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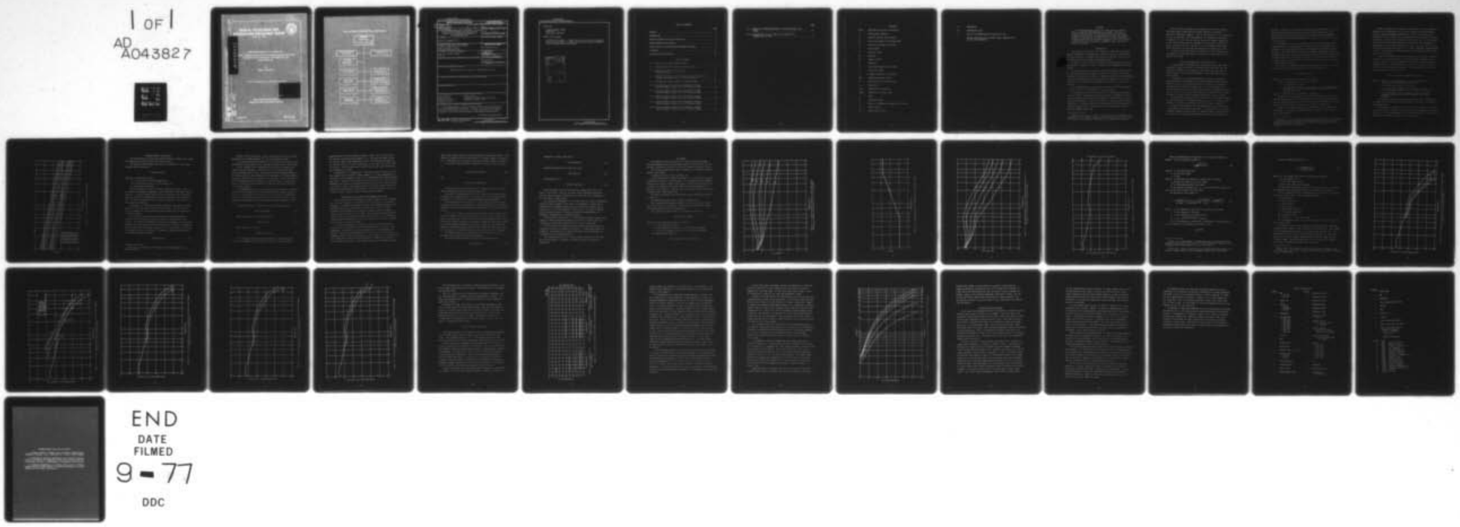

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PASSIVE BROADBAND AURAL DETECTION – PART 1: SIGNAL EXCESS DETECTION-RANGE CALCULATIONS WHICH ACCOUNT FOR THE FREQUENCY DEPENDENCE OF THE SONAR EQUATION

by

Edford O. Chambers, II

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SHIP ACOUSTICS DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

August 1977 Report 77-0045

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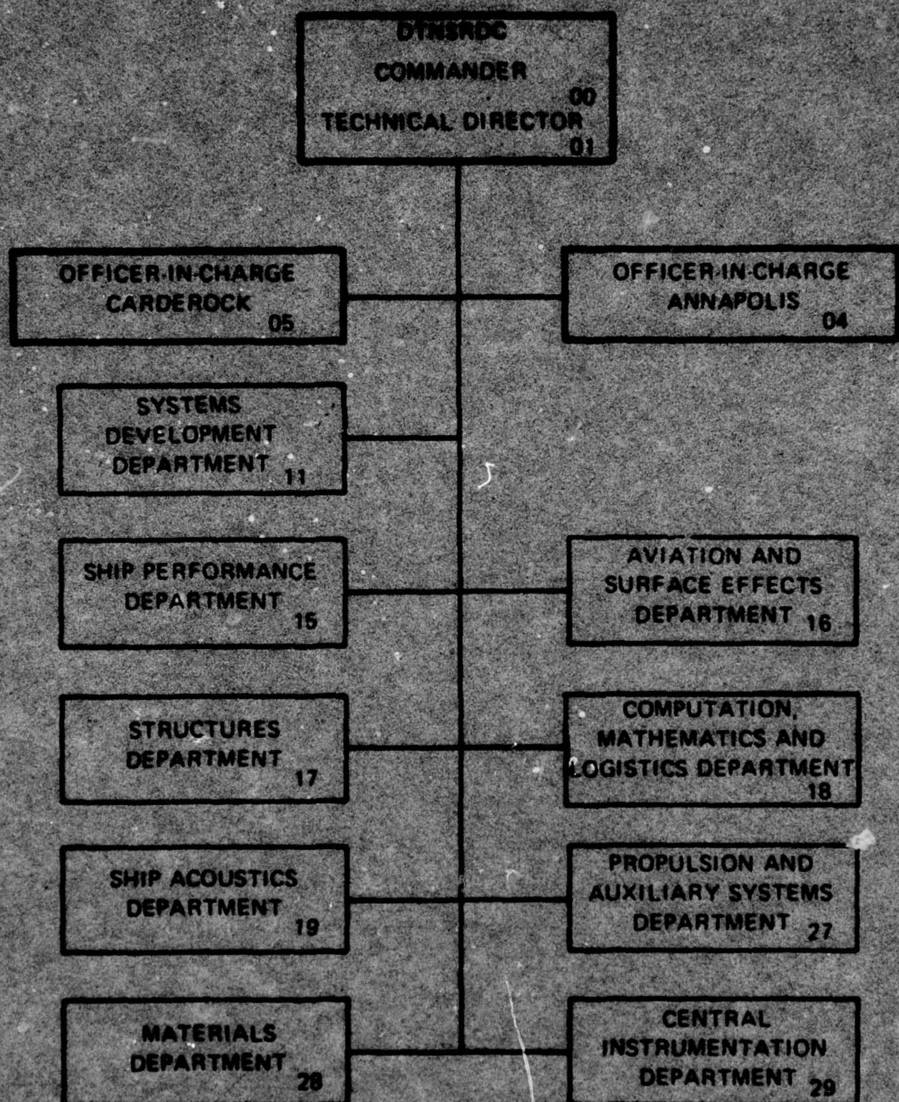

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: DTNSRDC-77-0045	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): PASSIVE BROADBAND AURAL DETECTION--PART 1; SIGNAL EXCESS DETECTION-RANGE CALCULATIONS WHICH ACCOUNT FOR THE FREQUENCY DEPENDENCE OF THE SONAR EQUATION.	5. TYPE OF REPORT & PERIOD COVERED: Final
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Edford O. Chambers, II	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: David W. Taylor Naval Ship Research and Development Center, Bethesda, Maryland 20084	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: (See reverse side)
11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Sea Systems Command, SEA 037	12. REPORT DATE: August 1977
	13. NUMBER OF PAGES: 38
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aural detection
Passive sonar
Detection threshold
Figure of merit
Signal excess
Frequency-dependent transmission loss
Minimum detectable level

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The figure-of-merit form of the sonar equation causes a bias in calculated broadband-detection ranges. The bias is caused by the necessity of treating the figure of merit as if it were concentrated at a single frequency, since only single-frequency--transmission-loss graphs are

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Program Element 25634N
Task 19774
Work Unit 1-1922-004

(Block 20 continued)

practically available. A signal-excess form of the sonar equation is used in this report to remove the bias from passive, broadband, aural, detection-range calculations.

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NOTATION

$A(d')$	Psychometric function in decibels
a	Proportional constant
c_0	Speed of sound at source depth
DI	Directivity index of receiving sonar
DT	Detection threshold in decibels
d	Source depth
d'	Detection index
dB	Decibels
FM	Figure of merit
f	Frequency
g	Sound speed gradient with depth
H	Mixed layer depth
ℓ	Leakage coefficient in decibels
MDL	Minimum detectable levels
NL	Noise level at receiving sonar
n	State of sea
P(D)	Probability of detection
P(FA)	Probability of false alarm
R	Range
R_0	Transition range
r	Radius of curvature of sound rays in a duct
SE	Signal excess
SL	Signal source level

T	Temperature
TL	Transmission loss
W	Width of broadband spectrum detected by ear
′	Primed quantities are in narrow bands, unprimed ones are for the bandwidth W

ABSTRACT

The figure-of-merit form of the sonar equation causes a bias in calculated broadband-detection ranges. The bias is caused by the necessity of treating the figure of merit as if it were concentrated at a single frequency, since only single-frequency--transmission-loss graphs are practically available. A signal-excess form of the sonar equation is used in this report to remove the bias from passive, broadband, aural, detection-range calculations.

INTRODUCTION

The purpose of this paper is to develop a method for calculating passive, broadband, aural detection ranges that is more reliable than the present method. Broadband detections are important since many, if not most, detections are made on broadband energy.

In part 1 of this report, the method will be developed and illustrated with an example. In Part 2, more detailed examples will be presented.

In almost all present practice, a single-frequency method is used for calculating detection ranges. Generally, all terms of the sonar equation are functions of frequency. Adequate treatment of the broadband-detection problem must take into account the dependency of the calculations on both frequency and bandwidth of the signal in noise to be detected.

The single-frequency calculation is satisfactory when the task is to detect a tone or a narrowband of acoustic energy.

A critical term in the sonar equation is the detection threshold. A recent report[1] has presented an excellent and a comprehensive examination of many recent psychoacoustic papers concerned with the aural detection threshold. It has also presented an improved figure-of-merit calculation. The basic idea of that calculation will be used herein to develop a signal-excess calculation that will obtain more accurate detection-range predictions.

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[1] Stallard, J.M. and C.B. Leslie, "Psychoacoustics and Passive Sonar Detection," Naval Ordnance Laboratory Technical Report 74-27 (Sep 1974). This report has an extensive bibliography of psychoacoustic papers.

The calculation procedure to be developed will not be suitable for either manual calculations or simple desk-top calculators. It requires a high-speed computer. This is not really much of a restriction in this day and age, since minicomputers are becoming so widespread in usage that in the very near future they may be almost commonplace. In any case, information and knowledge have increased so rapidly in recent years--in the main, through use of the computer--that simple hand calculations are less and less adequate for present day needs.

A review of the main results of Reference 1 will be given, since the method for calculating detection ranges to be developed herein is based on that work.

DETECTION CAPABILITIES OF THE HUMAN EAR

A large number of psychoacoustic investigations have been made of individual factors that affect the human ear-to-brain detection capabilities. However, little practical application has been made of these studies to the real-world problem of aural detection through a passive sonar.

In Reference 1, the results obtained from many psychoacoustic papers have been consolidated into a report primarily concerned with quantification of a real-world detection threshold for the human ear and application thereof to passive sonar. The work, based on the modern statistical theory of signal detectability, combines the effects of five main factors to yield a new detection threshold for the human ear that is between 5 and 6 dB higher than shown in earlier works.

Two detection thresholds have been derived: one for tonal signals in noise and another for broadband signals in noise. Detection capabilities of the ear are different for the two kinds of signals.

A distinctive feature of the "ear-brain" detector is its ability to selectively filter signal and noise. It will search out the region of highest signal-to-noise ratio of a signal-plus-noise spectrum, and only the noise in that selected bandwidth will affect the detection process. In addition to the numerous papers quoted in Reference 1, a more recent paper[2] supports this view of the filtering capabilities of the human ear-brain. The critical band is the minimum auditory bandwidth: the ear forms its minimum bandwidth when its task is to discover or detect a tone in noise.

One consequence is that no hardware filters should be interposed between the ears of a sonar operator and output of the signal-plus-noise spectrum of the sonar when the task of the operator is to detect a signal in noise. This is particularly true for broadband signals and noise. A hardware filter could seriously degrade the ear-brain detection capabilities: it could partially or even totally exclude the most detectable portion of a target signal. After detection, filtering could be of help in classifying and trailing a target.

This report is concerned only with broadband aural detection. The new threshold of broadband aural detection given in Reference 1 is

$$DT = 1.6 + A(d') - 5 \log W \qquad (1)$$

where DT is the detection threshold in decibels

$A(d')$ is the psychometric function in decibels

d' is the detection index

W is the width in Hertz of that portion of the broadband target spectrum that is detected through the selective filtering ability of the ear.

Values of $A(d')$ are given in Reference 1, Figure 6.

The detection index depends on the desired probability of detection P(D) and probability of false alarm P(FA). The detection index together with associated probabilities P(D) and P(FA) can be obtained from receiver-operator curves (ROC); e.g., Reference 1 Figure 3 or Table 4-1.

Equation (1) indicates that as W becomes wider, DT is lowered and vice versa. A wide band of broadband signal in noise is more detectable than a narrow band.

---

[2] Moore, B.C.J. and D.H. Raab, "Intensity Discrimination for Noise Bursts in the Presence of a Continuous, Bandstop Background: Effects of Level, Width of the Bandstop, and Duration," Journal of the Acoustical Society of America, v. 57, p. 400 (1975).

The DT of Equation (1) is based on the results of a large number of psychoacoustic experiments and is thus an average value representing realistic human-performance capabilities. There are many sources of variability in the aural DT such as individual sonar operator capability, experience, fatigue, health condition, motivation, etc. For that matter all the terms of the sonar equation are subject to various degrees of variability or fluctuation; nevertheless, there is a need for more accurate detection-range calculations or, at least, reasonable approximations to such. The method to be developed herein is intended as another step toward this objective.

A detection prediction must be calculated for a specific bandwidth. The selective filtering ability of the ear presents a problem, since, normally, there is no way of knowing in advance what signal and noise bandwidth W will be most detectable to the ear. The next two sections of this report will present methods for circumventing this difficulty. For this purpose Reference 1 defines

$$DT'=DT+5 \log (W/af)=1.6+A(d')-5 \log (af) \qquad (2)$$

where ′ applies to the narrowbands in which the terms of the sonar equation are measured and analyzed

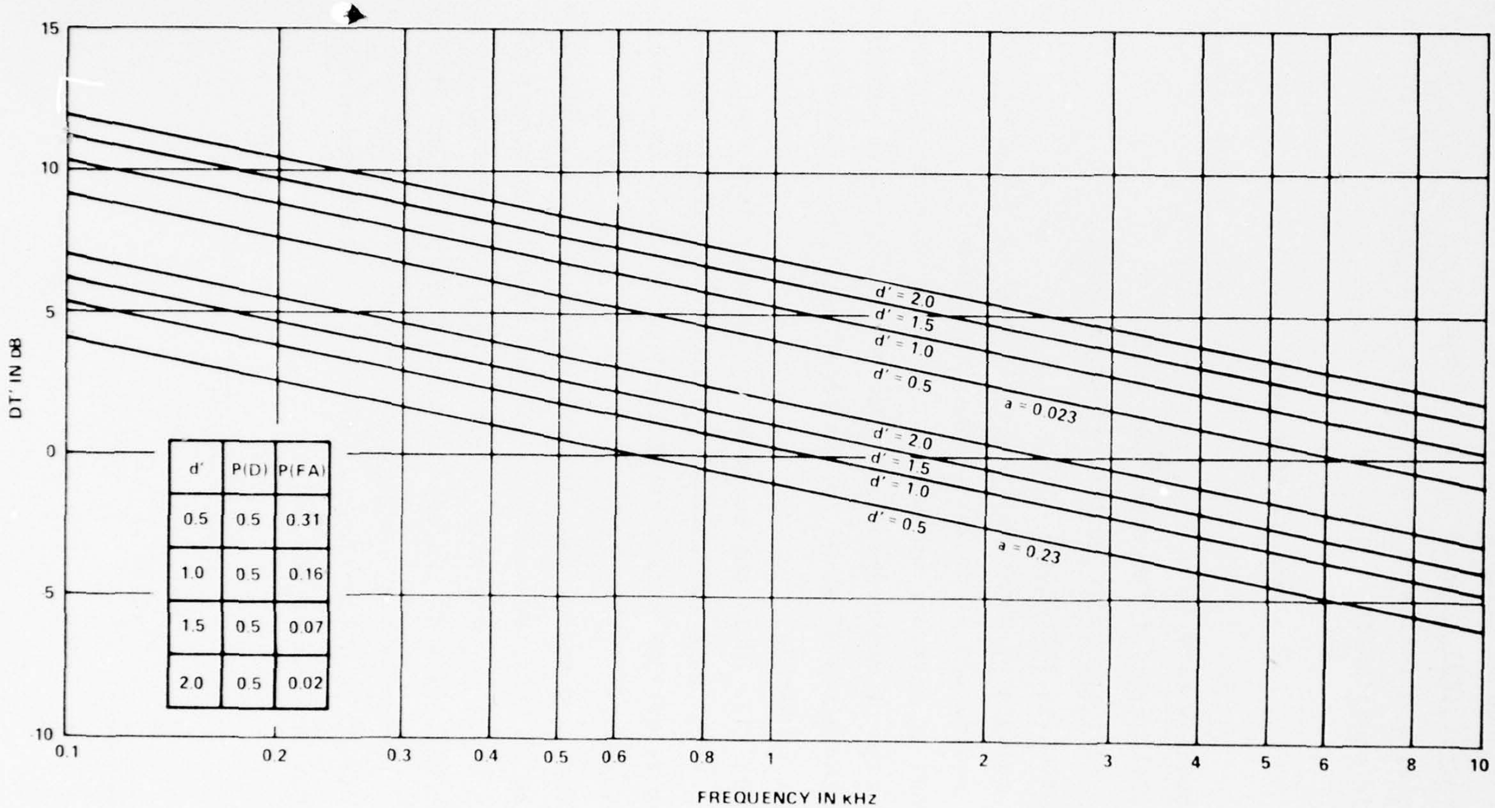
f is the geometric center of W in hertz

a is a proportional constant and is equal to 0.23 for 1/3-octave-analysis bands, 0.023 for 1/30-octave bands, etc.

af is the bandwidth of the analysis filters; for constant bandwidth filters, the term "af" would be the constant bandwidth.

The previously described artifice allows detection calculations to be made without there being prior knowledge of the band of frequencies causing detection.

In Reference 1, Equation (2) and data from its Figure 6 (d′ versus A(d′)) were used to produce the family of DT′ curves presented herein as Figure 1-1. Those curves were for 1/30-octave bands; DT′ for 1/3-octave bands has been added to Figure 1-1 for later use.



d'	P(D)	P(FA)
0.5	0.5	0.31
1.0	0.5	0.16
1.5	0.5	0.07
2.0	0.5	0.02

Figure 1-1 - DT′ for 1/30- and 1/3-Octave Bands

FIGURE-OF-MERIT CALCULATIONS

The usual method of calculating expected detection ranges is by using the figure-of-merit (FM) form of the sonar equation.

In decibels, and following the notation of Reference 3, the passive figure-of-merit equation is

$$FM=SL-(NL-DI+DT) \tag{3}$$

where SL is signal-source level

NL is noise level at the receiving sonar

DI is directivity index of the receiving sonar

DT is detection threshold.

A better measure of sonar self-noise is made at the sonar output. It is called the equivalent plane-wave, sonar self-noise on the main response axis LE. It has an inherent measure of the sonar directivity characteristics at the time of measurement and does not depend on the theoretical DI. It takes the place of NL-DI in the sonar equation. (Note that it is not stated that LE=NL-DI.)

In Equation (3), FM is the maximum transmission loss that the signal can suffer and still be detectable at the receiver. The FM is used to enter a transmission loss versus range graph by which FM is converted to a detection range.

In Reference 1 a method was discussed for developing a graphical solution of the FM equation that was intended to take frequency into account. This would be necessary for any proper treatment of the detection problem, since all terms of the sonar equation are functions of frequency. By using the method discussed, a graph of SL was constructed as a function of frequency; also, as a function of frequency, a graph was constructed of minimum detectable level MDL.

$$MDL=NL-DI+DT \tag{4}$$

---

[3] Urick, R.J., "Principles of Underwater Sound," McGraw-Hill, Inc., New York (1975).

Two MDL's were constructed: one for tones and the other for broadband detections, using different DT's for the respective cases.

In the earlier method and Reference 1, this term was called an equal detectability curve; however, the customary term MDL will be used herein.

In use, the MDL curve is overlaid on the SL curve, lining up the frequency-scaled abscissas. The MDL curve is then moved vertically until it touches the SL curve. In this position the difference between the decibel levels on the ordinates of the two graphs is FM--the numerical solution of Equation (3) as a function of frequency. In this treatment of the broadband detection problem, it is assumed that W is always the same as the width of the filters used to measure and analyze the terms of the sonar equation.

For broadband detections, it was assumed in the previously described method that the bandwidth for the detected energy was always one-third octave. It was realized in Reference 1 that the detection bandwidth of the ear was not restricted to the width of the analysis filters. Thus a correction was devised, using the previously defined Equations (2) and (3).

An equation similar to Equation (3) can be written using DT′

$$FM' = SL - (NL - DI + DT') \qquad (5)$$

Subtracting Equation (5) from Equation (3)

$$FM - FM' = DT' - DT \qquad (6)$$

Using Equations (1) and (2)

$$FM = FM' + 5 \log (W/af) \qquad (7)$$

After using the previously described method to determine an FM′ based on the bandwidth of the analysis filters, Stallard and Leslie[1] would determine W of the detected frequency region, and a correction to FM′ would be calculated using Equation (7). The upper and lower limits of W can be taken as the frequencies at which the separation between the SL′ and MDL′ curves is 3 dB on either side of the point of contact of the two curves. This is based on the one-half power points used in defining the bandwidth of filters.

In Reference 1, f in Equation (7) has been taken as the point of contact between the SL′ and MDL′ curves; however, it is more appropriate to calculate f as the geometric center of the 3-dB separation points mentioned previously. Owing to the various SL′s and MDL′s that exist, the detection bandwidth will usually be unsymmetrical about the point of contact between SL′ and MDL′ curves. There could also be two or more contact points between the curves within the 3-dB limits. It is possible too, that the two curves could be in contact across a large frequency region.

SIGNAL-EXCESS CALCULATIONS FOR BROADBAND DETECTIONS

With the previous FM calculations, it was intended to take frequency into account, since all of the terms of the sonar equation are freqency dependent. The method is adequate for tones or narrowbands; however, for broadband detections, the FM method is defective. This is because transmission-loss graphs are for practical purposes given in terms of loss at single frequencies. This means that the calculated broadband FM value must be used as a single frequency FM in order to enter a graph of single frequency-transmission loss versus range, which is used to convert the FM value to a detection range.

It would be impractical to attempt to provide transmission-loss curves for all the possible detection bandwidths that can occur. These bandwidths, in practice, are usually large; so no single frequency can properly represent the propagation loss or any of the other frequency-dependent terms of the sonar equation. In the example of the next section, some quantitative effects will be discussed. In addition, W found by the FM method is the same at all ranges; whereas, the bandwidth actually varies with range, owing to frequency-dependent transmission losses. This affects DT because when W becomes smaller, DT becomes larger; see Equation (1). A procedure for overcoming these difficulties is given as follows.

In terms of signal excess SE, Equations (3) and (5) can be written as

$$SE=(SL-TL)-(NL-DI+DT) \qquad (8)$$

and

$$SE'=(SL-TL')-(NL-DI+DT') \qquad (9)$$

The SL-TL term is the received level of target signal at the sonar after transmission loss (TL) through a range (R).

Each term of Equations (8) and (9) is a function of frequency, <u>now</u> including the transmission loss. The primes have the same significance as before, i.e., they refer to the narrow-measurement bandwidths.

The procedure now is to construct a set of curves of SL′-TL′ versus frequency with range as a parameter. As range increases, SL′-TL′ curves decrease in level, the high frequencies decreasing at a greater rate than the low.

The (SL′-TL′) curves are overlaid with the MDL′ curve; however, this time, the ordinate levels of the two curves are lined up as well as the abscissa frequencies. The SL′-TL′ curve that just touches the MDL′ curve provides the range that would be obtained if signal and noise were limited to a narrow-analysis bandwidth at the point of contact. The detection bandwidth is determined in the same way that the FM calculation was made and a correction is computed by means of the artifice given as follows.

The signal excess is zero when detection can just occur at the probabilities for which DT has been determined.

For the wide detection band, Equation (8) yields with SE=0

$$TL=SL-NL+DI-DT \qquad (10)$$

Equation (9) yields, with SE′=0

$$TL'=SL-NL+DI-DT' \tag{11}$$

Subtracting Equation (11) from (10) gives

$$TL-TL'=DT'-DT \tag{12}$$

Using Equation (2)

$$TL=TL'+5\log(W/af) \tag{13}$$

The final range would then be found by sliding MDL′ down by the amount 5 log (W/af). That is, the wider signal bandwidth associated with TL allows a greater transmission loss than the narrow bandwidth of TL′ and, thus, a longer range.

As cautioned by Reference 1 in the FM method, the analysis bandwidths should be narrow enough so that tones or narrowbands of energy can be separated from broadband energy, and W of the detected signal must be greater than a critical bandwidth. Additionally, the analysis filters should be narrow enough for quantities measured through them to be adequately represented at a single frequency.

The FM method of Reference 1 for calculating detection ranges, while capable of being carried out manually, is still too complex and time consuming for on-the-spot application such as in a sonar room.

The SE method of calculating detection ranges advocated herein is certainly not suited for manual calculations. A high-speed computer is essential. This need will be appreciated better after examination of the example in the following section.

The computer restriction is not the severe limitation it once was. Use of minicomputers is growing so rapidly that they may shortly be ubiquitous.

AN EXAMPLE

The example will be carried out for 1/3-octave-analysis bands. Smaller bandwidths would be preferable; however, the only data that are routinely available at present are measured through 1/3-octave filters.

The receiving sonar has NL given in Figure 1-2. These are actually ambient noise levels.

A hypothetical DI is given in Figure 1-3.

The 1/3-octave DT′ is taken from Figure 1. It is for $d'=1.5$, which corresponds to P(D)=0.5 and P(FA)=0.07. It is assumed that the observations will be made by a fairly experienced and alert sonar operator, who is capable of working at the rather high false-alarm probability of 7 percent--a low threshold. However, when the operator reports "detection," it should be at a much lower P(FA).

The MDL's constructed from the previously described data are given in Figure 1-4.

A hypothetical source level is given in Figure 1-5.

The transmission-loss model assumed is for a surface duct. Ducts are fairly common in the oceans of the world during the winter months. Other models would be used as appropriate.

For ranges less than or equal to a transition range (R_0)

$$TL=20\ \log R+(a+\ell)R+60 \qquad (14)$$

where TL is the transmission loss in decibels

R is the range in kiloyards

a is the absorption coefficient in decibels per kiloyard

ℓ is the duct leakage coefficient in decibels per kiloyard

For ranges greater than R_0

$$TL=10\ \log R_0+10\ \log R+(a+\ell)R+60 \qquad (15)$$

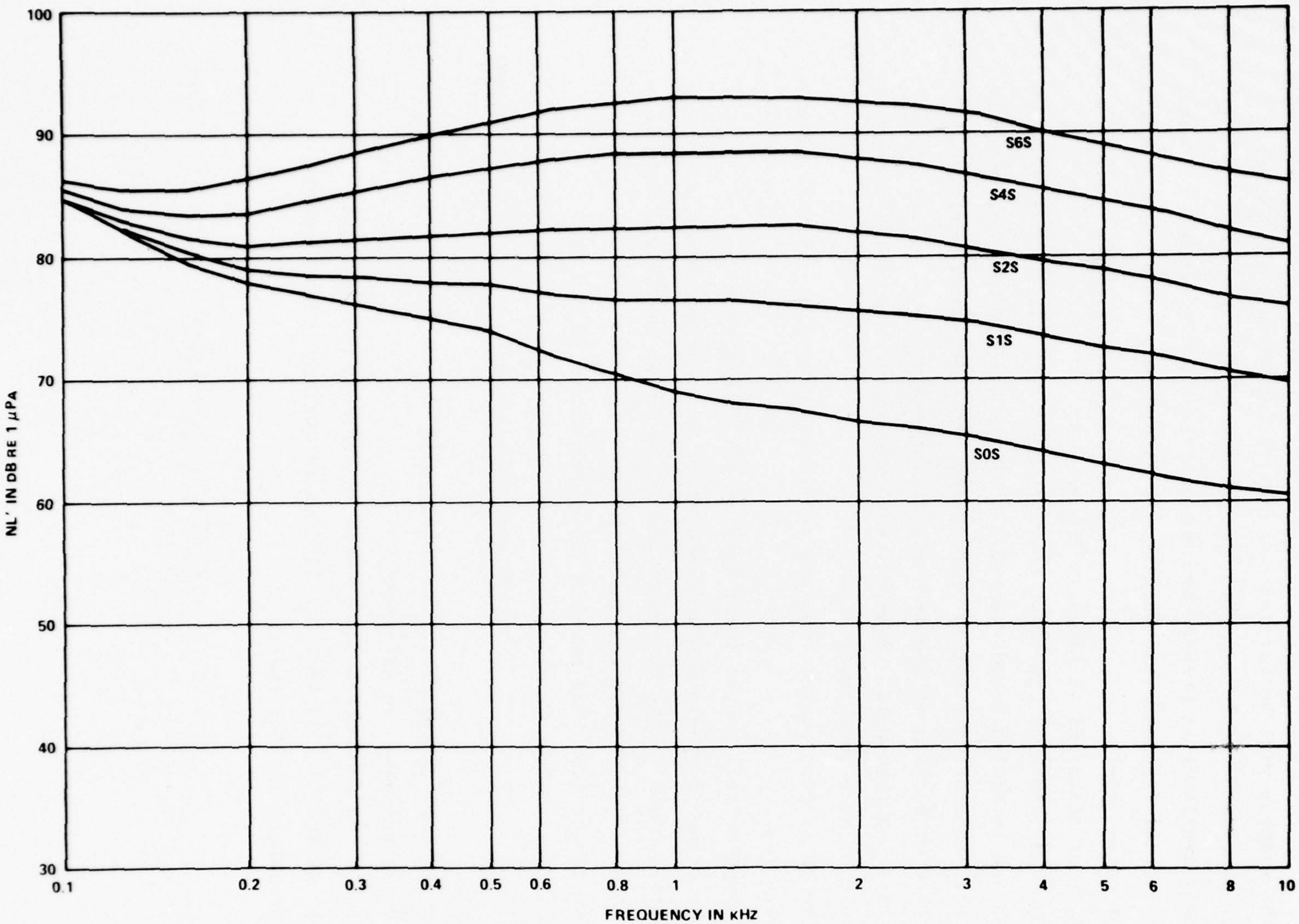


Figure 1-2 - Interfering Noise Levels at Receiving Sonar
(These are ambient noise levels in 1/3-octave bands)

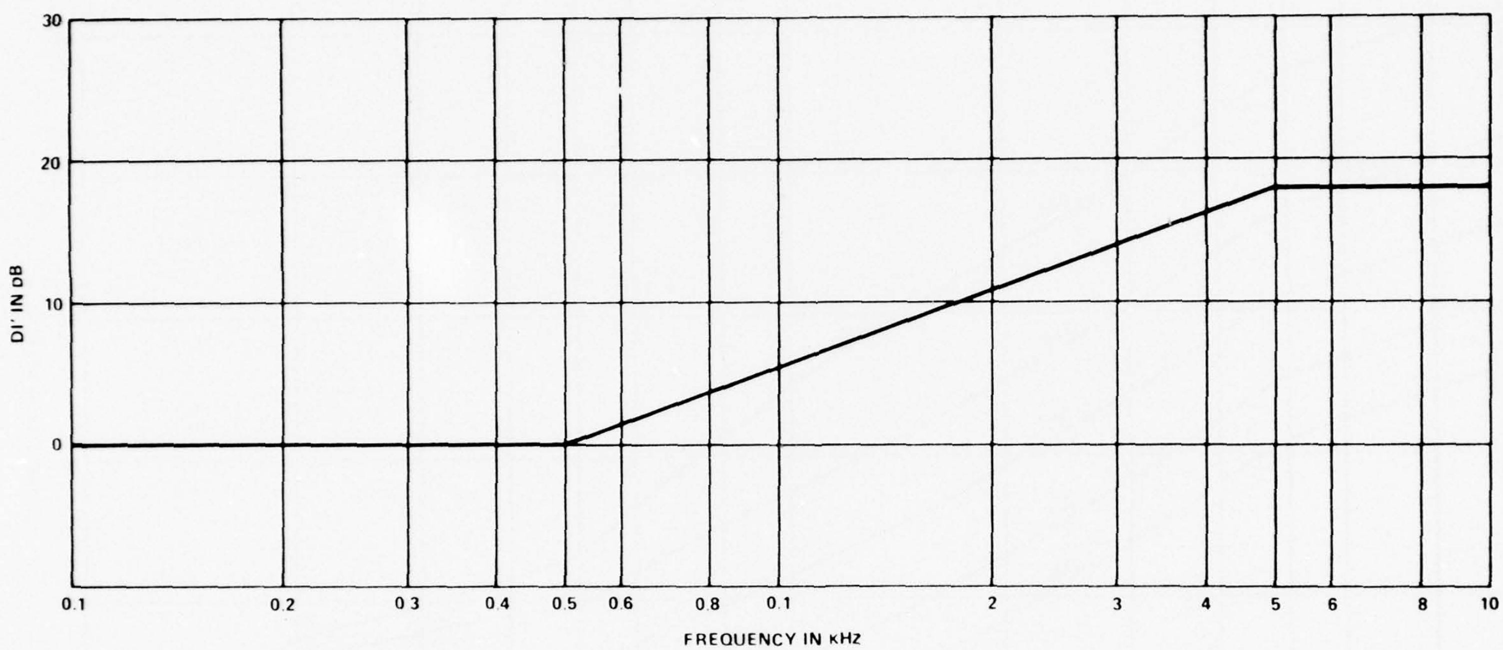


Figure 1-3 - Hypothetical Directivity Index of Receiving Sonar

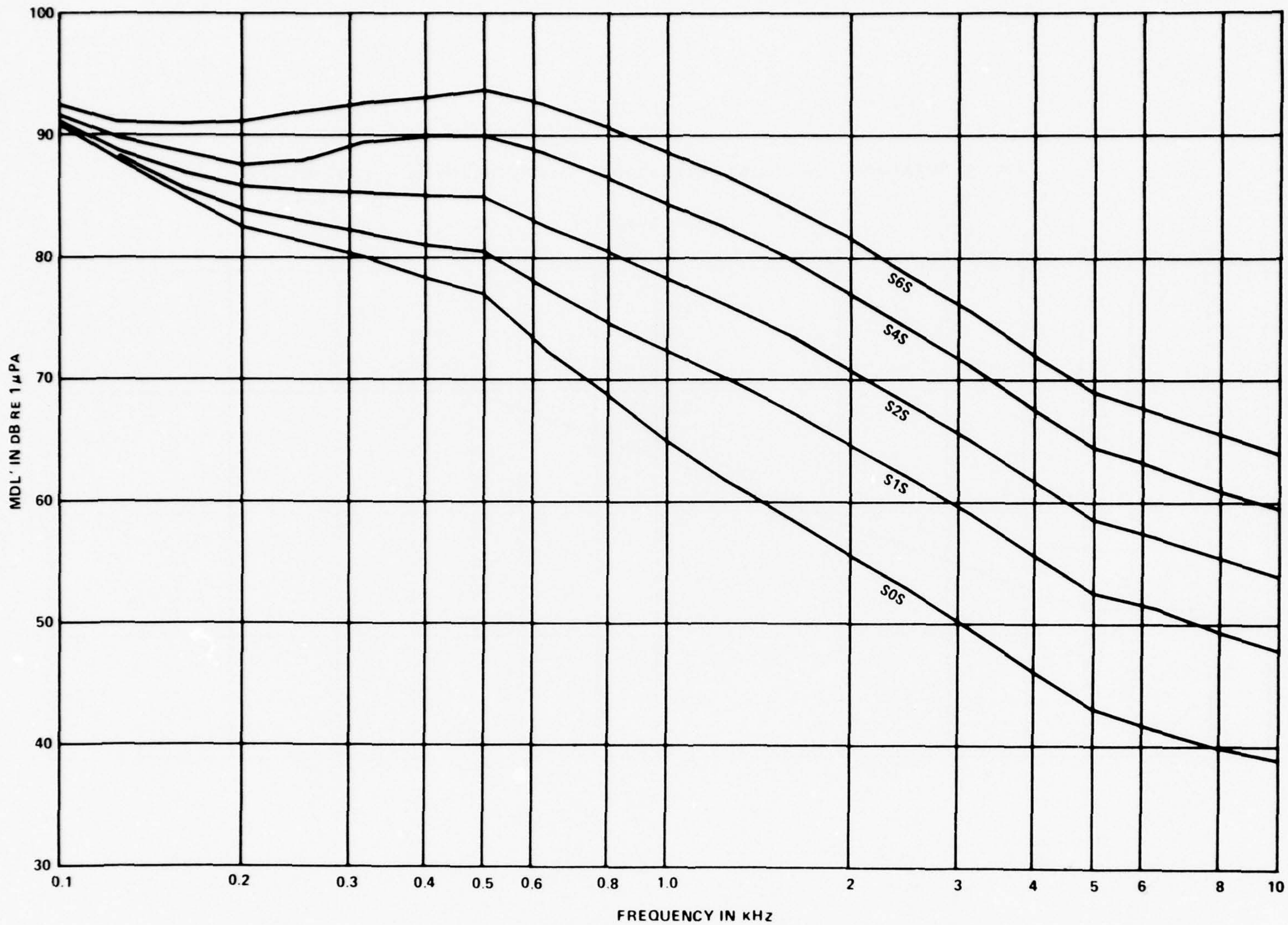


Figure 1-4 - Minimum Detectable Levels, Constructed from Figures 1-1 through 1-3; a=0.23, d=1.5; 1/3-Octave Bands

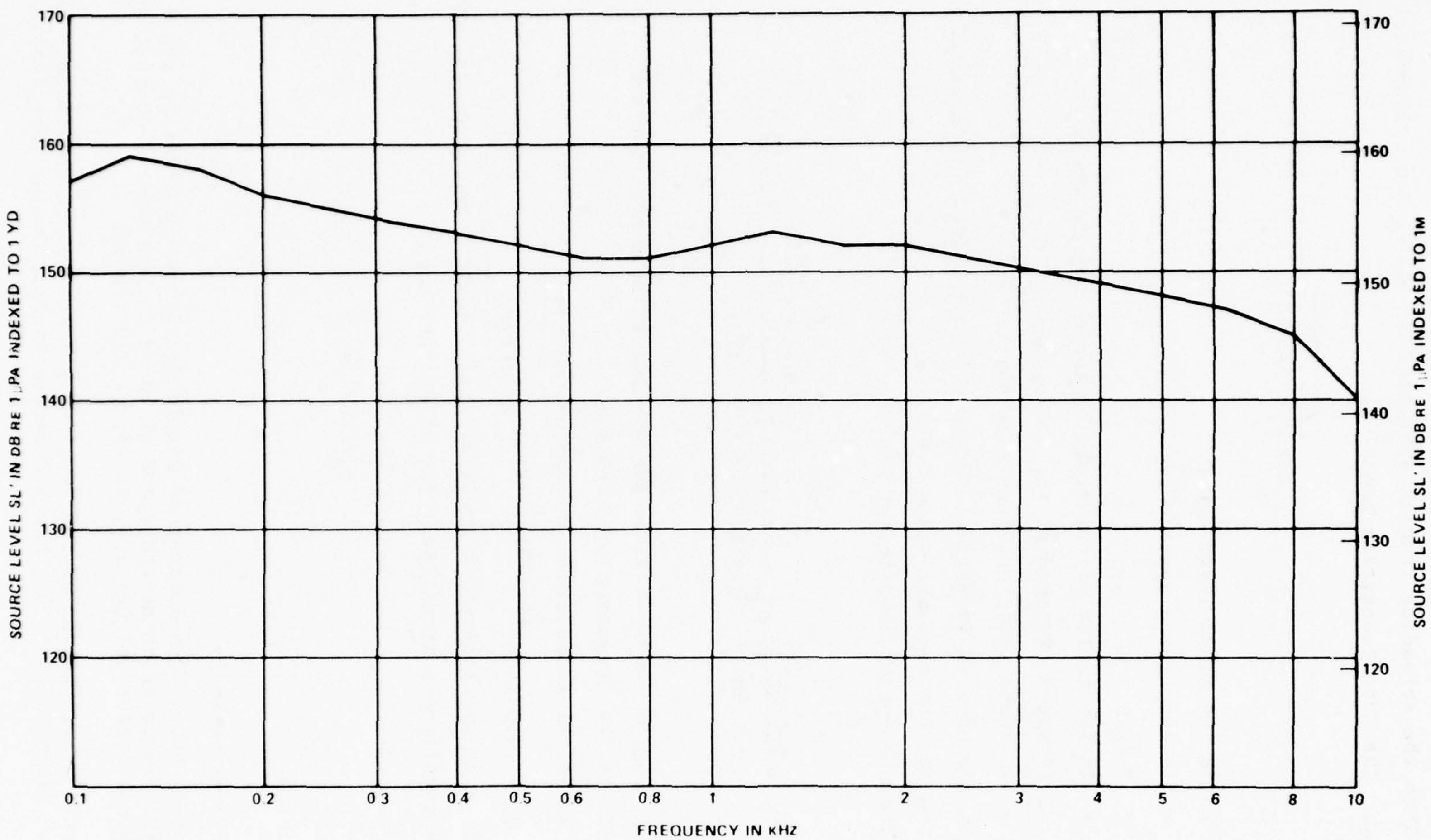


Figure 1-5 - Hypothetical Source Levels in 1/3-Octave Bands

Thus the spreading loss is spherical out to R_0 and cylindrical beyond. The duct transition range[3] is

$$R_0 = \sqrt{rH^2/2(H-d)} \qquad (16)$$

where H is the mixed-layer depth

d is the source depth

$r = c_0/g$

where r is the radius of curvature of sound rays in the duct

c_0 is speed of sound at the source depth

g is sound speed gradient with depth.

In the assumed isothermal duct, c_0 is calculated[4] with salinity of 35 pt; g has the constant value 0.017/sec.

The absorption coefficient[5] is

$$a = \frac{1.776f^{1.5}}{32.768+f^3} + \left(\frac{1}{1+32.768/f^3}\right)\left(\frac{0.6505f_Tf^2}{f^2+f_T^2} + \frac{0.02685f^2}{f_T}\right) \qquad (17)$$

where a is the absorption coefficient in decibels per kiloyard

f is the frequency in kilohertz

T is the temperature in degrees Celsius

$f_T = 21.9 \times 10^{(6T+118)/(T+273)}$ kilohertz

If a is the absorption coefficient in decibels per kiloyard, and a_m is the coefficient in decibels per kilometer, then

$$a_m = 1.0936a$$

---

[4] Leroy, C.C., "Development of Simple Equations for Accurate and More Realistic Calculation of the Speed of Sound in Sea Water," Journal of the Acoustical Society of America, v. 46, p. 216 (1969).

[5] Hall, H.R., "Values of the New Acoustic Absorption Coefficient of Sea Water," Technical Note 63, Naval Undersea Warfare Center (Feb 1968).

The duct leakage coefficient[6] is

$$\ell = \frac{26.6f(1.4)^n}{[(1452+3.5T)H]^{0.5}} \tag{18}$$

where ℓ is the leakage coefficient in decibels per kiloyard

n is the state of sea

H is the duct depth in feet

f and T are as previously defined.

The previously described conversion factor is also used to convert duct leakage from decibels per kiloyard to decibels per kilometer.

The T in Equation (18) has a negligible effect; however, in Equation (17) at more than 2 kHz it has a significant effect.

For the example:

H = 400 ft (121.9 m)

d = 200 ft (61 m)

T = 60 F (15.6 C)

C = 4954 ft/sec (1510 m/s)

r = 291.4 kyd (266.5 km)

R_0 = 3.6 kyd (3.3 km)

n = States 0, 1, 2, 4, and 6 seas.

The low-frequency cutoff for a 400-ft duct is 130 Hz, so it will not be of concern here.

The amount of source level (Figure 1-5) remaining after transmission through various ranges is given in Figures 1-6 through 1-10. Each figure is for a different state of sea in accordance with Equation (18). Only the pertinent SL′-TL′ curves are given in the figures, i.e., the curve needed for the initial range approximation and the one needed for the corrected range. Naturally, many other SL′-TL′ curves were computed in the course of finding two pertinent for each case.

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[6] Baker, W.F., "New Formula for Calculating Acoustic Propagation Loss in a Surface Duct in the Sea," Journal of the Acoustical Society of America, v. 57, p. 1198 (1975).

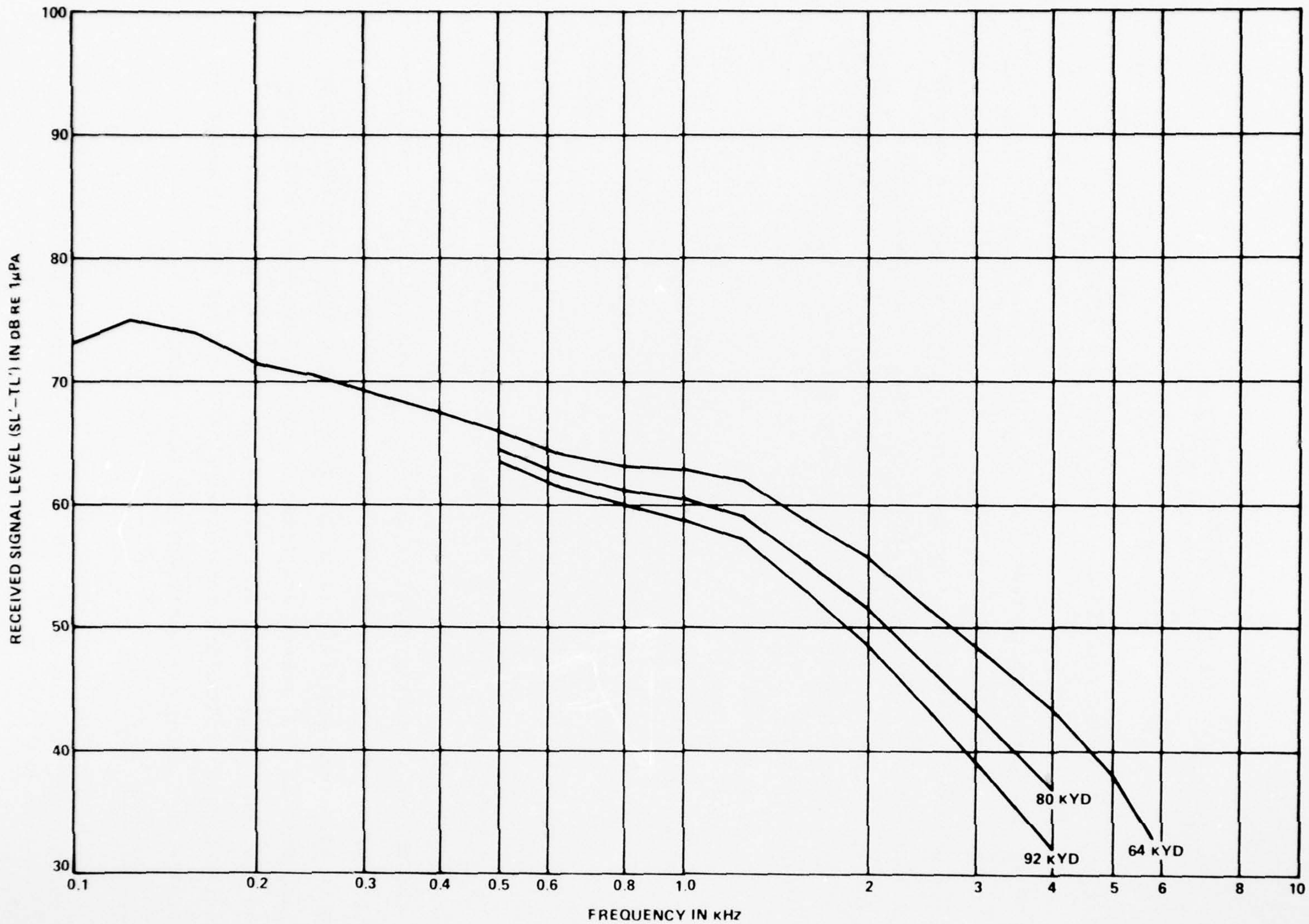

Figure 1-6 - Received Signal Levels after Transmission through Various Ranges at State 0 Sea in 1/3-Octave Bands

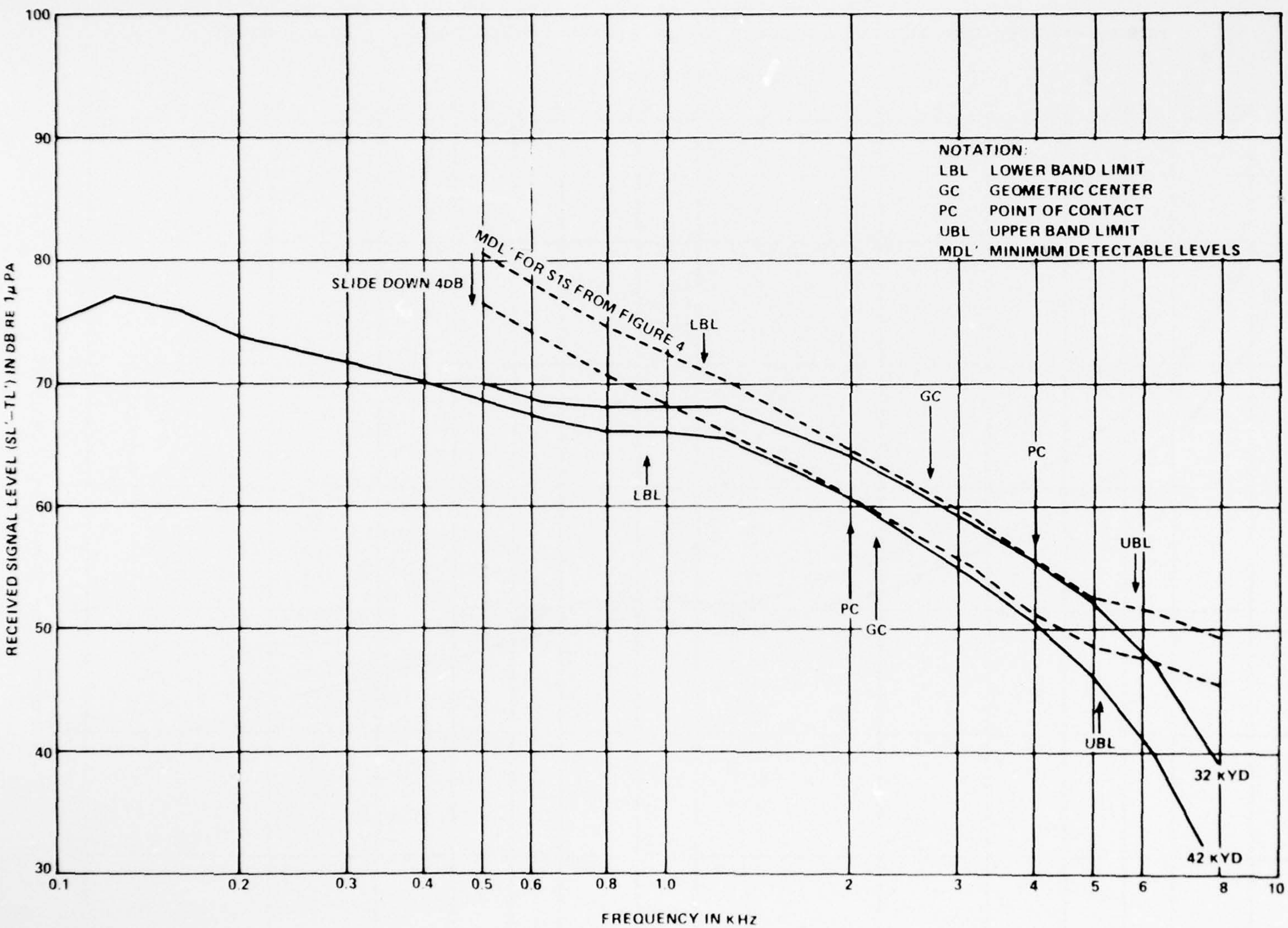

Figure 1-7 - Received Signal Levels after Transmission through Various Ranges at State 1 Sea in 1/3-Octave Bands

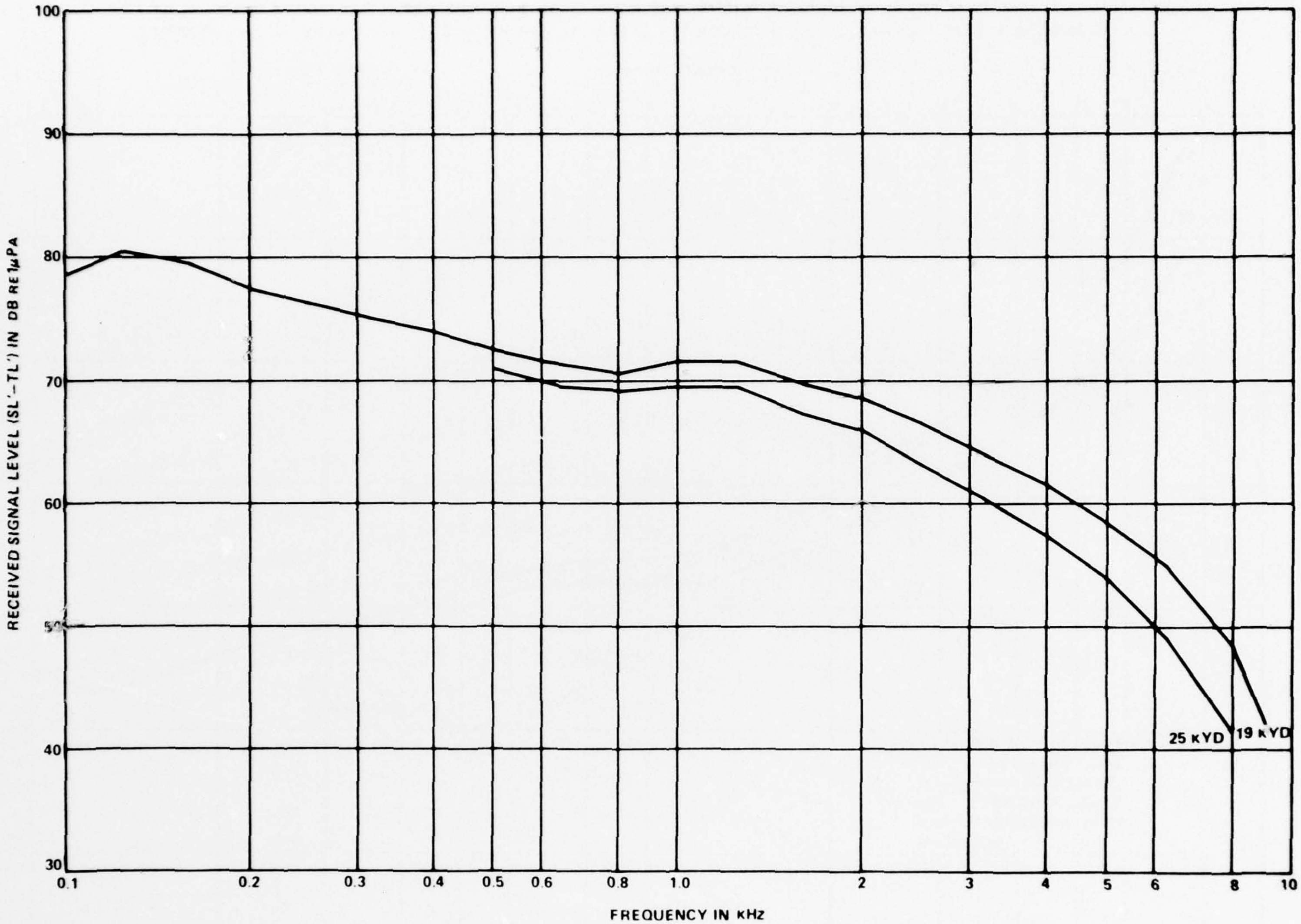

Figure 1-8 - Received Signal Levels after Transmission through Various Ranges at State 2 Sea in 1/3-Octave Bands

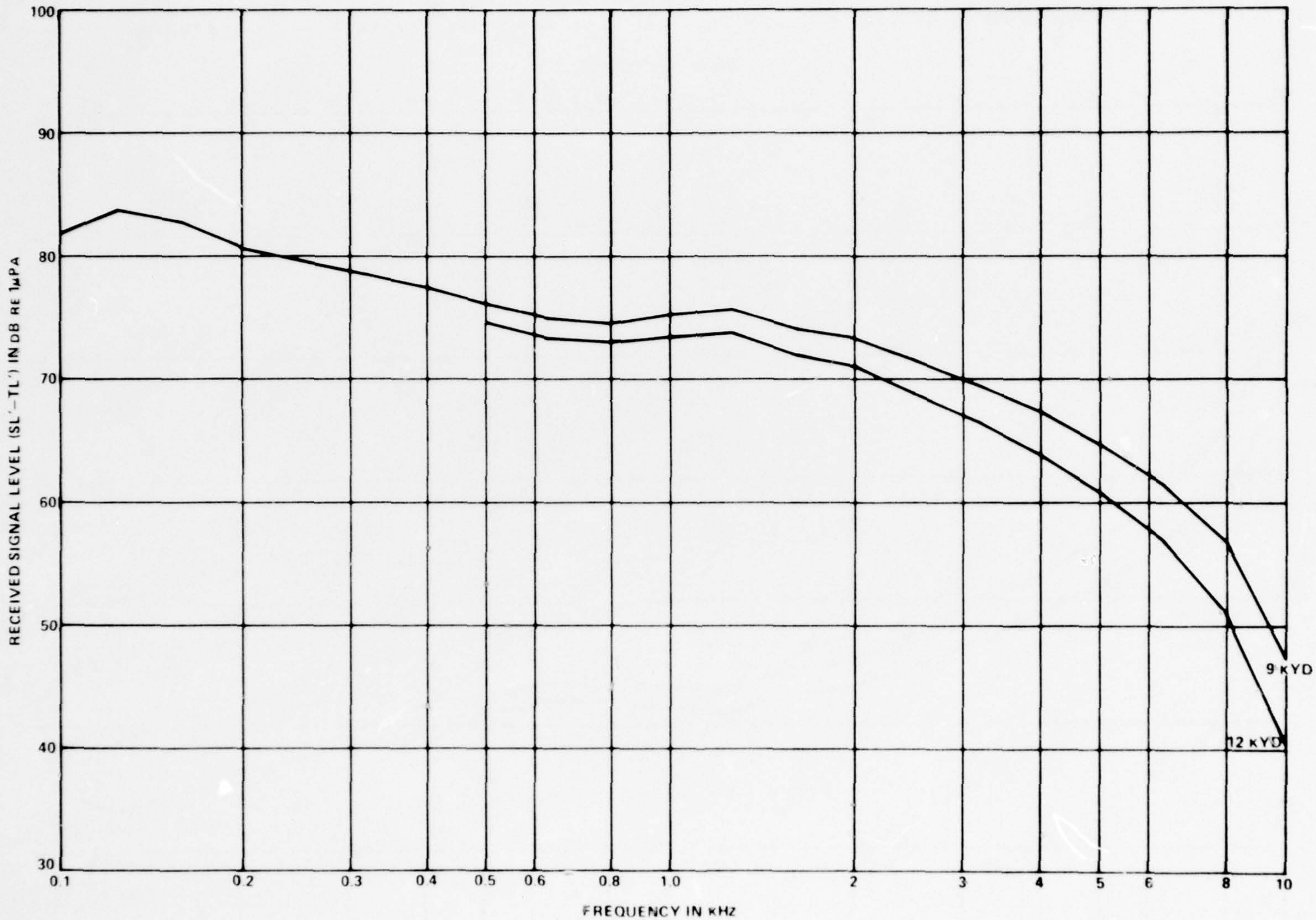

Figure 1-9 - Received Signal Levels after Transmission through Various Ranges at State 4 Sea in 1/3-Octave Bands

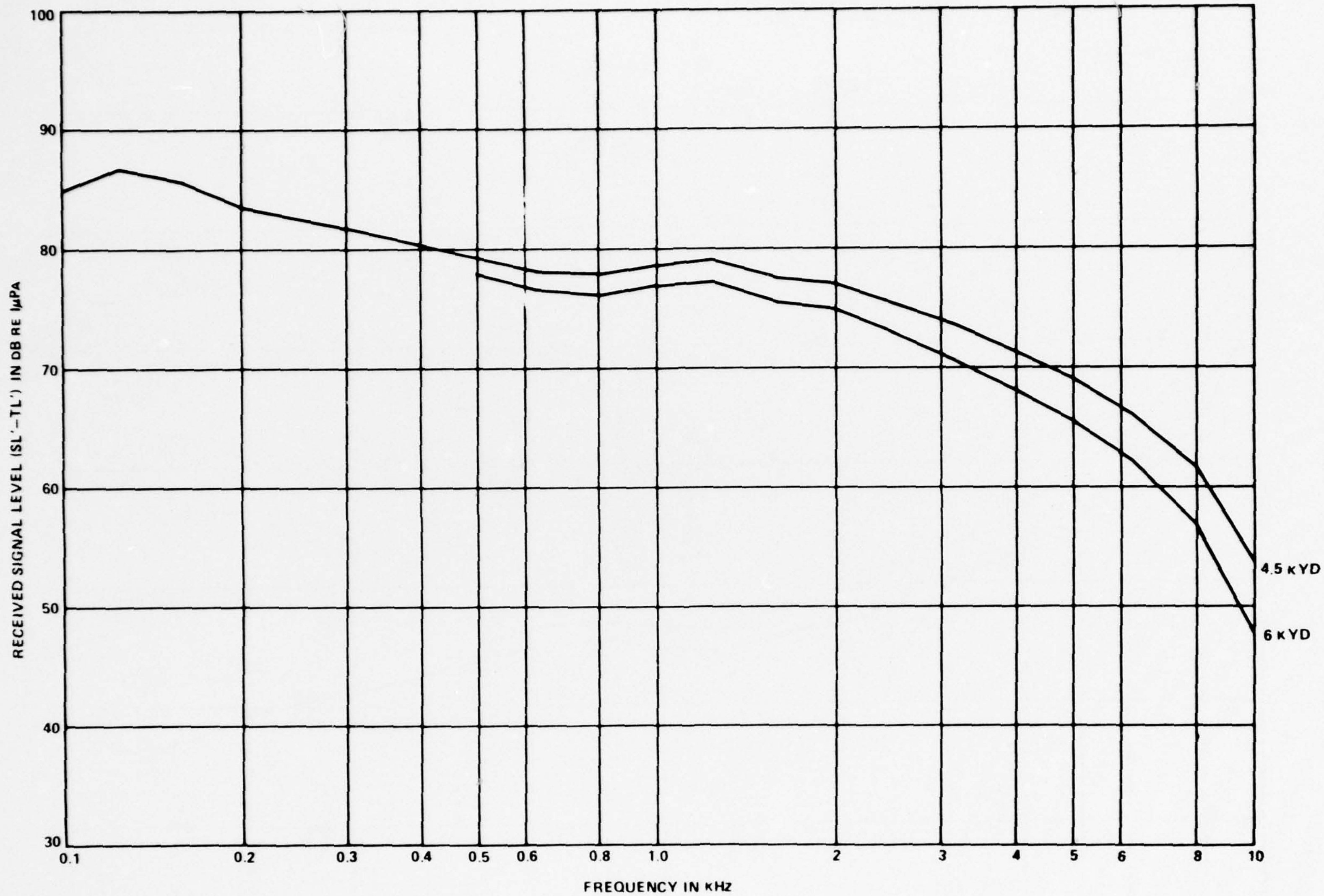

Figure 1-10 - Received Signal Levels after Transmission through Various Ranges at State 6 Sea in 1/3-Octave Bands

The procedure used to calculate a range was given previously in the section about signal-excess calculations. The procedure for one example will be given here.

The use of state of sea (n) herein can be slightly confusing. For the receiving sonar, n indicates the interfering-noise condition. For the received-signal level, n indicates the amount of duct leakage the signal has suffered.

On Figure 1-7, MDL′ for a State 1 sea has been "overlaid" on the SL′-TL′ curve, which is also for State 1 sea. The point of contact is found to be 4 kHz on the 32-kyd (29.3 km) SL′-TL′ curve. The lower and upper band limits (3-dB down rule) are found to be 1.3 and 5.8 kHz, respectively, which is a W_1 of 4.5 kHz. The geometric center f is 2.7 kHz, which is different from the contact point of 4 kHz. The correction from Equation (13) is then

$$5 \log 4.5/0.23(2.7)=4.3 \text{ dB}$$

By sliding the MDL′ curve downward 4 dB in accordance with Equation (13), the new contact point is 2 kHz on the 42-kyd (38.4-km) SL′-TL′ curve. This satisfies Equation (10). The new lower and upper band limits are 930 Hz and 5.1 kHz, respectively, which gives a W_2 of 4.2 kHz.

Since the detection bandwidth has decreased from 4.5 to 4.2 kHz, DT has increased, and TL should be corrected by 5 log (4.2/4.5)=-0.2 dB. The detection range would be decreased slightly; however, this correction is negligible. For MDL′ and SL′-TL′ for a State 0 sea, the secondary correction was not negligible. There a first approximation range of 64 kyd (58.5km) was found. A correction 5 log (W/af)=4 dB yielded a corrected detection range at 92 kyd (84.1 km). However, the detection bandwidth changed sufficiently for a second correction of 5 log (W_2/W_1) =-2 dB to yield a final detection range of 80 kyd (73.2 km).

Figure 1-11a gives the results obtained from Figure 1-4 and Figures 1-6 through 1-10 for the five signal and noise conditions. Detection

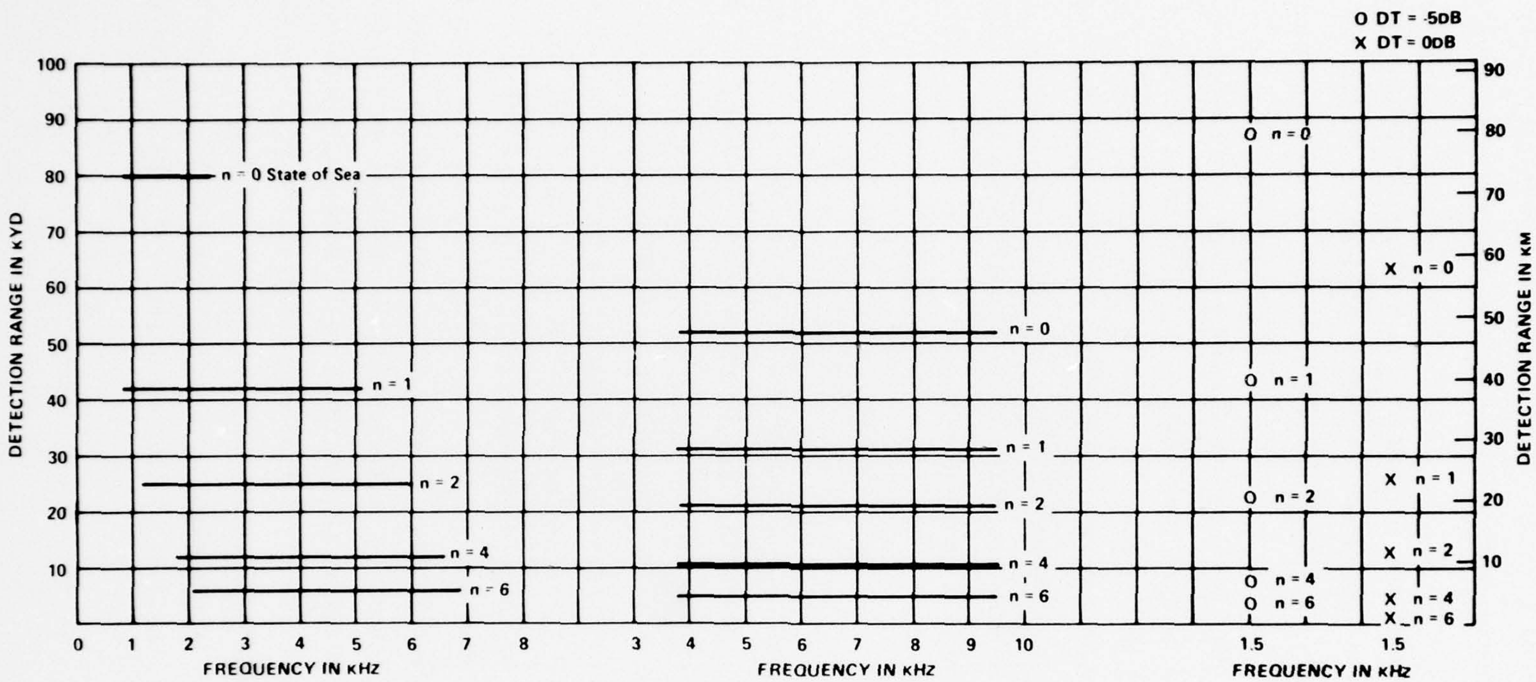

Figure 1-11a - Signal Excess Method Broadband

Figure 1-11b - Figure-of-Merit Method Broadband

Figure 1-11c - Figure-of-Merit Single-Frequency 1.5 kHz

Figure 1-11 - Results of Different Methods of Calculating Detection Ranges range is given as a function of frequency with n as a parameter. The bandwidth and frequencies of the detected signals can be compared directly on this figure.

The bandwidths of the detectable signal energies in Figure 1-11a are so wide that no single frequency is representative of either the frequency-dependent transmission loss or the other frequency-dependent terms of the sonar equation. Even for the comparatively narrow band (0.9 to 2.4 kHz) at 80 kyd (73.2 km) for a State 0 sea, a single frequency is not satisfactory. Looking at Figure 1-5, the original source level, the difference in level between 0.9 and 2.4 kHz (the band limits) is about 1 dB. Looking at Figure 1-6, the signal level after transmission through 80 kyd, the difference in level between these two frequencies is now 13 dB. Thus 12 dB of the latter difference is due to the frequency-dependent transmission loss. Actually, an "equivalent" single-frequency transmission loss for the previously described bandwidth and detection range could be selected; however, it would apply only to the specific SL, MDL, and TL as well as 80 kyd and the bandwidth from 0.9 to 2.4 kHz. Variations of the frequency-dependent terms would alter the range and bandwidth and, thus, the selected single frequency. Finally, the range and the corresponding bandwidth would have to be known before making the single-frequency--detection-range calculation, which cannot be known without either the graphical SE solution given herein or an equivalent.

At the opposite extreme, the short-range, 6-kyd detection of Figure 1-11a shows a 9-dB difference across the bandwidth (2.1 to 6.9 kHz) between SL′ and SL′-TL′ because of frequency-dependent transmission losses. The difference is obtained in the same way as described previously, using the bandwidth for n=6 on Figure 1-11a, SL′ of Figure 1-5, and SL′-TL′ of Figure 1-10. With so much difference across the detection bandwidth, it is again impossible to select an equivalent single-frequency transmission loss without prior knowledge of the bandwidth and frequencies involved.

In the first case (long range, 80 kyd) the difference in level between the end points of the comparatively narrow band (1.5 kHz) is magnified by the long range. In the second case (short range, 6 kyd) the difference is owing to the very wide bandwidth (5 kHz).

Figure 1-11a shows that as the interfering noise level and the duct leakage decrease (state of sea decreases), the detection range increases. Reduced noise levels allow the receiver to detect a lower level signal. Decreased duct leakage allows signal energy to be transmitted to greater ranges; however, Equation (18) indicates that there will always be some leakage even at a State 0 sea, and the leakage increases directly with frequency. The absorption of Equation (17) also removes high-frequency energy from the received signal. Thus, as Figure 1-11a shows, long-range detections will be made at lower frequencies and in narrower bands than will occur at short ranges.

Not considered herein are the effects of varying temperature and duct depth. Graphs made from Equation (17) indicate that as temperature increases, the absorption coefficient decreases at frequencies greater than 2 kHz. Temperature has a negligible effect on duct leakage. Equation (18) indicates that the deeper the duct depth, the less the duct leakage.

For comparison, detection ranges were calculated using the FM method of Reference 1. By overlaying the MDL's of Figure 1-4 onto the SL′ of Figure 1-5, a bandwidth of 6 kHz, having geometric center of 6 kHz, was found for all five MDL's. Then 5 log (W/af)=3 dB. The five FM values resulting were 108, 98, 93, 87, and 82 dB for noise conditions (states of sea) 0, 1, 2, 3, 4, and 6, respectively. To convert these FM values to ranges, the transmission loss was calculated at the geometric center, 6 kHz; see Figure 1-12. Entering Figure 1-12 with the five values of FM, five ranges were obtained. These are shown in Figure 1-11b.

Comparing Figure 1-11b with 1-11a, it is seen that the FM method produces smaller detection ranges than does the SE method. This bias

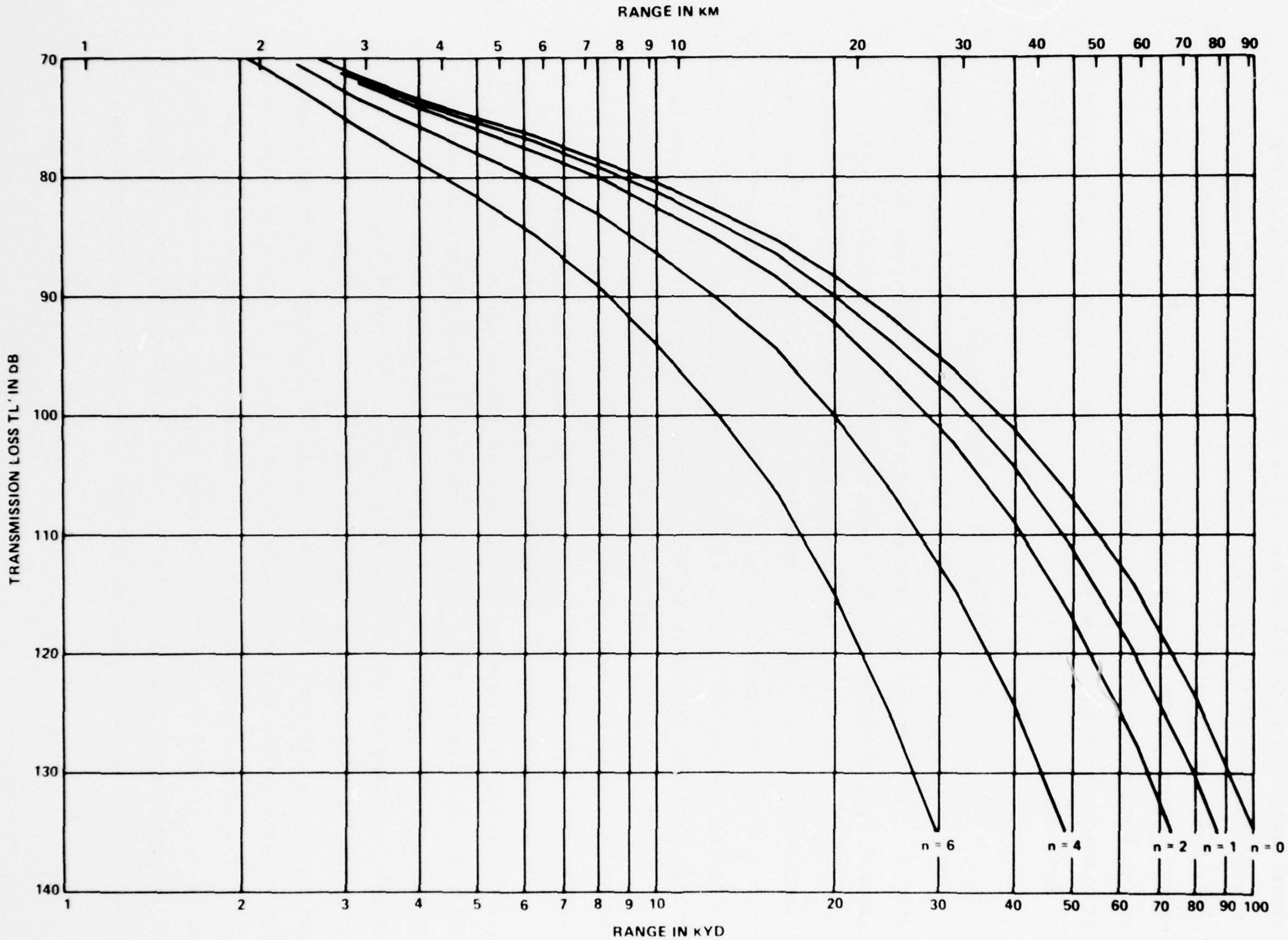

Figure 1-12 - Transmission Loss in a Duct at 6 Kilohertz for Example Given in Text toward lower ranges in the FM method is caused by restricting the frequency-dependent transmission loss to the single high frequency of 6 kHz, which was determined from the 1-yd source level; see Figure 1-5. However, owing to the frequency-dependent transmission losses, the detection band moves toward lower frequencies as range increases. The two methods converge to the same value at short range where only spreading loss applies.

DISCUSSION AND CONCLUSIONS

On one hand, the broadband FM method of Reference 1 assumes that the detection band remains the same at all ranges. Since this band is determined by overlaying an MDL′ curve on an SL′ curve (1-yd level), it will include high frequencies in most practical cases. The single frequency then chosen to represent this band in a transmission loss versus range graph will be correspondingly high. Thus calculated detection ranges are biased toward low values, since frequency-dependent losses are greatest at high frequencies. This is illustrated in Figures 1-11a and 1-11b. This method is generally valid only at short ranges in which the frequency dependent losses are low. Some modification could occur for exceptional signals and/or receivers.

On the other hand, a second method uses values of SL′ and MDL′ at a single medium frequency to calculate a figure of merit. This method is difficult to compare with the SE method, since the comparison depends on the relative spectral shapes of SL′ and MDL′, the value of DT, and the single frequency chosen for the calculation. If the SL′ and MDL′ curves are parallel with negative slopes, if circumstances permit a long range detection, if the detection band is narrow enough and can be reasonably represented by the assumed single medium frequency, then the calculated detection range could approximate the range obtained from the SE method. At lesser ranges, where higher frequencies would be detected, the medium-frequency calculation would bias the calculated ranges toward longer ranges. The actual frequency-dependent losses would be greater than for the single-medium frequency method. At longer ranges than the previously mentioned long range, the detection band would move toward lower frequencies than the fixed medium frequency so that the single-frequency method would be biased toward shorter ranges than would the SE method. If SL were more negatively sloped than MDL, these effects would be intensified.

For the example given earlier, in which SL′ (Figure 1-5) is comparatively flat, and MDL′ (Figure 1-4) slopes at approximately -8 to -9 dB/octave, the single-frequency method has been used in calculating detection ranges at an arbitrary frequency of 1.5 kHz with DT′s of 0 and -5. The results are given in Figure 1-11c. Two of the resulting ranges for DT=-5 dB are equal to or greater than the corresponding ranges calculated from the SE method. The other eight ranges are less than for the SE method. This single-frequency method can be made to agree with any individual detection range from the SE calculation by adjustment of the single frequency and/or DT.

There seems to be no systematic way to compare the single-frequency FM method with the broadband SE method. The many circumstances contained in the many different cases would have to be considered individually. Agreements between the two methods of calculating detection ranges would generally follow a random pattern.

The SE method developed herein does not have the previously described shortcomings. The detection band is allowed to vary in accordance with the combination of circumstances that influence occurrence of a detection. One possible drawback is the need for a high-speed computer for on-the-spot calculations. However, this should not be a problem much longer in view of the proliferation of high-speed minicomputers.

The SE method also provides more information about an expected detection. Not only a detection range is produced, but the band of frequencies at which detection is expected is also provided. The frequency information can be quite important because it can be used in modifying either the signal or the receiver characteristics so as to decrease or increase detection ranges.

All methods produce the same detection-range prediction at short range when only spreading loss applies, assuming that the same spreading-loss model is used in all methods and that a correct frequency is chosen for the single-frequency FM method. However, if very high frequencies are being dealt with, the frequency-dependent losses can be significant even at short range. At long range the frequency-dependent losses can be significant even at low frequencies.

The method of computing broadband aural- and counter-detection ranges developed herein is too complicated for expeditious manual calculations; however, if programed for a computer, ranges will be produced of greater accuracy and, perhaps more important, greater consistency than can be obtained by performing the usual simple manual calculations presently available in sonar rooms. Providing for this method to be an element in programing the general purpose digital computers that are incorporated in new sonar systems seems worthwhile.

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