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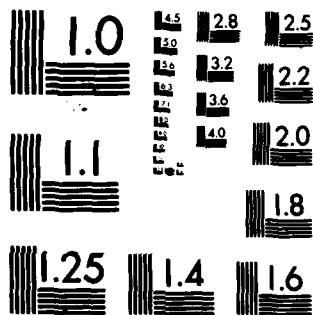
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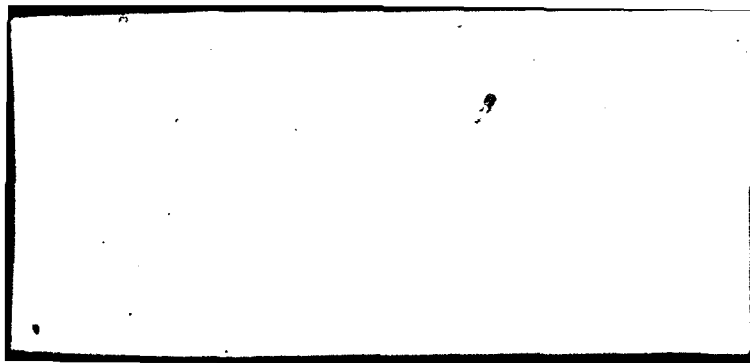
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DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
EXPERIMENTAL ASTRONOMY LABORATORY ✓
CAMBRIDGE, MASSACHUSETTS 02139

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PARAMETERS FOR THE EVALUATION OF
SONAR DEPTH MEASUREMENT SYSTEMS.

by
10 Joel B. Searcy

Contract N62306-67-C-0122 DSR-70320
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11 Oct. 1967

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EXPLANATORY NOTE

This is one of a series of Engineering Reports that document the back-ground studies to be used in a system design for HYSURCH (Hydrographic Surveying and Charting System). In general, these reports cover more detail than that finally necessary for a system design. Any subsystem recommendations contained in these reports are to be considered tentative. The reports in this series are.:

- | | |
|-------|--|
| RN-22 | Soundboat Navigation Equipment and Strategy for HYSURCH by John Hovorka |
| RN-23 | The Role of the HYSURCH Survey Ship in the Production of Nautical Charts by Edwin A. Olsson |
| RN-24 | An Investigation of Side-Looking Radar and Laser Fathometers as HYSURCH Sensors by Jack H. Arabian |
| RN-25 | A Computation Center for Compilation, Revision and Presentation of Hydrographic Chart Materials by Edwin A. Olsson |
| RN-27 | Parameters for the Evaluation of Sonar Depth Measurement Systems by Joel B. Searcy |
| RN-28 | Tidal Measurement, Analysis, and Prediction by J. Thomas Egan and Harold L. Jones |
| RN-29 | Applications of Aerial Photography for HYSURCH by A.C. Conrod |
| RN-30 | Sounding Equipment Studies, by Leonard S. Wilk |

RN-31 Error Analysis of a Dual-Range Navigation Fix
 and Determination of an Optimal Survey Pattern
 by Greg Zacharias

RN-32 Tethered Balloons for Sounding Craft Navigation
 Aids by Lou C. Lothrop

These reports were prepared under DSR Contract 70320,
sponsored by the U.S. Naval Oceanographic Office Contract
Number N62306-67-C-0122. The reports are meant to fulfill
the reporting requirement on Sub-system selection as specified
in the MIT proposal submitted in response to the Oceanographic
Office Request for Quotation, N62306-67-R-005.

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1.0

Introduction

For the benefit of those HYSURCH workers unfamiliar with sonar depth sounders, the following is a brief review of the principals of sonar design and the terminology used to describe sonar systems. The various parameters and figures of merit considered standard in the field of sonar will be defined, and the sonar range equation presented. The ambient acoustic noise environment and the acoustic transmission properties of sea water will be described, and typical data presented for reference.

Once the noise characteristics due to a particular craft are known, they may be combined with the other ambient noise sources, and the sonar range equation may be used to determine the range of operating frequencies which will result in a specified signal to noise ratio.

1.1

Acoustic Depth Measurement

The most common present-day method of depth measurement is by means of underwater acoustical echo ranging on the bottom, sometimes referred to as echo sounding. An echo sounder is a type of sonar, which, by measuring the time difference between the transmission of an electronically generated sound wave and its return after striking the bottom, gives the necessary data for depth determination. In order to achieve an accurate measurement, an average velocity of sound must be determined with respect to the local water temperature and salinity. The device consists of a transducer, either attached to the hull or to a towed vehicle, which serves as both a transmitter and receiver of the acoustical signals. An associated oscillator and amplifiers generate and receive the signals from the transducer. The frequency employed may be anywhere from a few kilocycles to a megacycle or more, the most common region being the low ultrasonic range (20 kc to 30 kc).

In most systems, a pulse-mode transmission is employed, but a continuous transmission, frequency modulation mode (CTFM) is also used. The details of these two types of systems will be discussed in Section 5, after consideration of the general nature of the underwater acoustical environment.

2.0 Velocity of Sound in Sea Water

The basic range accuracy of any sonar system is limited by the precision with which the velocity of sound in water is known. In sea water, the velocity of sound may be expressed as a function of depth, temperature and salinity as ⁽¹⁾

$$c = 4422 + 11.25 T - 0.045 T^2 \\ + 0.0182 D + 4.3 (S - 34) \quad (1)$$

where

c = the velocity of propagation of sound in sea water in ft/sec.

T = water temperature in °F

D = depth below the surface in feet

S = salinity in parts per thousand

for nominal conditions, ie. at the surface, for a salinity of 34‰, and for a temperature of 60°F, the velocity of sound in sea water is 4935 ft/sec. or 1504m/sec. For pure distilled water the velocity of propagation is 1460m/sec. at the same temperature.

Figures 1, 2 and 3 illustrate the variation of the velocity of propagation of sound in sea water with temperature, pressure and salinity.

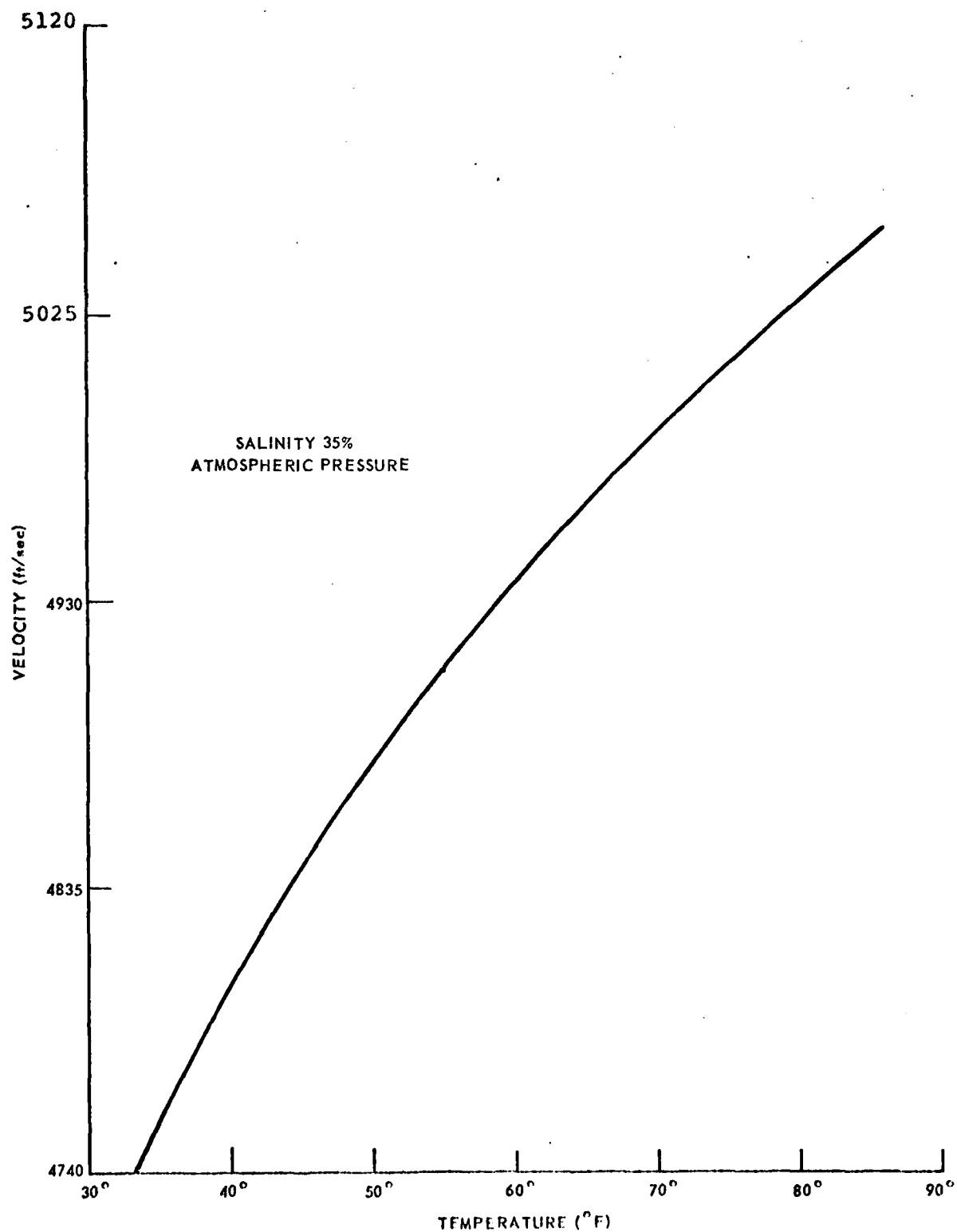


Fig. 1. The effect of temperature variations on the velocity of sound in seawater. (2)

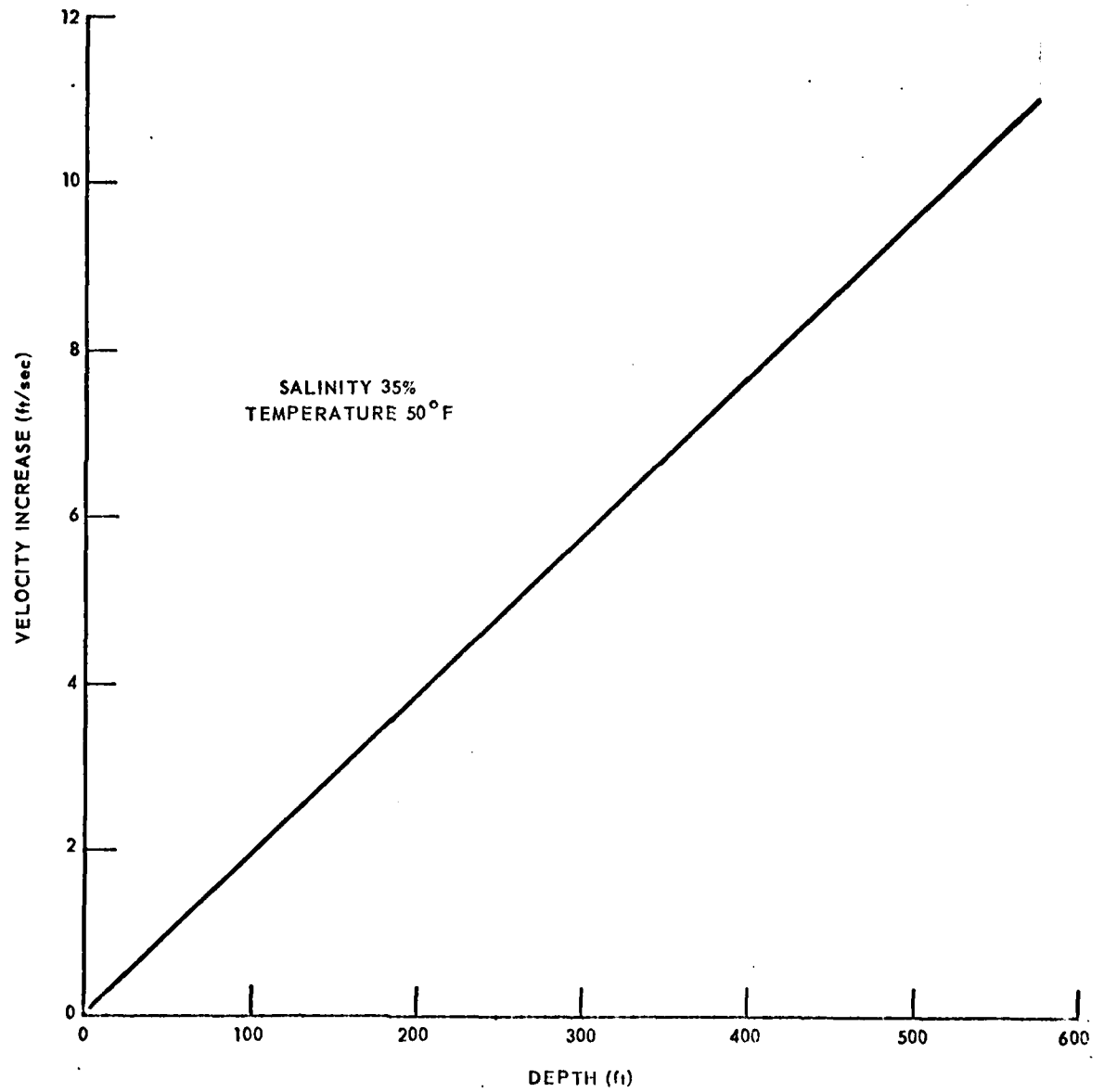


Fig. 2. The effect of pressure on the velocity of sound in seawater. ⁽¹⁾

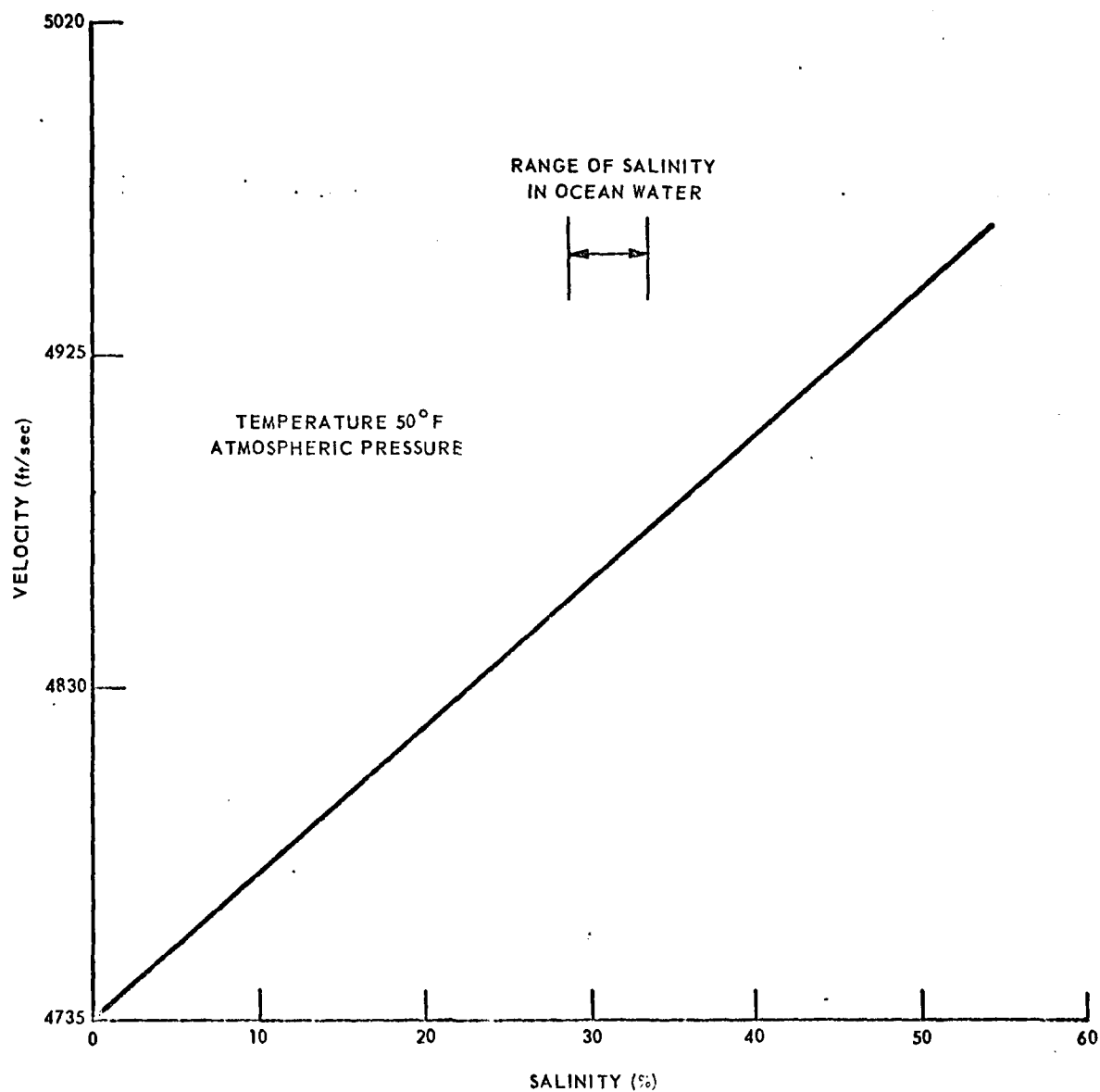


Fig. 3. The effect of salinity on the velocity of sound in seawater. ⁽¹⁾

3.0 Acoustic Intensities and Relative Magnitudes

The intensity of an underwater acoustical signal is measured in units of power per unit area. The signals which may be encountered range in intensity from 10^{-20} watts/cm² to 100 watts/cm². In view of the size of this range, and in order to emphasize the importance of fractional changes (rather than absolute changes), relative magnitudes are used. Changes in relative magnitude are expressed as ratios, and are given in log units such as the decibel. The reference value to which such relative magnitude ratios are computed must be specified also. This is commonly done by means of notation such as

$$A(\text{db}/n_0 \text{ watts/cm}^2)$$

which is to be read "an intensity level A db above a reference intensity of n_0 watts/cm²". This then supplies the information on units necessary for the conversion to absolute magnitudes.

4.0 Sonar Transducers

Acoustic transducers for use underwater vary greatly from those used in air. For any underwater transducer to conform properly to its environment, it should operate with about 60 times the force and one sixtieth the displacement, or velocity, of a transducer handling energy at the same rate in air. Underwater transducers must also operate in a high and rapidly changing ambient pressure field.

The most effective means of meeting these requirements is through the use of magnetostrictive and electrostrictive materials. When variations in the strength of a magnetic or electric field take place at acoustic frequencies in these materials, acoustic waves are generated due to the resulting mechanical stress. Conversely, when these materials are subjected to externally applied stress variation such as would be transmitted from an acoustic pressure field in water,

variation in the applied field strength are observed.

The most commonly used magnetostrictive materials are nickel and nickel alloys such as permalloy, nichrome, and monel. The most common electrostrictive transducers are quartz, tourmaline, Rochelle salt, and barium titanate.

5.0 Sonar Depth Measurement Systems

5.1 Vertical Beam Sonar Echo Sounders

The most elementary and widely used acoustical depth measurement technique is vertical beam sonar. In this configuration, the transducer is mounted on the survey craft hull or towed in a "fish" so that the main transmitted beam is directed downward. The time to the first returning echo then measures the range to the nearest point on the portion of the bottom insonified. The transmitted acoustic energy may be in the form of either a series of pulses or a continuous frequency modulated wave. In pulse mode systems, the pulse repetition frequency is limited by the maximum range to be measured by the relative

$$(\text{prf})_{\text{max}} = \frac{c}{2R_{\text{max}}} \quad (2)$$

where R_{max} is the maximum range (depth) expected and c is the velocity of sound in sea water.

A continuous transmission frequency modulated (CTFM) system transmits a linear ramp of frequency with time and measures continuously the frequency difference between transmitted and return signals (see Figure 4). Since the rate of change of frequency with time, df/dt is a known constant, the round trip time interval Δt can be determined from the relationship

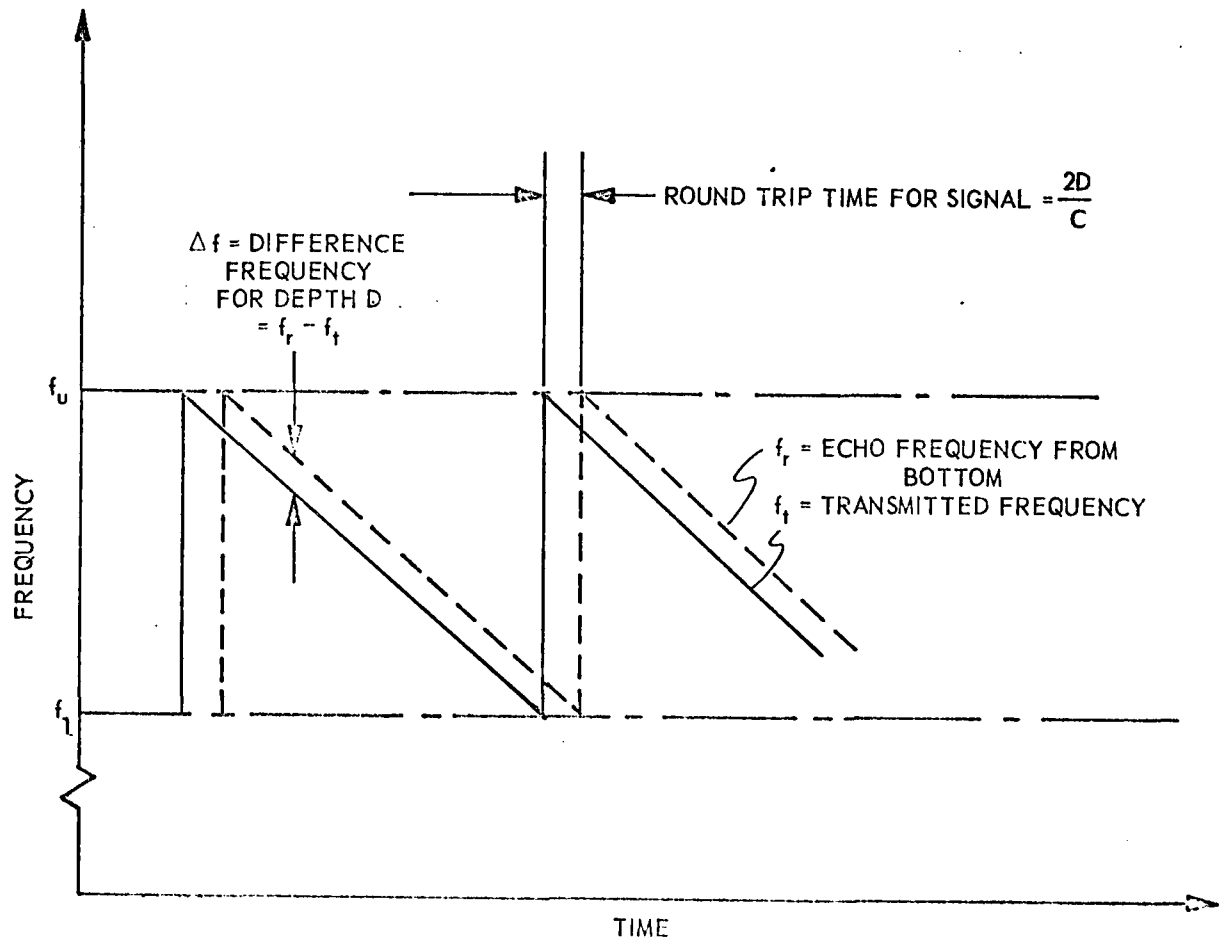


Fig. 4. Frequency vs. time for a typical CTFM sonar depthfinder.⁽⁴⁾

$$\Delta t \frac{df}{dt} = \Delta f \quad (3)$$

and range to the bottom is obtained as with the pulse system, from the range equation

$$R = \frac{c \Delta t}{2} \quad (4)$$

A CTFM sonar depth profile has been operated satisfactorily at 29 knots while mounted on a hydrofoil⁽²⁾.

5.2 Side-Looking Systems

There are two basic types of side-looking sonar systems. The most common type uses a fan shaped beam very narrow in the fore-aft direction and directed abeam. Pulses are transmitted and the return is displayed as a function of time along a line. Successive pulses build up a "picture" of the bottom abeam. Since the return is displayed against time rather than angle however, only slant range to acoustically irregular features on the bottom is available. Such a system is primarily useful for obtaining qualitative information or obstacle detection abeam, and might serve as an "acoustic wire drag"⁽³⁾.

A second type of side looking sonar is made up of one or more narrow beam transducers arranged to look abeam. In such a system, true depth at the insonified point can be computed provided the orientation of the beam (or beams) relative to the vertical is known. A system of this type is the phased array aboard the Silas Bent.

The remaining sections of this report will be devoted to a presentation of the parameters and figures of merit used to characterized performance in any type of sonar echo ranging system.

6.0 Ambient Acoustic Noise in the Sea

The ambient acoustic environment in the sea is, in general, due to a number of sound sources. These sources may be grouped into three broad categories; (1) noise due to water motion, (2) marine life noises, and (3) man-made noises. The general character of the noise to be expected from each of these sources will now be examined.

6.1 Noise Due to Water Motion

The motion of the water itself can generate acoustic noise in a number of ways. Surf breaking on a reef or shore may be detected for several miles. In shallow water, tidal currents may cause small stones or pebbles on the bottom to move sufficiently to create considerable sound. Waves cresting and breaking in open water, and the escape of air bubbles trapped as a result of wave action also create water noise.

Water noise varies greatly with time, location and weather, and considerable statistical averaging is necessary to arrive at representative data. Figure (5) shows some typical water noises spectrum levels for sea states 0 to 5. The curve labeled minimum water noise represents the level of noise that might be expected in deep open ocean water, and represents the minimum level that might be encountered in practice. The "thermal limit" shown on the figure represents the limit beyond which it is impossible to measure acoustic energy in water using an ideal hydrophone at 60°F water temperature.

A further indication of the effects of wind and wave action on water noise is given in Figures (6) and (7). Here, the statistical average of the band level of noise in the 0.1 to 10 KC band is plotted for various wind velocities and wave heights.

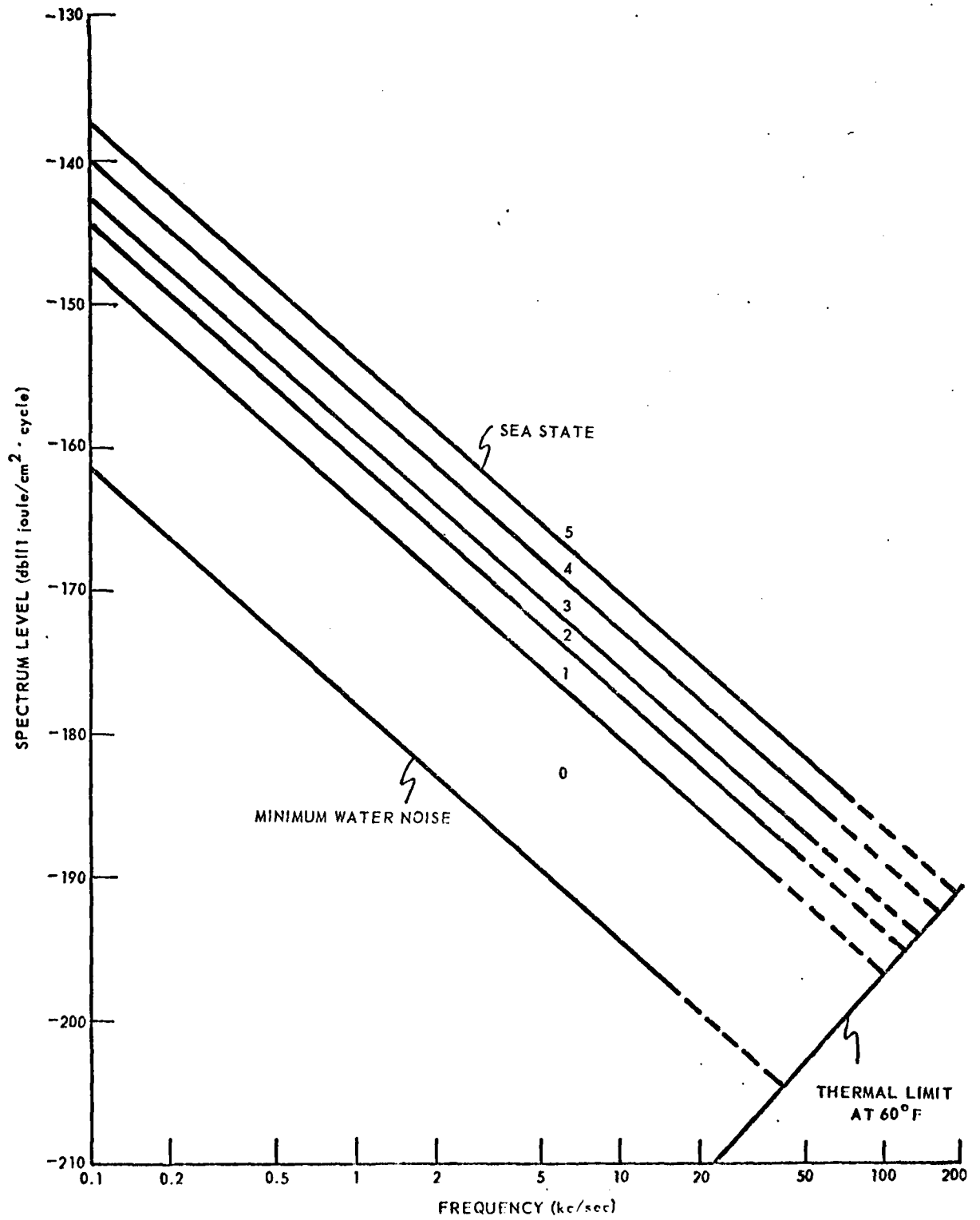


Fig. 5. Spectrum levels of water noise for various sea states. (1)

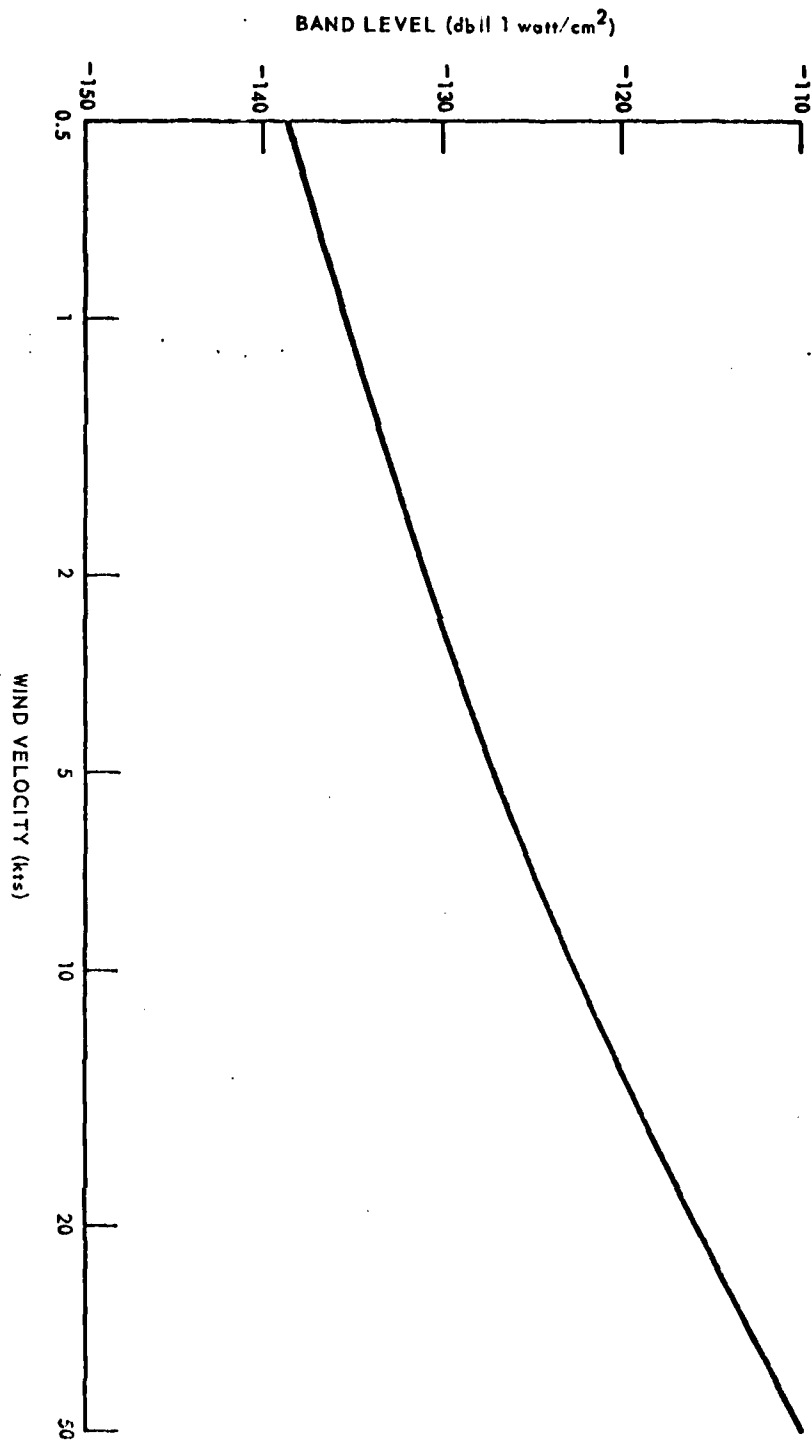


Fig. 6. Effect of wind velocity on water noise in the 0.1 to 10 kc band.

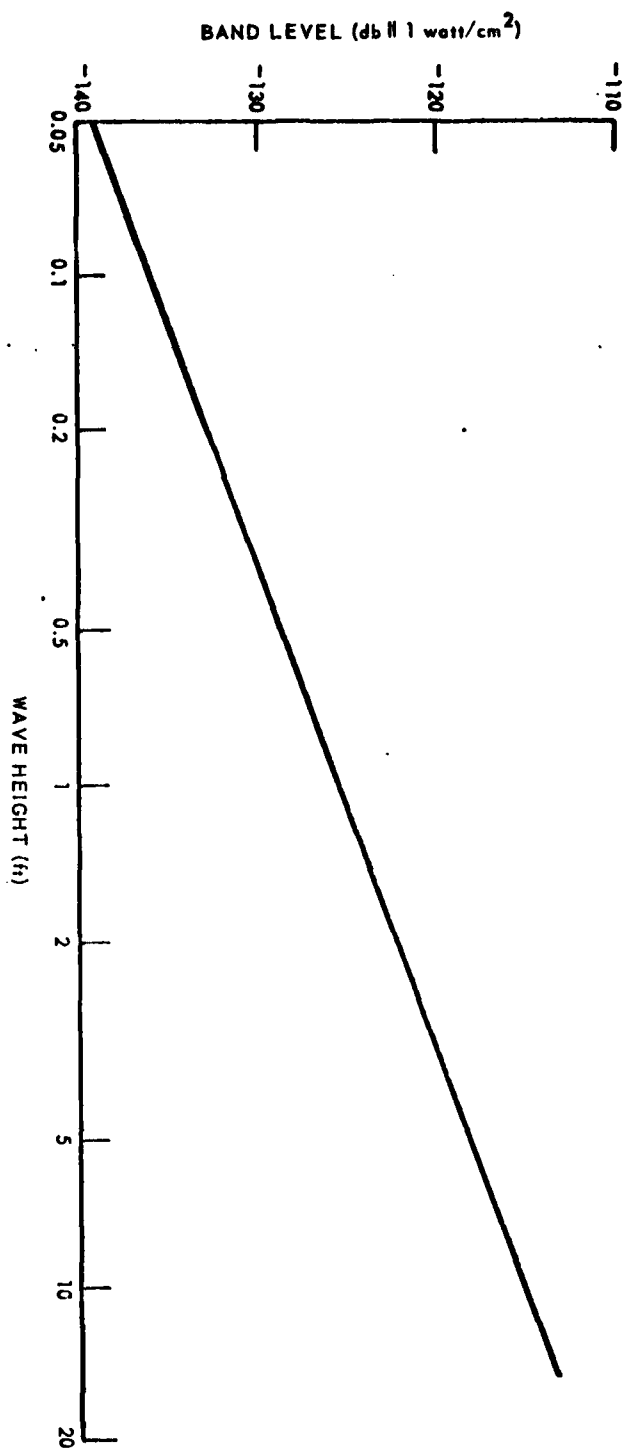


Fig. 7. Effect of wave height on water noise in the 0.1 to 10 kc band.

The noise due to movement of bottom materials is so diverse that it is impossible to even attempt a statistical representation of this effect.

6.2 Noise Due to Marine Life

Several forms of marine life create sonic disturbances, the most notable of these being croakers (a variety of drumfish) and snapping shrimp. The spectrum levels of the resulting noise varies greatly with location and time of day, but representative levels are shown in Figure (8).

6.3 Man-Made Noise

Many sounds existing in the ocean are of man made origin, the most common of these being ship noises. In harbors or industrial areas, a wide variety of noise sources might be present. Two typical spectra from these areas are shown in Figure (9). The general spectral shape of ship traffic noise does not differ greatly from general water noise although in practice it may exhibit more pronounced peaks.

The spectrum of noise due to a single ship is a function of hull type, speed and displacement. The variation of the noise spectrum with speed for a large cruiser is illustrated in Figure (10). In general it has been observed that the spectrum is relatively smooth for normal and high operating speeds, displaying a comparatively straight characteristics for frequencies above 1 kc/sec. The slope of this straight portion decreases with increasing speed, indicating the expected emphasis of higher speeds. Below 1 kc/sec, the spectrum begins to curve downward with decreasing frequency in such a way that it passes through a maximum between 100 and 500 cps. Low frequency peaks due to cavitation frequently fall in this same region.

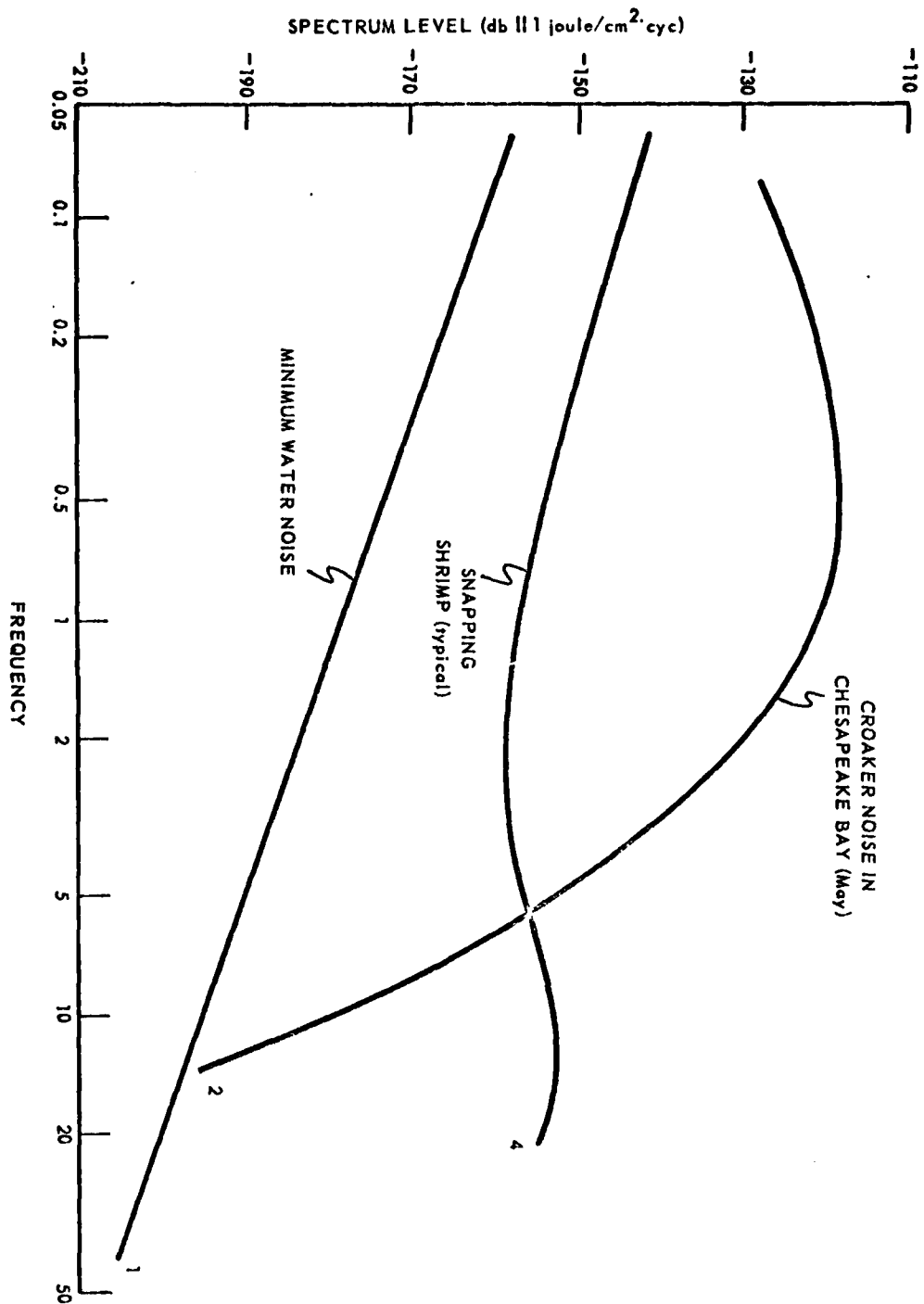


Fig. 8. Typical noise spectra due to marine life. (1)

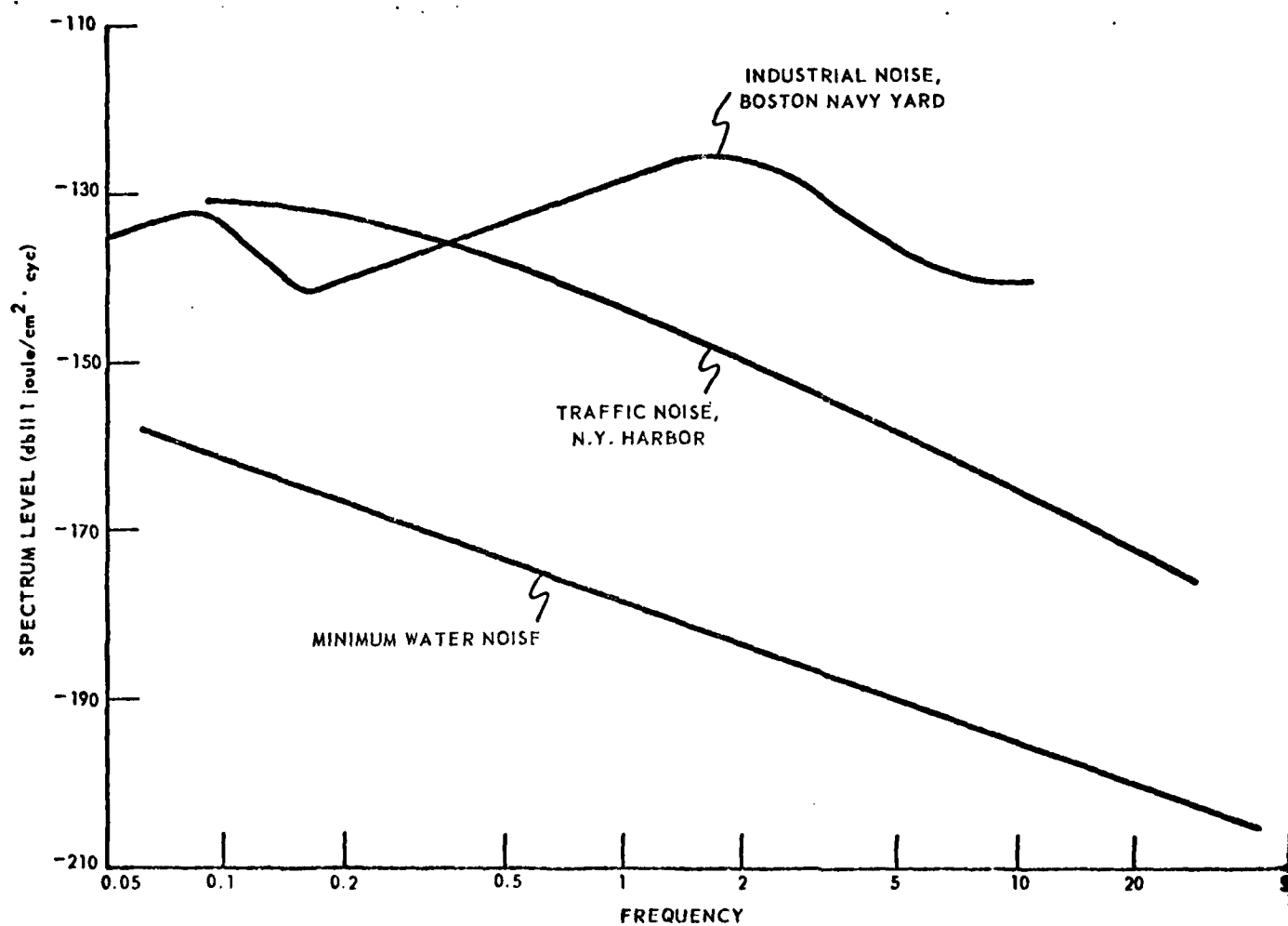


Fig. 9. Typical harbor noise spectra. (1)

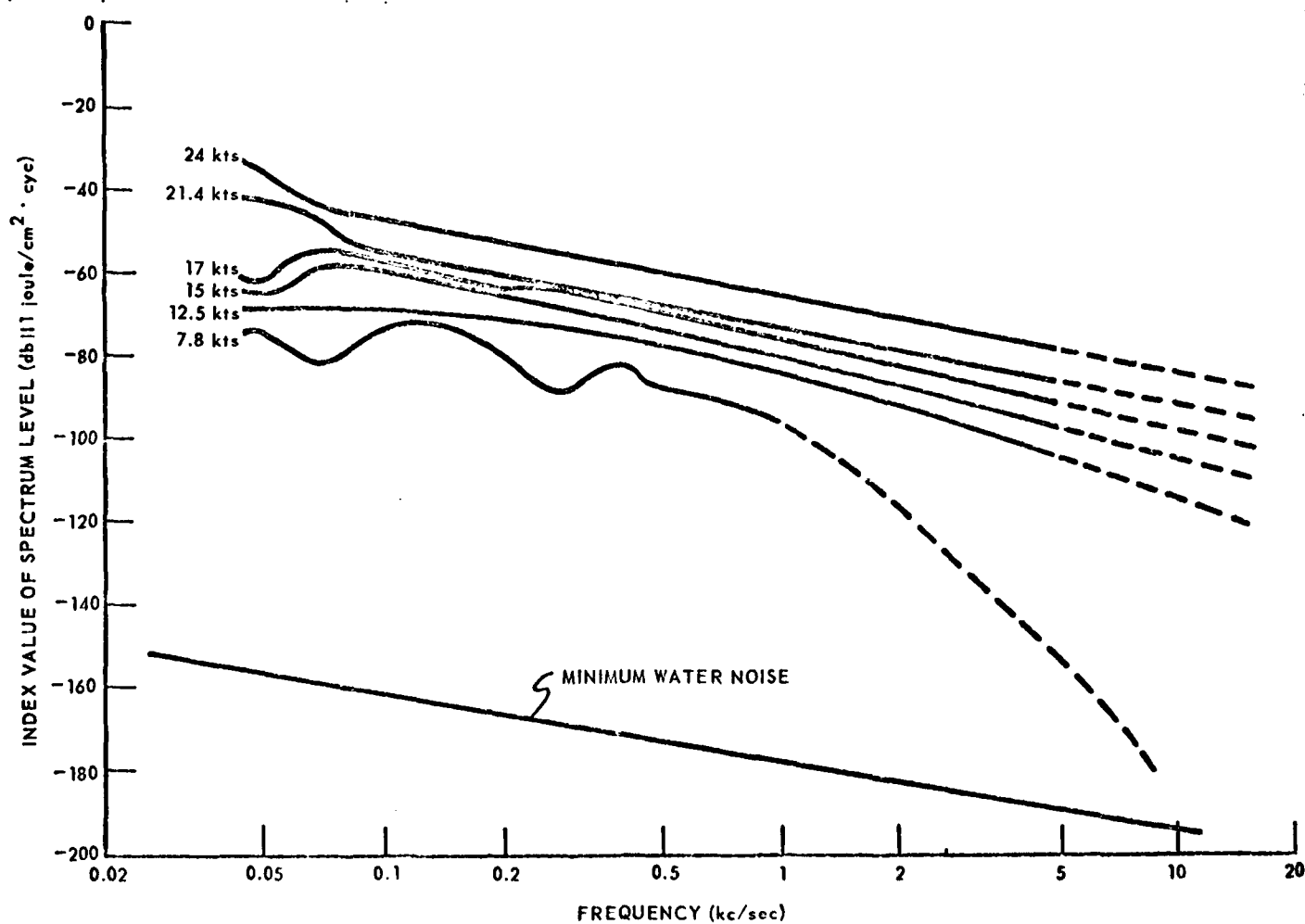


Fig. 10. Spectrum levels of acoustic noise due to a large cruiser. ⁽¹⁾

Figure (11) illustrates the variation of the index value of the spectrum at 5 kc/sec with velocity for a ship of 400 tons displacement.

The above data are presented as typical of large ships, and are not readily extrapolated downward to smaller ships.

6.4 Addition of Acoustical Levels

It is frequently necessary to determine the total acoustical transmission level of some sound which is known to be composed of two component sounds. If the intensities I_1 and I_2 of the component sounds are known, the level difference between the two sounds is

$$\Delta L = L_2 - L_1 = \lg t \left(\frac{I_2}{I_1} \right) \quad (5)$$

where $\lg t R = 10 \log_{10} R$.

The level difference between sounds having intensities $I_1 + I_2$ and I_1 is

$$L_{\text{sum}} - L_1 = \lg t \left(\frac{I_1 + I_2}{I_1} \right) = \lg t \left(1 + \frac{I_2}{I_1} \right) \quad (6)$$

Since these two level differences are both functions of the intensity ratio I_2/I_1 alone, they are unique functions of each other. Figure (12) shows the result of plotting values of $L_2 - L_1$ for corresponding values of $L_{\text{sum}} - L_1$. This plot then allows the determination of the acoustical level L_{sum} due to two sound sources which, if present alone would have levels L_1 and L_2 . This is particularly useful in connection with the separate noise source characteristics given in this section.

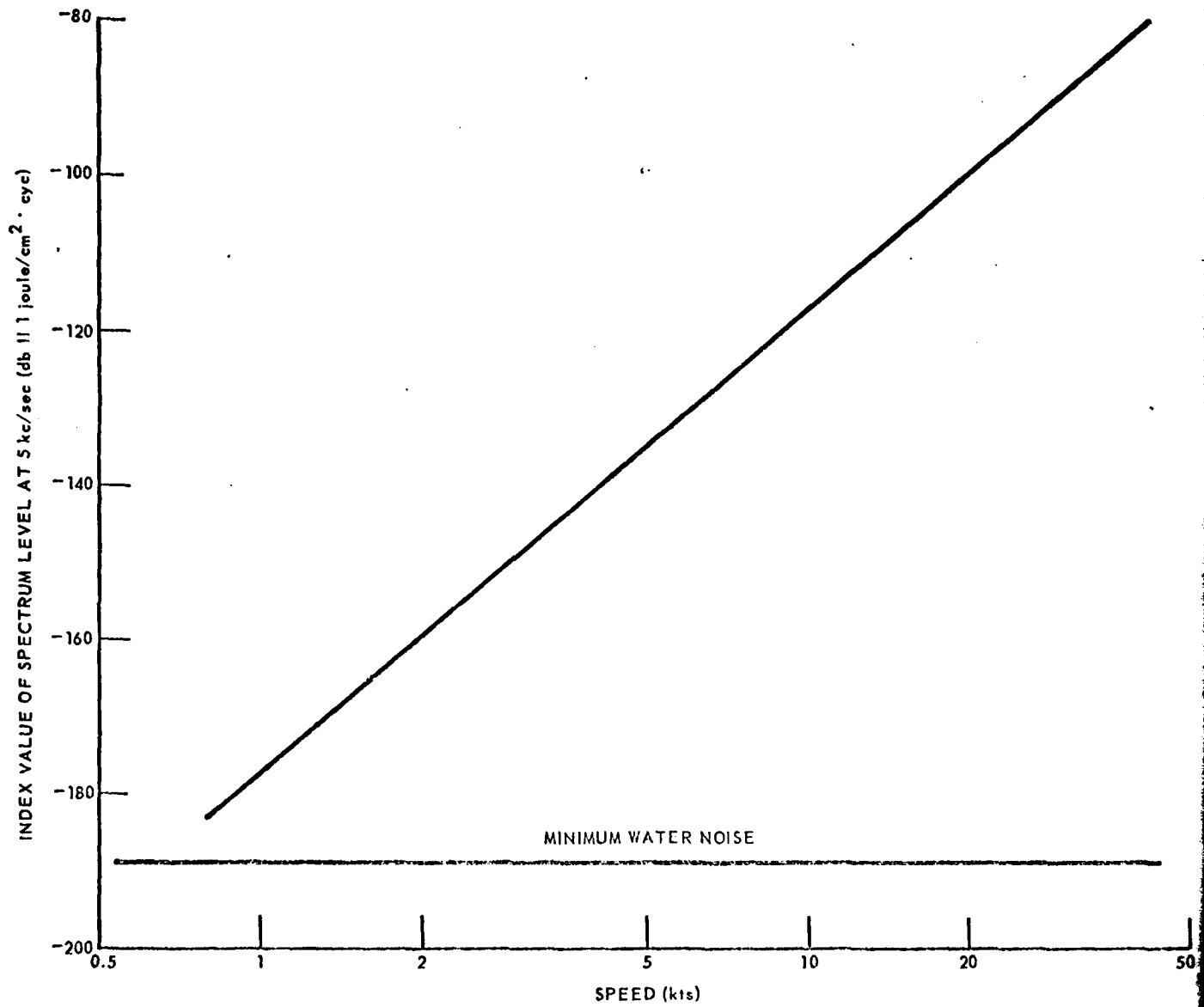


Fig. 11. Effect of speed on ship sounds (typical of ships of 400 tons).⁽¹⁾

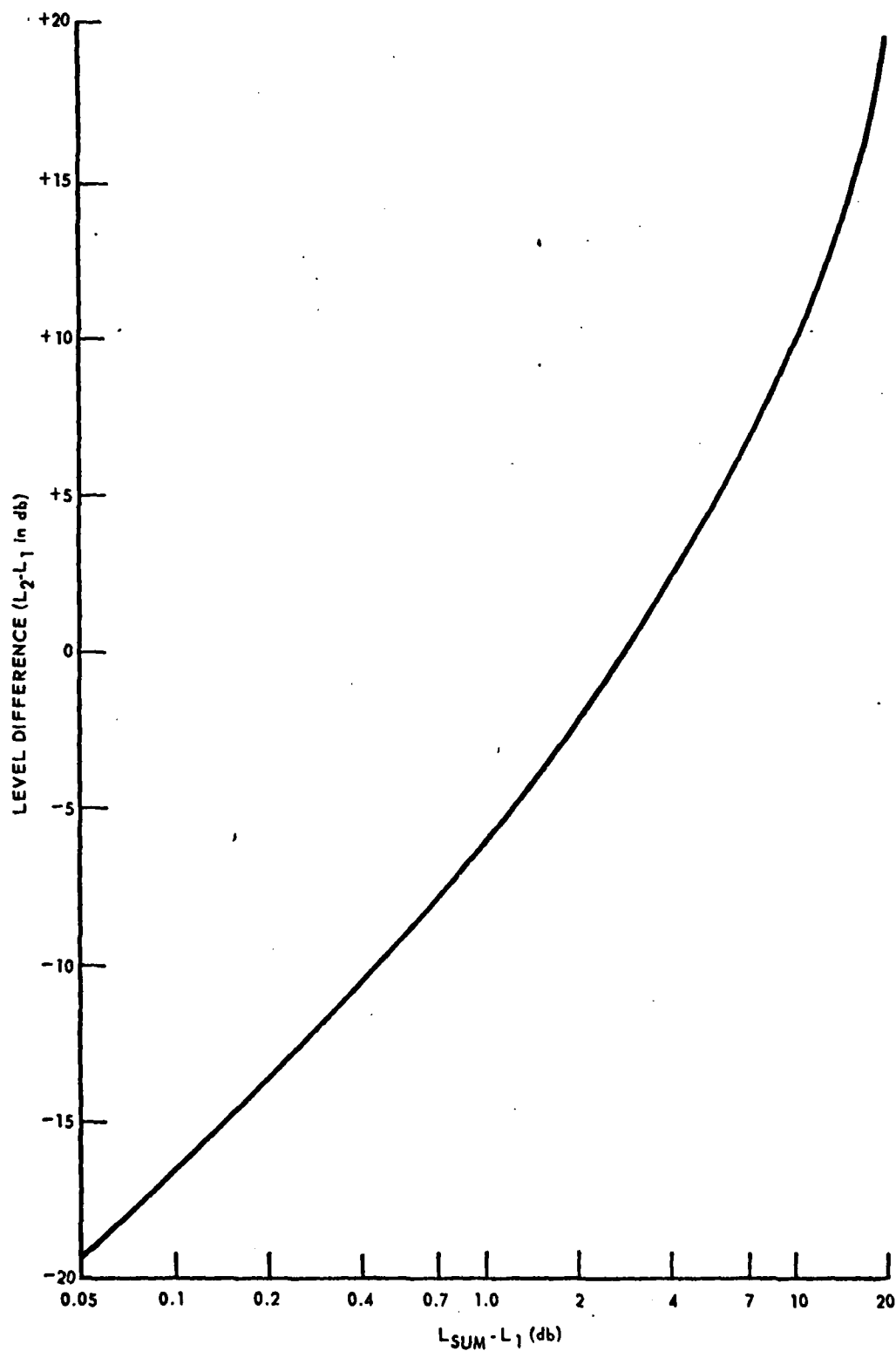


Fig. 12. The addition of acoustical levels.⁽¹⁾

7.0 Parameters and Figures of Merit for Sonar System

In order to evaluate the performance of a sonar system, we must first define several parameters and figures of merit which will enter into the basic sonar range equation. The most commonly used of the terms are defined below.

7.1 Propagation Loss

Sound energy propagation in sea water is subject to two classes of propagation loss. The first of these is called spreading loss, and for ranges less than a few hundred yards follows the inverse square law. At greater ranges, refraction and reflection of the wavefront cause departure from the inverse square law loss.

The second basic class of propagation loss is attenuation loss, and is due to the combined effects of scattering and absorption.

The relative contribution of spreading and attenuation losses to the total propagation loss, N_w , as a function of range is shown in Figure (13). Note that spreading loss predominates out to ranges of several hundred yards, thus would be the dominant mode of loss in shallow water acoustical depth sounders.

Attenuation loss is a function of the frequency of the acoustic signal. The attenuation coefficient in sea water is plotted as a function of frequency in Figure (14).

7.2 Source Level

The level of the acoustic pressure in the water produced by a given driving power to the transducer is referred to as the sonar level. The pressure is generally given in db relative to a reference level such as 1 dyne/cm² at 1 yard. Source level may then be written

$$L_s = TR/W + 10 \log_{10} P_{in} \quad (7)$$

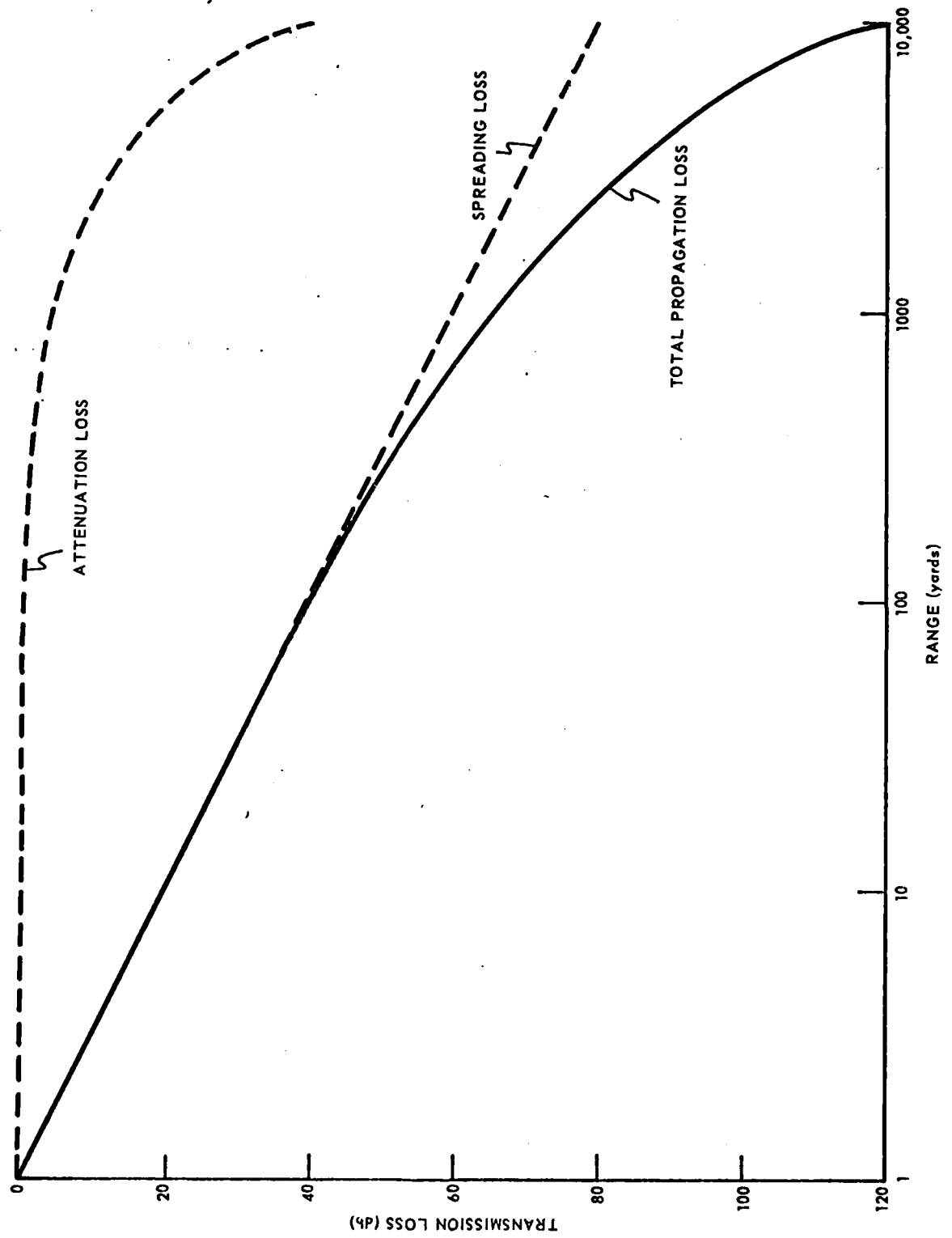


Fig. 13. The components of propagation loss as a function of range. (1)

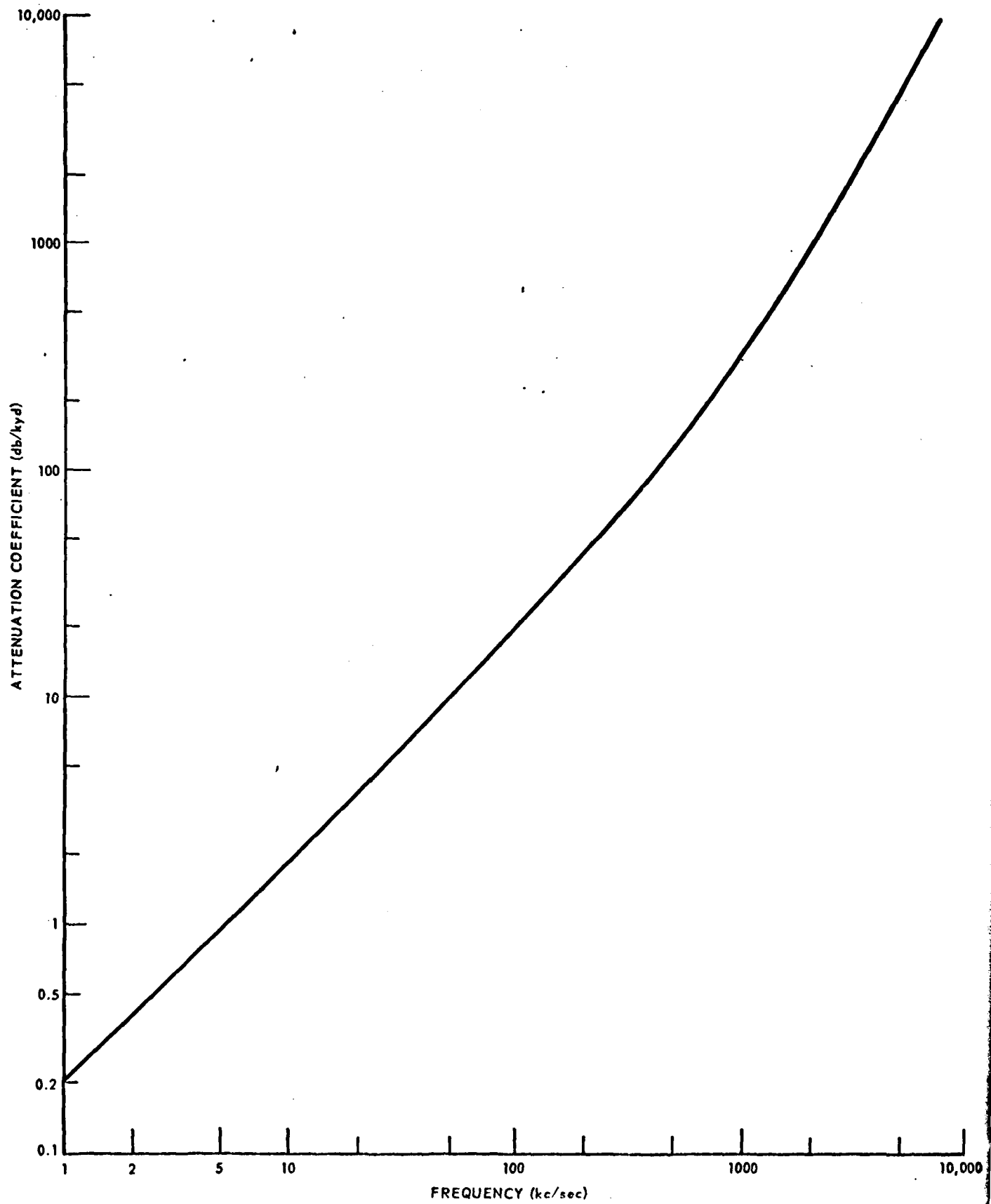


Fig. 14. Nominal acoustic attenuation coefficient in water. (1)

Where L_s and TR/W are source level and transmitting response per watt in db referenced to 1 dyne/cm² at 1 yard, and P_{in} is the transducer input power in watts. The transmitting response per watt is a transducer characteristic expressing (in db) the efficiency of the transducer in converting electrical power to acoustic power.

7.3 Directivity Factor and Directivity Index

The directivity factor is a figure of merit used to express the effect of the directional properties of a transducer on its overall operational performance. The transmitting directivity factor is defined as the ratio of the acoustic power radiated over all bearings by the transducer when excited by a given sinusoidal frequency and power to the acoustic power which would be radiated over the same bearings if the response of the transducer were the same for all bearings as for the bearing of maximum response. The receiving directivity factor is similarly defined and is generally numerically equal to the transmitting directivity index.

The directivity factor is therefore measured by the ratio of two rates of energy flow and describes a property of an energy transmission system which, like its efficiency, determines the effectiveness with which the system transmits or receives energy in a specified direction. The property thus described may then be described in terms of a transmission loss.

The transmission loss measured by the directivity factor of a sonar transducer is known as its directivity index, and is defined as

$$N_{DI} = 10 \log_{10} \frac{1}{\text{directivity factor}} \quad (8)$$

Typical directivity index values for a circular plate transducer and a line transducer as a function of 3 db beam width are shown in Figure (15).

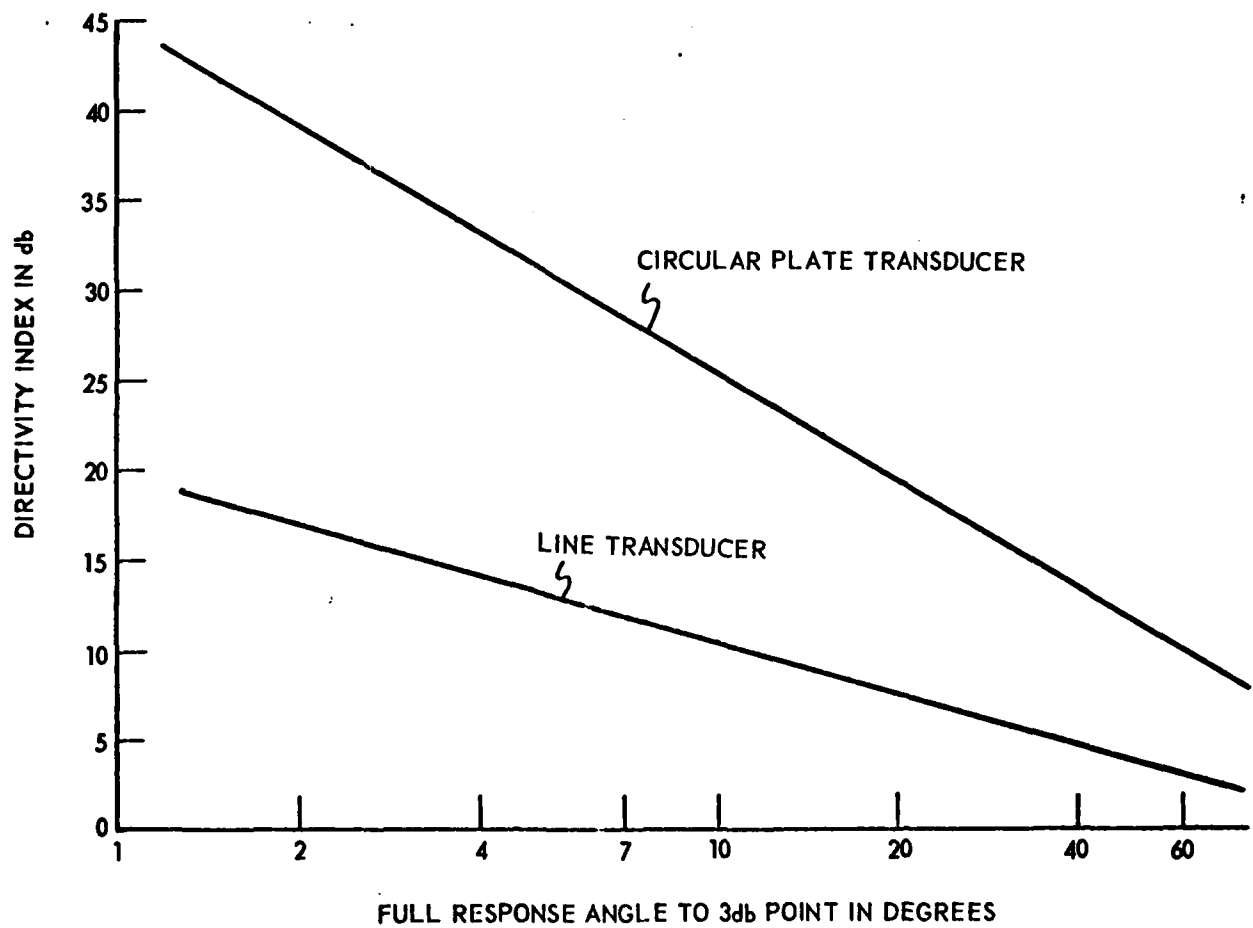


Fig. 15. Directivity index as a function of 3db beam width

7.4 Recognition Differential

As the magnitude of a received signal decreases relative to the noise present, the reliability with which the signal may be detected decreases. The reliability of an observation made at a given signal to noise ratio may be expressed in terms of the probability of detecting the signal. Figure (16) shows the variation in this probability with signal to noise ratio in db. The value, in db, of the signal to noise ratio characteristic of a specified observational probability is designated as the recognition differential, N_{RD} .

7.5 Target Strength

Target strength is a figure of merit used to describe that component of transmission loss due to target reflectivity, dimensions, and geometry. It is usually a measured characteristic of various targets, determined by the difference between measured two-way transmission loss and echo loss. In the case of echo sounding however, the target, the bottom, can be at least approximately modeled.

Target strength can be defined as the difference between the level of the echo corresponding to a target range of one yard and the level of the outgoing acoustic pulse. In the case where the target is a large plane surface, it has been shown (1) that the target strength is given by

$$N_{TS} = 20 \log_{10} R - 6 \text{ db} \quad (9)$$

where R is the range to the target plan in yards. In the case of a depth sounder, the range R would be replaced by the depth in the case of a vertical beam sonar, or by slant range in the case of a side looking sonar.

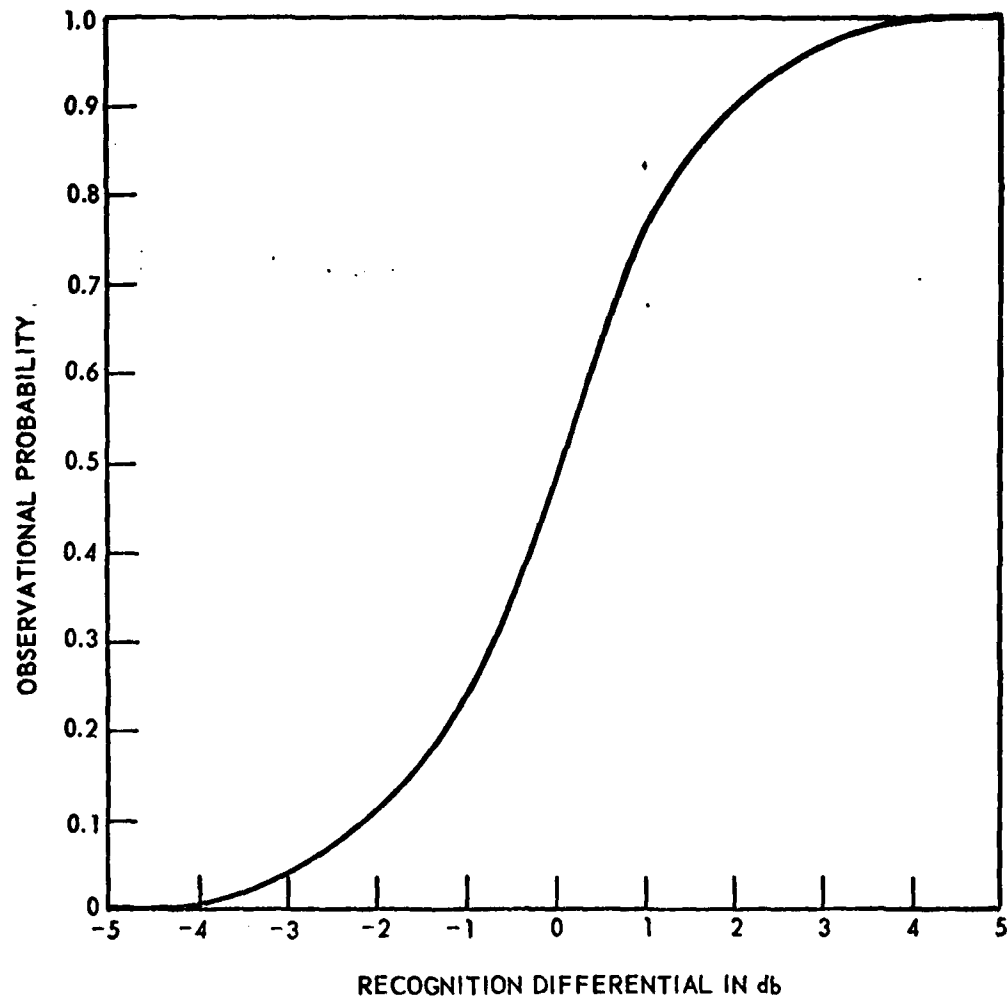


Fig. 16. Recognition differential as a function of the probability of correctly detecting the signal.

8.0 The Sonar Echo Ranging Equation

Using the variables and figures of merit described above, we may now write the sonar echo ranging equation as

$$N_{RD} = L_s + N_{TS} + N_{DI} - L_n - 2N_w \quad (10)$$

where

N_{RD} = the recognition differential, db.

L_s = the source level in db//1 dyne/cm² at 1 yard.

N_{TS} = the target strength, db.

N_{DI} = the directivity index, db

L_n = the local noise level in the frequency passband of the receiver in db//1 dyne/cm² at 1 yard.

N_w = the one-way^{*} propagation loss between the transducer and the target, db.

The equation may now be used to evaluate the maximum range at which the recognition differential has a minimum acceptable value with a given system, or to trade off system parameters such as transducer power, response and geometry against maximum range and recognition differential.

9.0 Conclusion Regarding Shallow Water Sounding

Since a shallow water spreading loss predominates over attenuation loss, we are generally free to choose the higher operating frequencies without significant penalty. The spectra of the interfering noise sources were seen to fall off steadily toward these higher frequencies, thus we would expect

* Note that the round trip propagation loss is twice the one-way loss rather than the loss associated with the round trip range due to the facet that the target acts as a secondary emitter of acoustic waves.

that for a given transducer power and range, that the signal to noise ratio would improve as the operating frequency is increased, until attenuation loss begins to predominate. For a given interfering noise spectrum, the optimum operating frequency may be determined by plotting equation (10) as a function of frequency for a given maximum range and transmitted power. The resulting curve will exhibit a peak at the frequency for which the signal to noise ratio is a maximum. In general, rather than determining the optimum frequency this procedure determine the band of operating frequencies over which the recognition differential, and thus the signal to noise ratio, is above some minimum acceptable value.

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