NRL Report 8434

Measurement and Analysis of Echolocation Clicks of Free-Swimming Dolphins *(T. truncatus)* in a Tank with Echo-Reducing Wood Lining

LYNN B. POCHÉ, JR., L. DWIGHT LUKER,
AND PETER H. ROGERS

Methods Section
Measurements Branch
Underwater Sound Reference Detachment
P.O. Box 8337
Orlando, Florida 32856

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Echolocation signals of two dolphins were measured in an experiment, and aspects of the measurement methodology are discussed. An anechoic wood tank lining was developed that gave an echo reduction of 15 to 25 dB and a transmission loss of 10 to 35 dB over the range of 10 to 150 kHz. The lining was constructed in modular panels and could be removed readily should the need arise. Echolocation click energy peaks in the 20- to 30-kHz and 100- to 130-kHz ranges were observed, but none in the often-reported range of 30 to 60 kHz. Peak-to-peak source (Continued)		

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20. ABSTRACT (Continued)

levels for the clicks averaged about 165 dB re 1 μPa. Clicks that had both low- and high-frequency energy peaks showed a fixed time relationship between these parts.

CONTENTS

MEASUREMENT AND ANALYSIS OF ECHOLOCATION CLICKS OF FREE-SWIMMING DOLPHINS (*T. truncatus*) IN A TANK WITH ECHO-REDUCING WOOD LINING

INTRODUCTION

The controversy associated with past measurements on dolphin echolocation signals [1,2] and the recent measurements that show peak energy at much higher frequencies than previously reported [3,4] indicate that more importance must be placed on the selection and application of hydrophones and recording and analysis methods for measuring such signals. Variations existing between reported measurements are of such a nature as to suggest that repeatability extends no farther than an individual experiment, research activity, or institution. With this in mind, we investigated the effects that result from using different types of hydrophones and different methods of recording on dolphin echolocation signals by making some comparative measurements. Our intent was to make a useful contribution derived from our experience in precision underwater acoustical measurements. While we are indeed able to identify certain measurement pitfalls, the principal purpose of this report is to present measurements that serve to increase the span of reported observations.

DESCRIPTION OF EQUIPMENT

Tank space, the use of experimental animals, and the services of trainers were provided by the Florida Branch of the Hubbs-Sea World Research Institute, which is a part of the Sea World organization in Orlando, Florida. This experiment was located in a rectangular medication tank, about 6 × 9 m in lateral dimensions and 2 m deep, which was connected at both ends to the main series of animal tanks and could be isolated by portcullis-type gates. An echolocation task was invented so we could be sure that the dolphin was actually echolocating when clicks were measured. To shorten the training time, a simple detection task of requiring the dolphin to detect the presence of an egg-shaped 1.8 × 2.9-cm lead sinker was used. This target was visually masked by lowering it inside a thin-walled, opaque rubber cup made of B.F. Goodrich RHO-C material. The cup, approximately 3 cm in diameter by 7 cm deep, had walls approximately 0.2 cm thick and was intended to present a minimum of acoustic reflection when filled with water. The cup, suspended by nylon monofilament lines, was raised from and lowered into the water for each trial. The lead target, also suspended by monofilament, was lowered inside the cup or left hanging above the surface, as called for by the random test schedule.

It was also necessary to eliminate as many as possible of the confusing jumble of echoes coming from the walls of the tank and to minimize any waterborne noise coming from any animals or other sources located in connecting tanks. To do this a tank lining of specially constructed wood panels was developed. Echo-reduction values of about 15 to 25 dB over the frequency range of 10 to 150 kHz were achieved. Transmission loss varied from about 10 dB at 20 kHz to 35 dB at 150 kHz. Although the performance of the lining has been described previously [5], the details of construction and test results are given here in the appendix. The only large echoes remaining after installation of the lining were those from the water surface and the tank bottom. Because the dolphins usually swim quite near the surface when working, the surface echo arrives very early and the bottom echo much later. There seems to be no practical way to absorb the surface echo. The only operable method is to keep the dolphin working deep enough so that the path-length differences between direct and surface-reflected energies will allow them to be separated in time.

Two of the Sea World show-performing dolphins were assigned to this experiment: Domino, an adult male, who is blind in one eye, and Goofy, an adult female. We elected to make our measurements with the animals in a free-swimming station rather than using a chin-cup or other type of head-positioning device that could introduce a disturbance in the acoustic field. Our concern here was based

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on behavioral as well as acoustical reasons. Doppler effects and flow-noise masking are possible causes for modification of echolocation signals. The animal's position was recorded by an overhead camera triggered from the recording instruments. Depth could be estimated from the photographic data when the dolphin was not fully submerged or computed from the delay times when a surface echo was observable.

DESCRIPTION OF RECORDING METHOD

Most experimenters who attempt to record and analyze echolocation signals use some form of analog magnetic tape recorder. Unfortunately, the frequency range of interest in dolphin echolocation dictates the use of direct analog recording, which, of all the recording methods available, degrades the signal most. The intention of this investigation was to make digital recordings and analog tape recordings simultaneously to allow direct comparison of the two methods. The chief limitation of our digital recording method was its short duration. A Nicolet Explorer III Digital Oscilloscope was used; it could store 4096 words of 12-bit length. Using a sample period of 500 ns, we digitized 2 ms, or about one click, of each click train. The digital recordings were stored on magnetic disks.

EXPERIMENTAL PROCEDURE

For the data presented here, the recording hydrophones were always placed near the cup. In most of the sessions the hydrophones were spaced horizontally 2.5 to 10 cm from the cup. In two sessions the two hydrophones were arranged vertically at depths of 0.5 and 1 m, with the cup at 0.5 m in front of the upper hydrophone. This spacing represented a vertical angle of 15° when the dolphin was at a distance of 1.8 m. The dolphin would be signaled when to begin echolocating by a tone emitted from a J9 transducer. At the same time the experimenter would enable the trigger of the digital recorder. The first click to exceed the trigger threshold would trigger the storage operation, the overhead camera, and a tone-pulse generator. The tone pulse was recorded on analog tape to place a time reference of the digital record on the analog record. Date, trial number, tape-reel number, and animal identification were included in the photographic record. When the animal had finished echolocating, it would signal its decision by the appropriate behavior, and the cup would be raised in preparation for another trial. No use was made of information from the detection part of the experiment, except to judge that the animals were continuing to make an effort to echolocate.

Two types of hydrophones were used in this investigation to make measurements; both types are currently used by other workers in the field. They are the LC-10, now manufactured by Celesco Industries, Inc., and the Bruel and Kjaer Model 8103, two of which were tested. These hydrophones were calibrated at the Underwater Sound Reference Detachment (USRD) over an extended frequency range (300 kHz for the LC-10 and 500 kHz for the B&K 8103s). These calibrations are shown in Figs. 1 through 3. The calibration charts supplied by the manufacturers are shown in Figs. 4 through 6. It is apparent that the manufacturers' calibrations do not extend high enough in frequency to give the potential user a complete picture of the output of these hydrophones, especially when transients are being measured. It is important to note here that these two models of hydrophones are oppositely polarized. The LC-10 gives positive voltage at its output for an increase in pressure, and the B&K 8103 gives negative voltage output for an increase in pressure.

The analog tape recorder used was an Ampex PR-2200 with intermediate band heads and electronics. It was operated at 152.4 cm/s (60-in./s) recording speed using Ampex type 787 tape, and all possible precautions were taken to insure the lowest noise level and to minimize crosstalk. A family of frequency response curves for various input levels is shown in Fig. 7. Overload compression is almost uniform with frequency, and no peculiar low-level nonlinearities are present such as reported earlier [1]. The tape recorder's passband at 152.4 cm/s (60 in./s) was 300 Hz to 300 kHz ± 3 dB. The preamplifiers used with the hydrophones were adjusted for a passband of 1 to 300 kHz at the −3-dB points.

Naval Research Laboratory
UNDERWATER SOUND REFERENCE DIVISION
P.O. Box 8337, Orlando, Florida 32806

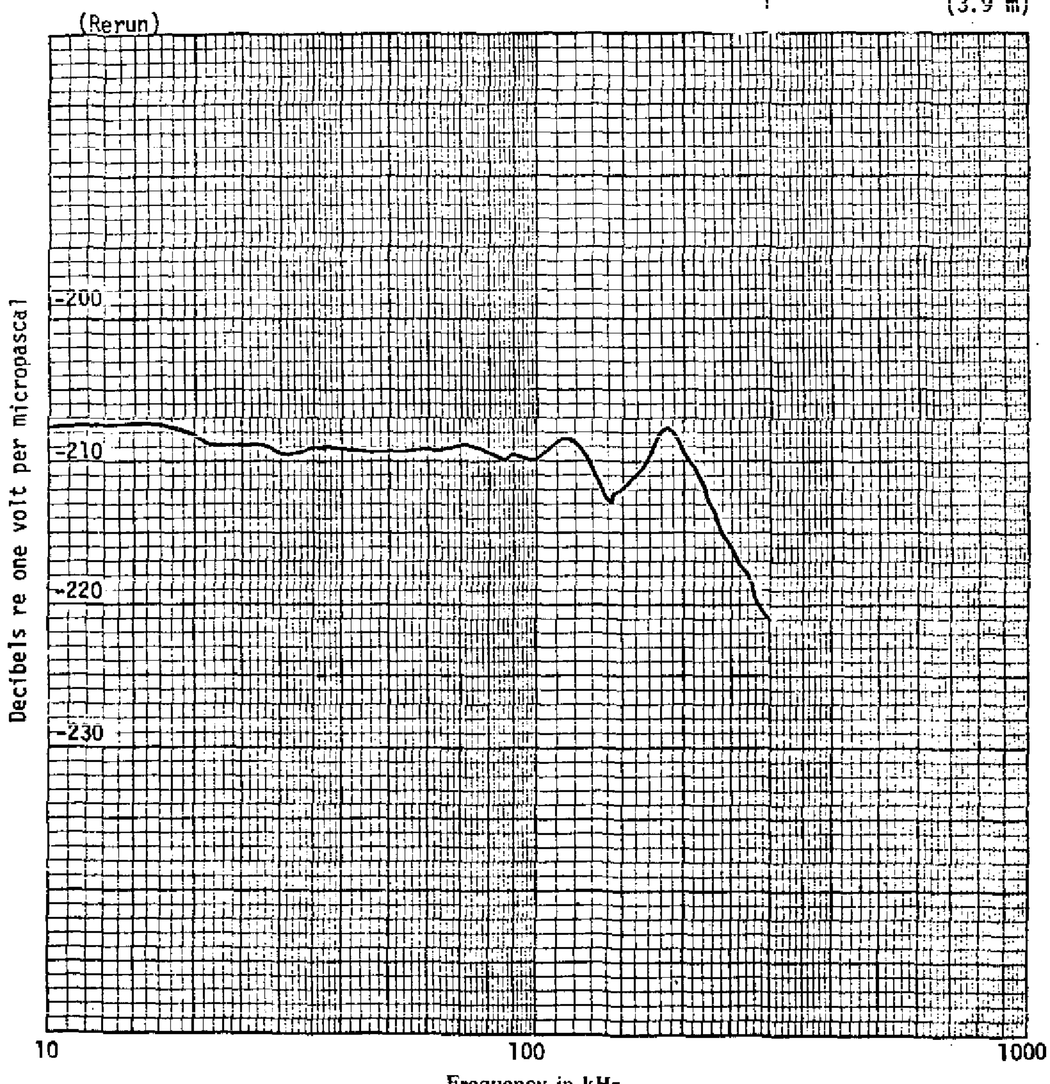
USRD No. 27C79
Date: July 1979

FREE-FIELD VOLTAGE SENSITIVITY
LC-10 Transducer Serial 2284

Open-circuit voltage at end of 9.5-m cable
UNBALANCED

Water temp. 29 °C

Hydrostatic Pressure 39 kPa (3.9 m)



6ND USRD ORL 3960/5 (REV. 7-76)

Fig. 1 — USRD FFVS calibration report of LC-10 hydrophone serial 2284

Naval Research Laboratory
UNDERWATER SOUND REFERENCE DIVISION
P.O. Box 8337, Orlando, Florida 32806

USRD No. 22C79

Date: 29 May 1979

FREE-FIELD VOLTAGE SENSITIVITY
(Model 8103 Transducer Serial 636737

Open-circuit voltage at end of 7-m cable
:UNBALANCED

Water temp. 25 °C

Hydrostatic Pressure 39 kPa (3.9 m)

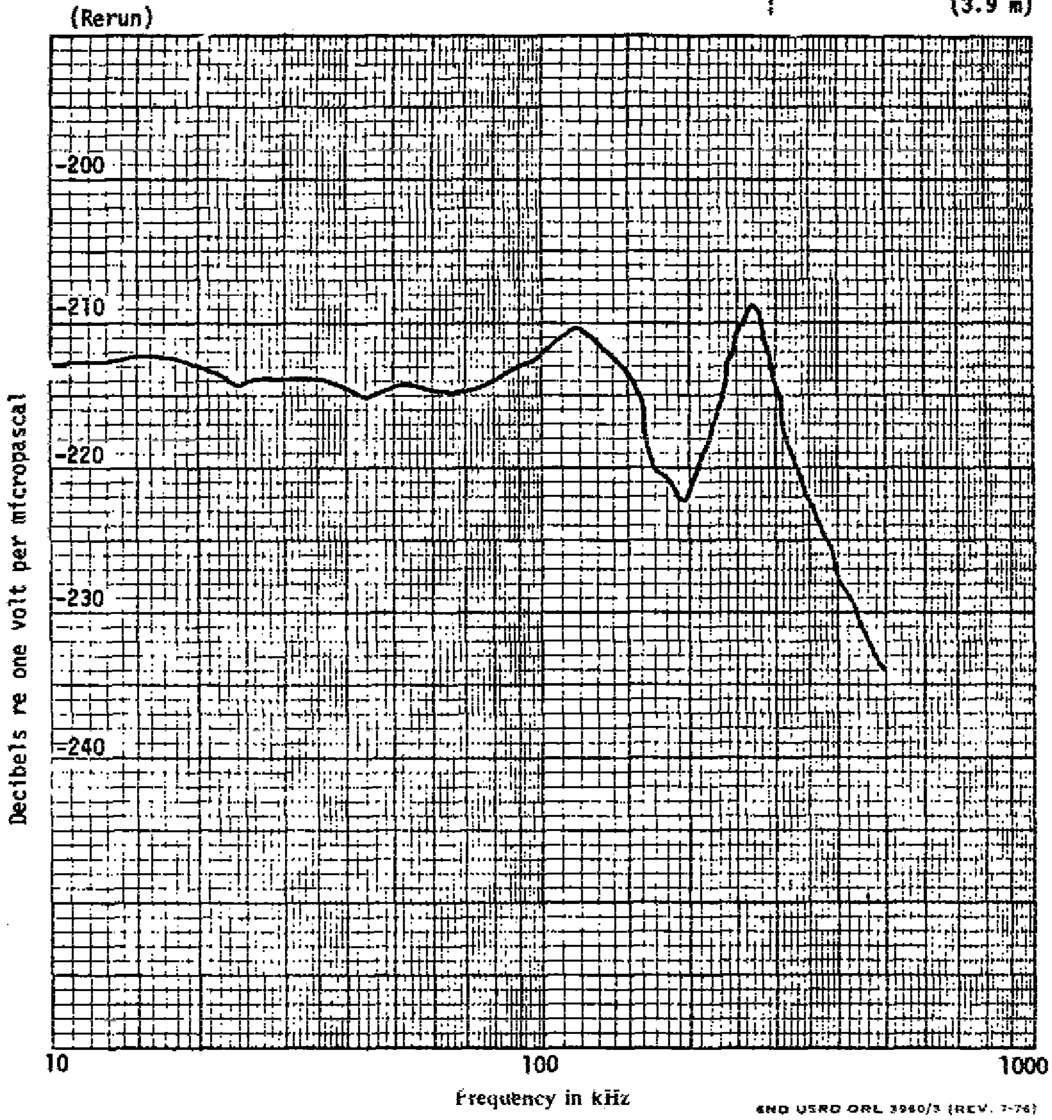


Fig. 2 — USRD FFVS calibration report of B&K model 8103 transducer serial 636737

Naval Research Laboratory
UNDERWATER SOUND REFERENCE DIVISION
P. O. Box 8337, Orlando, Florida 32806

USRD No. 26C79
Date: June 1979

FREE-FIELD VOLTAGE SENSITIVITY
B&K Model 8103 Transducer Serial 714332

Open-circuit voltage at end of 6-m cable
:UNBALANCED

Water temp. 28 °C

Hydrostatic Pressure 39 kPa (3.9 m)

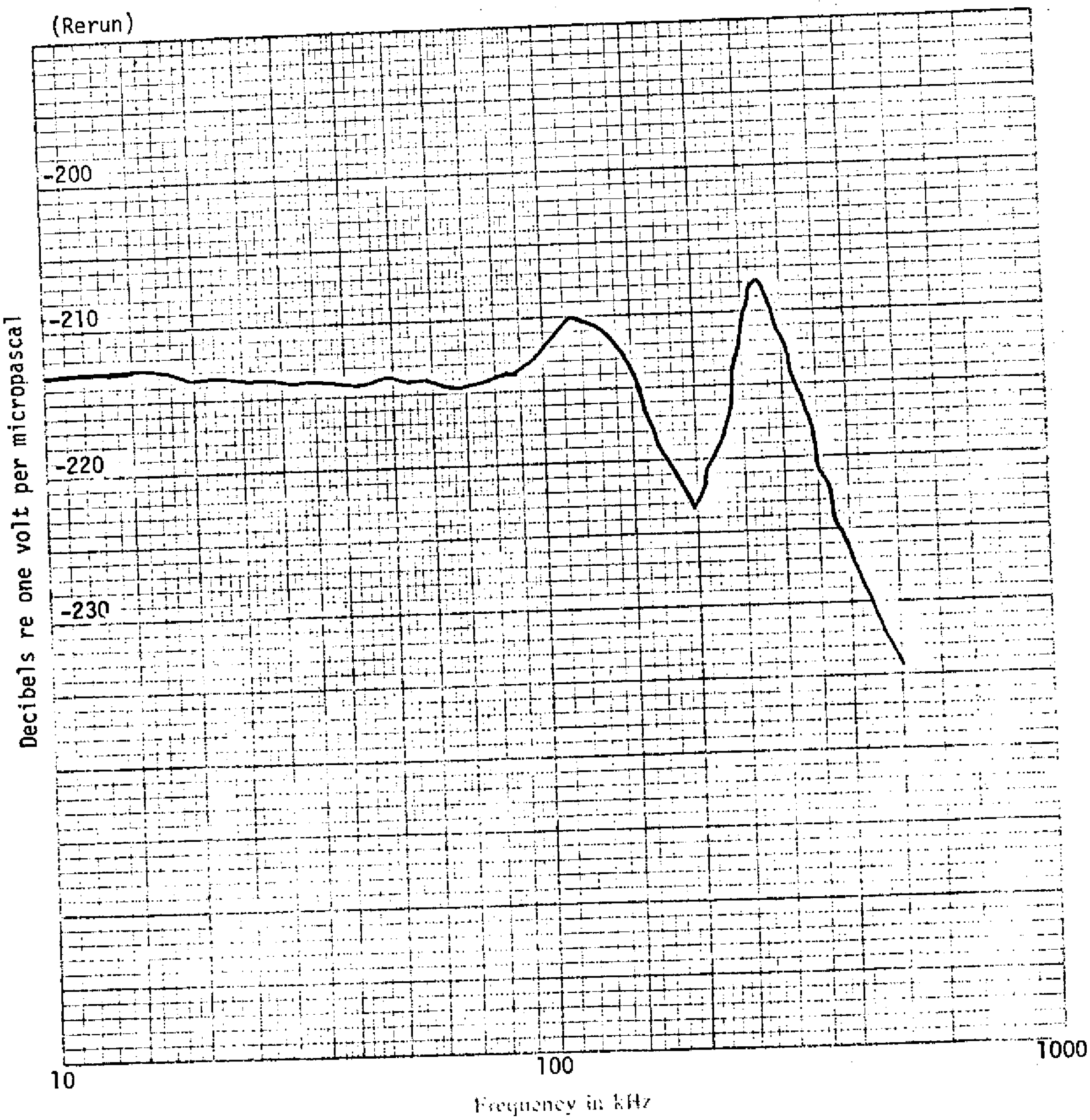


Fig. 3 — USRD FFVS calibration report of B&K model 8103 transducer serial 714332

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LC-10 TRANSDUCER SERIAL NO. 2284
AVERAGE FREE FIELD VOLTAGE SENSITIVITY 108.9 db

FREQUENCY IN KHz
METHOD OF CALIBRATION: COMPARISON
WITH STANDARD LC-32 SERIAL NO. 1260
WATER TEMPERATURE 20 °C. DEPTH 10 FT.
TEST TECHNICIAN
QUALITY CONTROL 3/29/73

CABLE LENGTH 25 FT
CAPACITANCE W/CABLE 7,290 Pf
DC RESISTANCE 50 K MEGOHMS
MOUNTING SLEEVE LEAKAGE
RESISTANCE 10 K MEGOHMS
DATE 3-29-73 BY 15680

FREE FIELD FREQUENCY RESPONSE

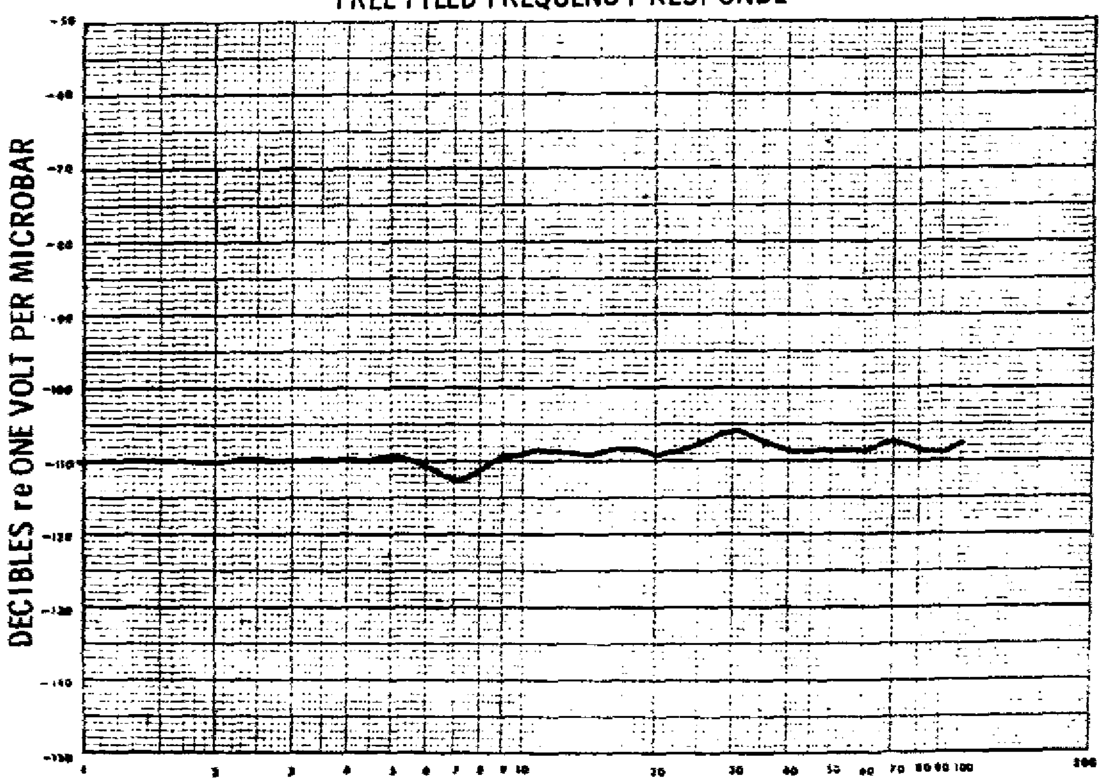

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Fig. 4 — Manufacturer's FFFR calibration report of LC-10 hydrophone serial 2284

Calibration Chart for Hydrophone Type 8103

Brüel & Kjær
Nærum Denmark

Serial No. 636737

Reference Sensitivity at 250 **Hz* at** 23 **°C**
including 6 m integral cable

Cable Capacitance 95 pF/m typical

Open Circuit Sensitivity:

Voltage Sensitivity:

−212,8 dB re 1 V/μPa**

−92,8 dB re 1 V per Pa or 22,9 μV per Pa

−112,8 dB re 1 V per μbar**

Charge Sensitivity: 76,9 pC per Pa

Capacitance (including 6 m cable) 3360 pF

Frequency Response:
Individual Free Field Frequency Response Curve attached

Date 11-11-76 Signature [signature]

Summarized Specifications
Usable Frequency Range: 0.1 Hz to 200 kHz (−10 dB)

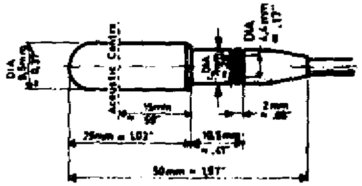
Linear Frequency Range:
0.1 Hz to 20 kHz ± 1 dB
0.1 Hz to 140 kHz ± 2 dB

Horizontal Directivity 200 kHz: (XY-plane)
typical ± 2 dB

Vertical Directivity 100 kHz: (XZ plane)
typical ± 4 dB

BC 0094

Physical:



Leakage Resistance:

> 2 · 10^4 MΩ at 23 °C

Operating Temperature Range:
−40°C to +120°C
−40°F to +248°F

Change of Sensitivity with Temperature:
Charge < 0.03 dB/°C
Voltage < −0.03 dB/°C

Change of Sensitivity with Static Pressure:
3×10^{-7} dB/Pa (0.03 dB/ato)

Temperature Transient Sensitivity: < 50 Pa/°C
(ANSI S.2.11-1969); measured with B & K Charge Preamplifier Type 2626, LLF 3 Hz

Allowable Total Radiation Dose: 5×10^7 Rad

Acceleration Sensitivity: < 130 dB re 1 μPa/g

Maximum Operating Static Pressure:
40 ato

Cable:
Double shielded low noise, low capacitance
Integral cable: 6 m with miniature plug

Weight (incl. cable): 170 g
* Traceable to NBS
** 1 Pascal = 1 N/m² = 10 μbar

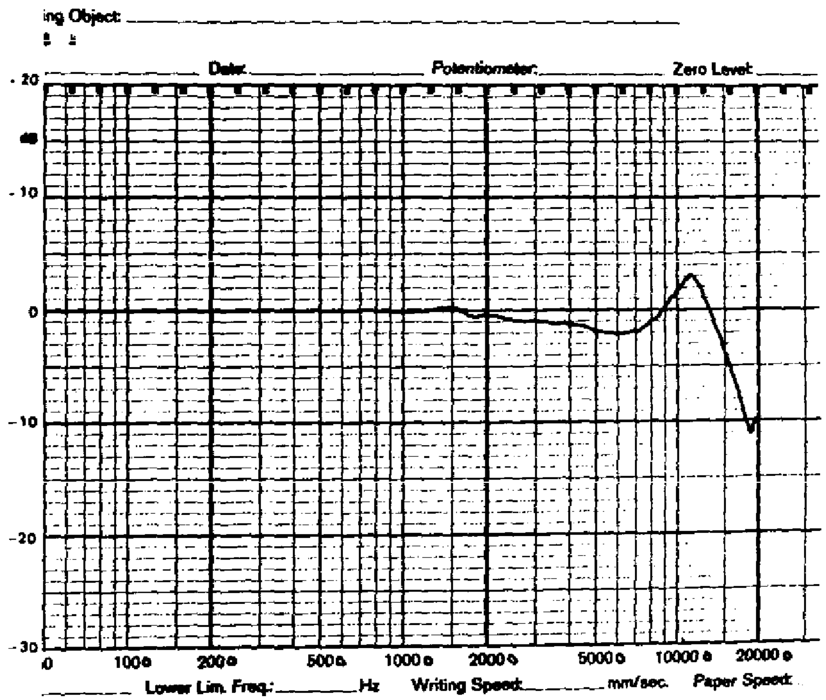


Fig. 5 — Manufacturer's calibration report of B&K model 8103 transducer serial 636737

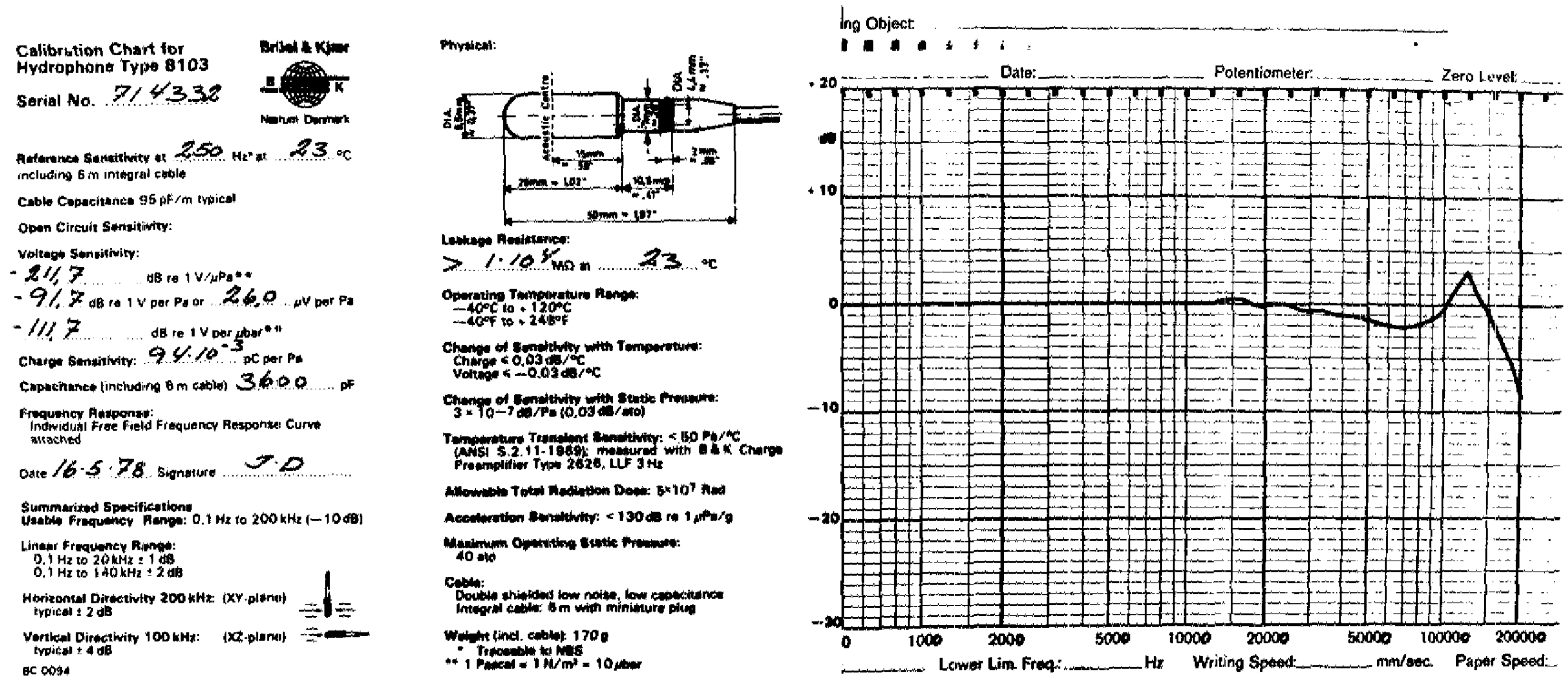


Fig. 6 — Manufacturer's calibration report of B&K model 8103 transducer serial 714332

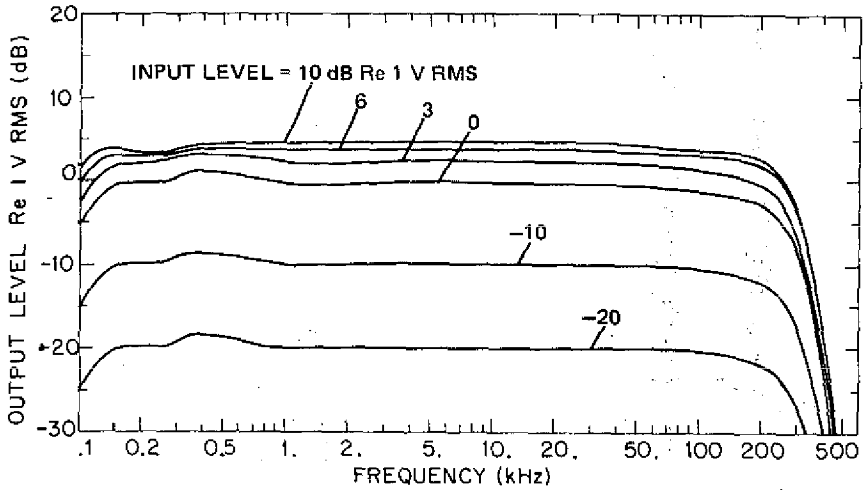


Fig. 7 — Analog tape recorder Ampex PR-2200, output level vs frequency for indicated input levels with Ampex type 787 tape

DISCUSSION OF RESULTS

Of approximately 365 recorded trials, we were able to use only 145 in which the overhead photographs showed the dolphin's rostrum to be pointed toward the immediate area of the target

The only startling information to come out of the hydrophone comparison is the "hidden" frequency response peak already seen in Figs. 1 through 3. The fact that the peak at 260 kHz exists in both B&K 8103s seems to indicate that it is a characteristic of the design. Users should be aware of the need to provide low-pass filtering of the output to the bandwidth of interest when observing transients in the time domain. Any remaining comments that could be made would concern the geometry and orientation problems of transient measurements in general: both the source and the receiver should be as near to mid-depth as possible. When interpreting received signals, beware of overlap between the direct signal and unwanted echoes. At high frequencies, directivity and surface scattering can distort echoes so that those arriving close after the direct signal appear to be part of a longer, more complex transient.

The comparison of recording methods revealed just what one would expect: the analog magnetic tape recorder, when properly adjusted and not pressed too close to the limits of its performance, is a basic, reliable tool. It suffers from dynamic range limitations, however, and dolphins seem to have no respect for the shortcomings of our instruments. A comparison of traces for the same click from the digital recorder and from the analog tape recorder is shown in Fig. 8. The tape-recorded trace seems much noisier; but a comparison of the spectra, seen in the same figure, shows that most of the noise energy is concentrated in a narrow frequency range in the upper part of the passband. The digital recorder does not have sufficient storage to record each click in a given train. Because of this, we had to rely on the analog tape records to examine a click sequence. The availability of a programmable digitizer would afford a more desirable means of recording these click sequences. This device would store only a predetermined number of digitized samples following each trigger signal. It would require enough storage to allow time for transferring a block of data to the mass storage medium while it continued to digitize incoming data.

The peaks and nulls in the frequency response of our various hydrophones (for example, Fig. 3) made us curious about the effect on the spectra of our click measurements. To determine this effect,

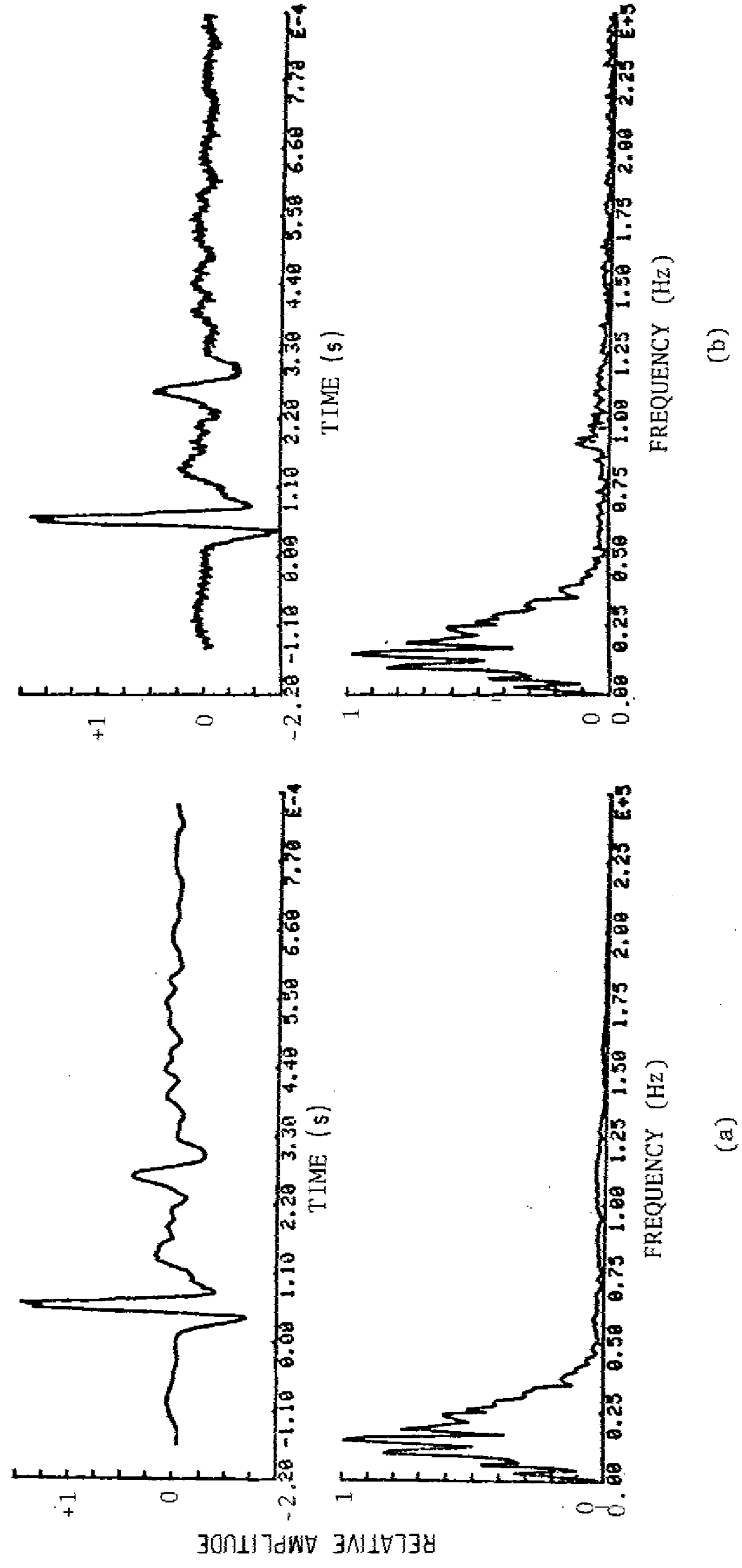


Fig. 8 — Comparison of recording methods: an echolocation click and its spectrum: (a) digital;
(b) playback from analog magnetic tape

we adopted an equalization operation in our program in which the frequency response function of the hydrophone was reduced to a small number of straight-line segments. Figure 9 shows an example of the approximation to the response of Fig. 3. It was possible to approximate each hydrophone response with errors no greater than 1.5 dB over the entire frequency range. The correction constants were stored in tables used by the program to correct each spectrum sample by the appropriate value. Examples of uncorrected and corrected spectra may be seen in Fig. 10.

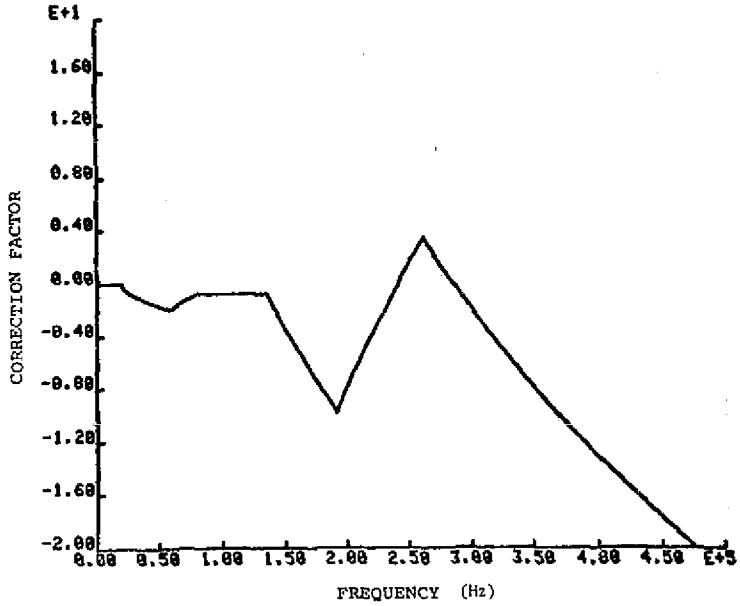


Fig. 9 — Straight-line approximation of B&K model 8103 transducer serial 714332 response

One particular signal artifact that might be worth mentioning can arise when the dolphin whistles and clicks at the same time. Our trainers attempted to eliminate this behavior by extinction, but it occurred often enough to give rise to some peculiar received signals. When two recording hydrophones were being used in a vertical array, the whistle would appear to shift from one hydrophone to the other, or to both. This effect was being caused by cancellation from the surface reflection. As the whistle was swept in frequency and as the dolphin approached the hydrophone array, cancellation occurred at different depths. This was not apparent until the entire array output was played back on a strip-chart recorder. It should be noted that when one uses a vertical configuration of two hydrophones whose depths are known it is possible and practical to compute both the range and depth of the dolphin from the time delays between the direct signals and the surface reflections received by the two hydrophones.

The use of filters during tape playback can lead to unexpected phase distortion, as shown in Fig. 11. In this case the signals were being reproduced at a lower tape speed to stretch the time interval between clicks and allow separate records of each individual click to be made on the digital recorder. A consequent effect was to scale the frequencies down by a factor of 32. The recorded bandwidth of 300 Hz to 300 kHz became 9.4 Hz to 9.4 kHz. The low-frequency cutoff of the tape recorder's playback electronics limited this to a bandwidth of 100 Hz to 9.4 kHz. A 200-Hz high-pass filter was used to reduce hum and low-frequency noise at playback. Because the lowest frequency at which energy appeared in the click train was about 15 kHz, the (200 × 32)-Hz rolloff was not expected to affect the data; however, phase shift in the filter passband was sufficient to completely distort the signal, as can be seen in Fig. 11.

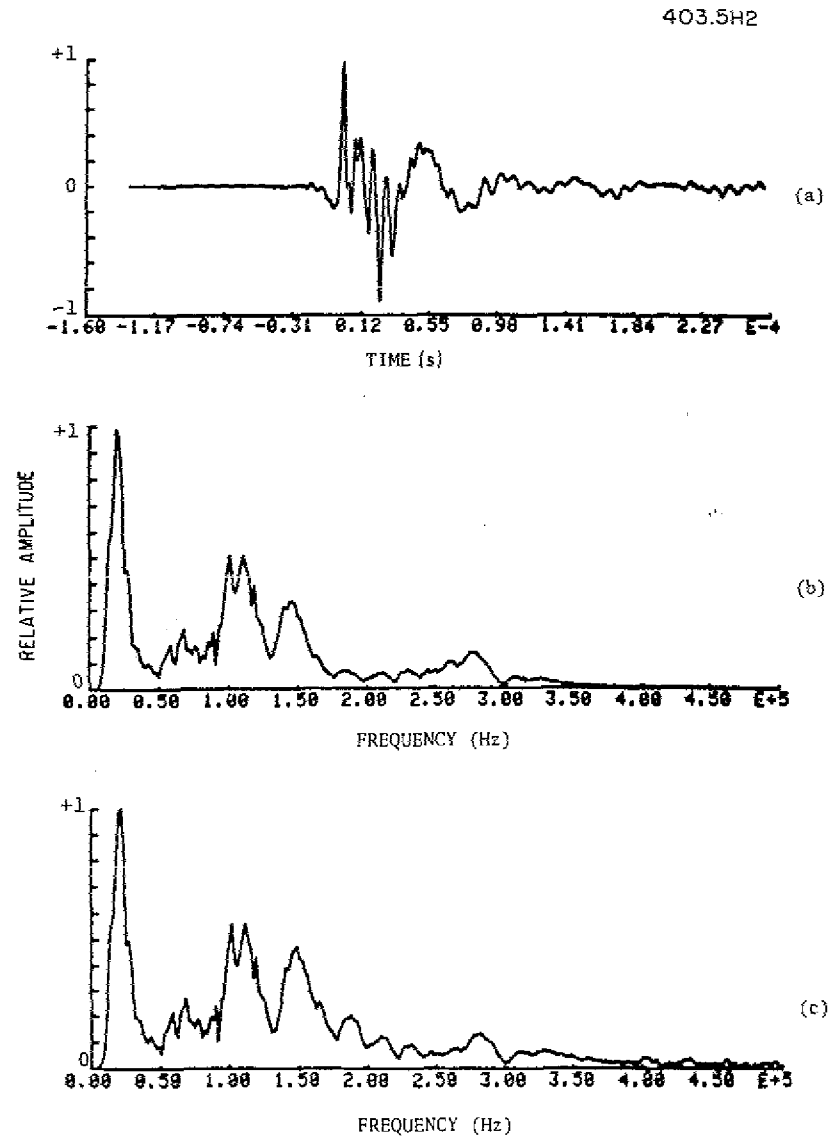


Fig. 10 — Correction for hydrophone frequency response: (a) time series, hydrophone output; (b) uncorrected spectrum; (c) corrected spectrum

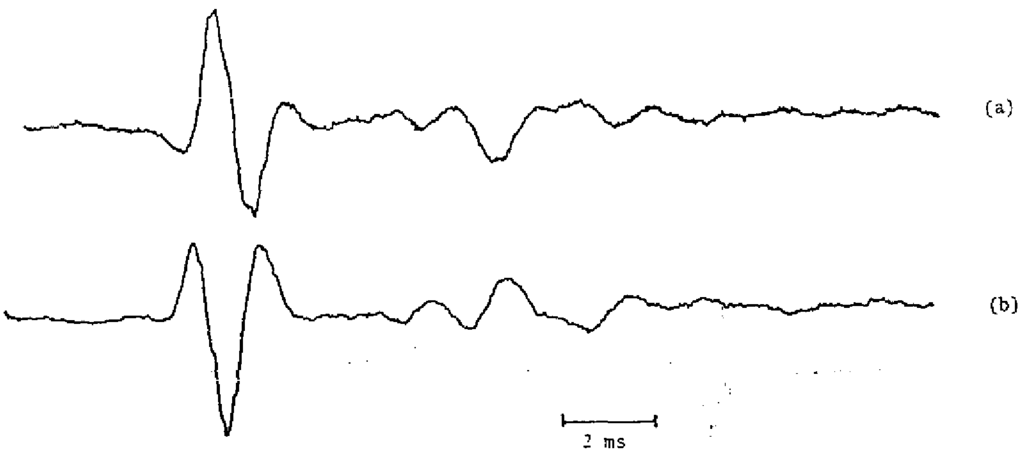


Fig. 11 — Phase distortion produced by filtering: (a) no filter; (b) 200-Hz high-pass filter

The standard description for echolocation pulses of *T. truncatus* was given by Evans [6]. He placed the energy peak of typical clicks at 30 to 60 kHz and their rms pressure source level at 140 to 180 dB re 1 μPa at 1 m. Later measurements in open water by Au et al. [4] showed peak energy at 120 to 130 kHz. They concluded that the upward frequency shift of the clicks was caused by an adaptation to the high level of ambient noise contributed by snapping shrimp in the open-water environment. As our collected data were examined it became obvious that both of our dolphins were producing clicks whose peak energies occurred at frequencies either much lower or much higher than those accepted as normal for animals working in tanks. Figures 12 and 13 show seven representative traces of individual clicks and their spectra from this experiment. Peak-to-peak and rms source levels were computed for these clicks using ranges and depths estimated from the overhead photographs. Figure 14 shows one of the photographs. Because the rms pressure turned out to be 15$\pm$1 dB below the peak-to-peak pressure, our peak-to-peak mean value of 166$\pm$5 dB for these seven traces falls within Evans' range of source levels. The spectral energy, as previously stated, shows an unusual variation in distribution. All of the clicks represented in Fig. 13 have an energy grouping in the 20- to 30-kHz range. Only in curves (*d*) and (*e*) is the major peak at a high frequency, and then it is in the 110- to 130-kHz area. These clicks are typical of all our measurements. In almost every case there was significant energy around 25 kHz. Sometimes there was a dominant peak around 120 kHz. Never was there any energy peak at 30 to 60 kHz. The 120-kHz peaks cannot be attributed to the presence of ambient noise; the tank used had a fairly low noise level. Separate measurements were made of noise in the tank using an H52 hydrophone, PAR 113 preamplifier, and HP141T spectrum analyzer. Polaroid photos were made directly from the analyzer screen with 0- to 20-kHz and 0- to 200-kHz bandwidths. This allowed replotting on a log frequency scale. The spectrum level in the 30- to 60-kHz band was about 50 dB. The entire noise spectrum is plotted in Fig. 15, along with the Knudsen spectrum, as given by Urick, for comparison.

It is not clear why our click measurements show two different main frequency components while those reported by Evans and Au show only one. Our measurements seem more closely related to those of Møhl and Andersen [7] and Dubrovskii and Zaslavskii [8], except for the difference of the animals' genus. *Tursiops'* echolocation signals, like those of *Phocoena,* seem to have a low-frequency part and a high-frequency part. The low-frequency part is a decade higher in our case, but it seems to follow a fixed time relationship with respect to the high-frequency part. The high frequencies always appear within the first full cycle of the low-frequency part. One common point between our experiment and those of Refs. 8 and 9 is that the animals were free-swimming with no head-positioning or tethering devices used. The observed dolphin signals seem to be composed of high-frequency (110 to 130 kHz) and low-frequency (20 to 30 kHz) components. When click spectra from the widely spaced vertical

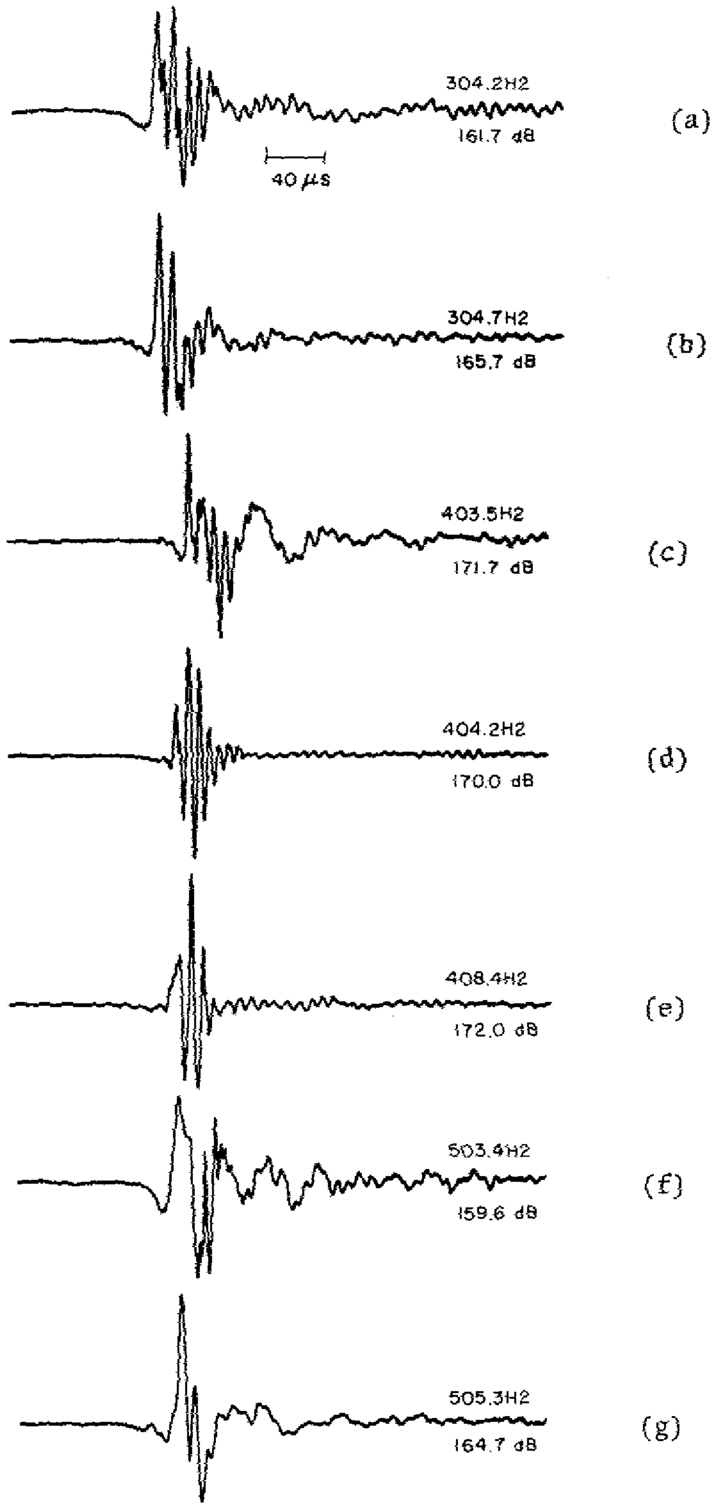


Fig. 12 — Representative click traces

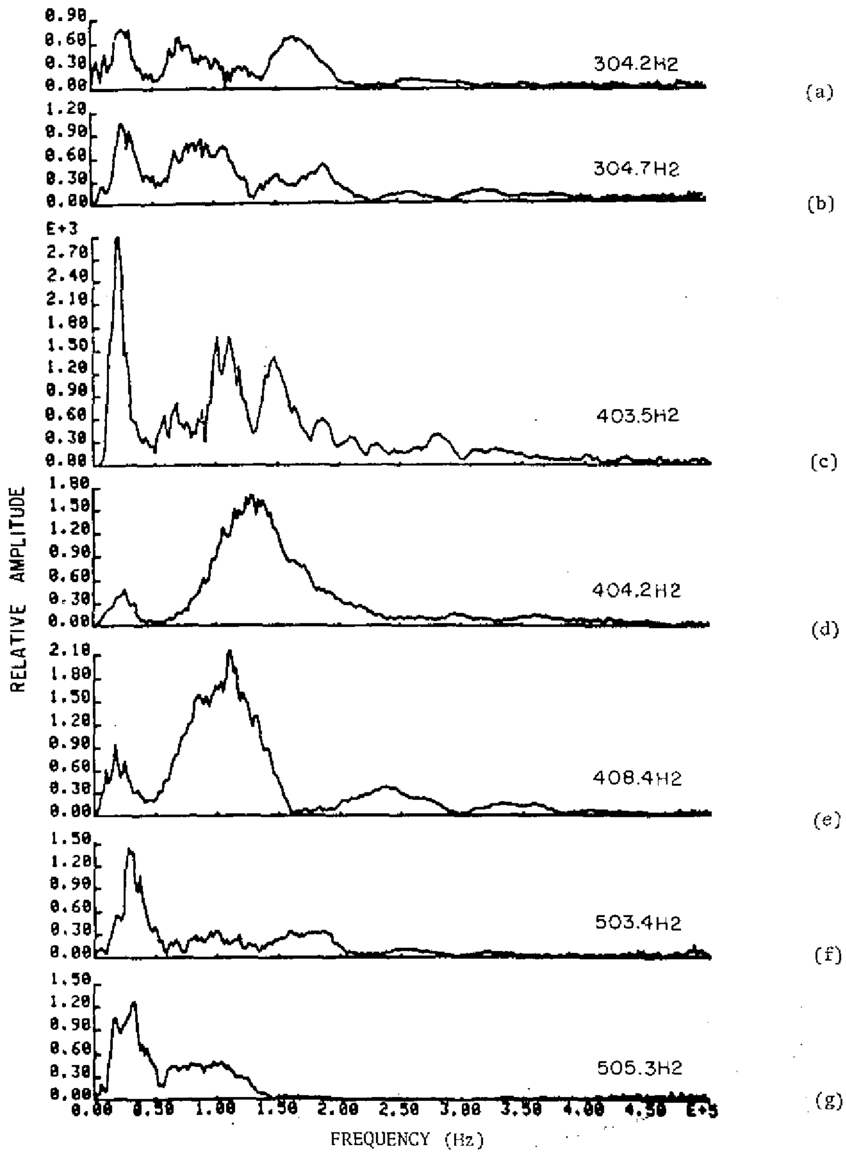


Fig. 13 — Spectra of representative traces

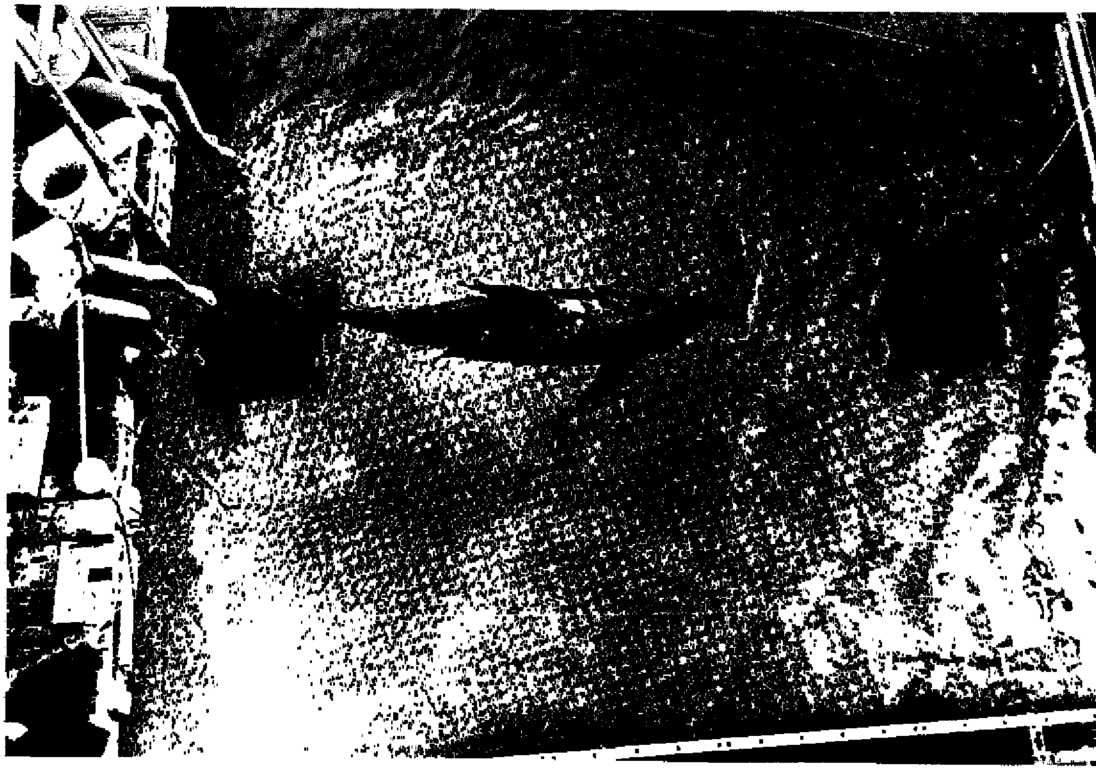


Fig. 14 — Typical data photograph

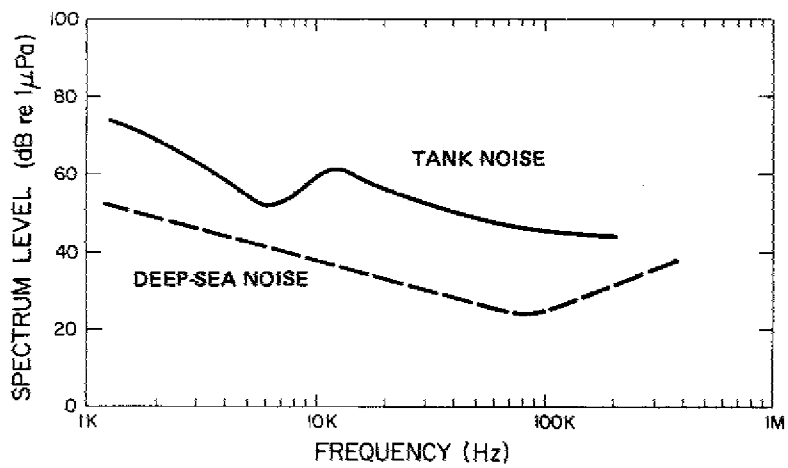


Fig. 15 — Spectrum of ambient noise in the tank

array are examined along with the corresponding photographs, it appears in most but not all cases that the relative amplitudes of the high- and low-frequency components are determined by alignment of each dolphin's acoustical axis with the hydrophone. The higher frequencies dominate when the orientation is better, and the low frequencies are dominant when the orientation is worse. In the other cases mentioned above, the absence or presence of high or low frequencies seems to be in the emitted signal.

A number of click sequences were examined to determine what degree of variability exists from pulse-to-pulse in the click train. Waveforms seen in different click trains are highly variable, but there does appear to be a "tuning-up" effect where both amplitude and spectral content are changed markedly for the first few clicks. The early pulses in many of the click trains have no high-frequency energy. Then the high frequencies gradually appear, superimposed on the low-frequency pulse. A good example of this type of sequence is seen in Fig. 16. Here traces *1* through *4* show the development stage, and traces *5* through *11* may represent scanning away from and then reacquiring the target. Traces *12* through *32* show variation chiefly in amplitude only. Whether the assumed scanning is done physically, either by head-swinging or beam-steering, is not clear, except that no obvious head-swinging movements were observed during the experiment.

CONCLUSIONS

We have made numerous carefully instrumented measurements of dolphin echolocation activity and at this point have seen sufficient unexplained variations in the nature of dolphin echolocation signals to convince us that sufficient information is not yet available to establish norms or hypotheses.

ACKNOWLEDGMENTS

During the course of this investigation, our experiments were critiqued by various expert trainers, behaviorists, and managers. In particular, we wish to thank Whitlow Au, James Fish, A. Earl Murchison, Ross Pepper, and H. O. Porter of the Naval Ocean Systems Center; Edward Asper, David Butcher, W. E. Evans, and trainers Alan, Dan, David, Didi, and Suzy of Sea World Orlando; and W. V. Carlson, Jack Evans, Carl Scott, and Donna Stuart of USRD.

REFERENCES

1. K.J. Diercks, R.T. Trochta, and W.E. Evans, "Delphinid sonar: measurement and analysis," J. Acoust. Soc. Am. **54**, 200 (1973).

2. W.A. Watkins, "Bandwidth limitations and analysis of cetacean sounds, with comments on "Delphinid sonar: measurement and analysis" [K.J. Diercks, R.T. Trochta, and W.E. Evans, J. Acoust. Soc. Am. **54**, 200-204 (1973)], J. Acoust. Soc. Am. **55**, 849 (1974).

3. W.W.L. Au, R.W. Floyd, and J.E. Haun, "Propagation of Atlantic bottlenose dolphin echolocation signals," J. Acoust. Soc. Am. **64**, 411 (1978).

4. W.W.L. Au, R.W. Floyd, R.H. Penner, and A.E. Murchison, "Measurement of echolocation signals of the Atlantic bottlenose dolphin, *Tursiops truncatus* Montagu, in open waters," J. Acoust. Soc. Am. **56**, 1280-1290 (1974).

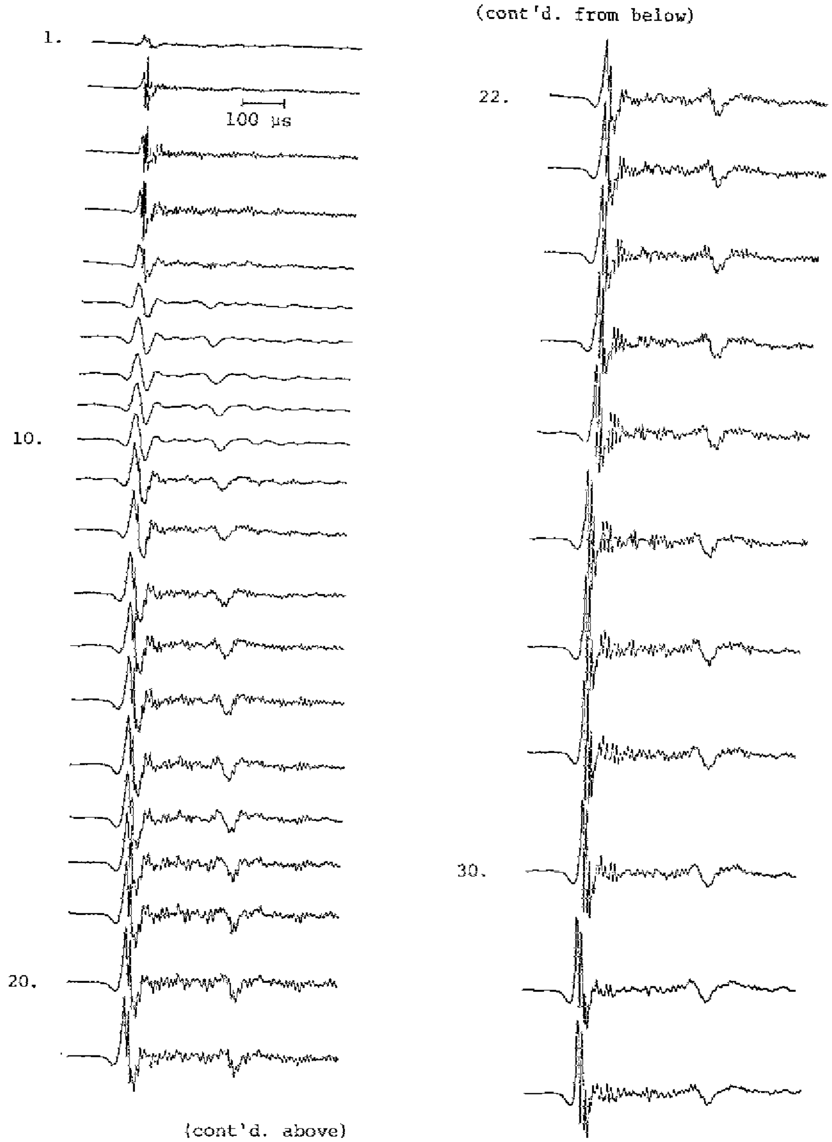


Fig. 16 — Echolocation click train: sequence of 32 consecutive clicks

5. L.B. Poché, Jr., P.H. Rogers, and W.V. Carlson, "Improving the acoustic properties of a dolphin tank," J. Acoust. Soc. Am. **62**, S89 (1977).

6. W.E. Evans, "Echolocation by marine delphinids and one species of freshwater dolphin," J. Acoust. Soc. Am. **54**, 191 (1973).

7. B. Møhl and S. Andersen, "Echolocation: high-frequency component in the click of the harbour porpoise *(Phocoena ph.* L.)," J. Acoust. Soc. Am. **54**, 1368-1372 (1973).

8. N.A. Dubrovskii and G.L. Zaslavskii, "Role of the skull bones in the space-time development of the dolphin echolocation signal," Sov. Phys. Acoust. **21**, 255-258 (1975).

Appendix
DESIGN OF AN ANECHOIC WOOD LINING

Tank space is in constant demand at Sea World. Their needs are constantly changing due to various programs of animal breeding, rescuing beach-stranded animals, etc. For this reason, our acoustical treatment had to be of a portable nature that would permit its removal at the end of the project. In fact, it was necessary for us to move the lining once during the project, when a change of tanks became desirable. This was done successfully and with a minimum of lost time.

The walls and bottom of the tank were smooth concrete, and reflections from these surfaces had to be reduced as much as possible. A wall-lining material was required that would absorb sound in the dolphin sonar frequency range of approximately 10 to 150 kHz. It was also necessary to reduce the noise from adjacent tanks that passed through the common openings. This required a high transmission loss when the wall-lining material was used as a barrier. The large wall area to be covered (approximately 30 m^2) necessitated using an inexpensive, easily fabricated material. For this reason, we chose to investigate wood.

The acoustical treatment took the form of a lining constructed of modular curtain panels about 1.8-m square, which stood about 15 cm from the wall. The panels were made up of brick-size cypress blocks strung on stainless-steel cables and interlocked to form a free-standing panel (Fig. A1). At the bottom of each panel, a precast concrete beam served as a weighted base. Its ends were grooved to interlock with adjoining panels. The tops of the cables were secured by a steel channel (Fig. A2), which was clamped to the tank wall by metal standoffs.

DEVELOPMENT OF THE LINING

Data on absorption of underwater sound by woods are difficult to find. A number of woods were tested by Lastinger [A1] in an impedance tube at high hydrostatic pressures, but only at lower frequencies (3 to 8 kHz).

We set out to measure echo reduction (ER) and transmission loss (TL) directly and devised a fast-working, convenient method. This consisted of using a small ($1 \times 0.6 \times 0.6$-m) polyethylene laboratory tank and a 30-cm-square sample of wood approximately 5 cm thick. We measured ER at normal incidence only and used a simple pulsed system, reading the receiving hydrophone signal directly from an oscilloscope. Figure A3 shows a view of the tank with a sample in place for an ER measurement. Measurements were possible from 150 kHz down to 30 kHz with these sample and tank sizes. The ER measurements were made by moving the receiving hydrophone on axis toward or away from the sample until the best pulse envelope shape was obtained. The amplitudes of the incident pulse and the reflected pulse were recorded and corrected for spherical spreading. To check the spherical spreading correction, we used a 30-cm-square, 6.35-mm-thick plate of stainless steel as a total reflector in place of the sample. The deviation of measured reflection from total reflection was less than 0.5 dB across the entire frequency range.

The TL was measured simply by recording the sound pressure with the receiver on axis behind the sample, then removing the sample and taking the ratio of the two readings.

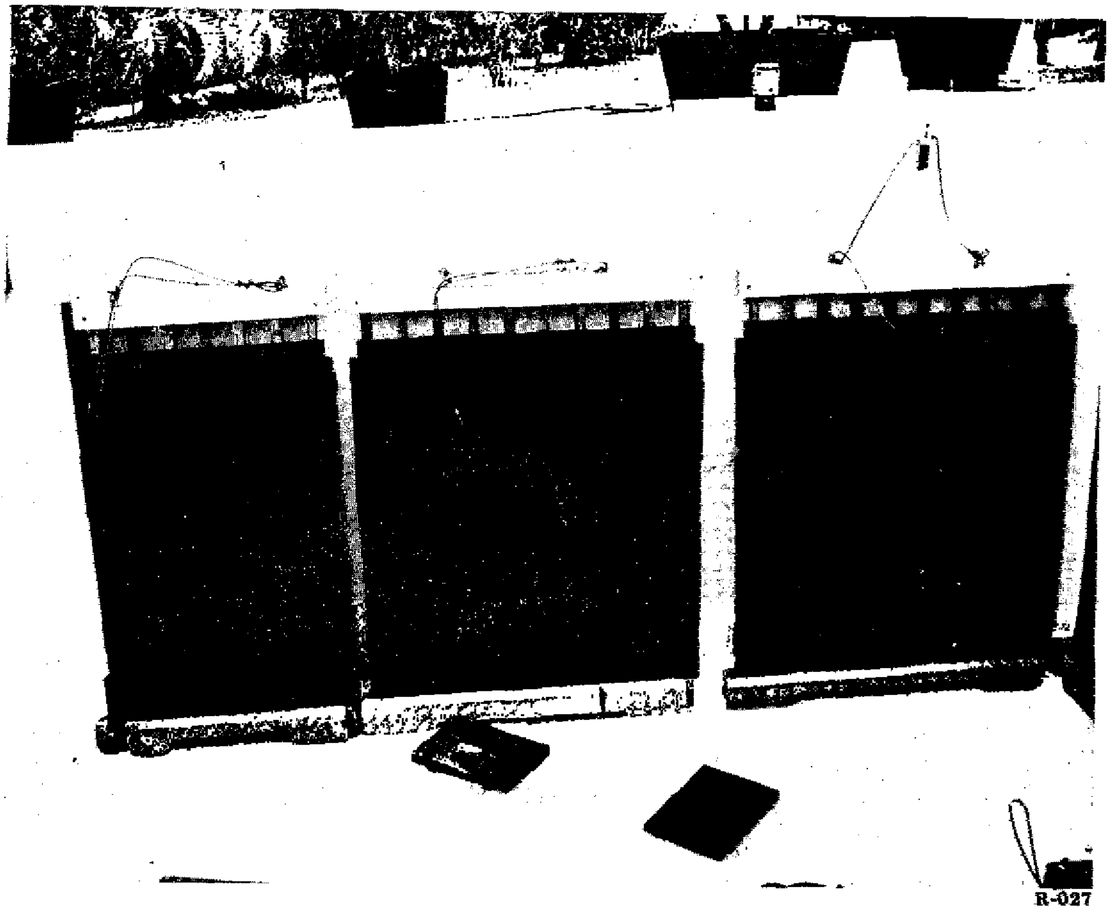


Fig. A1 — Modular wood lining panels in tank during installation

Lastinger's results showed that the angle of grain orientation with respect to the incident sound is important to absorption. The absorption is very low for all woods when the grain is oriented perpendicularly to the sound. Grain orientations of 0° and 45° give higher attenuation, with 45° yielding a generally closer match of sound speeds, according to Lastinger. In addition, he routinely pressure-soaked the samples to expel air from the wood and saturate them with water, thus obtaining the highest values of attenuation.

We fabricated our test samples by nailing the 5-cm-thick blocks to a piece of 1.2-cm-thick fir plywood from the rear. Each panel was submerged in a pressure vessel, and pressure was cycled from atmospheric pressure to 7 MPa at least twice. After this, each panel was kept submerged between tests to prevent drying out. We tested redwood and cypress samples of 0° and 45° grain orientation in the laboratory tank. The results for echo reduction (Fig. A4) showed redwood to have a slight advantage over cypress. It appeared to be extremely impractical to use a 45° grain orientation rather than 0°, when we considered the great difficulty in fabricating a structure with 45° grain orientation, to obtain the slight advantage it would have in echo reduction.

The results for TL (Fig. A5) look more conclusive, but they must be interpreted cautiously. A highly reflective panel might appear to have a TL as great as a highly absorptive one. In this figure both types of wood show acceptable results for TL.

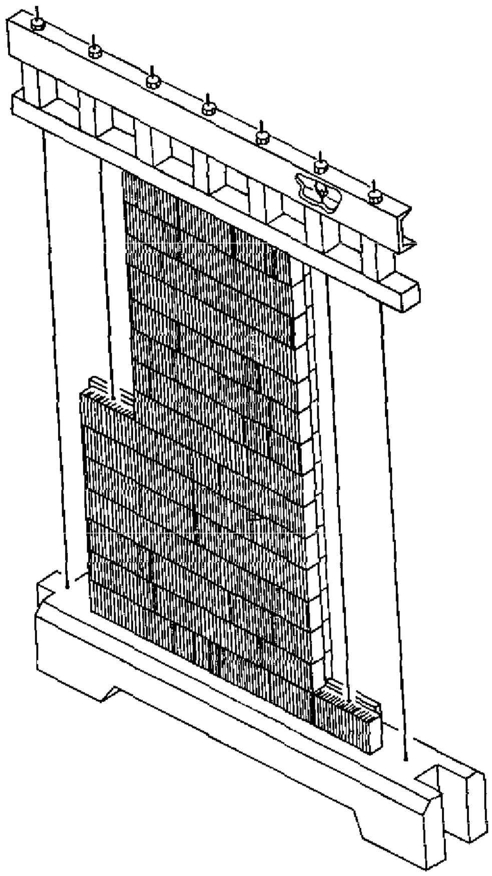


Fig. A2 — Panel construction details

We decided to use cypress because of its local availability and because redwood bleeds a dark-colored, opaque stain into the water. Soaking the wood under high hydrostatic pressure was found to be absolutely essential for high, stable values of ER. Our criterion for sufficient soaking was negative buoyancy. The first samples tested were smooth-faced. We decided to try to improve ER by increasing the surface area. This could be done by grooving the face of the panel. Two patterns of grooving were tested. The first was a cross-hatch pattern of 0.64-cm-deep cuts, 0.32 cm wide, on 1.27-cm centers. The second was a pattern of parallel cuts 1.91 cm deep, 0.48 cm wide, on 1.91-cm centers. The second pattern proved slightly better for TL (Fig. A6) and required fewer saw cuts to fabricate.

The results from the test samples looked quite encouraging, so we decided to build and test a full-size panel. This panel was tested in the USRD Lake Facility using the same methods we had used in the laboratory tank. The results for ER were about equal to those of the small panel except for frequencies above 100 kHz. The TL was considerably reduced from the small panel's performance, but still at acceptable levels (15 to 40 dB). Figure A7 shows results for the large panel tested in the Lake Facility.

CONSTRUCTION AND INSTALLATION

Figure A8 is a photograph of one of the blocks used in the panels. The overall dimensions are approximately 9 × 19 × 6 cm. The blocks were made by multiple passes on a table saw. They were

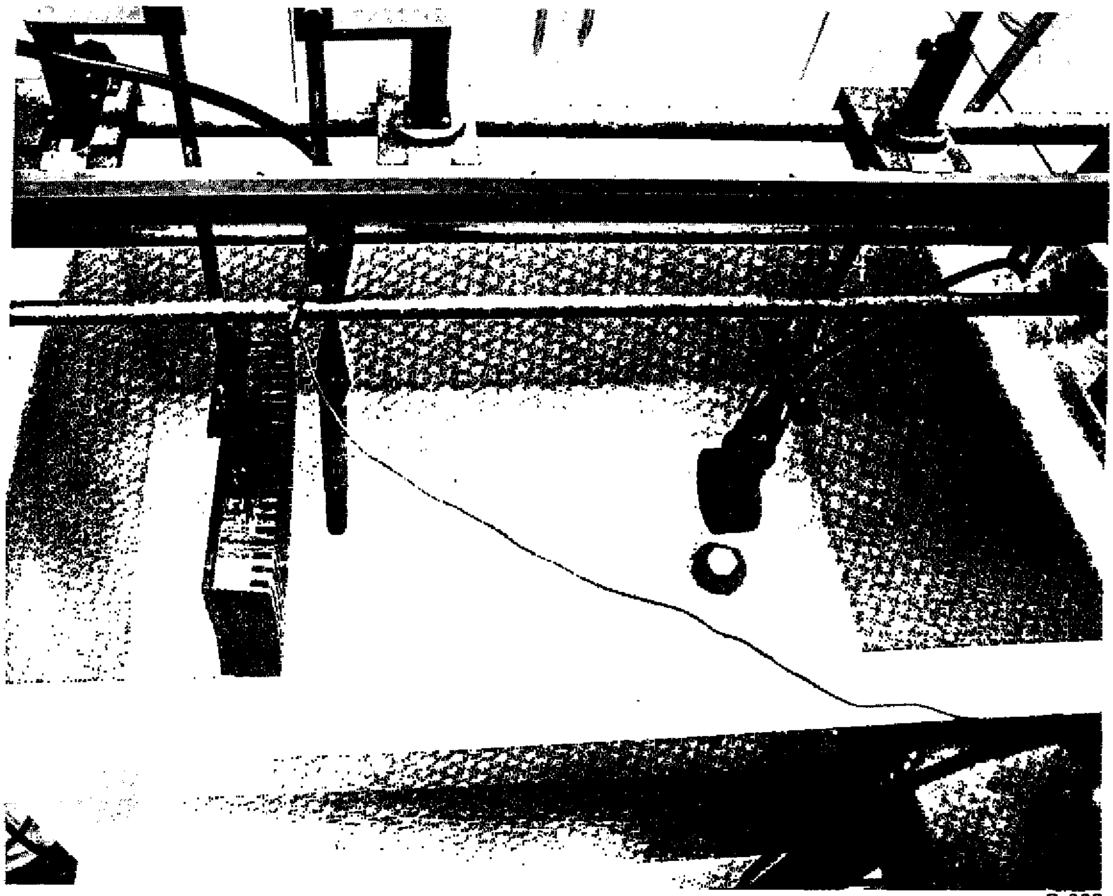


Fig. A3 — Sample panel and instruments in laboratory test tank

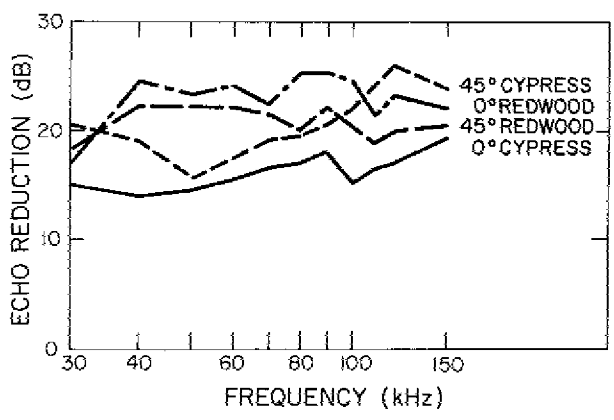


Fig. A4 — Echo-reduction values for two woods, 30-cm × 30-cm smooth-faced panels

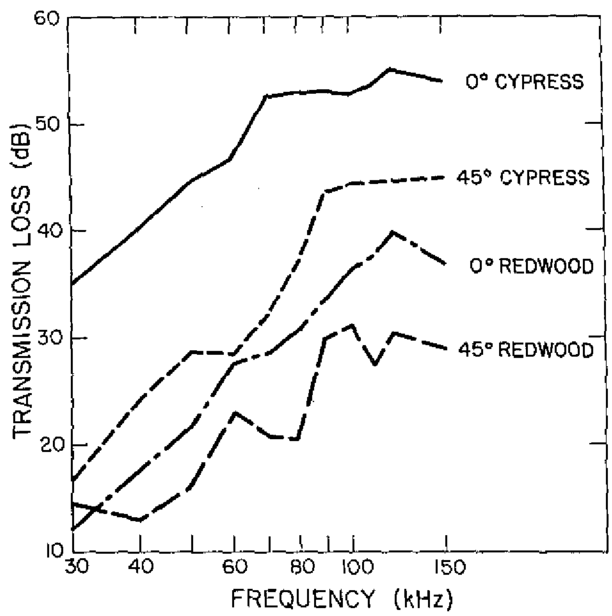


Fig. A5 — Transmission-loss values for two woods, 30-cm × 30-cm panels

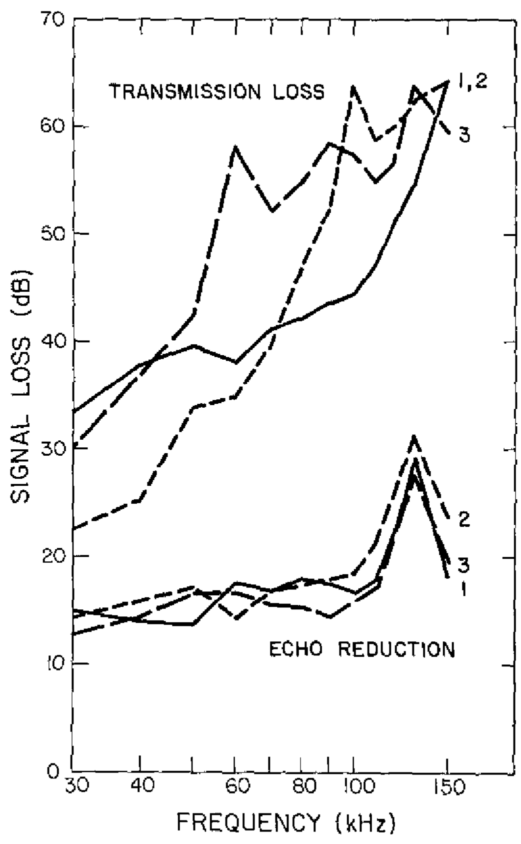


Fig. A6 — Acoustical performance for two surface patterns, 30-cm × 30-cm panels (1,2 — surface pattern 1; 3 — surface pattern 2)

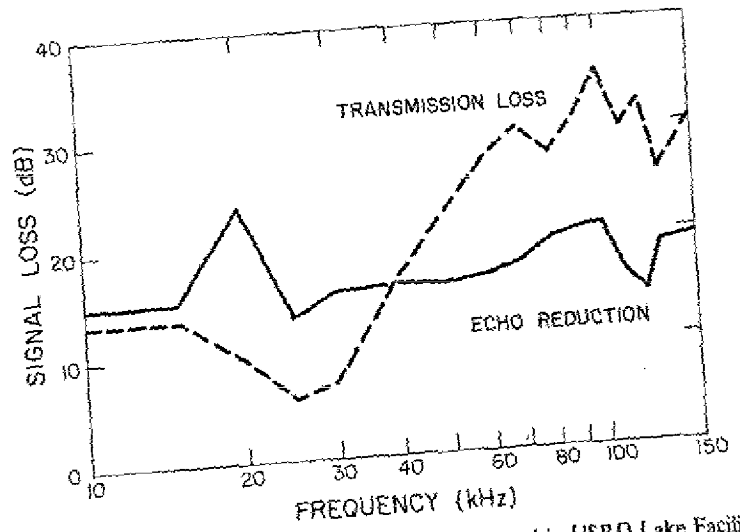


Fig. A7 — Acoustical performance of full-size panel in USRD Lake Facility

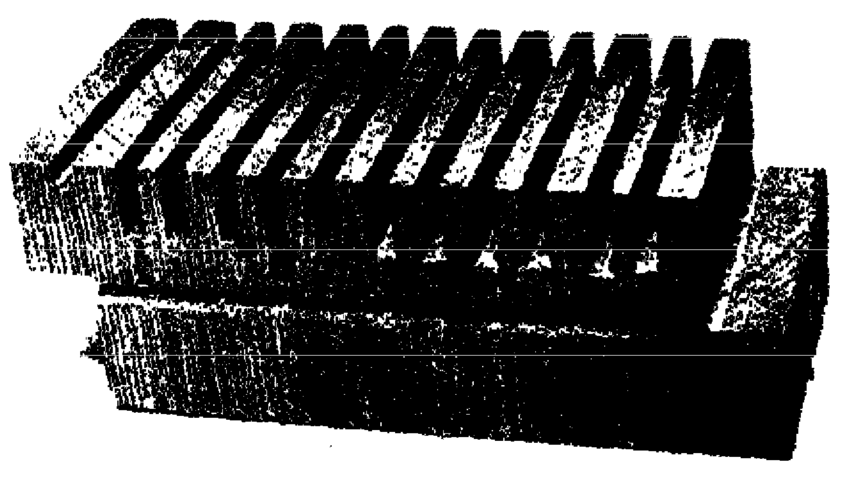


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Fig. A8 — Photograph of individual cypress block then drilled for stringing on the cables. The irregular spacing of the deep cuts on the face of each block was intentional. The built-up construction of the panels was necessitated by the pressure treatment of the wood and the grain orientation that was required. Block size was limited to the cross section of the largest practical size of lumber available from the local sawmill. The blocks had to be pressure treated before assembly, because the diameter of the aperture in the pressure vessel used was 76 cm. The configuration shown in Fig. A2 proved to be an optimal solution to the above constraints. The sides of the blocks are grooved to overlap slightly, and some rows of blocks have interlocking grooves to prevent spreading. The panel shown in Fig. A2 has a concrete base intended for straight-wall application. Corner panels have special bases with interlocking grooves at 90°. The top channels can be bolted together for free-standing sections.

The dry blocks were loaded into 55-gal drums, cycled in the pressure vessel, and then stored under water in the drums until needed for assembly. Panels could be assembled from the wet blocks and transported to the dolphin tank at Sea World for installation before the wood started to dry.

RESULTS AND CONCLUSIONS

ER and TL measurements were made on sections of the lining after the initial installation at Sea World. Repeatability was difficult in these measurements because the aeration and low temperature of the water continuously encouraged bubble formation on the instruments. We used a small water jet to flush bubbles from the hydrophone and projector every few minutes. Figures A9 and A10 show the final results of ER and TL measured from the tank lining after installation.

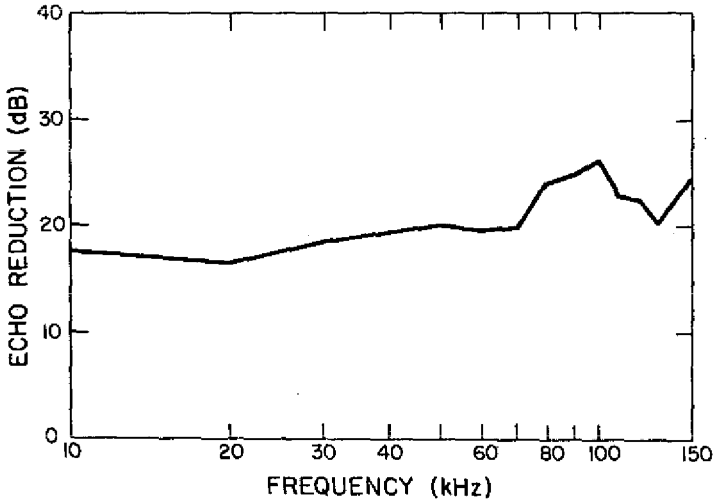

Fig. A9 — Echo-reduction value for installed lining in Sea World tank

After a few months, the wood surfaces became covered with a slimy brown growth which did not alter the acoustical properties of the lining. Sea World uses an artificial seawater purified with ozone. This provided an antagonistic environment for all metal parts and elastomers in our experiment, but the wood and concrete were quite unaffected.

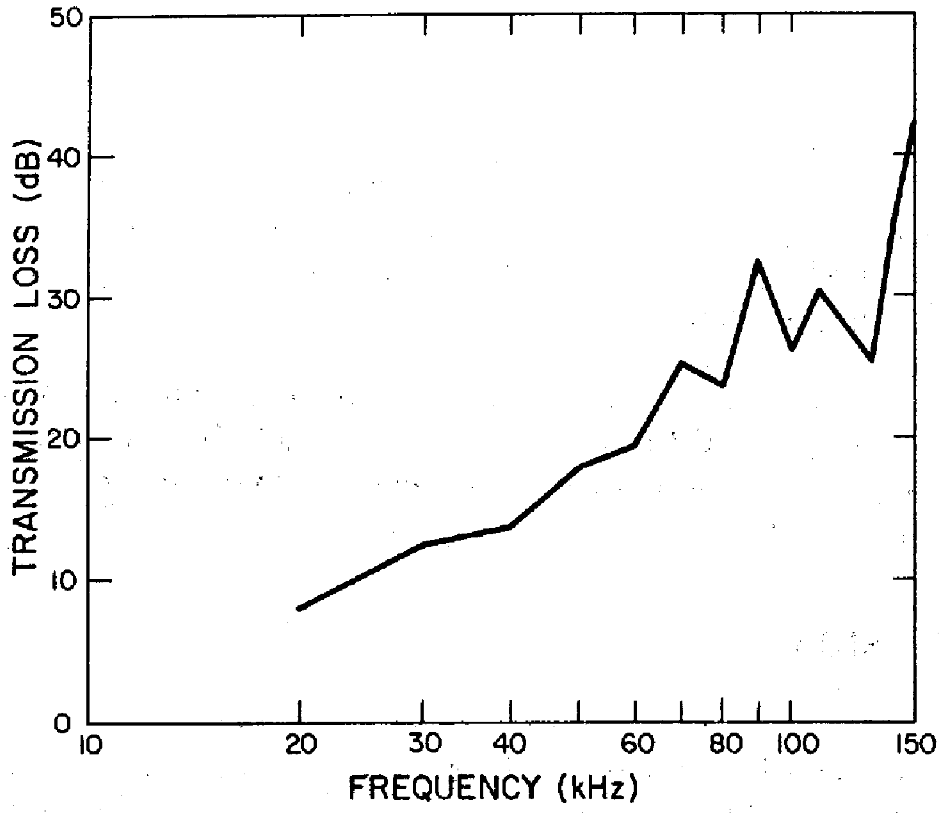

Fig. A10 — Transmission-loss value for installed lining in Sea World tank

REFERENCE

A1. Lastinger, J.L., "Acoustic characteristics of woods at high hydrostatic pressure," J. Acoust. Soc. Am. **47**, 285 (1970).