thirteen

# design and prediction in sonar systems

## 13.1 Sonar Design

The various applications of the sonar equations fall into two general classes. One involves *sonar design,* where a sonar system is to be devised to accomplish a particular purpose. In a sonar design problem, a set of sonar parameters that will provide the desired performance must be found. This can usually be expressed in terms of *range,* through its counterpart, by some assumed propagation condition, the parameter *transmission loss.*

This selection of parameters in sonar design is beset with difficulties arising from constraints that are of economic, mechanical, or electrical origin. Sonar systems must often be primarily inexpensive, as in expendable units such as sonobuoys. Sometimes they must fit in a confined space, as in a torpedo, where the maximum size of the transducer to be used is dictated by dimensions over which the design engineer has no control. Sonar systems may also have to be designed to consume only a limited amount of electric power, as in a battery-powered underwater acoustic beacon, where a limitation is placed on the available acoustic power output and the pulse length. Generally speaking, one or more of the parameters related to the system itself, such as directivity index or source level, may be fixed or limited by practical considerations not under the designer's control. The final design is achieved by "trade offs" and compromises between performance and achievable values of the equipment parameters. It is reached by what amounts to repeated solutions of the sonar equations—by a trial-and-error process wherein successive adjustments of parameters and performance are made until a reasonably satisfactory compromise is reached. Complications arise when the desired performance involves two or more of the variables. For example, a certain search rate, or area searched for a target in a given time, may be desired; this is a function of both range and beam width. In such problems, a number of trial solutions of the sonar equations will be needed to give a "feel" for the best set of conditions.

Sometimes the fortunate design engineer has a free choice of the operating frequency, or the operating frequency band, of the sonar under design. Then the choice will be influenced by the optimum frequency appropriate to the desired maximum range of the sonar. This choice will be considered in a section to follow.

In an active-sonar design problem, the design will depend in part on whether the echoes occur in a background of noise or reverberation. In active-sonar systems, the range increases with acoustic power output until the echoes begin to occur in a reverberation background. When this happens, the range is said to be *reverberation-limited.* Beyond this value of output power, no increase of range is available, since both echo level and reverberation increase together with increasing power. It follows, as a precept in active-sonar design, that the acoustic output power should be increased until the *reverberation level is equal to the level of the noise background at the maximum useful range of the system.* Unfortunately, although this is a useful general rule, it cannot always be followed because of limitations imposed by the amount of available power or because of interaction effects and cavitation at the sonar projector.

## 13.2 Sonar Prediction

The other broad class of problems has to do with *performance prediction.* Here the sonar system is of fixed design—and, indeed, may already by in operational use—and it is desired to predict its performance under a variety of conditions. Alternatively, if field trials of a system have already been made, it may be necessary to account for the performance that has been achieved—a kind of "postdiction," in which a numerical explanation is required for the results obtained. This class of problems normally requires solving the appropriate form of the sonar equation for the parameter containing the range. The passive-sonar equation may be written

$$\begin{aligned} TL &= SL - NL + DI - DT \\ &= FM \end{aligned}$$

where the sum of the parameters on the right is called (Table 2.2) the *figure of merit* FM for the particular target referred to in the parameter SL. Similarly, the active-sonar equation for a noise background may be written as

$$\begin{aligned} 2(\mathrm{TL}) &= \mathrm{SL} + \mathrm{TS} - \mathrm{NL} + \mathrm{DI} - \mathrm{DT} \\ &= \mathrm{FM} \end{aligned}$$

where FM is the figure of merit for the target implied by the value used for the parameter TS. The prediction of range requires the conversion into range of the value of transmission loss that is equal to the figure of merit. The conversion demands a specification of the propagation conditions, such as layer depth and propagation path, under which the equipment will be, or has been, used. With reverberation backgrounds, the transmission loss is usually the same for both the target and reverberation, and the range occurs implicitly in the terms 10 log $A$ or 10 log $V$, representing in decibel units the reverberating area or volume, respectively.

## 13.3 The Optimum Sonar Frequency

***Existence of an optimum frequency*** When range calculations at different frequencies are made for a sonar set of a particular design and for some specified propagation and target conditions, it is often found that the range has a maximum at some particular frequency. This frequency is the *optimum frequency* for the particular equipment and target characteristics being considered. At the optimum frequency, a minimum figure of merit is required to reach a given range. Hence, the optimum frequency is a function of the detection range as well as the specified set of medium, target, and equipment parameters. If the operating frequency is made much higher than optimum, the absorption of sound in the sea reduces the range; if the operating frequency is made much lower than optimum, a number of other parameters become unfavorable and act to reduce the range. Examples of such parameters are the directivity index, background noise, and detection threshold (through a necessarily smaller bandwidth at the lower frequencies), all of which conspire to reduce the system figure of merit at low frequencies.

Curve $AA$ of Fig. 13.1 shows a range-versus-frequency plot for a hypothetical sonar. If, by some means, the figure of merit of this sonar is raised by an amount that is the same for all frequencies, the range-frequency curve is shifted to $BB$. Although the range is increased at all frequencies, the optimum frequency, at which the maximum range occurs, has become lower. The locus of the peak values of a series of such curves gives the best frequency to use to obtain a desired range. Its shape and position depend on the system figure of merit and on the transmission loss and, more importantly, on how both vary with frequency.

***Illustrative example*** The determination of the optimum frequency can best be illustrated by an example. Consider a passive listening system that employs a line hydrophone 5 ft long. It is desired to find the optimum frequency for

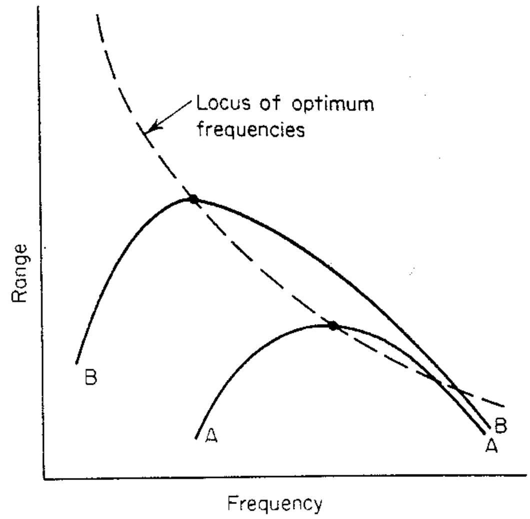


***fig. 13.1*** *Range as a function of frequency for two sonar systems of different figures of merit.*

the detection of a freighter traveling at a speed of 10 knots. The noise background is taken to be the ambient noise of the sea in sea state 3 (wind speed 11 to 16 knots), and the detection threshold is zero decibels. Let the transmission loss be determined by spherical spreading plus absorption according to the relationship $\text{TL} = 20 \log r + 0.01f^2r \times 10^{-3}$, where $f$ is the frequency in kilohertz and $r$ is the range in yards. Based on this expression, Fig. 13.2 shows curves of TL as a function of frequency for a number of different ranges. Superposed on the same plot is the line *AA*, equal to FM at different frequencies for the particular problem at hand, using appropriate values of the parameters.* At any frequency, the detection range is that for which TL = FM. This range has a maximum, for the curve *AA*, of 6,000 yd and occurs at 5 kHz. This is the optimum frequency for the assumed conditions. At this frequency, the slopes of the line *AA* and of an interpolated member of the family of TL curves are equal. At frequencies different from 5 kHz, the range is less, becoming reduced to 5,000 yd at both 2 and 10 kHz. If, by redesigning the system, the FM is increased by an amount that is constant with frequency, the line *AA* might be shifted to *BB*; the range will be increased to 19,500 yd and the optimum frequency lowered to 1.7 kHz. If the redesign is such as to change the slope of the FM curve, an altogether new optimum frequency will be obtained.

***Analytic method*** When, as in the example just given, the transmission loss can be expressed as a particular function of range for the conditions of interest, the optimum frequency can be found analytically. In the equality TL = FM, the maximum (or minimum) range is obtained by differentiating both sides with respect to frequency and setting $dr/df$ equal to zero. With the preceding expression for TL, we would have

$$\text{TL} = 20 \log r + 0.01f^3r \times 10^{-3} = \text{FM}$$

* SL: Table 10.2; NL: Fig. 7.5; DI: Fig. 3.6; DT = 0.

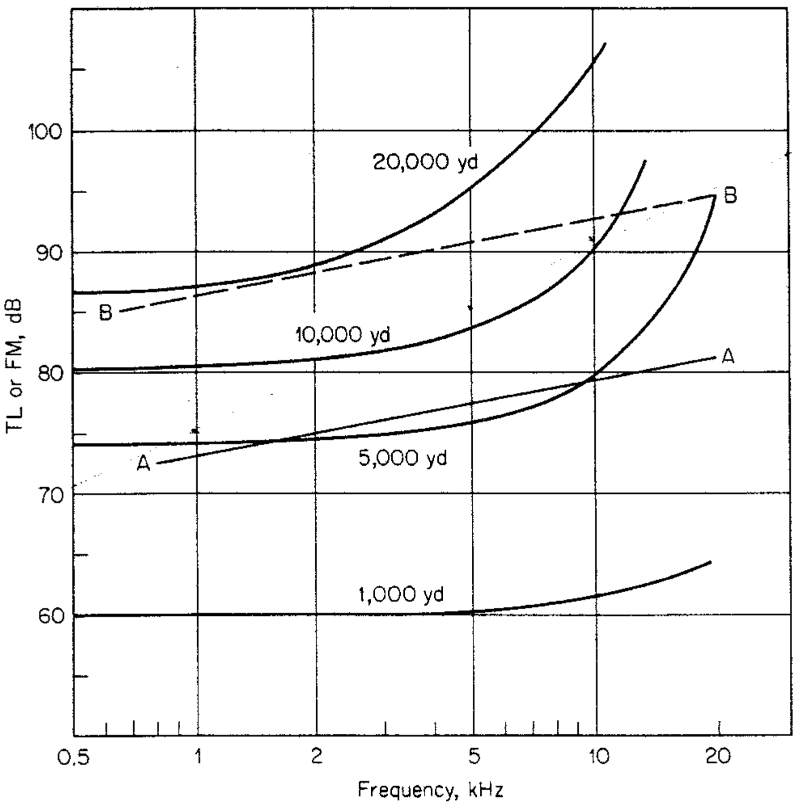


***fig. 13.2*** *Curves of transmission loss and figure of merit as a function of frequency.*

On differentiating and placing $dr/df = 0$, we obtain

$$0.02 f_0 r_0 \times 10^{-3} = \frac{d(\text{FM})}{df}$$

where $f_0$ = optimum frequency
$r_0$ = maximum range
$d(\text{FM})/df$ = rate of change of FM with frequency, dB/kHz

In terms of the more conventional unit of decibels per octave of frequency, we can write

$$\left.\frac{d(\text{FM})}{df}\right|_{\text{db/octave}} = \frac{f_0}{\sqrt{2}} \left.\frac{d(\text{FM})}{df}\right|_{\text{db/kHz}}$$

since the octave whose geometric mean frequency is $f_0$ is $f_0/\sqrt{2}$ Hz wide. It therefore follows that

$$\frac{0.02}{\sqrt{2}} f_0^2 r_0 = \frac{d(\text{FM})}{df}$$

and the optimum frequency becomes

$$f_0 = \left[\frac{70.7}{r_0} \frac{d(\text{FM})}{df}\right]^{1/2}$$

where $d(\mathrm{FM})/df$ is the rate of change of FM with frequency in units of decibels per octave, and $f_0$ and $r_0$ are in units of kilohertz and kiloyards, respectively. Since for a passive system

$$\mathrm{FM} = \mathrm{SL} - \mathrm{NL} + \mathrm{DI} - \mathrm{DT}$$

it follows that

$$\frac{d(\mathrm{FM})}{df} = \frac{d(\mathrm{SL})}{df} - \frac{d(\mathrm{NL})}{df} + \frac{d(\mathrm{DI})}{df} - \frac{d(\mathrm{DT})}{df}$$

so that the quantity $d(\mathrm{FM})/df$ is the sum, with due regard for sign, of the rates of change with frequency of the sonar parameters of which it is composed. Considering the example given above (Fig. 13.2), $d(\mathrm{FM})/df$ would be found to be approximately equal to $-6 + 5 + 3 + 0 = +2$ dB/octave. On substituting in the above expression for $f_0$ and taking $r_0 = 6{,}000$ yd, $f_0$ becomes equal to 5.3 kHz. In echo ranging, where the two-way transmission loss is involved, the expression for $f_0$ becomes

$$f_0 = \left[\frac{35.4}{r_0}\frac{d(\mathrm{FM})}{df}\right]^{1/2}$$

The optimum frequency accordingly depends upon the frequency variation of all the sonar parameters and is especially sensitive to the frequency variation of the absorption coefficient. It is not sharply defined, but is the peak of a broad maximum extending over a frequency range of several octaves. The optimum frequency may be defined in terms other than range, as, for example, search rate or processing time, as discussed by Stewart, Westerfield, and Brandon (1). For reverberation backgrounds, the figure of merit is itself a function of range, and the optimum frequency is not as easily determined. Normally, an optimum frequency does not exist in reverberation-limited systems since the frequency-dependent absorption coefficient is ordinarily the same for the echo and for the reverberation background.

An extended discussion of the subject is given by Horton (2), who can be credited with having first recognized the existence of optimum frequencies in sonar applications. More recently, Stewart, Westerfield, and Brandon (3) have published curves of optimum frequency versus maximum range for active sonar detection using more recent expressions for attenuation as a function of frequency.

## *13.4 Applications of the Sonar Equations*

### *Sonar Problem Solving*

The following are some examples of how the sonar equations may be used to solve problems in a number of different applications of sonar. The examples given and the conditions assumed do not necessarily have any practical significance, but are selected more or less at random to illustrate how the equations are used in some specific problems concerning the many modern uses of sonar.

The approach to problem solving by means of the sonar equations is to select the equation appropriate to a particular problem and then to solve it for the unknown parameter in terms of the other parameters which are either specifiable or can be selected, with more or less uncertainty, from specified conditions on which they depend. Typical values for nearly all conditions of interest can be found in curves or tables given in earlier chapters.

In an actual design problem the usually straightforward computation should be accompanied by a plot of echo or signal level, together with the reverberation and noise masking levels, as a function of range. Such a plot will indicate most strikingly how the range, determined by intersection of the curves of signal and background, will vary with changes in level. This plot will lend confidence to the numerical computations. Once the range is determined, other quantities of perhaps greater significance, such as area searched per unit time, can be readily computed.

### *Active Submarine Detection*

PROBLEM: An echo-ranging sonar mounted on a destroyer has a power output of 1,000 watts at a frequency of 8 kHz. Its DI is 20 dB and it uses a pulse length of 0.1 second, with a receiving bandwidth of 500 Hz. Find the range at which it can detect a beam-aspect submarine at a depth of 250 ft in a mixed layer 100 ft thick when the ship is traveling at a speed of 15 knots. Detection is required 50 percent of the time, using incoherent processing, with a probability of 0.01 percent of occurrence of a false alarm during the echo duration.

SOLUTION: The active-sonar equation, solved for TL, is

$$TL = \tfrac{1}{2}(SL + TS - NL + DI - DT)$$

SL is given by Fig. 4.4, using $DI_T$ = 20 dB, as 221; by Table 9.3, TS = 25; by Fig. 11.11 and reducing from 25 kHz by assuming −6 dB/octave spectral slope, NL = +53 + 20 log (25/8) = +63; DI = +20; by Fig. 12.6, $d$ = 15 and DT = 5 log (15 × 500/0.1) = +24. Therefore TL = ½(179) = 90. Referring to Fig. 6.7*b*, for a layer depth of 100 ft, and assuming that the transmission is the same as that for a source depth of 50 ft, the range corresponding to this value of TL is 5,500 yd.

### *Passive Submarine Detection*

PROBLEM: A submarine radiating a 500-Hz line component at a source level 160 dB crosses a convergence zone. Another submarine, located 30 miles away, listens with a nondirectional hydrophone. Assuming a noise background equivalent to that of the deep sea in sea state 3, how long an observation time will the second submarine need to detect the first if it uses incoherent (energy) processing in a receiver band 100 Hz wide and if a detection probability of 50 percent, with a 1 percent false-alarm probability, is satisfactory?

SOLUTION: When solved for the parameter of interest, the passive-sonar equation is

$$DT = SL - TL - NL + DI$$

SL is given as 160; TL is taken as being equal to spherical spreading to 30 miles plus a convergence gain of 10 dB, or TL = 20 log (30 × 2,000) − 10 = +86; by Fig. 7.5, NL = 66; DI = 0 for a nondirectional hydrophone. Therefore DT = +8. By the formula, DT = 5 log $(dw/t)$, with $w$ = 100 (given) and $d$ = 6 (Fig. 12.7), we find an observation time of $t$ = 15 seconds. The signal energy must therefore be integrated for this length of time in order for detection to occur at the required probability levels.

### *Minesweeping*

PROBLEM: A minesweeper tows behind it, for the purpose of sweeping acoustic mines, a broadband sound source having a source spectrum level of 150 dB in a 1-Hz band. The mines to be swept are sensitive to noise in the band 100 to 300 Hz, and are suspected to be set to be actuated when the level of noise in this frequency band is 40 dB above the spectrum level of the ambient-noise background in coastal waters at a wind speed of 30 to 40 knots. If spherical spreading describes the transmission loss, at what range will the minesweeper sweep (actuate) these mines?

SOLUTION: Solving the passive equation for TL, we have

$$\mathrm{TL} = \mathrm{SL} - \mathrm{NL} + \mathrm{DI} - \mathrm{DT}$$

Since the spectrum of the broadband source is 150 dB, the level in the sensitive frequency band of the mines is SL = 150 + 10 log 200 = 173; by Fig. 7.8, NL = +84; DI = 0 is implied by the nature of the problem; DT = 40 is given. Therefore, TL = 49. For spherical spreading, this corresponds to a swept range of 280 yd.

### *Depth Sounding*

PROBLEM: A fathometer transducer is mounted on the keel of a destroyer and is pointed vertically downward. It has a DI of 15 dB with a source level of 200 dB at a frequency of 12 kHz. Assuming that reflection takes place at the sea bottom with a reflection loss of 20 dB, at what speed of the destroyer will the echo from the bottom in 15,000 ft of water be equal to the self-noise level of the ship in the 500-Hz receiving bandwidth of the fathometer receiver?

SOLUTION: Because reflection at the sea bottom has been postulated, the actual source can be replaced by an image source in the bottom at a range equal to twice the water depth. The transmission loss then will be

$$\mathrm{TL} = 20 \log 2d + 2\alpha d \times 10^{-3} + 20$$

where $d$ is the water depth in yards. With $d$ = 5,000 yd and $\alpha$ taken at 1 dB/kyd, TL = 110 dB. The appropriate form of the sonar equation is

$$\mathrm{SL} - \mathrm{TL} = \mathrm{NL} + 10 \log w - \mathrm{DI}$$

where NL + 10 log $w$ is the noise level in the bandwidth $w$ of the receiver. Solving for the unknown parameter.

$$\mathrm{NL} = \mathrm{SL} - \mathrm{TL} - 10 \log w + \mathrm{DI}$$

With SL = 200 dB (given), 10 log $w$ = 10 log 500 = 27 dB, DI = 15 dB, we find NL = 78 dB at 12 kHz. This would correspond at 25 kHz to a value of NL = 78 − 20 log (25/12) = 72 dB. Referring to Fig. 11.13, the ship speed at which the 25-kHz isotropic self-noise level is 72 dB is 25 knots.

***Mine Hunting***

PROBLEM: A mine of average aspect lies on a sand bottom. It is desired to detect the mine at a slant range of 100 yd by means of an active sonar located 20 yd from the bottom. If a pulse length of 10 ms is used, what horizontal beam width will be required if detection can be achieved at a detection threshold of zero decibels?

SOLUTION: The sonar equations for a reverberation background are

$$\mathrm{SL} - 2\mathrm{TL} + \mathrm{TS} = \mathrm{RL} + \mathrm{DT}$$
$$\mathrm{RL} = \mathrm{SL} - 2\mathrm{TL} + S_s + 10 \log A$$
$$A = \Phi r \frac{ct}{2}$$

Solving for $A$ and eliminating common terms from the first two expressions, we obtain

$$10 \log A = \mathrm{TS} - S_s - \mathrm{DT}$$

By Table 9.3, we estimate TS = −17 dB; by Fig. 8.27 and estimating for a grazing angle equal to $\sin^{-1}(20/100) = 12°$, $S_s = -37$ dB; DT is given as zero. Therefore 10 log $A$ = 20 dB and $A$ = 100 yd$^2$. Solving the third equation for $\Phi$, with $A = 100$, $r = 100$, and $ct/2 = 1{,}600 \times 0.01/2 = 8$ yd, we find $\Phi = 1/8$ rad = 7.2°. By Table 8.1, this would require a horizontal line transducer 11 wavelengths long.

***Explosive Echo Ranging***

PROBLEM: A 1-lb charge is used as a sound source for echo ranging on a submarine. Find the detection range of a bow-stern aspect submarine target in a background of deep-sea ambient noise in sea state 6. Detection is required 90 percent of the time with a 0.01 percent chance of a false alarm in the echo duration of 0.1 second. A nondirectional hydrophone with a 1-kHz bandwidth centered at 5 kHz is used for reception. Let the source and receiver depths be 50 ft in a mixed layer 100 ft thick, and let the target depth be 500 ft.

SOLUTION: For short transient sources, the source level is

$$\mathrm{SL} = 10 \log E - 10 \log t_e$$

where $E$ = source level in terms of energy density
$t_e$ = echo duration

Solving the active sonar equation for TL, we obtain

$$\mathrm{TL} = \tfrac{1}{2}(10 \log E - 10 \log t_e + \mathrm{TS} - \mathrm{NL} + \mathrm{DI} - \mathrm{DT})$$

The quantities $t_e$ and DI are given in the problem statement. Since the source is broadband, and using Fig. 4.19 at 5 kHz, $E$ = 180 + 10 log 1,000 = 210 dB in the 1-kHz receiver bandwidth; by Table 9.3, TS = 10 dB; by Fig. 7.5, NL = 57 dB; by formula, DT = 5 log $(dw/t)$, using $d$ = 25 (Fig. 12.7), $w$ = 1,000 and $t$ = 0.1, DT = 27. DI = 0 (given). With these values TL is found to be 73 dB. By Fig. 6.6$c$, the range is 2,600 yd at 2 kHz; by Fig. 6.7$c$, the range is 2,200 yd at 8 kHz; on interpolating for 5 kHz, the estimated range becomes 2,400 yd. However, it should be remarked that in this problem the range is likely to be reverberation-limited instead of noise-limited.

***Torpedo Homing***

PROBLEM: In an active homing torpedo, a detection range of 3,000 yd is required on an average-aspect submarine. A detection threshold of 30 dB is needed to cause the torpedo to "home" on its target. If the torpedo transducer is a plane-piston array restricted to a diameter of 15 in., how much acoustic power output is needed at an operating frequency of 40 kHz? The transmission loss is assumed to be adequately described by spherical spreading and absorption at a temperature of 60°F, and the self-noise is to be taken equal to the ambient noise of the deep sea in sea state 6.

SOLUTION: Solving the active-sonar equation for SL, we obtain

$$SL = 2TL - TS + NL - DI + DT$$

From Fig. 5.8, TL = 95 dB; by Table 9.3, TS = 15 dB; by Fig. 7.5, NL = 41 dB; by Fig. 3.6, DI = 30 dB; DT = 30, given. We therefore find SL = 216 dB, and by Fig. 4.4, with $DI_T = 30$, the required power output is found to be 30 watts.

### *Fish Finding*

PROBLEM: A compact school of fish containing 1,000 members, each averaging 20 in. in length, lies 100 yd from a fishing boat equipped with a fish-finding sonar. What will be the level of the echo from this school of fish at a frequency of 60 kHz, assuming that the transducer has a beam pattern broad enough to contain the entire school? The sonar projector radiates 100 acoustic watts of power and is a circular plane array 10 in. in diameter.

SOLUTION: The echo level is the left-hand side of the active-sonar equation and is equal to SL − 2TL + TS. By Fig. 3.6, DI = 30 dB; by Fig. 4.4, SL = 221 dB; with spherical spreading and absorption, using $\alpha = 19$ dB/kyd (Fig. 5.5), TL = 42 dB; by Fig. 9.19, TS = −31 for a single fish 20 in. long; and for 1,000 fish, TS = −31 + 10 log 1,000 = −1 dB. The echo level becomes 136 dB re 1 $\mu$Pa. If the transducer has a receiving sensitivity of −170 dB, the echo would appear as a voltage equal to 136 − 170 = −34 dB re 1 volt across the transducer terminals.

### *Communication*

PROBLEM: In the sofar method of aviation rescue, a downed aviator drops a 4-lb explosive charge set to detonate on the axis of the deep sound channel. How far away can the detonation by heard by a nondirectional hydrophone, also located on the axis of the deep sound channel, at a location of moderate shipping in sea state 3? The receiving system uses a frequency band centered at 150 Hz and squares and integrates the received signals for an interval of 2 seconds—an interval estimated to be sufficiently long to accommodate all the energy of the signal. A signal-to-noise ratio of 10 dB is required for detection.

SOLUTION: Solving the passive equation for TL, we obtain TL = SL − NL + DI − DT. Recognizing the existence of severe signal distortion, we convert to energy-density and obtain TL = $10 \log E_0 - (NL + 10 \log t) + DI - DT$, where $E_0$ is the source energy-density and $t$ is the integration time. From Fig. 4.19, $10 \log E_0$ for a 4-lb charge at 150 Hz = 207 dB; by Fig. 7.5, NL = 68; DI = 0 dB, DT = 10 dB, and $10 \log t = 3$ dB are given in the problem statement. Therefore, TL = 126 dB. To convert to range, we write (Sec. 6.2) $TL = 10 \log r + 10 \log r_0 + \alpha r \times 10^{-3}$. Assume that $r_0 = 10{,}000$ yd. Using the formula (Sec. 5.3) $\alpha = 0.1f^2/(1 + f^2)$, where $f$ is in kilohertz, we find that $\alpha = 0.00225$ dB/kyd. Drawing a curve of TL against $r$, we read off, for TL = 126, the value of $r$ = 8,000 kyd, or 4,000 miles.

### An Echo Repeater

PROBLEM: It is desired to build an echo repeater which when suitably triggered will return a simulated echo to a range of 1,000 yd equal in level to the echo from a beam-aspect submarine at the same range. The echo that it must simulate is obtained with a sonar having a source level of 210 dB re 1 $\mu$Pa. How much acoustic power should it radiate? How much electric power will be needed to drive it if its projector has an efficiency of 50 percent? How much power should it radiate at 100 yd? Assume spherical spreading plus absorption at the rate of 3 dB/kyd.

SOLUTION: The echo level is EL = SL − 2(TL) + TS = 210 − 2(20 log 1,000 + 3) + 25 = 109 dB re 1 $\mu$Pa, where 25 is the target strength of the submarine (Table 9.3). The simulated echo level is SL′ − TL = SL′ − (20 log 1,000 + 3) = SL′ − 63. Equating the two levels, we find SL′ = 172. By the relation SL′ = 171.5 + 10 log $P$ + $DI_T$, we find 10 log $P$ = ½; hence, $P$ = 1 watt, if $DI_T = 0$. At 50 percent efficiency, 2 electric watts will be needed to drive it. At 100 yd, the acoustic power rises to 220 watts! *Note:* A practical echo repeater would simulate much more than the level of the echo; its echoes would have a doppler shift and other realistic echo characteristics.

## 13.5 Concluding Remarks

A few words of caution must be said regarding the "pat" solutions of the problems just given. Everything depends upon the values of parameters assumed in their solution. These values are always accompanied by uncertainties arising from two sources: first, uncertainty that the conditions assumed are really those of actual interest and importance; and second, uncertainty that, under these conditions, the chosen values of the parameters are valid.

The first of these two sources of uncertainty involves the specification of the conditions, some natural, some of human origin, that the engineer feels will be representative of the environment and the target in and against which the system must operate. Here extreme cases will often need to be worked out in the hope that conditions beyond the selected limits will not be of practical significance. The second uncertainty arises from the presently crude state of underwater sound as a body of quantitative knowledge. Even when all the necessary nature and target conditions are specified, the associated acoustic parameter is likely to be uncertain by several decibels or more, simply because of insufficient quantitative information.

## REFERENCES

1. Stewart, J. L., E. C. Westerfield, and M. K. Brandon: Optimum Frequencies for Sonar Detection, *J. Acoust. Soc. Am.*, **33**:1216 (1961).
2. Horton, J. W.: Fundamentals of Sonar, *U.S. Nav. Inst., art.* 7C-3, 1957.
3. Stewart, J. L., E. C. Westerfield, and M. K. Brandon: Optimum Frequencies for Noise Limited Active Sonar Detection, *J. Acoust. Soc. Am.*, **70**:1336 (1981).