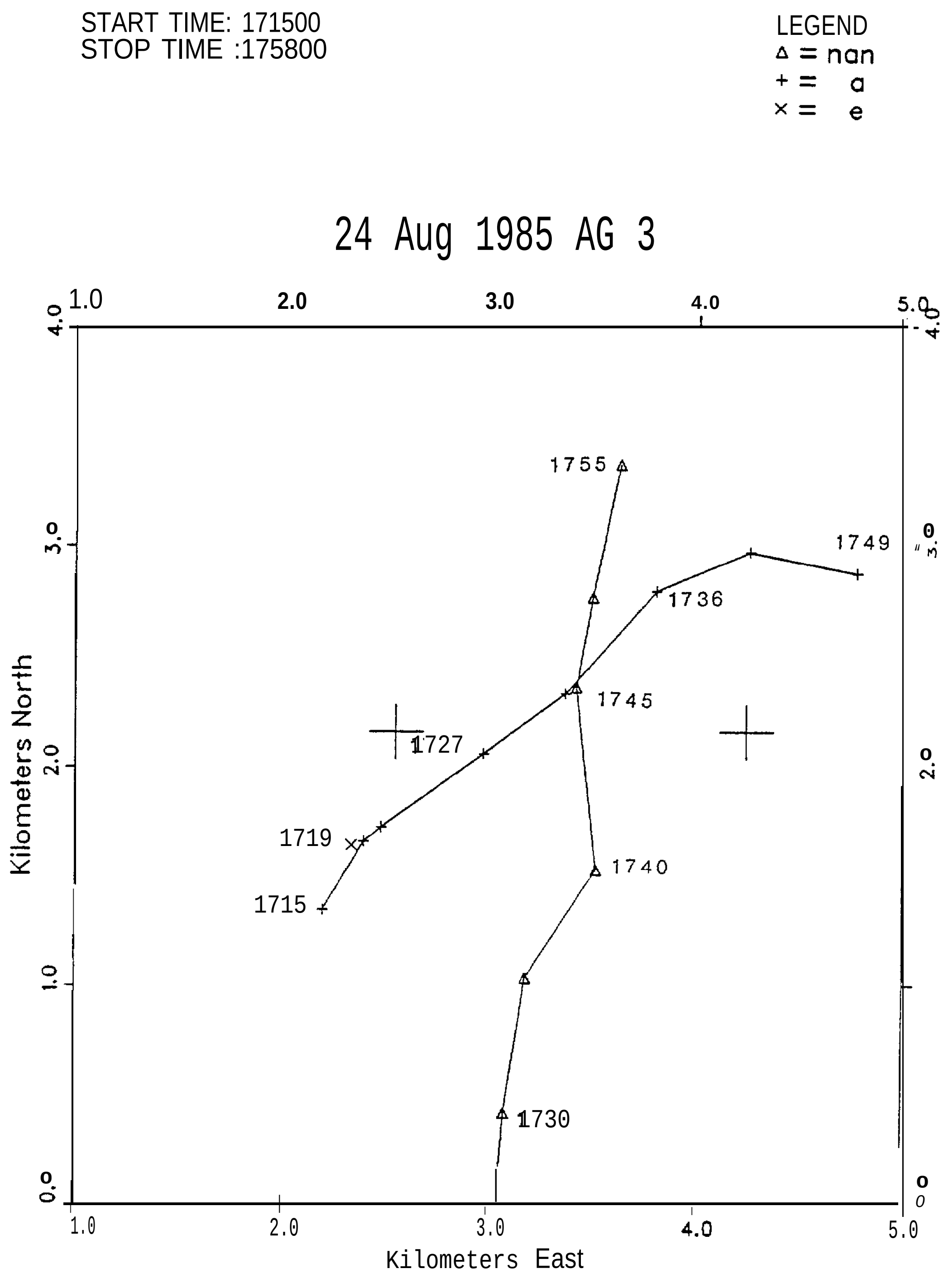


FIG. 3.25B. (CONTINUATION OF FIGURE 3.25) SHOWING THE NORTHWARD MOVEMENT OF M/V NANCY H. AND THE TRACK OF WHALE A DURING AG 3.

similar direction. Peak RSL of 160 dB was reached at 1740 at which time Whale A was moving almost directly west and offshore. It could not be determined if the whale was feeding after 1731; however, the steady offshore movement indicates that it was not.

During post-AG 3 control, Whale A continued to move offshore. Whale A’s increasing distance from land-based observers, coupled with high sea state, prevented effective transiting of this whale’s movement. As a result, only one further reading was successfully taken, at 1804. At this time the whale was approximately 0.6 km ENE of its 1749 position.

Whale B was first observed by land-based personnel at 1609 and was noted feeding at 1615. This whale continued to feed in the same general location throughout the pre-AG 3 control, AG 3, and post-AG 3 control periods. As noted previously, Whales A and B were observed moving towards each other at 1632. At 1658, Whale B was observed moving toward whale group A+E. In neither instance did Whale B join these other whales. Figures 3.26 through 3.28 show the movement pattern of Whale B during the three experimental periods.

At 1717, 2+ minutes after the onset of AG 3, RSL at Whale B was 158 dB, with the NANCY H 1.51 km to the SSW. RSL increased to a peak of 165 dB at 1734 with NANCY H 0.66 km distant. An examination of Fig. 3.27 shows that after this time the whale moved inshore slightly. This inshore movement may have been the result of increased RSL; however, the whale was observed to be feeding during this entire time and small changes in movement such as this are consistent with normal feeding behavior. By 1757, NANCY H was 2.72 km to the northeast of the whale and RSL was 153 dB.

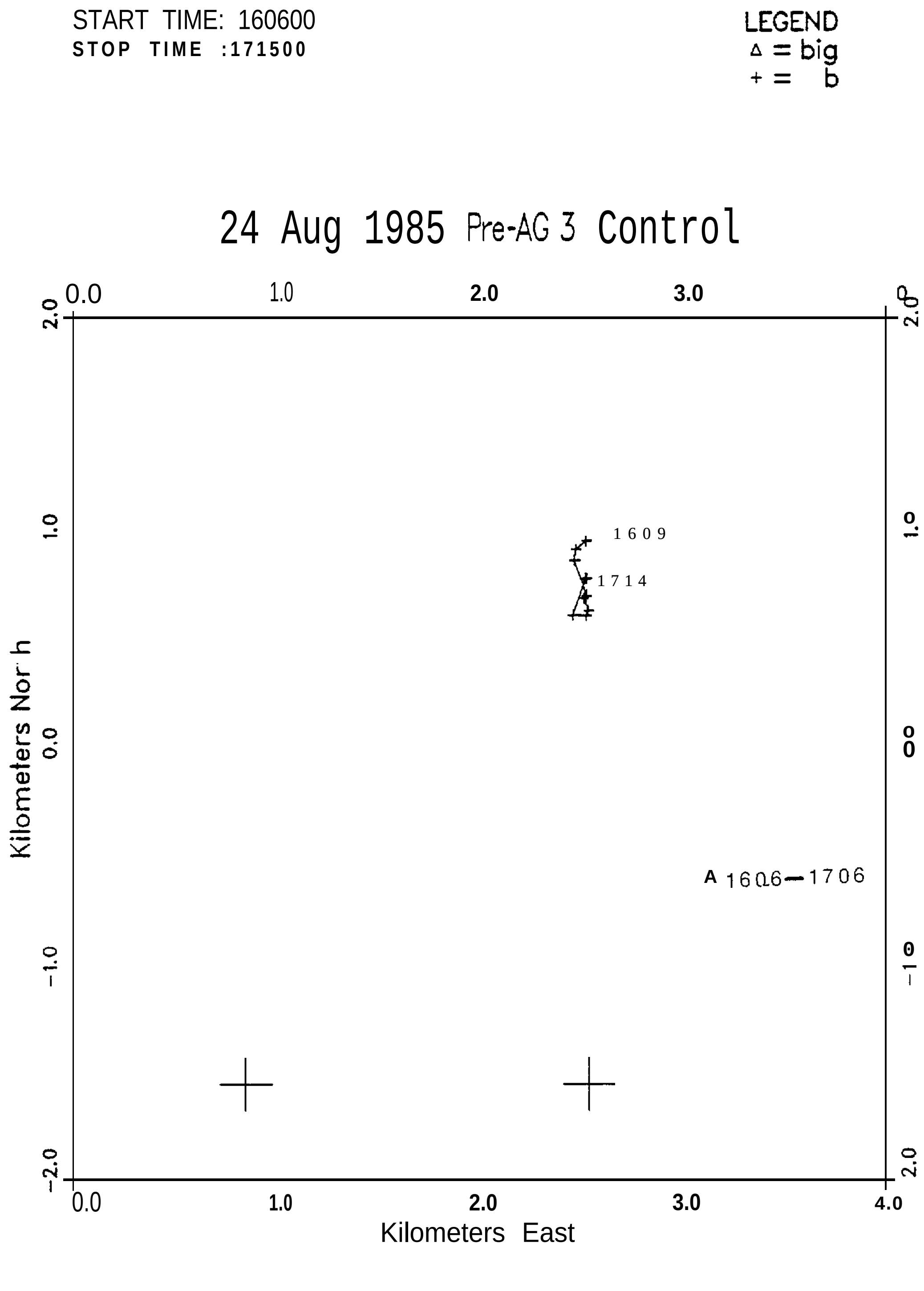


FIG. 3.26. TRACK PLOT OF WHALE B DURING PRE-AG 3 CONTROL ON 24 AUGUST.

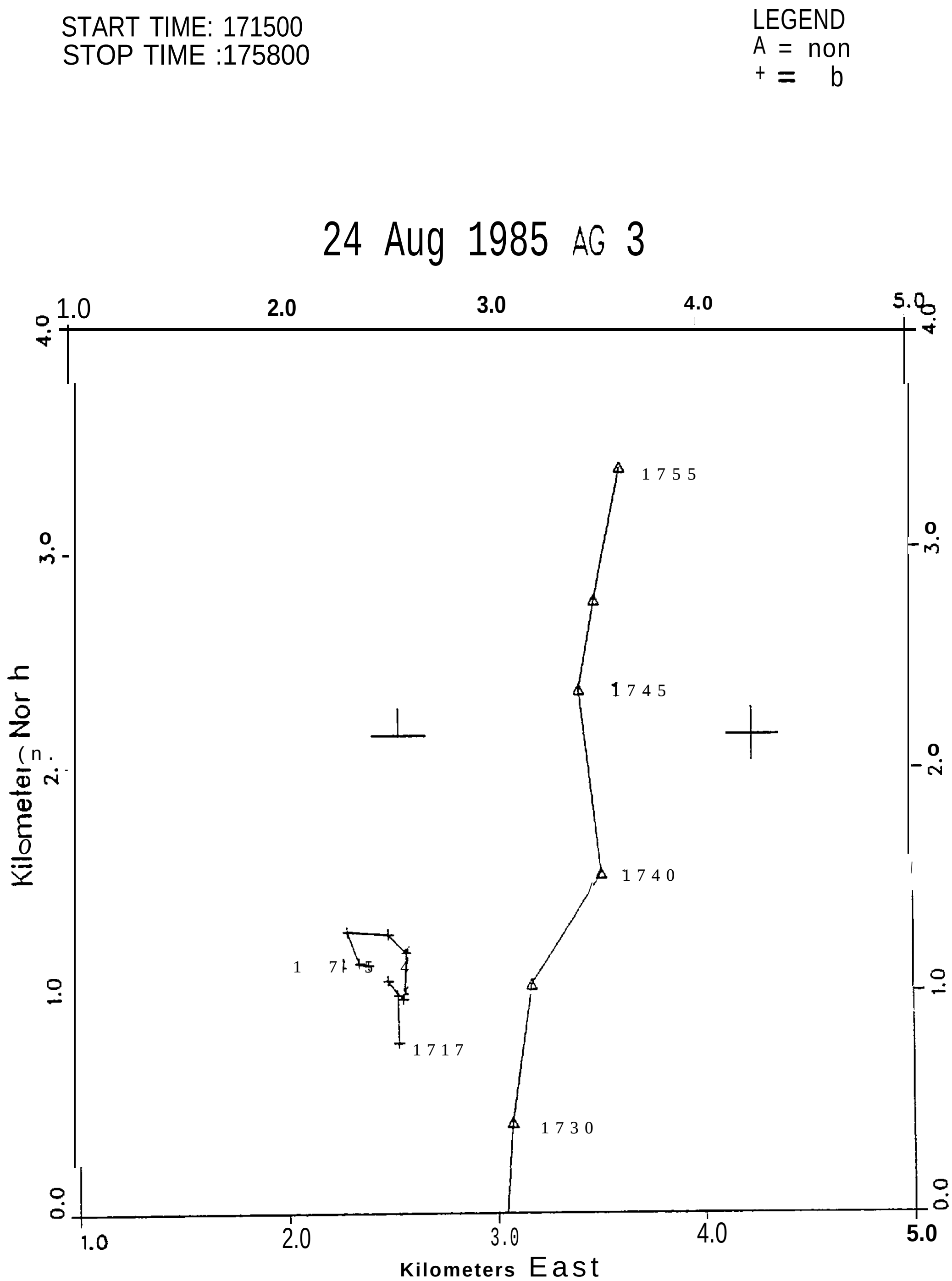


FIG. 3.27. TRACK PLOT OF WHALE B DURING **AG 3 ON 24** AUGUST.

Figure 3.28 is a plot of Whale B's movement during the post-AG 3 control period. This whale was observed to be feeding the entire time in the same general location as it had been during the two previous experimental periods.

AG 4, 24 August, 1929-2026

As noted above, Whale B was observed to be feeding during the control period between AG 3 and AG 4 (see Fig. 3.28). Figure 3.29 shows the movement pattern of this whale relative to the NANCY H during AG 4. At the onset of AG 4, RSL at Whale B was 159 dB with the NANCY H 1.75 km to the north. Whale B continued to feed and between 1942-1954 was moving slowly to the north, toward the NANCY H, which was motoring southward. During this period, RSL was increasing and at 1957 it had reached 176 dB with the NANCY H 0.18 km directly offshore of Whale B. At this point, observers noted that the whale had turned and was moving rapidly to the south, diving with flukes out. This was the first time during the entire period of observation that Whale B displayed a full fluke out upon diving, and this action was unusual since the whale was in shallow water (depth < 9 m) in which fluke outs do not normally occur. The whale continued to move south, and at 2002 another full fluke out was noted. At this point, RSL had reached a peak of 177 dB with the NANCY H 0.17 km distant. Mud was observed with this dive, and Whale B was presumed to be feeding. The whale continued moving slowly to the south until approximately 2011, at which time it began to mill. By 2015, mud was again associated with Whale B, and the whale continued to feed throughout the remainder of AG 4, staying in the same general location. RSL at Whale B was decreasing during this period and by the end of the experiment was 159 dB, with the NANCY H 1.80 km to the southeast of the whale's location. Whale B continued to feed during the post-AG 4 control and was last observed at 2042. Figure 3.30 presents a track of Whale B's movement during this period.

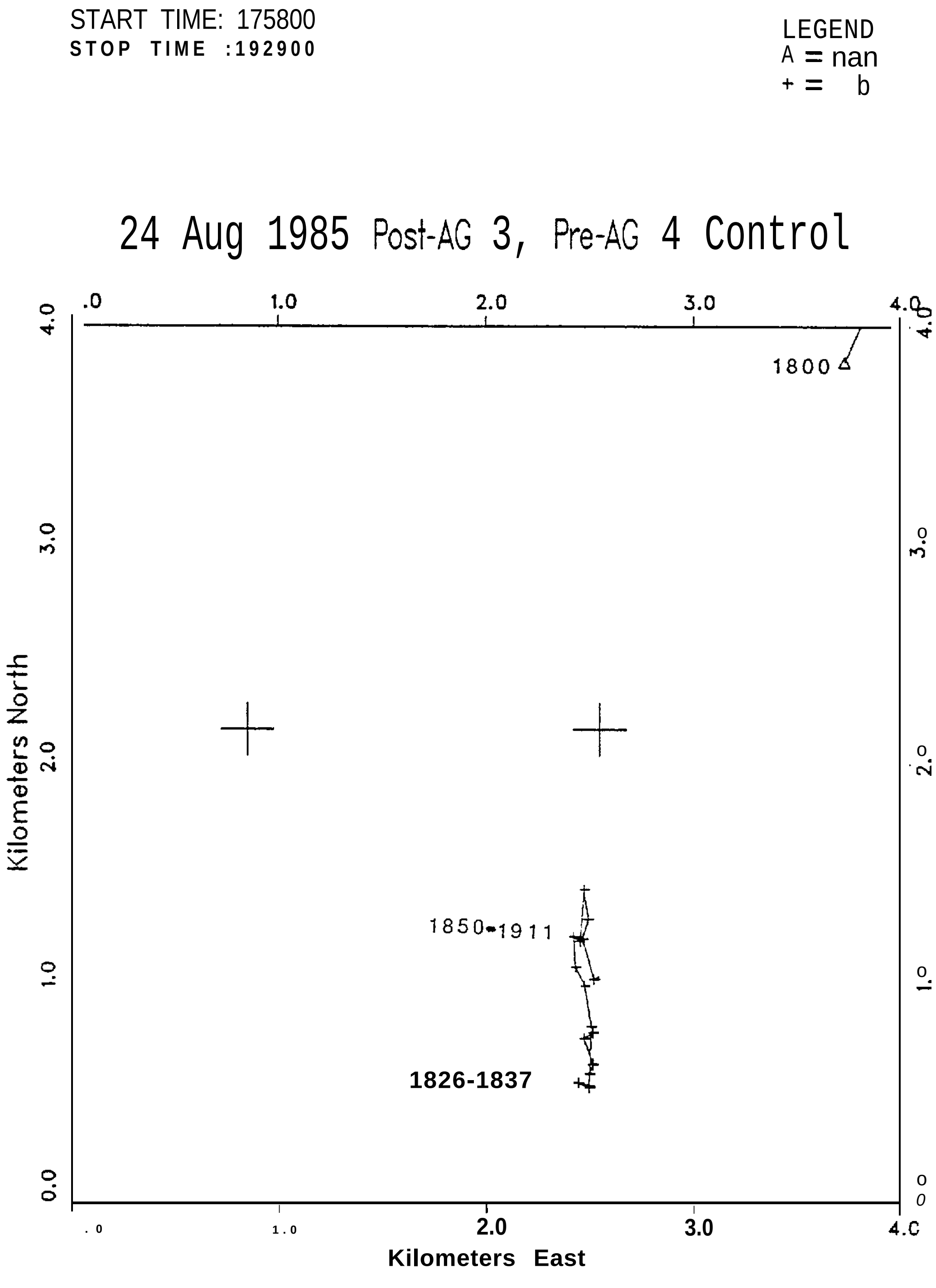


FIG. 3.28. TRACK PLOT OF WHALE B DURING POST-AG 3 CONTROL ON 24 AUGUST.

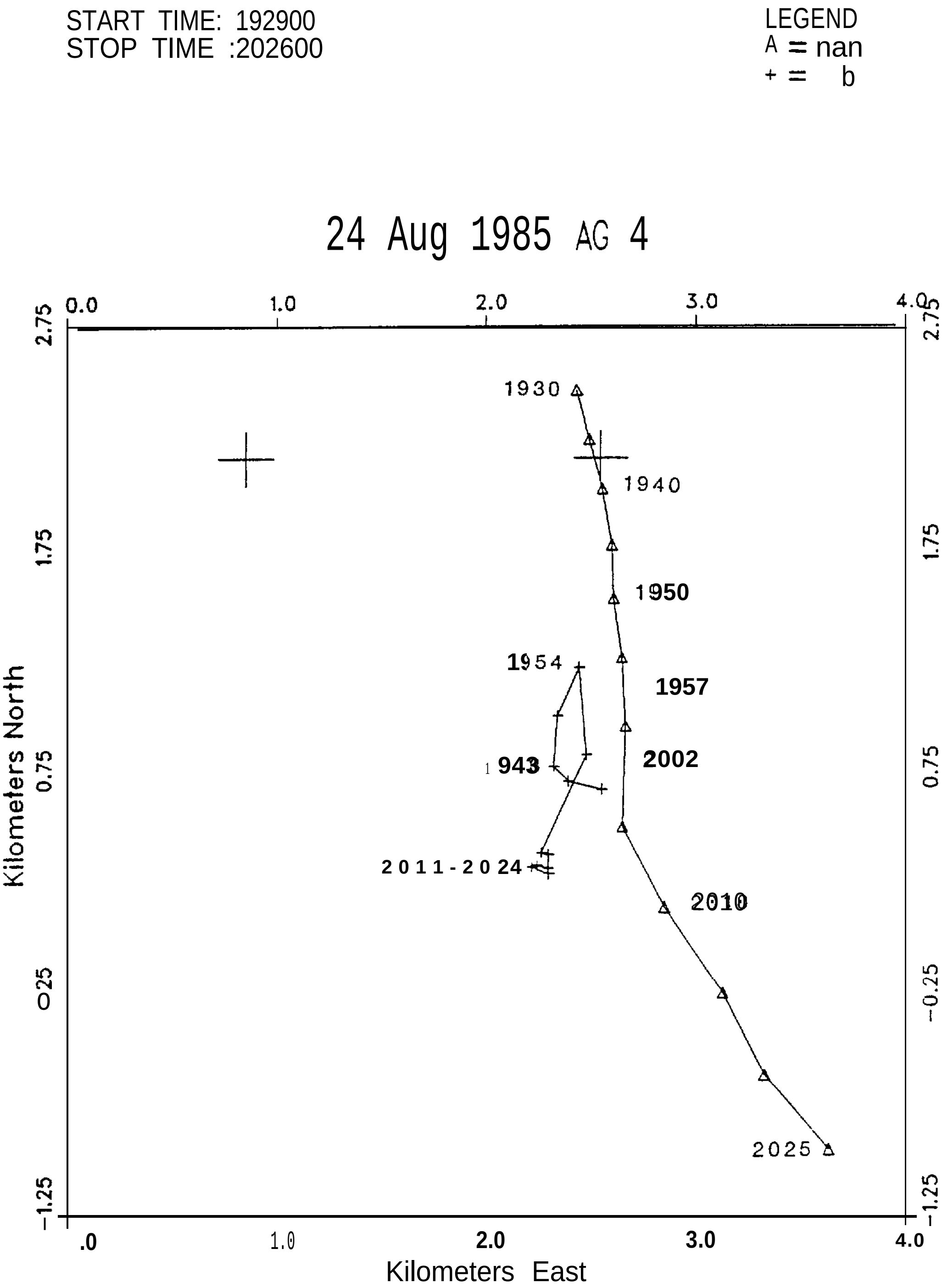


FIG. 3.29. TRACK PLOT OF WHALE B DURING AG 4 ON 24 AUGUST.

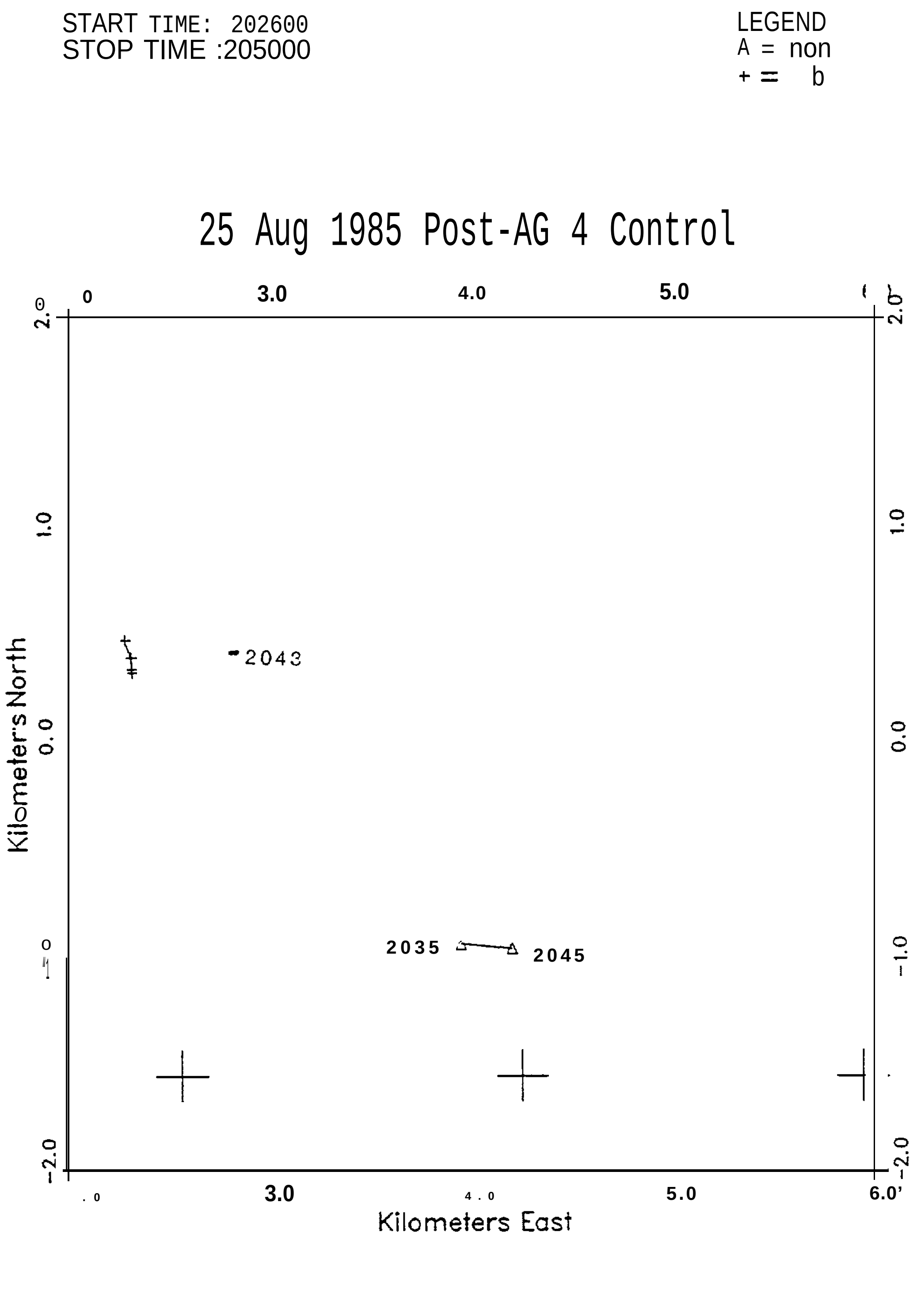


FIG. 3.30. TRACK PLOT OF WHALE B DURING POST-AG 4 CONTROL ON 24 AUGUST.

AG 5, 25 August, 1220-1323

Whale K was first observed by Zodiac personnel at 1042 and was followed until 1227. Unfortunately, poor visibility during much of this period restricted observers on board the BIG VALLEY from taking readings on this whale, with the first reading taken at 1207. Whale K was noted as feeding from 1042 to at least 1155, moving slowly to the north and west during much of this time. At 1129, Whale K and Whale L, another feeding whale under observation, joined for a brief period, then separated, staying in the same general area. At approximately 1158, Whale K began to move to the northeast, continuing on this heading until approximately 1212, when it headed to the southeast. Figure 3.31 shows Whale K's movement pattern between 1207 and the end of the pre-AG 5 control. As noted above, BIG VALLEY personnel were having difficulty in keeping the Zodiac and the whales under observation and were forced to motor closer, anchoring at 1205, approximately 0.4 km from Whale K. This NNW movement can be seen in Figure 3.31. At the time that Whale K started its northeast movement (1158), observers on the Zodiac noted that the whale moved out of the area in apparent response to the approaching BIG VALLEY .

At the onset of AG 5 at 1220, RSL at Whale K was 160 dB, with the NANCY H 2.4 km distant. Figure 3.32 shows Whale K's movement during the first 4 minutes of AG 5. At 1223, Whale K breached, with RSL at this point approximately 160 dB, with the NANCY H 2.3 km distant. At 1224, Zodiac personnel made the decision to select Whale L as the focal animal since it was assumed that Whale K was leaving the area. However, an examination of Figure 3.32 shows that Whale K had moved back towards the southeast by 1223. Given the movement of the BIG VALLEY into the area during the pre-AG 5 control period and the limited data on Whale K after the onset of AG 5, it is unclear whether Whale K responded to AG 5.

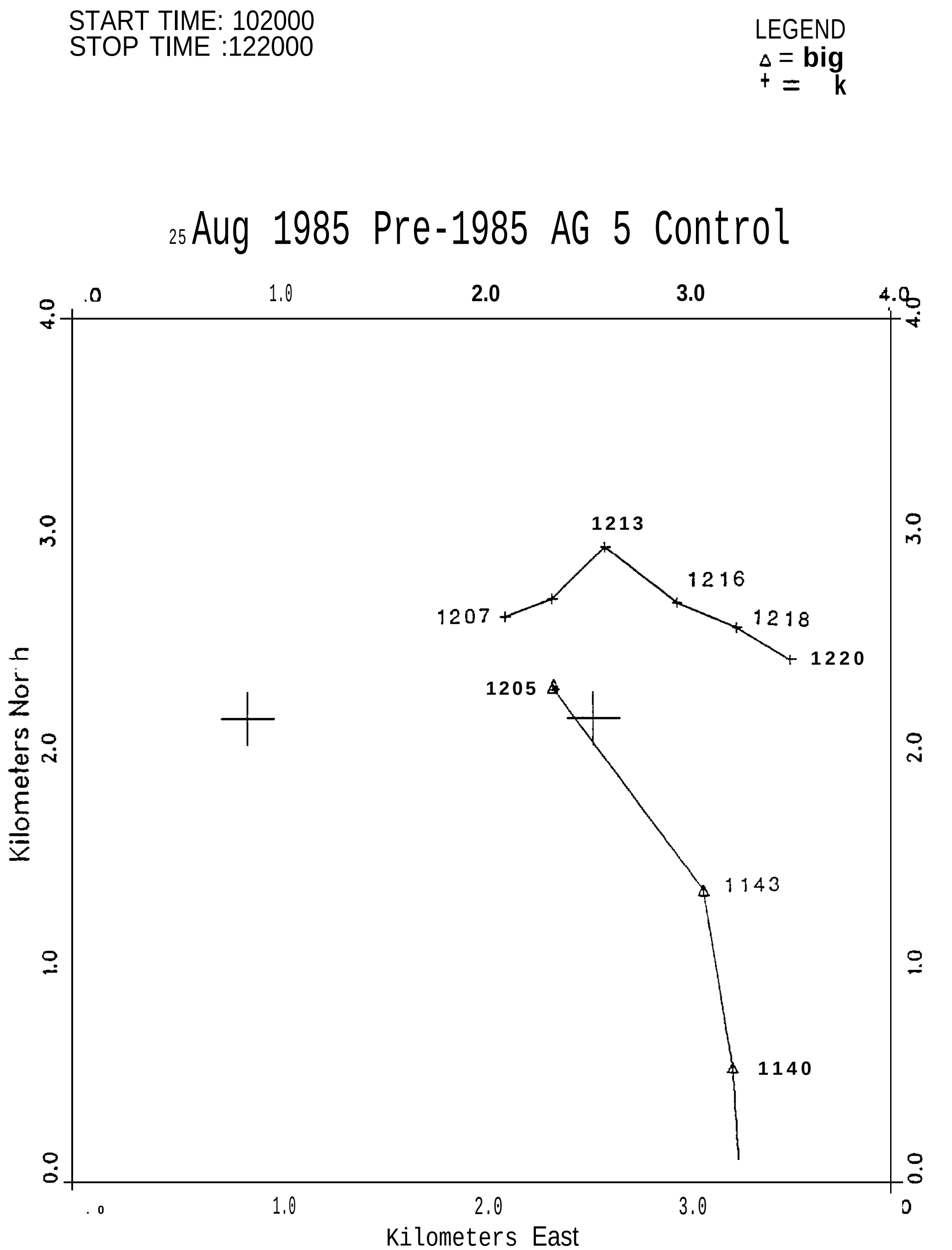


FIG. 3.31. TRACK PLOT OF WHALE K DURING PRE-AG 5 CONTROL ON 25 AUGUST AFTER THE M/V BIG VALLEY MOVED INTO THE AREA .

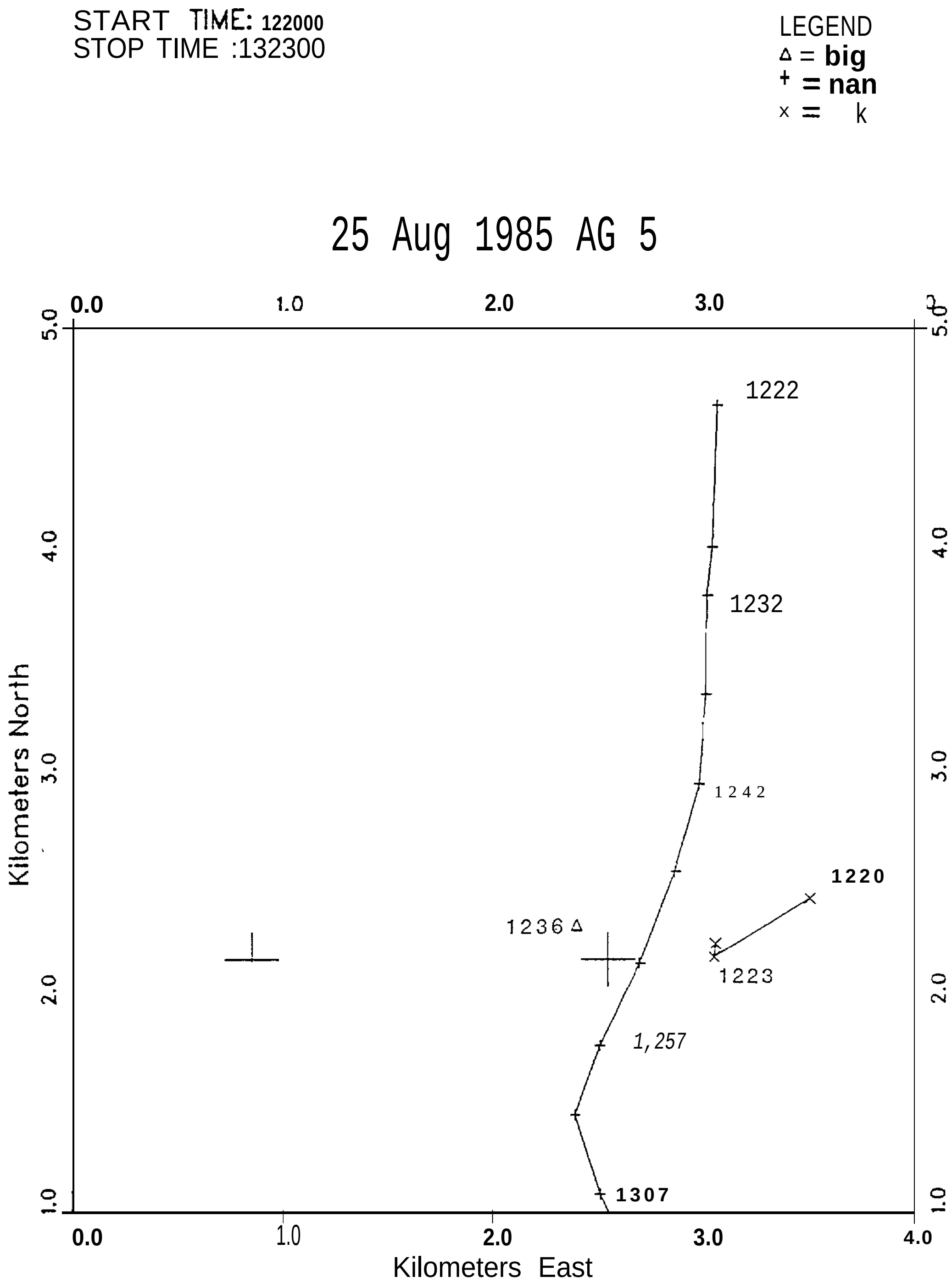


FIG. 3.32. TRACK PLOT OF WHALE K DURING AG 5 ON 25 AUGUST.

Whale L was first sighted at 1120 and, as noted previously, was in the same area as Whale K, joining this whale briefly at 1129. Whale L was feeding much of the time during the pre-AG 5 control period; however, we do not have reliable track information on this whale until 1236 (see Fig. 3.33), 16 minutes after the onset of AG 5. At this point, RSL at Whale L was 163 dB with the NANCY H 1.96 km distant and moving to the SSW. Whale L was moving to the south and feeding at 1250. RSL at this time was 167 dB, with the NANCY H 1.25 km distant. At 1258, Whale L moved toward and joined Whale N, a feeding whale first sighted at 1249. The two stayed together, slowly moving to the southwest until approximately 1336, During this time, Whale N was feeding, surfacing, blowing, and diving at regular intervals. Whale L was generally observed not to be feeding, spending a majority of time at or near the surface. At 1300, Whale L spyhopped, lifting its head vertically out of the water. Several more spyhops by this whale were noted over the next 9 minutes, during which time RSL peaked at 170 dB with the NANCY H 1.1 km directly offshore of group L+N. This group continued to move to the southeast (see Figure 3.33), with Whale N feeding the entire time.

At approximately 1336, 13 minutes after the end of AG 5, Whales L and N separated, with Whale L continuing to move to the southeast. Figure 3.34 shows the movement of Whales L and N during the post-AG 5 control period. We followed Whale L after the separation, and by 1352, Whale L had increased its speed, moving rapidly out of the area. The whale was last sighted at 1400, still moving southeast.

AG 6, 25 August, 1600-1706

In the course of following Whale L, observers noted another whale feeding in the same general area, and after leaving L started to follow this whale. By 1433, this whale was moving rapidly to the south and was last sighted at 1447. Whale N was

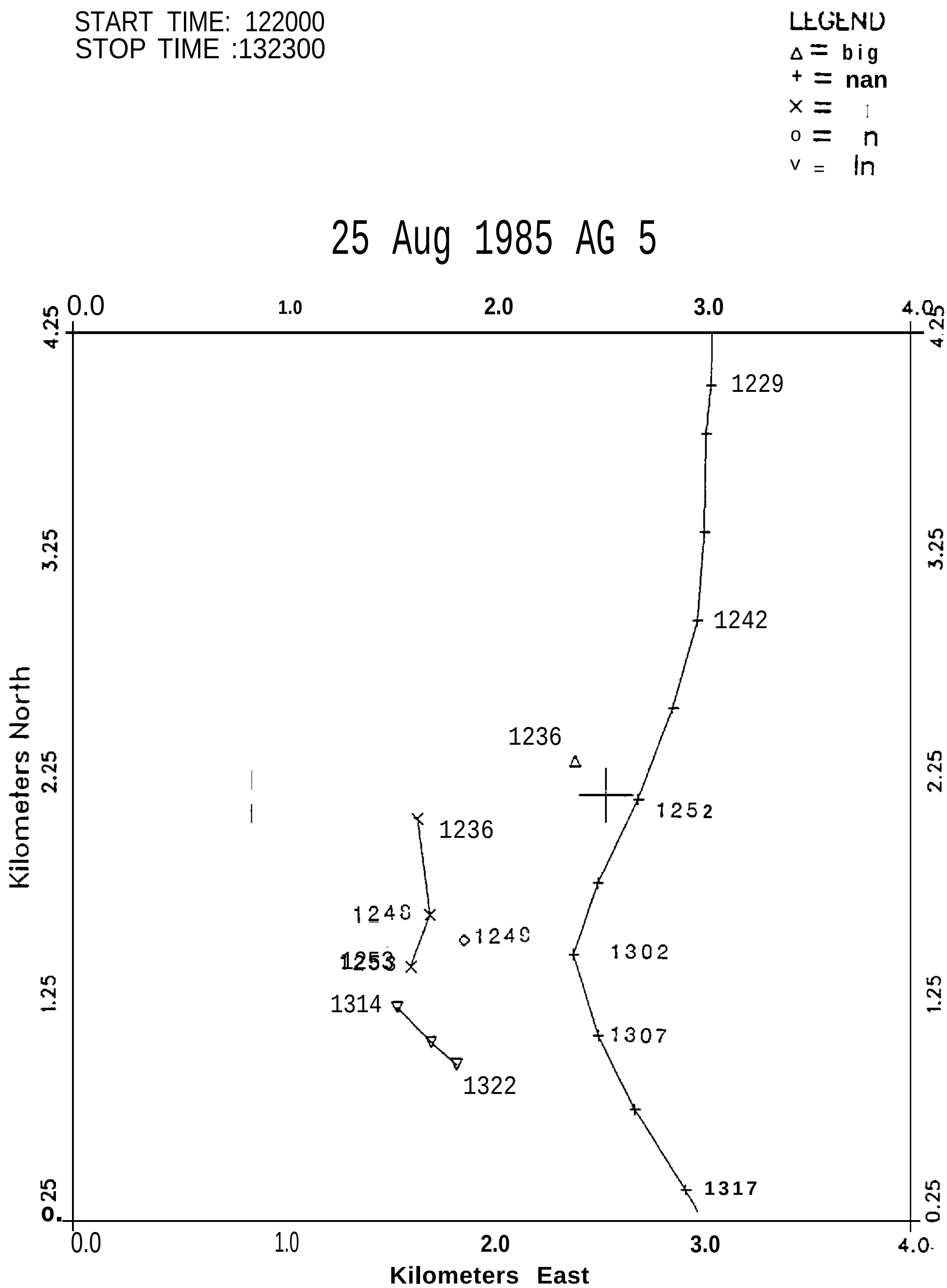


FIG. 3.33. TRACK PLOT OF WHALES L, N, AND GROUP L+N DURING AG 5 ON 25 AUGUST. WE DO NOT HAVE POSITION INFORMATION ON THESE WHALES BETWEEN 1253 AND 1314.

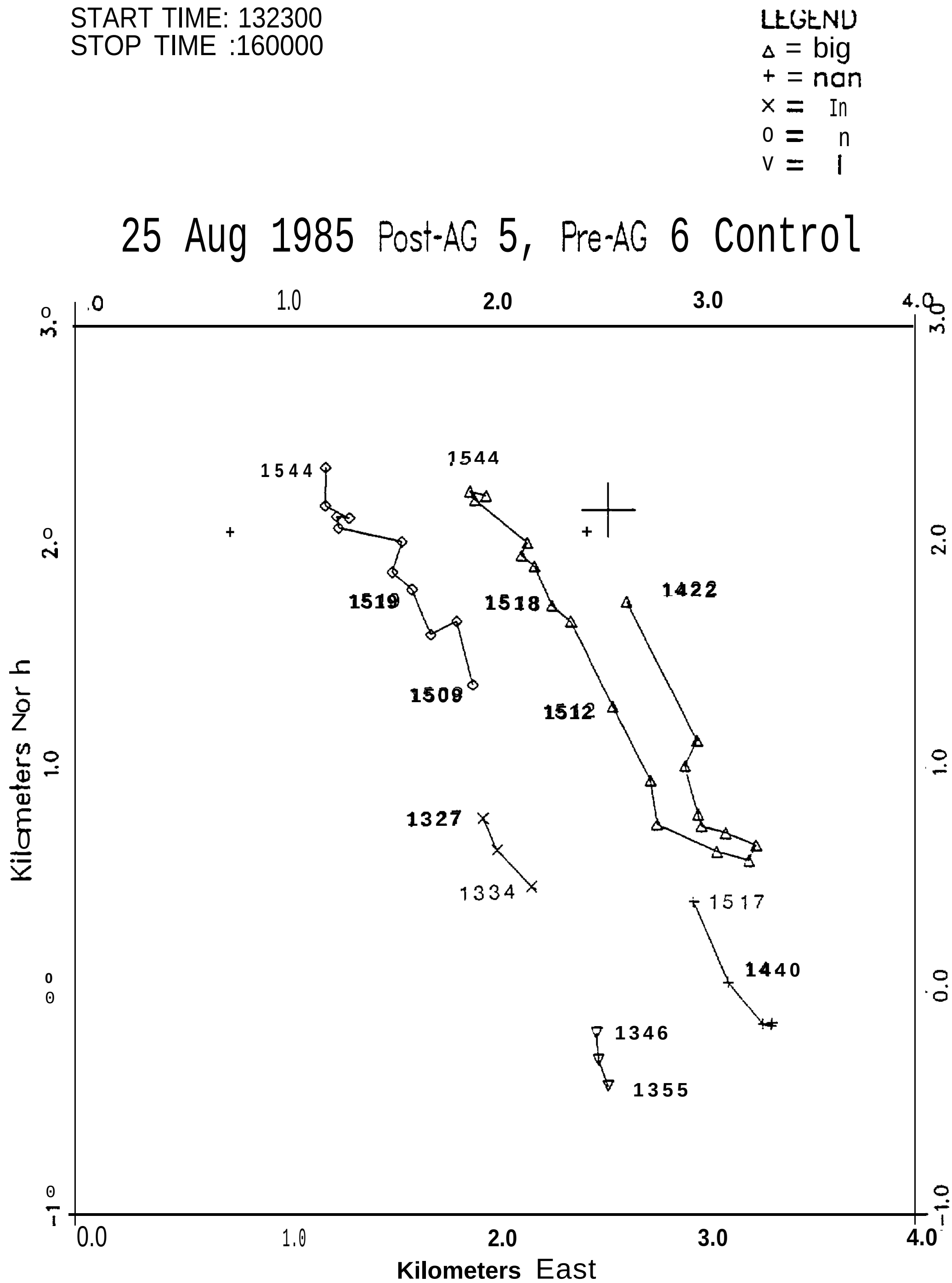


FIG. 3.34. TRACK PLOT OF GROUP L+N AND WHALE L DURING POST-AG 5 CONTROL AND WHALE N DURING PRE-AG 6 CONTROL ON 25 AUGUST.

resighted at 1500; it was feeding. Whale N was kept under continuous observation for the next 4 hours. Figure 3.34 shows the slow NNW movement of this whale. During the same period the BIG VALLEY was moving into position prior to AG 6, anchoring at 1544. Because of fog that moved into the area at 1502, the BIG VALLEY was forced to move fairly close to the Zodiac and Whale N. As can be seen in Fig. 3.34, the BIG VALLEY was at times approximately 0.5 km from Whale N. However, no unusual behavior was noted and the whale continued to feed throughout this period.

By 1545, 15 min. before the start of AG 6, viewing conditions had deteriorated further and observations of the Zodiac and Whale N from the BIG VALLEY were impossible. As a result, we do not have a plot of Whale N's movement during AG 6 and therefore RSL are not available. However, Zodiac personnel kept Whale N under close observation during AG 6. The following is a summary of the whale's behavior and movement during AG 6 with reference to Figure 3.35, the track plot of the NANCY H during the AG 6 experiment.

Whale N continued to feed until at least 1605, 5 minutes after the onset of AG 6. By this time, however, the whale had increased its speed, moving generally northward. After this time, Whale N was not observed to feed until 1807. Between 1635-1650 (see Figure 3.35), Whale N was paralleling the course of the NANCY H, at times coming to within 100 m of the vessel. At these ranges, Whale N must have received sound levels in excess of 188 dB. Observers on the Zodiac had the impression that the whale was attempting to move offshore during this period. At 1653, Whale N moved across (or possibly underneath) the bow of the NANCY H, coming very close to the vessel. Once on the offshore side of the NANCY H, Whale N moved rapidly to the northeast. Whale N continued to move offshore, alternating its rate of travel, until approximately 1715, 9 minutes after the end

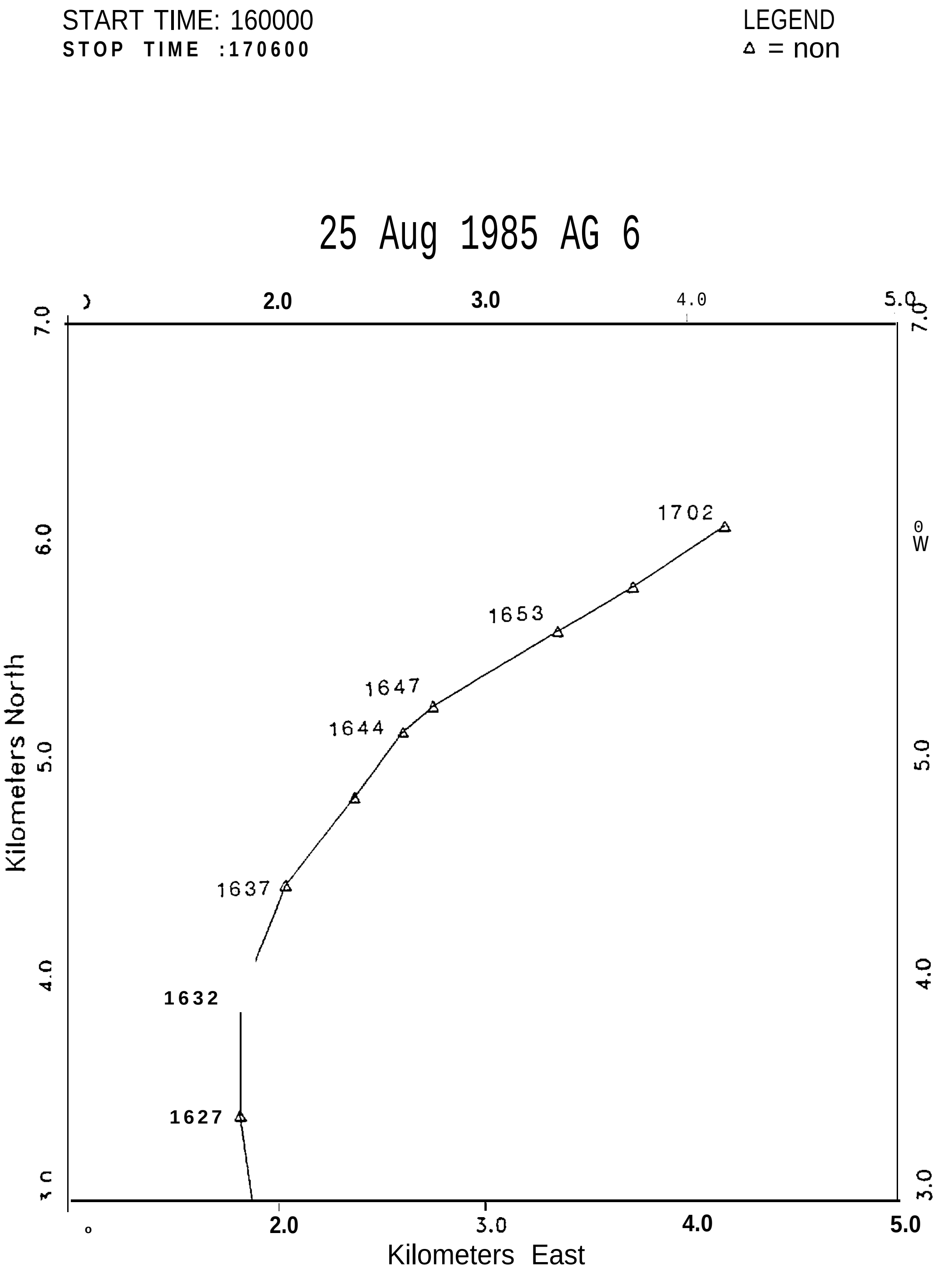


FIG. 3.35. TRACK PLOT OF M/V NANCY H. DURING AG 6 ON 25 AUGUST.

of AG 6. At this point the whale started to move back inshore. By 1727, observers on the BIG VALLEY were able to see both the Zodiac and the whale and were able to take position readings in coordination with Zodiac personnel. Figure 3.36 shows Whale N's movement from this time to the end of observations at 1902. At 1741, Whale N increased its speed, and between 1742-1746 it breached three times. The whale continued to move inshore, and at 1807 mud was seen associated with it, the first indication of feeding since 1615. At this point, Whale N moved slowly south, feeding the entire time. By the end of observations at 1902, the whale was in the same general area in which it had been feeding prior to AG 6. In fact, Whale N was within 200 m of where it was first sighted feeding at 1249 (see Figure 3.33).

Summary and Discussion of Movement Patterns

Drillship Playback

The two playbacks for which whale movement data are available, DS 2 and DS 3, suggest that the whales did not alter their movement patterns with RSL at 103 to 110 dB and the BIG VALLEY as close as 1.12 km. In one case (DS 3), a whale continued to feed in the same general area during both control and experimental periods. However, during the pre-control period for DS 2, whales appeared to respond to the presence of the BIG VALLEY, thus complicating interpretation of results. During DS 1 and DS 4, whales in the vicinity of the BIG VALLEY did move out of the general area; however, we were unable to obtain track data on individual whales and therefore RSL for specific focal animals are not available.

There have been very few controlled experiments involving drillship playbacks to non-migrating baleen whales. Richardson et al. (1985) and Richardson, Wells, and Würsig (1985) found some evidence for bowhead whale avoidance at distances of 4 to 5 km

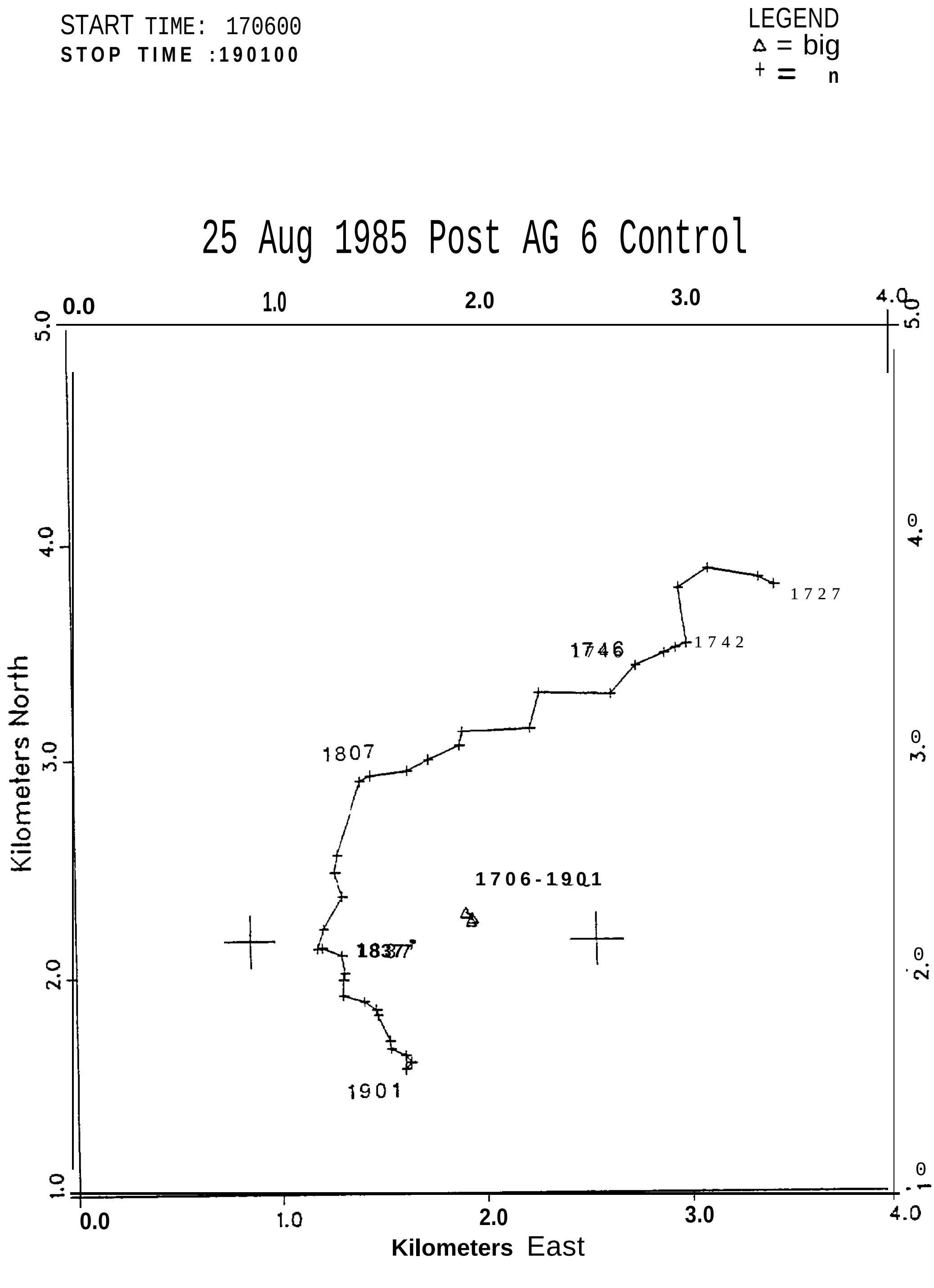


FIG. 3.36. TRACK PLOT OF WHALE N DURING POST-AG 6 CONTROL ON 25 AUGUST.

from the playback vessel with RSL at the closest whales ranging from approximately 100 dB to 112.5 dB. They note, however, that because of the limited number and short duration of the play-backs, more experiments are needed and that their results "...must be considered preliminary." (Richardson et al. 1985. p. 222*) Malme et al. (1985) conducted two drillship playback experiments on feeding humpback whales in Frederick Sound, Alaska. There were no consistent responses of whales at ranges to the sound source of >0.5 km with RSL >116 dB.

Air Gun

Alterations in whale movement patterns and/or feeding behavior were noted during each of the six air gun experiments. Table 3.8 summarizes the behavior of eight of the nine focal whales under observation during the experiments. As the pre-control behavior of Whale K on 24 August during AG 5 was possibly affected by the presence of the BIG VALLEY, this whale has not been included.

Responses were noted at RSL ranging from 149 dB to 176 dB at distances up to approximately 4 km. However, in one case, RSL reached a peak of 165 dB with the NANCY H 0.66 km distant with very little, if any, response observed. We did observe the cessation of feeding with apparent movement away from the experimental vessel during some part of air gun sound exposure on five occasions. However, in three of these cases the whales resumed feeding either during the experiment (one case) or during the post-control period (two cases). In the remaining two cases, one whale stopped feeding with apparent movement away from the experimental vessel (Whale A, AG 3) and continued to move out of. the area during the post-control period; the other whale (Whale L) stopped feeding during AG 5; however, we do not have information on its pre-control movement pattern.

TABLE 3.8. SUMMARY OF FOCAL WHALE RESPONSE TO AIRGUN EXPERIMENTS, 22, 24-25 AUGUST 1985.

Date (Aug.)	AG# & Time	Focal Whale	Pre-Control Activity	AG Activity	Time of Response, Source	RSL (dB)	Distance (km)	Peak RSL and Source Distance	Post-Control Activity	Figure Reference
22	AG 1 1440-1600	E	Feeding	Movement away, stopped movement as AG approached, no feeding	1446,	-149,	-4.0	172, 0.19	Return to Pre-Control area, f[illegible]	3.19-3.21
22	AG 2 17[illegible]8	E*	Feeding	Direction change, move towards and then away from N. H.[1] feeding before and after move	1739,	-172,	-0.47	172, 0.47	F[illegible]g, movement possibly affected by B.V.[2]	3.22-3.33
24	AG 3 1715-1758	A	Feeding, joined Whale E	Group split at AG onset, A move north & east offshore, feeding to 1731	1731	157	1.74	160, 1.17	Continued offshore movement	3.24-3.25
24	AG 3 1715-1758	B*	Feeding	Feeding with inshore movement as N. H. moved past (possibly feeding related)	1740,	-162,	-0.9	165, 0.66	Feeding same general area	3.26-3.28
24	AG 4 1929-2026	B*	Feeding	Feeding, turn, speed increase, dive, fluke out, resume feeding	1957,	176	0.18	177, 0.17	Feeding same general area	3.29-3.30
25	AG 5 1220-1323	L*	Feeding, no track plot	Joined by Whale N, some feeding, spyhops, southeast movement	1300,	--169	--1.0	170, 1.02	Group split, L increase speed moving southeast out of area, no feeding	3.33-3.34
25	AG 5 1220-1323	N	Unknown	Joined Whale L, feeding	--	--	--	170, 1.02	Feeding, group split	
25	AG 6 1600-1706	N	Feeding	Feeding to 1605, movement parallel to N. H. then offshore	1605	174	(est.)	>188, < 0.10	Offshore to 1715, then back to original location and feeding	3.36

*Response when N.H. broadside to whale.

[1]NANCY H

[2]BIG VALLEY

Most of the responses involved either an abrupt change in direction and/or an increase in speed with apparent movement away from the experimental vessel. On one occasion a whale spyhopped several times in apparent response to increasing RSL. We did note that in three and possibly four cases (marked with an asterisk in Table 3.8) whales showed a response to the operating air gun at a time coinciding with the NANCY H moving past the whale's position, at which point the whales were experiencing peak RSL. Malme et al. (1983) observed a similar response pattern in mother/calf gray whales to a moving seismic vessel.

Richardson, Würsig, and Greene (1986) conducted air gun experiments on non-migrating bowhead whales using a single 0.66-1 Bolt air gun. During three experiments in 1981 and 1983 involving a moving source, they found no evidence of avoidance at distances from 3 to 5 km with RSL near the whales ≥ 118 to 133 dB. In 1984, two experiments were conducted using a stationary source. Results showed that at 0.2 to 1.2 km and 2 to 4.5 km with RSL described as "intense" (not measured because of sonobuoy overload) and 124 to 131 dB, respectively, whales moved away from the source vessel. Malme et al. (1985) conducted single air gun (100 cu. in.) experiments on feeding humpback whales in Frederick Sound, Alaska. They found no overall pattern of avoidance with RSL up to 172 dB. However, observers did note startle responses by whales at air gun onset on three occasions with RSL at 150 dB to 169 dB at ranges up to 3.2 km.

More data on focal whales under control and experimental conditions are needed before firm conclusions regarding the effects of drillship playbacks and air gun operations on feeding gray whales can be made. The present data set shows that feeding gray whales can respond in a variety of ways to a moving, single air gun and that these responses can occur at RSL ranging from 149 dB to 176 dB with whale distance up to 4 km from the source.

3.4.2 Surfacing-dive behavior

Four basic characteristics used to describe the surfacing-dive behavior of gray whales were (1) respiration or blow interval, (2) length of surfacing, (3) length of dive, and (4) number of blows per surfacing. A fifth characteristic, blow rate, was calculated from length of surfacing? length of dive, and number of blows per minute (Würsig et al. 1984, Würsig et al. 1986). The frequency distributions of the five characteristics are shown in Fig. 3.37. Blow interval and blow rate approximate a normal distribution, while the distributions of the other three characteristics are highly skewed. Consequently, blow interval and blow rate were analyzed with parametric testing procedures (by analysis of variance and Student-Newman-Keuls multiple comparisons tests), while length of surfacing, length of dive, and number of blows per surfacing were analyzed nonparametrically (by Kruskal-Wallis, Mann-Whitney-U, and nonparametric multiple comparisons; Zar 1974, Sokal and Rohlf 1981).

Whales were labelled as undisturbed during non-experimental days when large boats were not moving in the study area, and during the first pre-disturbance control periods of each experimental day. We did not label subsequent control periods of experimental days as "undisturbed" for the purposes of surfacing-dive behavior analysis, since the data indicate that such subsequent control periods may not have represented a true undisturbed situation, but instead whales were potentially affected by the previous experiment of that day.

There are clear correlations between several of the surfacing-dive characteristics (Fig. 3.38). Number of blows per surfacing increases with length of a surfacing, and whales surface for longer times between longer dives. These longer surfacings allow the whales to respire sufficiently between long

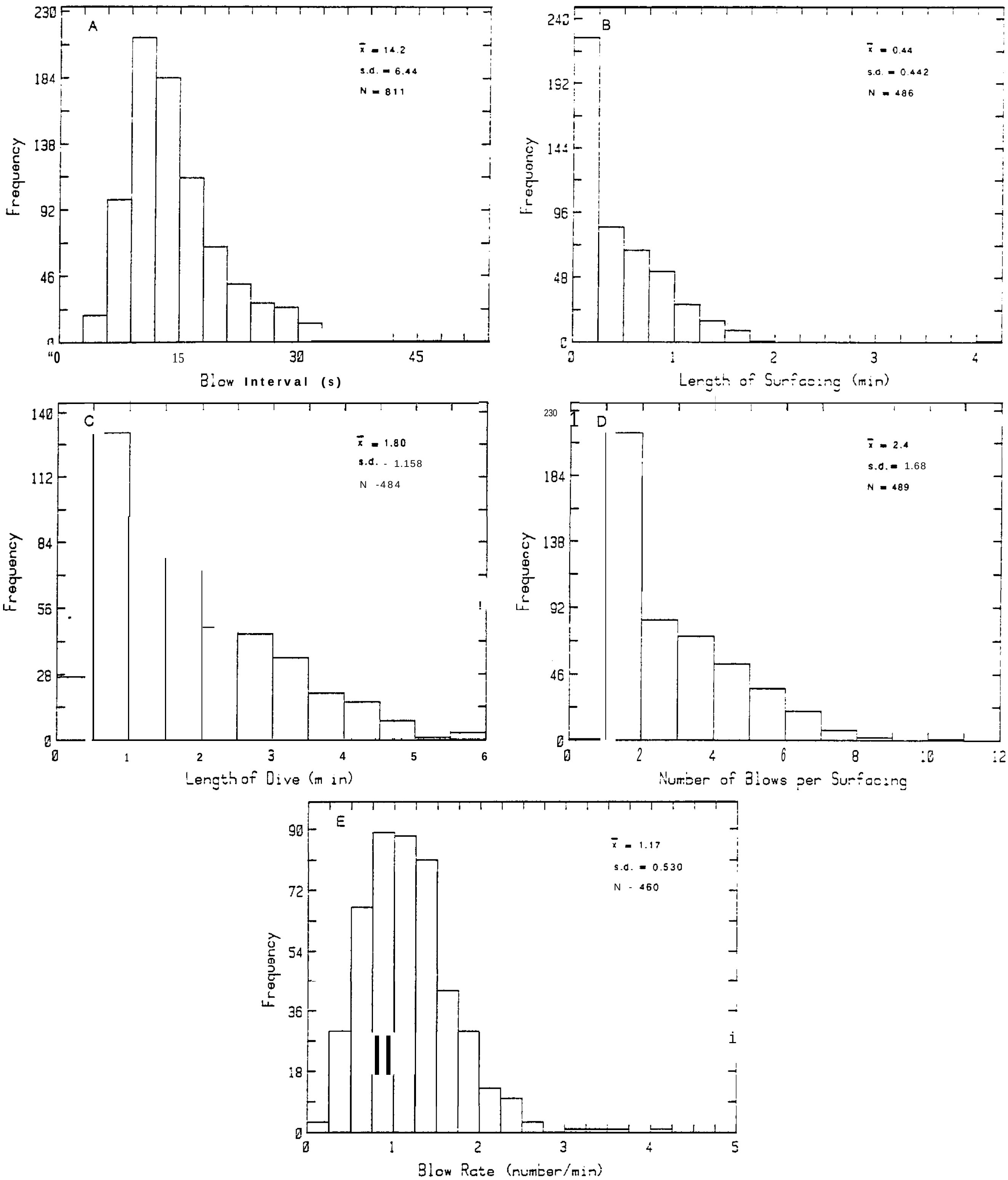


FIG. 3.37. FREQUENCY DISTRIBUTION OF SURFACING-DIVE DATA ON UNDISTURBED WHALES. SEE TEXT FOR DEFINITION OF UNDISTURBED .

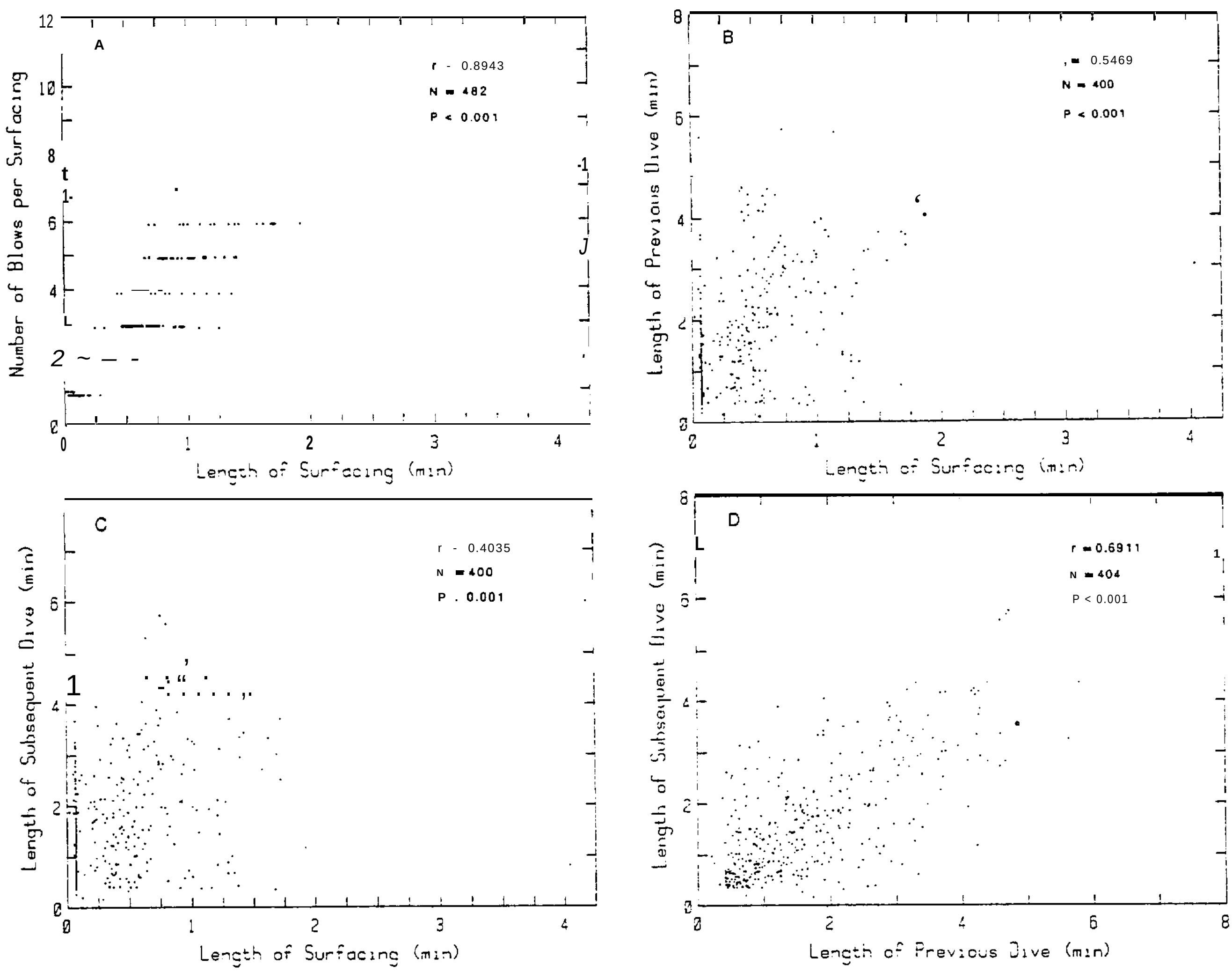


FIG. 3.38. CORRELATIONS BETWEEN SEVERAL SURFACING-DIVE VARIABLES, UNDISTURBED WHALES.

dives and, as a result of this interplay between characteristics, blow rate remains relatively constant between short and long dives. The correlation between dives before and after a certain surfacing (Fig. 3.38D) indicates that whales tend to dive for similar lengths of time in sequence. Frequency distributions and correlations between surfacinq-dive characteristics for whales subjected to drillship and air gun experiments were similar to the undisturbed condition.

Although we divided our data into the broad behavioral categories of milling, traveling, socializing, and bottom feeding, we had too few surfacing-dive data in different behavioral categories for statistical analyses and meaningful interpretation. We therefore present no behavioral subdivisions in the present analysis, but will do so if further data are gathered in the area in the future.

3.4.3 Pooled experimental comparisons

There were significant differences in surfacing-dive characteristics between the condition of no known disturbance and the potential disturbances of drillship playbacks and air gun experiments (Table 3.9, Fig. 3.39). Blow interval decreased; and length of surfacing, length of dive, and number of blows per surfacing all increased during drillship playbacks. For air gun sounds, the response was opposite to that of drillship, with blow interval increasing and the other three primary characteristics decreasing. Interestingly, blow rate did not change from the presumed undisturbed situation, because blow intervals made up for shifts in lengths of surfacings and dives.

Figures 3.40 and 3.41 show these summary data in more detail. For drillship playback experiments, the surfacing-dive characteristics stay at a “disturbed” level within a one-half

TABLE 3.9. SUMMARY STATISTICS FOR UNDISTURBED WHALES AND WHALES DURING DRILLSHIP PLAYBACKS AND AIR GUN EXPERIMENTS.

Experimental Situation	Blow Interval(s)			No. of Blows/ Surfacing			Length of Surfacing (rein)			Length of Dive (rein)			Blow Rate (No./Min.)		
	$\bar{x}$	s.d.	n	$\bar{x}$	s.d.	n	$\bar{x}$	s.d.	n	$\bar{x}$	s.d.	n	$\bar{x}$	s.d.	n
Undisturbed	14.2	6.44	811	2.4	1.68	489	0.44	0.442	406	1.80	1.158	494	1.17	0.530	480
Drillship	12.5	5.18	115	3.0	2.76	46	0.52	0.314	45	2.32	1.414	45	1.20	0.790	41
Air gun	16.5	6.01	147	2.0	1.40	135	0.38	0.430	135	1.54	1.081	134	1.20	0.570	131

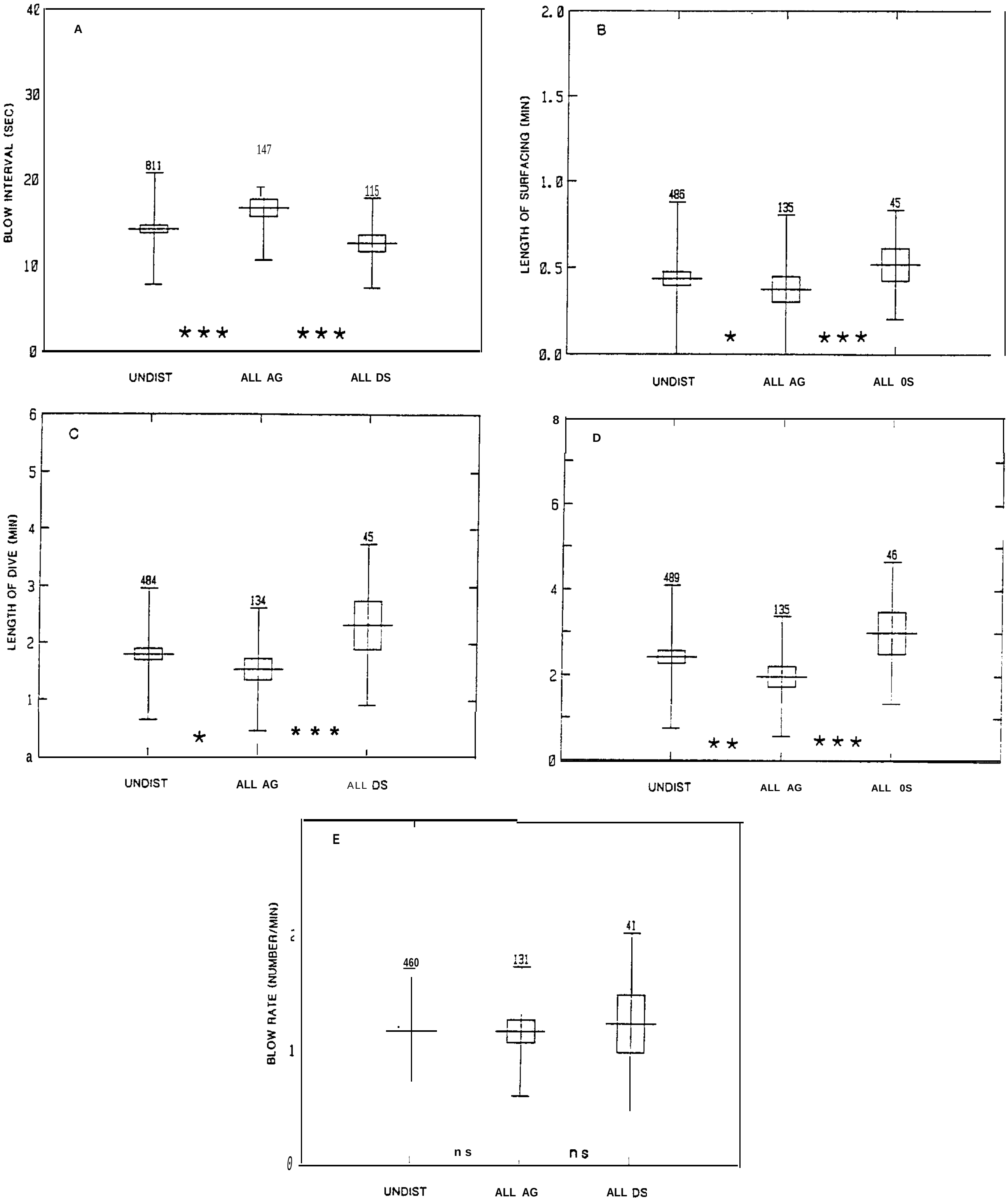


FIG. 3.39. SUMMARY STATISTICS FOR UNDISTURBED WHALES, AND WHALES DORING DRILLSHIP PLAYBACK (DS) AND AIR GUN EXPERIMENTS (AG). CENTER BARS DENOTE MEANS, BOXES DENOTE 95% CONFIDENCE INTERVALS, BARS DENOTE 1 S.D. ABOVE AND BELOW THE MEAN, AND NUMBERS DENOTE SAMPLE SIZE. ASTERISKS SHOW SIGNIFICANCE LEVELS OF PROBABILITY: * = 0.05, ** = 0.01, *** = 0.001. NS = NOT SIGNIFICANT.

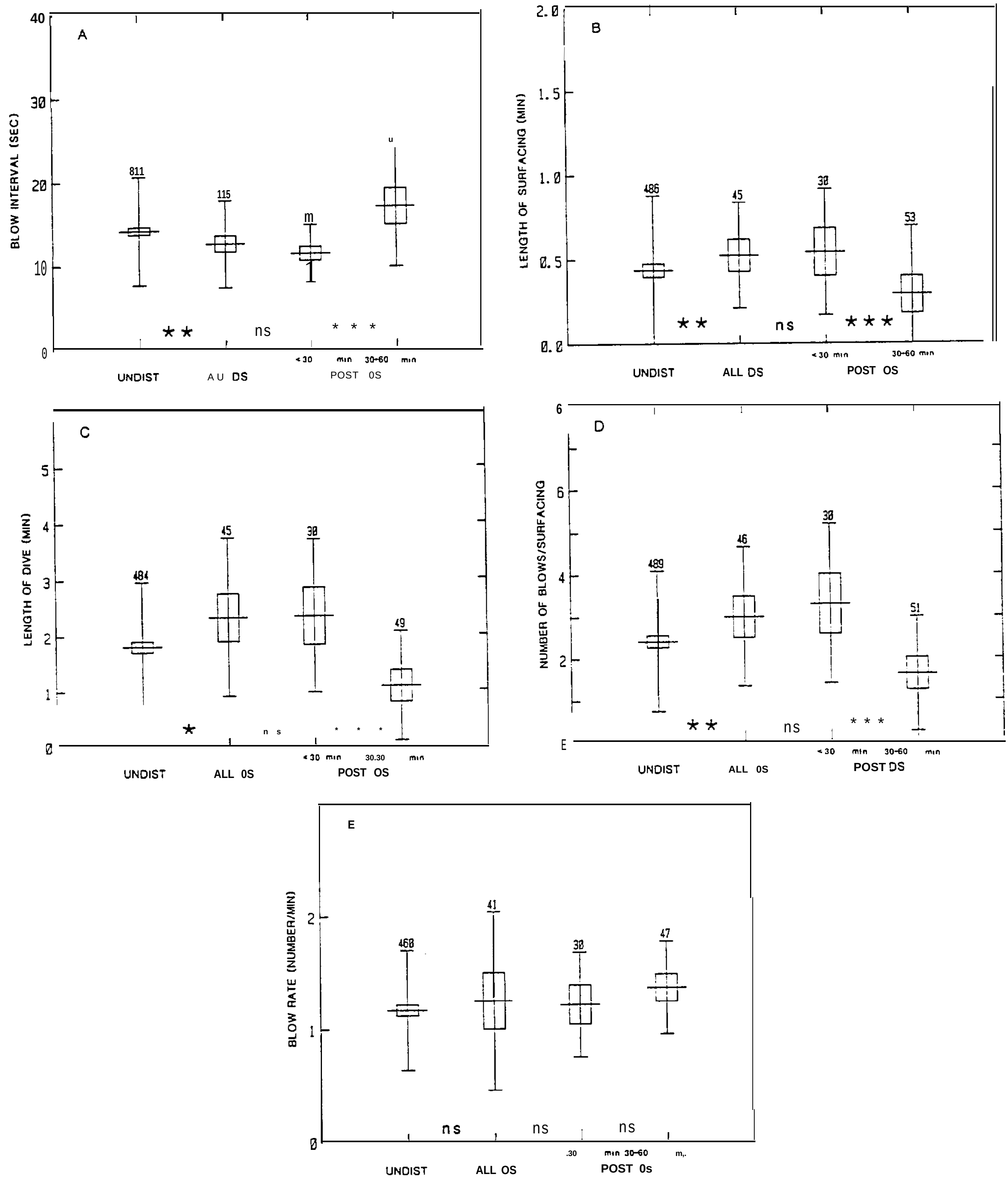


FIG. 3.40. SUMMARY STATISTICS FOR UNDISTURBED WHALES, AND WHALES DURING AND AFTER DRILLSHIP PLAYBACKS. DISPLAY AS IN FIG. 3.39.

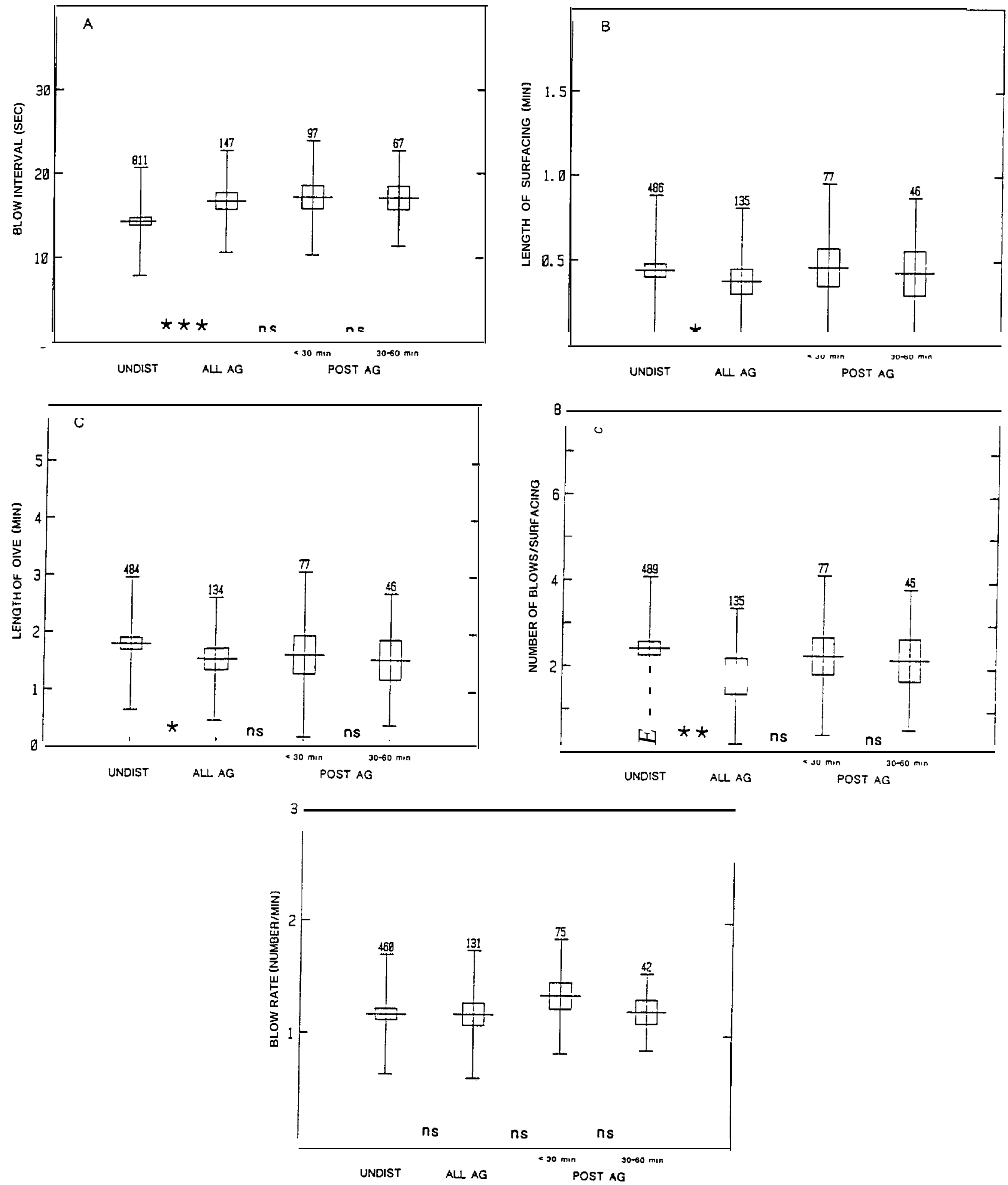


FIG. 3.41. SUMMARY STATISTICS FOR UNDISTURBED WHALES, AND WHALES DURING AND AFTER AIRGUN EXPERIMENTS. DISPLAY AS IN FIG. 3.39.

hour period after exposure of whales to drillship sounds. Whales shift their surfacing-dive characteristics close to the pre-disturbance level in the 30 to 60 minute period after exposure. They even appear to "overshoot" the presumed undisturbed level, with blow interval higher and the other three primary characteristics lower, than during the presumed undisturbed situation (Fig. 3.40). Responses of whales to air gun do not tend to go back to the presumably undisturbed condition within one hour of air gun sounds, especially for blow intervals and length of dives. These data indicate that air gun sounds have a longer-term effect on the normal behavior of primarily feeding gray whales than do drillship sounds (Fig. 3.41). A caution is necessary, however: drillship sounds were made by playbacks which may have some differences in sound characteristics from real drillships, and air gun sounds were supplied by only one air gun instead of the many often used during seismic mapping activities (see sound section for more detail).

3.4.4 Specific experimental comparisons

<u>19 August 1985</u>

Few numerical data exist for 19 August, and we can make no firm statements about surfacing-dive characteristics relative to stages of the drillship experiment (DS 1) of this date. During the almost four hours of control period before drillship sound playback, >15 whales were sighted within 2 km of the BIG VALLEY, and at least 2 to 3 whales were present within 600 M of the vessel at any one time. During the playback, only one whale was seen briefly at the beginning of playback, and then no whales were seen close to the vessel for >30 minutes. Four whales were seen 1.0 to 1.5 km from the vessel just after playback. As a result, we have almost no data during the drillship experiment and for the 30 min. post disturbance period (Fig. 3.42). During the 30 to 60 min. post disturbance period, blow interval

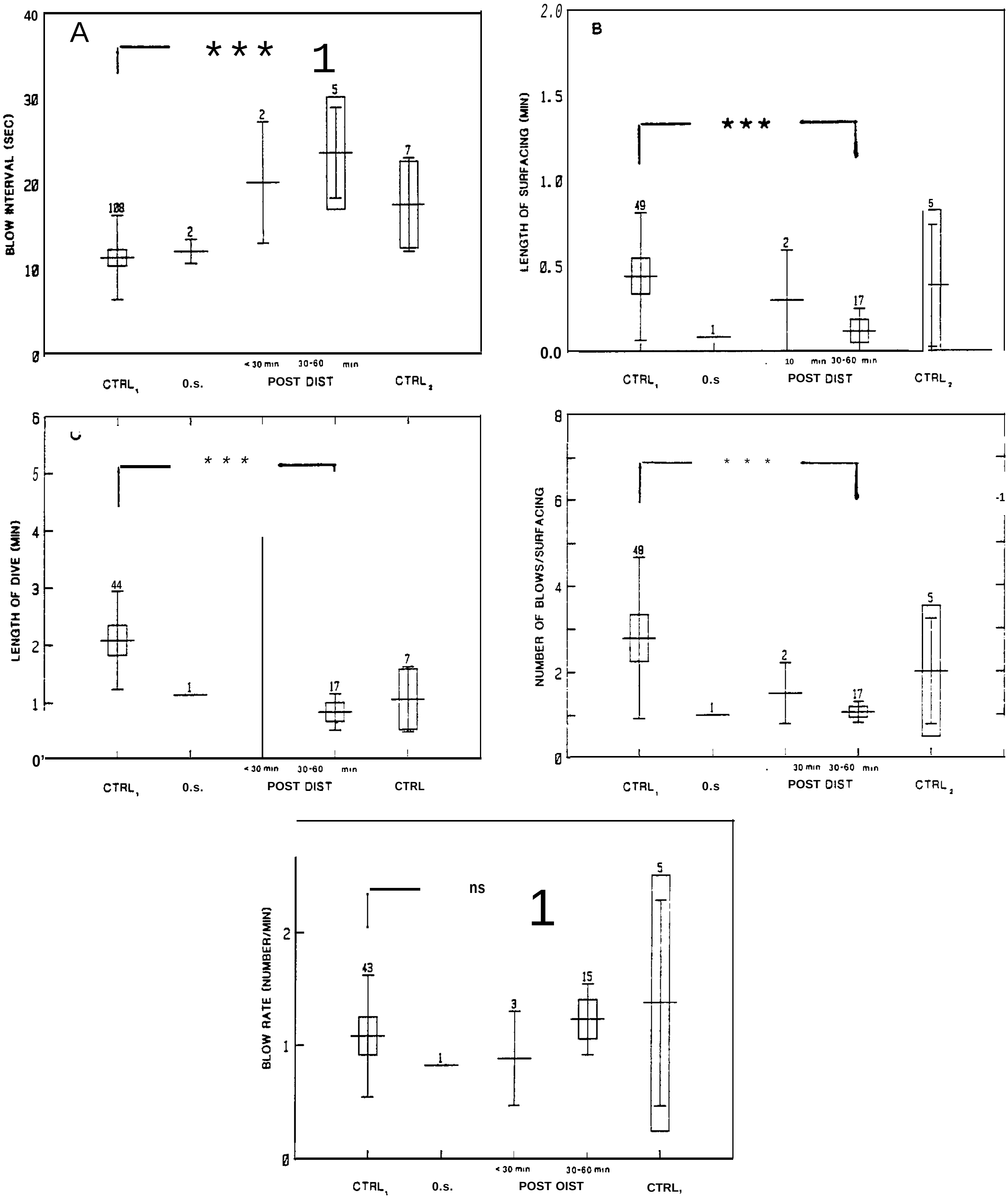


FIG. 3.42. AUGUST 19: DIFFERENT STAGES OF A DRILLSHIP EXPERIMENT COMPARED BY SURFACING-DIVE CHARACTERISTICS. DISPLAY AS IN FIG. 3.39.

increased over control, and length of surfacing, length of dive, and number of blows per surfacing all decreased (all at $p < 0.001$ level). Blow rate showed no clear trend. It is possible that the data for the 30 to 60 min. period represent an adjustment of surfacing-dive patterns after an unknown reaction during the actual noise playback. Unfortunately, we do not know what this reaction may have been, although we can guess from summary data of drillship exposure that blow interval decreased - and the other three primary characteristics increased from the pre-disturbance category.

21 August 1985

On this date, we performed three drillship playback experiments, but with few data on the third of this series of playbacks (Figure 3.43). There was a tendency for all blow intervals to decrease during playback, and not to go entirely back to pre-disturbance levels between playbacks. Responses to drillship are not as clear for the other surfacing-dive characteristics, however. During experiment 1 of the day (DS-2), length of surfacing, length of dive, and number of blows per surfacing tended to increase. They then stayed at high levels during post-disturbance times, however, and throughout the second experiment showed a steady decrease. It is likely that the second experiment (DS-3) was strongly affected by the first, and that whales did not show consistent changes in surfacing-dive characteristics because of this effect. During playback 1 of the day, the reaction of whales was not great, but was actually larger during the O to 30 minute post-disturbance times. It is possible that this corresponds to a delayed reaction by the whales, and the apparently disparate reactions. of Exp. 1 and 2 of the day may be due to the cumulative effects of the first and second experiments as well as the continued presence of the vessel near the reacting whales.

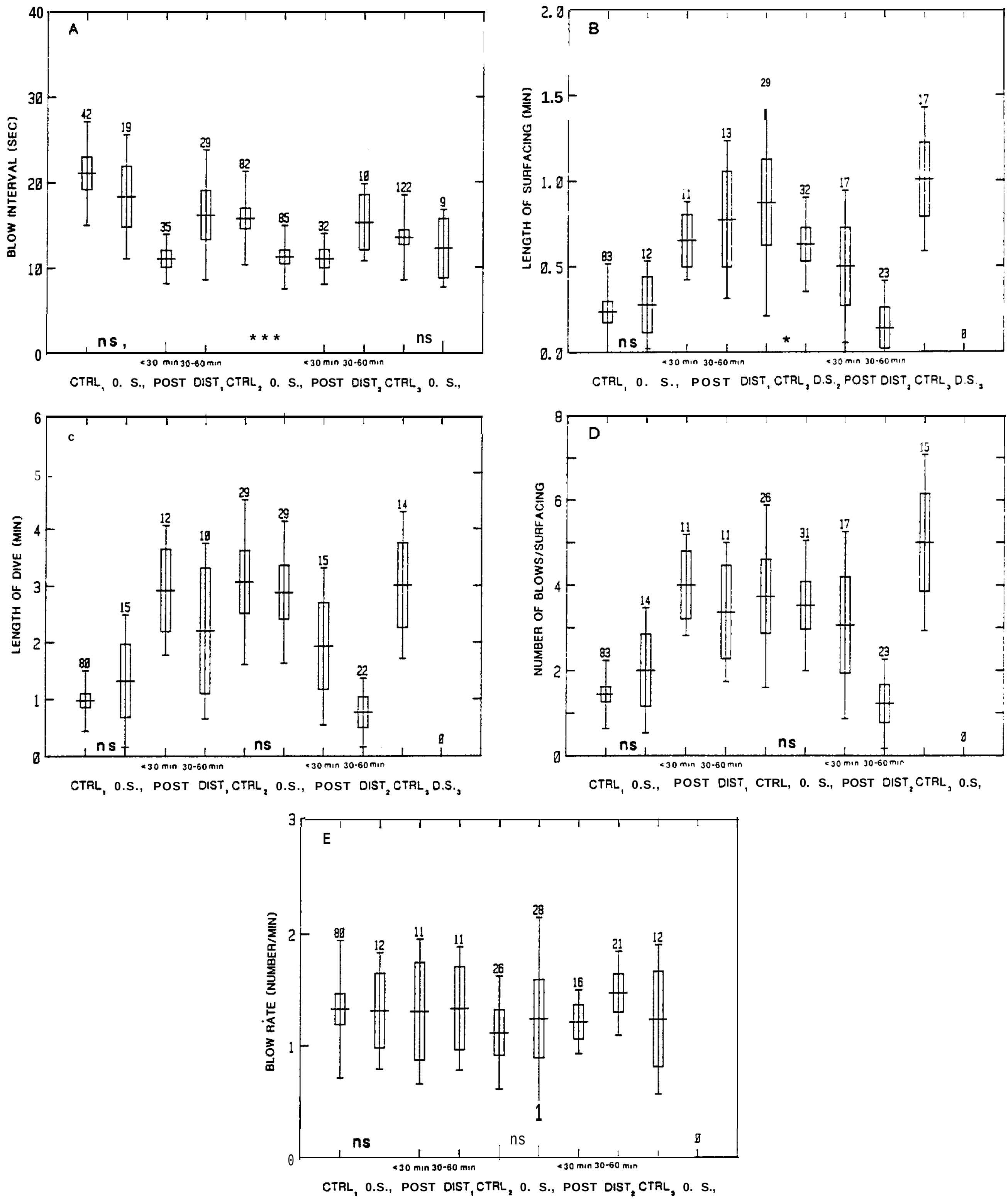


FIG. 3.43. AUGUST 21: DIFFERENT STAGES OF THREE DRILLSHIP EXPERIMENTS, PERFORMED SERIATIM THROUGHOUT THE DAY, COMPARED BY SURFACING-DIVE **CHARACTERISTICS.** DISPLAY AS IN FIG. 3.39.

22 August 1985

As stated earlier, the overall surfacing-dive reaction of whales during air gun sounds was opposite to the reaction whales showed during drillship sounds. This finding is illustrated well during the two experiments of 22 August. Blow interval showed a non-significant tendency to rise during the first air gun experiment (AG 1), but no rise during the second experiment (AG 2). Length of surfacing, length of dive, and number of blows per surfacing all decreased (at a $p < 0.001$ significance level) during the first experiment, and showed a generally non-significant trend to decrease during the second experiment. These decreases in length of surfacing, length of dive, and number of blows per surfacing tend to correlate with whales ceasing to feed during the air gun experiments, and traveling (see general behavior section). During the 30 to 60 minute post-disturbance for experiment 1, and the subsequent control period, values for these three surfacing-dive characteristics were exceptionally high (Figure 3.44b,c,d), and the second air gunperiod did not bring values down to the same level as seen during the first air gun period. Those high levels may represent an overcompensation to a pre-disturbance situation, as seen previously, but sample sizes are too low to make this conclusion firmly. After experiment 1, values during the O to 30 minute post-disturbance period remained similar to the air gun period, and then increased after that time. Values after experiment 2 increased during the O to 30 minute post-disturbance period and then decreased after that time. It appears that whales subjected to air’ gun sounds react for a longer period of time than do whales subjected to drillship sounds, and that a cumulative effect tends to lengthen this period after repeated exposure. Data are few for this set of experiments, however, and larger sample sizes and number of whales are needed for a proper assessment.

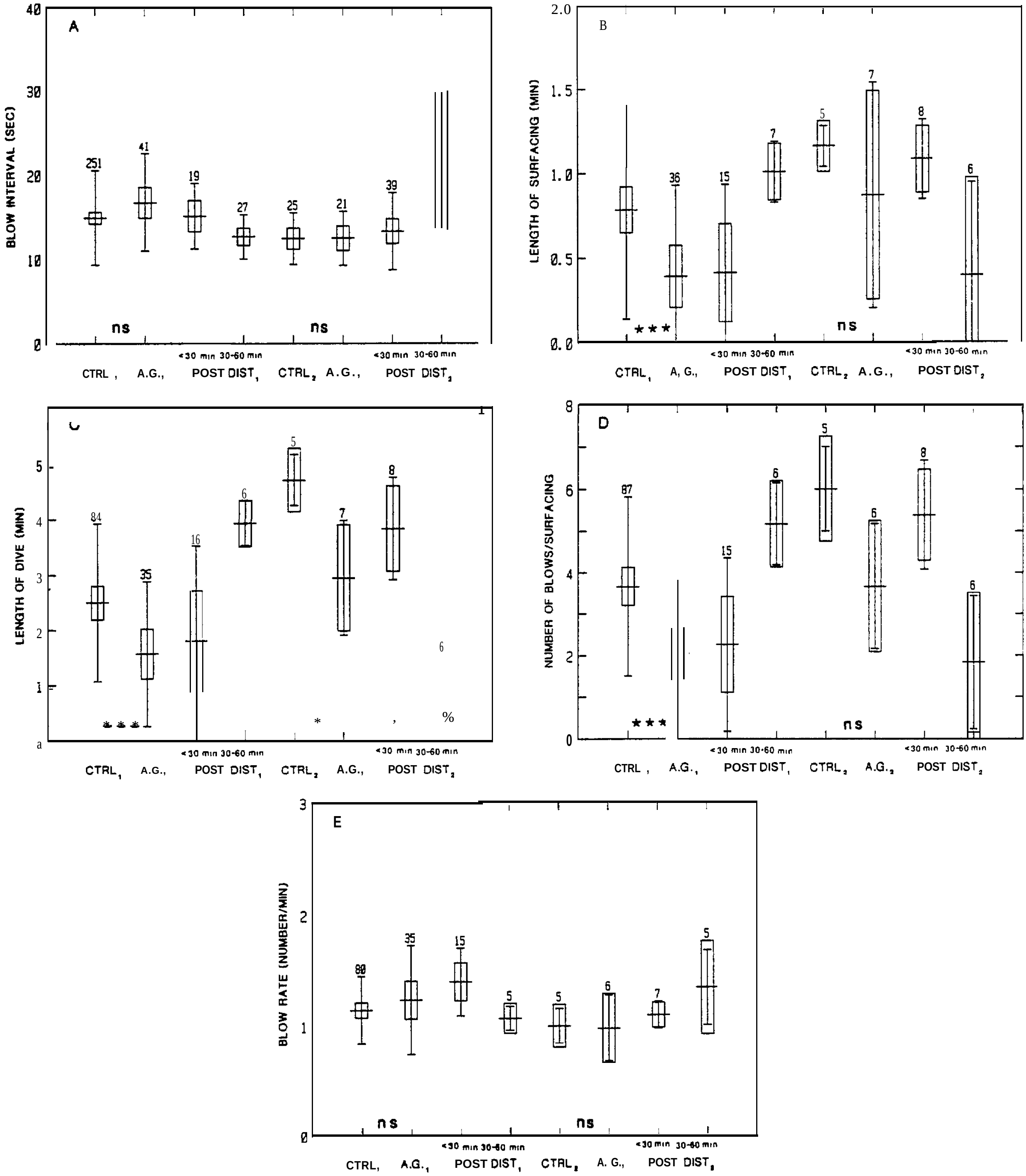


FIG. **3.44.** AUGUST 22: DIFFERENT STAGES OF TWO AIR GUN EXPERIMENTS, PERFORMED SERIATIM, COMPARED BY SURFACING-DIVE CHARACTERISTICS. DISPLAY AS IN FIG. 3.39.

24 August 1985

No surfacing-dive data were gathered for experimental comparisons, but movement patterns relative to AG 3 and AG 4 experiments and general behaviors are discussed on pages 3-72 through 3-81.

25 August 1985

There was a non-significant trend for blow intervals to increase during disturbance of both air gun experiments on 25 August . Other characteristics changed non-consistently (Fig. 3.45). There was a weak but discernible trend for length of surfacing, length of dive, and number of blows per surfacing to increase during experiment 1 (AG-5), but decrease significantly during experiment 2 (AG-6). It is likely that the non-consistent reactions to air gun sounds of experiment 1 of the day are due at least in part to an apparent disturbance reaction noted before the onset of air gun sounds as whales moved away from the BIG VALLEY, and described on pages 3-83 through 3-91. As well, we observed that one whale, “N”, apparently continued feeding throughout the air gun experiment, and this behavior was accompanied by continued high values of surfacing-dive characteristics (see Fig. 3.51). During the second experiment, on the other hand, this whale moved away from the vessel while the air gun was on, and this cessation of feeding while traveling resulted in decreases in length of surfacings, length of dives, and number of blows per surfacing. We conclude that whales were generally more disturbed during the second than during the first experiment of the day.

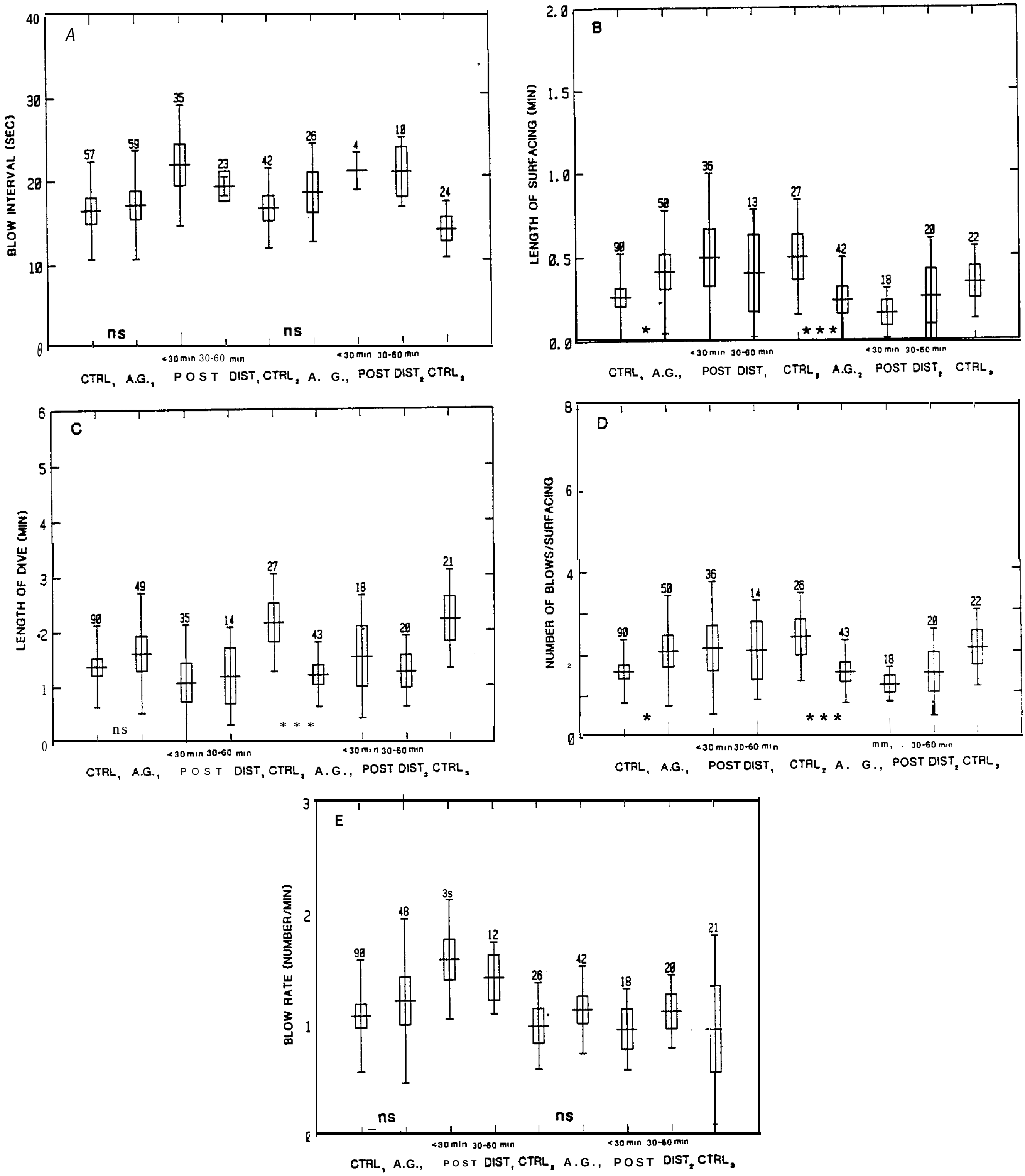


FIG. **3.45.** AUGUST 25: DIFFERENT STAGES OF TWO AIR GUN EXPERIMENTS, PERFORMED SERIATIM, COMPARED BY SURFACING-DIVE CHARACTERISTICS. **DISPLAY** AS IN FIG. 3.39.

Specific Whales and Sound Levels

21 August 1985, Whale W

Whale W was observed before, during, and after drillship playback #2 of 21 August (DS-3) (see pages 3-60 through 3-62). The whale fed during most of that time, with some socializing for a 12-minute period during the control period before DS-3 playback. Surfacing-dive characteristics indicate a decrease in blow interval, length of surfacing, and length of dive (with a possible decrease for number of blows per surfacing as well) for the drillship versus control periods (Fig. 3.46). Recovery towards pre-disturbance level occurred within 60 minutes. Our observations indicated that Whale W did not cease feeding while it was subjected to the playback, and it stayed in the same area throughout our observations (pages 3-60 through 3-62). It is interesting that both length of surfacing and length of dive decreased during the playback. This indicates a more rapid cycling of the surfacing-dive repertory, and this may indicate a high “excitement” or “nervousness” level. Blow rate also showed a tendency to increase during drillship playback (albeit non-significant, possibly due to low sample size).

It is instructive to compare received levels of drillship sound, calculated for Whale W by taking distance of whale from the sound source and sound propagation characteristics of the area into account. We find that the decreases in blow interval, length of surfacing, and length of dive appear to be most pronounced during the lower than the higher exposure levels (Figure 3.47a,b,c). Higher sound levels occurred during the beginning of Whale W’s exposure to the sound, and levels decreased as the whale slowly moved away. It is possible that the apparently greater response during the lower received levels is due to a cumulative effect of sound, and that Whale *W* reacted more strongly towards the end of drillship playback despite the

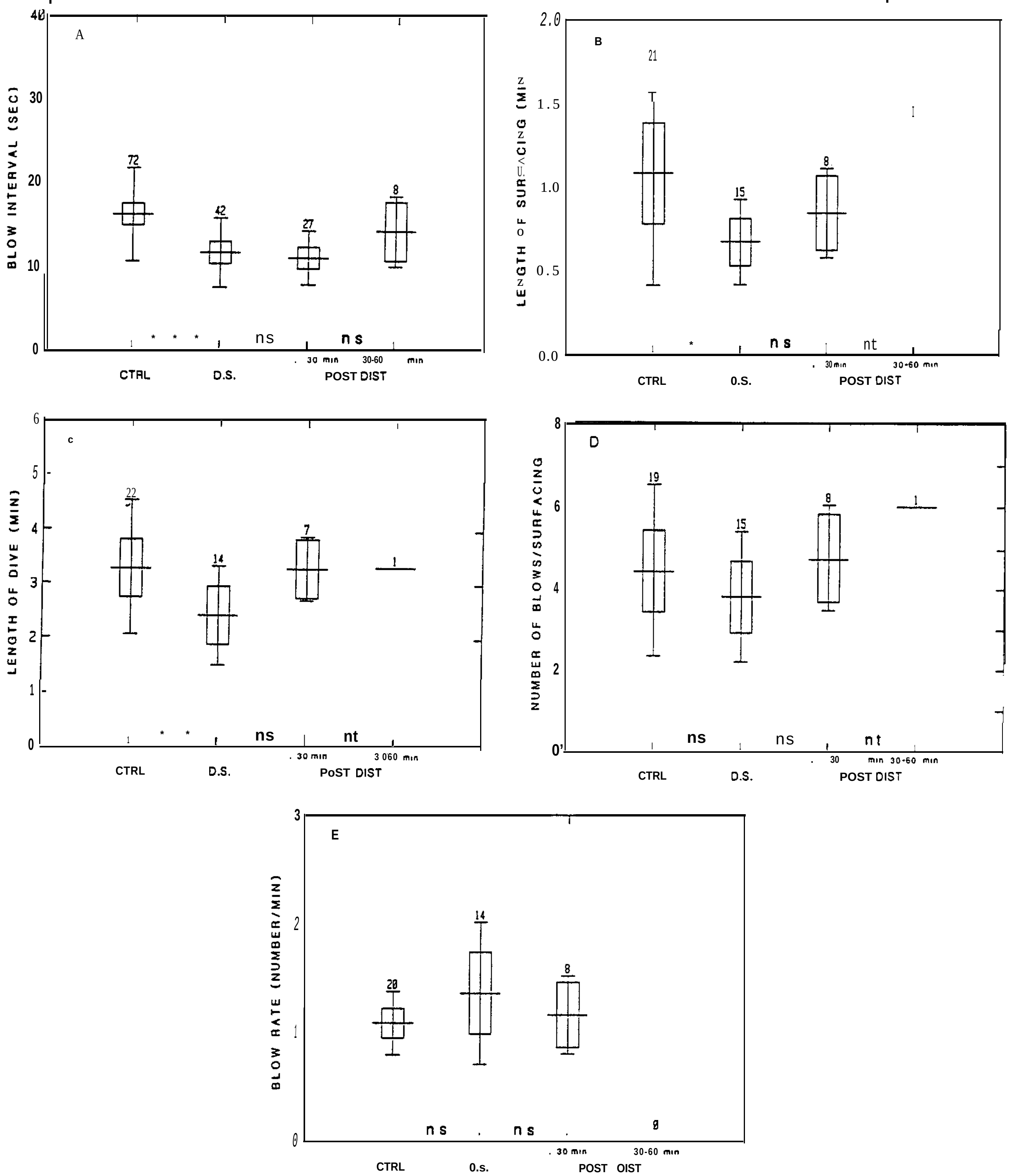


FIG. 3.46. AUGUST 21, WHALE "W" ONLY. DIFFERENT STAGES OF REACTION TO DRILLSHIP EXPERIMENT #2 OF THE DAY, COMPARED BY SURFACING-DIVE CHARACTERISTICS. DISPLAY AS IN FIG. 3.39; NT = NOT TESTED.

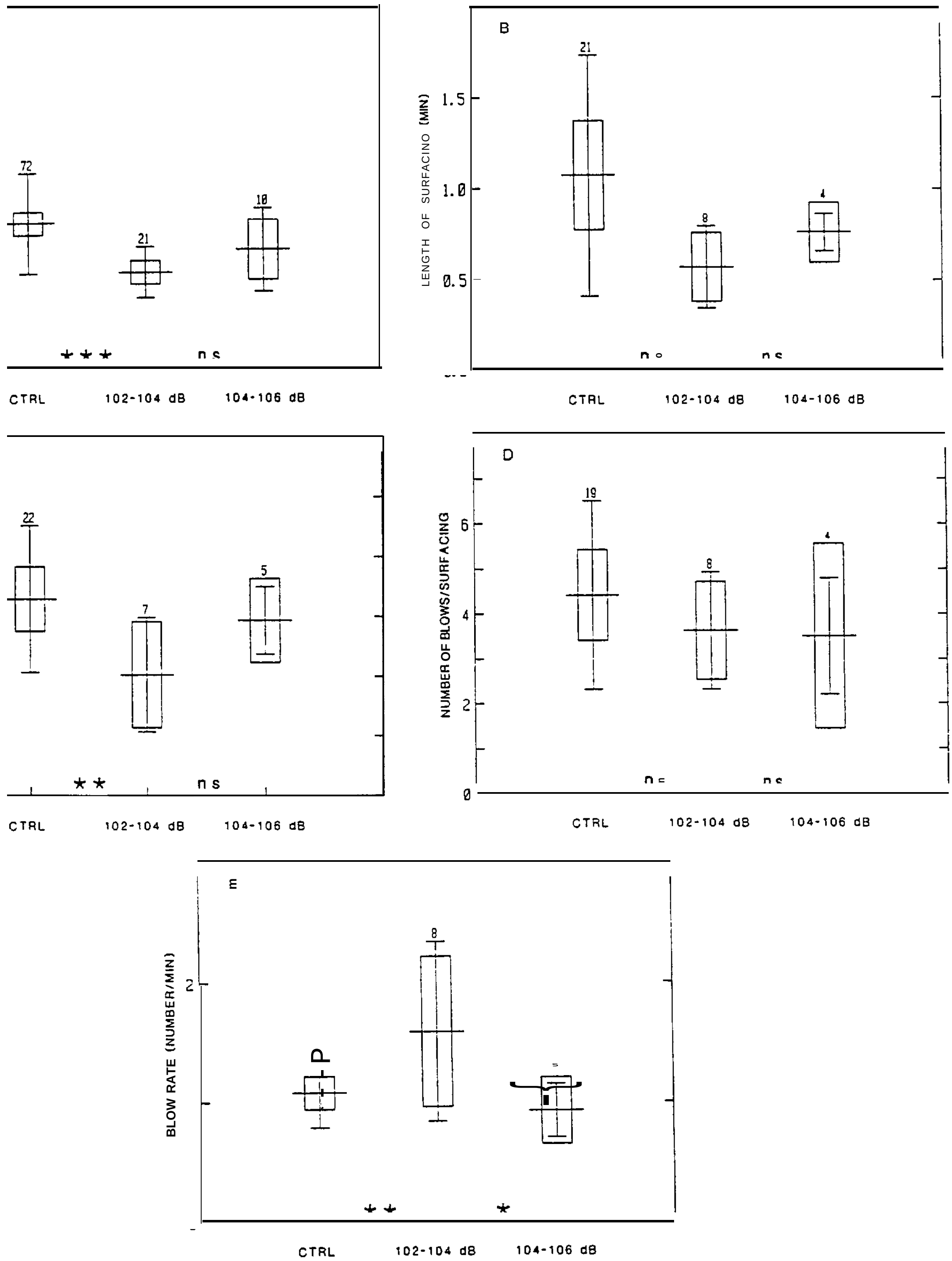


FIG. 3.47. AUGUST 21, WHALE W ONLY. CALCULATED RECEIVED LEVELS OF DRILLSHIP SOUND, DRILLSHIP EXPERIMENT #2 OF THE DAY, COMPARED BY SURFACING-DIVE CHARACTERISTICS. DISPLAY AS IN FIG. 3.39.

lower level of received sound due to this heightened sensitivity. The control period for this experiment was affected by the preceding experiment (see Fig. 3.43), and this must be taken into account when evaluating the apparent response of Whale W to drillship sound.

22 August 1985, Whale E

Surfacing-dive characteristics were collected on Whale E for approximately 7 hours, through both air gun experiments of the day. The results reflect general surfacing-dive characteristics for overall data of 22 August, since Whale E was responsible for much of the data gathered (compare Figs. 3.44 and 3,48). During air gun experiment 1 of the day (AG 1), Whale E remained in the area as the air gun vessel moved from about 3.8 km to as close as 0.2 km towards the end of the experiment. The surfacing-dive reaction of the whale was strong. Blow interval rose, and length of surfacing, length of dive, and number of blows per surfacing all decreased (Fig. 3.48). During the second experiment later in the day (AG-2), blow intervals did not change, and the other three characteristics showed a non-significant trend to decrease (non-significant possibly due to low sample sizes). Received sound levels ranged between 149 and 172 dB during the first experiment, and they varied between 163 and 172 dB during the second experiment. The average RSLS were thus higher for the second experiment. We have some evidence that Whale E continued to feed throughout the second experiment, and this apparent decrease in reaction between the first and second experiment may be due to partial habituation of Whale E to air gun sound by experiment #2. This conclusion should be treated with caution, however, because we gathered too few data on surfacing-dive characteristics for experiment #2 for firm conclusions.

We wondered whether there was a general difference in surfacing-dive characteristics, depending on the received level

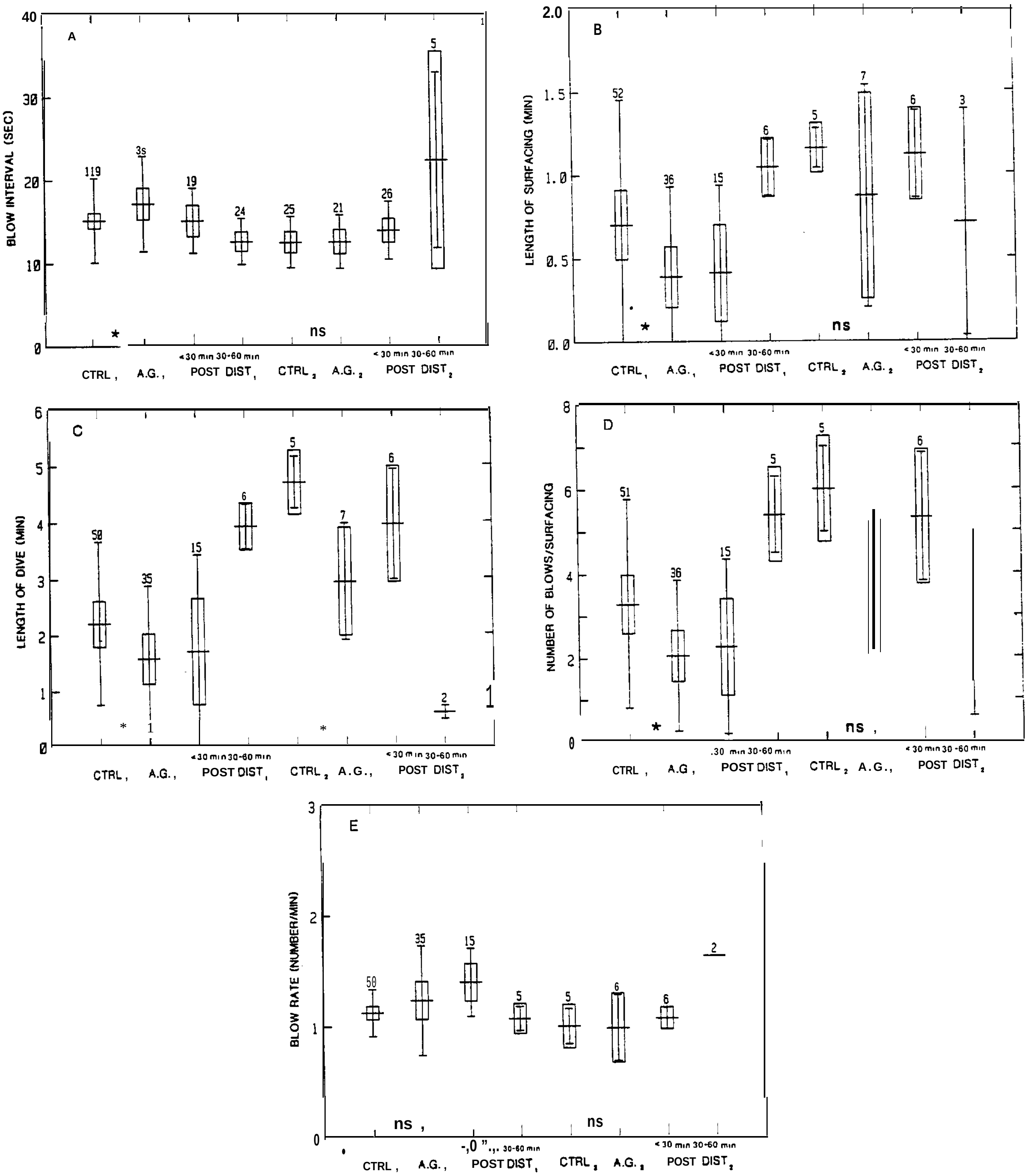


FIG. 3.48. AUGUST 22, WHALE E ONLY. DIFFERENT STAGES OF REACTION TO TWO AIR GUN EXPERIMENTS, COMPARED BY SURFACING-DIVE **CHARACTERISTICS.** DISPLAY AS IN FIG. 3.39.

of air gun sound. Whale E was the only whale for which enough data for comparison existed. We divided data into received levels of <155 dB (approximately 149 to 155 dB) and ≥155 dB (approximately 155 to 172 dB). In general, reactions to the higher sound levels appeared to be somewhat stronger than those to the lower levels, but once again data are non-significant and suggestive only, due to low sample sizes (Fig. 3.49).

25 August 1985, Whales L and N

The final focal whale comparisons for surfacing-dive characteristics related to air gun sounds were made for two whales for which behavior was well-documented. Whale L was observed during experiment #l of the day (AG-5). Whale L apparently fed as it milled within 3.5 to 1.2 km of the air gun sounds (distance decreasing as the air gun vessel moved past the whale), for approximate received sound levels of 155 to 168 dB. It showed an increased mean blow interval and a decreased length of dive during and immediately after the air gun sounds. Blow rate also increased from the pre-disturbance level. Blow interval, length of dive, and blow rate did not go back to pre-disturbance levels within 60 minutes of the air gun sounds (Fig. 3.50).

Whale N was followed through both experiments of the day. During the first experiment, it stayed in the same area and continued to feed despite the presence of the air gun vessel as close as 1.23 km and an approximate received sound level of 168 dB. We have no pre-disturbance surfacing-dive data for this experiment, however. During the second experiment (AG-6), Whale N stopped feeding and moved across the bow of the air gun vessel, and then away from it. Whale N came back to its original pre-disturbance location within 116 minutes after the air gun was turned off, and there resumed feeding (see movement pattern analysis, pages 3-89 through 3-91). During its travel while exposed to the air gun sounds, Whale N showed an increased mean

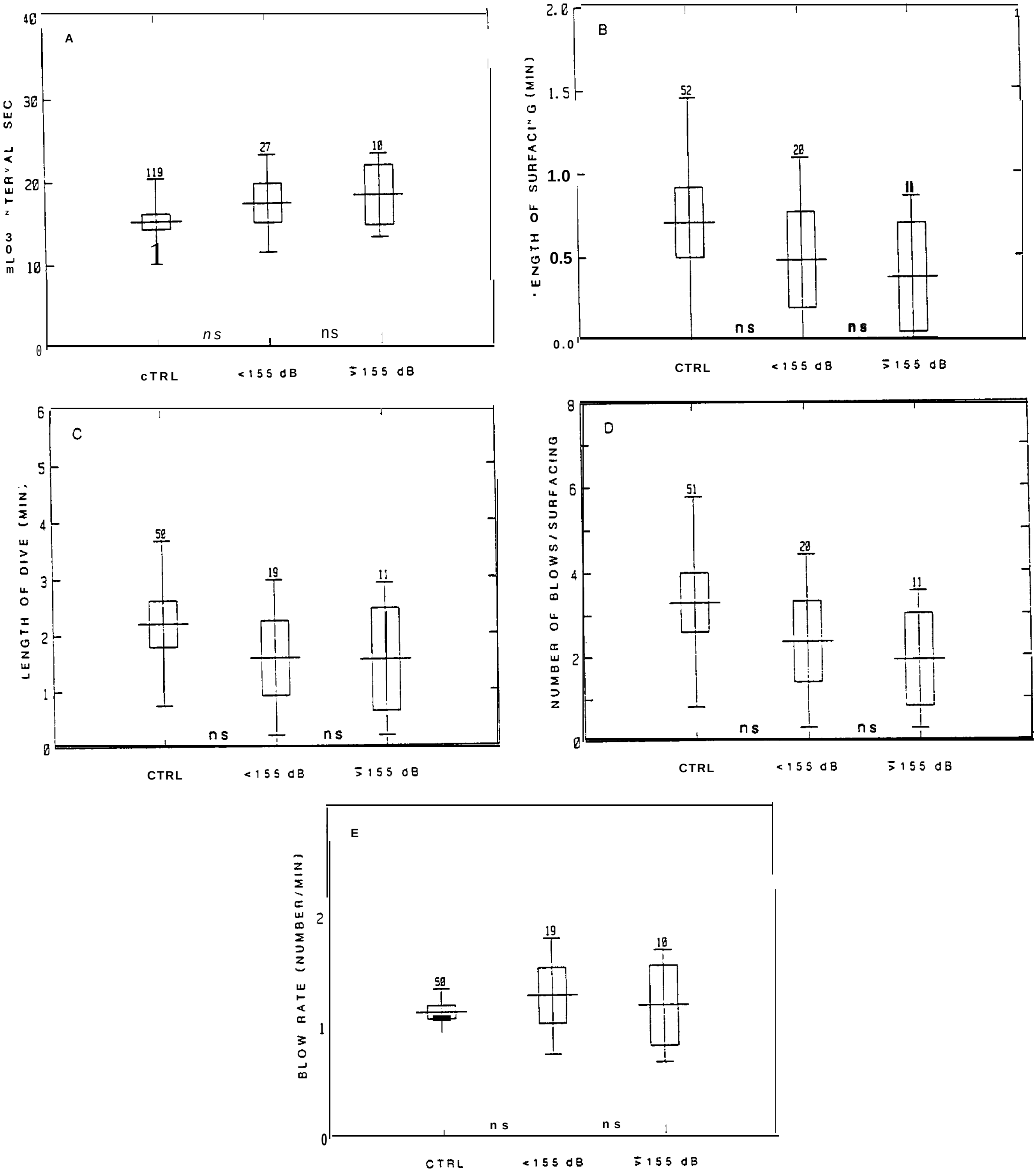


FIG. 3.49. AUGUST 22, WHALE E ONLY. CALCULATED RECEIVED LEVELS OF AIR GUN SOUND FROM TWO EXPERIMENTS, COMPARED BY SURFACING-DIVE CHARACTERISTICS. DISPLAY AS IN FIG. 3.39.

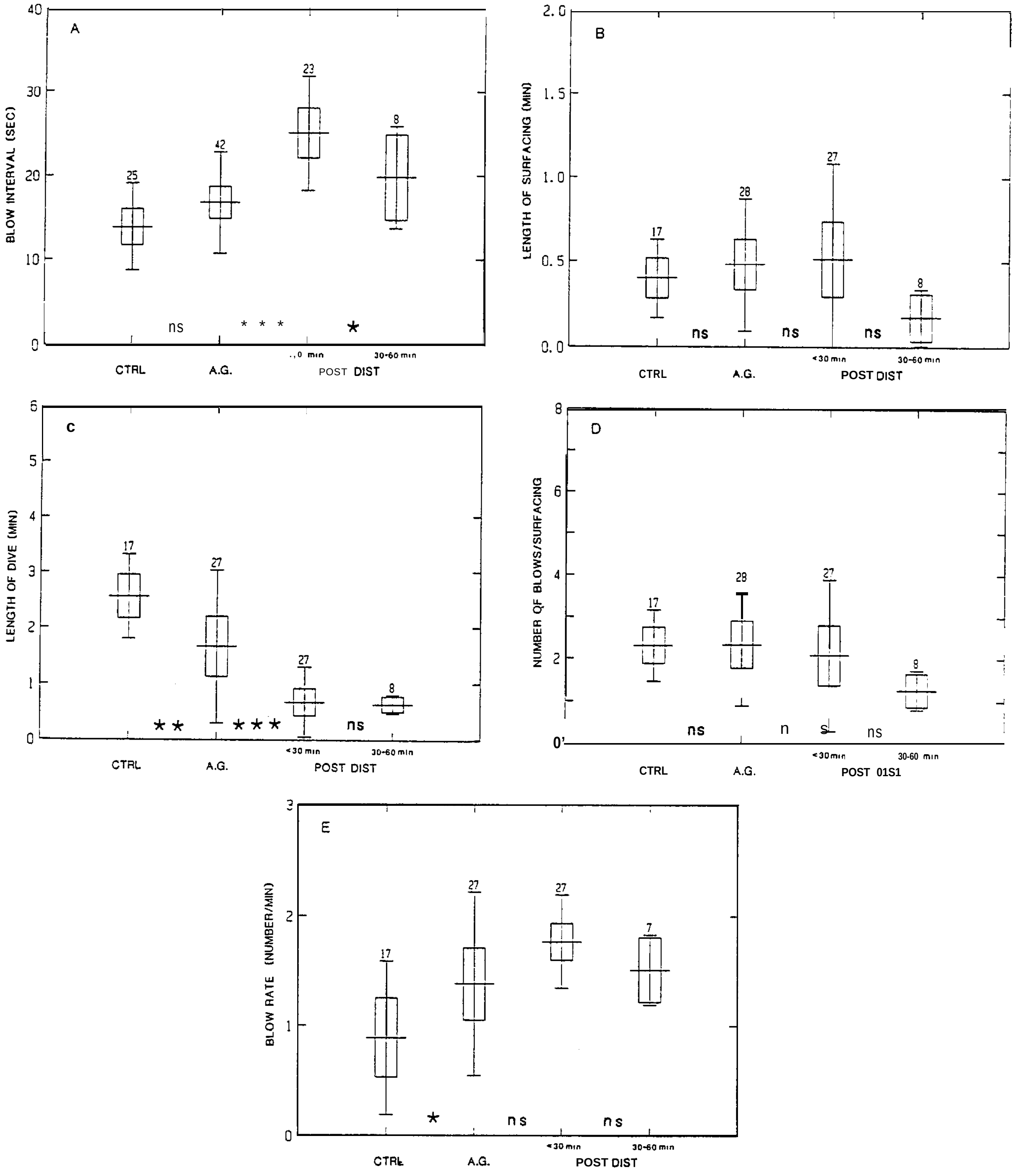


FIG. 3.50. AUGUST 25, WHALE L ONLY. DIFFERENT STAGES OF REACTION TO AIR GUN EXPERIMENT #1 OF THE DAY, COMPARED BY SURFACING-DIVE CHARACTERISTICS. DISPLAY AS IN FIG. 3.39.

blow-interval, and decreased length of surfacing, length of dive, and number of blows per surfacing. Blow rate also increased, possibly due to its energetic travel as Whale N moved away from the vessel (Fig. 3.51). Disturbance lasted throughout the 60 minute post-disturbance period, and surfacing-dive characteristics went back to pre-disturbance levels after that time. Unfortunately, we do not have enough calculated received sound levels for Whales L and N in order to compare surfacing-dive characteristics by different sound levels.

Summary

Although relatively few surfacing-dive data were collected for only several days, some interesting trends have emerged. In general, blow intervals decreased during drillship sounds, and length of surfacing, length of dive, and number of blows per surfacing increased. This trend indicates that whales are cycling through their basic surfacing-dive patterns more slowly while subjected to drillship sounds. They went back towards a pre-disturbance level relatively quickly, usually after about one-half hour post disturbance. Blow rate altered little. Air gun related behavior was different. Whales increased blow intervals and tended to decrease length of surfacing, length of dive, and number of blows per surfacing. In other words, they cycled through their repertory more rapidly, as they apparently alternated feeding with travel, or travelled away from the sound source. This trend was especially strong during several occasions when we noticed a definite cessation of feeding and movement away from the sound source. Recovery to “normal” levels was less rapid than for drillship sounds, but tended to occur about one hour after disturbance.

For both types of experimental situations, subsequent experiments of a day appeared to be affected by the earlier experiments. This took both the form of surfacing-dive data not

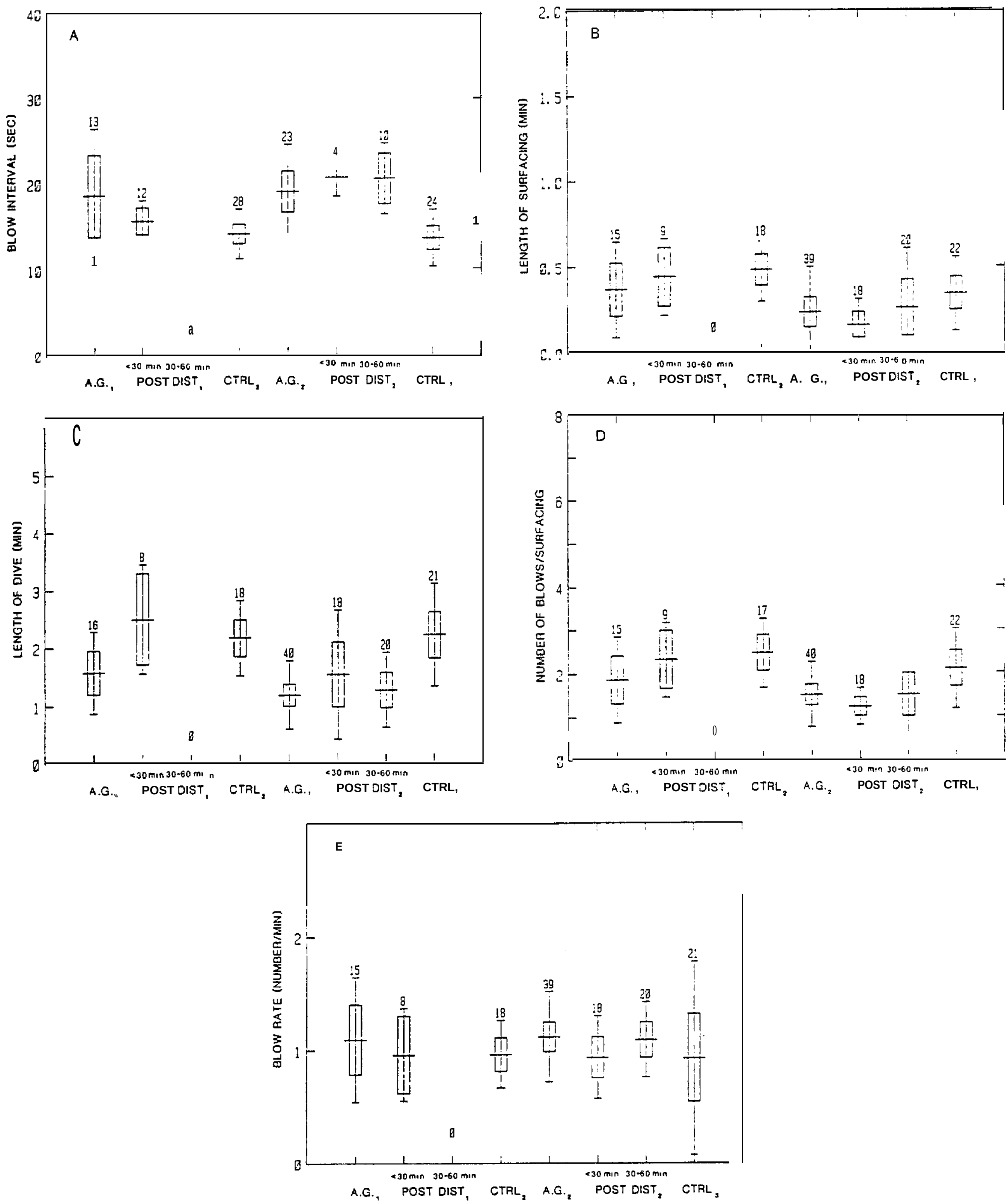


FIG. 3.51. AUGUST 25, WHALE N ONLY. DIFFERENT STAGES OF REACTION TO AIR GUN EXPERIMENTS #1 AND #2 OF THE DAY, COMPARED BY SURFACING-DIVE CHARACTERISTICS. DISPLAY AS IN FIG. 3.39.

always going back to a pre-disturbance level after the first experiment of the day, and whales at times reacting less strongly to a subsequent experiment. This is not a firm conclusion, however, because many other factors such as time of day, presence of one or two boats in the area, and general behavior of the whales may have served as confounding factors. Interestingly, number of blows per surfacing, length of surfacings, and length of dives were all lower during the present study than for presumed undisturbed gray whales studied in July and September 1982 in the same area (Würsig et al. 1986). We wonder whether our present results may have been affected by the presence of at least one large vessel near the whales at almost all times, unlike the situation in 1982, when observations were generally made from a small skiff > 1 km distant from the mothership. This possibility of a level of disturbance even during presumed "undisturbed" situations does not negate our results, however, since industrial disturbance is likely to be accompanied by the presence of larger vessels in real situations.

Disturbance reaction during air gun playback was extremely similar to the reaction found for surfacing-dive characteristics of bowhead whales (Balaena mysticetus) when subjected to air gun sounds (Richardson et al. 1985, Ljungblad et al. 1985a, Richardson et al. 1986). In bowheads, blow intervals increased and length of surfacing, length of dive, and number of blows per surfacing all decreased during air gun firing. The same basic behavioral shift from feeding or milling prior to air gun sounds to traveling away from the sound source were noted for bowheads during several experiments with full-scale seismic vessels (Ljungblad et al. 1985a).

3.5 Interpretation and Application of Results

3.5.1 Comparison with migrating activity

In this section we compare the results obtained by Malme et al. (1983, 1984) on the effects of industrial noise stimuli on the behavior of migrating gray whales to the results of the present study.

In general, the present study results are comparable in that measurable responses were observed at similar sound exposure levels. However, comparisons of gray whale behavioral reactions between these studies are difficult for three reasons. First, the whales under study were involved in very different behaviors, migrating in the earlier studies and feeding in the present study. Second, although blow rate and blow interval analysis was performed during the first set of studies, this analysis was done only on mother/calf pairs as opposed to analysis done on non-mother/calf pairs on the feeding ground. Third, the main focus of the migrating gray whale behavior studies was on the statistical analysis of migration track deflection scores and speed of movement as well as other movement-related behaviors. These measures were very sensitive because of the highly oriented movement of migrating gray whales. The present study focussed primarily (for statistical purposes) on the surfacing and respiration characteristics of gray whales. Since feeding gray whales turn so frequently and have such variable movement patterns, the track deflection analysis was not appropriate.

In spite of these differences in analytical methods, we can ask whether feeding or migrating gray whales show different behavioral reactions at similar exposure levels to industrial noise. We have chosen to present comparisons in narrative rather than tabular form because of the complexity of the study procedures.

Industrial Noise Sources

Malme et al. (1983) found that during playbacks of a variety of industrial noise stimuli to southbound migrants, each sound stimulus caused a statistically significant response and that each of these responses was different when compared to control conditions. Patterns of response appeared to vary predictably as a function of received sound level. Responses generally involved avoidance of the sound source, based on track deflection scores for whales exposed to playbacks of drilling platform, helicopter, and production platform sounds and a drop in speed for whales exposed to drilling platform, drillship, semisubmersible, and helicopter sounds. During drilling platform and helicopter sound playbacks, apparent avoidance of the source area out to about 250 m was noted with sound levels at this range approximately 111 to 118 dB.

During January 1984, similar industrial noise playbacks were conducted on southbound migrating gray whales (Malme et al. 1984). An analysis procedure was developed which permitted determination of the probability of avoidance of the region near the playback source. This measure showed that avoidance behavior began at sound exposure levels of around 110 dB for the overall signal and was greater than 80% for regions with signal levels higher than 130 dB. Some variation among the various playback stimuli was observed with the drillship producing the greatest avoidance and the production platform the lowest, for levels between 110 and 125 dB. However, for levels between 125 and 130 dB, the reactions to all playback stimuli were comparable.

During the present study, data on whales exposed to drillship sound playback suggest that gray whale movement was not affected by RSL at 103 to 110 dB and at distances to the sound source as close as 1.12 km. During two of the four drillship experiments, we did note a change in movement pattern with whales leaving the immediate area of the sound source; however, whale movement data are not available for these two experiments (see Section 3.4.1). During one of these latter two experiments, RSL at the whales moving out of the area was estimated at 108 to 119 dB at distances of approximately 1 km to 0.3 km, respectively. Results of drillship playbacks during the present study appear consistent with our earlier findings.

<u>Seismic Sources</u>

Malme et al. (1983) conducted experiments with seismic exploration sources on northward migrating mother/calf pairs during April and May 1983 using a stationary and towed single air gun and a 40 gun towed array. Overall, results showed that the most predictable responses of the whales to air gun activity occurred at received levels of > (greater than) 160 dB re 1 μPa when the air gun source was within 2 km of the animals.

Small sample sizes prevented definite quantification of response for average pulse pressure levels between 140 and 160 dB, but analysis showed that some behavioral changes did occur at these levels. In general, whales would slow down and turn away from the source. In several cases, groups were seen swimming into the surf zone and also positioning themselves in the sound shadow of a rock, island, or outcropping. There were significant differences, independent of range or level of exposure, in milling indices, speed indices for groups <u>prior</u> to exposure and those same groups during exposure to the air gun noise. There were also significant differences in milling indices and speed indices for groups during exposure and <u>after</u> exposure to air gun noise.

Of the ten groups of northward migrating mother/calf pairs that were exposed to RSL >160 dB during the air gun array runs, of April-May 1983, four were being overtaken from behind by the boat during the entire observation period; five were overtaken from behind and were passed by the boat, and one was approached and passed. None of the four that were being chased turned south, milled, or moved inshore. All five of the groups that were overtaken from behind and were passed turned south and/or moved inshore within five min. after the vessel passed its closest point of approach (CPA), then continued to mill and behave in a disoriented and confused manner. The one group that was approached head on and eventually passed turned south, away from the boat, when it was within one minute of its CPA. Again, this group milled and moved in close to shore. These responses are probably related to the high level of directivity in the horizontal plane of the air gun array. As the array passed a group broadside, the group would experience a sudden increase in sound level on the order of 20 dB. As noted in Section 3.4.1 in the present study, responses were observed in three and possibly four cases where the whale was passed by the air gun vessel. In all four cases, RSL was greater than 160 dB.

During the southbound January 1984 migration, seismic experiments were conducted using both a stationary single air gun and a towed single air gun. During stationary air gun experiments, whales avoided the sound source area by moving further offshore or inshore of the air gun vessel. This avoidance response was first detected at 2 km north of the vessel and persisted until the whales were at least 2 km south of the vessel. No identifiable avoidance response was observed during moving air gun experiments. However, these experiments were of short duration and sample sizes were low.

The probability of avoidance analysis for the stationary air gun source showed that the threshold of avoidance behavior occurred for average pulse pressure levels of approximately 164 dB. This was somewhat higher than the level of 160 dB which was observed to produce changes in the migration behavior of mother/calf pairs during the April and May 1983 field experiments.

During the present study, we did not conduct stationary single air gun experiments. We did, however, observe a variety of responses to the moving single air gun experiments as outlined in Section 3.4.1. Responses were observed at average pulse pressure levels at the whales of between 149 and 176 dB at distances up to 4 km, with four of the six responses, where RSL was known, occurring at levels > 160 dB. These sound levels and distances are comparable to results obtained during our earlier studies on migrating gray whales.

It is difficult to compare experimental results concerning migrating gray whales with those of feeding gray whales. Different behavioral responses were measured in feeding and migrating gray whales. The pattern of gray whale responses may scale not only with RSL, but also rate of change of RSL or movement of the sound source. Both of these parameters varied with ‘moving vs. stationary air gun sources. A priori one may expect the response of gray whales to noise stimuli to be a function of behavioral state as has been pointed out by Brodie (1981) and Richardson et al. (1985). However, the results of our studies on the behavioral responses of migrating and feeding gray whales to drillship sound playback and air gun operations indicate measurable responses at similar exposure levels.

3.5.2 Application of results

In the previous studies of migrating gray whales, the large number of whales sighted and tracked during the field observation periods provided a good data-base for statistical analysis. As a result, it was possible to quantify the response of the whales in terms of exposure level for a given stimulus. A measure of the degree to which whales would tend to avoid the region near the source was developed and termed “probability of avoidance.”

This procedure is difficult to apply in experiments where the source is moving as well as the whales since the distance from the source to the whales, which determines the exposure level, is not controlled by whale swimming response alone. Moreover, the number of whale position sightings obtained is considerably reduced when it is necessary to move the experiment to find new subjects.

In order to determine whether or not the probability of avoidance procedure could be applied to the observations obtained near St. Lawrence Island, histograms and cumulative sighting distributions were developed showing the number of sightings as a function of received level for the combined drillship playback periods and the combined air gun periods. Similar distributions were developed for the corresponding control (no sound stimulus) periods. The control period data were plotted using a virtual received level, i.e. , the level that would have existed with the source operating.

The resulting histograms and distributions for the drillship playback data are shown in Fig. 3.52. If the whales consistently avoided the high sound level region near the source, a comparison of the cumulative distributions for the control and experimental periods would show the number of sightings at high sound levels during the experimental periods to be lower than the number of sightings at the same range (virtual sound level) during the control periods. Examination of the data in Fig. 3.52 shows that this did not occur. While the cumulative density at the 120 - 116 dB level is slightly lower for the stimulus condition, no definite shift in the sightings away from the source region during the experimental periods can be seen. In fact, Fig. 3.53 for the air gun stimulus shows a higher sighting density near the source during the stimulus periods than during the control periods. We do not believe that this proves that whales are attracted by the air gun sound. Rather, it suggests that the distance from the source to a whale under observation was strongly influenced by the initial geometry at the start of an

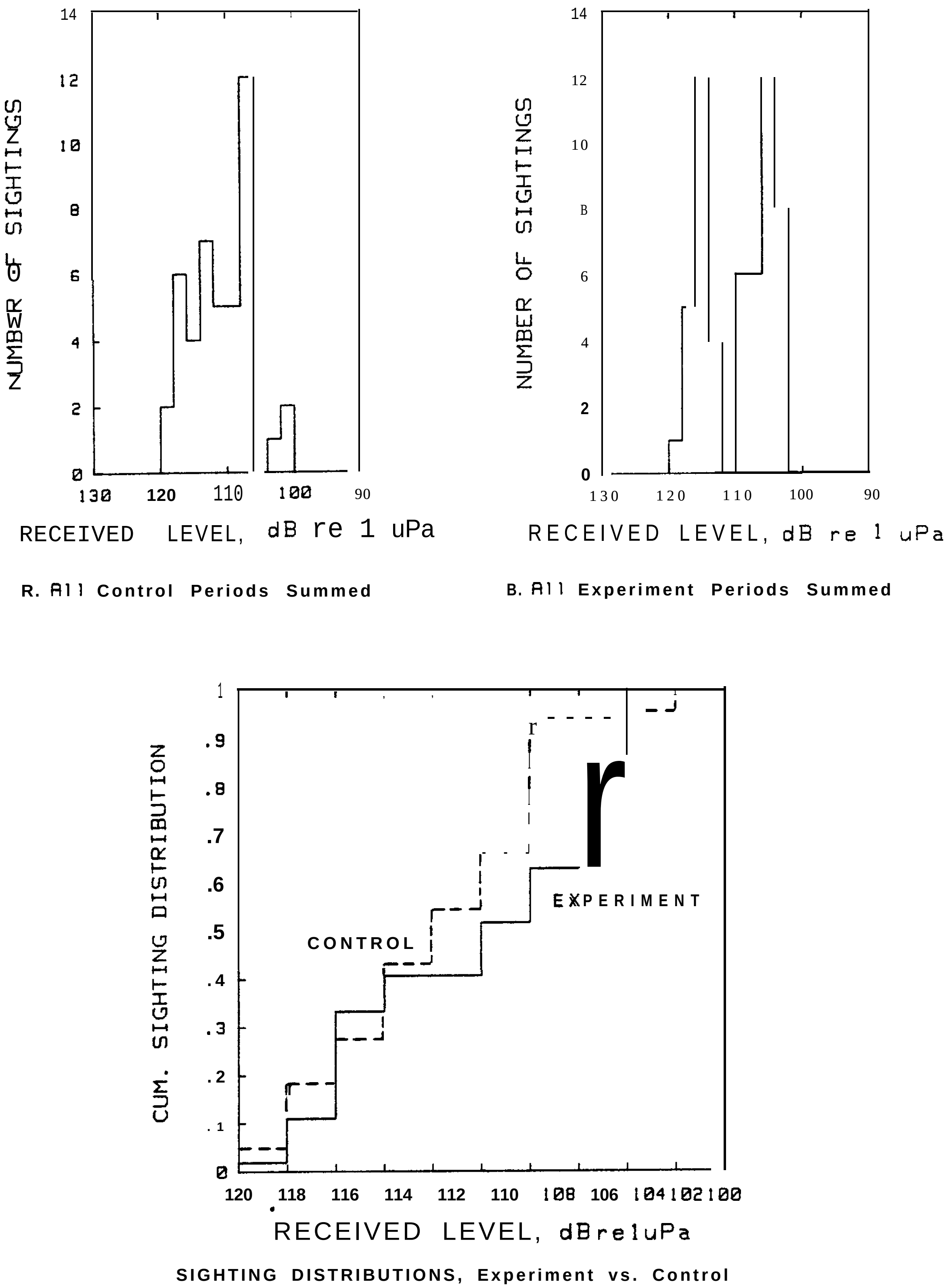


FIG. 3.52. DRILLSHIP STIMULUS, WHALE SIGHTING DATA.

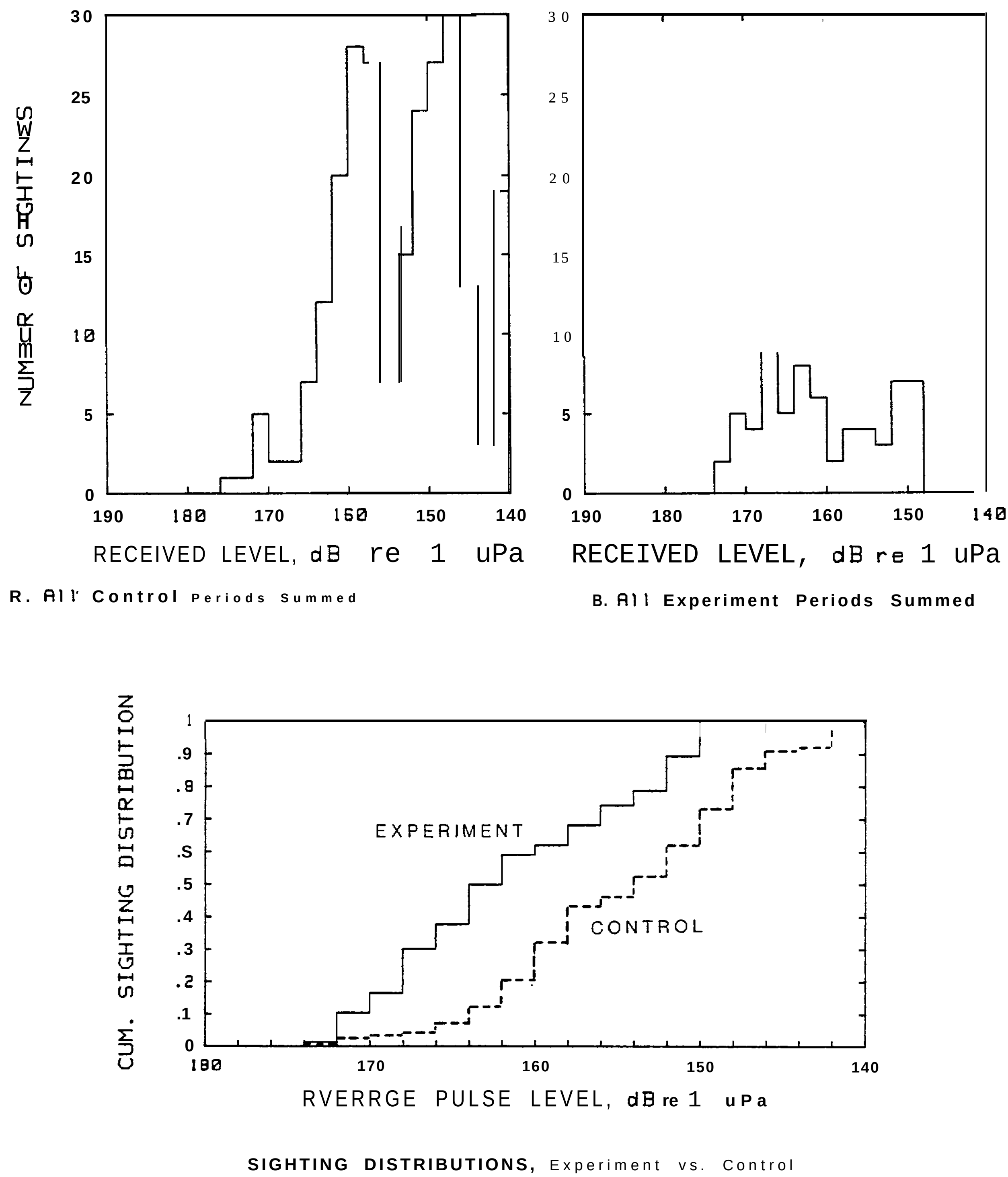


FIG. 3.53. **AIR GUN** STIMULUS, WHALE SIGHTING DATA.

experiment and by the track of the source vessel during the stimulus presentation period and probably influenced less by any avoidance behavior by the whale. Consequently, the probability of avoidance analysis technique cannot be used for moving source experiments unless the vessel movement procedures are identical for both control and experimental periods. In the St. Lawrence tests, the air gun vessel was repositioned during control periods to set up the approach geometry for the next experimental period. This was done in order to maximize the number of samples obtained from a dispersed whale population. As a result, the source vessel-whale distances were generally greater during control periods than during the experimental periods when the vessel was being actively maneuvered toward the whales.

In order to derive a general guideline for estimating the probable behavioral response of summering and feeding gray whales to air gun noise, it is necessary to examine the summary of individual whale responses presented previously in Table 3.8. On the basis of the information presented in this table, the summary cumulative distribution function shown in Fig. 3.54 was developed. The number of whales included in this function is less than those shown for the combined air gun tests in Fig. 3.53 because Fig. 3.54 only includes whales for which detailed track and observation records are available. Moreover, it includes only those whales for which a definite interruption of feeding activity was observed. If a whale resumed feeding after the air gun vessel had moved away or stopped firing, the corresponding original response exposure level is marked “F”.

The resulting cumulative distribution can be seen to be somewhat skewed, having an interpolated median value of 173 dB and a calculated mean value of 169,6 dB. If the data values shown are considered to be representative samples of the true acoustic response statistics which might be obtained with more extensive testing, it is useful to calculate the confidence

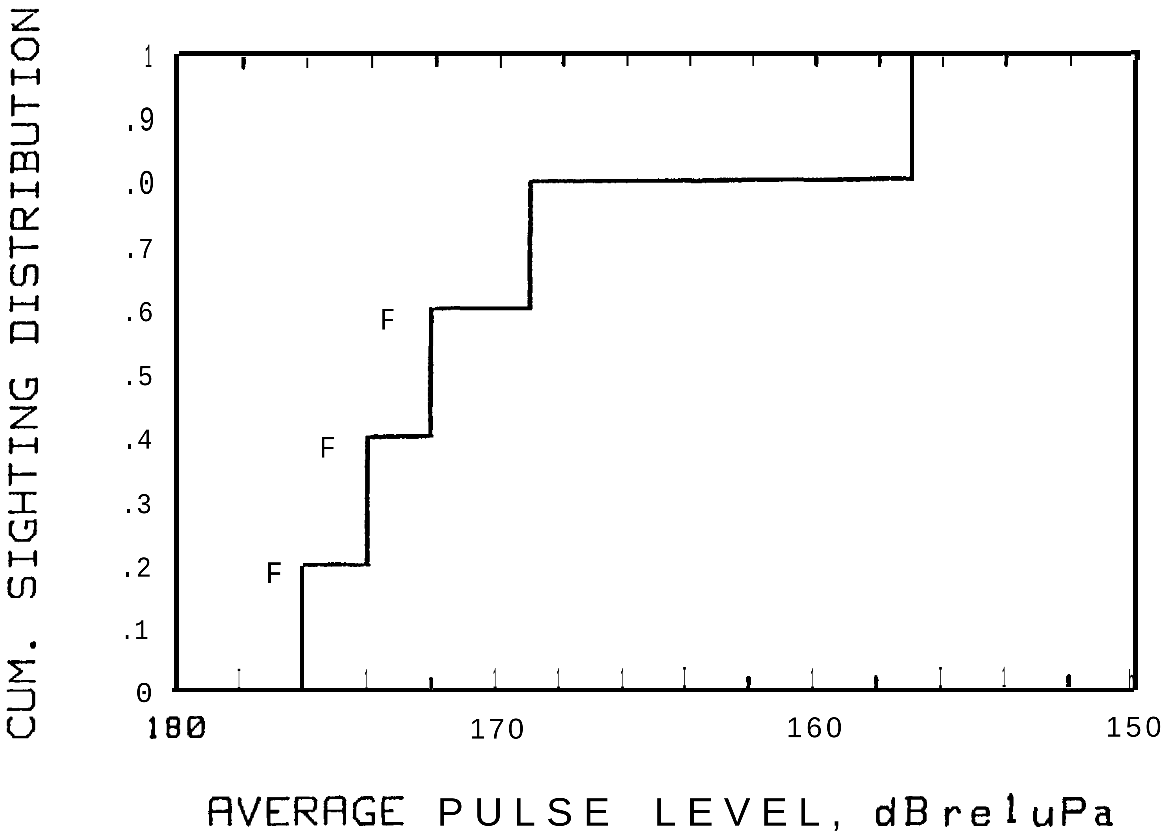


FIG. 3.54. CUMULATIVE DISTRIBUTION FOR OBSERVED FEEDING DISTURBANCE (DATA FROM TABLE 3.8, F - WHALE RETURNED AND RESUMED FEEDING).

limits of the acoustic response measures determined by the present data. We need to estimate how well the data represent the range of expected feeding gray whale responses to air gun noise disturbance.

A distribution-free confidence interval test for the median was developed by Thompson (1936). This test provides a means of calculating the confidence level of a median estimate based on a number of samples from a parent population having an unknown distribution form. The results of applying this test to the data shown in Fig. 3.54 give a confidence estimate of 68% that the true median (.5) response level lies between 170 and 175 dB and a 94% confidence estimate that it lies within the interval of 163 dB to 177 dB.

For skewed distributions, the median is a better estimator for the expected value than is the mean, Zar (1974), p. 24. Thus, an average peak pressure level of 173 dB will be considered as the level of air gun noise at which 50% of feeding gray whales will probably interrupt feeding activity. Based on the data shown in Fig. 3.54 and on the confidence limit calculation, 163 dB will be considered as the air gun noise level which will probably cause 10% of feeding gray whales to interrupt feeding activity.

Comparing these values with the probability of avoidance values obtained for migrating gray whales, we find that a 0.1 probability of avoidance occurred for an air gun noise level of 164 dB and a 0.5 probability of avoidance occurred for a level of 170 dB. The acoustic sensitivity of gray whales to air gun noise when feeding is thus apparently not greatly different from their sensitivity while migrating.

Drillship Playback

The sighting data presented in Fig. 3.52 for the combined drillship playback experiments showed that a number of whales were exposed to levels that produced avoidance behavior for migrating gray whales (110 to 120 dB). No definite pattern of avoidance of the source area was observed. However, until more testing is performed at higher exposure levels, we believe that the application of the probability of avoidance results for migration activity would provide a conservative response estimate for feeding activity. For the purpose of estimating zones of influence, we will consider that exposure of feeding gray whales to noise levels of 110 dB or more (from a continuous stationary source, such as from a drillship), would result in possible avoidance of the region near the source, and exposure to levels of 120 dB or more would probably cause avoidance of the area by more than one-half of the gray whales. These values will be used in the zone of influence analysis discussed in Sec. 4.5.4.

4. ESTIMATES OF THE EFFECTIVE RANGE OF INDUSTRIAL NOISE SOURCES IN BERING SEA GRAY WHALE FEEDING AREAS

By combining what has been learned about gray whale behavioral response to industrial noise with acoustic modeling techniques, it is possible to estimate the “zone of influence” of a noise source if its acoustic source level is known. The results of this procedure are described in this section for studies of the Chirikof Basin area and the region near Unimak Pass. The locations of these areas and the location of the 1985 field study near St. Lawrence Island are shown in Fig. 4.1.

The response of gray whales to industrial noise can be quantified in terms of an absolute measured or estimated noise exposure level or in terms of a relative signal-to-noise ratio (S/N). In this case, the “signal” is the industrial noise and the noise is the normal background ambient noise - generally due to wave splash (wind) noise and distant ship traffic. In this study and in the previous study of migrating gray whales, the behavioral responses have been quantified in terms of the absolute noise exposure level since it was not possible to obtain behavioral response data under several different ambient noise conditions to obtain an independent measure of response to S/N variations for a constant signal level. Studies of the behavioral response of bowhead whales have generally reported results in terms of the signal-to-noise ratio (see Richardson, et al. 1985, for example). The results of this model study, therefore, incorporate estimates of ambient noise levels in the areas studied so that zones of influence can be estimated using either received exposure levels or signal-to-noise ratios.

The following discussion includes a description of the physical parameters relevant to underwater sound propagation in the areas of concern, estimates of the ambient noise

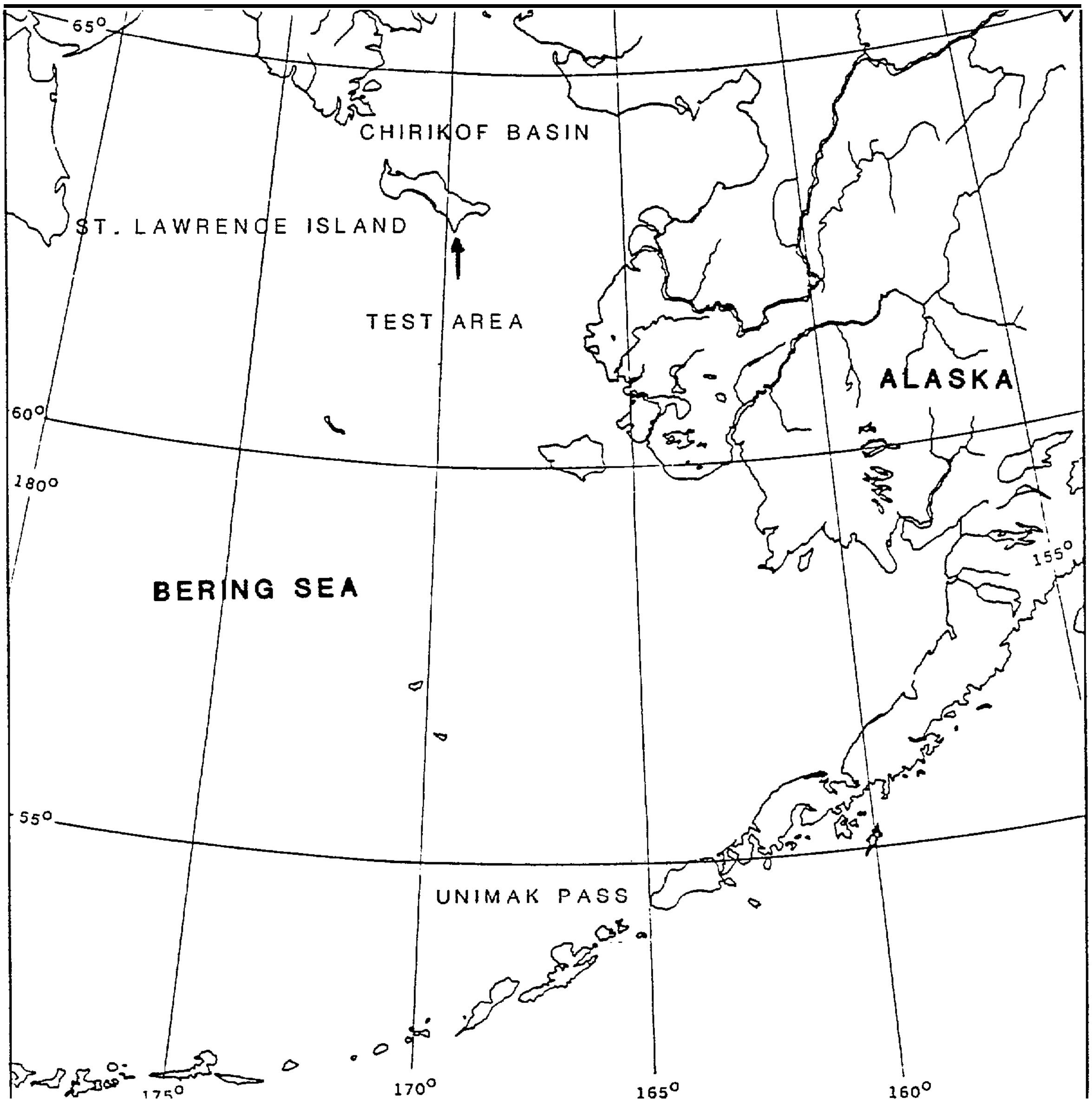


FIG. 4.1. STUDY SITE LOCATIONS.

characteristics, discussion of the sound propagation modeling procedure, comparison of model predictions with reported data, and presentation of received level predictions to permit the estimation of zones of influence for representative petroleum industry noise sources.

4.1 Acoustic Parameters of the Areas Studied

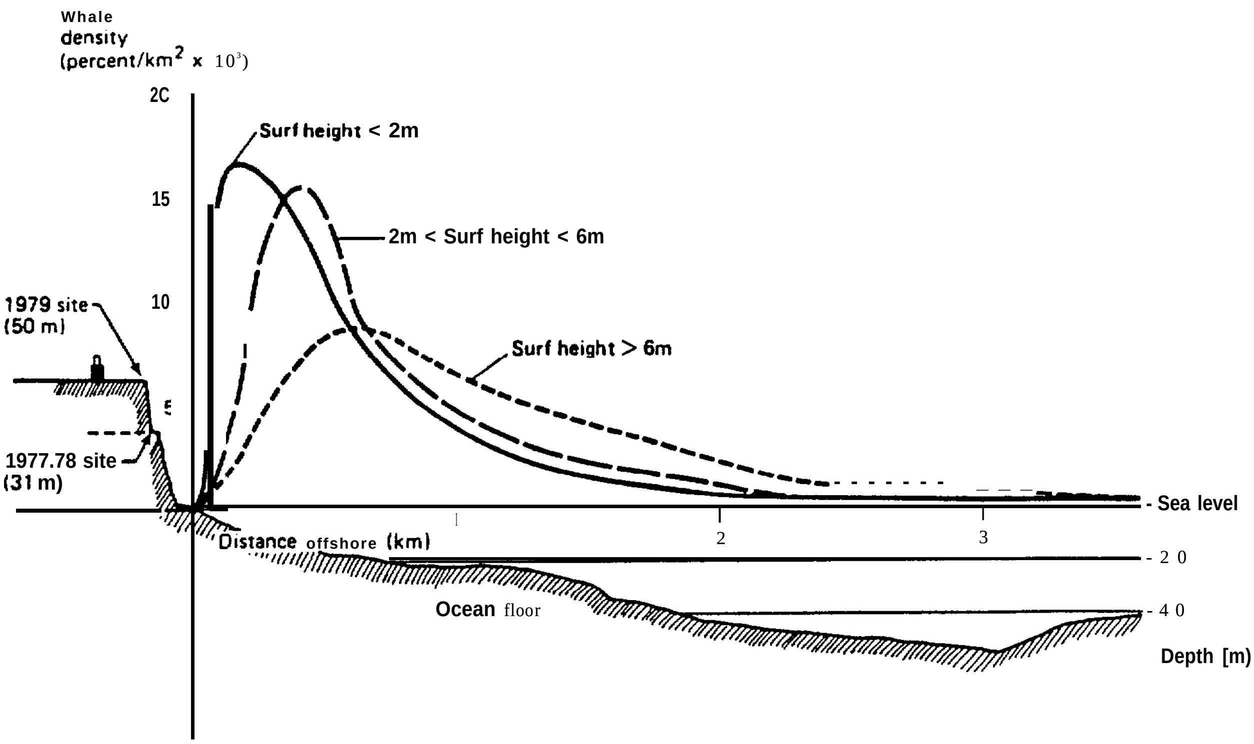
The study was concerned with two areas in the Bering Sea which have high concentrations of gray whales during portions of the summer feeding season. Unimak Pass is used by all of the migrating gray whales that regularly feed in the Bering and Chukchi Seas. They pass through close to the shore of Unimak Island on their northbound migration in April through June with the highest density occurring around 1 May (Braham 1984). The southbound migration occurs in November and December with a peak around 1 December (Rugh 1984). During the northbound migration, the whales feed as they move north along the coast of Unimak Island and continue up along the Alaska Peninsula. Some whales remain in this area during the entire summer.

The Chirikof Basin north of St. Lawrence Island has been observed to have high concentrations of feeding gray whales for a number of years (Ljungblad 1985b). They reach this area around late May and remain through mid-October. This area is uniformly shallow (40 m) and is representative of other areas in the Bering Sea where gray whales have been observed to feed.

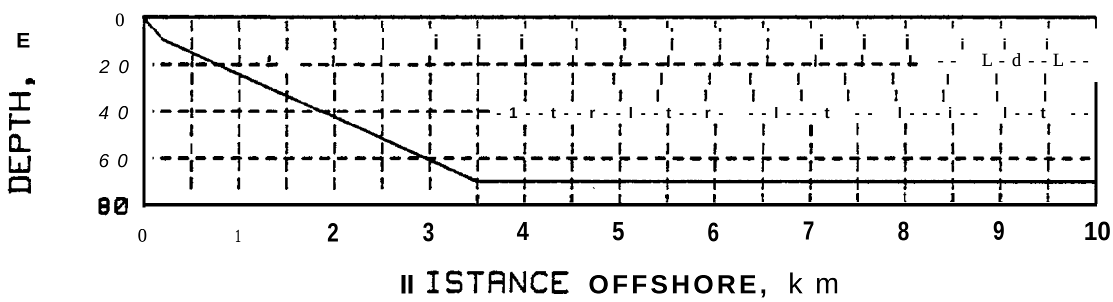
The Bering Sea has two major provinces of approximately equal area. Oceanic depths lie to the northwest of Unimak Pass and an extensive shallow continental shelf to the northeast. The areas of interest for this study are located along the continental shelf which extends under Bristol Bay and on up to St. Lawrence island and beyond to the Bering Strait. Bottom sediments on this shelf consist primarily of fine sand, silt, and clay.

In the shallow shelf areas of the Bering Sea, the sound velocity profile (SVP) shows little vertical structure under winter ice cover conditions. In the spring as the ice edge recedes, the surface layer begins to warm up and a higher velocity layer forms near the surface. This effect is in contention with a surface layer of slower sound speed fresh water from rivers and estuaries. Generally, the temperature effect is dominant and a deep surface layer of warmer, higher sound speed water forms which may extend over as much as 1/2 of the water column (Mackensie 1973). This upper layer causes strong downward refraction of sound rays, which results in higher propagation losses, because of the increased number of bottom contacts, than would occur under isospeed or upward refracting conditions.

Since the whale migration corridor near Unimak Island is generally near shore (Rugh 1984), it is necessary to consider not only the bottom composition but also its slope in modeling the sound propagation near the island. Near Unimak Island the sand is of volcanic origin. The sediment thickness ranges from 5 to 10 meters with a volcanic rock sub-bottom (Mackenzie 1973, Rugh 1984). The whale migration occurs in water depths of 15 to 20 m where the bottom slope ranges from .008 to .03. The distribution of whales observed near Cape Sarichef for the southbound migration is shown in Fig. 4.2A. The bottom profile near the cape is irregular so an approximation was necessary for use with the acoustic model. The approximate slope profile is shown in Fig. 4.2B.



A. Depth profile offshore of Cape Sarichef related to whale density during fall migration (from Rugh 1984)



B. Approximate depth profile used in model

FIG. 4.2. WHALE MIGRATION DENSITY AND DEPTH PROFILE NEAR UNIMAK ISLAND.

4.2 Ambient Noise Estimates

For the purposes of this study it was necessary to estimate the ambient noise spectrum statistics for the regions used in the propagation modeling. The ambient noise spectra were estimated in l/3-octave bands since this type of proportional bandwidth analysis is representative of mammalian hearing processes. The spectra representing the 5th, 50th, and 95th percentile average ambient levels* for the summer months were developed by examining wind speed and wave height data in the NOAA Climatic Atlas for the Bering Sea (Brewer, Diaz, and Prechtel 1977).

Figure 4.3 shows the estimated ambient noise spectra for the Chirikof Basin and Unimak Pass areas. These spectra were developed by using the wind speed and wave height statistical data from the atlas together with published ambient noise data (Urick 1983). The spectrum levels for the Unimak Pass area are somewhat higher than those of the Chirikof Basin because of the proximity of deeper water and a slightly higher influence of ship traffic noise at low frequencies. The region considered in this case is off the north side of the island and extending northward into Bristol Bay. Generally both areas considered here are sheltered from the influence of shipping noise by the effect of shallow water producing high sound attenuation at low frequencies and by the absence of nearby lanes of heavy ship traffic.

4.3 Shallow Water Sound Propagation Models

No analytic or computer-based transmission loss model exists that is capable of handling all of the significant environmental parameters that influence shallow water sound propagation. The major modeling difficulties occur at low frequencies for sites

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*The 5th percentile spectrum represents the rms levels which are not exceeded 5% of the time, for example.

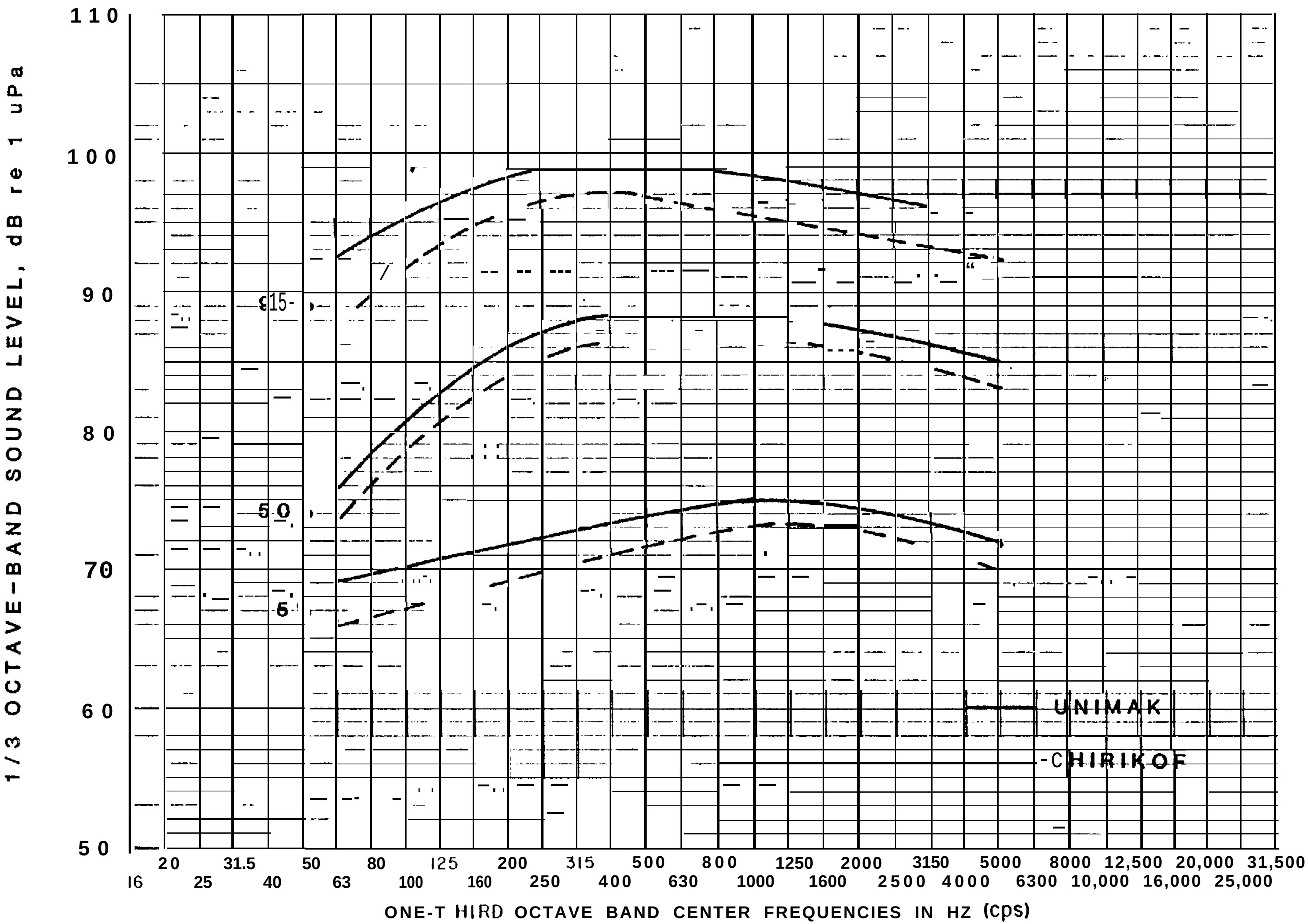


FIG. 4.3. ESTIMATED AMBIENT NOISE SPECTRA FOR CHIRIKOF BASIN AND UNIMAK PASS AREAS.

with a sloping bottom and strong sound velocity gradients. As a result, for this study and other similar acoustic model studies,* we have developed semi-empirical models which use sound transmission data obtained from in-situ measurements to provide a general sound propagation characteristic for a specific area. These semi-empirical models have been developed assuming both the 10 Log R and 15 Log R spreading loss characteristics. In addition, a computer-based analytic model has also been found to be useful within the restriction that it is appropriate only for conditions of neutral or small sound speed gradients. All of these models have been applied in analyzing the transmission loss data to obtain the most general interpretation of the results. The following discussion covers the development and application of both the analytic and empirical models.

4.3.1 Analytic sound propagation model

The shallow-water environment is very complex from the acoustical viewpoint. A complete specification would involve descriptions of:

- the sound speed profile in the water
- bottom topography
- bottom stratigraphy as function of location.
- surface conditions (roughness, ice).

Elaborate computer programs would then be required to use this information in a prediction of transmission.

Fortunately, since such detailed information is rarely available, it has been found possible to make reasonable predictions from simple formulas in the typical case where the sound

*See Malme, Smith, and Miles 1986; and Miles, et al. 1986.

speed is nearly independent of depth and the bottom slopes gradually, with nearly constant slope. These formulas have been developed and tested by Dr. D.E. Weston of the British Admiralty Research Establishment (Weston 1976).

In the simplified formulas, there are five parameters:

1. dominant frequency
2. water depth at the source
3. bottom slope along track

4,5. two parameters to describe the reflection loss of the bottom.

In these formulas, the term for the reflection loss (RL) in decibels for reflection of a plane sound wave incident at a grazing angle ϕ is taken to be:

$$\text{RL (dB)} = 4.34\, b \sin\phi, \text{ if } \phi < \phi_{cr}, \text{ or}$$
$$\text{RL} = \text{large}, \text{ if } \phi > \phi_{cr}. \tag{8}$$

The two parameters to be estimated are b and the critical angle ϕ_{cr}"

Because of bottom stratigraphy, the bottom reflection loss parameters are found to vary with frequency (Smith 1986). The explanation is Simple. A typical bottom in shallow water consists of a layer of sand or silt overlying rock. If the layer is thin, the sound 'senses' the rock; if the layer is thick, the sound is effectively isolated from the rock. Calculations indicate that the transition occurs when the surface layer thickness equals about one-half wavelength of sound.

Typical values of the bottom loss parameters are:

sand/silt: b = 2 , $\sin\phi_{cr} = 0.4$
hard rock: b = 0.4 , $\sin\phi_{cr} = 0.7$.

Soft rock, such as limestone or chalk, can be very absorptive because of transmission of energy in the shear wave. The values of the parameters are also very sensitive to the value of the shear wave speed (Smith 1986).

Weston's formulas for transmission loss divide the track into four regions, each of which has a characteristic range dependence. The regions are, in order of increasing range:

a. spherical spreading, where bottom-reflected rays are steeper than the critical angle;

b. a transitional, cylindrical spreading region;

c. a "mode stripping" region, wherein energy striking the bottom at steeper angles is attenuated more rapidly than that at shallower angles;

d. the "lowest-mode" region, wherein only the fundamental mode carries significant energy.

Only in the last region is transmission dependent on frequency, so long as the sand layer is either thin ($d < \lambda/2$) or thick ($d > x/2$) at all frequencies of interest. (See discussion of bottom reflection loss, above.)

In addition to water depth and bottom composition, the slope of the bottom is also important in determining transmission loss in shallow water. For sound transmission from a shallow region to deeper water, the increasing depth permits the sound energy to spread out over a larger volume than would have been available if the depth had remained constant. This results in a reduction in sound level. On the other hand, the increase in depth results in fewer bottom and surface reflections and thus less energy loss per kilometer. For most bottom types, the reduction in reflection loss has the strongest influence so the net effect of a positive bottom slope (increasing depth with increasing range) is lower transmission loss. This effect is most pronounced when neutral or upward refracting sound speed gradients exist. For these conditions sound transmission becomes ducted and is no longer influenced by bottom reflection loss.

For sound transmission into a decreasing depth region (negative bottom slope), the decrease in available volume for the sound energy would normally cause the sound level to be higher than it would be at the same range in a constant depth region. However, the number of surface and bottom reflections increases as the depth decreases. This causes the sound level to drop. This effect again usually predominates and the transmission loss becomes higher as sound propagates upslope. As the depth decreases, a depth is reached where there is a transition from multimode to single mode propagation. This usually results in a shift from a 15 Log R to a 10 Log R spreading loss characteristic. The attenuation per kilometer is determined primarily by the bottom material and may be quite high for soft bottom sediments. As water depth continues to diminish, there will be a point when effective propagation to long distances for frequencies of interest is not efficient (transmission loss becomes very high).

The Weston formulas noted previously apply to both positive and negative uniform bottom slopes as well as to the constant depth case.

A BASIC computer program was designed by P.W. Smith, Jr. at BBN which incorporates these formulas, yielding a value of transmission loss (dB re 1m) when given a value of range. This model, which we have called the Weston/Smith model, does not incorporate refraction effects produced by sound speed gradients and is appropriate for conditions where gradients are small or neutral. Nevertheless, it has been found to provide good predictions in shallow water conditions and thus was used as a comparison to the measured data at several sites.

4.3.2 Empirical sound propagation models

Multi-Mode Model (15 Log R)

This empirical model is based on the shallow water acoustic ray theory for an isospeed sound channel. The transmission characteristic for this case where many propagating modes are present has been given as (Smith 1971):

$$T = (2\pi/bHR^3)^{1/2} e^{-a_v R} , \qquad (9)$$

where b is a bottom loss factor defined previously in Eq. (8), H is the bottom depth, R is the range from the source, and a_v is the volumetric absorption. This is the characteristic that applies in the region c (mode stripping) portion of the computer model discussed previously. To develop the empirical model, we allow for an approximately uniformly sloping bottom by substituting:

$$H_{av} = (Hs + H_r)/2 = H \quad (m) \qquad (10)$$

where H_{av} is the average depth. An additional range-dependent loss factor is added to account for surface and bottom scattering and for losses produced by refraction not accounted for in the original analytic expression. The resulting modified transmission characteristic is:

$$T = (2\pi/bH_{av}R^3)^{1/2}\ e^{-a_a R/H_{av}}\ e^{-a_v R} \qquad (11)$$

where a_a is an anomalous attenuation factor which can be considered as a "loss-per-bounce," with the number of ray bounces being determined by the ratio of the range to the average depth. For convenience, Eq. (11) is converted to the logarithmic form of transmission loss (TL), where TL = -10 Log T or

$$TL = 5 \log (bH_{av}) + 15 \log R + A_a R/H_{av} + A_v R - 4 \text{ (dB)} \qquad (12)$$

Equation (12) is similar in form to a semi-empirical formula developed earlier by Marsh and Schulkin (1962) for intermediate range shallow water transmission loss prediction. In applying this relationship, the attenuation factor A_a is determined by analyzing a set of measured received level data which have been obtained in the area of interest. A calibrated sound source is used to obtain these data. To implement this analysis, Eq. (12) is used in the received level equation

$$L_r = L_s - TL$$

where Ls is the source level (dB re 1 μPa at 1 m) or:

$$L_r = L_s' - 5 \log H_{av} - 15 \log R - A_a R/H_{av} - A_v R + 4 \text{ (dB re 1 μPa)} \qquad (6)$$

where:

$L_s' = L_s + A_n - 45$, dB re 1 μPa at 1 km

Ls = Source Level, dB re 1 μPa at 1 m

R = range, km

A_v = volumetric absorption, dB/km (may be neglected for ranges less than 10 km and frequencies less than 1 kHz)

A_a = bottom and surface absorption and scattering losses, dB/bounce.

This equation is used in a computer-implemented, two-parameter, least-squares analysis using the measured values of L_r versus range. The results of this analysis produce estimated values of effective source level L_s' and A_a. Since the actual source level is known, this permits estimation of the effective change in source level resulting from surface- and bottom-reflected energy. This change will be called the local anomaly, A_n. For low sea states where surface losses are negligible, An = -5 log b. Since the usual values of the local anomaly, An are small, the mean error of the regression curve fit must also be small to obtain a good estimate of the loss factor, b. Conversely, if a good calibration of the local anomaly for a given area is available, this permits estimation of the source level of an uncalibrated source.

Cylindrical Spreading Model (10 Log R)

The analysis procedure using Eq. (12) and Eq. (13) is not appropriate at low frequencies in water depths where only a few modes are propagating and ray acoustic theory does not apply. It also is not appropriate at higher frequencies when ducted or upward refracted, surface-reflected (RSR) sound propagation paths dominate.

For these conditions, Eqs. (12) and (13) have been modified to incorporate a cylindrical spreading loss and a continuous boundary attenuation loss

$$TL = 10 \log H_{av} + 10 \log R + A_s R + A_v R \text{ (dB)} \quad (14)$$

or

$$L r = L \sim - 10 \log H_{av} - 10 \log R - A_s R - A_v R \text{ (dB re 1 } \mu\text{Pa)} \quad (15)$$

where:

$L_s' = L \sim + A n -$ 30 dB re 1 Pa at 1 km

A_s = boundary attenuation loss, dB/km.

Equation (14) is also similar to the cylindrical spreading TL equation developed earlier by Marsh and Schulkin (1962). Equations (14) and (15) are not suitable for areas where there is a large variation in bottom depth along the propagation path (> 20%).

4.4 Results of Predictive Modeling and Comparison with Reported Data

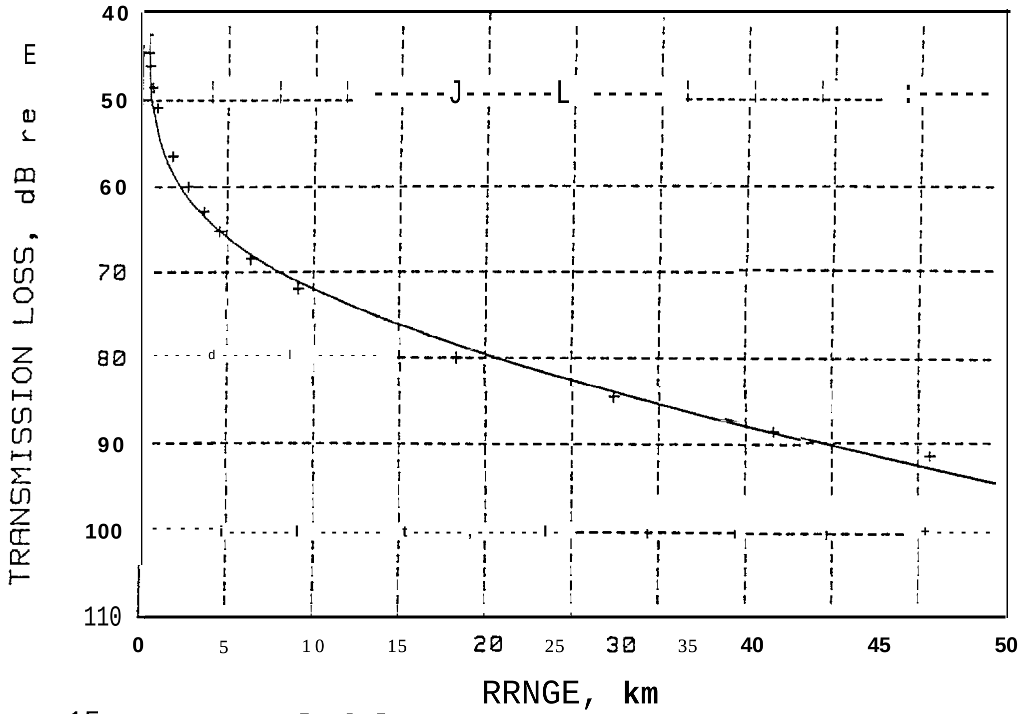
The semi-empirical sound propagation model described previously has the capability of closely matching a set of measured data and providing a means of extrapolating sound transmission characteristics beyond the measured range of the data. However, for sloping bottoms where the depth becomes too shallow to support multimode propagation, this model has no provision for changing over to single mode calculation procedure. We have, therefore, developed a procedure for matching the Weston/Smith analytic model to a measured set of data. This model is capable of making a transition in computation procedure when required by changes in the depth along the propagation path. Thus, extrapolation estimates using this model are expected to be more accurate in applications where significant changes in depth occur along the sound propagation path.

4.4.1 Chirikof Basin

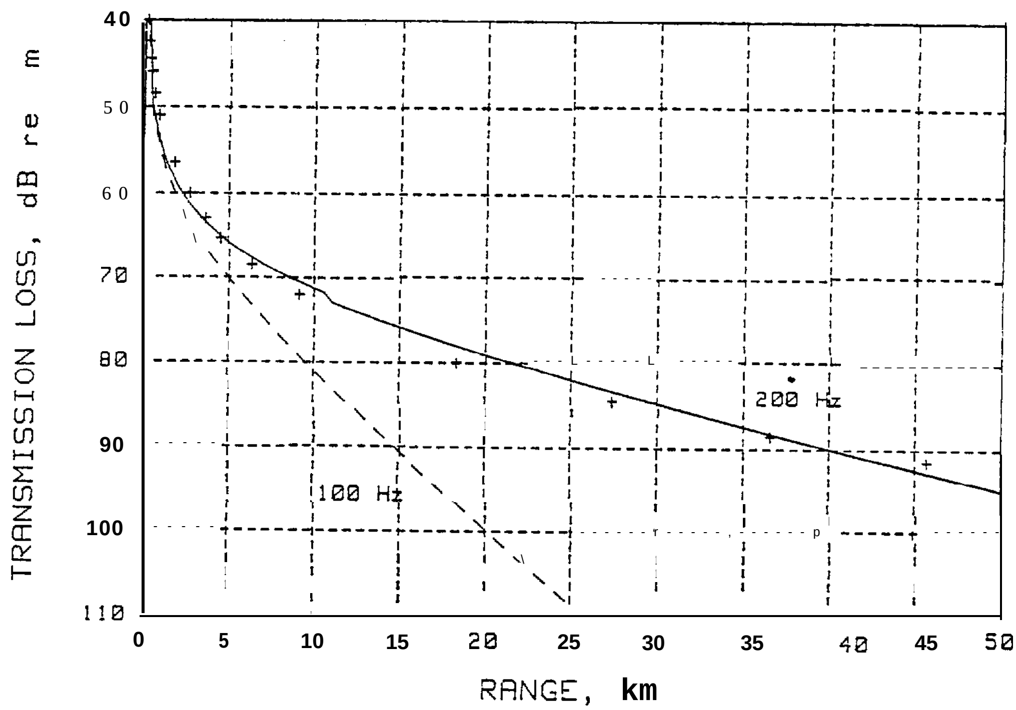
The air gun sound propagation data obtained near St. Lawrence Island were obtained in depths of 10 to 20 m, whereas the average depth of the Chirikof Basin is 40 m. It was necessary therefore to obtain sound transmission data for the Chirikof Basin or similar areas to compare with the measurements near St. Lawrence Island and verify the model predictions for the Chirikof Basin. Fortunately, Mackensie (1961, 1973) has reported measurements that can be used to compare with the model predictions.

Figure 4.4A shows the results of matching a Semi-empirical Model curve with data reported by Mackensie for measurements at 200 Hz. The values of the reflection loss coefficient A_r obtained are comparable to values obtained for the test areas near St. Lawrence Island that were well offshore (see Table 3.6). The values for A_r obtained in this area of the Bering Sea are considerably lower than the value of $A_r = 85$ obtained for the transmission loss measurements at the California test site.

The Mackensie transmission loss measurements were made using a source depth of 4.5 m and receiver depths of 5 m and 30 m. The transmission loss to the deep receiver was about 2 to 5 dB more than that obtained to the shallow receiver for most of the measurement ranges. This may have been caused by modal propagation conditions wherein sound levels are not uniform throughout the water column. These conditions are also believed to be responsible for the negative local anomaly values (An) obtained from the curve-fitting analysis program. In shallow water, positive values of An usually occur because of the added energy of bottom and surface reverberation. When strong modal effects exist, the sound level at the receiver is influenced not only



A. 15 Log R Model, A=12, An=-5



B. Weston/Smith Model, b=0.8, Sin ϕcrit=0.5, An=-5

FIG. 4.4. **MODEL PREDICTIONS** COMPARED WITH REPORTED DATA FOR TRANSMISSION LOSS IN THE CHIRIKOF BASIN (MACKENSIE 1961 ++).

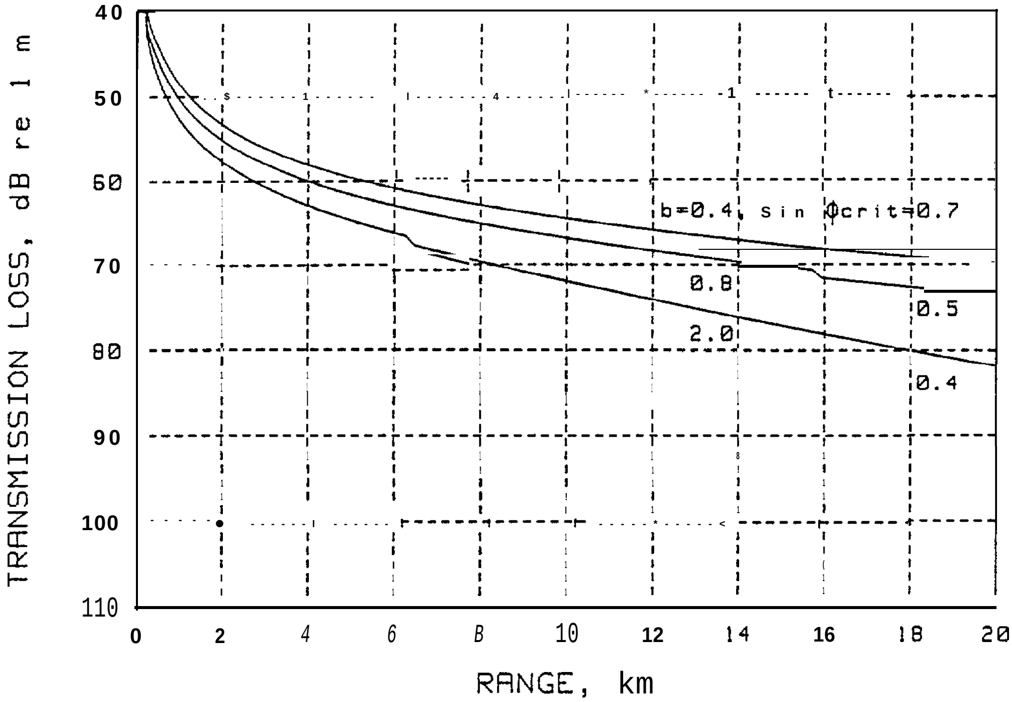
by the range to the source but also by its location in the modal standing wave pattern. We have chosen to model the propagation from a surface source to a deep receiver since that is believed to represent the usual geometry for an industrial noise source and feeding whales.

The curve shown in Fig. 4.4B was obtained using the Weston/ Smith Model to match the Mackensie data. The bottom parameter values used to obtain the curve shown are intermediate between those for silt/sand and those for soft rock. The sound energy may be reflecting off both the bottom and sub-bottom layers. At lower frequencies, the energy is reflected primarily from the sub-bottom rock layer resulting in lower transmission losses than would occur for a silt/sand bottom alone.

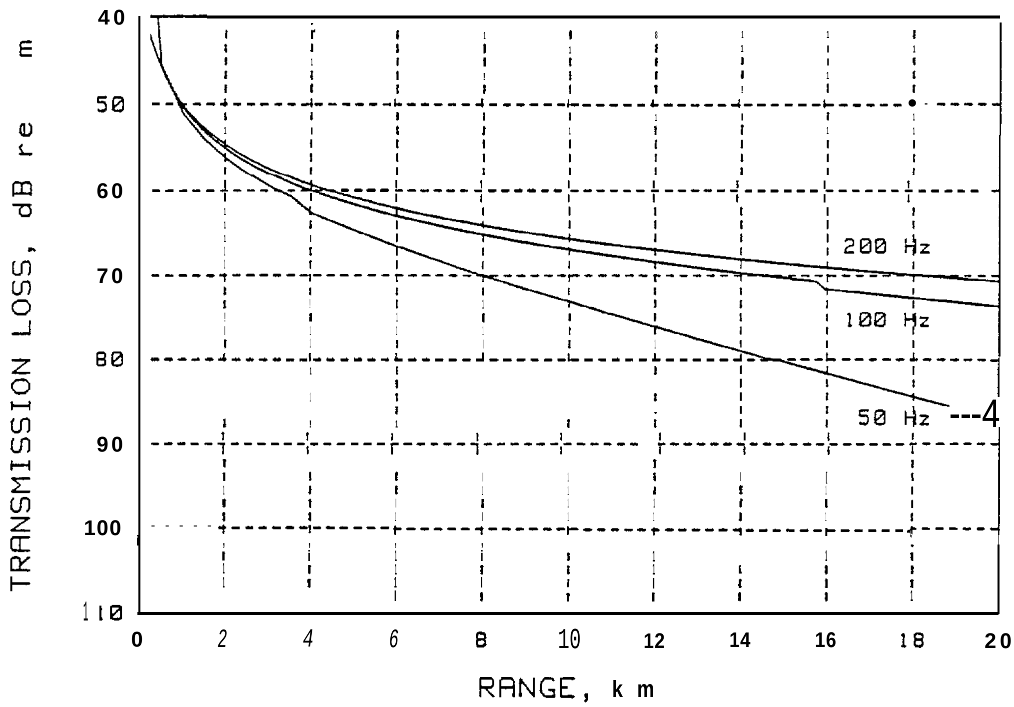
4.4.2 Unimak Pass

Since the whales travel quite close to shore, it is likely that any industrial activity will be located offshore from their position or potentially at a comparable distance offshore. Thus, the model predictions will include consideration of upslope propagation as well as propagation along a constant depth path.

Figure 4.5A shows the predicted transmission loss characteristics for constant depth conditions near Unimak Island. Characteristics for several types of bottom material are shown since no measured transmission loss data were found for this area. The upper curve is the characteristic for a soft rock bottom and the lower curve is for a sand/silt bottom. The intermediate curve is for the bottom parameters used for the Chirikof Basin transmission loss model. Since the bottom composition in the Unimak Island area is also sand and gravel with an underlying rock layer, we will use the same intermediate bottom parameters for the modeling work in this area. However, a



A. Effect of Bottom Parameters, 100 Hz, Depth 70 m



B. Frequency Dependence, b=0.8, Sin ϕcrit=0.5, Depth 70 m

FIG. 4.5. TRANSMISSION LOSS CHARACTERISTICS NEAR UNIMAK ISLAND, WESTON/SMITH MODEL.

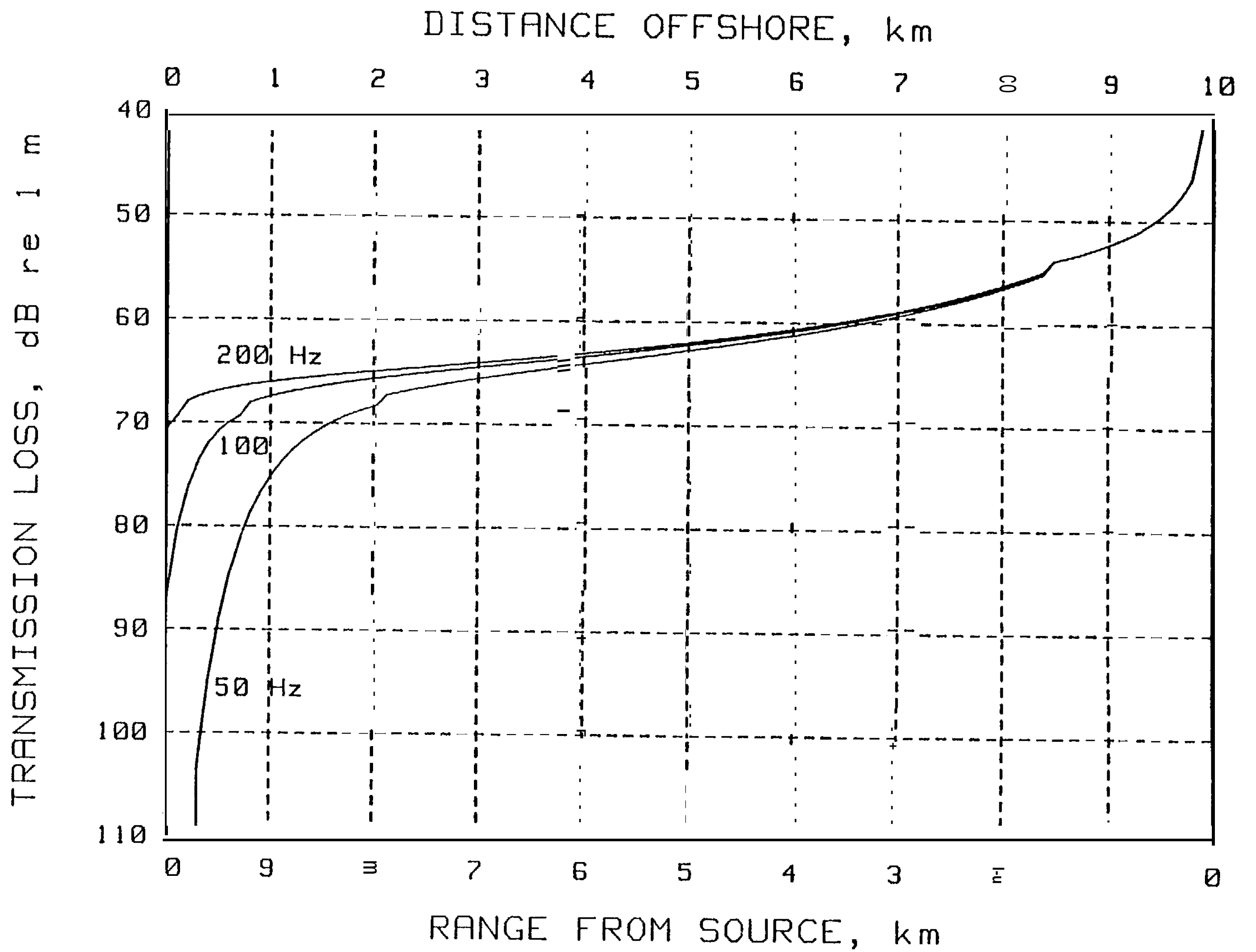
local anomaly of 0 dB will be used instead of -5 dB since no measured transmission loss data are available for this area to provide specific information on An. This will have the effect of reducing the estimated transmission loss for a given range and water depth compared to that for the Chirikof Basin.

Figure 4.5B shows the frequency dependence of the transmission loss for constant depth. The 70 m depth used in the figure corresponds to a relatively flat region starting about 3 to 4 km offshore to the north of Unimak Island. Frequencies below 100 Hz can be seen to be attenuated more rapidly than higher frequencies because of the shallow water.

The transmission loss characteristics for a source located offshore to the north of Cape Sarichef are shown in Fig. 4.6. The characteristics are shown for propagation upslope toward shore from a source located 10 km offshore. This geometry is relevant to offshore seismic survey activities and to offshore platform or drillship locations. Note that the effect of a sloping bottom is to produce a rapid attenuation of low frequency sound as shallow water is reached. This is beneficial in reducing the sound exposure levels in the migration zone.

4.5 Predicted Zones of Influence of Petroleum Industry Sound Sources

Three types of sources were considered in developing the predictions of zones of influence. These were large air gun array, small air gun array or single gun, and drillship. While there are a large number of source types that could be included, we selected these as representative of the output source levels, frequency range, and source directivity factors that must be considered in using the prediction model. The resulting curves can thus be used with other sources by changing the source level value.



Bottom Slope = .018, b=0.8, Sin ϕcrit=0.5, Depth at Source 190 m

FIG. 4.6. TRANSMISSION LOSS CHARACTERISTICS FOR UPSLOPE PROPAGATION TOWARD UNIMAK ISLAND, WESTON/SMITH MODEL.

4.5.1 Received level calculation procedure

The received sound level for a given source and propagation path is predicted by the following relationship:

$$L_r = \left(L_S(f) + D(f, \theta, r)\right) - TL(f, r) \text{ (dB re 1 } \mu\text{Pa)} \quad (16)$$

where the source level, L_S, is a function of frequency; the directivity factor, D, is a function of frequency and the sound radiation angle, θ. The source directivity is sometimes also a function of range when, for shallow sources or large arrays, the negative surface reflection causes an additional interference loss which is range-dependent (Malme et al. 1984). The transmission loss, TL, is a function of frequency and range.

4.5.2 Source level-determination

The source level for large seismic arrays is usually given as the peak pressure value at one meter on the axis of the main beam. It is usually measured in deep water at a sufficient distance from the array so that the pulses from all of the individual sources are in coincidence (far field). The measured pressure is then corrected to an equivalent of one meter using a spherical spreading loss of 20 log r. The peak pressure measured to the side of a large array is less than the main beam peak pressure because the individual sources are not in coincidence. For an array geometry consisting of two or more parallel linear subarrays, the peak pressure measured horizontally is maximum along the broadside axis because the pulses from all of the sources in a subarray are in coincidence. A directivity correction for radiation along this direction can be estimated by dividing the main beam peak pressure by the number of subarrays (assuming that all subarrays have the same number of sources), or in logarithmic terms:

$$D = 20 \log 1/N_s \text{ (dB)} \qquad (17)$$

where N_s is the number of subarrays. For arrays that do not have a simple linear geometry, a more detailed examination of the axes of maximum pulse coincidence must be made to determine the ratio of the total horizontal pulse pressure to the main beam pulse pressure (Malme, Smith, and Miles 1986).

For large air gun arrays, the transmission loss characteristic has been observed to have a 25 log range dependence instead of the usual 15 log range dependence generally observed in shallow water (Malme et al. 1983). The additional 10 log r factor is believed to result from the close proximity of the array to the surface and is observed primarily near broadside aspect and not at endfire. This effect is included as a directivity factor in the modeling procedure so that the same TL characteristics can be used for both single air guns and arrays. The following combined directivity relationship results for large arrays:

$$Da = 20 \log 1/N_s - 10 \log r \text{ (dB)} . \qquad (18)$$

For small arrays where the effective dimension of the array with respect to the sound propagation direction is less than 1/2 wavelength at the dominant output frequency and the depth is greater than 1/4 wavelength, the additional 10 log r factor should not be used.

The source level of drillships and other large distributed sources is determined by measurements of the radiated sound level at a number of successive distances from the source which are large compared to the overall dimension of the source. The measurements are then analyzed using an appropriate propagation model, such as Eqn. (3), to estimate what the effective sound level would be at 1 m from an equivalent point source. A calibration of the transmission path should be made using a calibrated sound source to determine the local transmission anomaly caused by site-specific bottom and surface reflection properties. This allows correction of the measured source level to an equivalent deep water value.

Large Air Gun Array Example

Peak-to-peak pressure on axis, 60 Bar-meters

Acoustic Source Level (Peak), 250 dB re 1 μPa at 1 m

Broadside directivity, D, -6 dB (two linear subarrays)

Ratio of peak to average pulse pressure levels, 4 dB
(assumes range independent pulse durations based on St. Lawrence Island data)

Average pulse pressure level, 240 dB re 1 μPa
($L_p = Ls + D - 4$)

Dominant frequency range, 50 to 200 Hz

Single Air Gun or Small Array Example

Peak-to-peak pressure, 3 Bar-meters

Acoustic source level (peak), 224 dB re 1 μPa

Horizontal directivity, D, O dB (omnidirectional)

Ratio of peak to average pulse pressure levels, 4 dB

Average pulse pressure level, 220 dB re 1 μPa

Dominant frequency range, 50 to 200 Hz

Drillship Example (Explorer II)*

Acoustic source level (rms), 165 dB re 1 μPa at 1 m

Dominant frequency range, 80 - 1600 Hz (loudest tonals at 72 and 239 Hz)

4.5.3 Received level estimates for source examples

The transmission loss characteristics developed for the Chirikof Basin and Unimak Pass areas were combined with the source level examples in accordance with Eq. (16) to obtain predictions of received level versus range from the source.

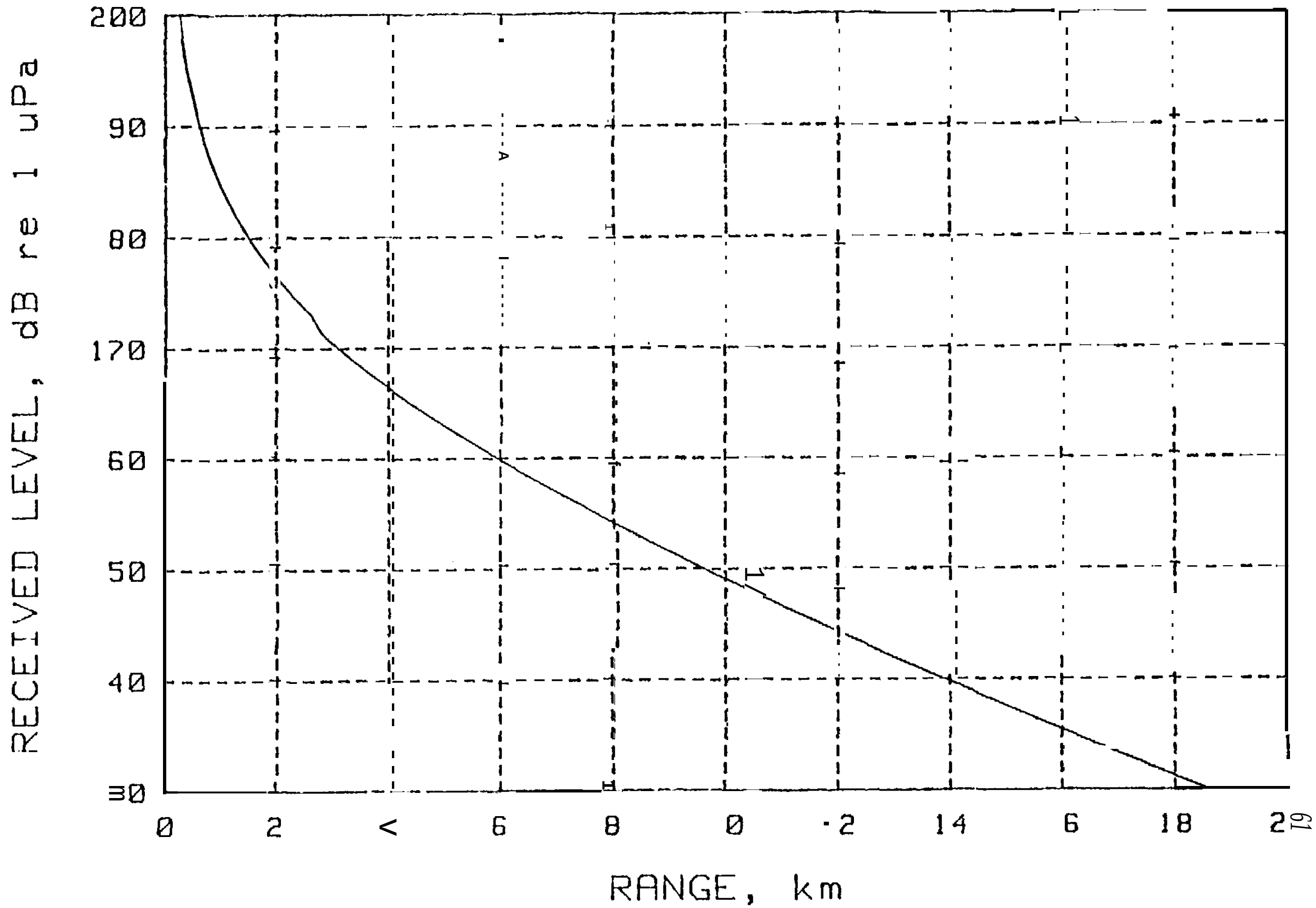
Chirikof Basin

Figures 4.7 through 4.9 show the results of this procedure for the Chirikof Basin. Figure 4.7, for a large air gun array, incorporates the additional 10 log r attenuation due to the vertical directionality of the source. These figures can be used to predict the received levels for sources other than those of the examples by adjusting the predicted value of L_r by the amount of the source level difference. Figures 4.7 and 4.8 should be used for large air gun arrays and single air guns (or small arrays), respectively. Figure 4.9 should be used for sources having a higher frequency acoustic output with dominant components in the range of 200 to 300 Hz.

Unimak Pass

The received level characteristics for the example sources in the Unimak Pass area are shown in Figs. 4.10 through 4.12.

*Measurements reported by Greeneridge Sciences in 1985 show that the radiated noise spectrum of the drillship Explorer II has changed from that measured previously in 1981 (Greene 1982). The 1981 radiated noise recordings are the source for the playback stimuli used in the gray whale behavioral response study.



Weston/Smith Model, b=0.8, Sin φcrit=0.5, An=-5, 100 Hz +10 Log R

FIG. 4.7. AVERAGE PULSE PRESSURE LEVEL VS. RANGE IN CHIRIKOF BASIN
LARGE AIR GUN ARRAY, L_s = 240 dB re 1 μPa at 1 m*

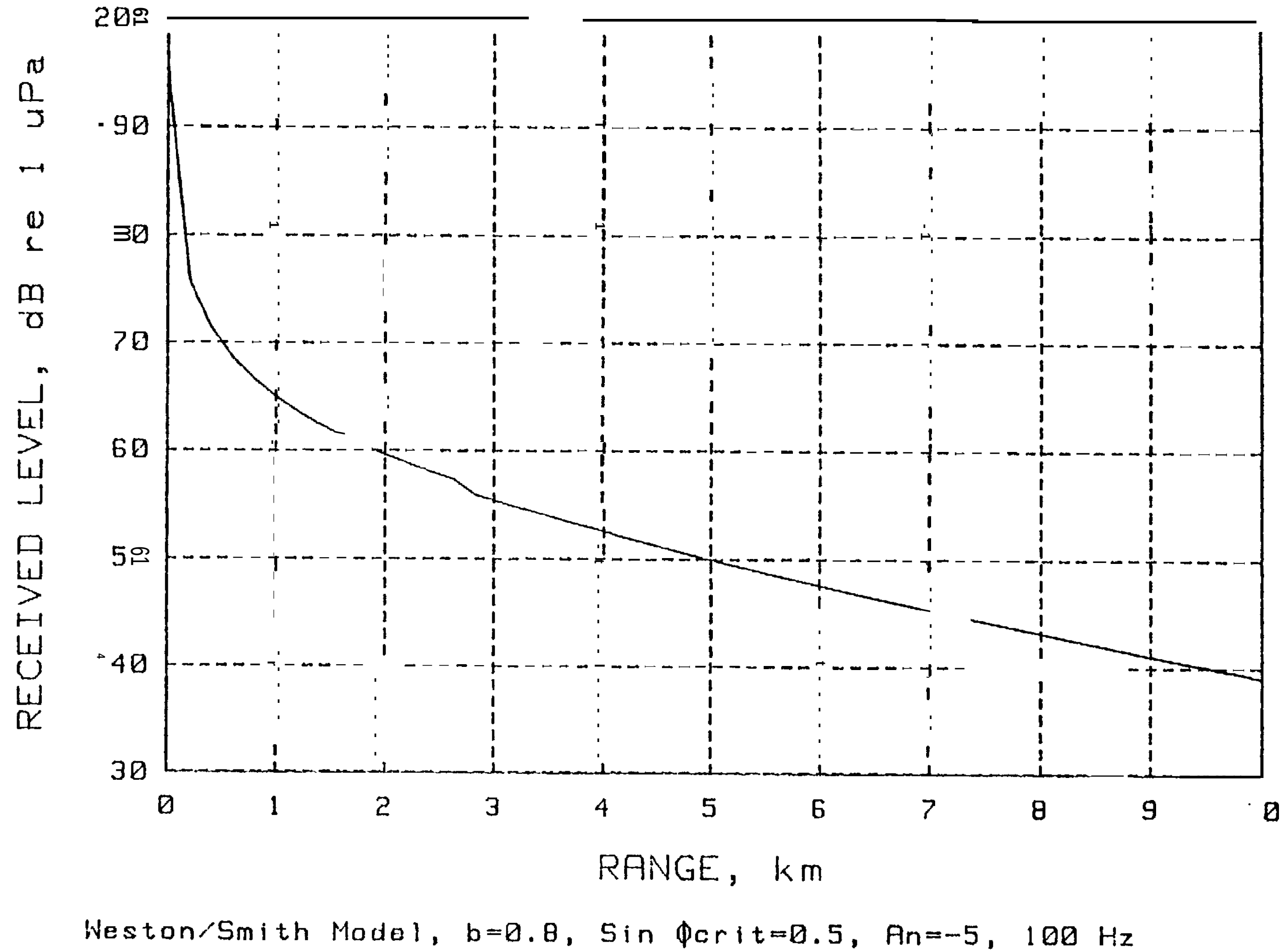
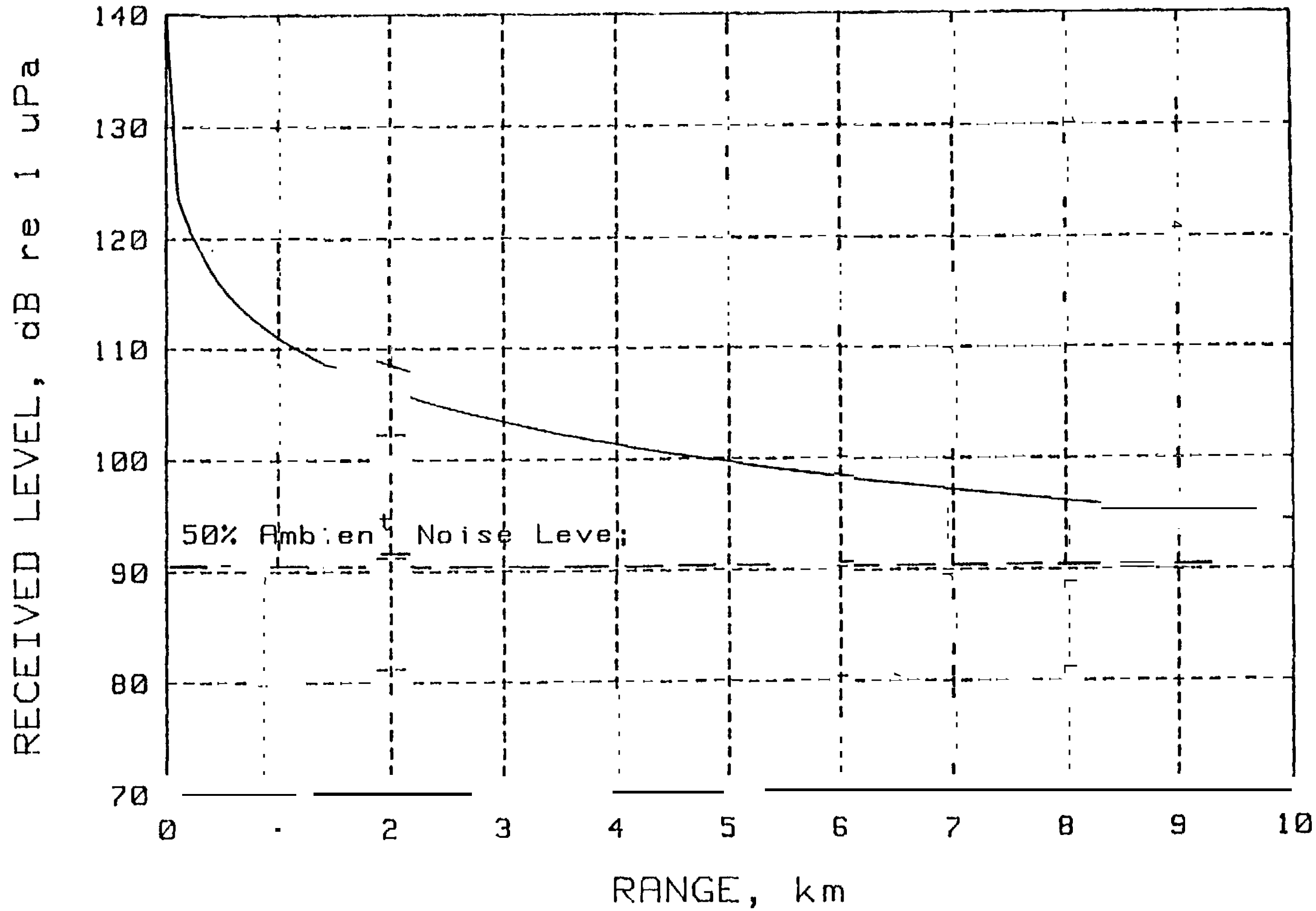
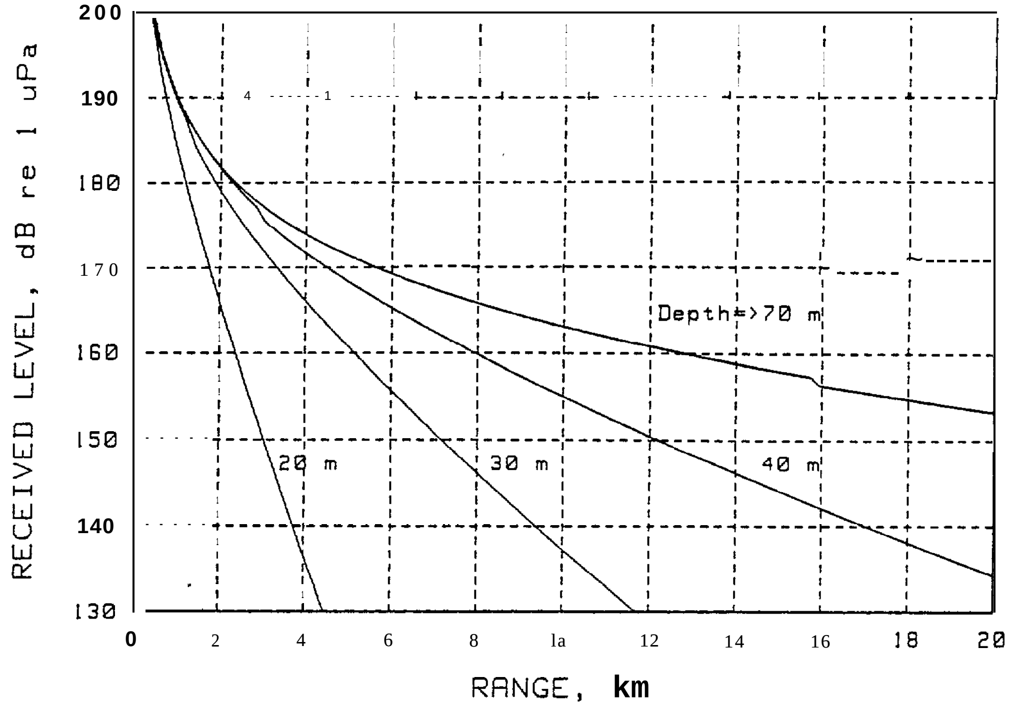


FIG. 4.8. AVERAGE PULSE PRESSURE LEVEL VS. RANGE IN CHIRIKOF BASIN AIR GUN OR SMALL ARRAY, L_s = 220 dB re 1 μPa at 1 m.

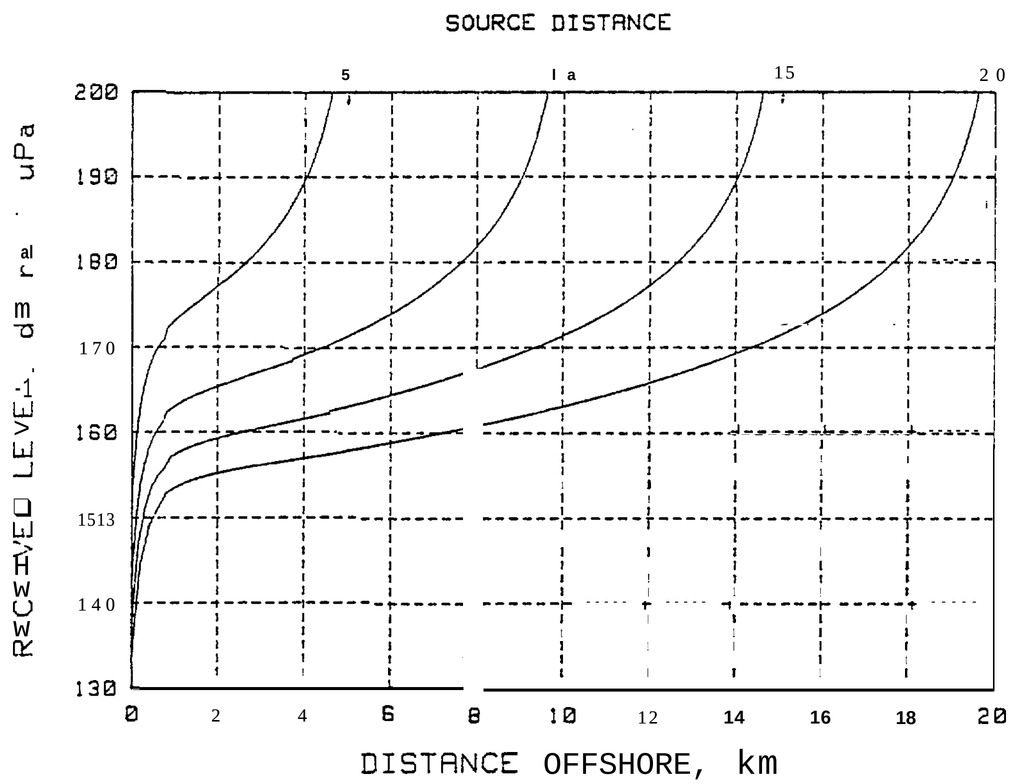


Weston/Smith Mode , b=0.=, Sio Φcrit=0.5, An= 5 =50 Hz

FIG. 4.9. RECEIVED LEVEL VS. RANGE IN CHIRIKOF BASIN
DRILLSHIP (EXPLORER II) L_s = 165 dB re 1 μPa at 1 m.

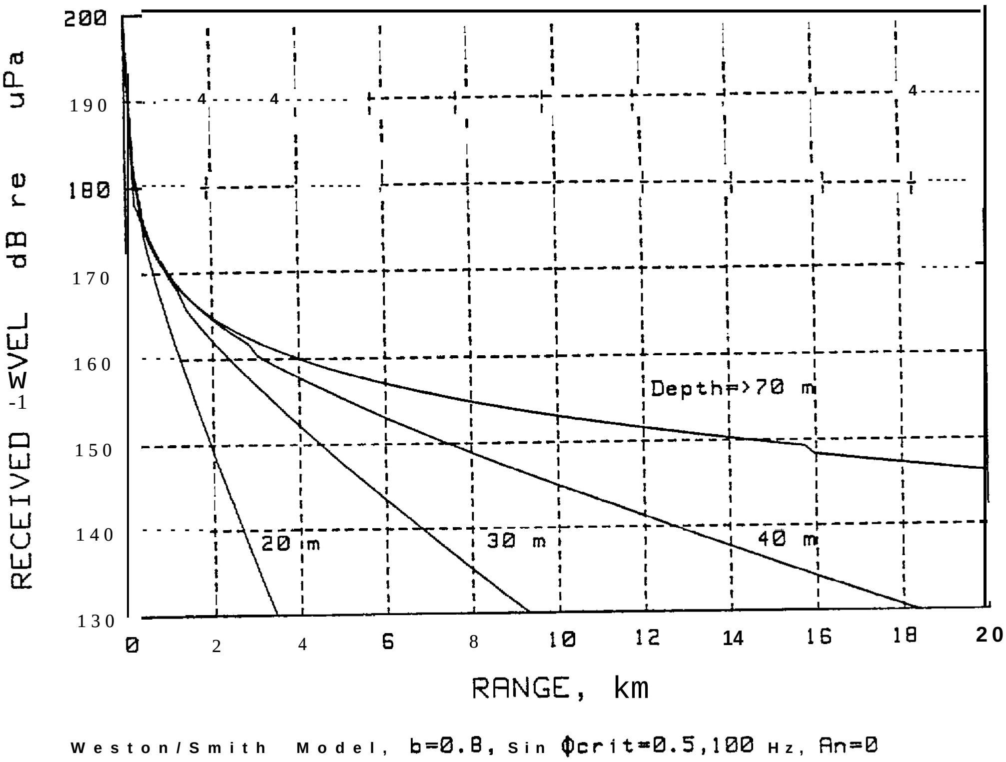


A Weston/Smith Model, b=0.8, Sin Φcrit=0.5, 100 Hz, An=0, +10 Log R



B Weston/Smith Model, b=0.8, Sin Φcrit=0.5, 100 Hz, An=0, +10 Log R

FIG. 4.10. AVERAGE PULSE PRESSURE VS RANGE, UNIMAK LARGE AIR GUN ARRAY, L_S = 240 dB re 1 μPa AT 1 m. A. CONSTANT DEPTH; B. UPSLOPE .



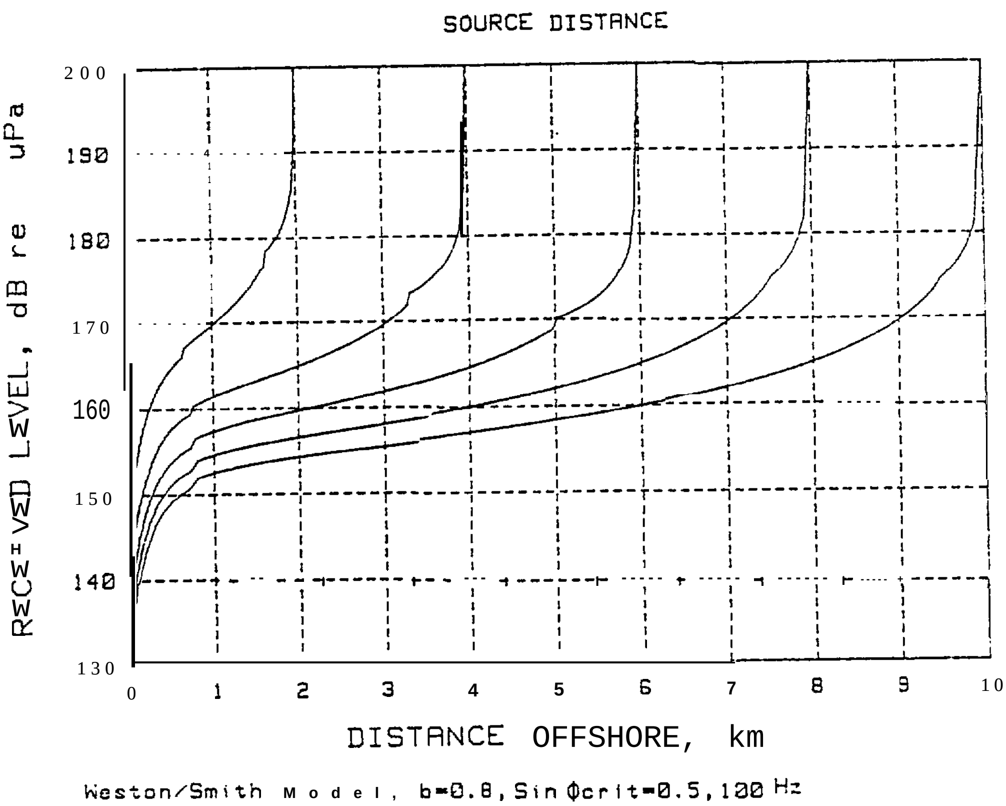
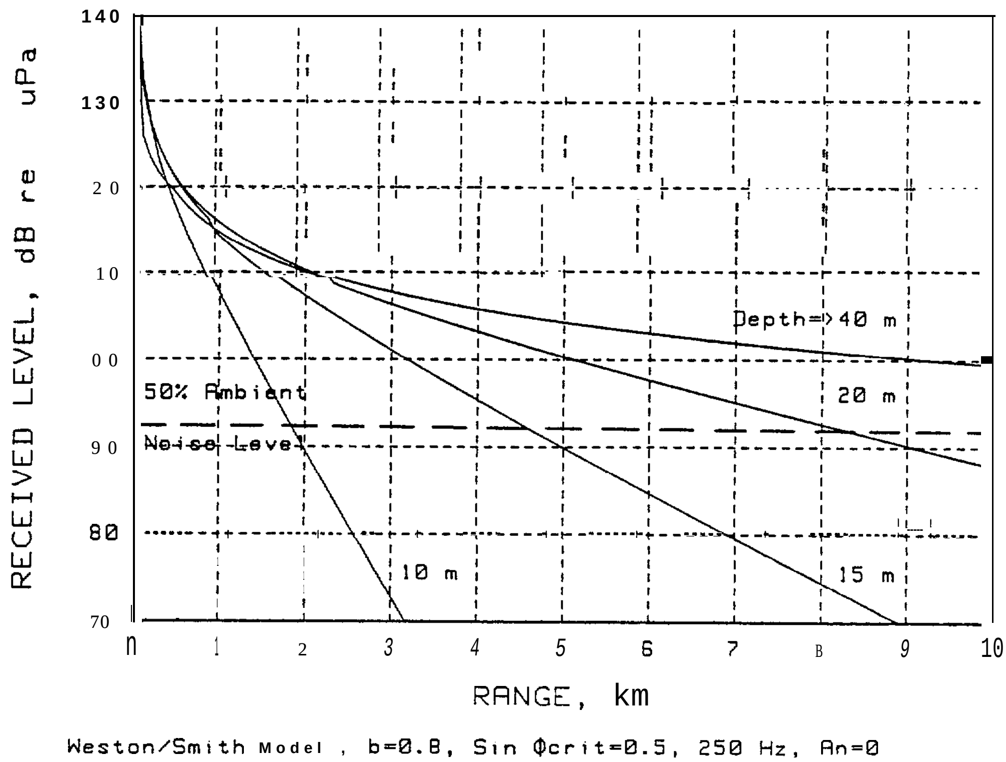


FIG. 4.11. AVERAGE PULSE PRESSURE VS RANGE, UNIMAK AIR GUN OR SMALL ARRAY, L_s = 220 dB re 1 μPa AT 1 m. A. CONSTANT DEPTH; B. UPSLOPE.



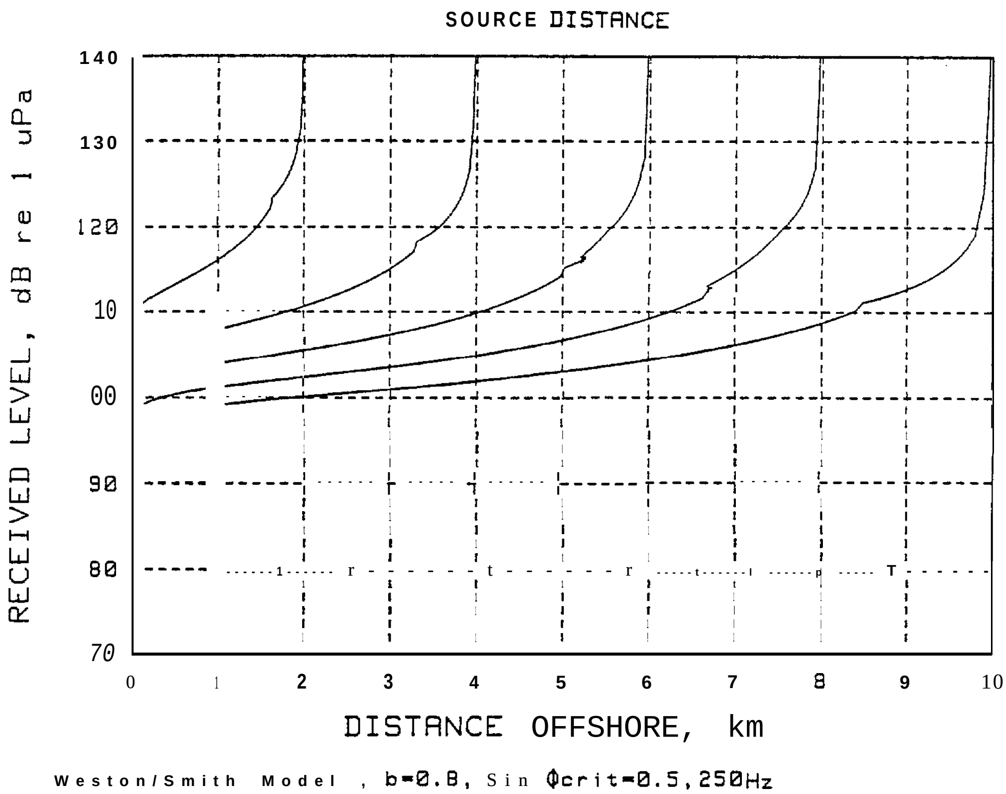


FIG. 4.12. RECEIVED LEVEL VS RANGE, UNIMAK DRILLSHIP (EXPLORER II), L_s = 165 dB re 1 μPa at 1 m.
A. CONSTANT DEPTH; B. UPSLOPE.

Here, predicted levels are shown for propagation at constant depth (parallel to the shoreline of Unimak Island) as well as for propagation from an offshore source toward the shore. The characteristics for upslope propagation are given for the offshore source distances indicated at the top of the curves. Interpolation between the curves may be done for intermediate source positions. These curves may be used for both fixed and moving offshore sources. For moving sources, the received level indicated for a given offshore source distance and receiver location would be the level occurring at the closest point of approach. Thus, for example, referring to Fig. 4.10B, whales in the migration corridor .5 km offshore would experience average pulse levels of 170 dB for passage of the example seismic array about 5 km offshore. For the single air gun, a level of 170 dB .5 km offshore would be created by passage of the source vessel at an estimated 1.5 km offshore as shown by interpolation in Fig. 4.11B. When the source and receiver are about the same distance offshore, the constant depth characteristics shown can be used. For example, if the seismic array were operating in the migration corridor where the depth is 20 m, the 170 dB received level would occur at a range of about 1.7 km as shown in Fig. 4.10A.

4.5.4 Zone of Influence estimates

The information developed in the received level curves may be used to predict zones of influence for the example sources. To do this, it is necessary to use criteria which determine the received level at which a sound is likely to produce a given behavior in gray whales. As discussed previously in Sec. 3.4, the general criteria which seems appropriate for summering and feeding activity are:

Air gun and air gun arrays (moving sources)

Criterion	$L_{\overline{p}}$
0.1 probability of feeding disturbance	163 dB re 1 μPa
0.5 probability of feeding disturbance	173 dB re 1 μPa

(Including temporary avoidance of source region)

Continuous sources such as drillships (fixed location)

Criterion	L_r
0.1 probability of avoidance	110 dB re 1 μPa
0.5 probability of avoidance	120 dB re 1 μPa

The above criteria have been used to develop Table 4.1 which shows the zones of influence for the example sources.

Observations of the behavioral response of bowhead whales to industrial noise in the Beaufort Sea has resulted in the development of response criteria based on the S/N of the industrial sound to the local ambient noise level (Richardson et al. 1985). It was found that a 20 dB industrial\ambient noise ratio produced occasional avoidance of the source region and that a 30 dB ratio resulted in probable avoidance. The results of applying this type of criteria to gray whales in the two Bering Sea study regions are also shown in Table 4.1. Note that for the 50th percentile ambient noise spectra used in the table, the zone of influence ranges for the drillship as determined by both noise exposure level criteria and the S/N ratio criteria are similar. The ranges for the 20 dB and 30 dB S/N of the array and single gun have not been listed since there have been no observations of behavioral response to air gun transient signals below 130 dB.

TABLE 4.1. ZONES OF INFLUENCE FOR REPRESENTATIVE PETROLEUM INDUSTRY NOISE SOURCES.

Source Type	Chirikof Basin (water depth, 40 m)			Unimak (water depth, 30m)			Unimak (Toward Shore) (receiver 0.5 km offshore)		
	Array[1]	Single[2] Gun	Drillship[3]	Array	Single Gun	Drillship	Array	Single Gun	Drillship
Received Level	km	km	km	km	km	km	km	km	km
173 dB	2.6	.32		2.8	.63		3	0.55	
163 dB	5*O	1.3		4.5	1.8		7	1,5	
120 dB			0.3			0.5			0.7
110 dB			1.1			2.1			2.5
s/N (50%)4									
30 dB			0,3			0.4			0.6
20 dB			1.1			1*7			2

Notes: [1]Array main beam peak source level 250 dB re 1 µPa at 1 m Horizontal effective source level 240 dB average pulse pressure.

[?]Single air gun or small array, peak source level, 224 dB, 220 dB average pulse pressure.

[3]Drillship source level, 165 dB.

[4]Ratio of drillship noise to 50th percentile ambient noise in effective drillship bandwidth.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Analysis of the surfacing-dive data showed that blow intervals decreased during drillship sounds, and length of surfacing, length of dive, and number of blows per surfacing increased. Pre-disturbance rates were re-established within about 1/2 hour after the stimulus was turned off. Blow rate changed little. The response to air gun sound was different. Blow intervals increased but length of surfacing length of dive, and the number of blows per surfacing all decreased. This trend was strongest on occasions when cessation of feeding and movement away from the source vessel were observed. Recovery to pre-stimulus conditions occurred in about one hour after disturbance. Detailed statistical analysis to quantify dive cycle and respiration data in terms of acoustic exposure level was not possible because of limited sample size.

The two-vessel tracking procedure provided whale position information which was useful for determining the whale source distance necessary for noise exposure estimation. The error of this procedure is estimated to be within 10% for ranges less than 1 km. This procedure was used to obtain the movement patterns of focal whales during control and experimental conditions.

Limited playback experiments using a drillship stimulus showed no consistent evidence of feeding disturbance or avoidance of the source for exposure levels up to 110 dB. Some whales were observed to leave the test area for exposure levels up to 119 dB. However, observations during control periods showed that whales appeared to respond to the presence of the sound source vessel itself, thus complicating interpretation of results. Until more data are obtained, we recommend that the level of 110 dB be considered as the level which will possibly cause disturbance of feeding activity by a continuous industrial noise. This was the level of drillship noise observed to produce a 0.1 probability avoidance for migrating gray whales. A level of 117 dB was observed to cause a 0.5 probability of avoidance for drillship noise and 119 dB caused a 0.5 probability of avoidance for the average of all of the noise stimuli tested. As a reference value, we recommend that 120 dB be considered the level of a continuous industrial noise which will probably disturb at least 1/2 of the feeding gray whales.

Experiments using a 100 cu. in. air gun at exposure levels up to 176 dB (average pulse pressure) showed that gray whale behavioral response while feeding is varied. At high exposure levels some were observed to stop feeding and move away from the source area, while others continued feeding. Because of the moving source geometry used to simulate air gun array operations, it was not possible to perform the probability of avoidance type of analysis as was done for previous studies of migrating gray whales. Instead, detailed observations of focal animals were used to determine a range of air gun pulse pressure levels that would generally cause disturbance of feeding activity. Based on a limited number of samples, average pulse pressure levels of 173 dB and above were observed to result in cessation of feeding activity and movement away from the source area for at least 50% of the whales exposed. Movement back to the original area and resumption of feeding occurred in most of the observed reactions after the source had moved away. Average pulse pressure levels of 163 dB were determined to cause disturbance of feeding activity with some avoidance reaction for 10% of the whales exposed.

The results of the sound propagation model study were used for prediction of zones of influence for representative oil industry sources in Chirikof Basin and near Unimak Pass. The transmission loss predictions were aided by data obtained near St. Lawrence Island for the behavior study and by data reported in the literature. Sound propagation in the Bering Sea is better than would normally be expected for a shallow sea because of the presence of a sub-bottom rock layer. As a result, the zones of influence of industrial noise sources extend further than would be the case for propagation at similar depths off the California coast.

5.2 Recommendations

The data obtained during the short field period in 1985 near St. Lawrence Island were limited by weather conditions and by relatively few whales in the study area. Augmentation of the available data would be highly desirable to be able to have a better statistical base for establishing maximum sound exposure criteria for gray whales engaged in feeding activity.

An extended field study should be performed at St. Lawrence Island earlier in the season when the whale population is higher and the weather is better. This would permit establishment of a theodolite station on the island so that only one large support vessel would be required. It would also allow for more extended control periods so that the degree of interaction between successive test periods would be minimized.

The procedure for conducting moving air gun tests should be revised so that the control periods involve the source vessel moving in the same manner as during the active air gun period. This will significantly increase the required time for each complete test sequence, however. If a second large vessel is not required as an observation platform, this would help eliminate a potential confounding factor.

Playback sequences need to be much longer than those used with migrating whales to minimize the start-up transient effects. It would be highly desirable for the source vessel to spend several days at a site near active feeding areas. This would simulate the actual source more realistically as well as allow for the whales to adjust to the presence of the vessel during an initial long control period.

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APPENDIX

COMPARISON OF TRIANGULATION, THEODOLITE, AND RADAR LOCATION DATA OF SHIPS TO THE SHIPS' LORAN READINGS

Peter Tyack

APPENDIX: COMPARISON OF TRIANGULATION, THEODOLITE, AND RADAR LOCATION DATA OF SHIPS TO THE SHIPS' LORAN READINGS

Triangulation vs LORAN

On 22 and 25 August 1985, the location of the NANCY H was determined by observers on the BIG VALLEY and the Zodiac using the same triangulation method used to locate whales on these days. By comparing these readings to LORAN readings from the NANCY H, we can analyze potential errors of the technique. In the table below, the column marked "error" indicates the difference between the triangulation reading of the NANCY H from the BIG VALLEY and the LORAN reading from the NANCY H. Ranges and errors are in kilometers.

Time of Localization			
Triangulation	LORAN	Range	Error
1207	1207	2.887	1.454
1236	1252	0.347	0.184
1436	1440	0.706	0.100
1516	1517	1.382	0.057
1515	1515	1.397	0.550
1550	1549	0.314	0.081
1600	1557	1.103	0.074
1650	1649	1.748	0.407
1730	1730	0.398	0.080
1750	1752	1.595	0.381

Table 1 shows the same data sorted by range along with a linear regression of error as a function of range. The correlation of error and range is 0.85 indicating a robust ($p < 0.01$ that $r = 0$ from this sample) increase. in error with increasing range. Figure 1 plots the actual vs estimated error and residuals from Table 1. Figure 2 shows a scatter plot of the data along with the regression line. The error actually appears to be relatively constant at approximately 100 m out to a range of just over 1 km and then to increase rapidly. The 100 m error at short ranges is probably due to the limits of precision of the LORAN which should not increase with range. More data is required to calibrate the triangulation technique, but this data indicates it is accurate to 100 m at ranges of up to 1 km, but that it may not be useful at greater ranges.

TABLE 1. LINEAR REGRESSION OF ERROR VS RANGE FOR TRIANGULATION TECHNIQUE.

Linear Regression - **Range** vs **Error**

Index	Actual Range	Actual Error	Estimated Error	Residuals
1	0.31	0.08	-0.06	-0.14
2	0.35	0.18	-0.05	-0.23
3	0.40	0.08	-0.02	-0.10
4	0.71	0.10	0.12	0.02
5	1.10	0.07	0.30	0.22
6	1.38	0.06	0.43	0.37
7	1,40	0.55	0.43	-0.12
8	1.59	0.38	0.52	0.14
9	1.75	0.41	0.59	0.19
10	2.89	1.45	1.11	-0.34

Estimated Regression equation is:

error (y) =	variable	x	coefficient	error
x(0)	constant		-0.20	0.14
x(1)	range		0.46	0.10

Correlation coef (r) = 0.852 coefficient of determination r^2 = 0.725 standard error of estimate (see) = 0.24

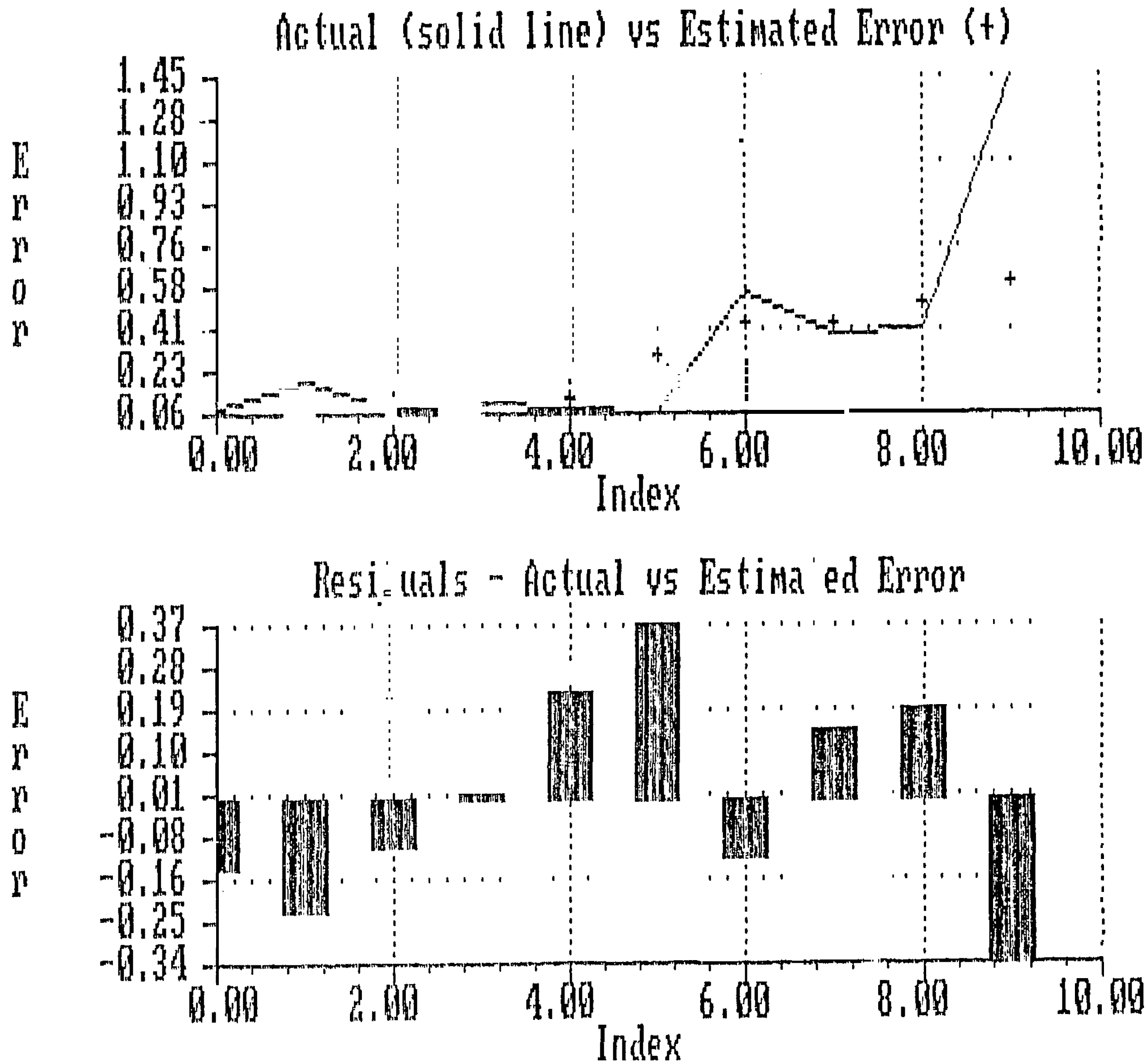

FIG. A.1. PLOT OF ACTUAL VS. ESTIMATED ERRORS FROM REGRESSION ANALYSIS OF TRIANGULATION DATA.

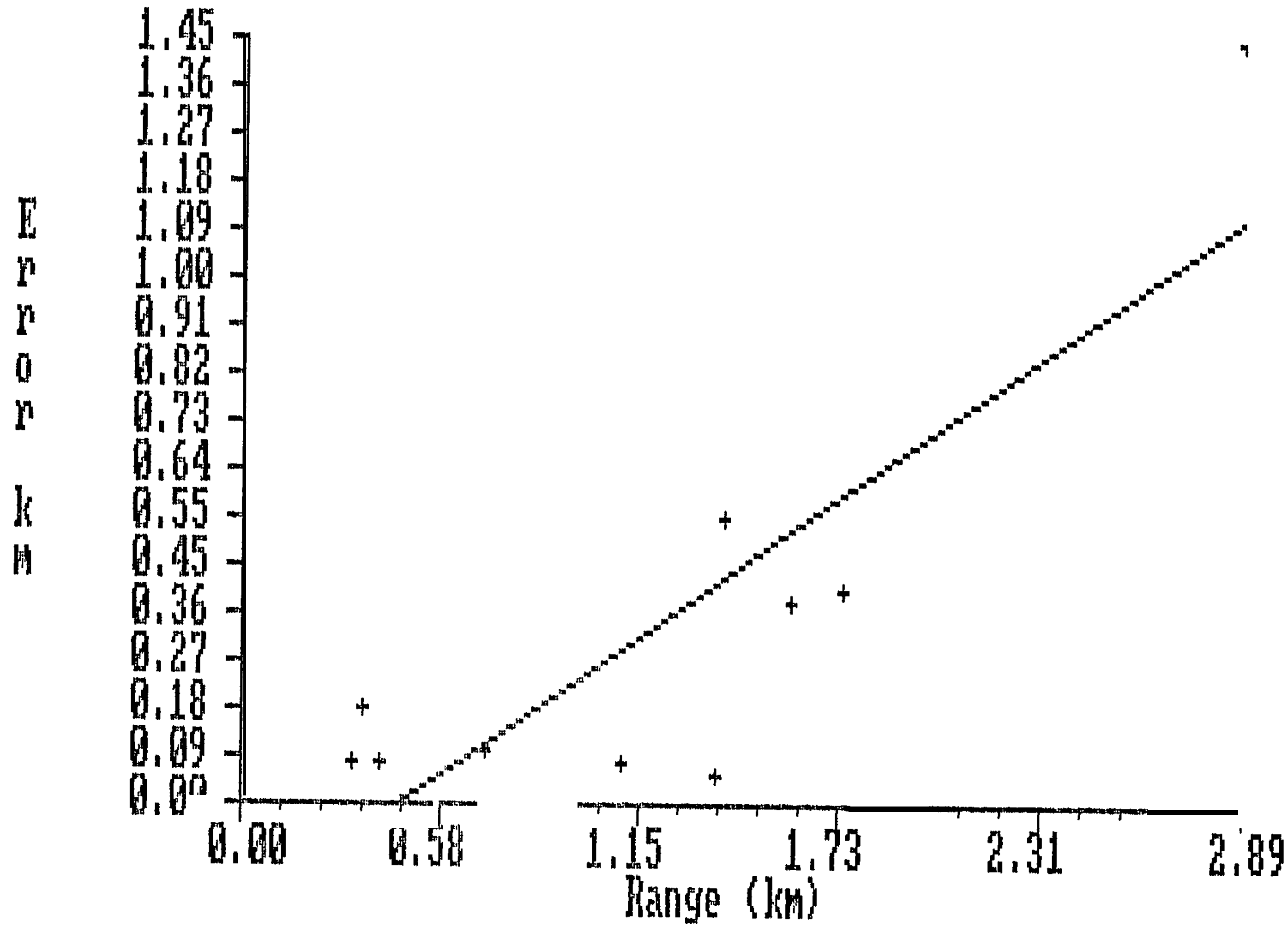

FIG. A.2. SCATTER PLOT OF RANGE VS. ERROR FOR TRIANGULATION TECHNIQUE.

Theodolite vs LORAN

On 24 August 1985, observers at the theodolite station fixed the location of either of the two vessels 13 times within two minutes of a LORAN fix of the vessel. The location of the theodolite station was not determined in the field and it initially was estimated by triangulating azimuths of landmarks on a chart. Comparison of LORAN readings with vessel fixes revealed a range-independent offset of 490 m W and 1059 m N. This was within the range of precision of our determination of the station location, and the location was corrected by this offset. The following table shows the differences of theodolite and LORAN fixes of the boats after offset correction.

Time Transit	LORAN	LORAN Range	Error
1603	*1606*	3.185	0.295
1609	*1610*	6.675	0.672
1637	*1637*	7.378	0.920
1718	*1717*	2.935	0.380
1725	*1725*	3.035	0.312
1734	*1735*	3.339	0.165
1740	*1740*	3.830	0.373
1807	*1805*	5.578	0.581
1847	*1845*	6.294	0.639
1847	*1848*	3.185	0.294
1931	*1930*	3.462	0.232
1944	*1945*	3.146	0.148
2010	*2010*	2.854	0.258

Table 2 shows the same data sorted by range along with a linear regression of error as a function of range. The correlation of error and range is 0.94 indicating a robust ($p < 0.01$ that $r = 0$ from this sample) increase in error with increasing range. Figure 3 plots the actual vs estimated error and residuals from Table 1. Figure 4 shows a scatter plot of the data along with the regression line. The errors of the transit technique were on the order of 200 to 300 m out to ranges of 4 km. These errors did not appear to be strongly range-dependent and may be, in part, due to limits in the precision of the LORAN used to calibrate the transit. Errors tended to increase with greater range up to an error of almost 1 km at a range of 7.4 km.

TABLE 2. LINEAR REGRESSION OF ERROR VS RANGE FOR THEODOLITE TECHNIQUE.

Index	Actual Range	Actual Error	Estimated Error	Residuals
1	2.85	0.26	0.22	–0.03
2	2.93	0.38	0.24	-0.14
3	3.03	0.31	0.25	-0.06
4	3.15	0.15	0.26	0.12
5	3.18	0.29	0.27	-0.03
6	3.18	0.29	0.27	-0.03
7	3.34	0.16	0.29	0.12
8	3.46	0.23	0.30	0.07
9	3.83	0.37	0.35	-0.02
10	5.58	0.58	0.58	0.00
11	6.29	0.64	0.68	0.04
12	6.67	0.67	0.73	0.06
13	7.38	0.92	0.82	-0.10

Estimated regression equation is:

error (y) =	variable	x	coefficient	error
x(0)	constant		-0.15	0.07,
x(1)	range		0.13	0.01

Correlation coefficient (r) = 0.938 coefficient of determination r^2 = 0.880 standard error of estimate (see) = 0.08.

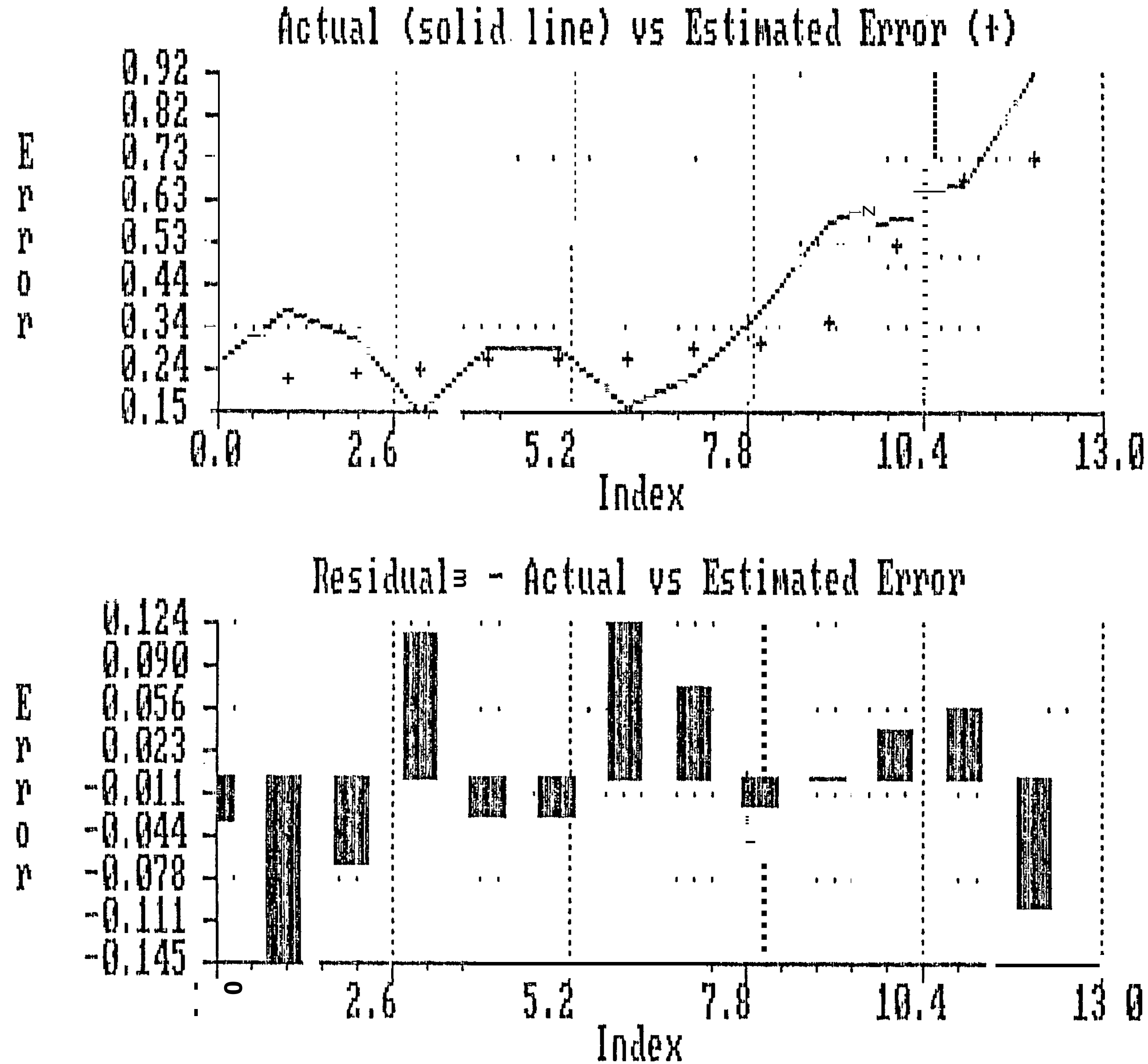

FIG. A.3. PLOT OF ACTUAL VS. ESTIMATED ERRORS FROM REGRESSION ANALYSIS OF THEODOLITE DATA.

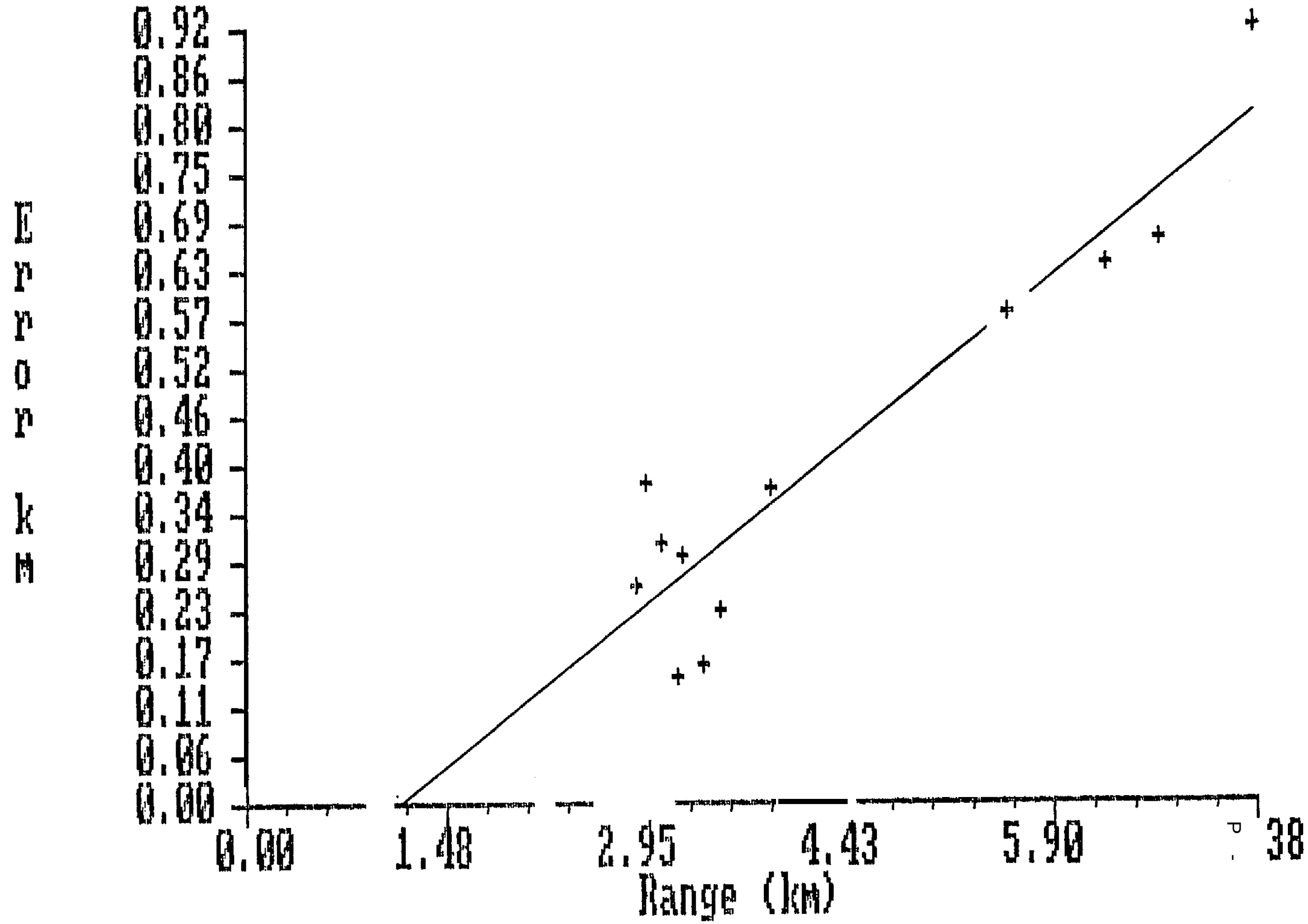

FIG. A.4. SCATTERPLOT OF ERROR VS. RANGE FOR THEODOLITE TECHNIQUE.

Radar vs LORAN

On 25 August, a careful radar range between the Nancy H and the BIG VALLEY was made within five minutes of LORAN readings from both vessels. This allows us to double check both methods for consistency. The origin of the coordinate system is centered on the theodolite station of 24 August.

1600 Radar range of 0.75 nm from NANCY H to BIG VALLEY

		km N/S	km E/W
1603	LORAN reading of BIG VALLEY	1.445	3.308
1605	LORAN reading of NANCY H	-2.168	-2.435
		-0.723	0.873

LORAN Distance 1.1335

Radar Distance = 0.75 nm x 1.852 km/rim = 1.389

These two readings are off by 256 m, which is probably within the limits of precision of the radar readings. This indicates that the two LORANS gave consistent readings at ranges of over 1 km.

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