POTENTIAL IMPACTS
OF MAN-MADE NOISE ON RINGED SEALS:
VOCALIZATIONS AND REACTIONS

by

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

Figure 27. Spectrum of a single quacking bark analyzed at peak amplitude (upper), analyzing filter bandwidth, 18.75 Hz. Power spectral densities (O-1 kHz) of the arrival of a quacking bark at two hydrophores in the triangular array, analyzing filter bandwidth, 3.7 Hz.

Figure 28. Source spectrum level of a quacking bark recorded and located with the triangular array. Analyzing filter bandwidth, 7.5 Hz.

Figure 29. Histogram showing the long-term increase in the rate of ringed seal vocalizations from the array (sounds, excluding scratches) over the recording period beginning with Julian day 86 (26 March 1984). The data were normalized for unequal recording times each day (see text).

Figure 30. Histograms showing the long-term increase in the rate of rub (upper) and squeak (lower) sounds from ringed seals over the recording period beginning with Julian day 86 (26 March 1984). Periods marked by underlying bars were not recorded.

Figure 31. Histograms showing the long-term occurrence of ringed seal sound production rates of quacking barks (upper) and scratches (lower) over the recording period beginning with Julian day 86 (26 March 1984). Per-iods marked by underlying bars were not recorded.

Figure 32. Histogram of pooled data involving all sound categories at the triangle, including scratches, recorded over the entire period beginning with Julian day 86 (26 March 1984).

Figure 33. Histograms showing the hourly occurrence of all ringed seal sounds from the triangular array, pooled over the number of days indicated and normalized for unequal numbers of recordings (upper) and the same data smoothed by a moving average of 3 (lower).

Figure 34. Histograms showing the hourly occurrence of all ringed seal scratches from the triangular array, pooled over the number of days indicated and normalized for unequal numbers of recordings (upper) and the same data smoothed by a moving average of 3 (lower).

Figure 35. Histograms showing the hourly occurrence of all ringed seal vocalizations from the triangular array, pooled over the number of days indicated and normalized for unequal numbers of recordings (upper) and the same data smoothed by a moving average of 3 (lower).

Figure 36. Fast Fourier Transform (FFT) of the frequency of occurrence of ringed seal vocalizations (sounds, excluding scratches) showing two possible periodicities of about 7 and 2 hours (from pooled data of 3,359 vocalizations at the triangle).

I. EXECUTIVE SUMMARY

This is a report of studies related to possible impacts of man-made noise on the ringed seal (Phoca hispida), with emphasis on seal vocalizations and noises associated with near-shore geophysical exploration. The research was supported by the Minerals Management Service through interagency agreement with the National Oceanic and Atmospheric Administration, Office of Oceanography and Marine Services, Juneau, Alaska, as part of the Outer Continental Shelf Environmental Assessment Program under Contract 83-ABC-00065. It was conducted in Kotzebue Sound, Alaska, during March and April 1984.

The study area was typical of that used or planned for offshore seismic exploration. It was covered with first-year landfast ice, deformed with ridges, hummocks, and refrozen fractures, in a shallow-water area found to be inhabited with ringed seals. Surprisingly, there was evidence that at least two bearded seals (Erignathus barbatus) also resided there. A bearded seal pup was found in a lair, and very distant bearded seal trills were recorded on two occasions. The major task was to characterize the types of ringed seal sounds in this location by means of long-term field recordings, and to determine their frequency of occurrence as a possible clue to any changes in sound production resulting from the artificial introduction of "industrial" underwater noise.

The field activities centered on a precisely located 3-hydrophore array, which resulted in not only a very large number of recorded hours, but some Vocalizations of sounds and sound source levels (intensity). Data were also obtained from outlying hydrophores, including a recording 192 km away. Not counting duplications on recordings of up to six hydrophones at once, we recorded and monitored 245 hrs of data, comprising nearly 25,000 biological sounds.

Ringed seal sounds were of comparatively low source level. Located seal and ice sounds originated mostly in areas of active ice, i.e., refrozen fractures or ridges, at distances up to 0.6 km. The frequency of occurrence of vocalizations dramatically increased over the study, presumably as breeding and parental activity increased. Ice scratching occurred mostly at two times of the day, and the occurrence of vocalizations also showed dependence on time of day. More vocalizations occurred during daylight hours. There were more vocalizations during periods of low windspeed, perhaps the effect of decreased aural masking by wind generated noise for the human listener. The number of scratches was not correlated with windspeed or temperature. The number of vocalizations increased during lower temperatures. Temperature and windspeed were not statistically correlated.

The rubs, squeaks, and quacking barks recorded by us appear to be very similar to ringed seal” sounds described by Stirling and coworkers.

The results of underwater noise playback had to be considered in light of an overlying long-term natural increase in sound production. Consequently, comparable periods were kept reasonably short. Two comparisons before and after playback (6 and 23 hrs) of recorded “industrial” noise showed no statistical difference in sound production. Two other periods of comparison before and after (10 and 72 hrs) showed that sound production increased after playbacks, possibly related to an expected overall heightening of breeding and parental activity as the season progressed. There is a possibility that noise unassociated with our activity intensified ringed seal sound production based on the initialization of certain vocalizations by distant sources of low frequency pulses supposedly of man-made origin.

Recommendations basically involve the need for more research with narrower focusing, i.e., sound propagation, attenuation and modeling studies, and more controlled experimentation. Based upon this study, there was no evidence that petro-exploratory industrial noise reduced the occurrence of sound production of ringed seals. In some instances, it could have increased sound production. For example, a different kind of noise (low frequency pulsing believed to be of man-made origin) incited ringed seals to produce rub, squeak and quacking bark sounds. Since the source levels of ringed seal sounds were relatively low, there could have been a potential indirect effect from acoustical masking.

Compared to other pinnipeds, ringed seals did not produce many vocalizations under the circumstances of this study. Consequently, future research that is intended to utilize vocal sound production as indices to population enumeration, distribution or behavior may, of necessity, be limited. On the other hand, ice scratching sounds were very common, and they could possibly be used for these purposes.

II. INTRODUCTION AND BACKGROUND

A. The Problem

Ringed seals, Phoca hispida, are extremely abundant in Arctic Polar regiens. Of all the marine mammals of this region, this species is the most numerous and widespread, being circumpolar in distribution (King, 1964). In recent years there has been a large-scale development of hydrocarbon energy sources in the near- and on-shore regions of Arctic Alaska. Associated with industrial activities involving exploration, development, and production, are increased levels of man-made noise and vibration (Malme and Miawski, 1979; Holliday et al., 1980, 1983, 1984; Cummings et al., 1981(6 references); Cummings & Holliday, 1983(3 references); Green, 1981; Ljundblad, 1983; Turl, 1982; LGL, 1981). Please refer to J. Acoust. Sot. Am., Suppl 1, Vols. 70, 74 for abstracts of other reports on man-made underwater noise based on work outside of the Alaskan Arctic region.

Airborne noise and vibration from petro-industrial activities may be of potential impact on Arctic wildlife; in particular, the ringed seal. OCSEAP has expressed concern that noisy activities could adversely affect the bioacoustical behavior of ringed seals, especially during the sensitive period of their life cycle as pups or mothers in early spring reproductive activities. A major source of noise in certain of Alaska's coastal ice regions is associated with on-ice geophysical exploration wherein low frequency sound is used to detect deposits of hydrocarbons in the underlying strata. Added to the noise from seismic profiling itself, are numerous other noise sources such as bulldozers, tank trucks, ice drilling rigs, and transport vehicles.

In addition to possible lair abandonment or displacement (ASA, 1980), the effects of man-made noise may be manifested as changes in the vocal behavior that presumably is important to the animals' welfare. For example, sound production in birds and fish has been shown to cease in the presence of loud man-made noise. There is also an indication that the frequency of occurrence of gray whale sounds is affected by man-made noise (Malme et al., 1983, 1984). The sound production of ringed seals could possibly be affected, but before any changes could be detected in their vocal behavior, a ground truth data base must be established. Thus, the main purpose of this research was to study the ringed seal's vocal activities, first, in a relatively undisturbed situation, and second, when the animals were exposed to possibly disturbing man-made noise. Hopefully, the work would yield information on apparent behavioral roles of vocalizations.

The Alaska office of OCSEAP and the Alaska Eskimo Whaling Commission (AEWC) contracted with Oceanographic Consultants and Tracer in 1981 for the purpose of developing an underwater sound localization system for ringed seal studies and for measurement of Vibroseis®[1] seismic profiling noise. The results of that work are described in a report by Cummings, et al. (1981). In 1983, OCSEAP supported our studies on acoustic and vibration measurements related to possible disturbance of ringed seals off Prudhoe Bay (Holliday et al., 1984). The present study was funded via a prime contract with Tracer, Inc., and a subcontract to Oceanographic Consultants.

B. The Ringed Seal and Its Bioacoustics

Although ringed seals are circumpolar in distribution, significantly large numbers occur on or very near landfast ice during the winter months (King, 1964). They are an important species to Inuit cultures because of their abundance and use for food, shelter, clothing, and artifacts (D. Brice-Bennett, Inuit Tapi risat of Canada, pers. communication).

Male and female ringed seals grow to about the same size (90 kg, 1.4 m) and may live to be over 40 years of age. The pups are born during a period from about mid-March to mid-April. Birth takes place in a natural ice cave or in a lair excavated by the mother where an access

[1]The use of trade names or model numbers in this report does not imply endorsement.

hole is kept open. Other holes are kept open only for the purpose of breathing. Ringed seal pups are greatly dependent upon their mothers for nourishment, and they nurse for about eight weeks (Scheffer, 1958; McLaren, 1958; Burns and Eley, 1976).

Ringed seals feed on crustaceans and small fish. Their enemies include killer whales, polar bears, Arctic foxes, man, and pathogens (King, 1964).

Smith and Stirling (1975) described the wide variety of lairs as being composed of two general types. They also described the process by which they are constructed. One type, the birth lair, probably originates with the other, the haul-out lair. Birth lairs may have tunnels, whereas haul-out lairs generally are a single chamber. Lairs provide thermal insulation and a hiding place from polar bears and foxes. The reported lair sizes varied from 45 - 65 cm high, 196 - 355 cm long, and 135 - 227 cm wide. These authors indicated that populations may be limited by the amount of suitable breeding ice.

The hearing capabilities of seals were given an early review by Mohl (1968). Terhune and Ronald (1975a, 1975b, 1976) reported on the hearing of ringed seals and the following is mostly based upon their work. There is virtually no quantitative information on the sensitivity of seals to vibrational energy (displacement of the medium vs hearing).

We can assume that the audiogram of ringed seals is U-shaped; however, due to technical difficulties in producing uniform low-frequency sound fields at known received levels in small underwater enclosures, hearing sensitivity below about 1 kHz has not been measured. However, ringed seals do produce (and presumably hear) sound below 1 kHz (Cummings et al., 1981). Terhune and Ronald reported a fairly uniform sensitivity ($\pm$ 7 dB) from 1 to 45 kHz, with increases of about 60 dB/octave above that frequency to 90 kHz. Thresholds below 45 kHz are about -30 to -20 dB re 1 µbar (70 to 80 dB re 1 µPa). Critical ratios vary between 30 $\pm$ 5.4 dB (at 4 kHz) to 35 $\pm$ 4.5 dB (at 32 kHz). Critical bandwidths over these frequencies vary from 1 to 3.16 kHz. They concluded that the loss of both sensitivity and pitch discrimination effectively places the upper limit of useful hearing at 90 kHz. On this basis, ringed seals are capable of hearing noise spectra above 1 kHz that is associated with gas and oil exploration on the ice. It would be difficult to predict the masking effect of this noise on their own sounds without more research.

Most animals produce a lexicon of sounds which may occur in well-defined patterns. Examples are the long, involved repetitions of hump-back (Payne) and bowhead whale (Ljungblad et al., 1982; Cummings et al., 1983) sounds, or the rhythmical sounds of wild porpoises. We (Holliday et al., 1980) have shown that bearded seal calls off Barrow, Alaska, occurred in a diurnal pattern. The ability to recognize patterns implies categorization and recognition of the components, which can be described in physical terms such as frequency, temporal, and amplitude characteristics.

Very little information has been published on ringed seal sounds. Stirling (1973) described barks, yelps, high-pitched growls, and chirps of ringed seals that extended up to a maximum of about 6 kHz. Cummings et al. (1981) presented some spectra of ringed seal sounds: a gargle-type with peak energy at 1 kHz, a rub that extended from about 0.7 - 2.6 kHz, a bubbling sound thought to have been produced from an underwater exhalation, .05 - 11 kHz, and a scratching sound from a ringed seal working on its breathing or access hole, or in the lair above, 0.5 - 3 kHz. Stirling, et al. (1983), observed that ringed seal vocalizations were more frequent in late April than earlier in the season or in late June, and that the sounds have the potential of being useful for information on distribution and abundance. Their sonagrams indicated considerable low frequency energy in the ringed seal's sounds, below 500 Hz.

Although the behavioral significance of these sounds is unknown, we may assume that some sounds involve inter-animal communications. Likely functions of the signals doubtlessly are associated with courtship, parent-offspring, food finding, and territorial behavior. Based upon what is known of the importance of sound production in other species, it could be assumed, a priori, that ringed seal sound production is a requirement for survival in the natural environment.

To our knowledge, man-made noise had not previously been experimentally played back to ringed seals. Watkins and Schevill (1968) used playbacks to Weddell seals that consisted of the seals' sounds. They reported varied responses and described an apparent learning to ignore. Cummings played back killer whale sounds and random noise to California sea lions off Catalina Island and in the Gulf of California in an unsuccessful attempt to displace them from fishing operations (unpublished). There either was no apparent reaction or the seals appeared to be attracted to the underwater transducer. P. Shaughnessy had much the same results in experiments for the same purpose with fur seals and sea lions in South Africa (pers. communication). On the other hand, Dr. Bruce Mate and co-workers, Oregon State University, have experienced success with underwater playback of noise to harbor seals in the attempt to reduce their predation upon salmon in a restricted area (personal communication). Schusterman and Moore (1981) stressed the importance of individual and group behavioral variability of response to noise.

C. Acoustic Environment

Most models involving the reception of acoustic energy will include three basic parameters, the received level (RL), total propagation losses (TL), and the source level (SL). Thus RL will depend upon the degradation of the propagated sound (TL) and the power of that sound at its source (SL). The most simplified expression of this relationship is:

$$RL = SL - TL \qquad \text{(eq. 1)}$$

where all three variables are given in decibels (dB). As used in this report,

$$dB = 20 \log_{10}(P_1/P_0) \qquad \text{(eq. 2)}$$

where P_1 signifies measured acoustic pressure and PO signifies a reference of the pressure measurement, herein defined as 1 μPa (one micropascal). While the dB may seem to be a very indirect method of indicating acoustic levels, it is used by convention because the normal range in pressure units may be in the millions. Since the dB is actually a multiple of a logarithm, its unit is much more manageable in acoustic measurements than the unwieldy large numbers encountered in the direct measurement of pressure, the physical stimulus perceived by the ear.

Also by convention, the term “signal” as applied here denotes the sound of interest, e.g., the warning bark of a seal, whereas the background or accompanying sound may be termed “noise”. In most applications, it is the reseacher’s arbitrary choice to define sound(s) as signal or noise. In practice, this choice usually does not depend upon aural pleasure or discrimination.

At first glance of eq. 1, it may appear that the loudness of a received level (RL) to a listener will depend upon its magnitude, source level, and total propagation loss. While all three variables are involved in auditory perception, given a satisfactory receiver, the ultimate limitation involves signal to noise ratio (S/N) usually given in dB. In other words, regardless of the signal’s received level, audibility (recognition) will depend upon the ratio of its level to an equivalent or nearly equivalent frequency band of noise. Remembering that dB basically is a logarithmic quantity, if the signal and noise are of equal level, S/N = O. The reader is referred to Urick (1967, 1975, 1983) for discussions of these principles, and there are numerous other references.

The measurement and physical characteristics of petro-industrial and natural background (ambient) noise are of paramount importance in any basic understanding of how this noise may affect marine mammals. In a given model it is conceivable that the RL of man-made noise may be less than that of the natural noise such that it may not be the most important limiting factor in masking of an important biological signal. Or the reverse may be true, in which case the level of man-made noise may be the dominant factor in making an important signal inaudible.

Aside from aspects of the basic sonar equation (eq. 1) that relate to masking and detection, there are possible behavioral responses to man-made noise. In other words, if a signal is audible in the presence of the noise, will it elicit a behavioral response that affects the animal's welfare? For example, in the presence of offensive man-made noise an animal may flee its accustomed location to experience the consequences of a new location. Moreover, if the received noise is sufficiently high and of critical duration and frequency, it could possibly cause physical or psychological impairment, either temporary or permanent. Given the necessary parameters of detection, but lacking those responsible for any direct or indirect harm, in all probability the animal will learn to ignore a given noise source, a process sometimes called acclimation. Acclimation can occur even though a noise may be of some indirect harm.

No one study of acoustics and bioacoustics can sufficiently address all of these items, especially over short-term study periods. Instead, each project must focus on certain priorities. The ultimate objective is a mosaic of facts that will provide management with a sufficient scientific basis for effective decision making.

III. OBJECTIVES

The present study had three main objectives as follows:

(1) Determine vocalization characteristics and patterns for ringed seals in the southern Chukchi Sea region during the study period.

(2) Determine any bioacoustical responses of ringed seals to taped playbacks of man-made noise associated with seismic activities.

(3) Describe any apparent roles of vocalization in reproduction and pupping behavior.

All three goals involve important information for the decisions required before and during offshore oil and gas development. First, to determine if man-made noise affects the sound production of ringed seals, vocalization characteristics and any patterns of vocalization for this species must be known under undisturbed ("normal") conditions. Since winter seismic profiling occurs during the active reproductive season, and it can be assumed that vocalization is part of the reproductive behavior, the resulting man-made noise may possibly affect vocalization and the behavioral role of reproduction-related sounds. Secondly, it would be very useful to determine the apparent reproductive roles of vocalization. Finally, the purposeful introduction of previously recorded man-made noise may indicate bioacoustic responses by the seals that may be indicative of what to expect in the presence of noisy on-ice operations.

IV. METHODS

A. Study Period, Personnel, Location

The technical preparation for this study began on 16 January 1984. This basically consisted of design, purchase, fabrication and testing of the sensing and sound projecting instrumentation as specified in our proposal. A special effort was made to calibrate the receiving transducers in San Diego. The projectors had already been calibrated.

The field personnel were divided into two teams, each consisting of three people. D. V. Holliday headed the first team which was responsible for setting up the ice" camp, the initial installation of hydrophores, and the initial recordings near the camp. The second team, headed by W. C. Cummings, reinstalled some of the equipment, completed the recordings, conducted the noise playback experiment, and disassembled the camp. The first team departed for Kotzebue on 18 March, returning on 30-31 March. The second team departed on 29 March and returned on 15 April 1984. Field work was undertaken by:

	D. V. Holliday, Tracer, Inc., San Diego, CA
Team I	C. F. Greenlaw, Tracer, Inc., Philomath, OR
	B. Narimatzu, Tracer, Inc., Silverdale, WA
	W. C. Cummings, Oceanographic Consultants, San Diego, CA
Team II	D. E. Bennett, Tracer, Inc., Silverdale, WA
	C. T. Lee, Tracer, Inc., San Diego, CA

Our camp was located on landfast ice at the entrance to Kotzebue Sound (66° 41.1′ N, 162°55.9′ W, Fig. 1), a site about 28 km southwest of the village of Kotzebue. The nominal thickness of ice in this region was 2 m. Snow cover was light. The area was moderately ridged, landfast first year ice with hummocks and fractures. The bottom in this location is flat, the depth being about 14.5 m to the top of the flat ice. The camp was occupied from 22 March-13 April 1984. The period of 19-21 March

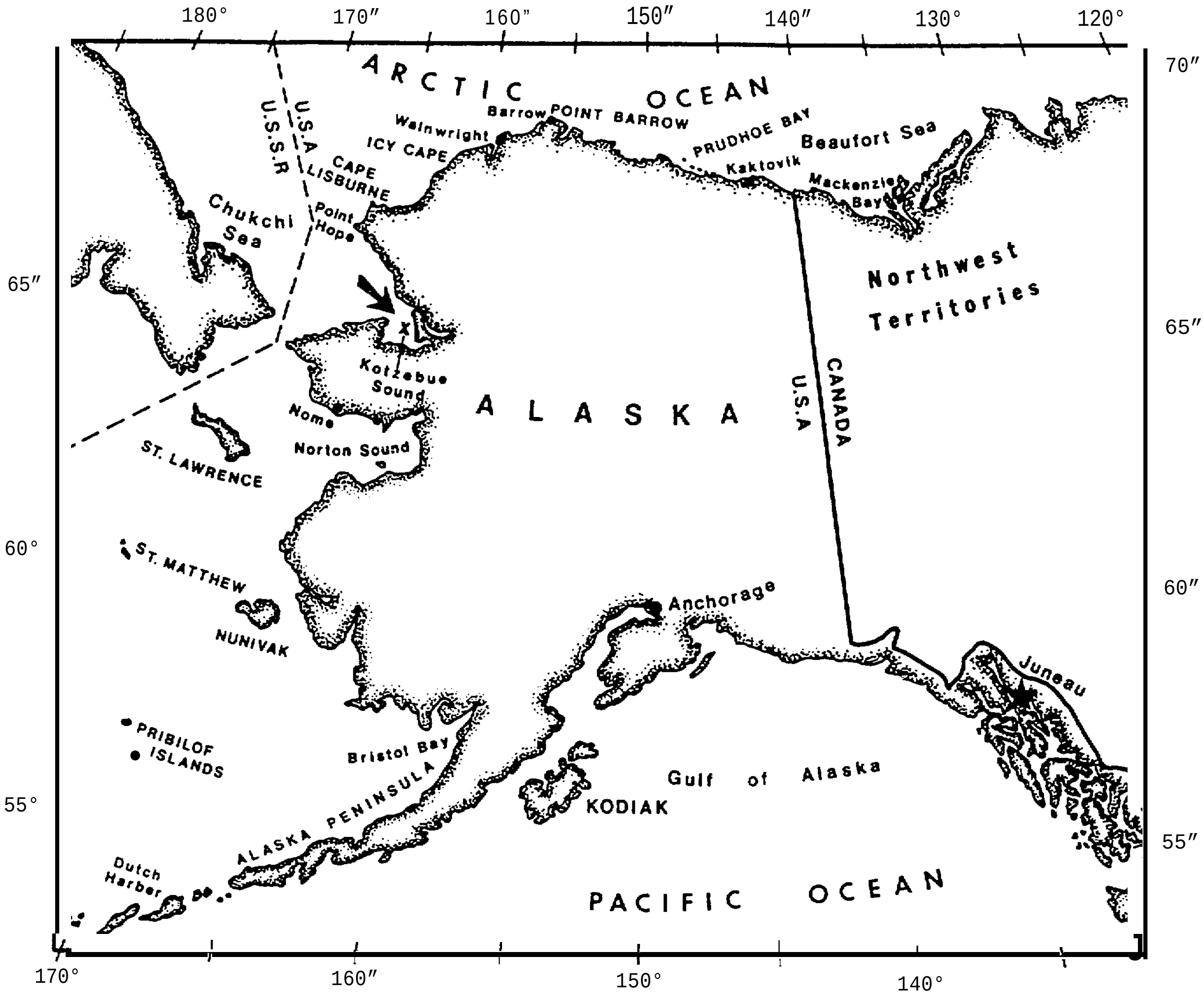


Figure 1. Study site (arrow) at the offshore edge of Kotzebue Sound, Alaska.

was spent assembling snowmachines, readying the field instrumentation, and locating ringed seals. The latter task, of considerable importance to the project, was undertaken by J. Burns (Alaska Department of Fish and Game), B. Kelly (University of Alaska) and associates working with trained dogs. Within a 5.6 km radius of camp, 21 locations were marked signifying breathing holes, and active or abandoned lairs.

Transportation and shipping to and from the base of our operations at Kotzebue were furnished by a NOAA helicopter and crew. Snowmachines were used for local transportation of personnel and gear near the study site, although we also walked long distances to minimize disturbance to the seals.

B. Sensors, Telemetry, Sound Speed

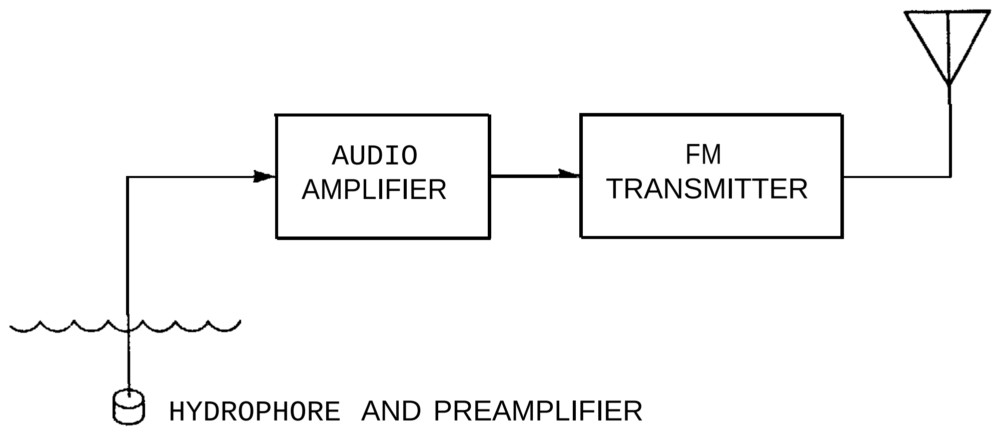
Underwater sound was received with hydrophores (Wilcoxon H-505, InterOcean R-130, and sonobuoys AN/SQQ-57A) placed through holes drilled in the ice. PVC pipe casings and antifreeze were used to prevent loss of the Wilcoxon hydrophores due to freezing. Besides being an antifreeze mechanism, the pipe casings also isolated the hydrophore cable from vibrations due to stress relief (cracking) in the ice. These vibrations can interfere with measurements if the ice is allowed to freeze around the cable. The InterOcean hydrophores were used while being attended, thus they were recoverable. However, the sonobuoy sensing units and cables had to be sacrificed.

When certain of the measurements were made at frequencies greater than 15 kHz, a portable recorder (Nagra 4-SJ) was connected directly to the hydrophore and a portable, wideband amplifier in the field. One recording channel was “hard-wired” to a hydrophore via coaxial cable. Appropriate amplifiers and line drivers were provided to prevent signal loss, and the entire system was calibrated as a unit. For other work, telemetry was provided by transmitters from modified AN/SQQ-57A sonobuoys . Considerable modification of these sonobuoys was necessary in order to dismantle the normal air eject mode, provide for long-term operation with large (105 amp/hr) 12V storage batteries, and provide for additional matched, variable gain amplification (Fig. 2). Just prior to the field work, all three types of hydrophores were calibrated at the U.S. Navy calibration facility in San Diego (TRANSDEC). The design of the instrument was such that these calibrations would not be expected to change due to water temperature changes between this facility and Kotzebue. All of the instrumentation exposed to outside temperatures was tested in a laboratory freezer during the period of preparation.

Three of the hydrophores were installed in a triangular array set up about 1 nm SW of our camp (Fig. 3). These were designated hydrophores A, B, and C, their separation being 118.9, 99, and 108.2 m, respectively. Hydrophore A, installed through a pipe casing, was cable-connected to our camp, a distance of 1.8 km. B and C (sonobuoys) were received at the camp by radio telemetry. Another sonobuoy (D) was installed about 3.7 km SW of the triangular hydrophore array. About 2.8 km NW of the triangular array, a bearded seal pup was found in an active lair consisting of a natural opening between ice blocks. The animal was identified by J. Burns. Here we installed a sonobuoy hydrophore as a microphone, above the water's surface. This location was designated as E, the "bearded seal lair".

A sixth sonobuoy (F) was used as a microphone in an active lair about 1.4 km NW of the camp. A seventh sonobuoy (G) was installed about 5.6 km N of the camp and 25 m from an access hole that was being used by a ringed seal and its pup. There was no den at G, and the seal hole was made through a refrozen fracture. We located this hole and two others in the general vicinity simply by scanning the area with binoculars on a comparatively warm, bright, sunny day. This fracture extended for miles and contained numerous breathing and access holes. The eighth recording location (H) was situated 192 km W of Kotzebue. Here we drilled a 1 m hole through a refrozen polynya and deployed a cable-connected InterOcean hydrophore for two recording sessions lasting two hours. This far off-shore site was an area of active ice. It was not possible to record there for a longer period because of the environmental limitations placed upon both airplane and personnel. Locations of all recording and playback sites are summarized in Fig. 3.

TELEMETRY UNIT



AN/SSQ-57A (MODIFIED)

Modifications:

- Remove rotor assembly
- Disarm antenna eject
- Extend antenna cable
- Remove seawater batteries
- Modify for external power
- Disable automatic transmitter cutoff timer
- Remove dissolving plug/paint/seal case

Hydrophore response: 1 Hz to 10 KHz (flat)

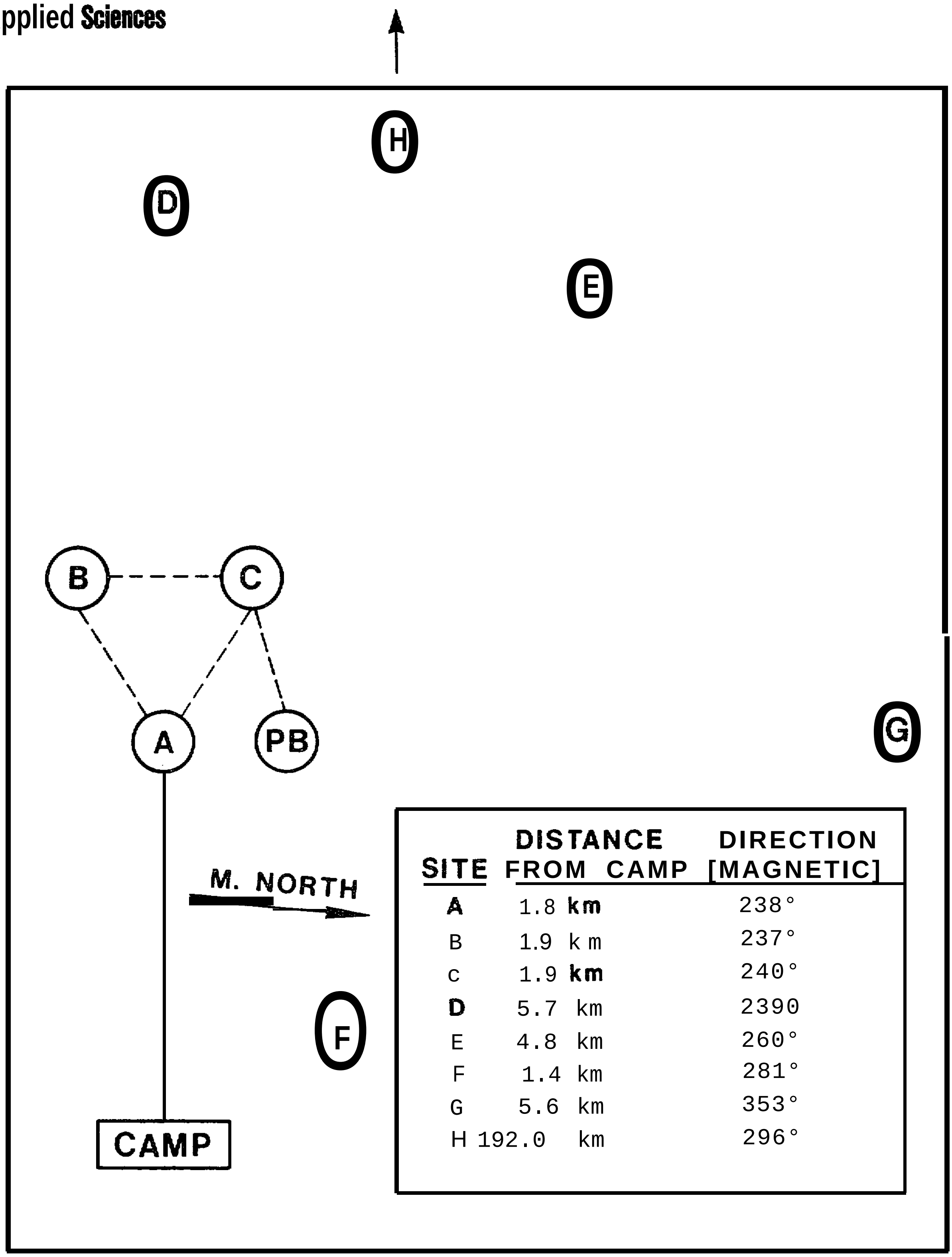
System telemetry response: 5Hz to 20 KHz [useful range]

Number of channels: 31

RF telemetry: 162.25 to 173.5 MHz

RF power: 1 watt

Figure 2. Schematic, modifications, and specifications of the telemetry units.



SITE	DISTANCE FROM CAMP	DIRECTION [MAGNETIC]
A	1.8 km	238°
B	1.9 km	237°
C	1.9 km	240°
D	5.7 km	239°
E	4.8 km	260°
F	1.4 km	281°
G	5.6 km	353°
H	192.0 km	296°

Figure 3. Sketch of recording site layout with distances and directions from camp (drawing not to scale).

Supporting data collected during the period of field work included measurements of windspeed and direction, air temperature, light, and underwater sound speed profiles.

C. Recording

To allow for seal location, site preparation, and dismantling, the actual data recordings and sound playback took place 25 March to 11 April 1984. During this period of time 209 hrs were recorded from the triangular array on magnetic tape, most of which included sounds from all three hydrophores recorded simultaneously. In other words, one hour of recording from the triangular array may have consisted of 1 to 3 channels, usually 3. In addition, there were 36 hrs of recordings from the other sensors (D-H) for a total of 245 hrs (Fig. 4). Recordings for long-term monitoring and localization were made with a 4-channel instrumentation recorder (Nagra T). Some long-term monitoring from the remote sensors was also done with uncalibrated recorders (GE, Mod. 3-5105F) for the purpose of determining the frequency of occurrence of sound production. Short-term calibrated recordings were made with a 3-channel instrumentation recorder (Nagra 4-SJ).

D. Playback

A series of playback sessions was undertaken in the area of the triangular array. The underwater sound projector (Navy Type J-9) was lowered to half depth through a large hole chiseled through 2 m of ice at a location 26.2 m from A and 99.5 m from C (Fig. 5). Peak source levels were 135 to 140 dB re 1 μPa, 1 m. Dimensions of the ice opening were 0.75 x 1 m.

Playback data were rerecorded from field recordings taken in prior years, in addition to alternating random noise and a 1 kHz tone. We used a 25-rein continuous series of Vibroseis sweeps alternated with 14 min of noise associated with Vibroseis operations (operating bulldozer, drilling,

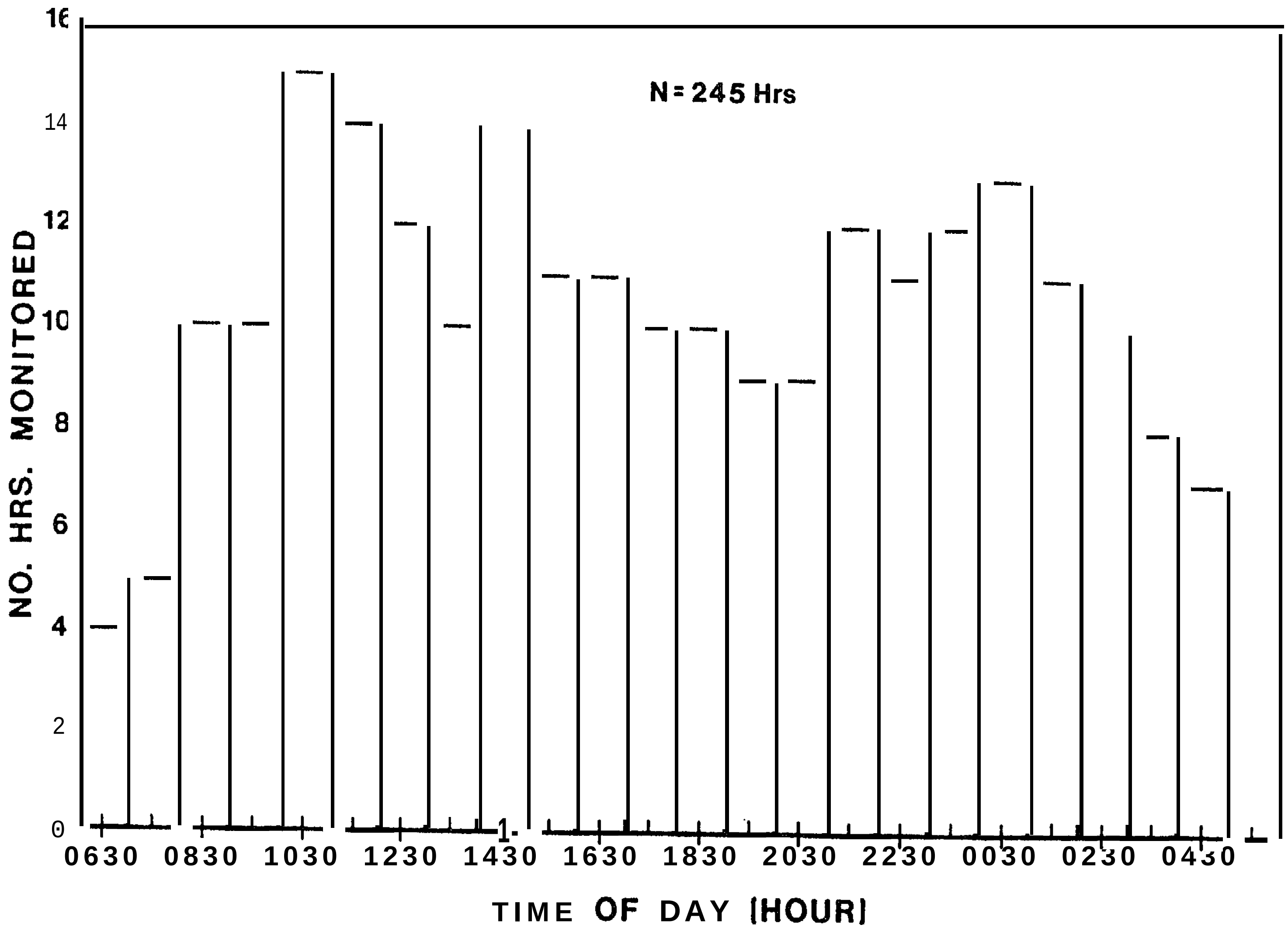


Figure 4. Histogram showing pooled monitoring (recording) effort.

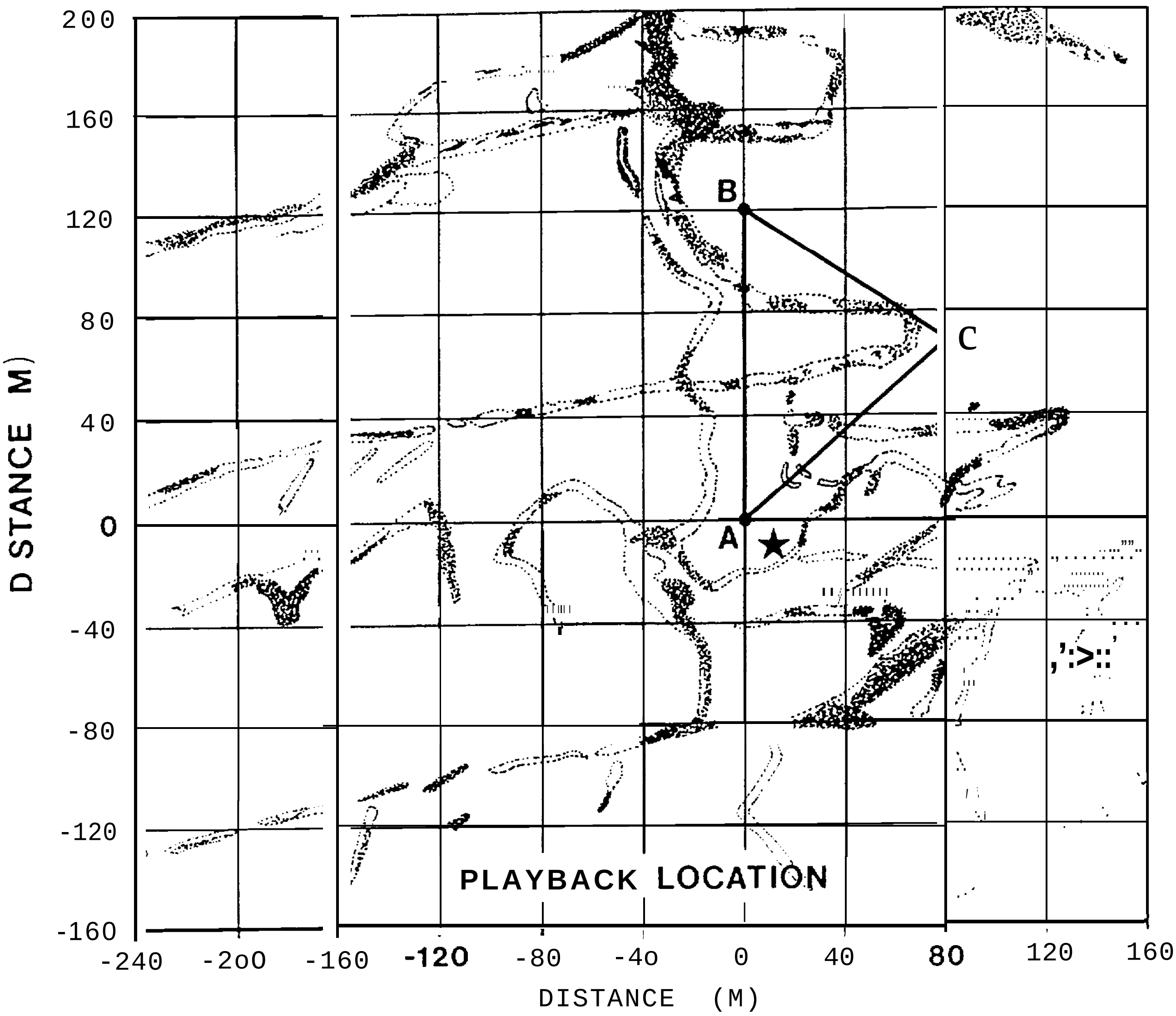


Figure 5. Orientation of the playback location (star) in relation to the triangular array of hydrophores. Surface topography (ridges, refrozen fractures, etc.) as reconstructed from surface measurements and aerial photographs is stippled. Heaviest stippling indicates surface relief of about 2 to 3 m.

movement of heavy track vehicles and personnel, etc.), Figs. 6 and 7. We also used 40 min of random noise alternated with 45 min of 1 kHz tones. Ten minute silent control periods were allowed between adjacent playback sessions. The total duration of playbacks was 14 hrs, 35 rein, scheduled as shown in Table 1, with inclusive short, silent control periods.

Playbacks were undertaken on 5, 6 and 8 April, with portions of the recordings at other times being used as controls. Continuous recording was underway during both playback and the interspersed silent control periods. The experimental design was to allow time for recordings of ringed seal sounds before and after playbacks.

E. Analysis

Five basic types of analysis were utilized in this study: 1) waveform and spectrum analyses, 2) determination of the rates of sound production (frequency of occurrence), 3) correlation, 4) sound localization, and 5) source level determination.

Waveform Analysis

Individual vocalizations or other sounds can be characterized by duration (time), level (power), and frequency (analogous to pitch). The last two parameters often change within an individual vocalization, and the first may be variable between sounds.

It is useful to convey the characteristics of a sound by plotting sound pressure level or some proportional quantity, such as a voltage from a pressure sensor, versus time, a technique that primarily utilizes the time domain. This type of display (Fig. 8) conveys at a glance the duration and complexity of a waveform in terms of level and frequency over the sound's duration. A close examination will reveal average and peak pressure levels, and variations (if any) of level and frequency.

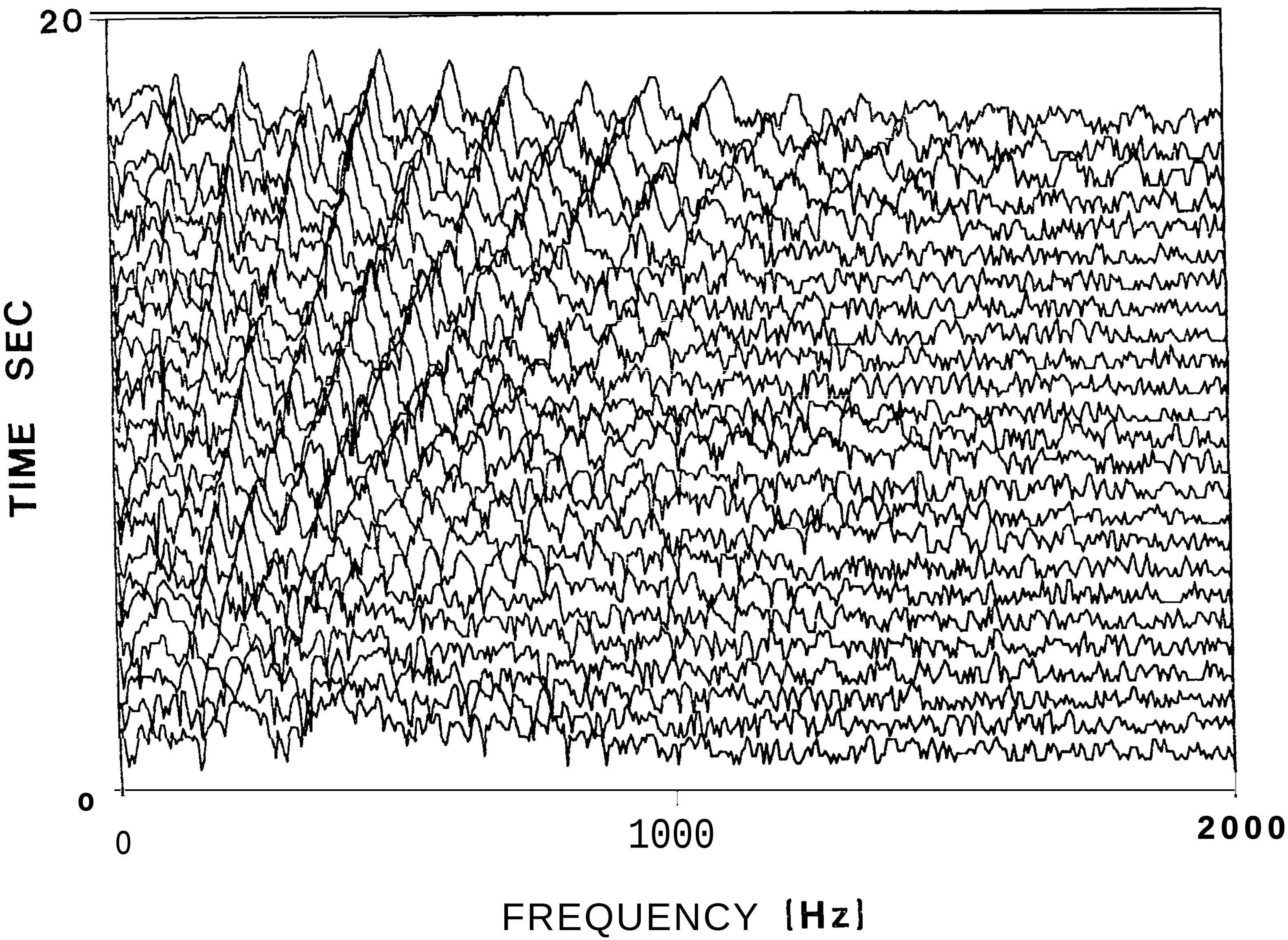
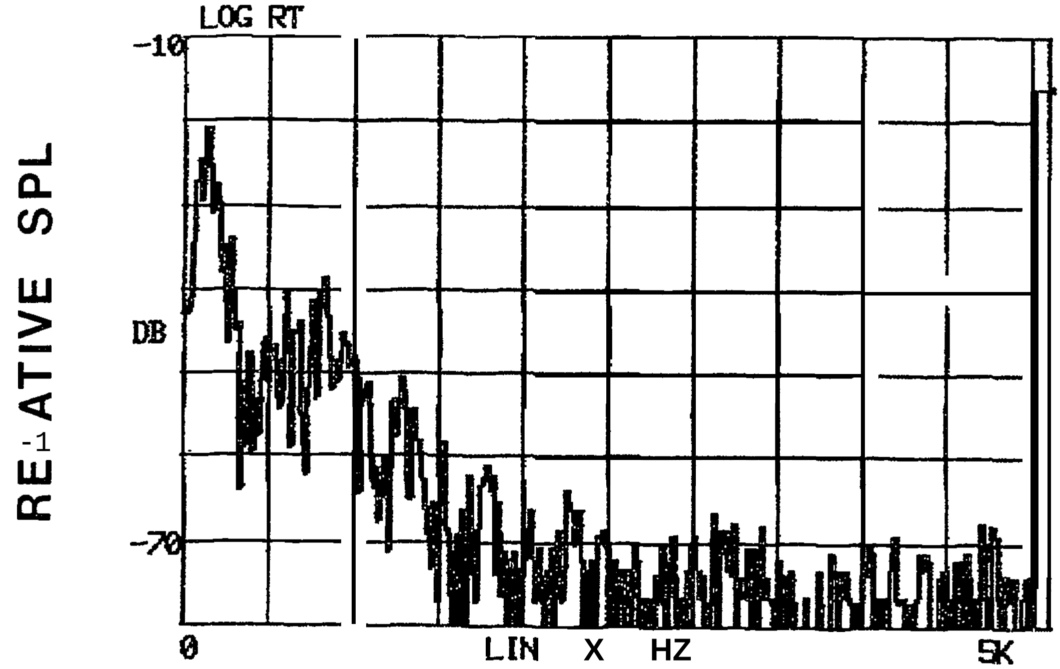
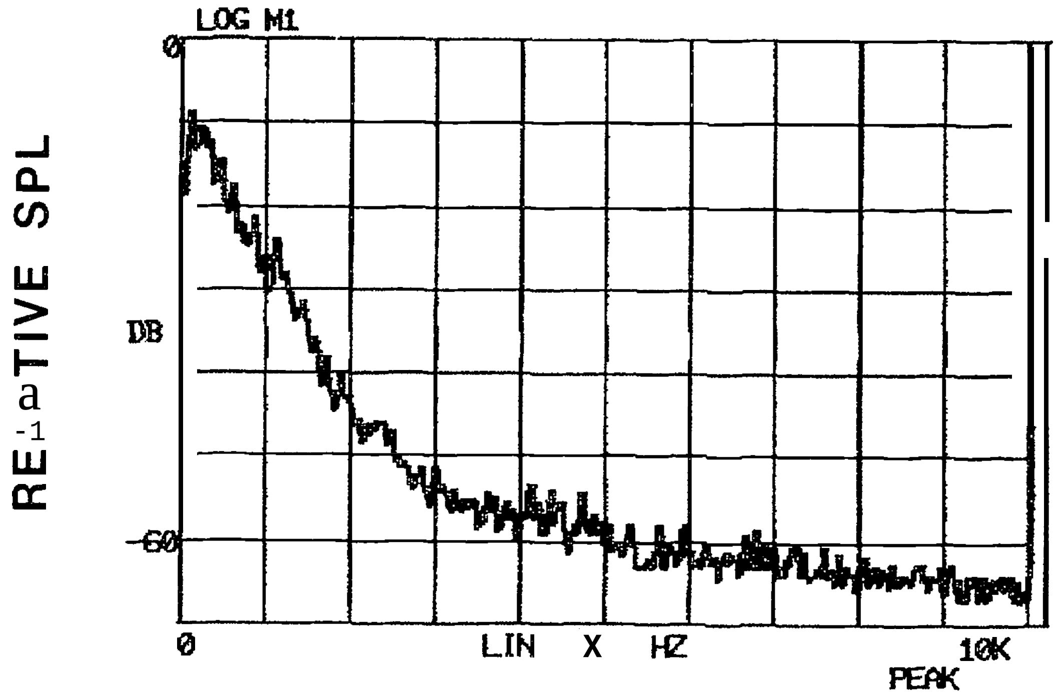


Figure 6. Waterfall display (time history) of Vibroseis and associated industrial noise playback, recorded on the triangular array, showing the fundamental and up to the llth harmonic, analyzing filter bandwidth, 7.5 Hz.



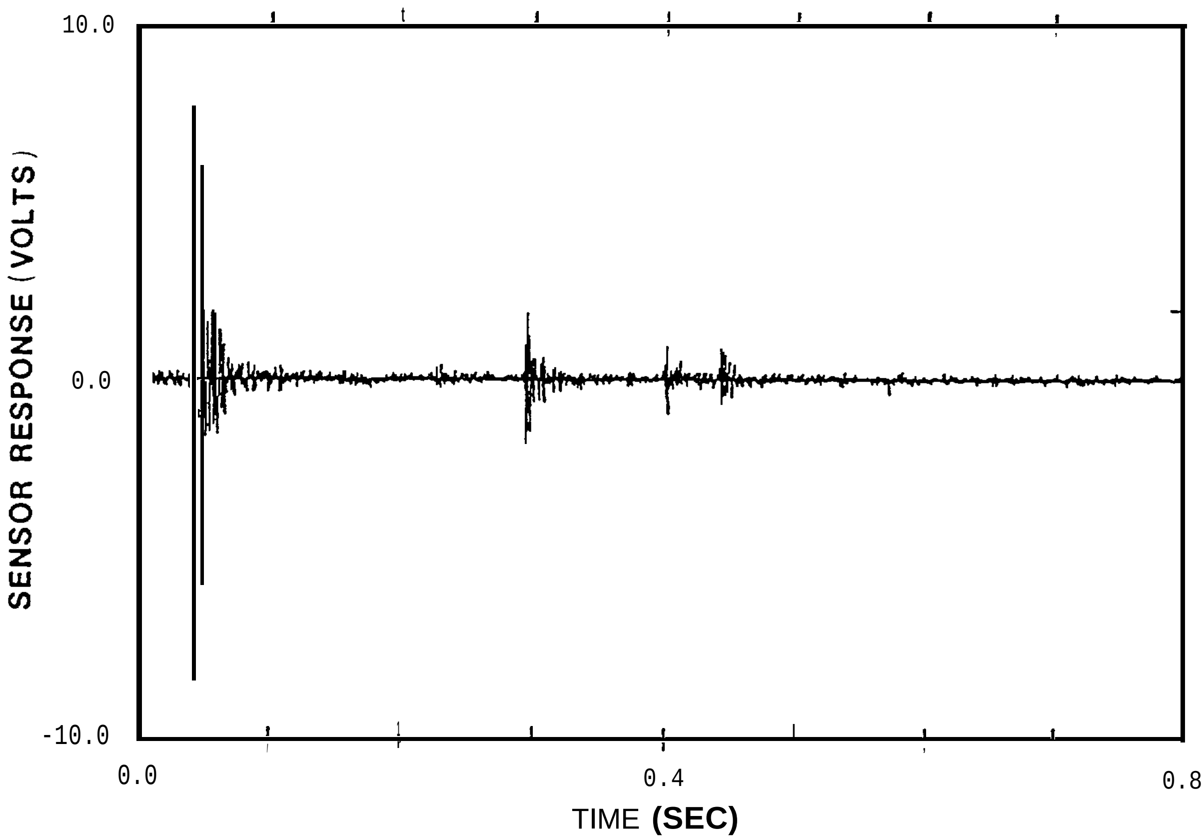


SPL = Sound Pressure Level

Figure 7. Instantaneous spectra (upper) **and 15 sec duration of peak hold spectra (lower) of seismic exploration convoy** noise playback consisting of D-6 cat scraping ice, drill, and trucks. Analyzing filter bandwidth 18.8 Hz and 37.5-Hz, respectively.

Table 1. Playback schedule of previously recorded underwater man-made noise, Kotzebue Sound, 1984.

	5 APRIL	6 APRIL	7 APRIL	8 APRIL
Bulldozer and Vibroseis	1544-2202 hrs	none	none	1652-2027 hrs
Random and 1 kHz	none	1351-1833 hrs	none	none



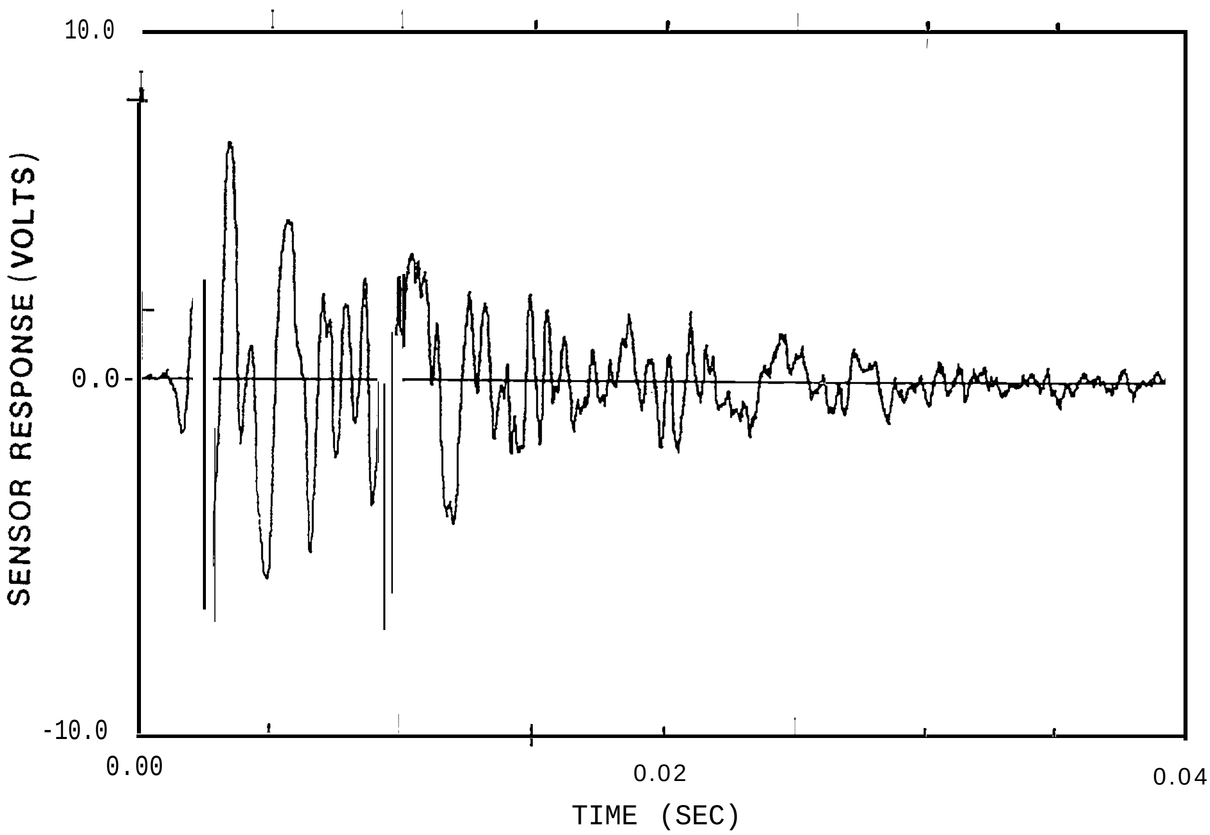


Figure 8. Voltage plotted as a function of time for a transient sound due to ice cracking (upper). Another transient (lower) is displayed with a time scale that is 200 times faster than the waveform in the upper figure.

Some sounds consist of multiple parts separated in time. Such an example appears in Fig. 8 (upper), where the voltage from a hydrophore is plotted versus time. The sound was ice cracking, a Common Arctic sound of stress relief produced by differential expansion and contraction of ice with ambient temperature changes. Four distinct arrivals of this sound and several less intense events are displayed. Peak and average pressure levels are calculated by means of calibration between voltage and sound pressure. Sound pressure level decreases after the initial transient for each of the four large signals. These sounds are described as pulses with sharp leading edges and exponentially decaying trailing edges or "tails".

Expanding the time base reveals additional detail in the pressure-time history of a sound (Fig. 8, lower). The signal envelope builds quickly to a peak and then decays relatively slowly over a total time of about 30 ms (milliseconds). The times at which the voltage (pressure) is zero are zero-crossings. If these are evenly spaced in time, the signal is defined as "narrowband", otherwise it is "broadband". Narrowband signals have a restricted frequency range. Wideband signals, including many transients, contain many different frequencies.

Spectrum Analysis

Spectrum analysis emphasizes the frequency domain of signals rather than their explicit temporal behavior. However, time and frequency domains are mathematically related and a unique transformation exists between them, i.e., the Fourier transform. If the variable, x, is a function of time, t, then the Fourier spectrum F, a function of frequency, f, i.e., F(f) is given by:

$$F(f) = \lim_{T \to \infty} \int_{-T}^{T} x(t)\, e^{-j2\pi ft}\, dt \qquad \text{(eq. 3)}$$

We often use the power spectral density, (f), of the waveform x(t) which is defined as:

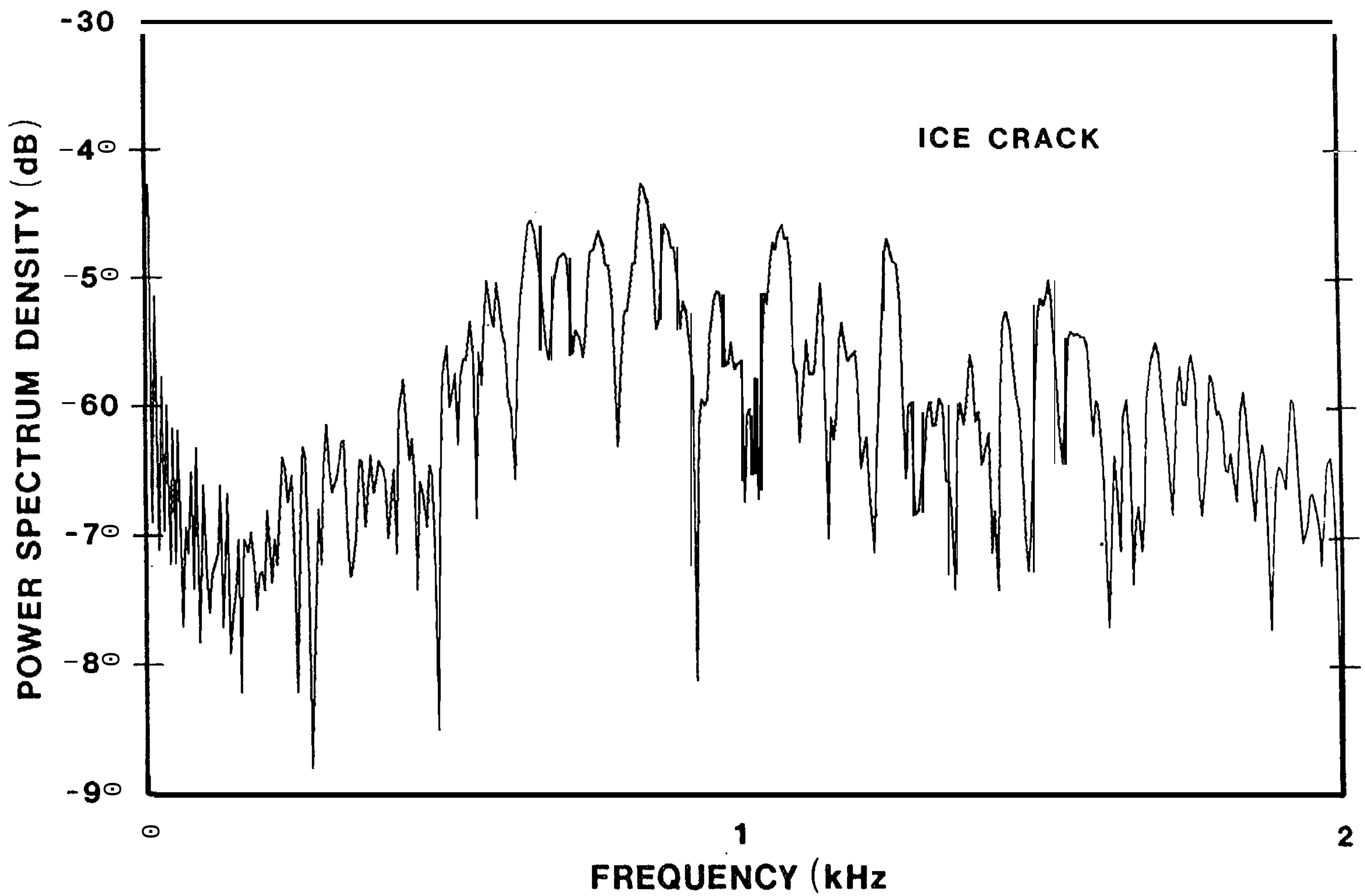
$$\Phi(f) = \lim_{T \to \infty} E \left\{ \frac{2 \cdot |F(f)|^2}{T} \right\} \qquad \text{(eq. 4)}$$

Here E represents the expectation operator and must be invoked only in the event the signal has a stochastic component. The symbol T represents time. As in most analyses done on modern computer systems, we implement these functions with the Fast Fourier Transform (FFT) algorithm (also see Bendat and Piersol, 1966; Otnes and Enochson, 1972; Anderson, 1971, and Middleton, 1960).

The power spectral density of an ice-cracking transient is displayed in Fig. 9. The curve represents the power in a 1 Hz (Hertz) band at frequencies over the analysis range, here 2 kHz. The power is distributed widely over the band, with maxima at about 10 Hz and near 900 Hz. Spectrum levels are approximately -43 dB for each peak. This electrical power spectral level corresponds, through the calibration constants for the measurement system, to a sound pressure spectrum level of 79dB re 1 µPa in the water.

Sound Frequency of Occurrence

One of our objectives was to report any differences in sound frequency occurrence over time. If present, such a trend may be a means of inferring changes in behavior. Many animals exhibit diurnal patterns in activity that are often indications of related behavior. Sound production is also known to be part of the reproductive behavior in many species. Our field period was explicitly chosen by the sponsor to begin before the pupping season for the ringed seal and to end after the season was well underway.



gure 9. Relat ve power spectrum dens ty of an ce-cracking sou[illegible].

In view of these and other possible temporal dependencies, we monitored all recordings, logging each occurrence of animal sound by type and accumulating totals in fifteen-minute periods. These data were then stored in a computer file for subsequent analysis, e.g., the frequency of occurrence for barks, scratches, squeaks, rubs, etc. The total numbers of animal sounds were also accumulated and plotted. Names of sound categories were mostly derived from their aural appearance, i.e., rub, quacking bark, etc., which does not imply the mechanism of sound production.

Correlations

Correlation analyses between environmental measurements and rates of sound production were undertaken using two techniques, graphical means and statistical calculation. For example, we calculated simple regression equations and coefficients of determination, and we applied the chi-squared and Student's t tests. As explained below, cross-correlation between two or more arrivals of the same sound was used in the localization procedure to determine the geographical origin of sound sources.

Localization

A single, omnidirectional hydrophore can be used to detect a sound, provided the level of the sound at the hydrophore is sufficiently high relative to background sounds, i.e., above 0 dB signal-to-noise ratio. By itself, such a hydrophore cannot be used to determine either the distance to the sound source or the direction from which the sound originated. However, with two sensors of this type, separated in the horizontal plane by a known distance, one can solve an equation to determine that the sound came from one of two possible directions (bearings). In practice, there usually is not sufficient information to resolve this ambiguity. However, by adding one additional hydrophore, not co-linear with the other two, one can calculate, not only the direction to the sound source, but also the distance.

Our technique for doing this was developed and tested for under-ice localization in an OCSEAP project off Prudhoe Bay in 1981. The procedure and results are fully documented (Cummings, et al., 1981). Basically, this involves measuring the difference in arrival times of the sound of interest at each hydrophore, generally the same method of triangulation as used in related disciplines, such as optical tracking.

In past efforts (also see Cummings, et al., 1983), we used the time of the initial arrival of the sound at each hydrophore to determine the time delay between hydrophores. This is relatively simple in the case of sounds with sharp leading edges or ones that have propagated over similar paths. It is considerably more difficult if the leading edge of the sound envelope is ambiguous, or if the waveforms differ on each hydrophore due to propagation perturbations. The optimal solution to determining the time delay at two sensors is by cross-correlation. The cross-correlation function, $R(\tau)$, is a function of the time delay, τ, between signals on two time functions, $x(t)$ and $x(t+\tau)$. The correlation function is defined as:

$$R(T) = \int_{-\infty}^{\infty} x(t)\, x(t+\tau)\, dt \qquad \text{(eq. 5)}$$

The remainder of this discussion utilizes a transient sound from cracking ice recorded on our triangular hydrophore array to illustrate the localization procedure. The identical procedure was employed to localize the animal sounds.

Three hydrophores (ales"ignated A, B, C) were positioned at a location 1.8 km from the ice camp. The geometry of the hydrophore locations and the surrounding ridge and refrozen fracture structure are illustrated in Fig. 10. The hydrophores were all located at a depth of 8 m from the ice surface in 14 m of water under 2 m of ice. The hydrophore signal from location A was transmitted, after amplification near the site, via a

1829 m coaxial cable (RG-174/U). Signals from hydrophores at locations B and C were telemetered to the ice camp, and all three sensor outputs were recorded simultaneously on a Nagra T recorder.

Plots of the voltage at hydrophores A and C (Fig. 11, upper) reveal that the signal at hydrophore C arrived about 72 ms later than at hydrophone A (ΔAC). Because of slight differences in propagation path losses and ambient noise, it is very difficult to measure the delay more accurately from this type display. The mathematically optimal manner for obtaining a more accurate estimate of the delay between the two signals is to compute the cross-correlation function (eq. 5). The result of that calculation (Fig. 11, lower) is a waveform with a distinct peak at the delay between the two signals, 72.27 ms. In the firmware implementation of the cross-correlator, provision is made to set a cursor on the peak, providing a direct digital display of the delay. A similar measurement of the delay between the sound arriving at hydrophores A and B resulted in AAB = 52.93 ms.

A computer algorithm was used to calculate the parabolic curve labeled AAB = +52.93 ms in Fig. 10. This was based on an average measured sound speed of 1437 ± 1 m/see. A sound originating at any position on this curve would arrive at hydrophore B, 52.93 ms later than at A. Similarly, the curve labeled ΔAC = 72.27 ms represents the locus of points from which a sound would reach hydrophore C, 72.27 ms later than at A. The intersection of these two curves is the location of the ice cracking sound. The coordinates, with respect to hydrophore A, are x = 218.2 m and y = -126.1 m. This corresponds to a range of R = 252 m and a bearing of θ = 240°, relative to location A and line A-B. Therefore, this particular sound originated on a discontinuous, linear ice ridge with relatively low, ca 1 m, relief (Fig. 10).

This procedure was used to localize additional ice-related sounds and a number of animal sounds. Our objective was principally to obtain a distance to the source of the sound in order to determine its source

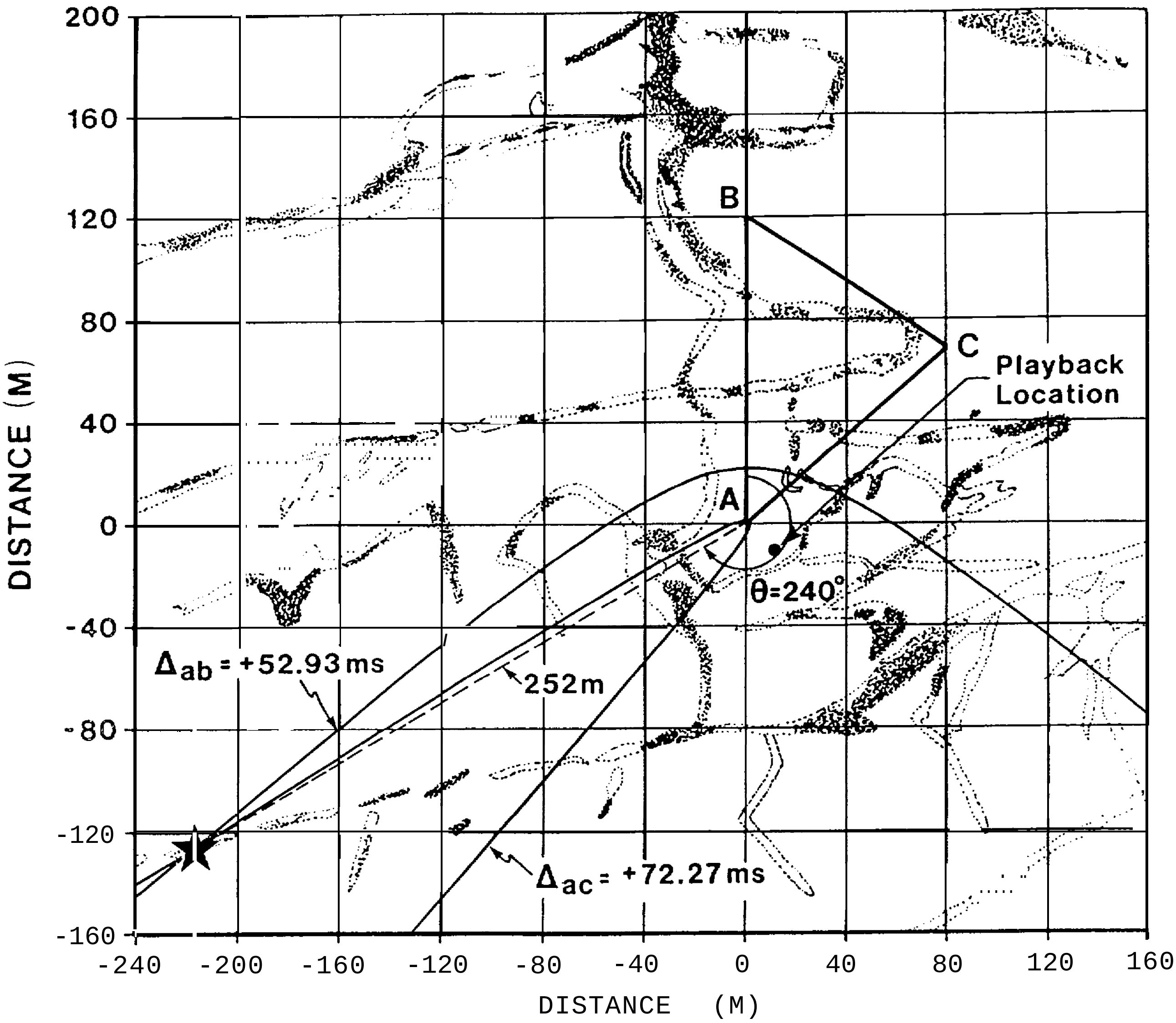


Figure 10. Sensor locations (A, B, C), ice ridges (stippled), triangular array, and the intersection of two parabolas (star) based on the indicated sound arrival time differences.

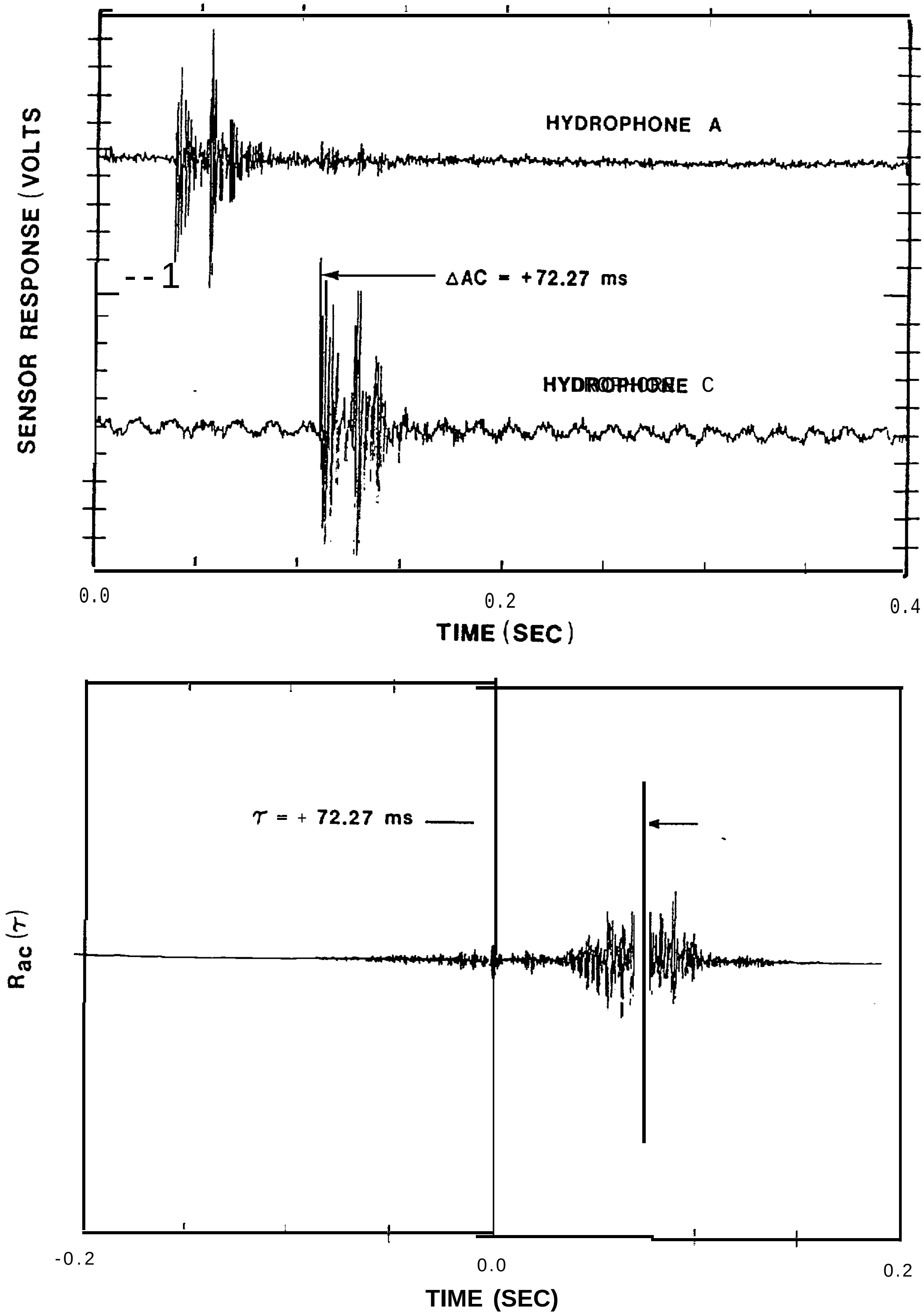


Figure 11. Arrivals of the same ice cracking transient sound at hydrophores A and C (upper) and their cross correlation function used to determine the arrival time difference, 72.27 ms (lower).

level in dB at a standard distance from the point of origin. Also, we wanted to look for any spatial clustering or association with ice surface features.

Source Level Determination

We define source level as the measure of the level or intensity of a sound. This quantity is defined as 10 times the common logarithm of the ratio of the intensity of the source, on its acoustic axis (if any), to the intensity of a plane wave with a root mean square pressure of one micropascal (μPa), referenced at a distance of 1 m from the source.

An absolute measure of the sound intensity at a known distance is required to measure source level. To our knowledge, this measurement has not been done in the case of pinnipeds in the wild. Knowledge of source level (SL, eq. 1) is required to quantify potential masking or other impact on a species from the addition of man-made noise to the environment. Thus, we carefully calibrated the instrumentation used to localize sounds with the triangular array of hydrophores.

V. RESULTS

A. Ringed Seal Sounds

A total of 24,373 individual animal sounds was recorded. Except for one bearded seal pup in a lair (location E), ringed seals were the only pinnipeds seen in the study area. It is possible that a small portion of the vocalizations could have been from bearded seals, based on the fact that some very weak bearded seal trills were heard over two days during our recordings in the Sound. They were powerful and numerous on the off-shore recording, 192 km distance.

We recognized 16 different categories of seal sounds. Most of the recorded sounds were scratches that were produced as the seals either clawed at their access or breathing holes to maintain the openings in the ice, or maintained their lairs. Eleven percent were rub sounds. Not considering scratching sounds, rubs were the most common of those sounds thought to be produced as vocalizations. A total of 4.2% of the sounds were squeaks. Quacking barks accounted for only 3.2% of the sounds, but they were outstanding vocalizations when present. Crackles were 1.1% of the total. A listing of the sound categories, including their percentage of occurrence, appears in Table 2.

Although totals are given for the three hydrophores comprising the triangular array and we frequently heard the same sound there on all three sensors, each occurrence was only counted once in these tabulations. About 70 percent of all the scratches came from location E where we had installed a hydrophore in an active lair that was occupied by a bearded seal pup and, presumably, an attending adult. Infrequent sounds, for which the percentage of occurrence is not given in Table 2, together amounted to 0.6% of the total number of seal sounds. Only the common sound categories are included in the following descriptions.

Table 2. Listing of ringed seal sound categories and their occurrence as to location and proportion.

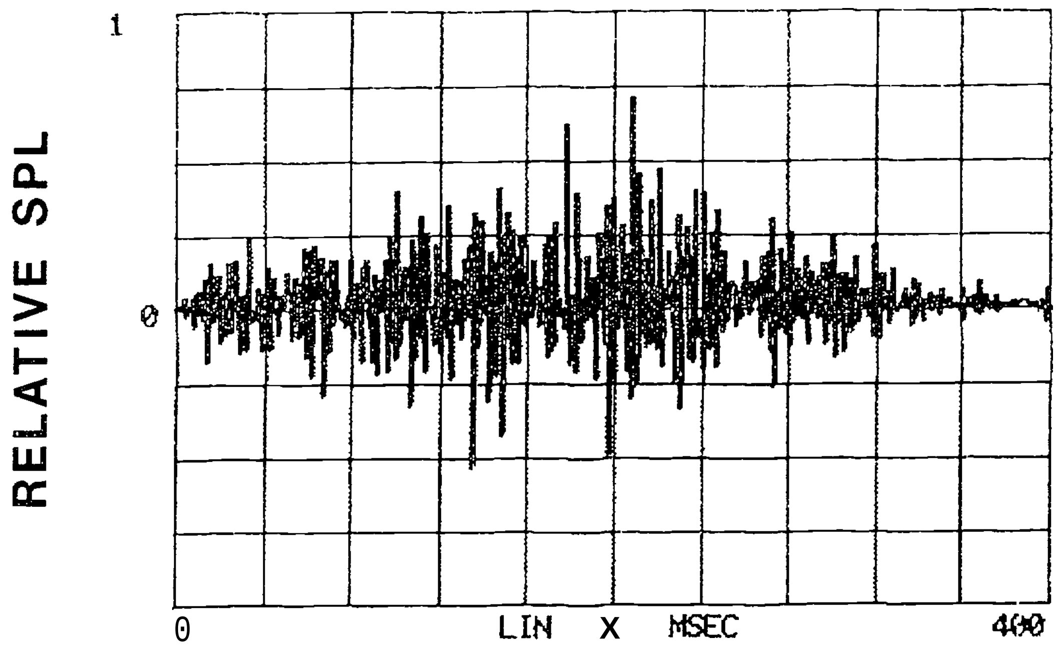
SOUND	TRIANGLE ONLY	OTHER SENSORS	TOTAL SOUNDS	%
Scratch	5,024	14,702	19,726	80.9
Rub	1,734	958	2,692	11.0
Squeak	1,027	5	1,032	4.2
Quacking bark	534	2	536	2.2
Crackle	0	274	274	1.1
Belch	14	0	14	
Bubbling	0	2	2	
Buzz	1	0	1	
Cry	8	0	8	
Crunch	0	3	3	
Growl	4	0	4	
Grunt	1	0	1	
Knocking	1	47	48	
Roar	23	0	23	
Snort	6	0	6	
Splash	1	0	1	
Explosive	2	0	2	
			24,373	

Scratches

We recorded a total of 19,726 scratches, representing 81% of all seal sounds recorded during the study period. Scratching sounds typically were 40-500 msec in duration (Fig. 12, upper) with peak frequencies of 1000-6000 Hz (Fig. 12, lower). Nearby scratching sounds, that were less affected by high frequency attenuation losses, contained energy up to 10 kHz, but for the most part the recorded sounds were below 6 kHz. The high frequency content and the peak frequency usually decreased over the duration of each scratch (Fig. 13). Scratches were a series of broadband transients that occurred at intervals of 400-600 msec (Figs. 14, 15). Aural characteristics were like strokes of sandpaper across a hard surface. Source spectrum' levels for two scratches are given in Figs. 16 and 17. Peak source spectrum level was 102 dB re 1 μPa, 1 m, for one and 98 dB for the other. A detailed analysis was done of the occurrence of these sounds (see B., Frequency of Occurrence, Scratches, below).

Rubs

A total of 2,692 rub sounds was recorded during the study. This represented 58% of all the vocalizations recorded at the array (excluding scratches). Rubs were the most common of all ringed seal vocalizations. We recorded as many as 239 rub sounds in 8 hrs of recording and as many as 92 in 15 rein, i.e., 9 April. This description was used because the sound so clearly resembled the rubbing of one's wet finger tips over a shiny hard surface, such as glass or the waxed surface of an automobile. Peak sound pressures of rub sounds occurred between 0.5 and 2 kHz, with most of the sounds' energy below 4 kHz (Figs. 18 and 19). The waveform of one rubbing sound and the cross-correlation are shown in Fig. 20. Durations of rub sounds fell in the interval from 80-300 ms, and the peak source spectrum level was about 95 dB re 1 μPa (Fig. 21).



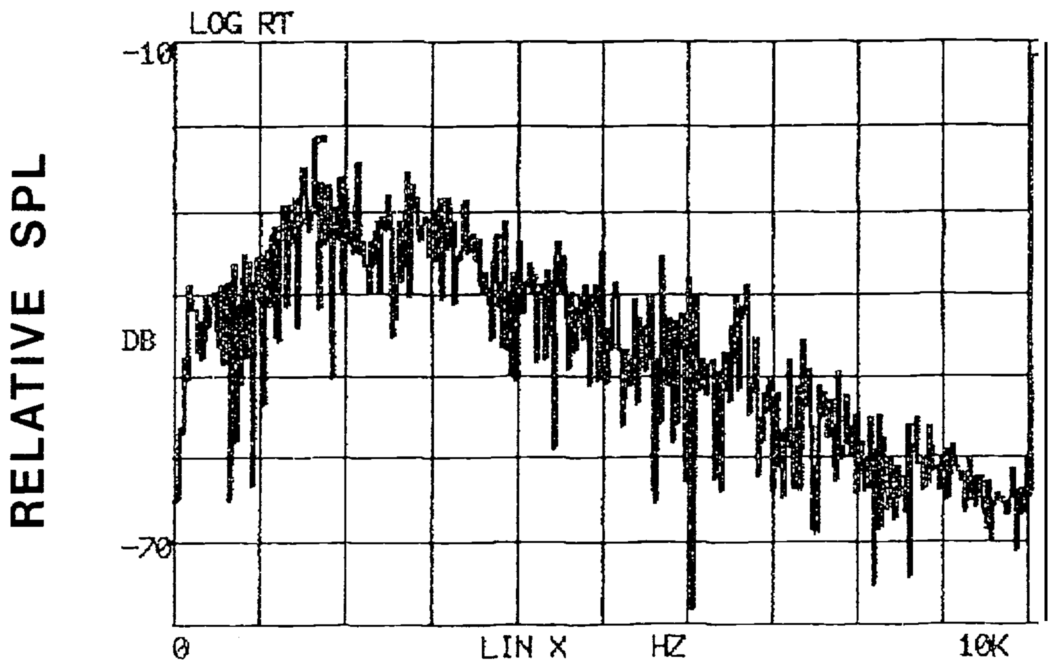


Figure 12. Waveform (upper) and spectrum (lower) of a single scratch sound, 30 March 1984. Analyzing filter bandwidth was 3.75 Hz (upper) and 37.5 Hz (lower).

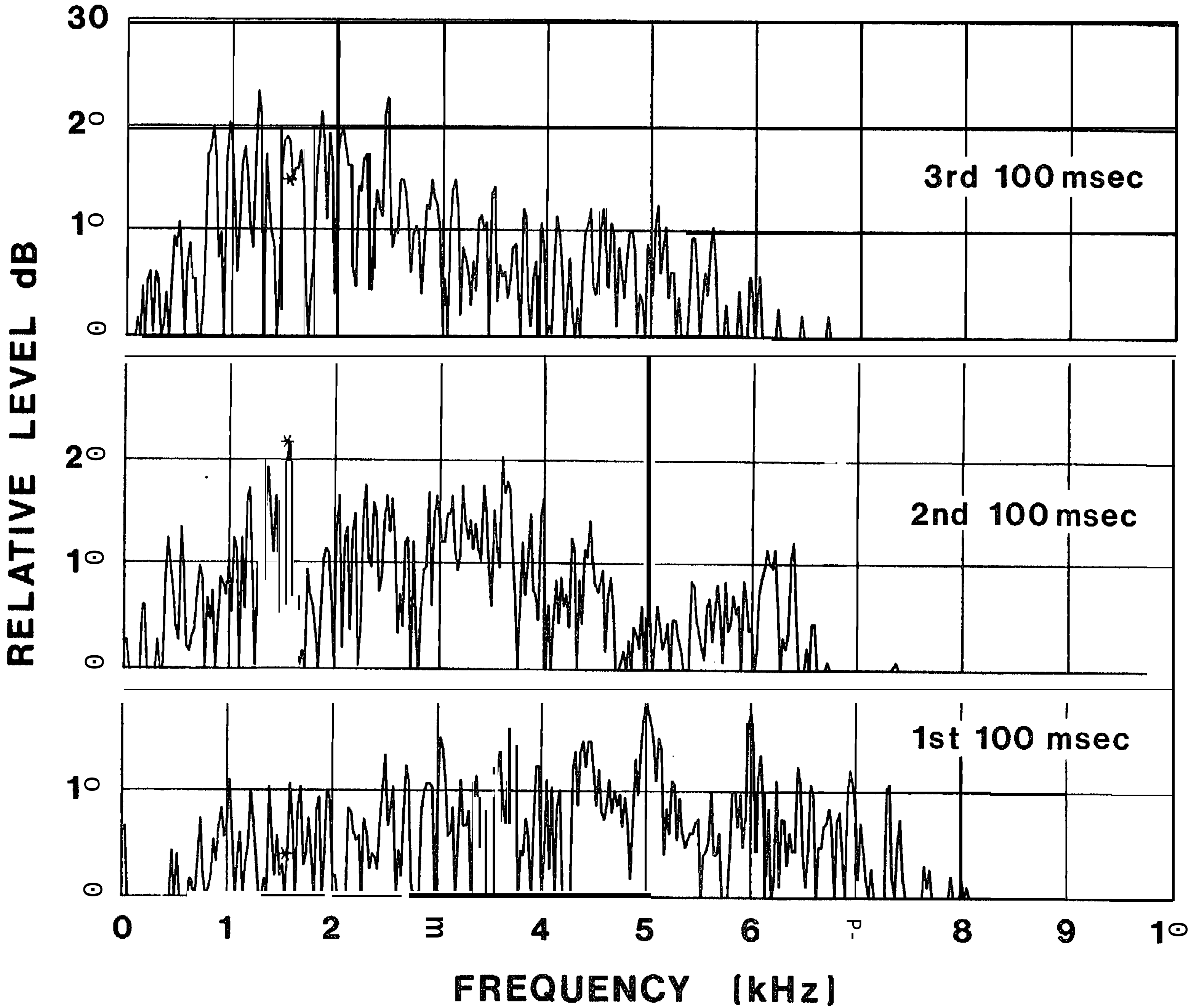


Figure 13. Spectra of a single scratch sound divided into 100 msec intervals showing a decrease in the high frequency content and the peak frequency with time, analyzing filter bandwidth, 37.5 Hz.

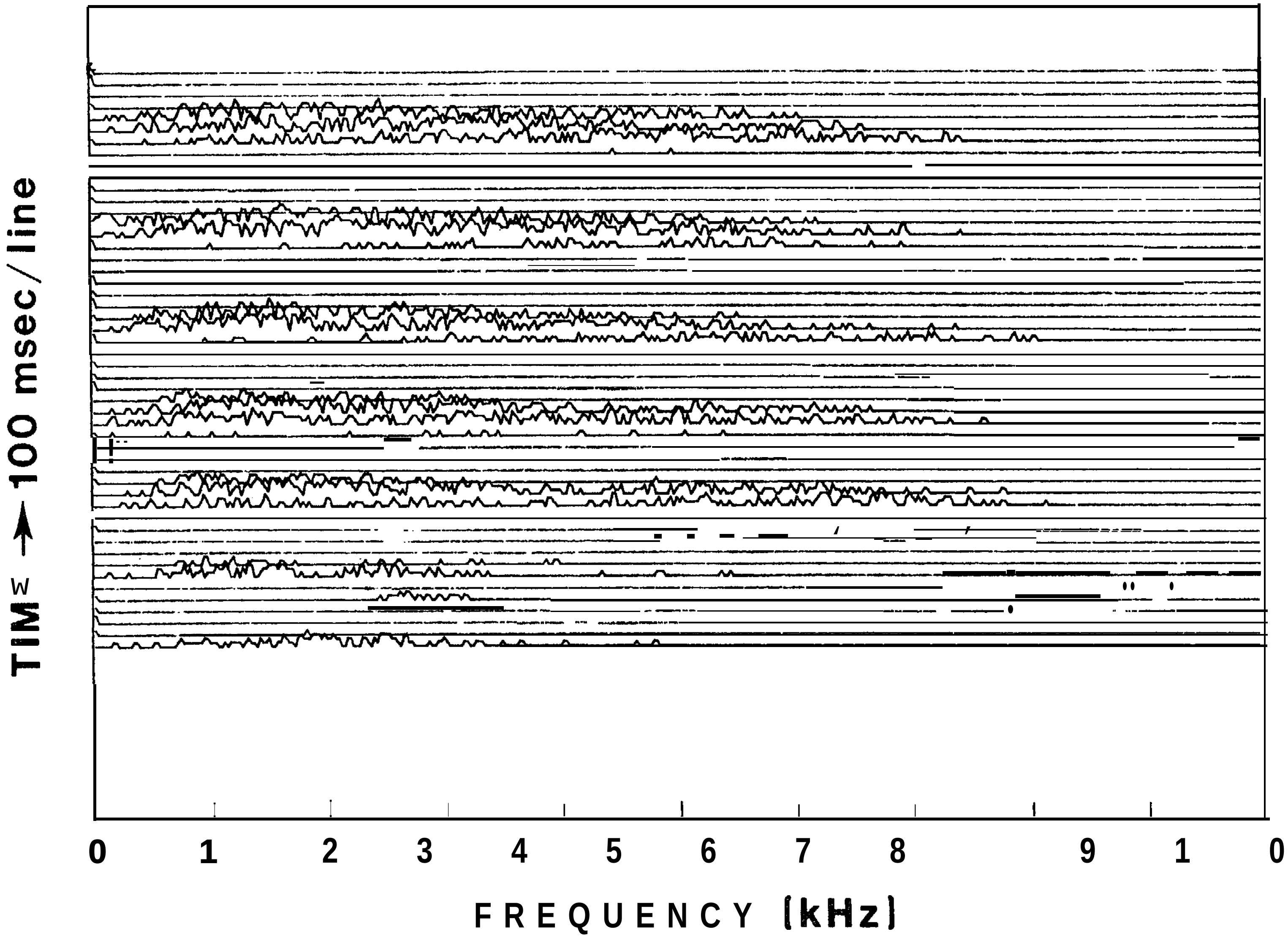


Figure 14. Time history spectra of six scratches in a bout, analyzing filter bandwidth, 37.5 Hz.

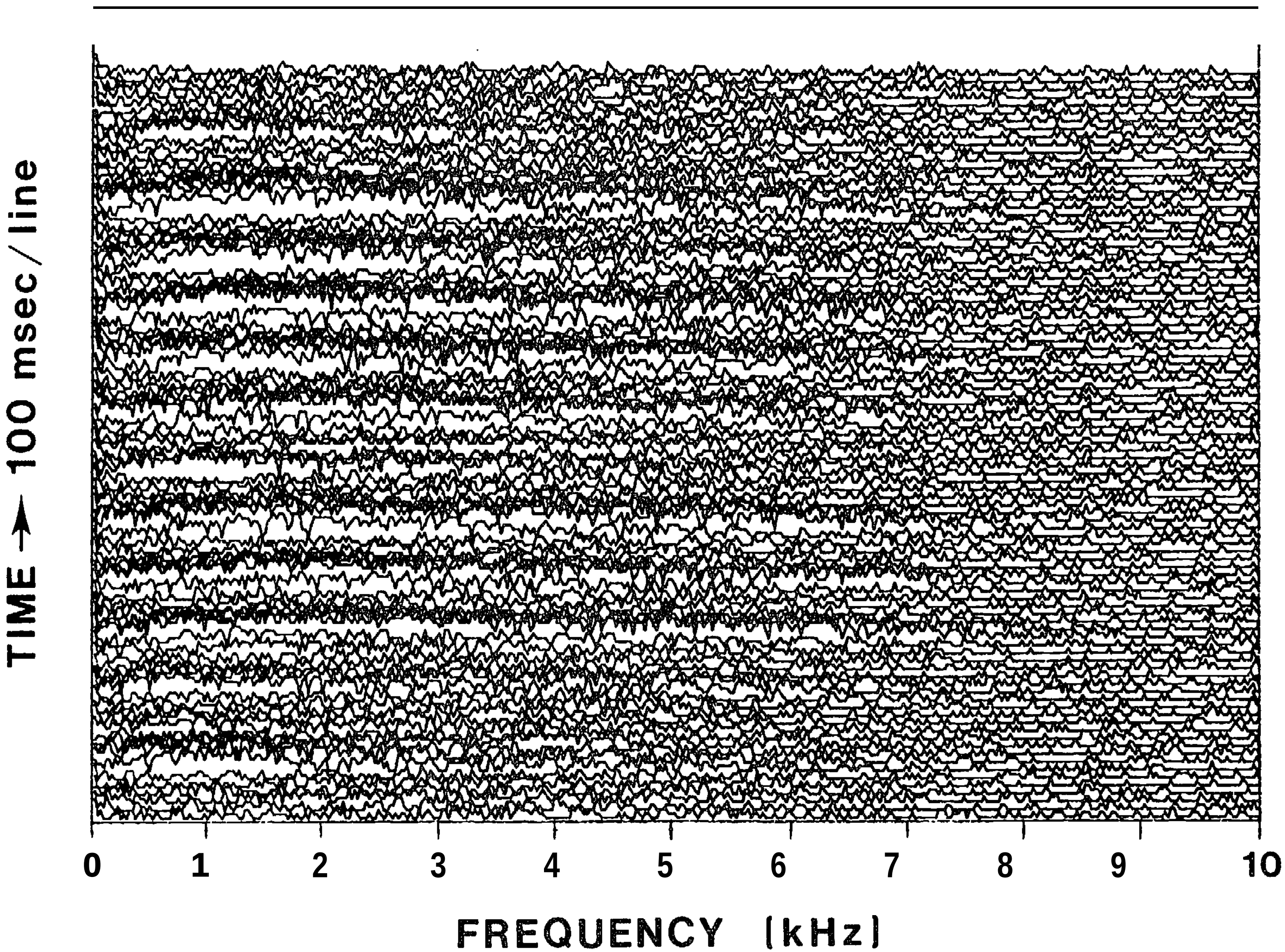


Figure 15. Time history spectra of entire scratch bout consisting of 12 individual scratches, analyzing filter bandwidth, 37.5 Hz.

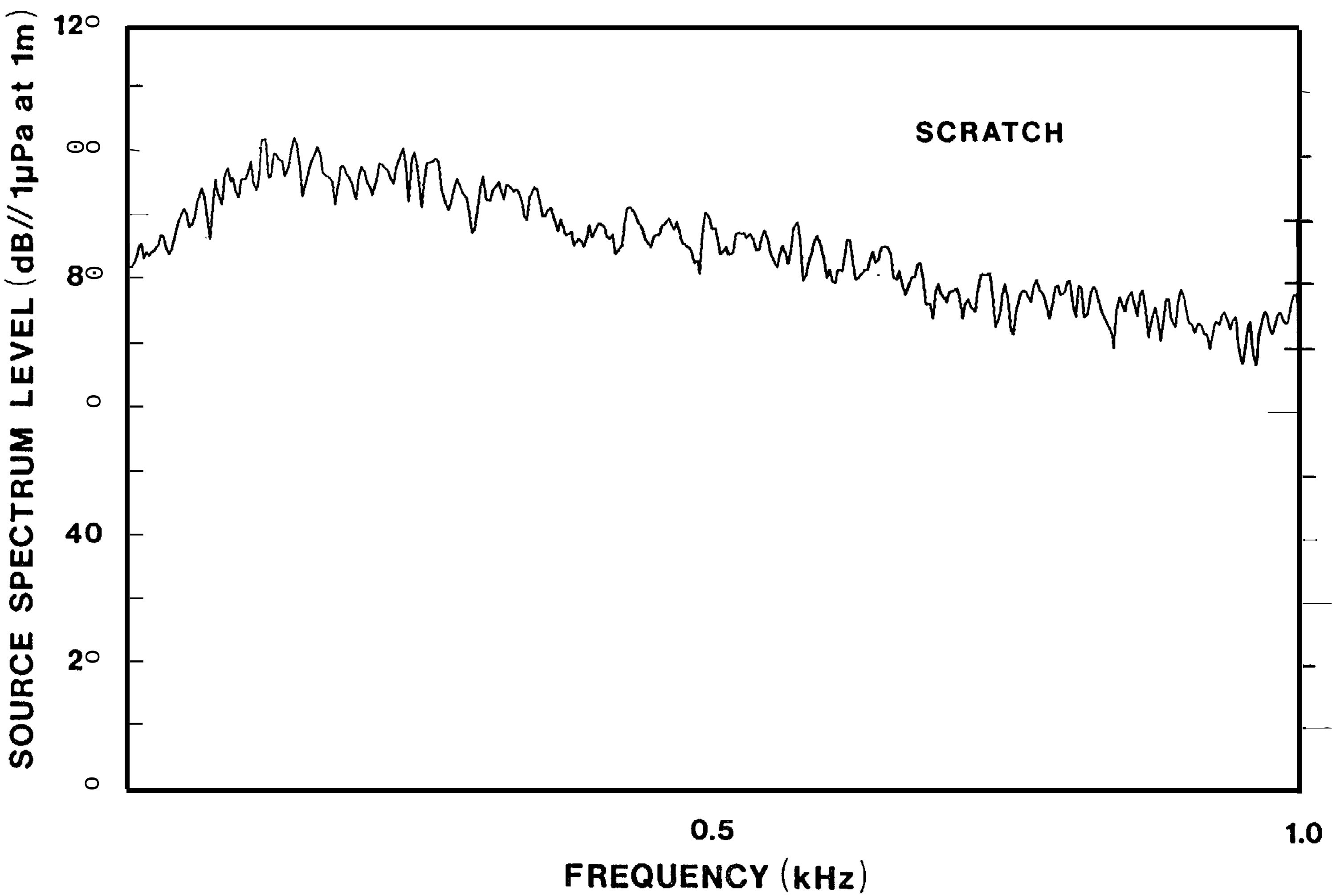


Figure 16. Source spectrum level (0-1 kHz) of a single scratch sound recorded from the triangular array, 28 March 1984, analyzing filter bandwidth, 3.75 Hz. The sound was localized with the array.

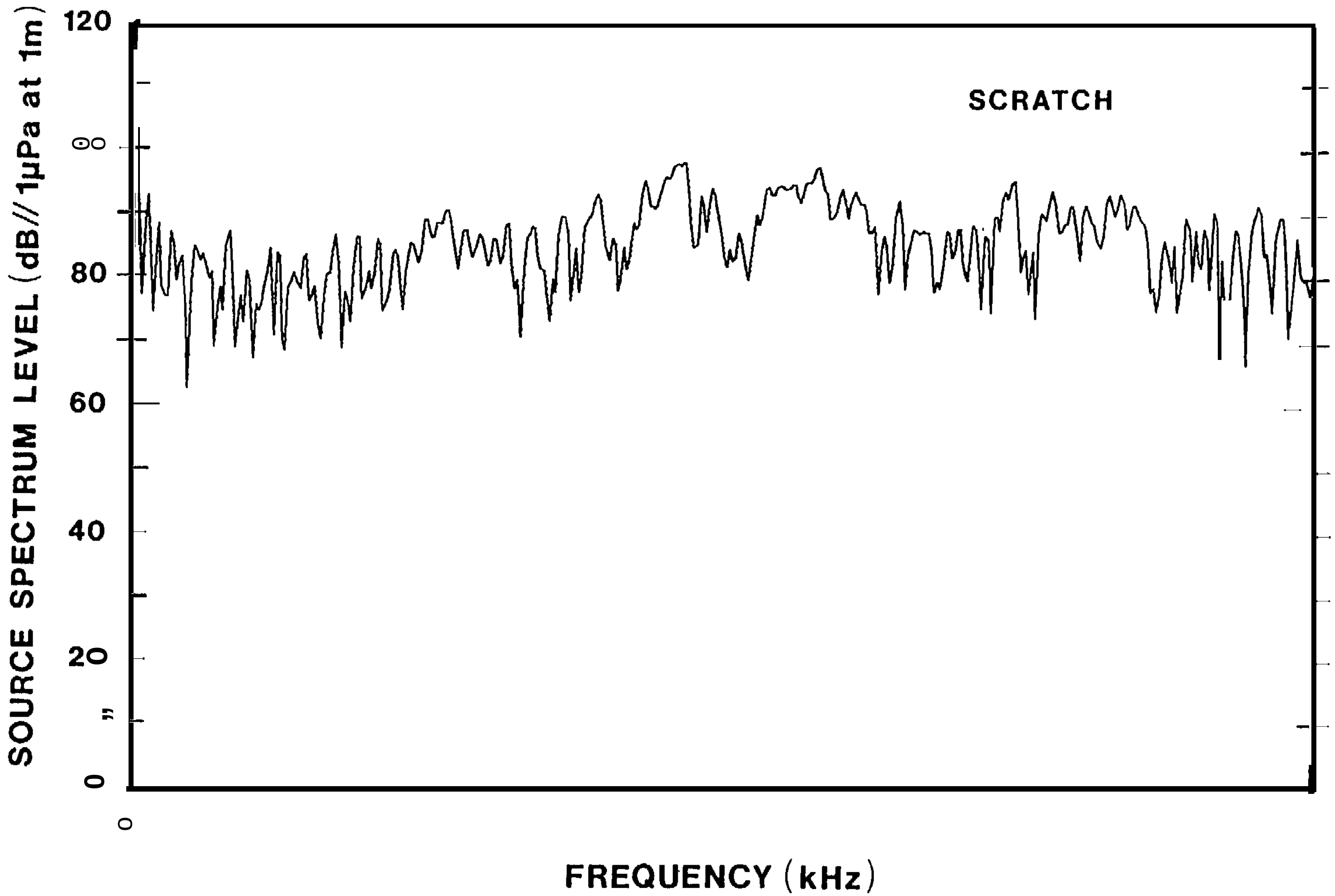


Figure 17. Source spectrum level (0-2 kHz) of another single scratch sound recorded from the triangular array, 28 March 1984, analyzing filter bandwidth, 7.5 Hz. The sound was localized with the array.

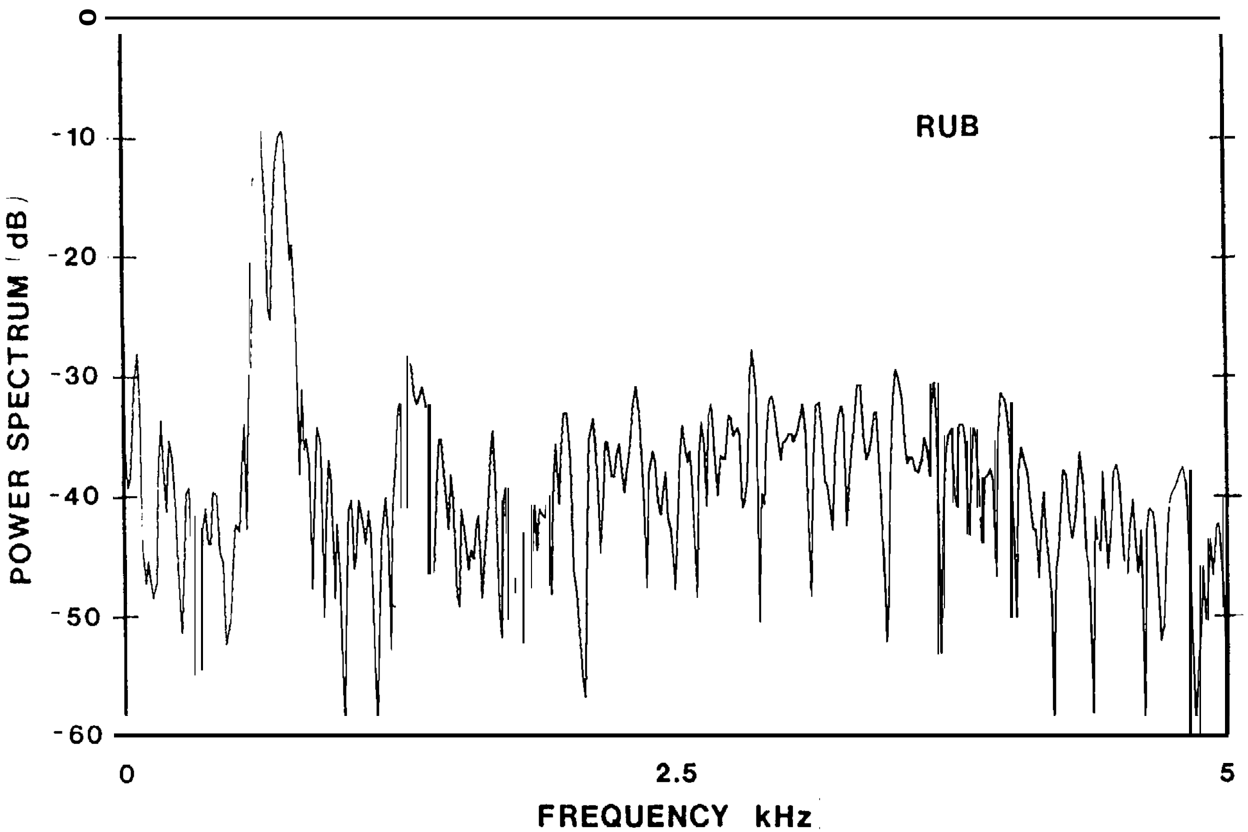
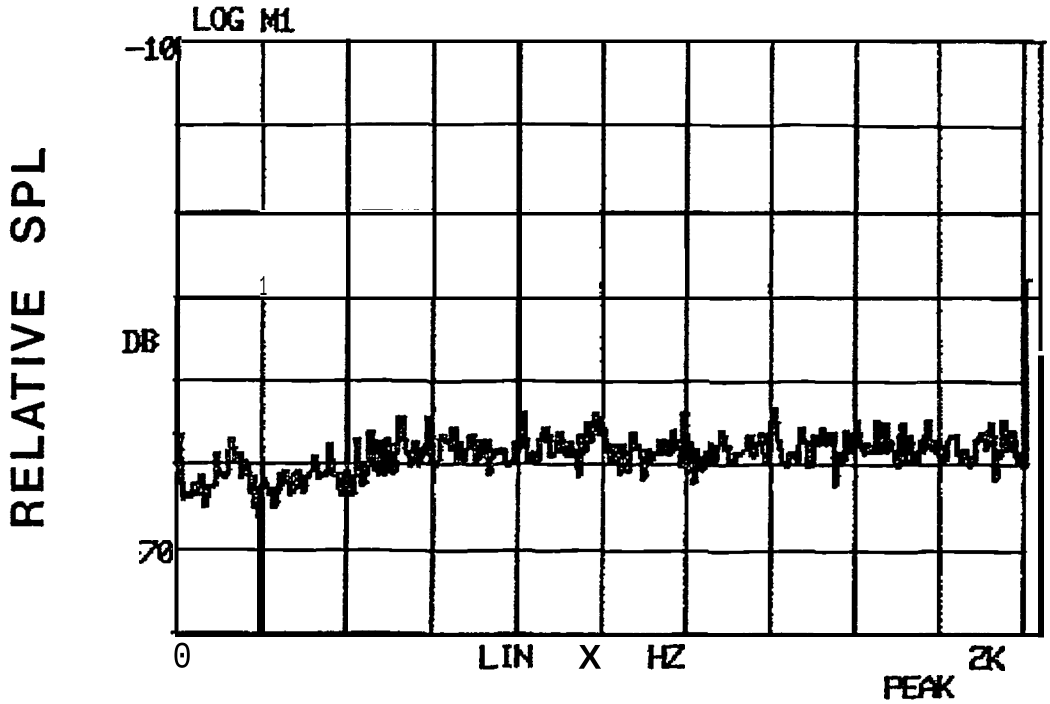


Figure 18. Power spectral density of a rub sound recorded at the tr·angular array, analyzing filter bandwidth, 18.75 Hz.



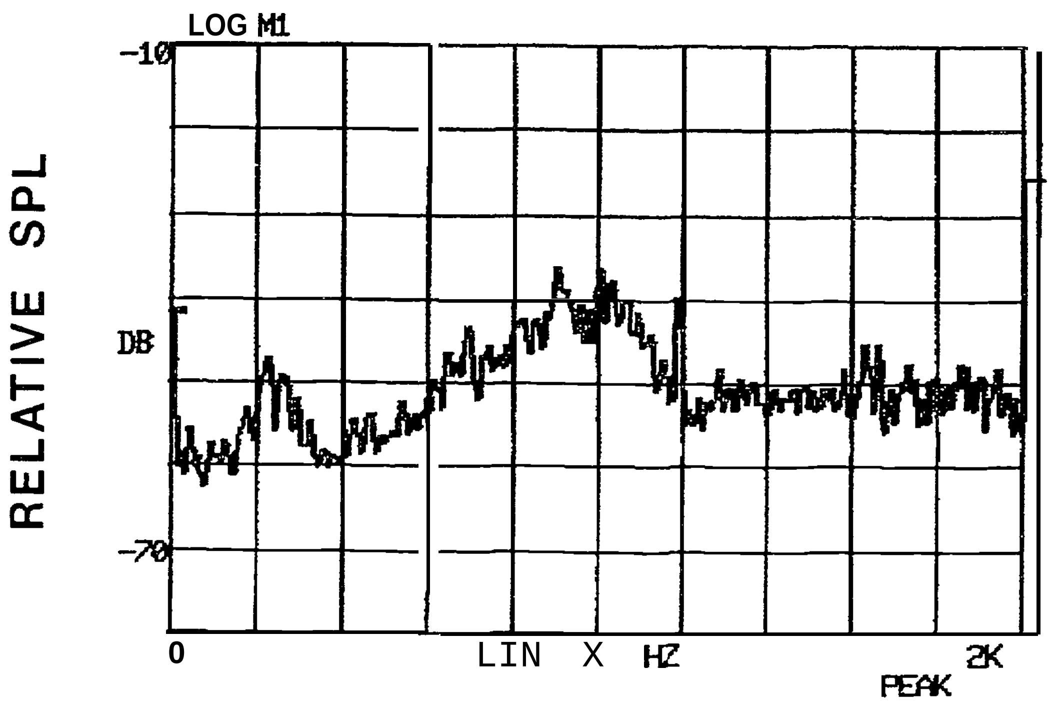
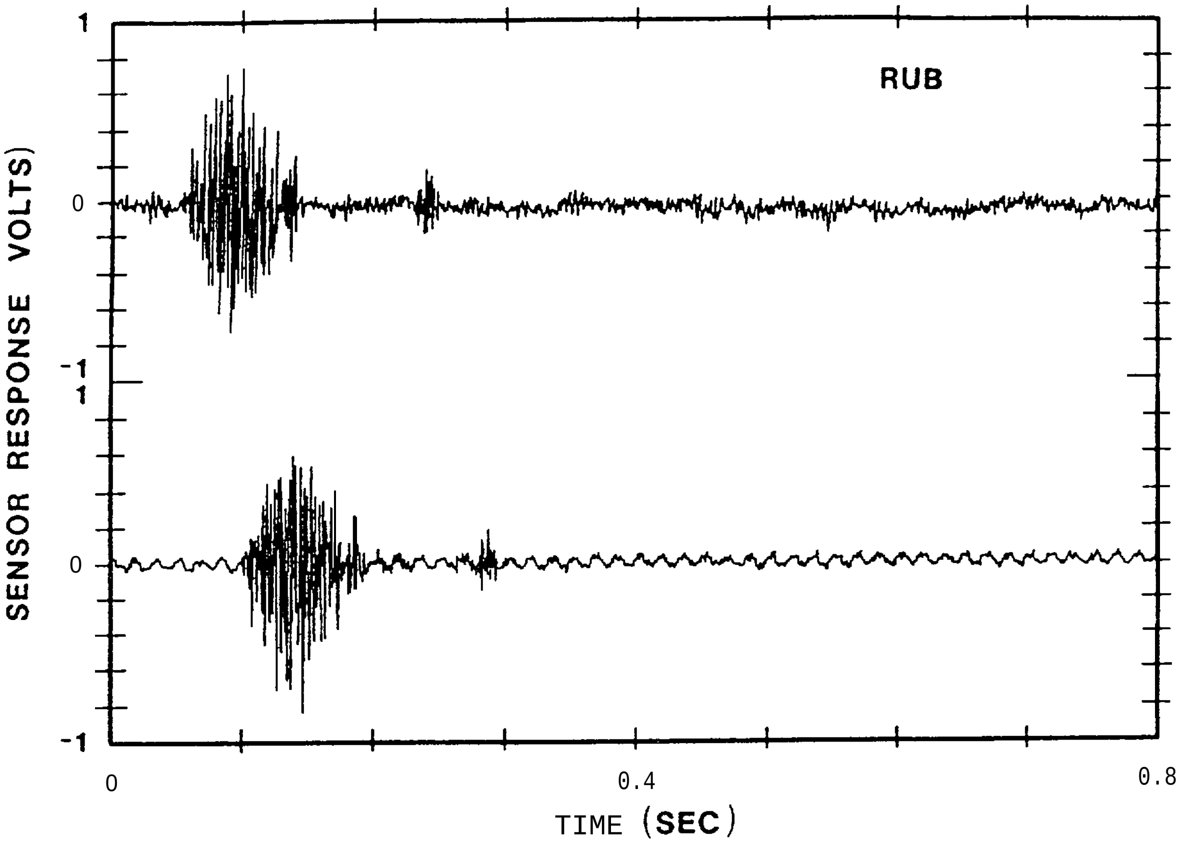


Figure 19. Ambient spectrum (upper) and the additive spectra of 12 rubs (lower) showing most of the energy is in the first 2 kHz with the peak at about 1 kHz, analyzing filter bandwidth, 7.5 Hz.



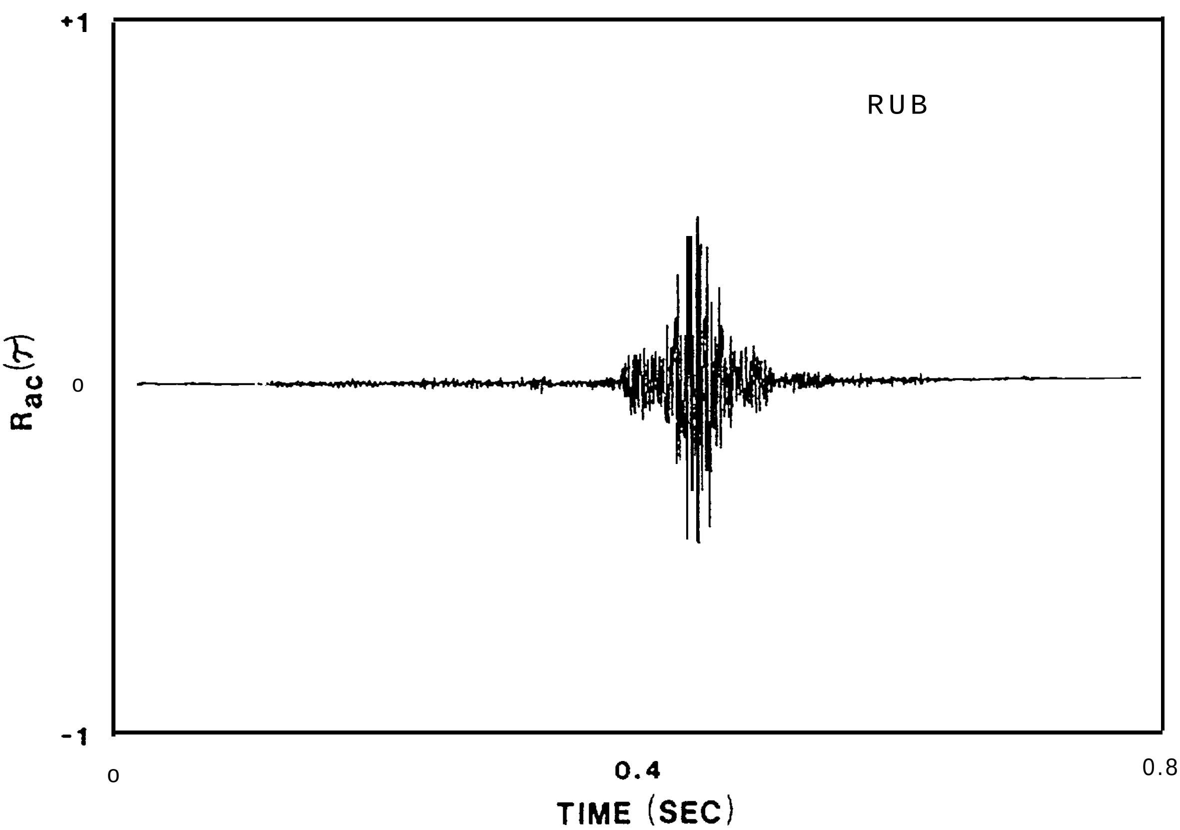


Figure 20. Waveforms of the arrivals of a rub sound at hydrophores A and C, in the triangular array (upper) and the cross correlation function of same (lower) showing the arrival time difference to be 46.88 ms.

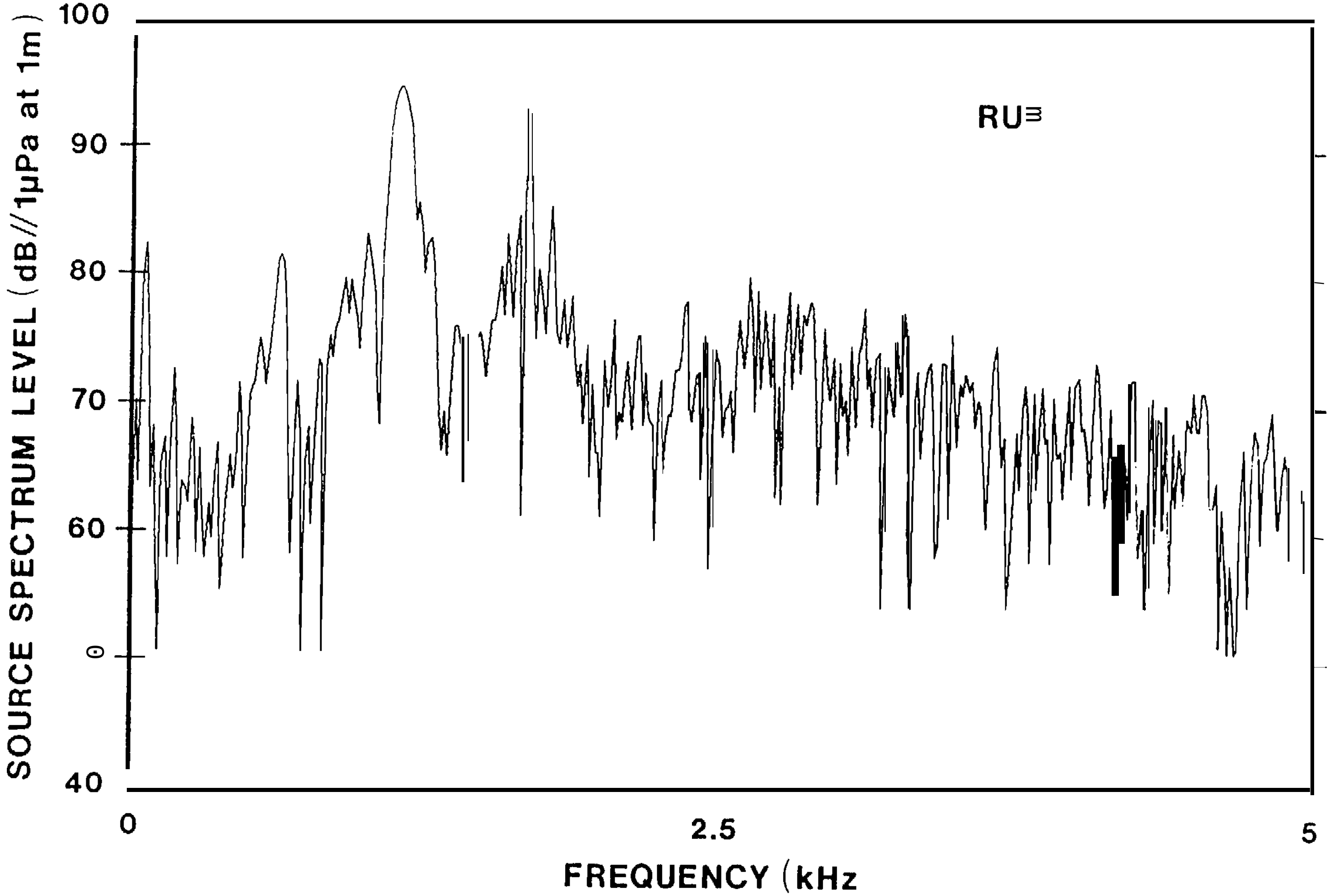


Figure 21. Source spectrum level of a rub sound recorded from the tri-angular array. The sound was localized with the array. Analyzing filter bandwidth, 18.75 Hz.

Squeaks

These sounds, recorded 1,032 times, were the second most common vocalization (excluding scratches). This represented 4.2% of all sounds or 22.2% of vocalization. Aurally, squeaks were like rubs but generally shorter in duration and higher in frequency. Spectra for two squeaks are given in Fig. 22.

The source spectrum level ofa squeak is given in Fig. 23. This sound peaked at 112 dB re 1 μPa, 1 m.

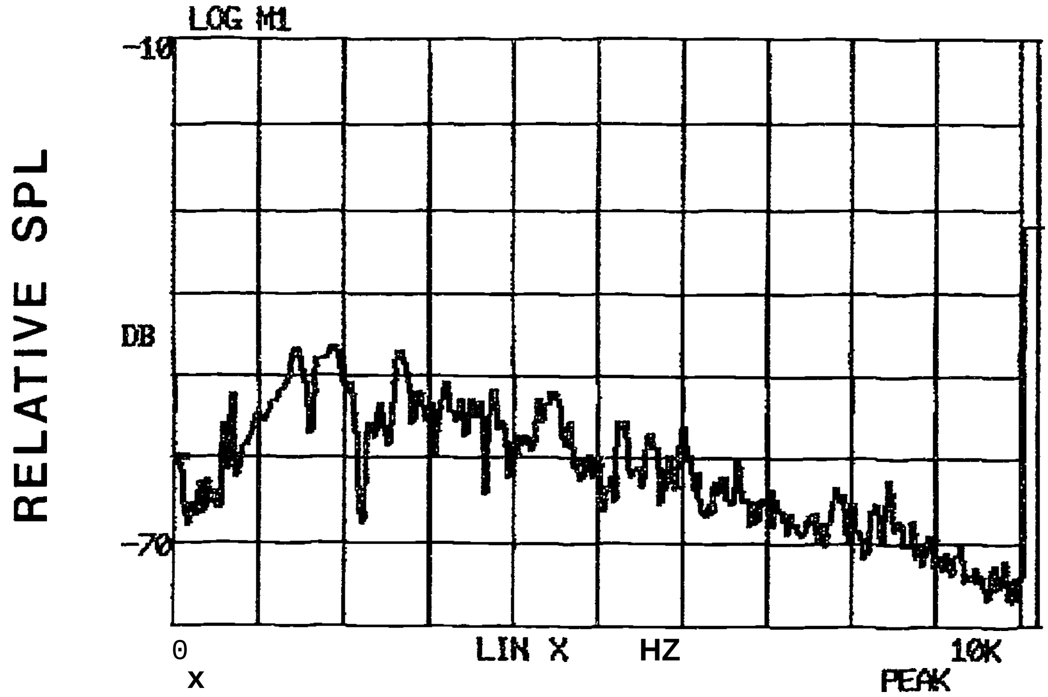
Quacking Barks

Quacking bark sounds strongly resembled vocalizations of ducks. They accounted for 2.2% of the total number of sounds recorded from ringed seals at the triangular array, or 11.5% of the vocalizations (excluding scratches). These sounds normally were produced in volleys of two to five sounds. The waveforms and cross correlation function of a two-element quacking bark appear in Fig. 24. Durations ranged from 30-120 ms with the peak frequencies occurring at 400-1500 Hz. Components of quacking bark sounds were found up to 5 kHz, but most of the energy was less than 2 kHz. The fundamental frequency was typically at about 90 Hz (Figs. 25- 27). A good example of how the propagation path can affect the spectrum of sounds appears in Fig. 27, lower, where the energy at 0.2 kHz is subdued as received from hydrophore A, compared to C. The source spectrum level of a quacking bark is given in Fig. 28. It peaked at 130 dB re 1 μPa, 1 m.

B. Frequency of Occurrence

Long-term (triangle)

Based on a histogram of the frequency of occurrence of recorded ringed seal vocalizations at the triangle, excluding scratches, the rate of sound production increased over the period of our recordings (Fig. 29).



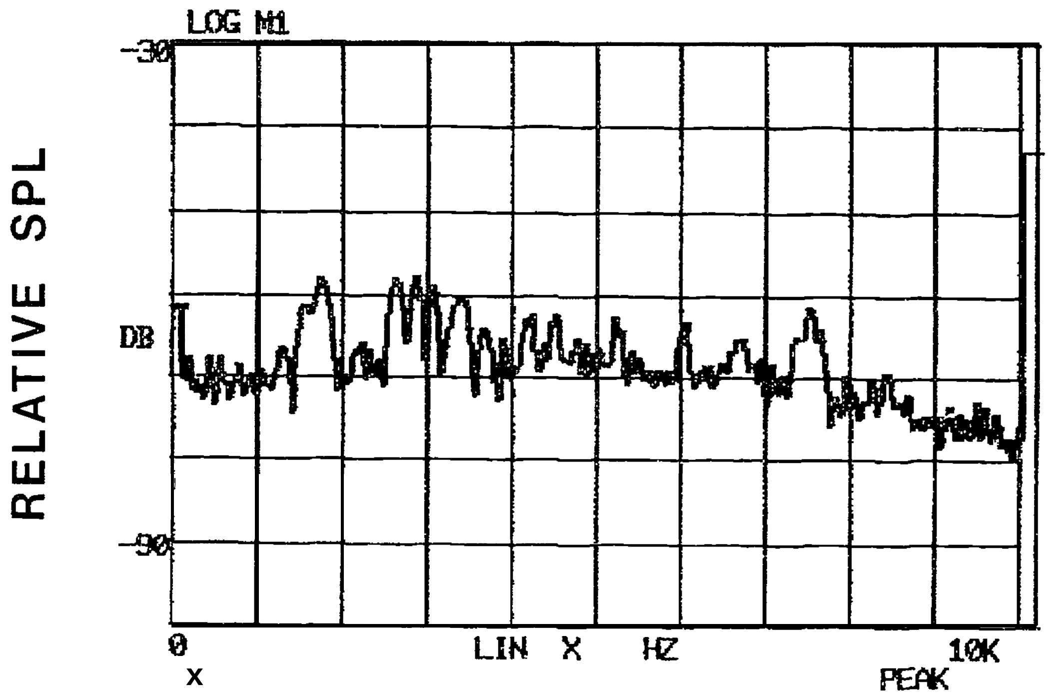


Figure 22. Spectra of a high S/N ratio squeak (upper) and one of low S/N (lower), analyzing filter bandwidth, 37.5 Hz.

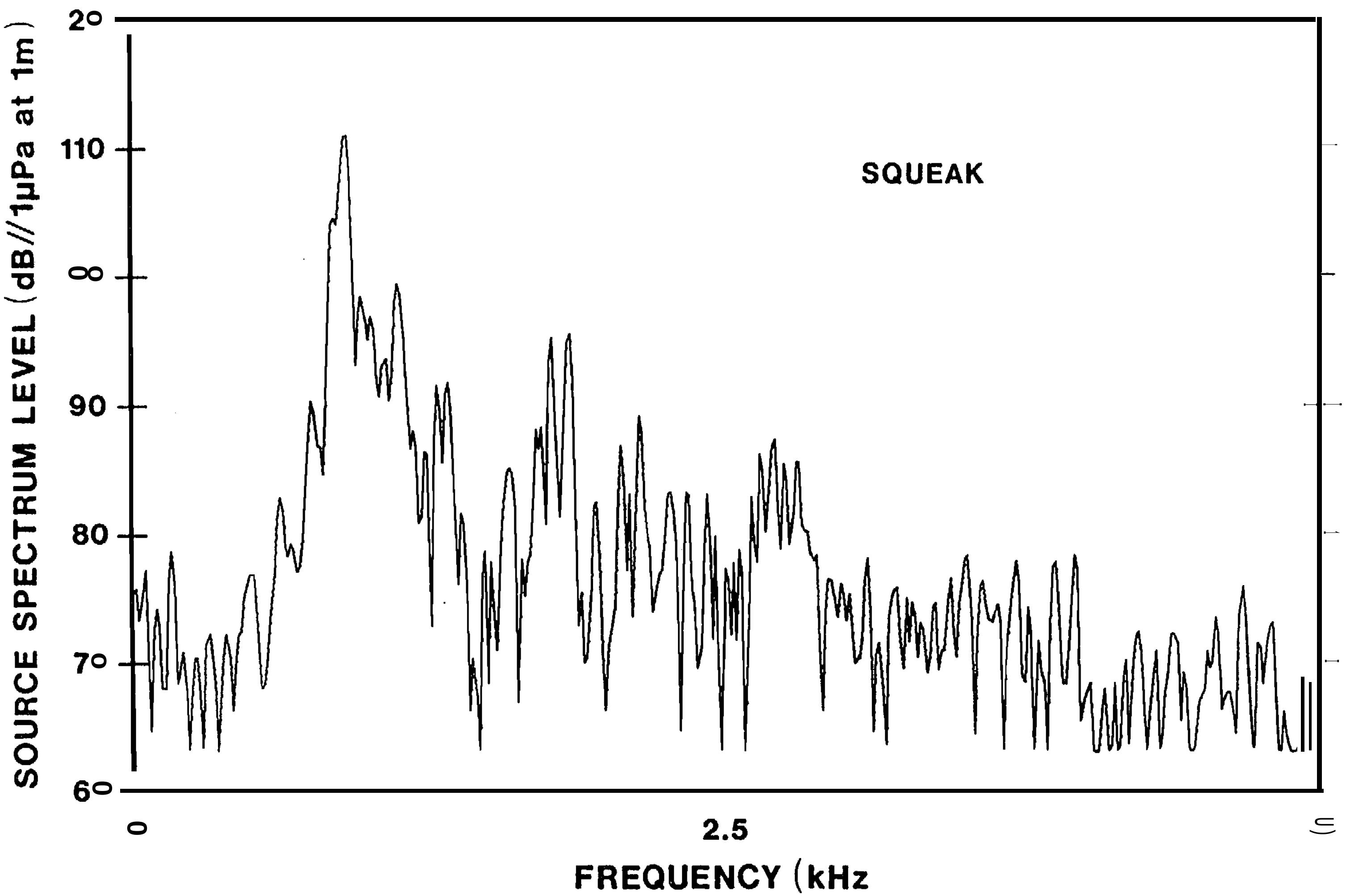


Figure 23. Source spectrum level of a squeak recorded and located from the triangular array. Analyzing filter bandwidth, 18.75 Hz.

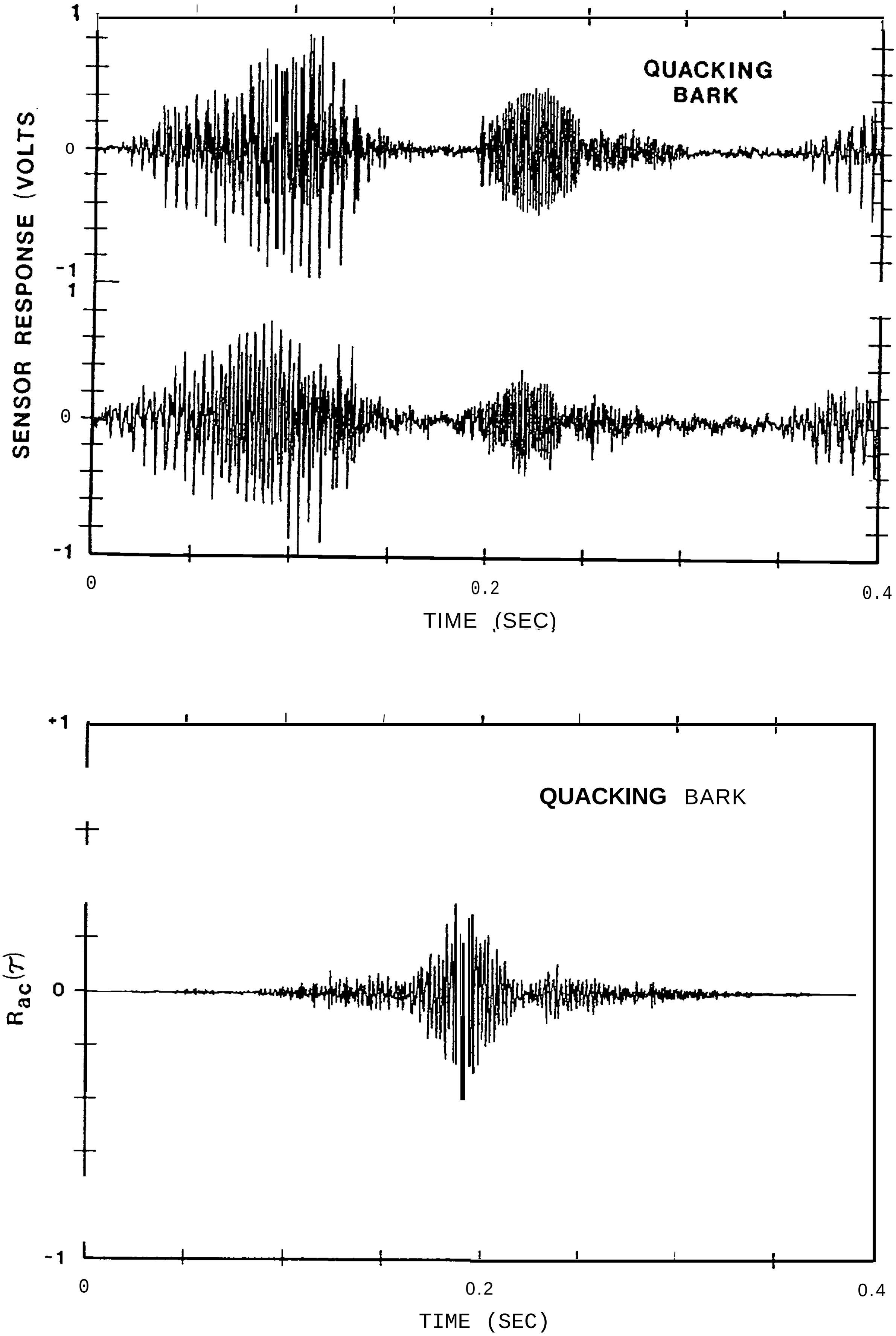


Figure 24. Waveforms of the arrivals of a two-element quacking bark sound at two hydrophores in the triangular array (upper) and the cross correlation function of same (lower) showing the arrival time difference to be 8.98 ms.

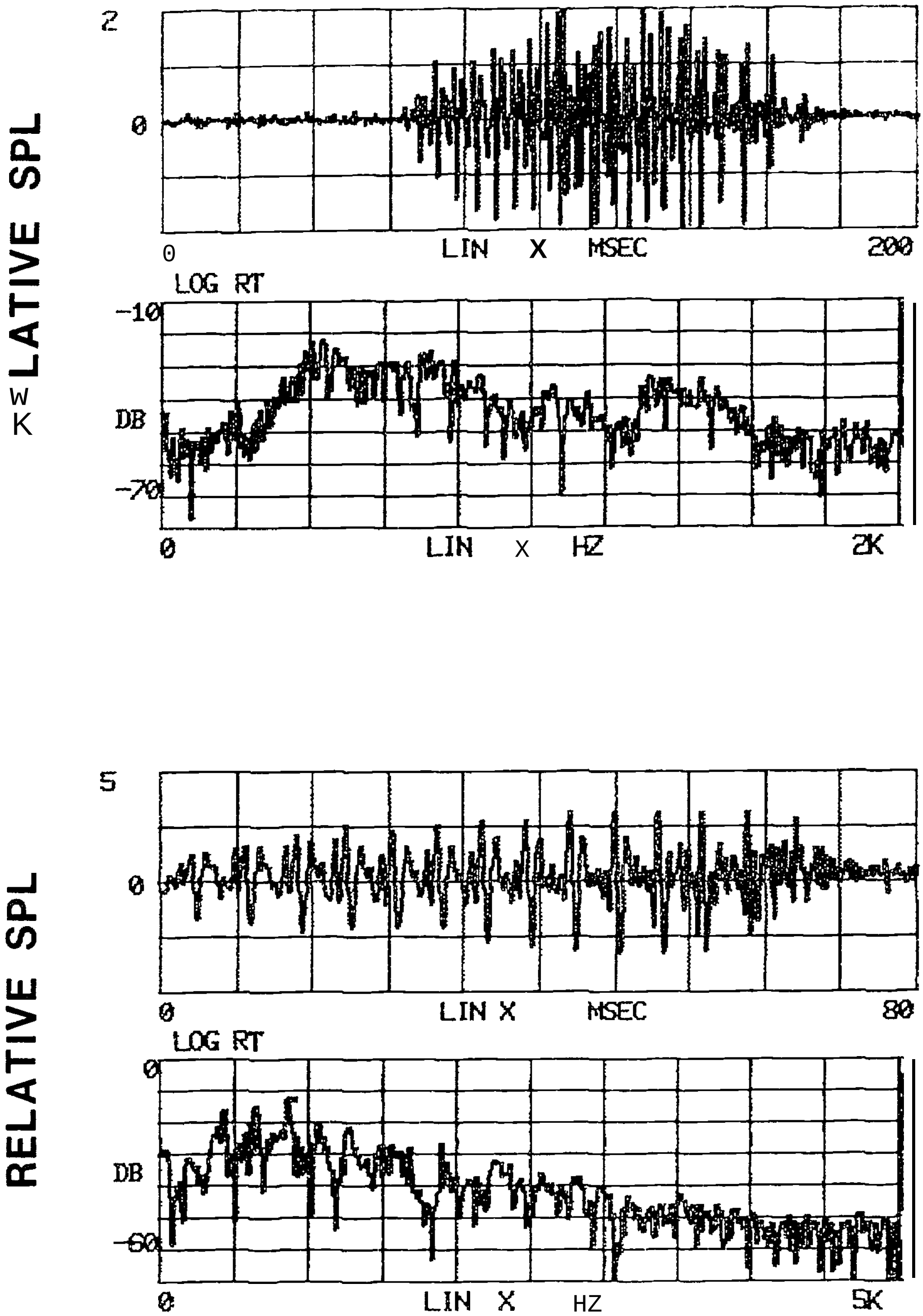
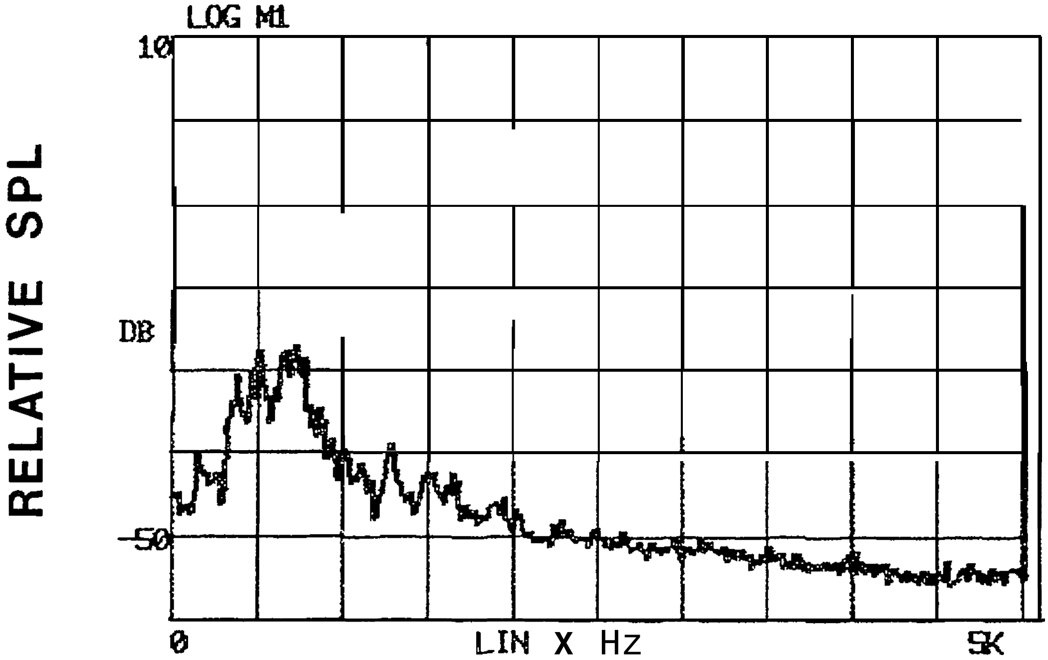


Figure 25. Waveform and spectrum of a single quacking bark (upper), and the same of another quacking bark (lower), stretching out the time scale for more detail of the waveform. Analyzing filter bandwidth, 7.5 Hz (above), 18.75 Hz (below).



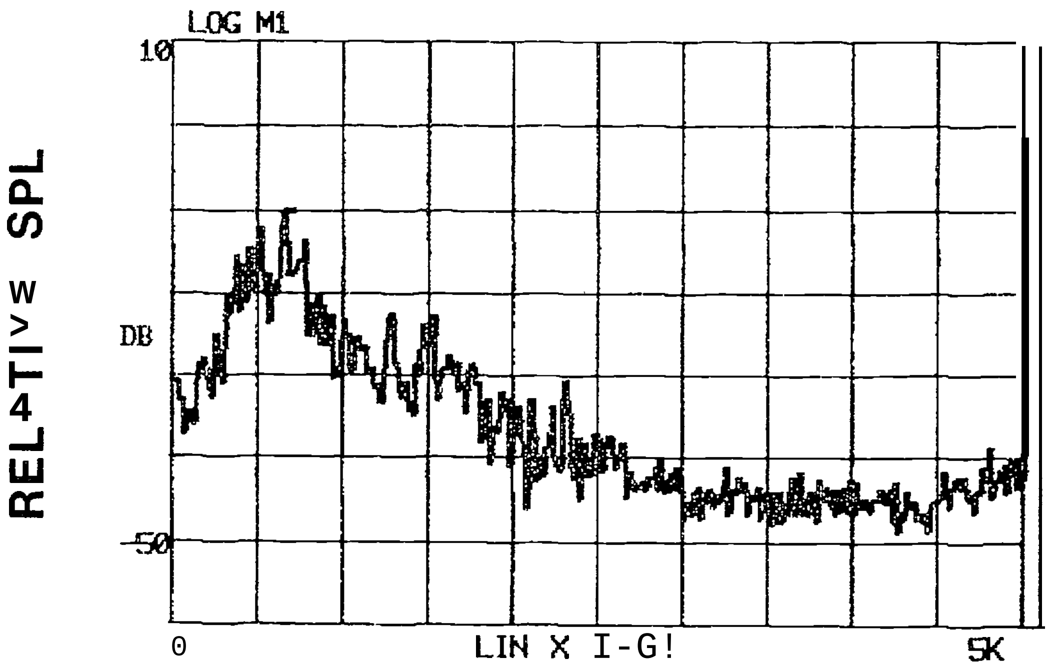
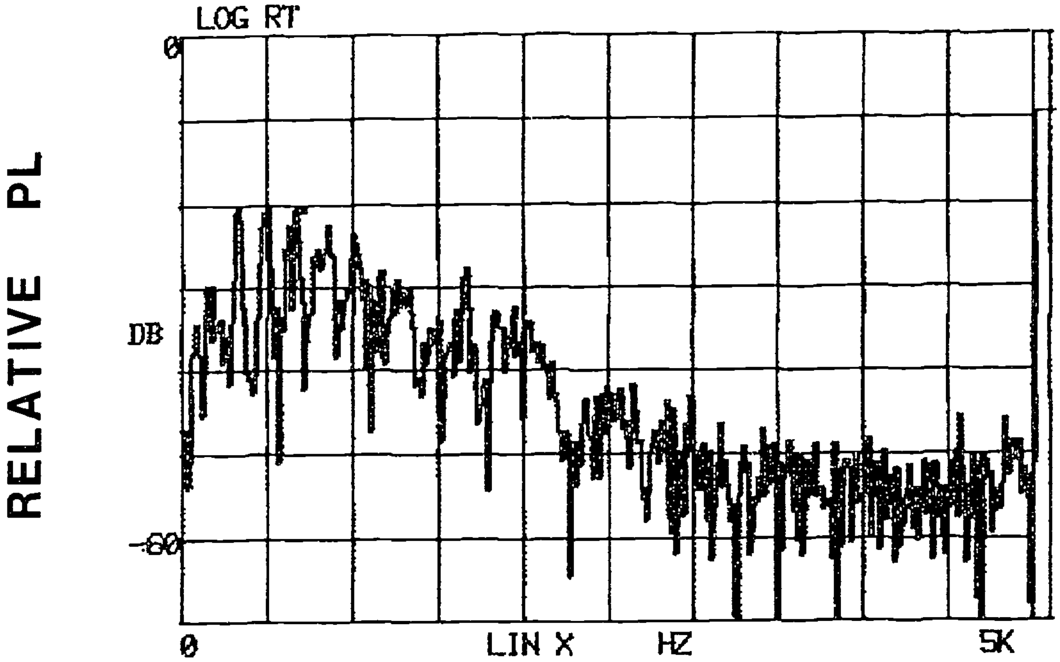


Figure 26. Addition of peak spectra over eight consecutive quacking barks (upper) and the exponential average of the same (lower). Duration, 3.09 see, analyzing filter bandwidth, 18.75 Hz.



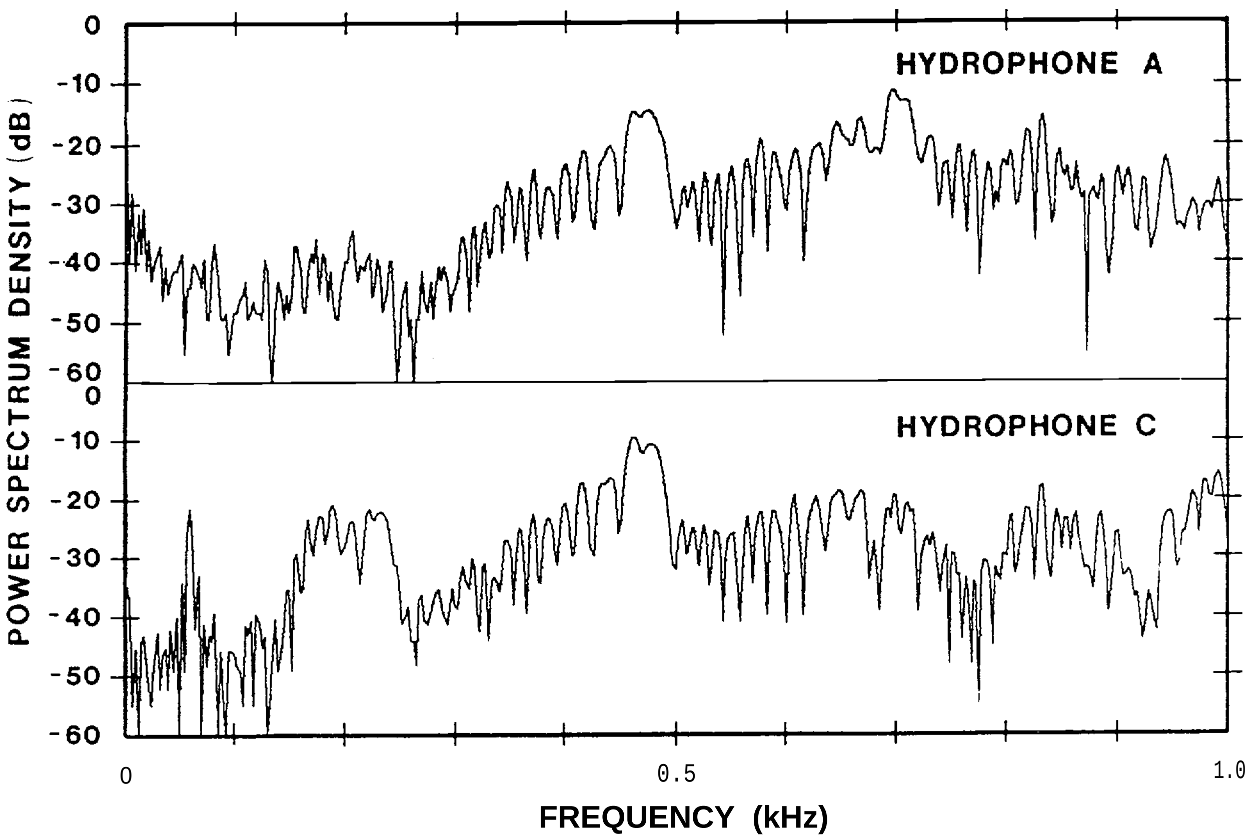


Figure 27. Spectrum of a single quacking bark analyzed at peak amplitude (upper), analyzing filter bandwidth, 18.75 Hz. Power spectral densities (0-1 kHz) of the arrival of a quacking bark at two hydrophores in the triangular array, analyzing filter bandwidth, 3.7 Hz.

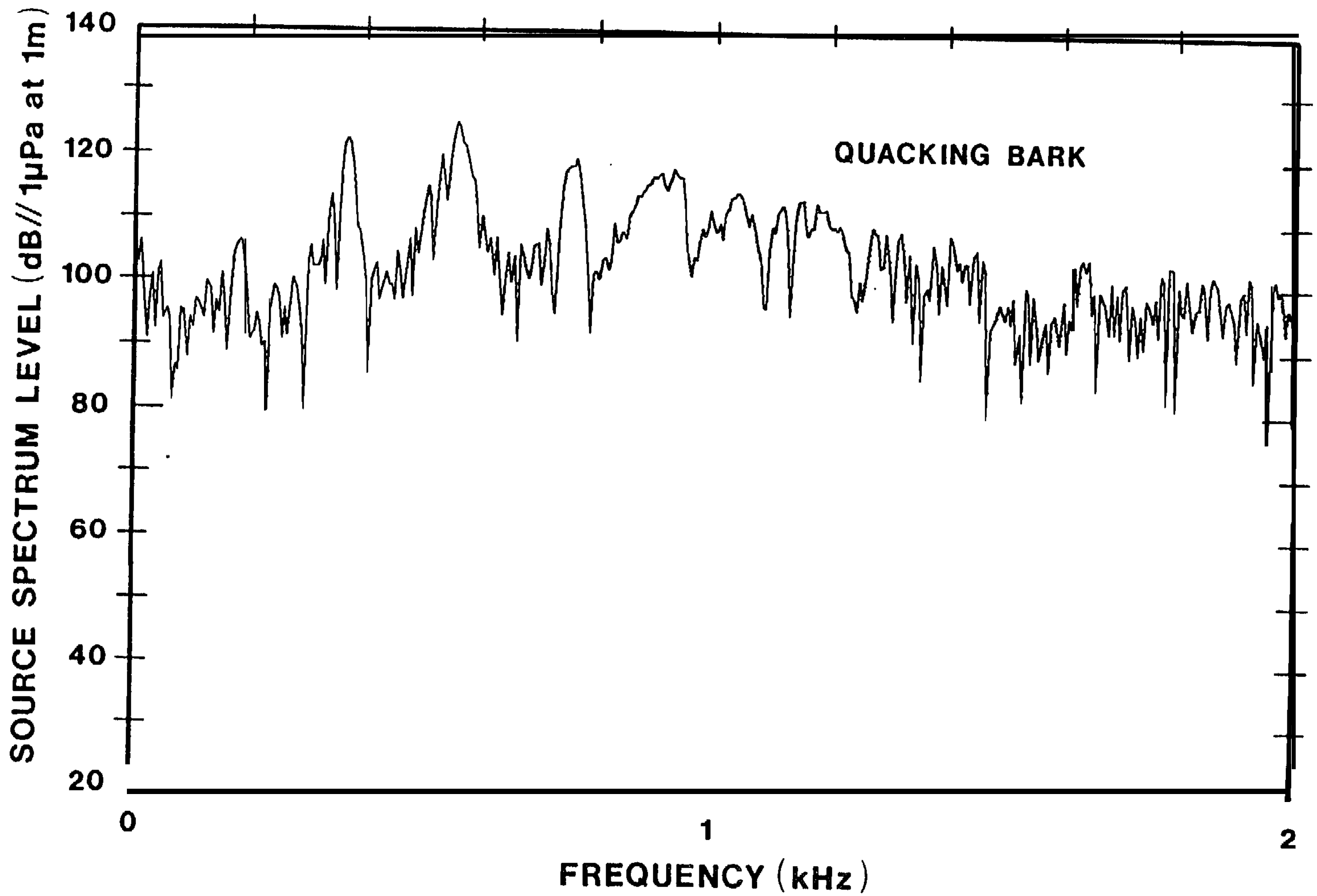


Figure 28. Source spectrum level of a quacking bark recorded and located with the triangular array. Analyzing filter bandwidth, 7.5 Hz.

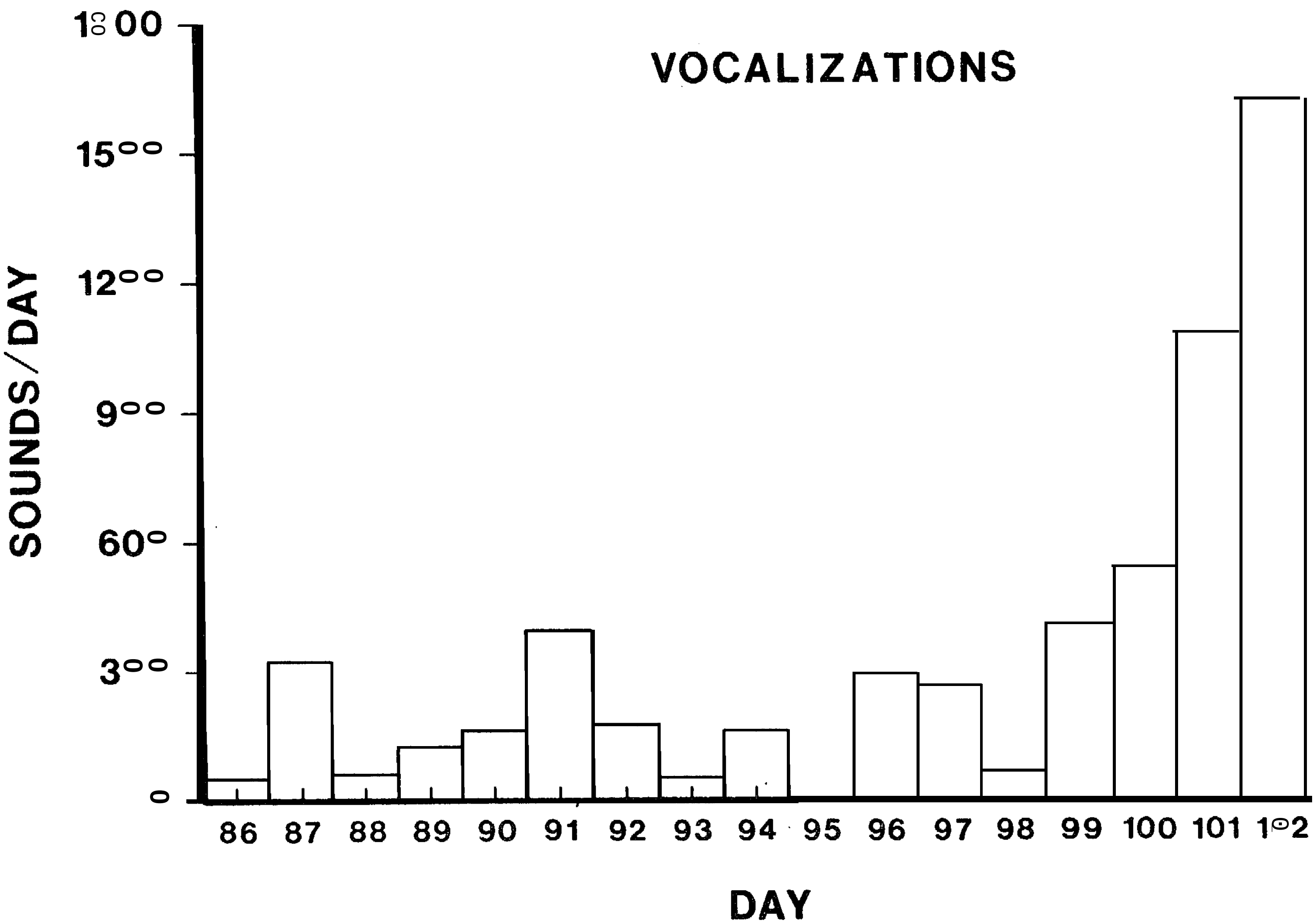


Figure 29. Histogram showing the long-term increase in the rate of ringed seal vocalizations from the array (sounds, excluding scratches) over the recording period beginning with Julian day 86 (26 March 1984). The data were normalized for unequal recording times each day (see text).

There appeared to be a rapid increase in sound production beginning 5 April 1984. It was necessary to normalize these data because of unequal recording effort between days. The data were analyzed by counting the number of all vocalizations from the triangular array in all categories per hour of recording in each day, and extrapolating by multiplying the average number of sounds per hour by 24, the hours in each day represented.

The long-term occurrences of the most prominent and frequent ringed seal sounds are shown in Figs. 30 and 31. The increase in sound production (bar heights, not numbers of bars) can readily be seen in the case of rubs, squeaks, and barks; however, the occurrence of scratches appeared to diminish over the recording period (Fig. 31, lower). These data were normalized for unequal recording durations since they were plotted as the number of sounds/hr. The total numbers of sounds, including scratches, were also plotted as a histogram in terms of sounds/hr, but the trend toward increasing sound production rates was obscured by the pattern of scratch occurrences (Fig. 32).

The occurrences of ten other sound categories recorded from the triangle were plotted as histograms using the computerized file of their counts, but the total numbers of sounds were too low and infrequent to depict as histograms. Instead, these infrequent ringed seal sound categories are tabulated (Table 3). This table can be referenced for the relative total frequency of occurrence for these sounds.

Long-term (other sensors, D, E, F, G)

The occurrence of ringed seal sounds at the remote hydrophores generally was too infrequent to detect long-term changes. A single exception was the occurrence of scratches at E, discussed below under "Scratches". These hydrophores were installed and disassembled at random times over the entire recording period of 25 March-n April. If one of them ceased to function, or the bioacoustic activity was nil for 24 hrs or more, we discontinued the station. Usable sensors were sometimes moved to other locations where we noted activity, e.g., to location G where a ringed seal mother and pup were spotted sunning themselves near a newly opened access hole in a refrozen fracture.

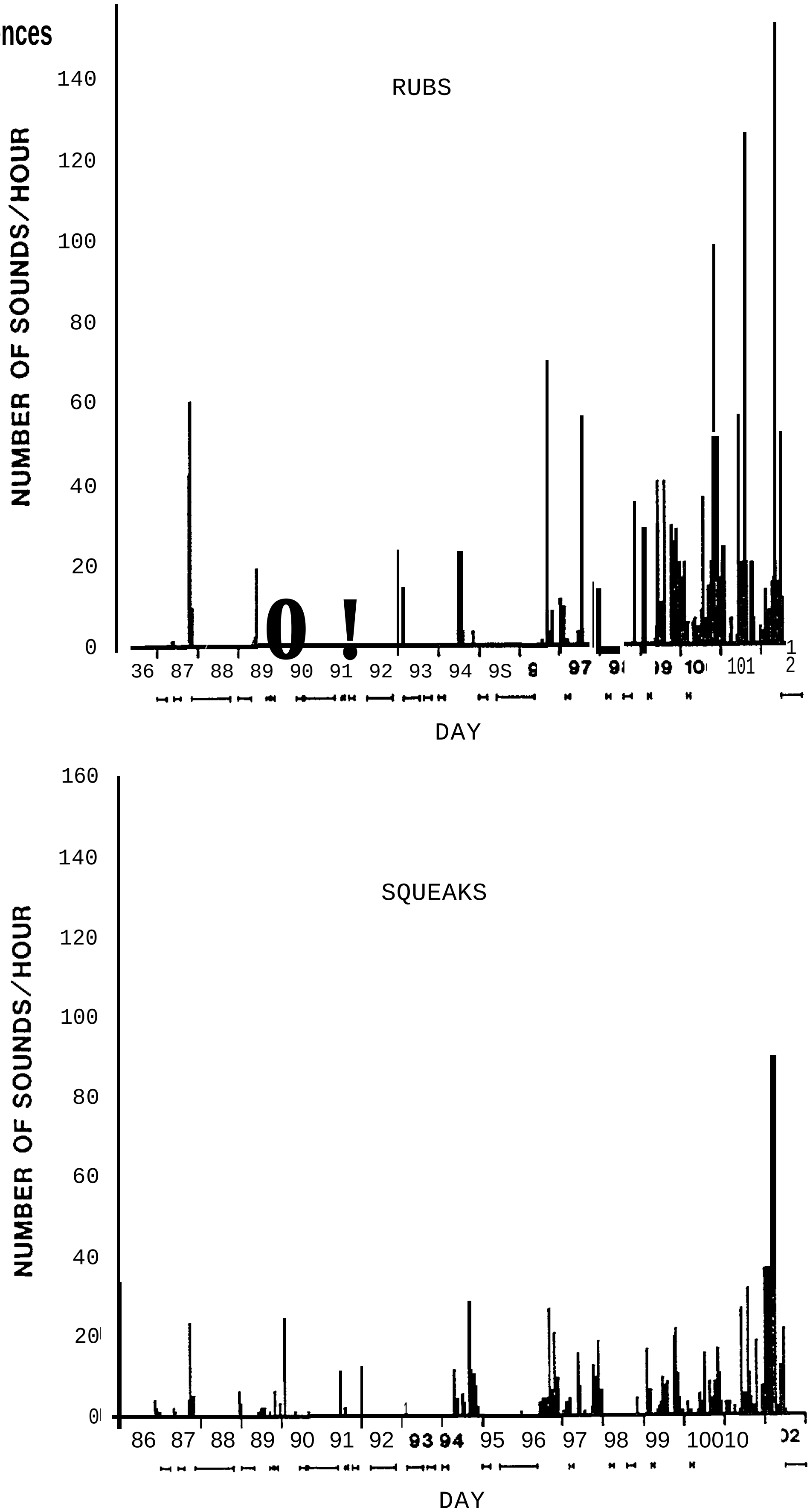


Figure 30. Histograms showing the long-term increase in the rate of rub (upper) and squeak (lower) sounds from ringed seals over the recording period beginning with Julian day 86 (26 March 1984). Periods marked by underlying bars were not recorded.

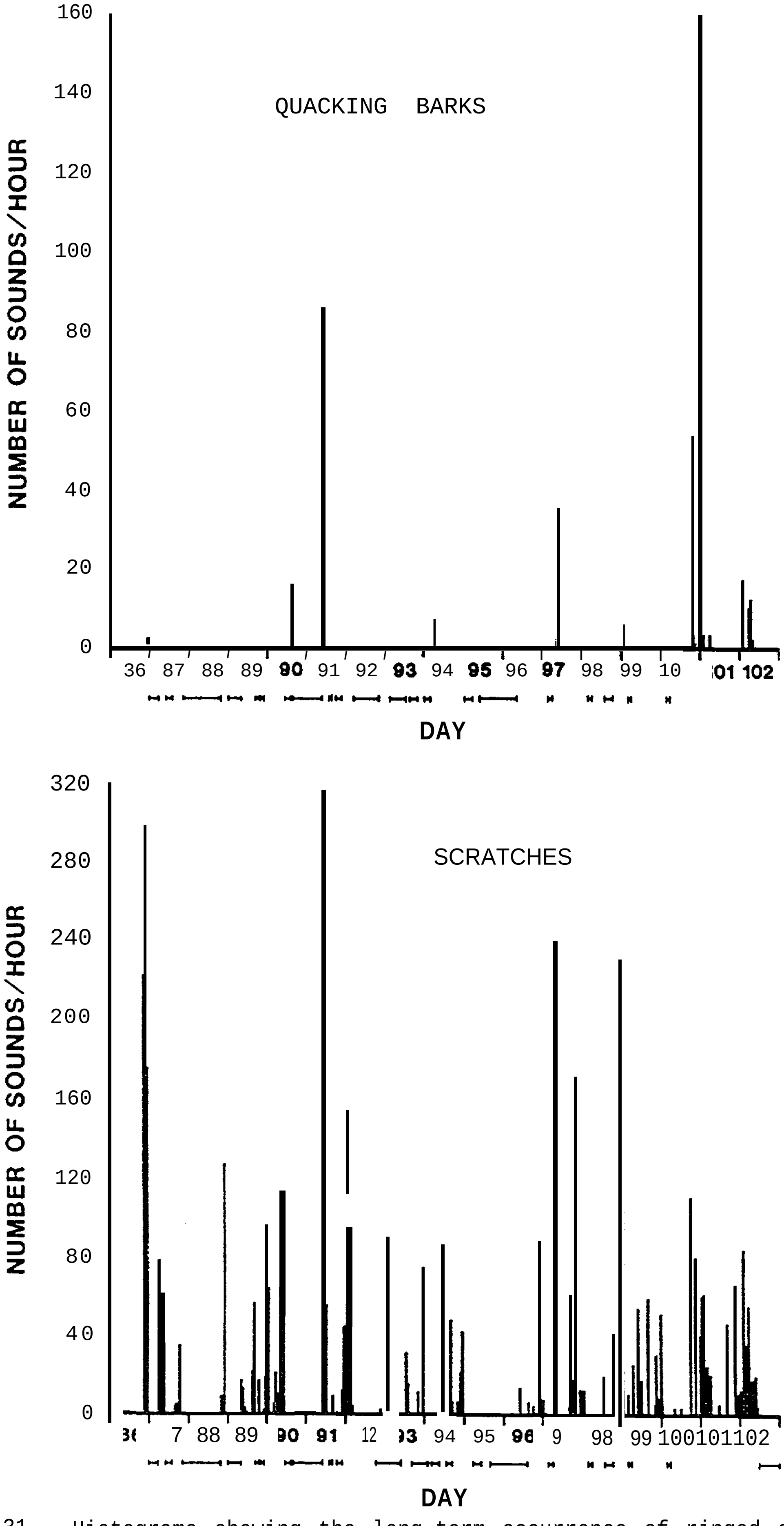


Figure 31. Histograms showing the long-term occurrence of ringed seal sound production rates of quacking barks (upper) and scratches (lower) over the recording period beginning with Julian day 86 (26 March 1984). Periods marked by underlying bars were not recorded.

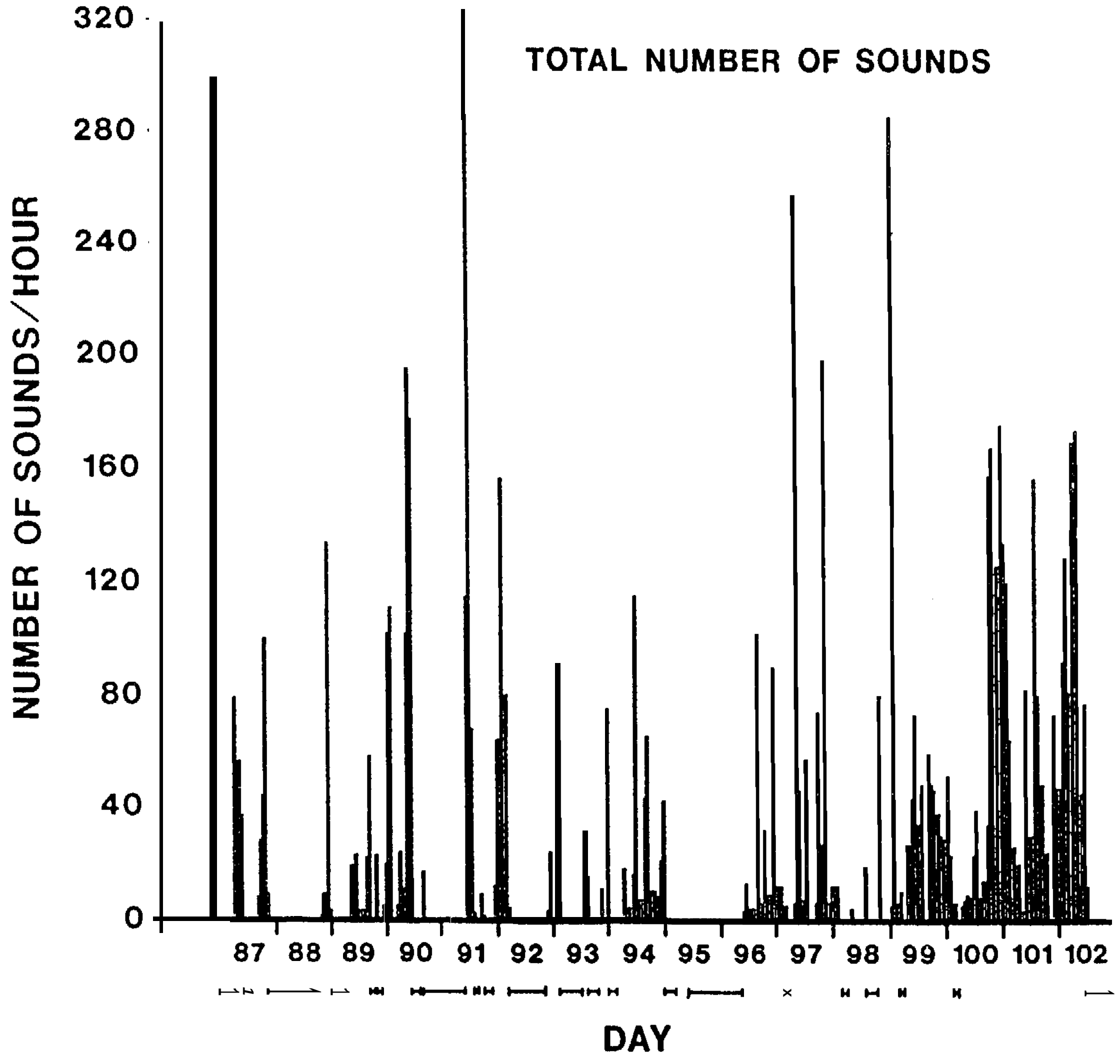


Figure 32. Histogram of pooled data involving all sound categories at the triangle, including scratches, recorded over the entire period beginning with Julian day 86 (26 March 1984).

Table 3. Occurrence of infrequent ringed seal vocalization categories from the triangular array period, 25 Mar-17 Apr 1984.

SOUND CATEGORY	DATES OF OCCURRENCE, '84	NUMBER OF SOUNDS PER HOUR[1]
Cries	27 Mar	8
Belches	30 Mar	1
	31 Mar	8
	6 Apr	4
Roar	9 Apr	22
Buzz	3 Apr	1
Knocking	29 Mar	1
Splash	9 Apr	1
Grunt	28 Mar	1
Snort	30 Mar	4
Explosive	30 Mar	1, 3, 1
Growl	17 Apr	4

[1]Denotes number of sounds that occurred during a recorded hour over which there was at least one occurrence.

The occurrences of six different sound categories are listed in Table 4 according to remote hydrophore locations D-G (also see Fig. 3). With the exception of 14,702 scratches (14,589 of which came from location E) and 597 rubs (location E), relatively few sounds were recorded from these other hydrophores outside of the triangular array.

Diurnal (triangle)

The data were searched for evidence of diurnal (daily) patterns of ringed seal sound production. This was done mostly by studying the frequency of sound occurrence plots resulting from data recorded at the triangular array of hydrophores. First, we pooled all of the sound categories [scratches included), adding all occurrences during recorded hours over a 24 hr period. Since the recording level of effort varied between hours of the day (comparing day to day), it was necessary to normalize summed data by dividing the total number of sounds by the number of days for which a given hour was recorded. The results (Fig. 33) suggested a bimodal distribution peaked at about 1100 and 0130 hrs.

We then searched the frequencies per category and determined that the bimodality, or apparent diurnal periodicity, was basically due to the occurrence of scratches (Fig. 34). In both Figs. 33 and 34, the lower distributions are smoothed versions of the upper distributions obtained by a moving average of 3. The occurrence of scratches peaked at 1030 and 2330 hrs (Fig. 34, lower).

Fig. 35 resulted from removing the scratching sounds and plotting the pooled data for vocalizations. Although it appears that the frequency of occurrence of seal vocalizations may be independent of the hour of the 24-hr day (averaged data for the triangular array), a statistical analysis showed there was some dependency (chi square = 38.8 > 35.2 (.05) 23 deg freedom). In the same way the raw data showed dependence (chi square = 127.95 > 35.17 (.05) 23 deg freedom).

Table 4. Occurrence of ringed seal sounds at sensors other than from the triangular array during the recording period, 25 March-n April 84.

SENSOR	SOUND CATEGORY	NO. SOUNDS PER HR[1]	RESPECTIVE DATES (J)
D	Rubs	2,3	86,88
"	Scratches	2 - "	88
E	Rubs	114,83,400	89,89,89
"	Scratches	See Fig. 38	
"	Squeaks	1,1,1,2	88,89,89,93
"	Crackle	104,2	96,96
"	Crunch	3	93
"	Knocking	9,9,2,8,21	93,93,95,96,96
F	Scratches	52	89
G	Rubs	21,13	96,96
"	Scratches	59	96
"	Crackle	120,43,3	95,95,96

[1]Denotes number of sounds that occurred during a recorded hour (included are the respectively listed Julian (J) dates, next column) over which there was at least one occurrence.

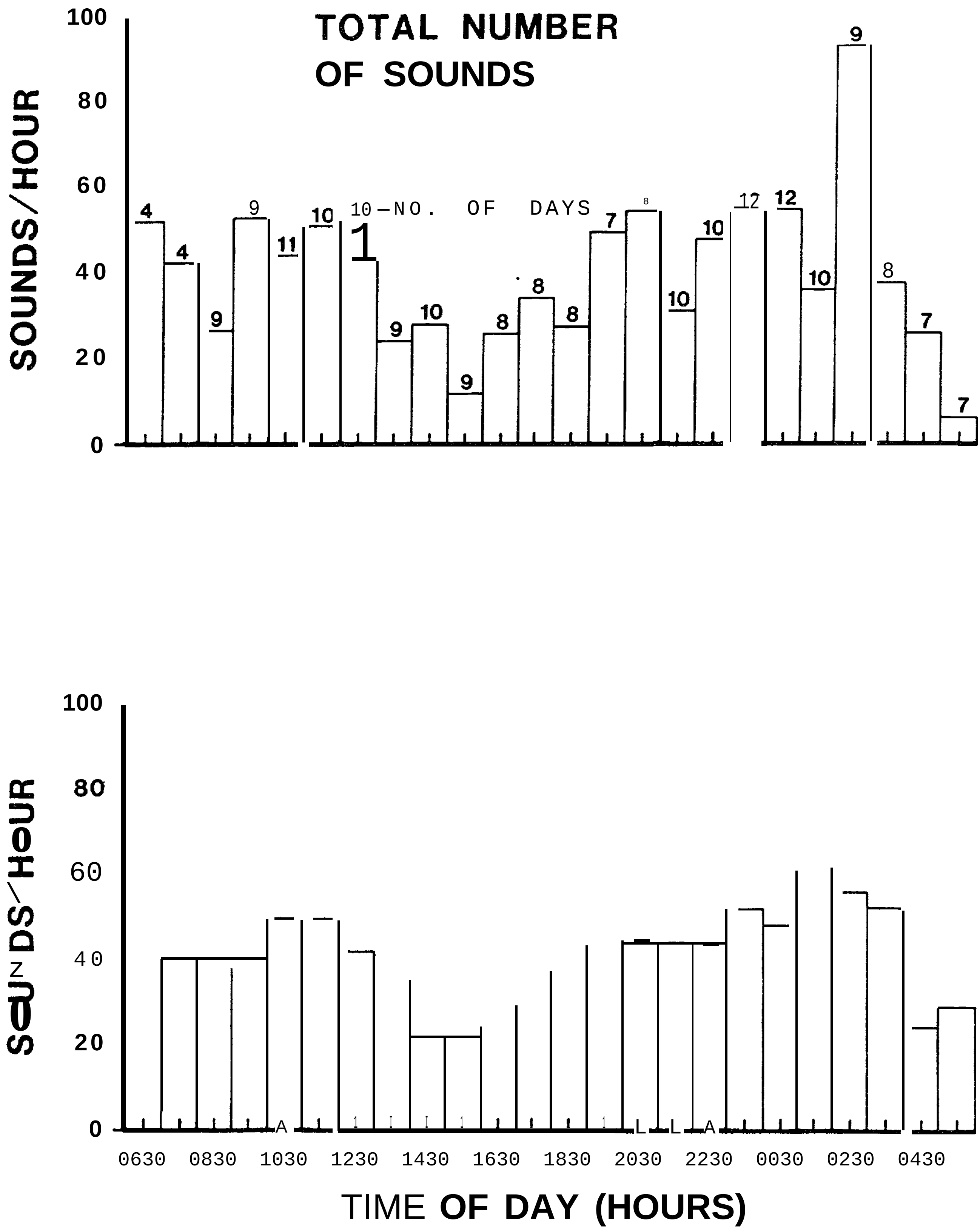


Figure 33. Histograms showing the hourly occurrence of all ringed seal sounds from the triangular array, pooled eve? the number of days indicated and normalized for unequal numbers of recordings (upper) and the same data smoothed by a moving average of 3 (lower).

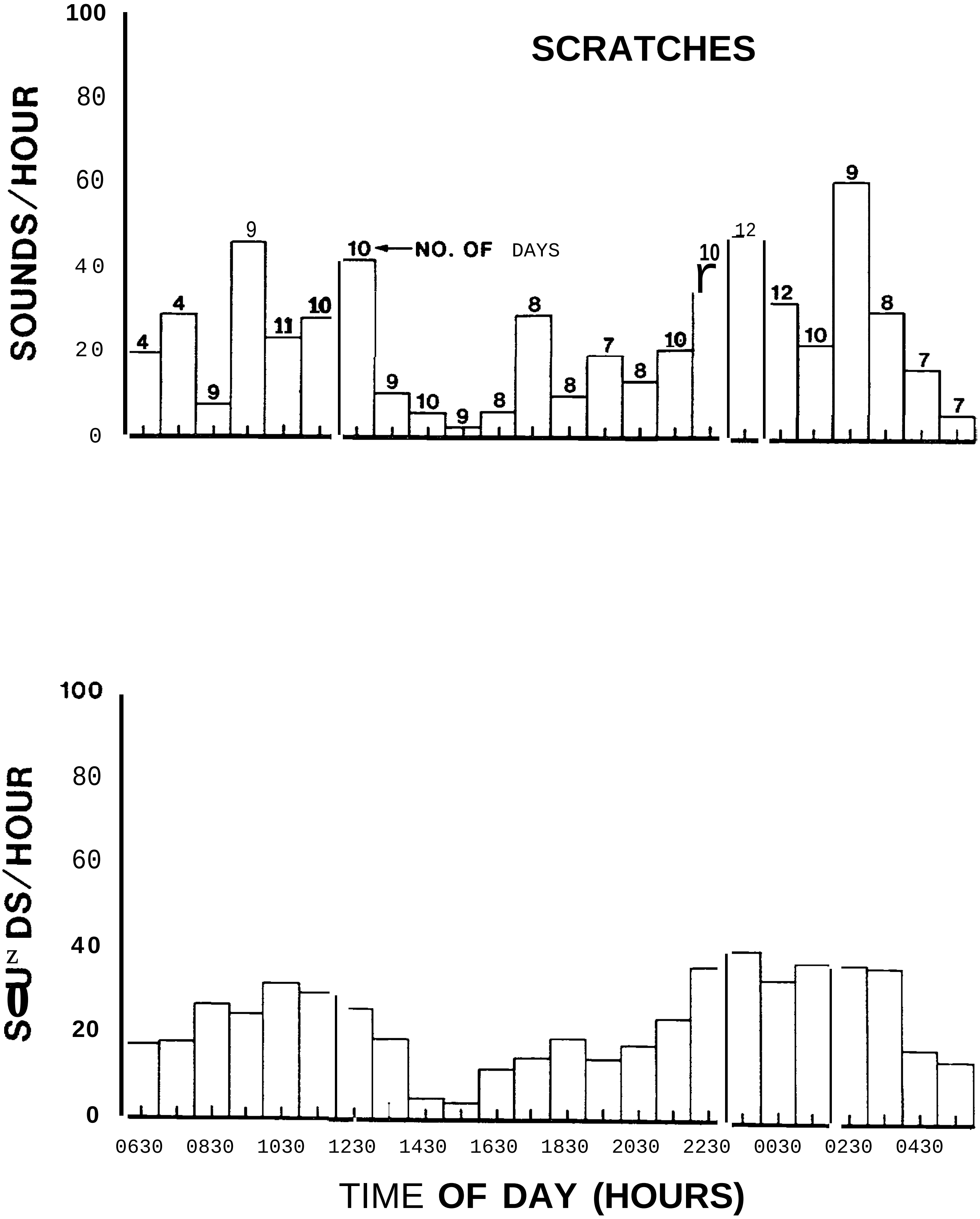


Figure 34. Histograms showing the hourly occurrence of all ringed seal scratches from the triangular array, pooled over the number of days indicated and normalized for unequal numbers of recordings (upper) and the same data smoothed by a moving average of 3 (lower).

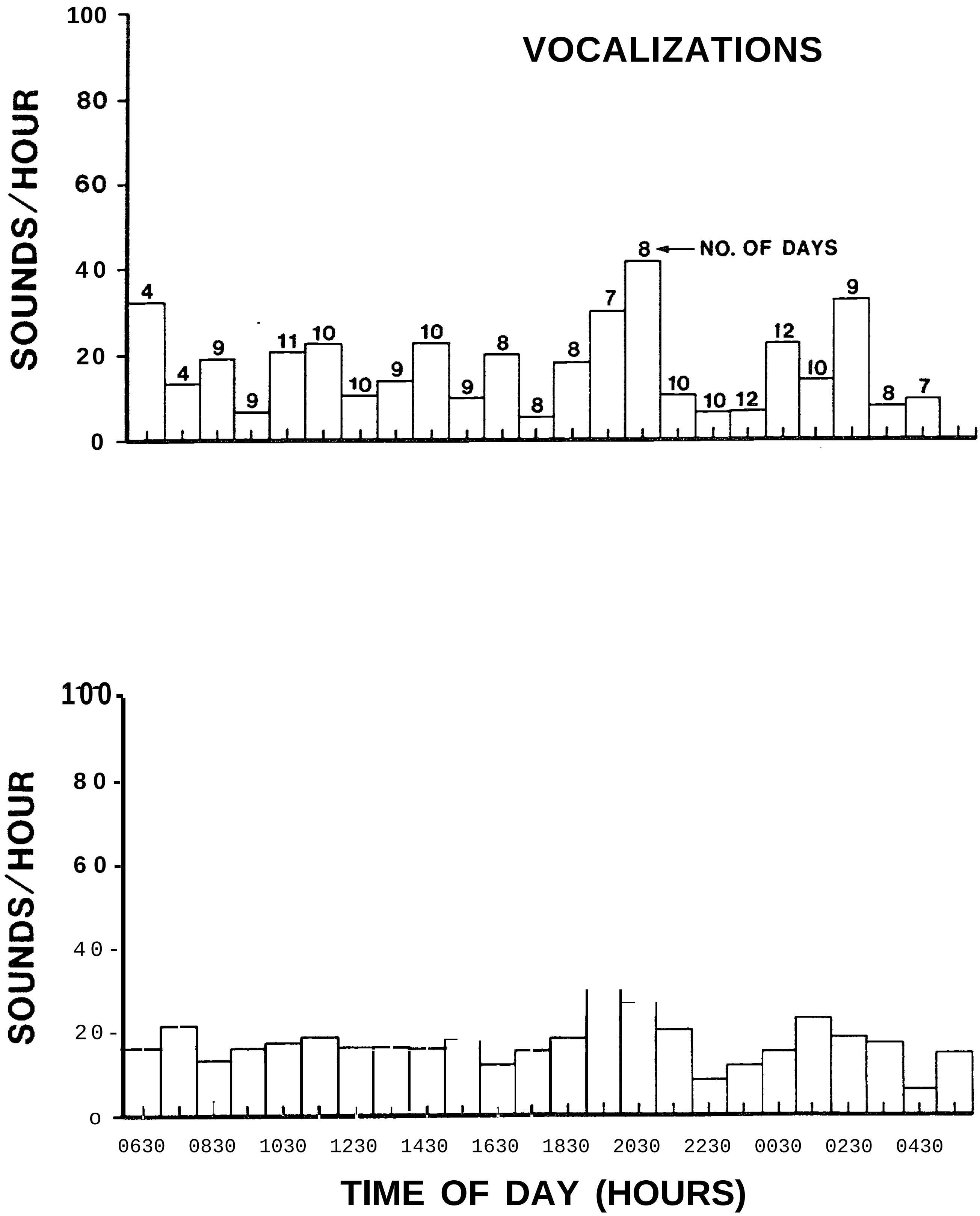


Figure 35. Histograms showing the hourly occurrence of all ringed seal vocalizations from the triangular array, pooled over the number of days indicated and normalized for unequal numbers of recordings (upper) and the same data smoothed by a moving average of 3 (lower).

A Fast. Fourier Transform (FFT) was then produced to illustrate the frequency of occurrence (Fig. 36). This indicated possible periodicities of 2 and about 7 hours in the occurrence of pooled data consisting of 3,359 sounds. Figs. 33 to 36 pertain only to data from the triangular array, which were not duplicated, i.e., only the occurrences on one hydrophore (nearly always A) entered these data even though all three hydrophores were recorded simultaneously.

Scratches

Since scratches were so numerous and they were associated with known types of behavior (breathing hole, access hole, or lair building/ maintenance), a study was made of their frequency of occurrence.

Individual scratches occurred in bouts that consisted of 1-126 sounds (mode 4; median 11). Bouts were defined as groupings of, scratches separated by at least 3 sec. The frequency of occurrence of given numbers of individual scratches per bout is shown in Fig 37. They comprised a skewed curve that appears to have three peaks centered on 4, 11, and 27 sounds per bout. By far the commonest number of scratches per bout was 6 or less.

A total of 310 bouts was recorded from the triangular array, 26 March to 11 April. Single bouts from a single seal lasted as long as 101 see, and as many as 34 bouts from more than one seal occurred over a period of 2 hrs. Although only one bout may have been heard in a given time period, bouts generally occurred in series (one group of scratches after another) with a long pause, e.g., 1 rein, between series. We never heard scratching from two locations at the same time, although on 26 March, a series from one location was immediately followed by another elsewhere.

On 29 March, we started to record from site E where a hydrophore had been buried in snow and ice at the periphery of an active lair. The lair contained a seal pup which, surprisingly, turned out to be a bearded seal (identified by John Burns, Alaska Department of Fish and Game). The most common sound recorded at this location was scratching. The frequency of

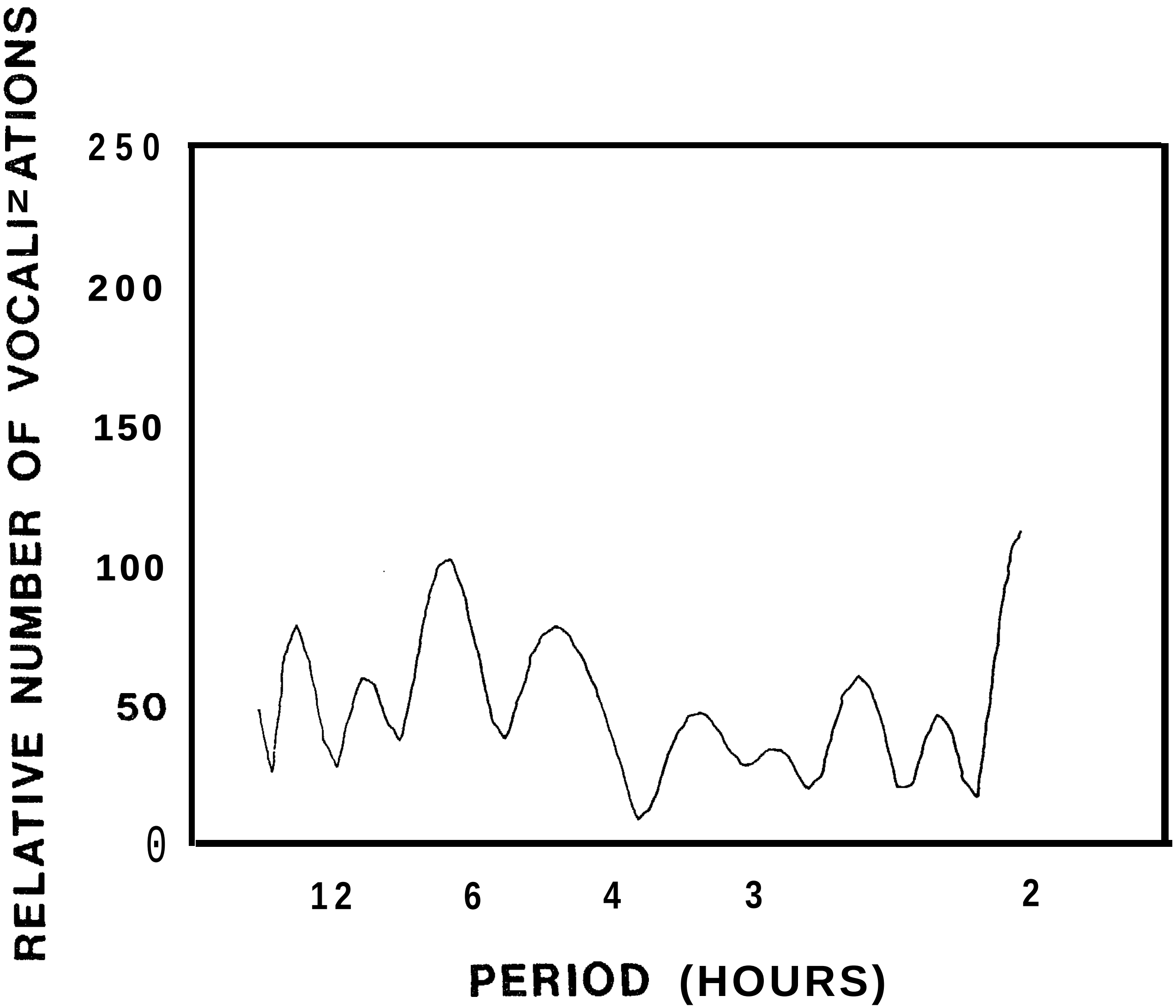


Figure 36. Fast Fourier Transform (FFT) of the frequency of occurrence of ringed seal vocalizations (sounds, excluding scratches) showing two possible periodicities of about 7 and 2 hours (from pooled data of 3,359 vocalizations at the triangle).

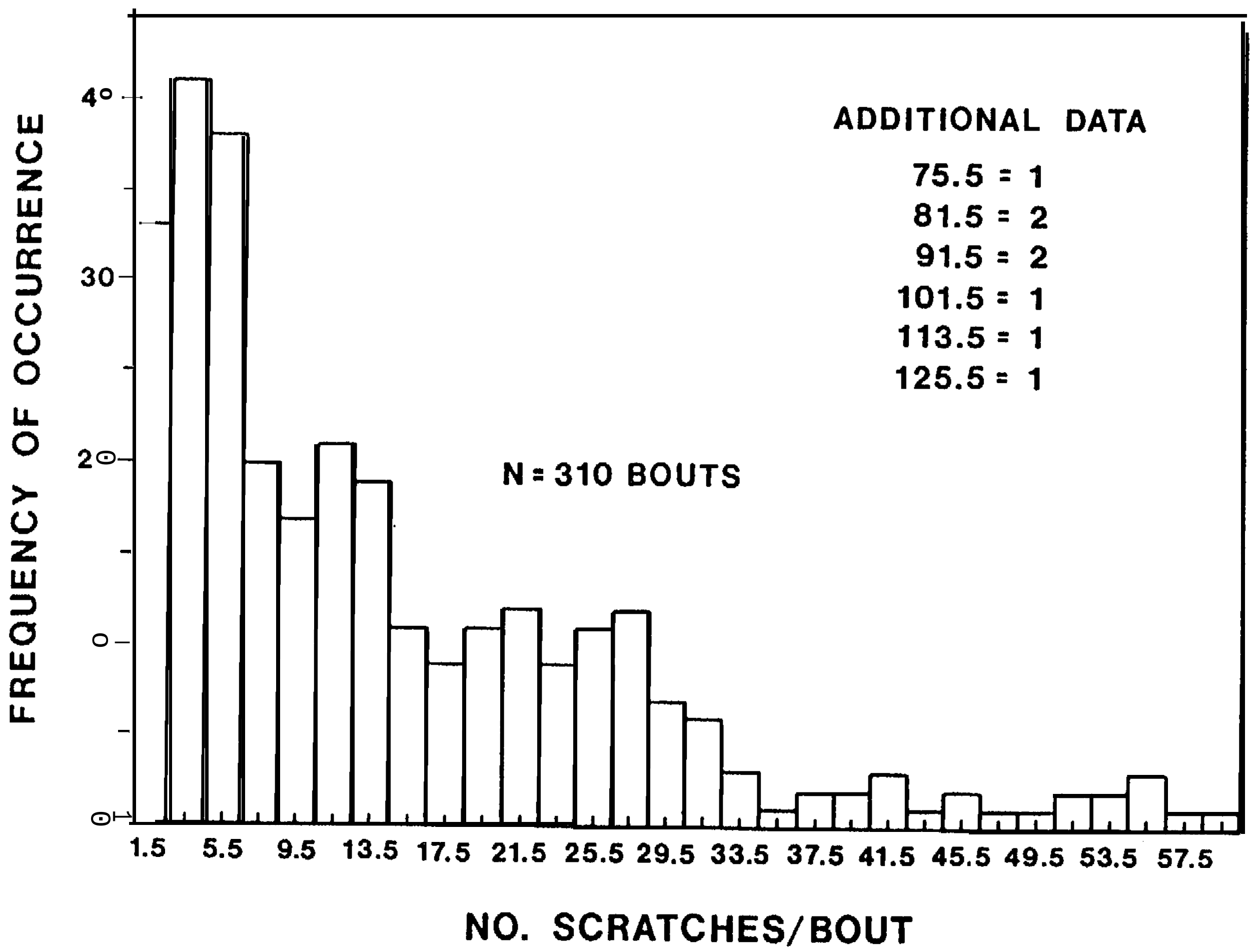


Figure 37. Number (frequency) of ringed seal scratches per bout, including 310 bouts, recorded from the triangular array over the recording period, 25 March-11 April 1984.

occurrence of these sounds was plotted over 56 hrs of recording, sampled over 10 days, 29 March-7 April (Fig. 38). The number of scratches peaked on the third day of recording (31 March) and then decreased until no more were heard after 5 April. At their peak, as many as 4,388 scratches were noted in one hour's time, beginning at 1205 hrs, 31 March.

On 9 April, the hydrophore signal was virtually absent from location E. The S/N ratio and the character of the noise indicated that the useful battery power had run out. Upon our inspection of the lair and the hydrophore, the pup was found frozen into the refrozen access hole with the top of its head and back just above the surface of the ice. We removed the transducer, battery, and transmitter. The site was inspected on 15 April and nothing had changed.

There were very noticeable changes in the acoustical characteristics of individual scratch sounds within bouts that presumably were caused by scratching different forms of ice in different ways. This occurred in virtually all bouts, regardless of location.

Physical Factors and Sound Production

Four environmental factors were measured in the conduct of this research: ambient surface light, windspeed, ambient air temperature, and underwater sound speed. We measured light, wind, and temperature because of the possibility that they may have been associated with the frequency of occurrence of ringed seal sounds. Underwater sound speed was needed for sound source local ization (see METHODS).

Light - The relationship of light intensity (μWatts/cm^2) and time of day was first plotted for each of 16 days, with individual datum points at the times of measurement. As reported by the local weather broadcasters over this period of time, daylight periods lengthened by an average of 10 rein/day. Pooled light measurements appeared as a strong modal curve which peaked at about 1400 hrs (local time), Fig. 39. The

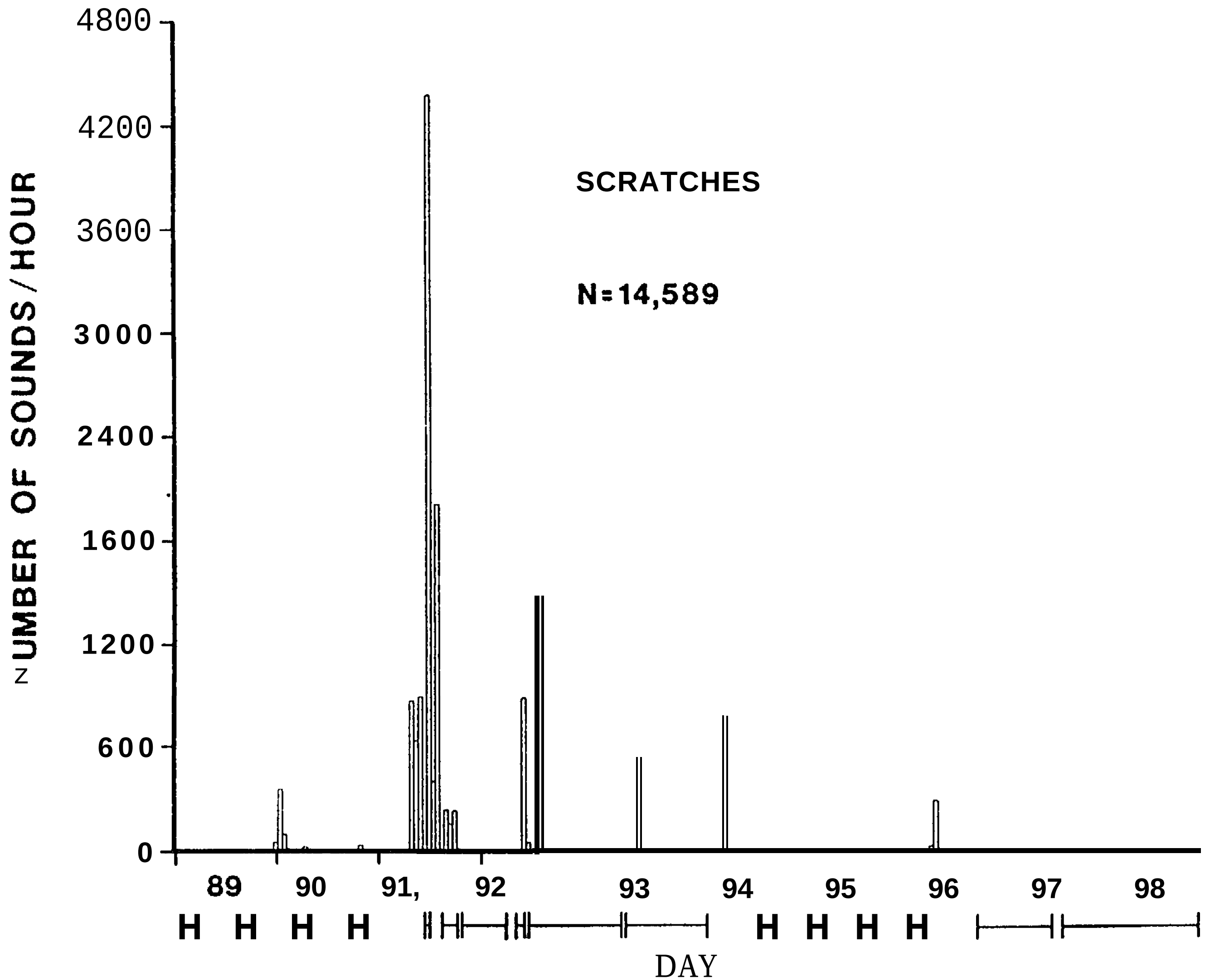


Figure 38. Occurrence of scratching sounds as recorded during 56 hrs over 10 days from the lair at site E, which contained a bearded seal pup, Julian days 89 to 98 (29 March-7 April 84).

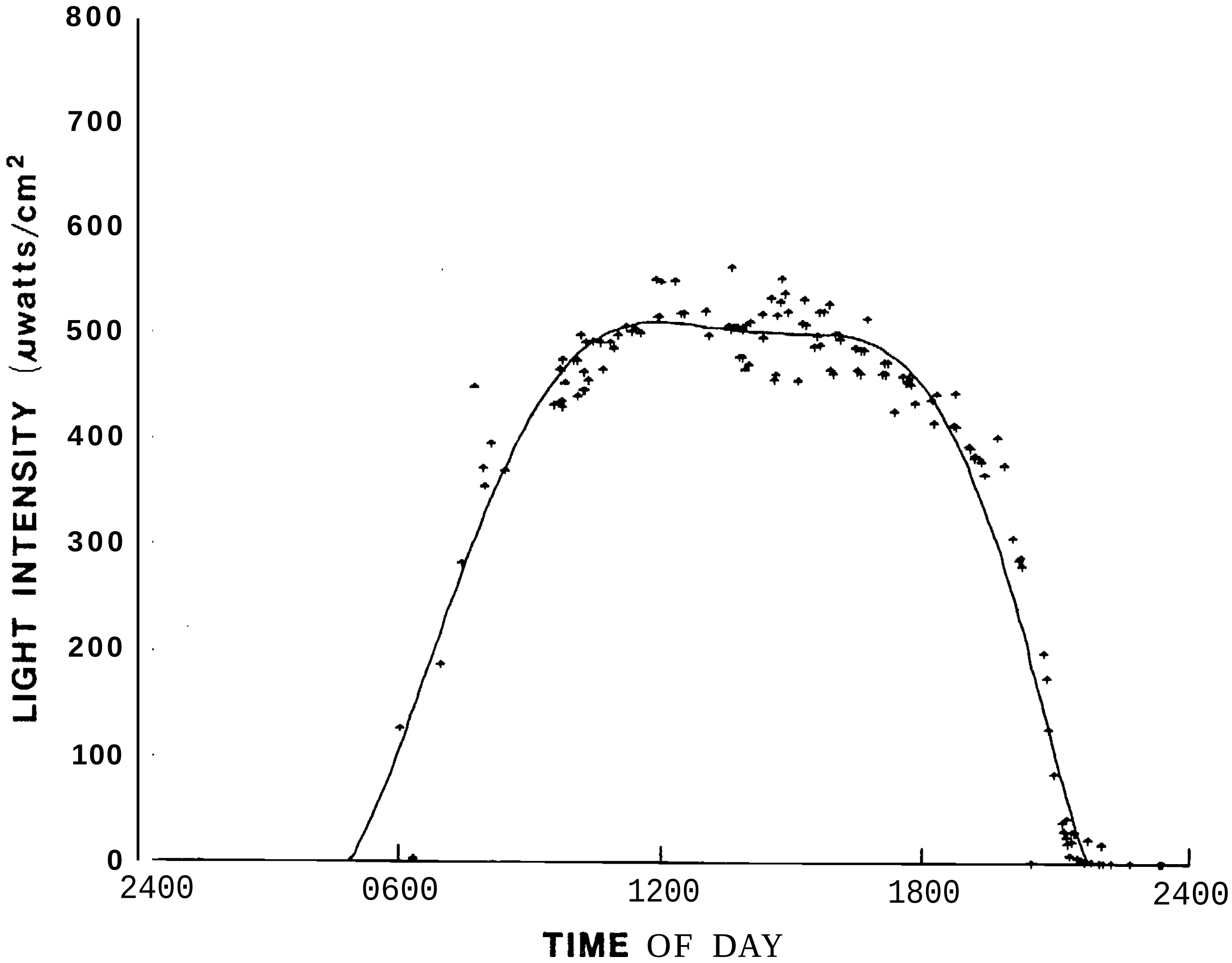


Figure 39. The total of 141 ambient light measurements vs time of day pooled over the recording time period, 25 March-10 April 84.

highest measurements varied from about 450-570 μWatts/cm^2, which occurred over the time period 0930-1800 hrs, depending upon overcast conditions. Our photometer was sensitive enough for measurements from about 0600-2130 hrs on the shortest day.

When the pooled sound data (excluding scratching), i.e., Fig. 35, were divided into light vs dark hours (averaging 0600-2100, 2100-0600 hrs), it was found that more vocalizations/hr appeared during the light hours (chi square = 5.0 > 3.8 (.05) 1 deg freedom). We have already shown that there was some dependency of the number of seal vocalizations/hr on time of day (Frequency of Occurrence, Diurnal).

Using the average light intensity values during times of the day (fitted line, Fig. 39) and the number of seal vocalizations/15 min period that occurred during times of measurable light, we examined the association of the two variables. Based on 901 pairs of observations, light and numbers of sounds were not statistically correlated (r = .014 < .062 (.05)).

<u>Windspeed</u> - The range, mean, and values of windspeed (mph) over 210 measurements on days of recording are given in Fig. 40. The tabulated and graphed values, ranging from calm to 45 mph (mean 11.3, SD 9.6), appear in the Appendix. There was a significant negative correlation between the number of ringed seal vocalizations and windspeed, based upon counts of sounds in the 15-min period following each windspeed measurement (r = |-0.185| > 0.114 (.05) 210 N). In other words, more vocalizations/hr were counted during low windspeeds. Over the above stated range of windspeeds, vocalizations/15-min period ranged from 0 to 183 (mean 8.4, SD 23.8).

The number of scratches/15-min period was not correlated with windspeed (r = .0027 < 0.114 (.05) 210 N) where scratches in the first 15-min period were counted directly after windspeed measurements. In this set of data, the number of scratches ranged from 0 to 96 (mean 4.9, SD 13.9). The range mean and standard deviation for windspeeds were the same as those in the association with vocalizations.

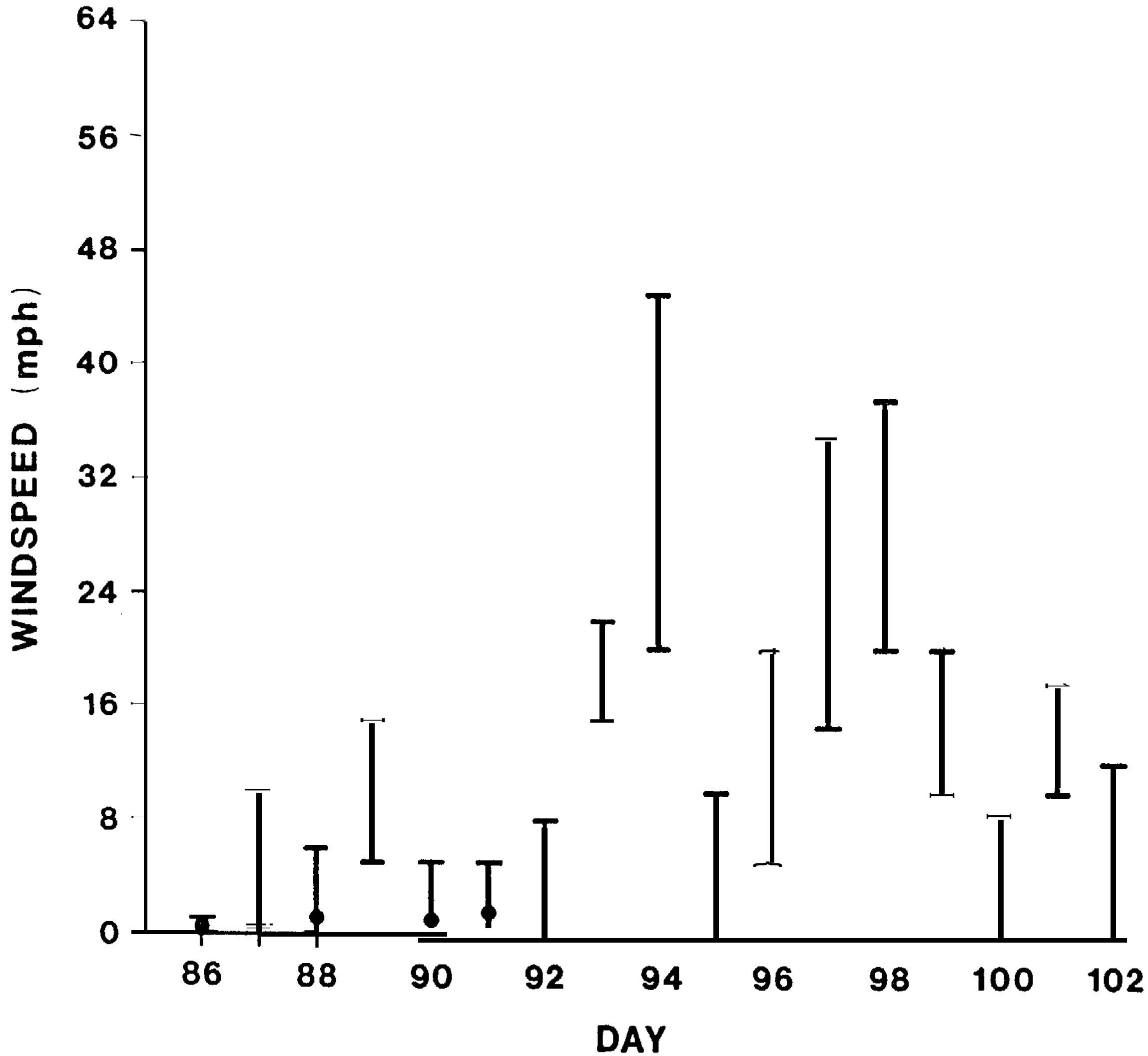


Figure 40. Range, mean and values of windspeeds measured on recording days (N = 210).

Temperature - The range and means of 210 temperature readings on the days of recording are given in Fig. 41. Tabulated temperature data, ranging from -37 to 10°C appear in the Appendix. Temperature variations over 2 April are shown in Fig. 42. As with most days, minima occurred during the hours of darkness, maxima at about 1330 hrs. The number of vocalizations/15-min period following each temperature measurement was significantly negatively correlated with temperature ($r = |-0.17| > 0.114$ (.05) 210 N). There were more vocalizations/15-min period during lower temperatures. The range, mean, and standard deviation for vocalization/15-min period were the same as this comparison with windspeed since the same set of vocalization data was used (range 0-183, mean 8.4, SD 23.8).

Because the number of vocalizations was negatively correlated with both windspeed and temperature, we wanted to examine the association between these two environmental factors. Using 198 pairs (recorded simultaneously) of the two variables noted throughout the recording period, it was determined that they were not statistically correlated ($r = .085 < 0.117$ (.05) 196 deg freedom).

The number of scratches/15-min period following temperature measurements was not significantly correlated with temperature ($r = |-0.036| < 0.114$ (.05) 210 N). The range, mean, and standard deviation of the number of scratches in this set of data were the same as in the comparison between windspeed and scratches (O-96, 4.9, 13.9, respectively).

Underwater sound speed - A set of measurements of underwater sound speed appears in Fig. 43. As described above, this parameter was needed for the localization work. The values were fairly uniform from the surface (in the ice hole and just below) to the bottom of the water column, as would be expected in such shallow water. The average value of 1437 m/see was used in the localization.

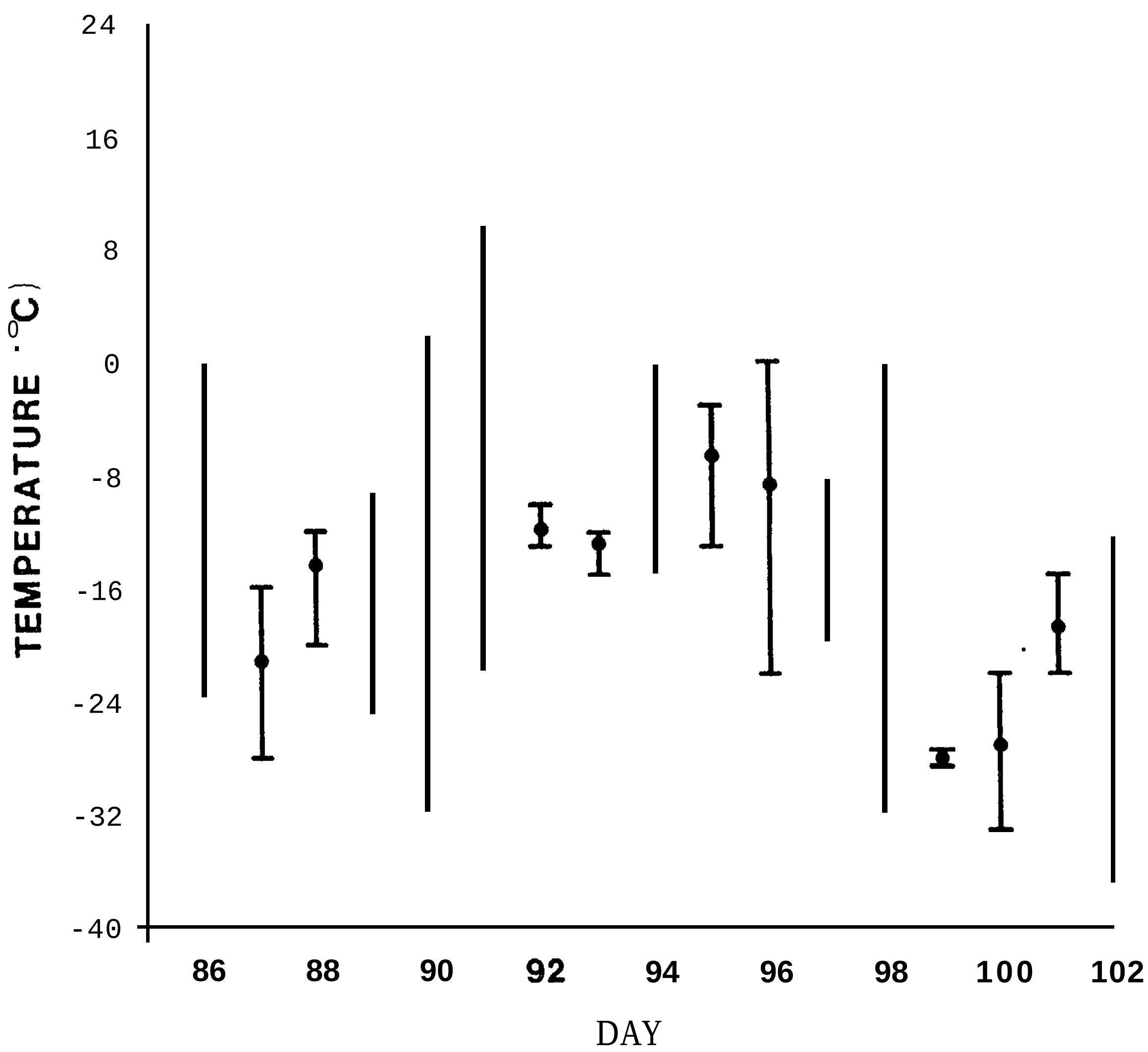


Figure 41. Range and means of temperature readings taken on recording days (N = 210).

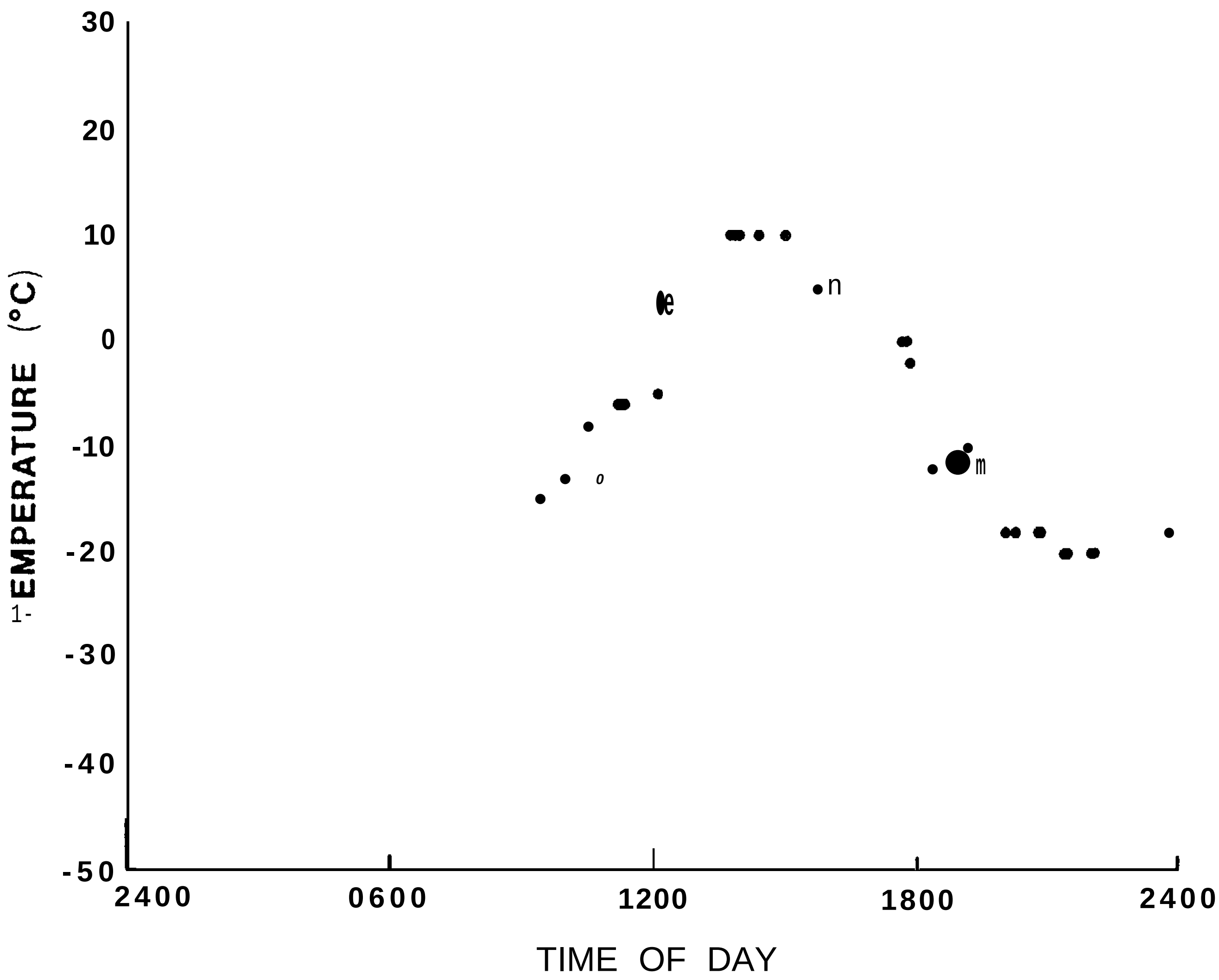


Figure 42. The range of ambient temperature readings taken during 2 April 84.

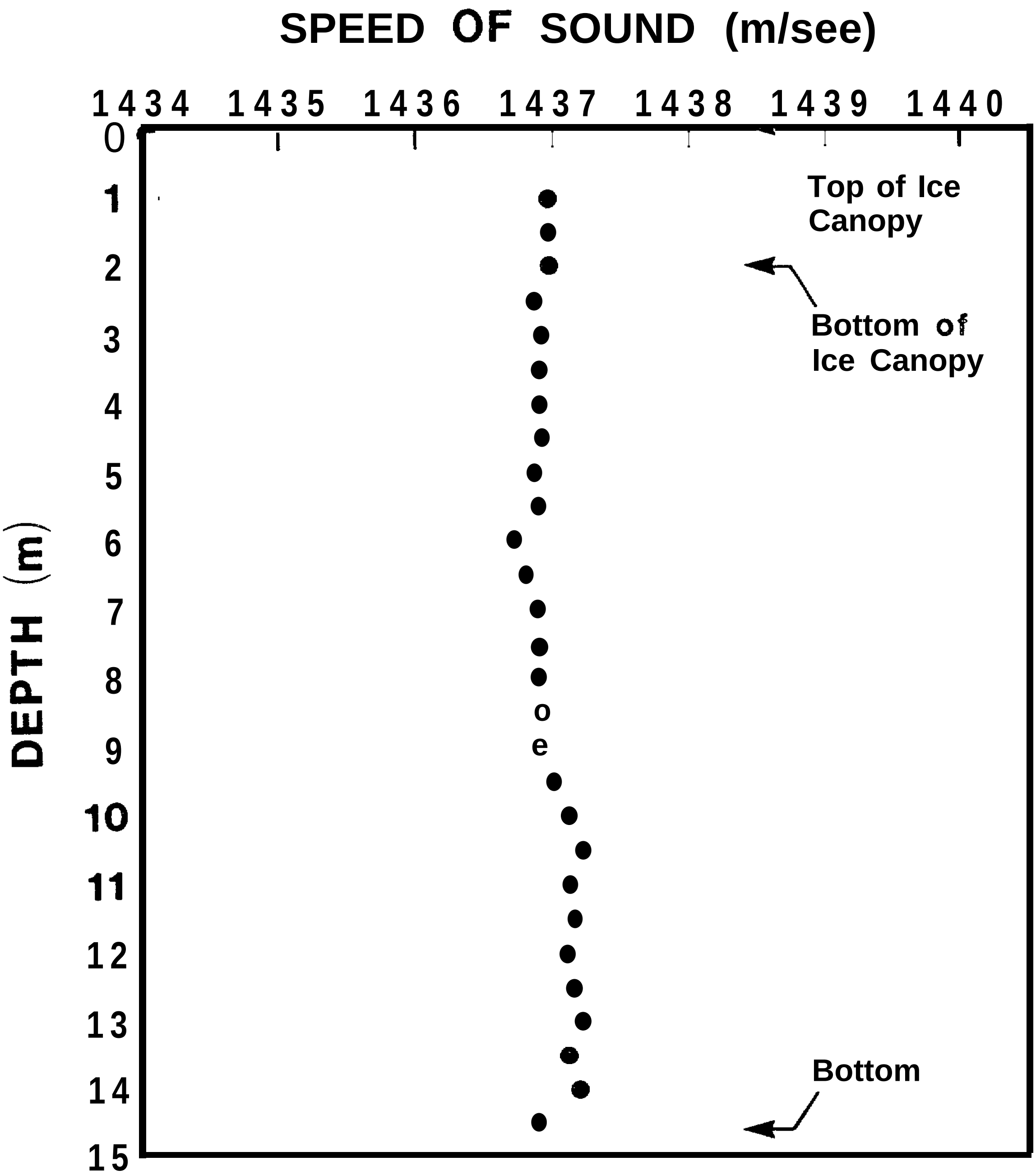


Figure 43. Speed of underwater sound vs depth as measured in Kotzebue Sound at the study site, 25 March 1984. The upper three measurements were in seawater in the drilled hole.

C. Other Recorded Sounds

Low frequency pulses

On more than 36 occasions during the overall recording period, a series of low frequency pulses (LFP) was recorded. These signals occurred in trains of varying total duration from 3 to 16 sec. The pulse-pulse interval was about 95 ms, and the fundamental frequency within a pulse was about 106 Hz (Fig. 44). The amplitude varied between pulses, but the received signal-to-noise ratio of a train was typically 26 dB. The temporal onset of the pulse train was very slow vs an abrupt off ramp.

LFP's originated from an offshore direction, but we were unable to localize them due to the limited size of the hydrophore array. They appeared to be of man-made origin, but we do not know the specific source of these curious sounds.

The onset of LFP's was rapidly followed by a series of ringed seal vocalizations consisting of quacking barks, squeaks and rubs on 31 of the 36 noted occurrences. The vocalizations occurred during the LFP trains, and they decreased when the trains stopped.

Water

Occasionally, we recorded dripping on the water's surface. Aurally, the sounds closely resembled those from pouring a small amount of water from a cup on the surface of a large volume of water. They were broad-band sounds extending up to 10 kHz. The waveform of part of such a series of dripping sounds and the spectrum of another appear in Figs. 45 and 46. We have recorded these sounds before near Prudhoe Bay and Barrow.

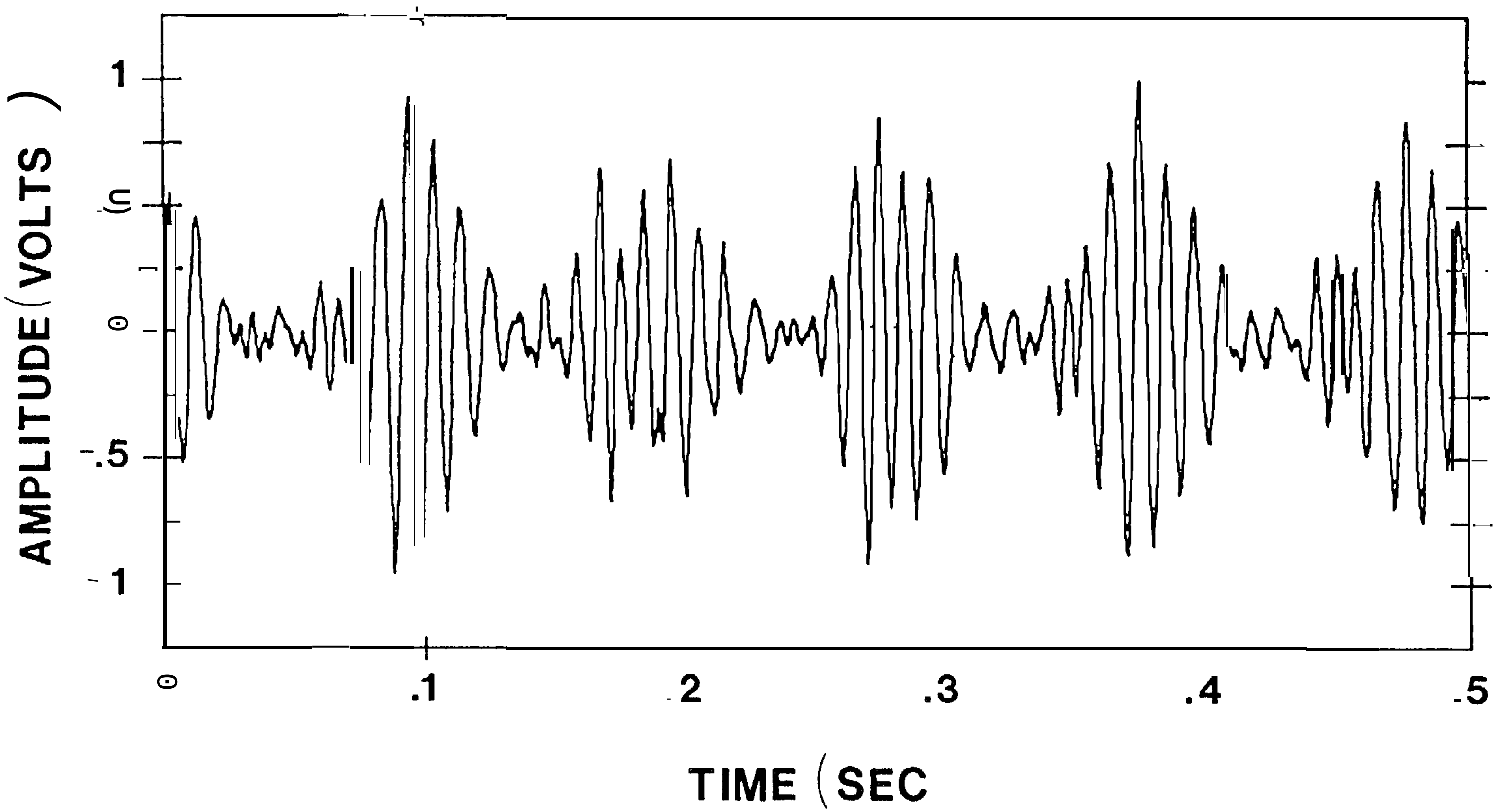


Figure 44. Waveform of a section of a Low Frequency Pulse train showing nearly five pulses.

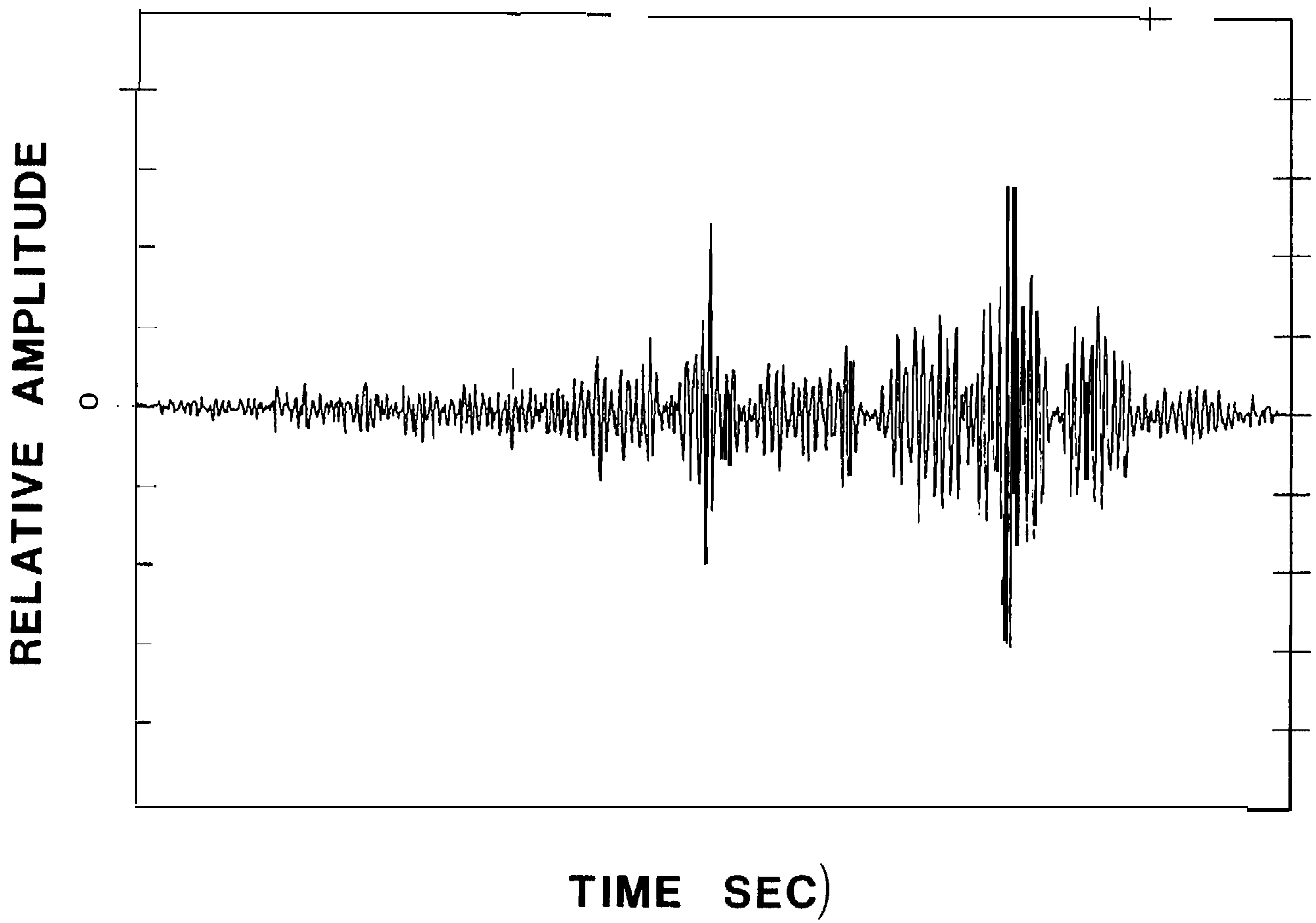


Figure 45. Waveform of water dripping sounds from the triangular array.

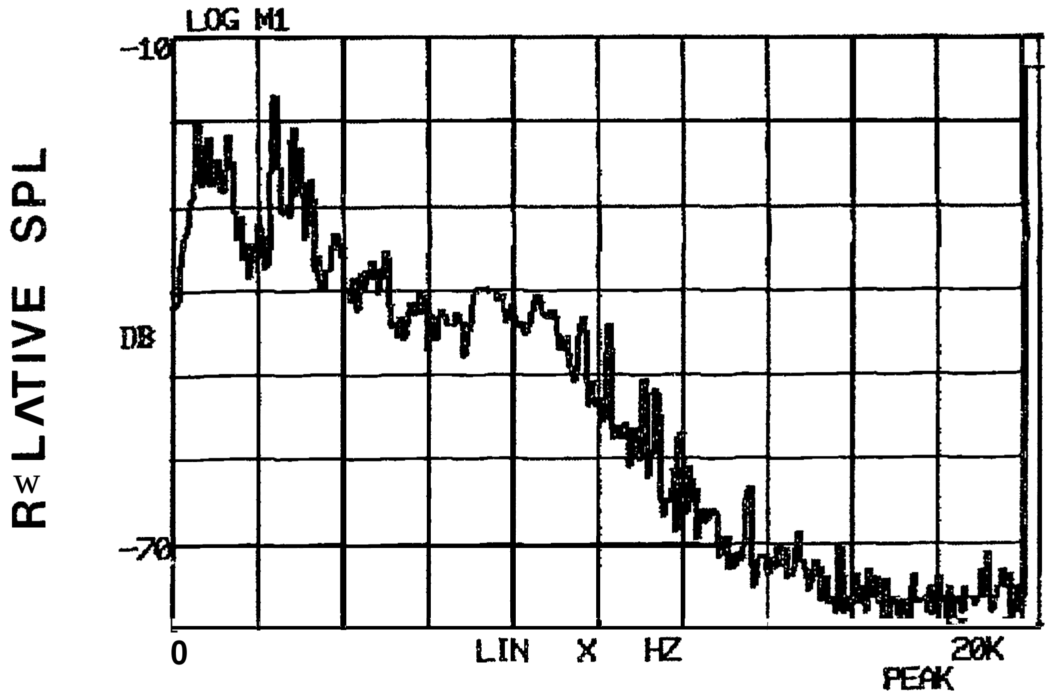


Figure 46. Peak spectrum of water dripping noise recorded from hydrophore A, 6 sec duration, analyzing filter bandwidth, 75 Hz.

Ice

During times of drastic temperature reduction, especially when the temperature dropped to around -30°C for a day or two, we experienced very active ice sounds that resembled sharp cracks followed by reverberation. A particularly active period was 6, 7, 8 April. Fig. 8 exemplifies the waveforms of ice cracking sounds, as does Fig. 11 which shows the arrivals of an ice cracking sound at separate hydrophores, A and C, and their cross-correlation function. Onsets of these sounds were always very fast and followed by a much slower decay rate.

Peak spectra of an ice cracking sound are given in Fig. 47. The source spectrum level of an ice cracking sound is displayed versus frequency (Fig. 48). The spectrum was previously shown in terms of power spectrum density (Fig. 9). The level given by the curve is the source level at the indicated frequency in a 1 Hz frequency band relative to 1 µPa at 1 m, Figs. 9, 47, 48 show that the frequency region of highest energy is 500-1500 Hz.

The positions of nine ice cracking locations are given in Fig. 55. All were associated with active areas of ice as revealed by their locations at ridges or refrozen cracks.

Chukchi Sea

Our purpose in recording from this site (192 km offshore of the triangular array) was to compare the bioacoustic activity there with what was being recorded in Kotzebue Sound. We saw only one open fracture on the way out to this offshore site, at about one-half the distance. The fracture, judged to be about 4 m wide, ran parallel to the International Date Line. Although limited flight time and fuel precluded further exploration, we could see several seals hauled out along the fracture's edge. These were mostly bearded and some ringed seals, including pups. When we did reach the intended recording site, the recording time was also limited because it was not possible to shut down the engine of our single engine plane for any longer than about two hours in such cold.

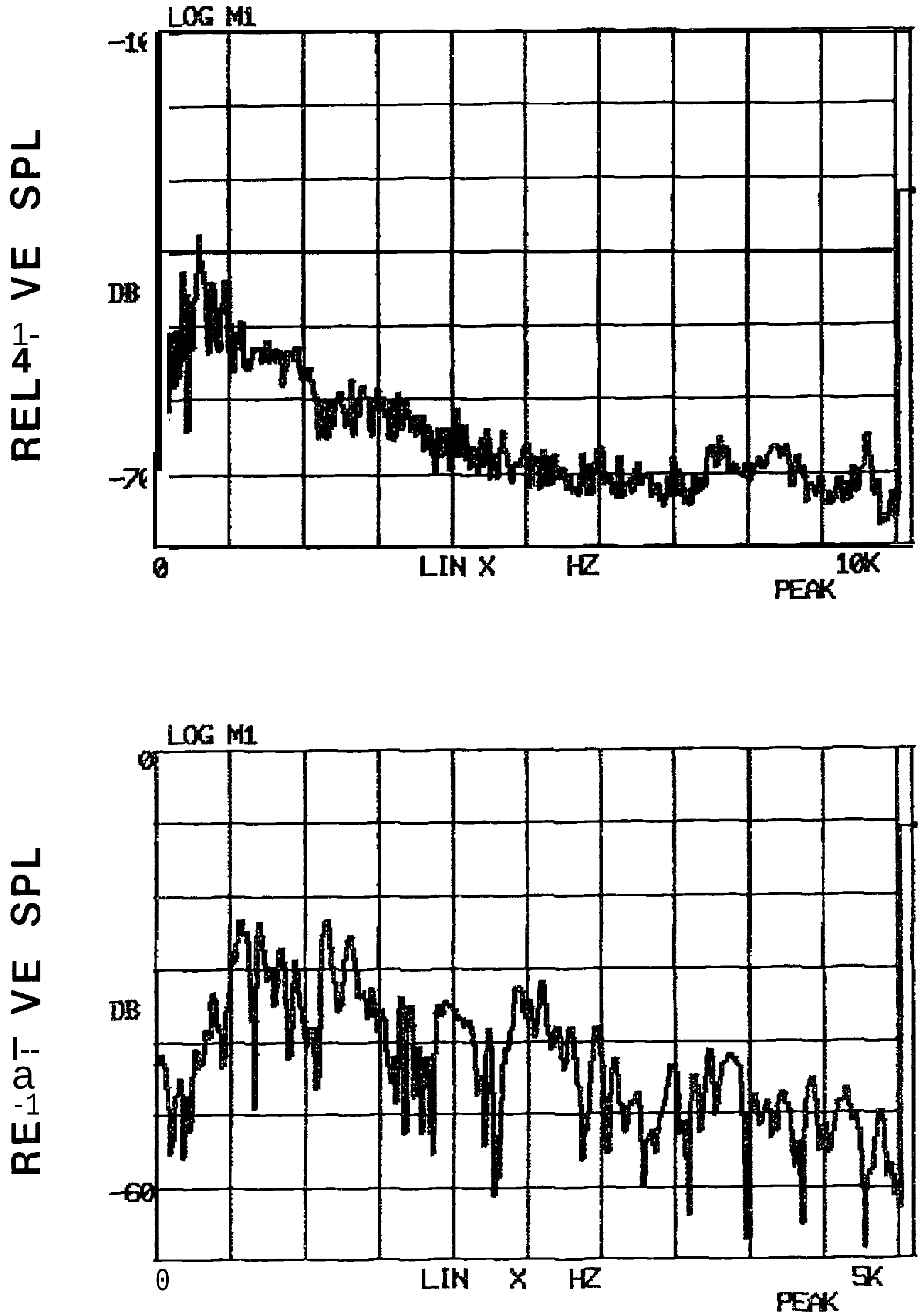


Figure 47. Peak spectra of ice cracking sound over two different bandwidths, 2151 hrs, 7 April 1984, analyzing filter bandwidth, 37.5 Hz, upper, 18.8 Hz, lower.

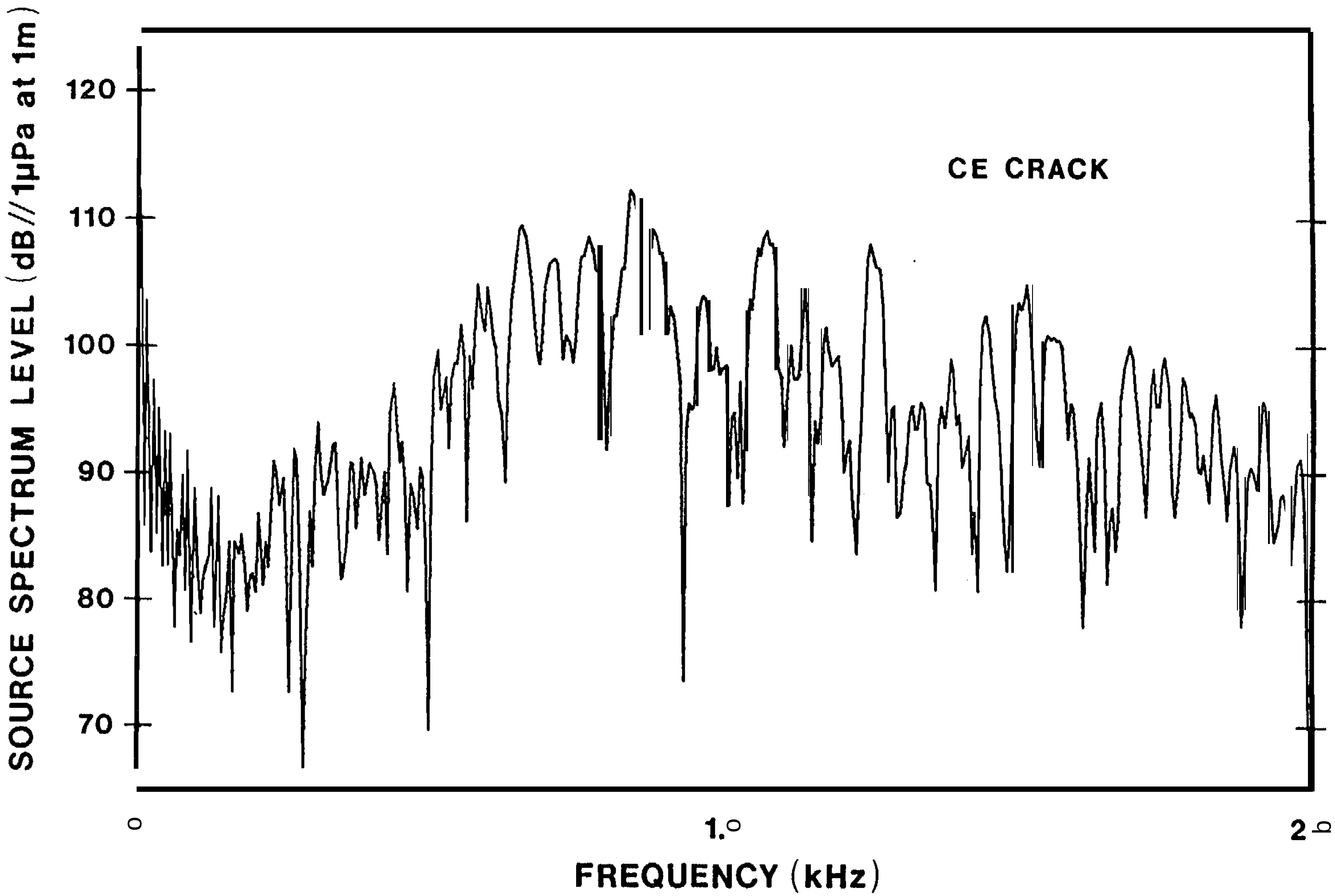


Figure 48. Source spectrum evel (per Hz) of an ice cracking transient sound from a low ice r dge 500 m from the hydrophone, Kotzebue Sound.

By far, the predominate sound in this region of the Chukchi Sea was bearded seal trills. The spectra (Fig. 49) were just like those from our previous recordings of bearded seals off Barrow. We also recorded ringed seal rubs and quacking barks in the Chukchi Sea. As evidenced by the wide refrozen polynya that we recorded under and the neighboring high ridges and cracks, this was an area of active ice which appeared to be a shear zone. The water was 44 m deep at this location.

D. Localization

The triangular array of hydrophores was designed for determining where ringed seal sounds originated (see METHODS). Cross correlation functions yielded the sound arrival time differences used in the localization algorithm. Table 5 lists the true bearings of located sounds and their ranges from hydrophore A. As seen in this table, the located sounds originated from as far away as 711 m, as in the case of ice cracking sounds. Located seal scratches were 55-88 m distance; rubs, 19-158 m; squeaks, 82-89 m; and quacking barks, 17-107 m.

The localization for several sound categories are given in Figs. 50 through 53. All of the located seal sounds appear in Fig. 54 and the ice sounds are in Fig. 55.

E. Response to Playback

A comparison was made of the frequency of occurrence of a total of 2,947 ringed seal vocalizations over test periods before and after noise playbacks. This involved monitoring 148.5 hrs of recordings. (See METHODS for a description of the noise sources.) In addition to expected constraints imposed by recording and playback schedules, the rationale for choice of test periods included “acclimation” sessions following playbacks. These consisted of 6 hrs of quiet after the first playback of seismic exploration and related noise, and 23 hrs of quiet after the playback of random and 1 kHz noise.

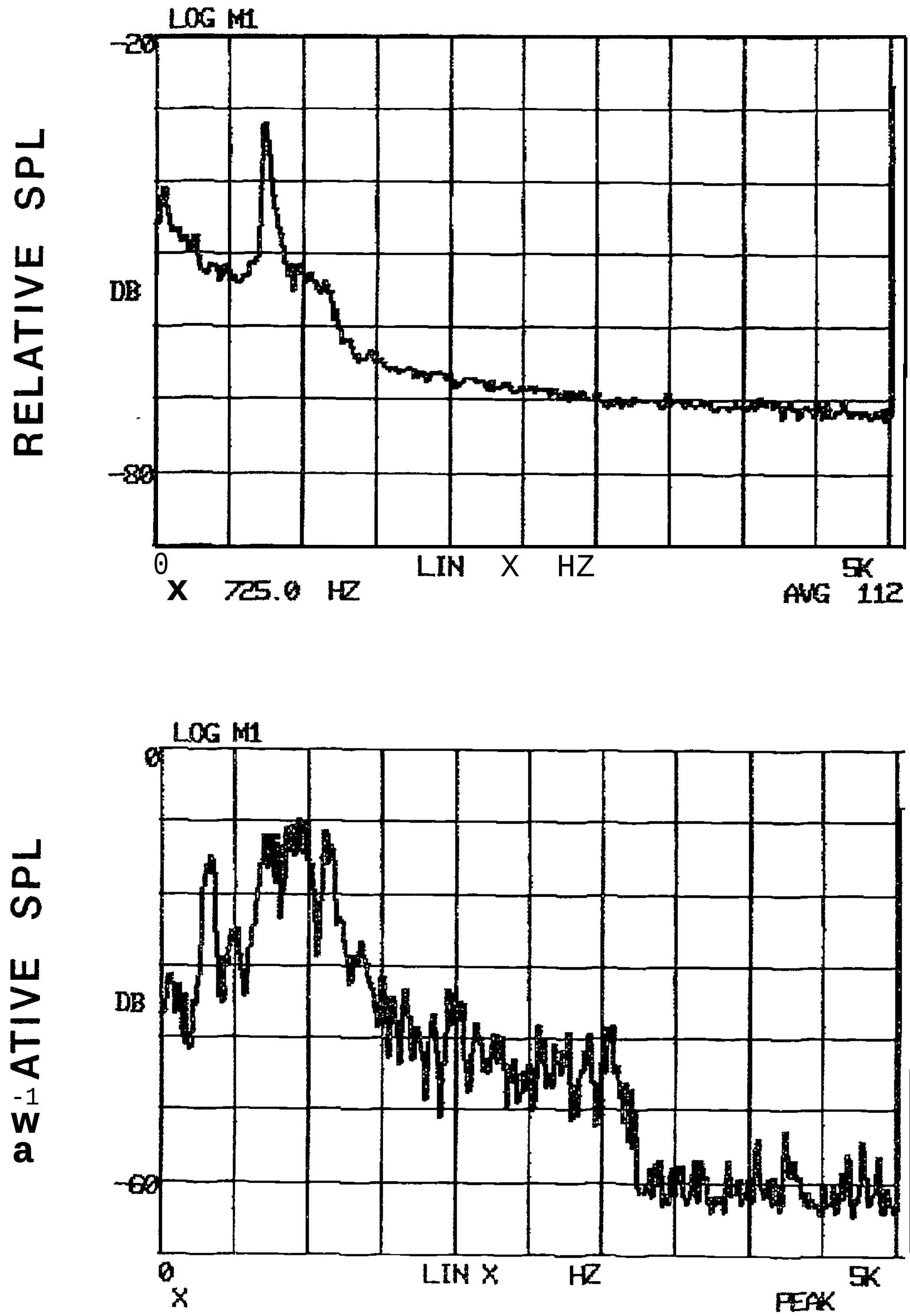


Figure 49. Spectra of Chukchi Sea recordings. Averaged spectra showing peak at 725 Hz from bearded seal trill (upper) and peak hold spectra over 10 sec duration (lower) containing multiple bearded seal trills and ringed seal harks, analyzing filter bandwidth, 12.5 Hz.

Table 5. Compilation of bearings and range of some sounds selected for localization, referenced to hydrophore A.

SOUND CATEGORY	BEARING (°T) °T = True bearing degrees.	RANGE (M)
Scratches	66.2	55
"	19.9	61
"	42.8	79
"	30.9	71
"	43.0	83
"	41.7	81
"	41.3	80
"	354.6	88
"	354.5	88
Rub	14.3	158
"	108.9	146
"	152.8	23
"	353.4	90
"	271.8	21
"	273.9	19
"	355.1	88
Squeak	42.6	82
"	355.6	89
Quacking bark	0.5	105
"	351.1	107
"	358.9	106
"	5.3	86
"	351.8	106
"	289.3	17
Ice crack	26.8	221
"	240.0	252
"	28.2	390
"	171.9	711
"	100.3	76

Table 5, continued

SOUND CATEGORY	BEARING (°T)	RANGE (M)
Ice crack (cent'd)		
"	174.5	597
"	287.2	586
"	265.7	147
"	166.0	143
"	169.7	136
"	4.7	111
"	91.1	8
Ice knock	12.2	69

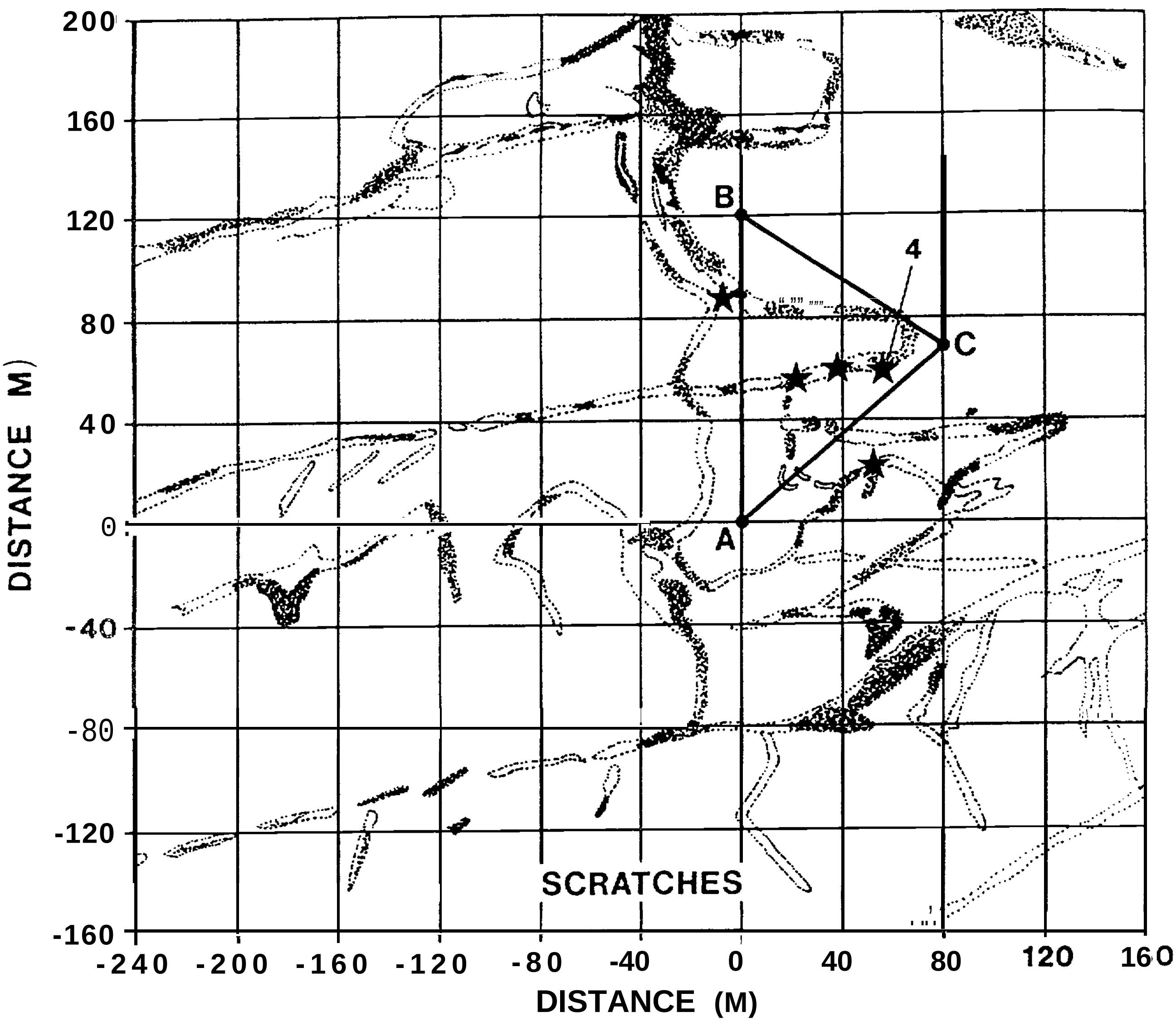


Figure 50. Positions (shown as stars) of eight scratching sound sources from ringed seals in or near the triangular hydrophore array. The number "4" indicates four sound sources.

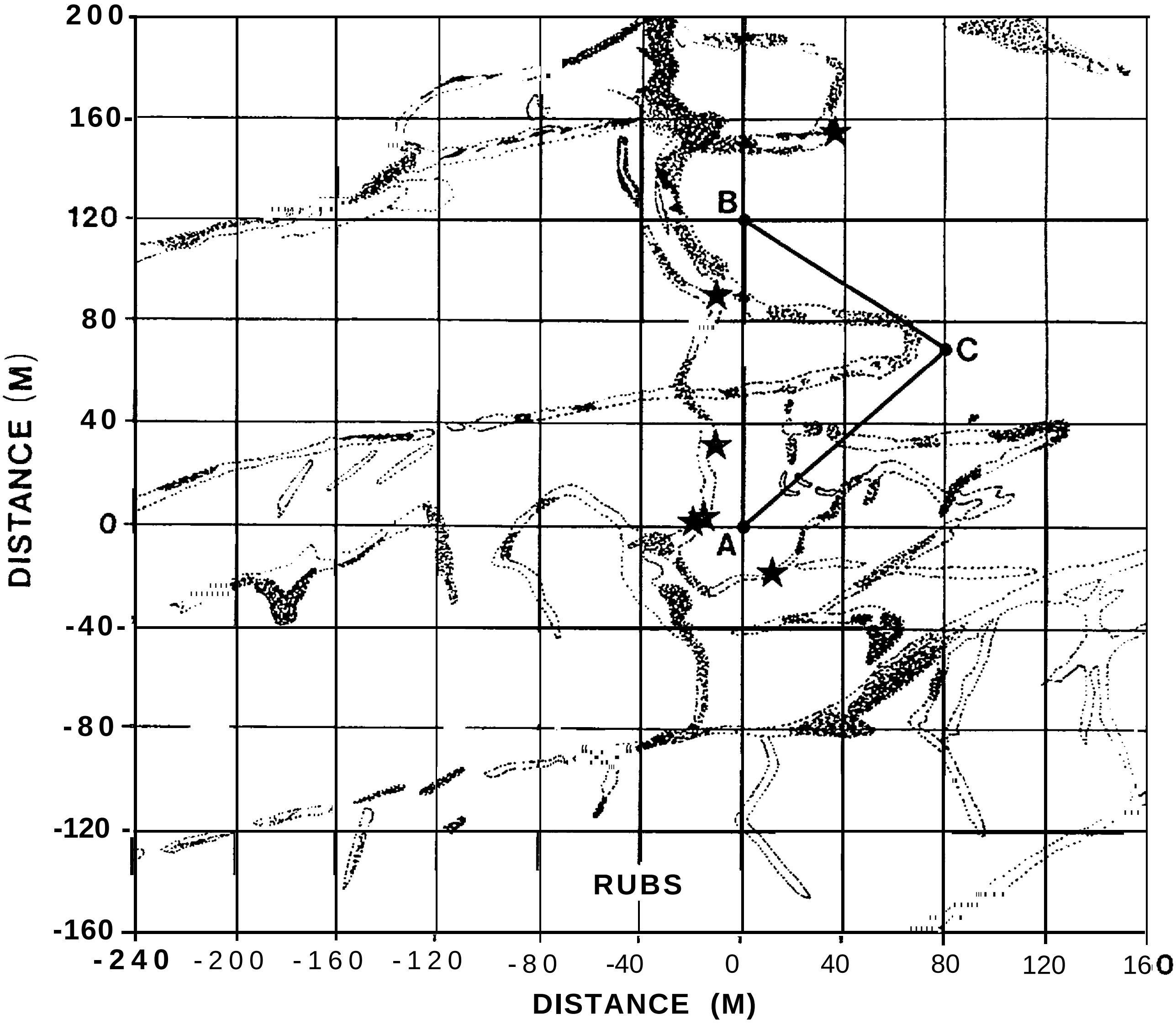


Figure 51. Positions (shown as stars) of five rub sound sources from ringed seals near the triangular array.

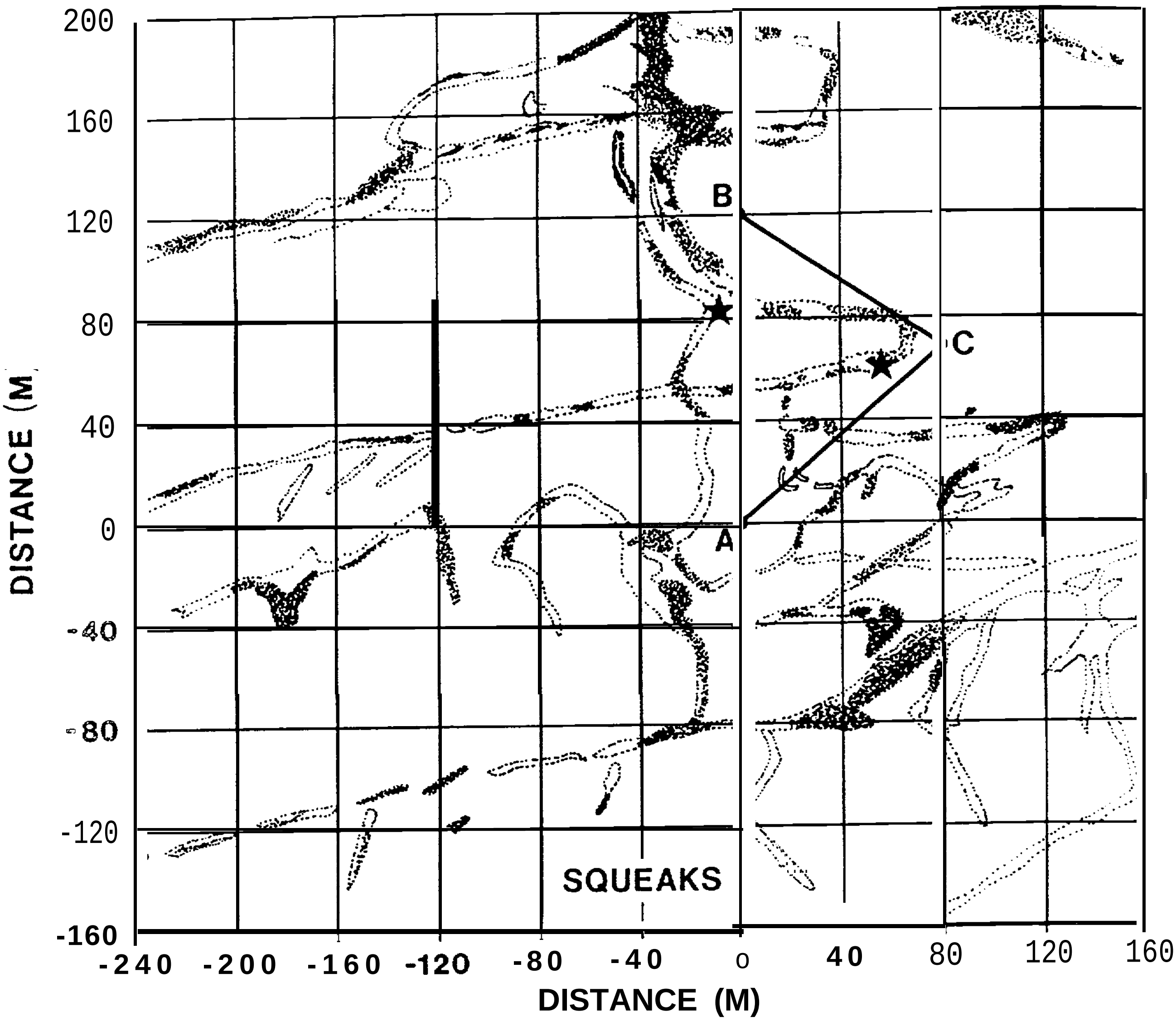


Figure 92. Positions (shown as stars) of two squeak sound sources from ringed seals in or near the triangular array.

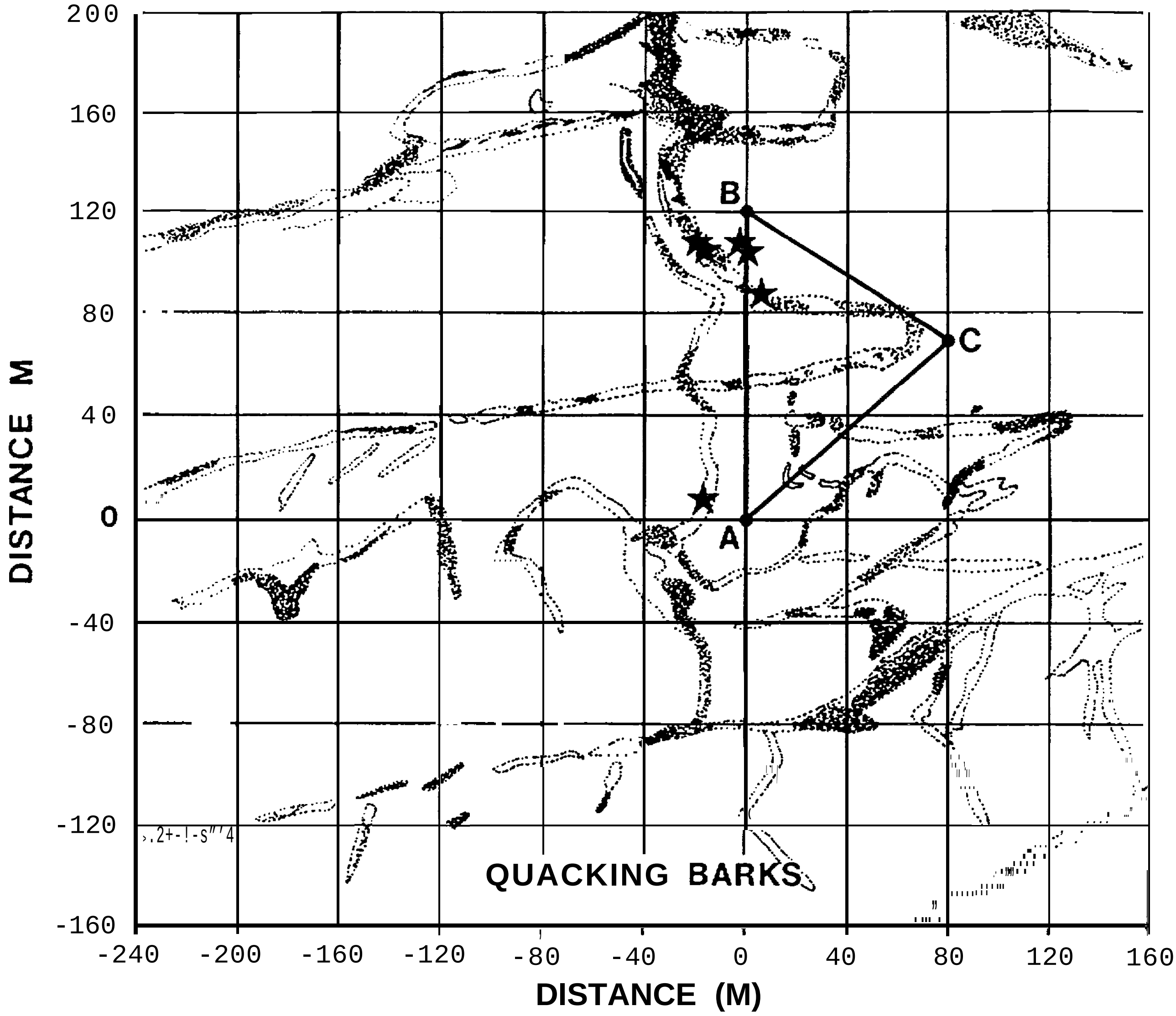


Figure 53. Positions (shown as stars) of six quacking bark sound sources from ringed seals in or near the triangular array.

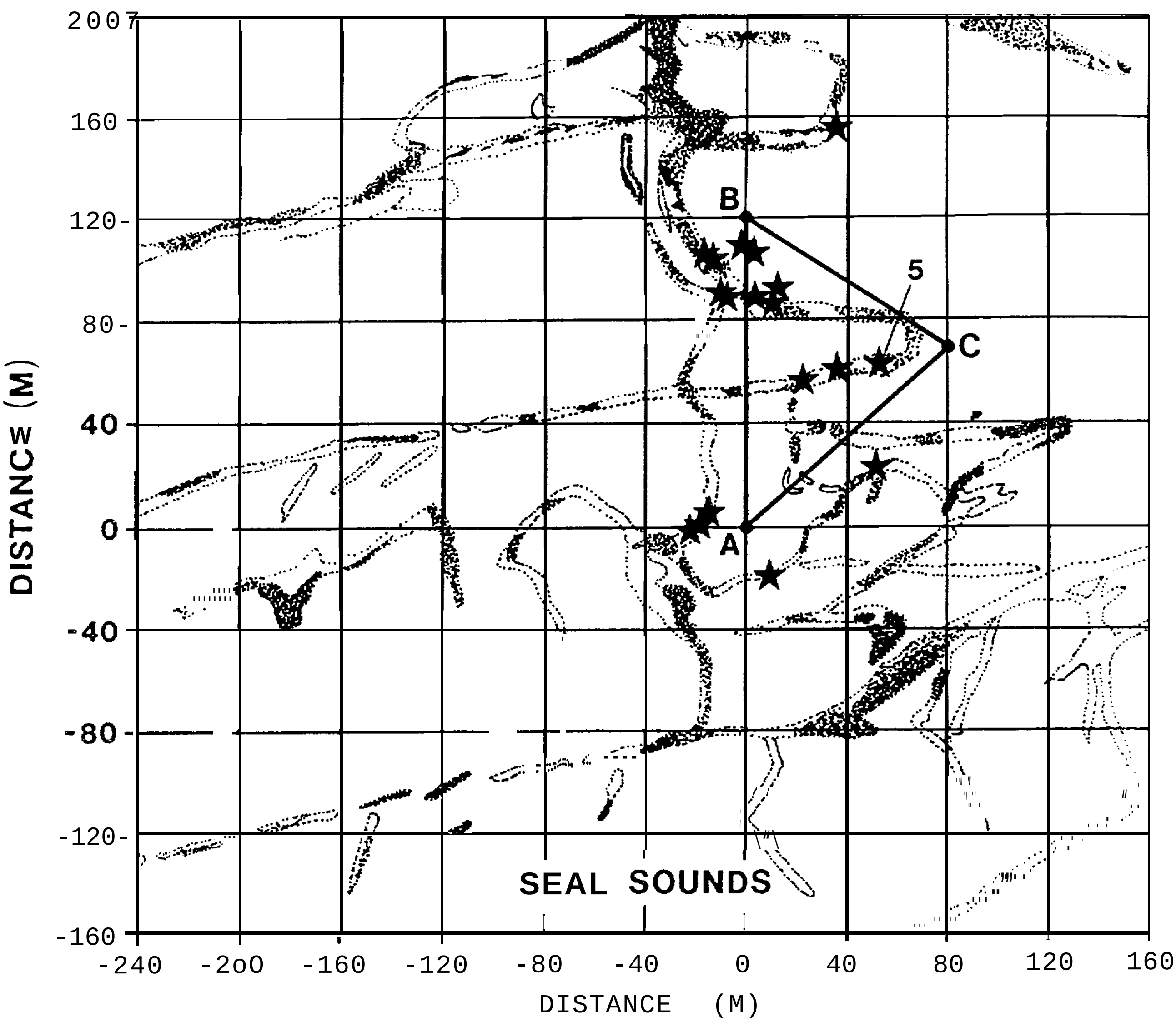


Figure 54. Positions (shown as stars) of all of the localized seal sound sources in or near the triangular array. The number "5" indicates five sound sources at one position.

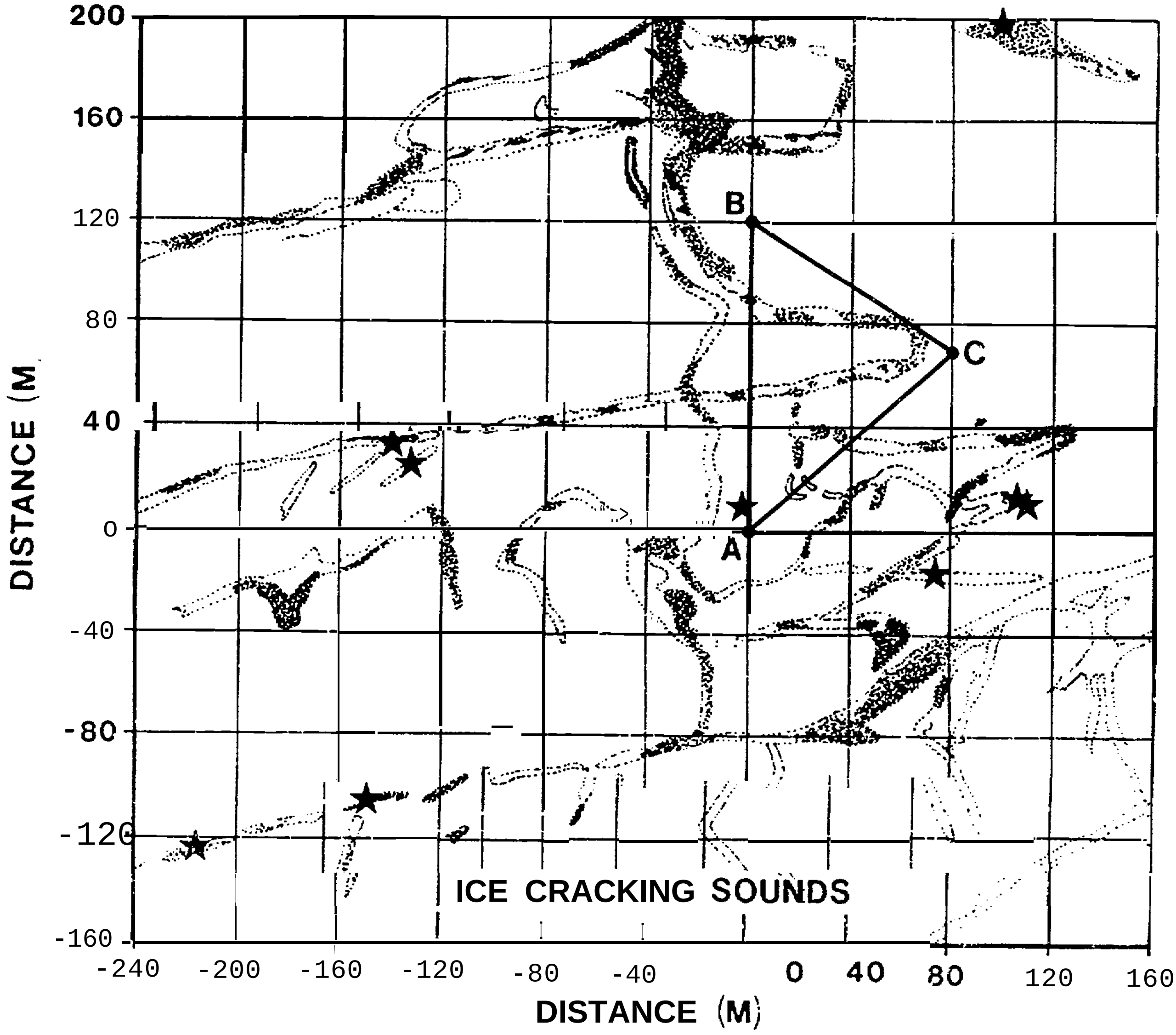


Figure 55. Positions of nine ice cracking sound sources (stars) near the triangular array.

Although vocalizations could be detected during recordings of playback, they could not be accurately counted during these periods because the introduced noise served as a very effective aural masker.

The distributions of the number of sounds/15 min vs number of observations are presented for the designated time periods before and after the given playback periods (Figs. 56 through 59). It was clear that these data could not survive a test of normality required for a parametric statistical test, thus the nonparametric statistic of chi square was used in a single classification test of independence. The data were appropriately grouped to avoid categories containing less than five observations each (Dixon and Massey, 1957; Cochran, 1954, 1963), except for one set of four observations of ≧ 3 sounds before Test II, an acceptable allowance (Zar, 1974). The data bases for these tests are tabulated (Table 6).

Data base units were defined as follows: SOUND, the discrete acoustical event counted, e.g., a rub or a quacking bark; SET, a 15-min period during which sounds were counted; CATEGORY, grouped and ungrouped units consisting of the number of sets (15-min periods) per test having a given number of sounds, the same categories being used before playback (defined as the "expected" quantity in the chi square calculation) and after playback (defined as the "observed" in the chi square calculation).

The results of these tests showed that in two cases (Test II, 6 hrs before and 6 hrs after the first playbacks of industrial noise, and Test IV, 23 hrs before and 23 hrs after the second playbacks of industrial noise) there was no significant difference in the occurrence of ringed seal vocalizations before and after playbacks (chi square 0.76 < 3.84 (.05) 1 deg freedom; chi square 8.99 < 9.49 (.05) 4 deg freedom, respectively). In the other two cases (Test I, 3 days before and 3 days after all playbacks, and Test III, 10 hrs before and 10 hrs after the playbacks of random and 1 kHz noise) the null hypothesis of no significant difference in the occurrence of ringed seal vocalizations was rejected (chi square 594.82 > 7.82 (.05) 3 deg freedom; chi square 7.59 > 5.99 (.05) 2 deg freedom, respectively). Results of these statistical tests are summarized in Table 7.

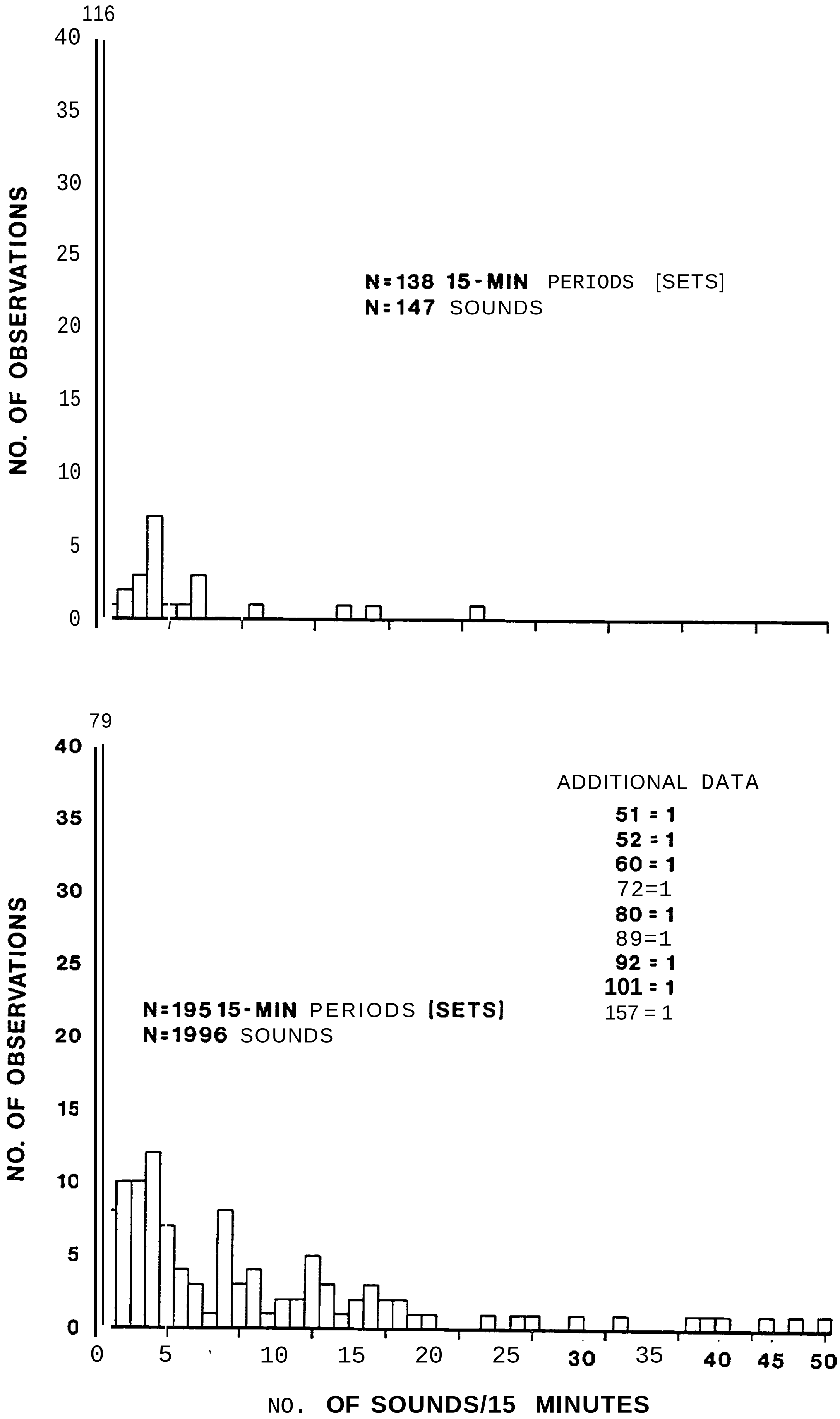


Figure 56. Distribution of numbers of ringed seal vocalizations/ 15 min periods over 72 hrs before any playback of man-made noise (upper) and 72 hrs after all playbacks (lower).

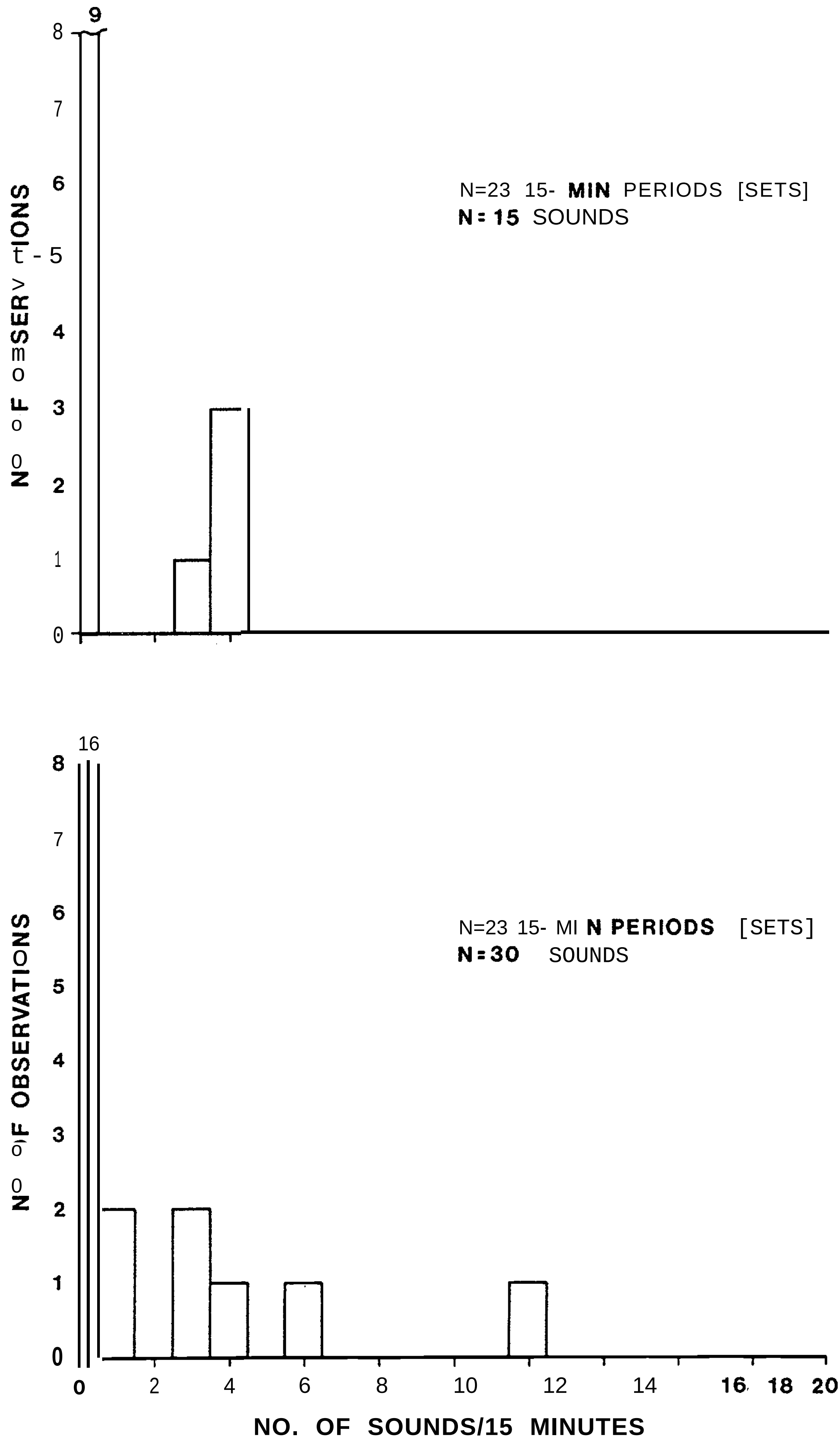


Figure 57. Distribution of numbers of ringed seal vocalizations/15 min periods over 6 hrs before playback of Vibroseis and related noise (upper) and 6 hrs after (lower).

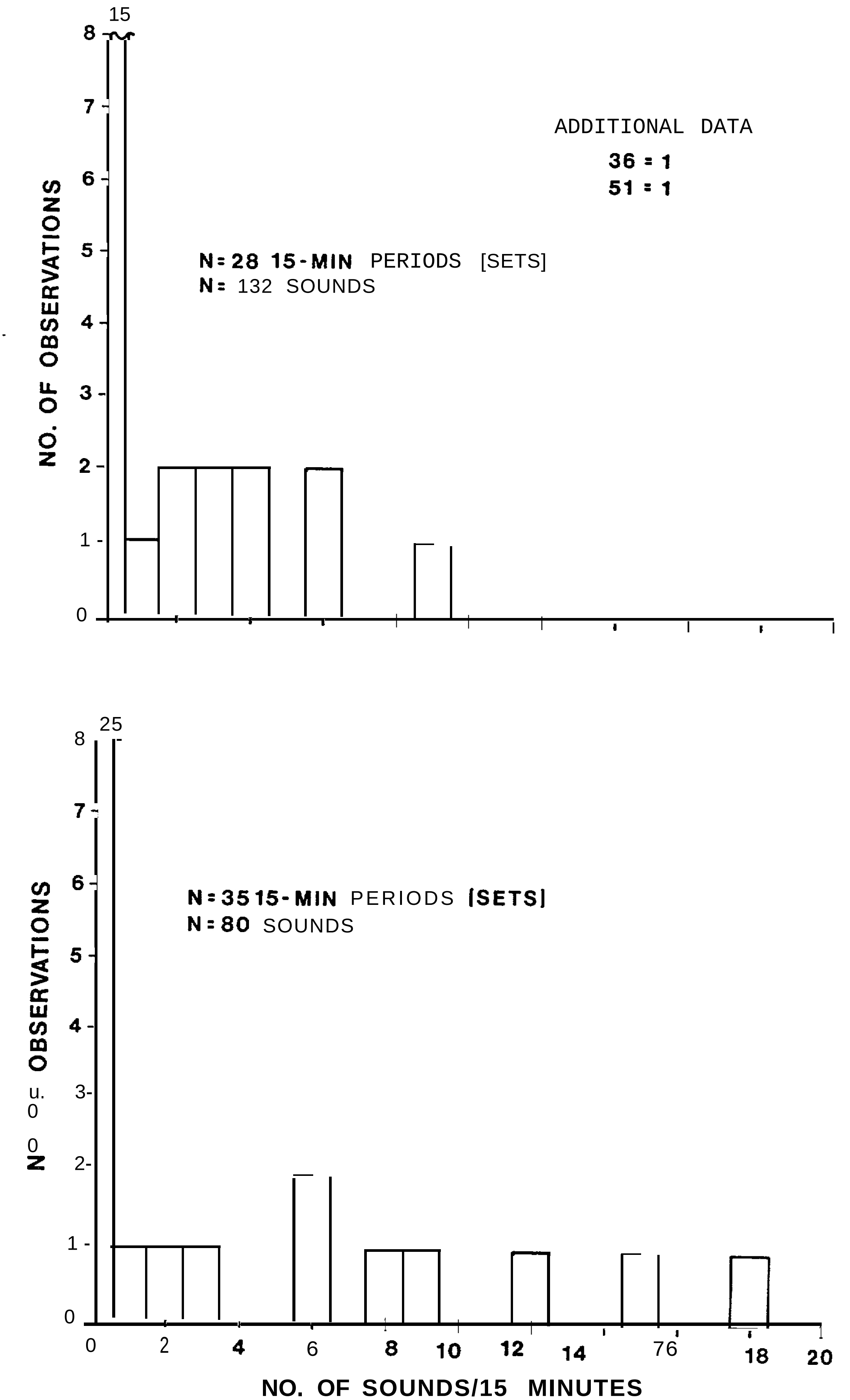


Figure 58. Distribution of numbers of ringed seal vocalizations/ 15 min periods over 10 hrs before playback of random and 1 kHz noise (upper) and 10 hrs after (lower).

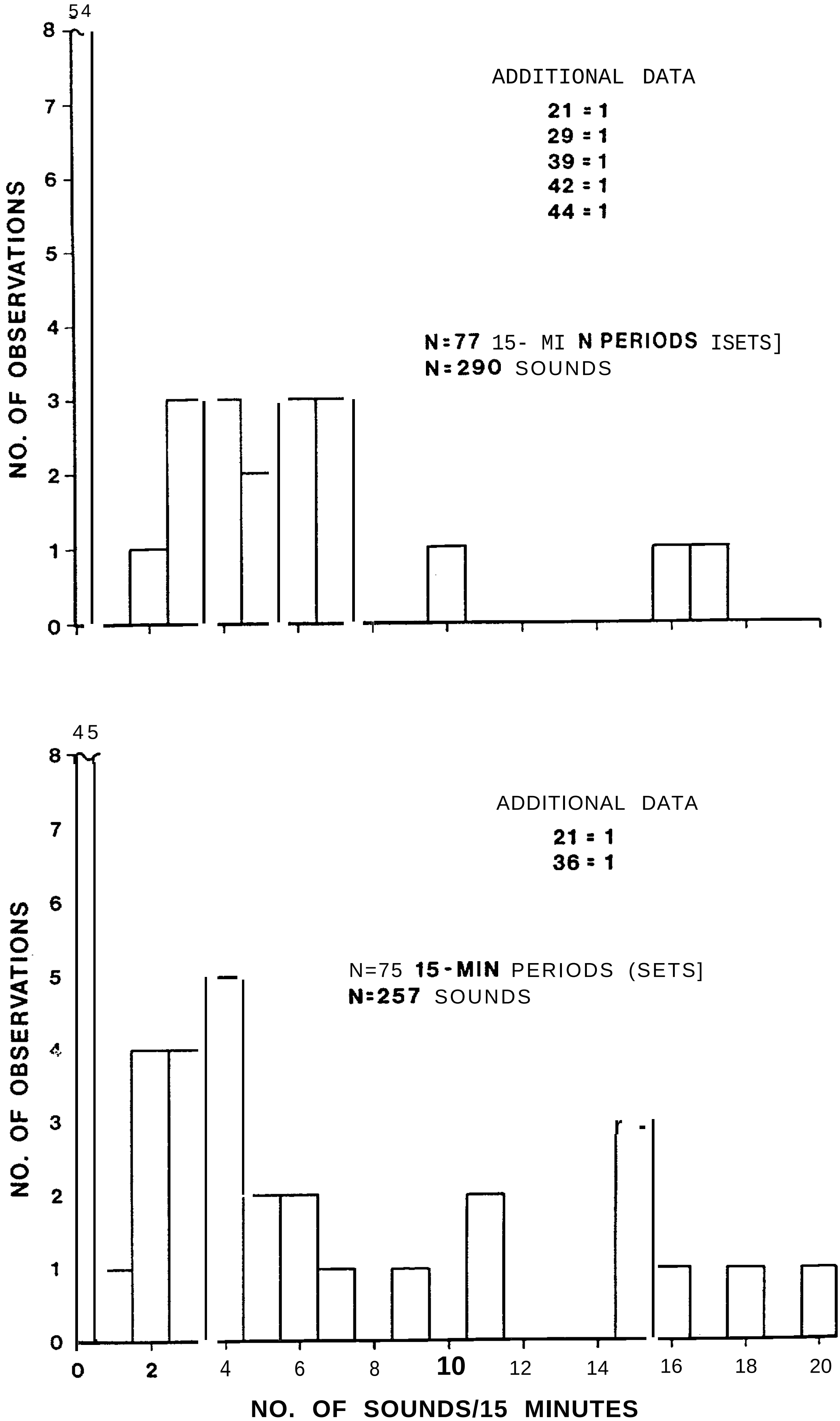


Figure 59. Distribution of numbers of ringed seal vocalizations/ 15 min periods over 23 hrs before third playback (Vibroseis and related noise, upper) and 23 hrs after (lower).

Table 6. Data base for chi square tests of independence.

TEST I

THREE DAYS BEFORE/AFTER ALL PLAYBACK OF NOISE (INDUSTRIAL, RANDOM, 1 KHZ)

EXPECTED (BEFORE)		OBSERVED (AFTER)	
Categories (No. Sounds)	Sets (15-min Periods)	Categories (No. Sounds)	Sets (Observations)
0	116	0	79
1-3	6	1-3	28
4	7	4	12
≧5	9	≧5	76
Σ147[1]	Σ138	Σ1996[1]	Σ195

TEST II

6 HRS BEFORE/AFTER FIRST PLAYBACKOF INDUSTRIAL NOISE[2]

EXPECTED (BEFORE)		OBSERVED (AFTER)	
Categories (No. Sounds)	Sets (Observations)	Categories (No. Sounds)	Sets (Observations)
o-2	19	0-2	18
≧3	4	≧3	5
Σ15	Σ24	Σ30	Σ23

TEST 111

10 HRS BEFORE/AFTER FIRST PLAYBACK OF RANDOM AND 1 KHZ NOISE

EXPECTED (BEFORE)		OBSERVED (AFTER)	
Categories [No. Sounds)	Sets (Observations)	Categories (No. Sounds)	Sets (Observations)
0	15	0	25
1-3	5	1-3	3
≧4	8	≧4	7
Σ132	Σ28	Σ 80	Σ35

[1]These sums represent the actual number of sounds in the two sides of each test.

[2]Yates correction for continuity applied since d.f. = 1, Test II.

Table 6. Continued

TEST IV

23 HRS BEFORE THIRD PLAYBACK (INDUSTRIAL NOISE)

EXPECTED (BEFORE)		OBSERVED (AFTER)	
Categories (No. Sounds)	Sets (Observations)	Categories (No. Sounds)	Sets (Observations)
0-1	54	0-1	46
2-4	7	2-4	13
5-6	5	5-6	4
7-16	5	7-16	8
≧ 17	6	≧ 17	4
Σ 290	Σ 77	Σ 251	Σ 75

Table 7. Summary of chi square single classification tests of independence for the occurrence of ringed seal vocalizations before and after designated playback experiments.

TEST	NOISE	PLAYBACK DURATION(HRS)	MONITOR DURATION(HRS) BEFORE	MONITOR DURATION(HRS) AFTER	x^2	DEG FREEDOM	$x^2(.05)$	NO SIGNIFICANT DIFFERENCE
I	All	14.6	72	72	594.82	3	7.82	REJECT
II	Industrial	6.3	6	6	0.76	1	3.84	ACCEPT
111	Random, lkHz	4.7	10	10	7.59	2	5.99	REJECT
IV	Industrial	3.6	23	23	8.99	4	9.49	ACCEPT

F. Vocalization Roles

The last of our research objectives for this study was to describe any apparent roles of ringed seal vocalizations. Our understanding from John Burns (ADFG) and the sponsors was that reproductive behavior e.g., pupping, at this location, would increase over the assigned study period. The noted increase in the frequency of occurrence of vocalizations (Fig. 29), especially the commonly occurring rubs, squeaks, and quacking barks, would indicate that these sounds may be an integral part of the reproductive behavior. However, the only recorded seal sound category known to be associated with a particular overt behavior was scratching, which was not a vocalization and which showed no apparent positive correlation with heightening of the breeding season (Fig. 32, lower).

VI. DISCUSSION AND SUMMARY

A. Ringed Seal Sounds

Considering that scratching comprised about 80% of the recorded seal sounds, the relatively small remainder (4,631) indicated that ringed seals did not produce many vocalizations during this study, compared with other pinnipeds. We believe this is a significant finding in view of the 245 hrs of recordings, not including the summation of recording effort during simultaneous multi-channel data accession. On the other hand, we do not know the population density within the maximum acoustical detection range (MADR) for these sounds.

In order of decreasing frequency of occurrence, the major vocalization sound categories were rubs, squeaks, and quacking barks. Most of the energy of these sounds was below 4 kHz, and source levels of located sounds ranged from 95 to 130 dB re 1 μPa, 1 m. All were of a transient nature, but they often appeared in short volleys.

Compared with other marine mammal sounds, e.g., large and small whales and other pinnipeds, ringed seal vocalization source levels are not very impressive. The MADR in the natural environment that prevailed during this research probably did not exceed 1 km. Low source level implies two consequences of importance to this study. First, their vocalizations would be of limited use in a population enumeration study because the radius of coverage (MADR) would be comparatively small. Moreover, their sound production is relatively infrequent. Second, masking by man-made or other noise would be more easily facilitated, i.e., vocalizations would be more susceptible to acoustic noise masking.

Scratching (presumably for hole or lair maintenance/building) was a very common activity. Detectable sound energy extended up to 10 kHz, with peak frequencies from 1-4 kHz. These were broadband signals that numbered nearly 20,000 during the study. The source level measured about 100 dB re 1 μPa, 1 m, with implications similar to those of vocalizations except the masking of these sounds by noise may not be as important, behaviorally, as with vocalizations. Since scratches are so common, they could possibly be of great utility in assessing distribution or relative abundance, unlike vocalizations.

In terms of frequency (Hz) and duration of “yelps” and “barks” described by Stirling (1973) and Stirling et al. (1983), it appears that those sounds and the rubs, squeaks, and quacking barks of our study are very similar. For the reasons given, in our opinion, with the major exception of scratches, the ringed seal sounds recorded by us probably would not have been very useful as a tool for studying distribution or abundance (see Stirling et al., 1983). Those researchers also noted an increase in sound production (late April) as pupping increased.

B. Frequency of Occurrence

The rate of ringed seal vocalizations increased markedly in the area of our operation, beginning about 5 April 1984. Sounds after this date became more prevalent each day, with the overall effect being a six-fold increase/day. We believe that this reflects an increase of breeding activity expected for this period.

In the search for any notable diurnal (daily) periodicity of ringed seal sound production, it first appeared that sonic activity was bimodal (1100 and 0130 hrs). However, by studying the occurrence of individual sounds, the bimodality was found to be the result of scratching periodicity about these times. Vocalization frequency was only slightly dependent upon time of day, with possible periodicities of 2 and about 7-hr cycles as revealed by FFT. More vocalizations occurred during the daylight hours compared to darkness.

Scratching occurred in bouts of 1-126 sounds (mode 4, median 11). Scratching bouts were up to 101 sec in duration and as many as 34 bouts were recorded in two hours. Bouts occurred in series.

Physical Factors and Sound Production

Measurements were made of four physical factors: ambient surface light, windspeed, ambient air temperature, and underwater sound speed. 'de studied the possible association of the first three with ringed seal sound occurrences, and sound speed (mean of 1437 m/see) was needed for localization of sounds.

The pooled light measurements varied from 450-570 μWatts/cm^2 (0930-1800 hrs) and peaked at about 1400 hrs. Dividing the days into light and dark periods (0600-2100 and 2100-0600 hrs) statistically more vocalizations appeared during the light hours.

When all data during the measurable (light) hours were considered, there was not a statistical correlation between light measurements and vocalization sound counts. On the other hand, more ringed seal vocalizations/hr occurred during the light hours, as compared with dark hours.

There was a significant negative correlation between the number of vocalizations and windspeed. However, this probably is not of biological significance because high windspeeds acoustically masked the presence of the sounds. Conversely, vocalizations were more apparent during lower windspeeds (lower ambient noise).

There was a statistical negative correlation between temperature and vocalization sound production. Surprisingly, the occurrence of scratching sounds was not correlated with temperature. We fully expected more scratching with lower temperatures. The fact that we did not find this relationship may have been due to the fact that the water temperature remained the same, the surface of the holes received protection from the wind and perhaps some insulation from the overlying snow and/or ice, and it was below freezing for virtually the entire duration of the study. On a longer term basis, with ambient temperatures ranging from nearly -40° to 15°C above freezing, one would expect such a correlation, especially during break-up.

Since the number of vocalizations was negatively correlated with both windspeed and temperature, we looked at the possible association between these two environmental variables over the duration of the study. They were not statistically correlated, thus there was indication of an indirect effect between temperature and sound production. We did notice that seals were up, presumably sunning themselves on the ice during the warmest days, which may explain why the number of underwater sounds was less during higher temperatures. As indicated, higher winds increase ambient noise and thus produce more masking of the seal sounds. These two findings, at least in part, may be responsible for the above noted negative correlation.

Sound Speed and Propagation

Under winter conditions, in water as shallow as 15 m such as at our study site, the classical models of propagation (e.g., Urick, 1983) do not apply. The situation in shallow water is compounded by the contiguity of under-ice and sea bottom boundaries, and the relative size of the ice keels and hummocks (WMO, 1970) in comparison to the water depth.

Although it is also frought with complexity, deep water under-ice propagation is normally characterized by significant upward refraction, as the result of a positive sound velocity profile gradient, and wave-length-related downward reflection, from the undersurface of the ice canopy (Welsh et al., 1984). Our sound speed measurements, taken for a representation of the on-site conditions (i.e., 1437 m/see) needed for sound localization, indicated a very slight positive gradient, beginning at about 9.5 m. For an indication of the importance of the location and depth of the sound source and receiver in shallow ice-covered water, the reader is referred to an account of our OCSEAP supported, brief study of sound propagation in 10 m of water at Prudhoe Bay (Cummings et al., 1981).

C. Other Recorded Sounds

Outstanding underwater sounds, other than seal vocalizations and scratches, consisted of our playbacks of "industrial", random and 1 kHz noise, ice and water sounds.

Ice cracking sounds were most prevalent during periods of steadily decreasing temperature. They are best described as thermal cracking from tensile stresses in the ice structure that are associated with falling air temperatures. Others (e.g., Milne, 1972; Dyer et al., 1984; Welsh et al., 1984) have described such sounds, but we may have been the first to localize the sounds and report source levels.

Another sound, originating on the ice, is that from blowing snow grains. Under conditions of high (>25 mph) winds, the broadband noise contribution from this source often masked nearly all seal vocalizations. Such noise intensity is not dependent upon snow grain size, but a flow, and it increases as the cube of windspeed (Milne, 1974).

We believe the recorded water sounds may have been from one or more of three sources: seals hauling out and shedded water dripping back into the access holes, water dripping back after being uplifted with moving ice, and the release of free brine found in small amounts in the ice structure.

The noise characteristics of the playbacks are described in detail in our previous reports of the noise recorded in the presence of on-ice seismic profiling.

Mainly because of its periodicity, regularity in waveform, and source direction (from the Chukchi sea), it appears that the low frequency pulses are of unknown man-made origin. At least, we do not know the origin. The important significance of these sounds is that they invariably caused ringed seals to immediately respond with a session of quacking barks, rubs, and squeaks which dissipated with the cessation of LFP's. Playbacks of these sounds may be a useful interrogation.

D. Localization

Using samples of the most prevalent sounds recorded from the hydrophone array, we located 8 scratch, 5 rub, 2 squeak, 6 quacking bark, and 9 ice crack sounds. Ranges from the reference hydrophore were 8-586 m, and nearly all of the located sounds came from ridges or refrozen fractures.

The association of seal and ice sound locations and these ice features is reasonable. It would be a decided advantage for the seal to frequent ridged ice because the uneven upward surface is more conducive to safe and effective lairs as a result of drifted snow and natural interstices. Refrozen fractures would" normally hold thinner new ice, a definite advantage in constructing or maintaining access or breathing holes. The seals would be inclined to continue to use an access hole that had previously been in the open water of a fracture, even when it became refrozen. We located two open access holes and numerous breathing holes in a long refrozen fracture, 4 km north of camp. A common cause of ice cracking is thermally stress-induced, such as the result of progressive toolings. This is precisely what happened at our study site on 7 April when the prevailing noise was ice cracking, an event very likely to occur in ridged or new ice, Ice cracking was not continuous; instead, it consisted of sharp impulses of variable occurrence.

We made no attempt to utilize a statistically significant sample, mainly because the localization effort was not part of the contract. However, the proximityof localized ringed seal sounds (17-158 m) and their relatively low source level indicated that the other recorded sounds also were from nearby animals.

E. Response to Playback

Using three noise playback sessions totalling 14.5 hrs and counting nearly 3000 vocalization sounds over 148.5 hrs of monitoring, we found no statistical evidence that the introduced noise caused any reduction in ringed seal sounds. There was no statistically significant difference in the number of vocalizations before and after each of two sessions of "industrial" noise playback. There was a statistically significant increase in sound production from before to after the four days of the playback experiments ', and there was a statistically significant increase from before to after the playback of random and 1 kHz noise. Although the noise levels of playbacks were of sufficient power and appropriate frequency spread to effectively mask many seal vocalizations, the louder sounds could be distinguished, even during playback.

The overall increase in ringed seal vocalization sound production, presumably as breeding activity heightened, appeared to dominate the frequency of occurrence in sound production. An exception to this overall effect may have been the increase noted in the 10 hrs before and 10 hrs after the 4.7 hrs playback of random and 1 kHz noise. We say this because the total monitoring and playback period was just a little more than 24 hrs--perhaps not enough to reflect the longer trend of increase. On the other hand, this day occurred at the beginning of the upward trend in sound production and could have reflected such a difference. A detailed trend analysis during this one day was not practical because of the relatively low number of sounds. On the basis of normalized data, there were nearly six times as many sounds in the latter eight days (which included the playback period) as in the first nine days.

The onset of low frequency pulses, thought to be of man-made origin, resulted in the immediate production of quacking barks, squeaks and rubs. We have no knowledge as to the source or purpose of these pulses that could have been produced by some kind of impulse mechanism hundreds of kilometers away. During periods of elevated natural ambient noise and low level pulses, it was difficult to aurally discern the pulses, but their presence, betrayed by the sudden appearance of barking, squeaks and rubs, could be confirmed using acoustic signal processing. We do not know the behavioral significance of these bioacoustical outbursts, nor even if the long-term upward trend in ringed seal vocalizations may not have been related to our own playbacks of man-made noise. It was not possible to separate the possible factors after only one season of field data. For certain, the noise playbacks did not elicit immediate ringed seal sound production, as did the occurrence of low frequency pulses. *A priori*, we are inclined to believe that the upward trend of sound production during the last eight days of our recordings was probably due to increased breeding activity or some other natural behavior, and not a manifestation of the noise playbacks.

F. Vocalization Roles

Although we apparently had several seals in the study site, sound production was not characterized by any kind of chorusing. In fact, there appeared to be no interchanges of vocalizations on the recordings.

The primary purpose of scratching is not to make sounds, but these sounds could have a behavioral role, such as signals of territoriality.

The sharp and steady increase in the number of vocalizations over the second half of our field work probably was a manifestation of heightened breeding activity and parental care.

VII. RECOMMENDATIONS

(1) Vocalizations among ringed seals, in the behavioral environment and season of the present study, are not very numerous compared with the biological sounds of many other marine mammals, including other pinnipeds. Vocalizations, per se, in the location and circumstances of this study, would probably not be very useful indices to ringed seal population size, relative abundance, population trends, distribution, or many behavioral activities. This does not imply that sound production in ringed seals may not be as significant in this species in terms of a necessary overt behavior. Scratching, on the other hand, is a very common and identifiable sound. It could very well be used as an index to several useful parameters.

(2) We recommend that an intensive acoustical study be made of underwater sound propagation and attenuation (overall loss) in an area highly populated with ringed seals and typical of sites undergoing on-ice petrochemical exploration. Frequencies (Hz) must be representative of both ringed seal vocalizations (this study) and industrial noise (our previous studies). There is a severe lack of data in such shallow areas because the geophysical industry is not interested in water column properties or the higher frequencies (kHz) and the U.S. Navy would consider the typical near-shore ringed seal habitat as being too shallow for viable Anti-Submarine Warfare operations.

(3) Based on the above parameters, the ringed seal audiogram, and what is now known of vocalization source level, a model should be developed under the framework of the basic sonar equation (eq. 1). The purpose of this model would be to predict a zone (area) of possible influence using both stochastic and deterministic approaches.

(4) The presently described recordings were made in a relatively small area at a specific time of year. Some recording effort should be undertaken at other times and locations, during which on-ice seismic exploration may be undertaken. Animal sound production is an overt manifestation of behavior and, consequently, is affected by seasonal and geographic variation.

(5) We recommend that a method be developed for experimentation on ringed seals under a semi-controllable situation involving their natural or acclimatized behavior and possible effects of man-made noise. For many reasons, this may be too difficult to achieve in the field.

VIII. ACKNOWLEDGEMENTS

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X APPENDIX

Temperature and Windspeed Records

JULIAN DATE	TIME	TEMP (°C)	WINDSPEED (MPH)
at	838	.C	.C
36	2126	-22.C	1.C
86	2238	-24.C	.C
86	2330	-22.C	.C
87	22	-22.C	1.C
87	112	-21.C	1.C
87	744	-28.C	2.C
87	839	'28.0	.5
87	934	-27.C	1.C
87	1028	-26.C	5.5
87	1122	-25.C	5.C
87	1215	-20.C	5.C
87	1450	-19.C	4.5
87	1544	-16.C	4.C
87	1636	-19.C	7.C
87	1731	-17.C	10.C
e7	1825	-17.0	6.0
87	1900	-17.C	3.s
87	2014	-18.C	7.C
67	2105	-19.C	10.0
87	2200	-20.C	5.C
88	1045	-20.C	.C
88	2020		3.C
68	2052	-12.C	.C
88	2120	-13.C	.C
8d	2141	-15.C	3.C
88	2216	-13.C	.C
86	2235	-13.C	.C
88	2250	-14.C	.C
88	2320	-14.C	.C
88	232S	-14.0	.C
88	2353	-10.G	6.C
89	950	-22.C	7.C
89	956	-22.C	7.C
39	1032	-21.C	7.C
69	1100	-20.C	6.C
89	1117	-20.C	7.C
E?	1149	-19.C	6.C
89	1152	-19.C	12.5
89	1432	-12.C	15.C

APPENDIX (Continued)

JULIAN DATE	TIME	TEMP (°C)	WINDSPEED (MPH)
89	1500	-17.8	6.0
89	1526	-17.0	5.5
89	1531	-17.0	7.5
89	1603	-9.0	12.0
89	1622	-14.0	15.0
89	1718	-15.0	15.0
69	2028	-23.0	7.5
89	2322	-25.0	5.0
89	2342	-23.0	5.0
90	12	-23.0	.0
9C	13	-23.0	.0
90	1?	-23.0	5.0
90	37	-23.0	.0
9C	47	-23.0	4.5
90	110	-23.0	.0
90	114	-24.0	.0
90	156	-24.0	.0
90	702	-32.0	.0
90	707	-32.0	.0
90	750	-25.0	.0
90	811	‘27.0	2.0
90	946	-23.0	.0
90	1125	-19.0	.0
90	1607	2.0	4.0
90	1913	-16.0	2.0
90	2018	-20.0	.0
90	2207	-24.0	.0
91	829	-22.0	.0
91	927	-15.0	.0
91	1100	-13.0	.0
91	1001	-13.0	.0
91	1032	-8.0	5.0
91	1033	-8.0	5.0
91	1112	-6.0	——
91	1116	-6.0	3.0
91	1119	-6.0	3.0
91	1205	-5.0	2.0
91	1210	3.0	5.0
91	1221	4.0	4.0
91	1345	10.0	.0
91	13s0	10.G	.0

APPENDIX (Continued)

JULIAN DATE	TIME	TEMP (OC)	WINDSPEED (MPH)
91	13s7	10.C	.0
91	1425	10.C	.0
91	1500	10.0	.0
91	1544	5.0	.0
91	1600	5.0	3.0
91	1612	5.0	.0
91	1759	.0	.0
91	1745	.0	.0
91	1750	-2.0	.0
91	1621	-12.0	.0
91	1910	-10.0	2.0
91	1915	-12.0	2.0
91	1928	-11.0	2.0
91	2005	-18.0	5.0
91	2016	-18.0	3.0
91	2047	-18.0	.0
91	2051	-18.0	.0
91	2123	-20.0	2.0
91	2126	-20.0	2.0
91	2128	-20.0	2.0
91	220C	-20.0	2.0
91	2204	-20.0	2.0
91	2347	-18.0	.0
92	953	-13.0	.0
92	1025	-12.0	2.0
92	1402	-10.C	.0
92	2203	-12.0	8.0
93	1340	-12.0	20.0
93	1408	-12.0	22.0
93	1536	-15.0	20.0
93	2051	-12.0	15.0
94	506	-15.0	30.0
94	947	-15.0	20.0
94	lolc	-12.0	20.0
94	1042	-12.0	20.0
94	1055	-12.0	20.0
94	1106	.0	45.0
94	1125	-12.0	20.0
94	1130	-12.0	20.0
94	1200	.0	30.0
94	1203	.0	30.0

APPENDIX (Continued)

JULIAN DATE	TIME	TEMP (°C)	WINDSPEED (MPH)
94	1232	.0	23.0
94	1236	.0	28.0
94	1306	-12.0	20.0
94	1310	-10.0	20.0
94	1425	-12.0	20.0
94	1445	-10.0	20.0
94	1520	-10.0	20.0
94	1525	-10.0	20.0
94	1605	-10.0	20.0
94	1610	-10.0	20.0
94	1633	-12.0	20.0
94	1641	-10.0	20.0
94	1645	-13.0	20.0
94	1713	-13.0	20.0
94	1718	-13.0	20.0
94	1747	-13.0	23.0
94	1750	-13.0	23.0
94	1945	-15.0	20.0
95	430	-13.0	10.0
95	1005	-8.0	.0
95	1010	-8.0	.0
95	1015	-8.0	.0
95	1352	-3.0	4.0
95	1356	-3.0	4.0
95	1755	-3.0	.0
96	937	——	10.0
96	945	-18.0	10.0
96	948	-18.0	10.0
96	1017	-17.0	20.0
96	1020	-17.0	20.0
96	1540	.0	10.0
96	1552	.0	20.0
96	1602	.0	20.0
96	1635	.0	20.0
96	1640	.0	15.0
96	1710	-3.0	13.5
96	1714	.0	13.5
96	1743	-7.0	20.0
96	1746	-7.0	20.0
96	1317	-6.0	15.0
96	1819	-8.0	15.0

APPENDIX (Continued)

JULIAN DATE	TIME	TEMP (°C)	WINDSPEED (MPH)
96	1846	-9.0	8.0
96	1851	-9.0	8.0
96	1908	-10.C	6.0
96	1921	-11.0	9.1
96	1924	-11.0	9.0
96	2321	-22.0	5.0
97	748	-15.0	14.5
97	1121	-20.0	16.5
97	1400	-8.0	30.0
97	1405	-6.0	30.0
S?	1440	-8.0	20.0
97	1442	-8.0	22.5
??	1513	-6.0	27.5
97	1727	-11.0	20.0
97	2241	-10.G	35.0
98	612	-25.0	37.5
98	1456	-25.0	27.5
98	1523	-2s.0	27.5
98	1558	-25.0	27.5
98	19s4	-30.0	22.5
98	2145	-32.0	20.0
98	2325	-30.0	27.5
99	1158	-28.0	20.0
99	1759	-28.0	17.0
99	2330	-28.0	10.0
Ioc	748	-33.0	8.5
ICC	1437	-22.0	7.5
100	1350	-23.0	5.0
100	2205	-30.0	.0
ICI	1205	-20.0	10.0
101	1224	-20.0	10.C
101	1342	-15.0	14.0
ICI	1451	-16.5	17.5
ICI	1650	-22.0	17.0
102	153	-37.0	12.0
102	604	-33.0	8.0
102	1022	-25.0	.0
1C2	1550	-12.0	.0