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Ship Acoustics Department

Departmental Report

Effects of Frequency, Temporal, and Spatial Averaging on Image Interference

by

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DTRC-SAD-90/35E-1945 Effects of Frequency, Temporal, and Spatial
Averaging on Image Interference



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ABSTRACT

This report describes a significant phenomenon affecting the propagation of underwater sound at ranges less than 1000 yards: the image interference or Lloyd-mirror effect. Previous models for the effect do not adequately take into account the effects of frequency averaging and spatial averaging due to sea surface roughness and finite source size. These refinements on the basic theory are developed here. Also a clarification of the meaning of the surface reflection coefficient is given for the case of omnidirectional sources and receivers -- the situation that prevails in ship radiated-noise trials.

ADMINISTRATIVE INFORMATION

The Target Physics Branch, Code 1965, of the Ship Acoustics Department, originated and prepared this technical note for use by the David Taylor Naval Ship Research and Development Center (DTNSRDC). The funding came from several projects sponsored by the Naval Sea Systems Command (NAVSEA 55N).

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INTRODUCTION

The reflection and scattering of underwater sound from the ocean surface is a phenomenon that has been studied extensively since the time of Rayleigh (1). In fact, the approach taken by Rayleigh has been followed by many investigators up to the present time. Most of the theoretical literature deals with the Rayleigh problem: a plane wave insonifying a small area on the sea surface. Reports on experiments often deal with an approximation to this; that is, a narrow-beam transmitter and receiver aimed at a small area on the sea surface or some model of the surface.

The situation of interest in ship acoustical trials is best represented by an omnidirectional source and receiver under a moderately rough sea surface. The received signal is time-averaged for a duration that is long compared with the sea surface fluctuations. This is a limiting case that is not directly reported in the literature; however it is relatively easy to devise an adequate expression to account for this case. Only the time-averaged rms pressure is needed; there is no need for consideration of coherent and incoherent scattering, or the statistics of the time-varying surface.

This report proposes simple equations for the time-average rms received pressure from an omnidirectional source in the vicinity of the sea surface.

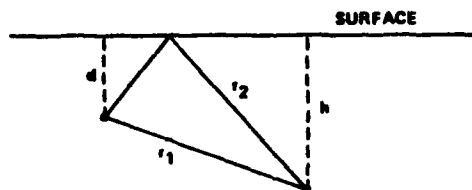


Figure 1 - Geometry of the image interference effect

At low frequencies where absorption is not significant, and neglecting refraction effects, the mean-square pressure at a receiver in the vicinity of a flat pressure-release surface can be written

$$\langle p^2 \rangle_t = \frac{P_0^2 r_0^2}{r_1^2} \left[1 + \frac{\mu^2 r_1^2}{r_2^2} - \frac{2\mu r_1}{r_2} \cos 2\pi f_0 T \right]$$

where r_1 and r_2 are ray distances as shown in Figure 1; f_0 is the signal frequency; $T = \frac{r_2 - r_1}{c}$ = the time difference in arrivals via r_1 and r_2 ; μ is the surface reflection loss coefficient (can vary from 0 to 1). (In the general case where the sound speed c is not a constant, refraction will be present, so r_1 and r_2 will not be straight lines.) For the sake of simplicity, let the reference pressure $P_0 = 1$ and $r_0 = 1$.

AVERAGE OVER A FREQUENCY BAND

It can be shown (Appendix A) that, for a band of frequencies of bandwidth B and arithmetic center frequency f_0 , the mean-square received pressure may be written as

$$\langle p^2 \rangle_t = \frac{P_0^2 r_0^2}{r_1^2} \left[1 + \frac{\mu^2 r_1^2}{r_2^2} - \frac{2\mu r_1}{r_2} \frac{\sin \pi \beta T}{\pi \beta T} \cos 2\pi f_0 T \right] \quad (2)$$

where the factor $\frac{\sin \pi \beta T}{\pi \beta T}$ may be interpreted as a dimensionless cross-correlation coefficient (with time delay T), between the sound pressures from the direct and surface-reflected paths. This equation only can apply when the sea surface is smooth enough so that the ocean wave height is small compared to acoustic wavelength, or when the surface scattering is small. If this is not the case, a more

general expression must be obtained that takes account of the sea roughness as well as bandwidth.

EFFECT OF ROUGH SEA SURFACE

The following five points constitute a heuristic argument to arrive at a more general theory for the omnidirectional transmission loss as a function of both bandwidth and sea surface roughness (wave height).

1. Most of the discussions of surface loss (2) in the literature apply to narrow-beam sources and/or receivers. Actually the value of μ referred to in this case is a partitioning factor indicating the relative amount of sound energy that is scattered out of the specular direction, that is, the ratio of specularly-reflected pressure to the total incident pressure. The justification for this interpretation of μ is that there is very little actual energy loss due to reflection of sound from the sea surface. The available mechanisms for such real dissipative surface loss are, in general:

- a) Transmission through the surface: causes a very small reflection loss of .005 dB
- b) Absorption by bubbles: also estimated at about .005 dB below 10 kHz
- c) Absorption by organisms: varies, but generally very small.

At high frequencies, (say 50 kHz) the loss due to bubbles may become significant at low grazing angles where the sound travels through an extensive thickness of bubbles. Therefore, with this exclusion, we can let $\mu = 1$ and remove it from equations 1 and 2.

2. Since ship noise measurements are almost always time-averaged measurements, it is not necessary to treat coherent and incoherent reflected sound separately, as is often done in the literature (2). Equation (2) is expressed in a convenient form such that there can be one correlation factor, g , which will com-

pletely describe the effect of the surface on reflected sound, for any degree of surface roughness.

3. Equation (2) describes a form of the image-interference effect as a function of bandwidth B which has the following properties:

a) For $B=0$, equation (2) reduces to equation 1, which is the case of image interference from a flat surface.

b) For $B \gg 2f_0$, equation (2) reduces to the limiting case of wideband noise:

$$p^2 = \frac{p_o^2 r_o^2}{r_1^2} \left[1 + \frac{r_1^2}{r_2^2} \right] = \left[\frac{1}{r_1^2} + \frac{1}{r_2^2} \right] p_o^2 r_o^2 \quad (3)$$

which is purely a function of geometry. This function is shown in Figure 2. The ordinate in this figure is plotted in terms of the increase in pressure level (in dB) due to the presence of the surface path. The 0-dB line represents the free-field transmission loss $20 \log r_1$. The abscissa is plotted in terms of the dimensionless geometry parameter $\sqrt{\frac{dh}{r_1}}$. (The levels given are strictly applicable only to the case of isovelocity water.) Notice however, that the maximum contribution from the surface path is only 3 dB. This indicates why exact theoretical derivations (such as by integrating the results for narrow-beam theory) are unnecessary and a simple definition of correlation is sufficient. Measurement precision and omnidirectionality of real transducers rarely are better than 1 dB.

4. The dimensionless surface roughness parameter commonly applied is the Rayleigh parameter

$$R = k \sigma \sin \alpha = 2\pi \frac{\sigma}{\lambda_o} \sin \alpha = \frac{2\pi f_o \sigma}{c} \sin \alpha$$

where σ is the rms wave height, α is the grazing angle of the specular ray, and

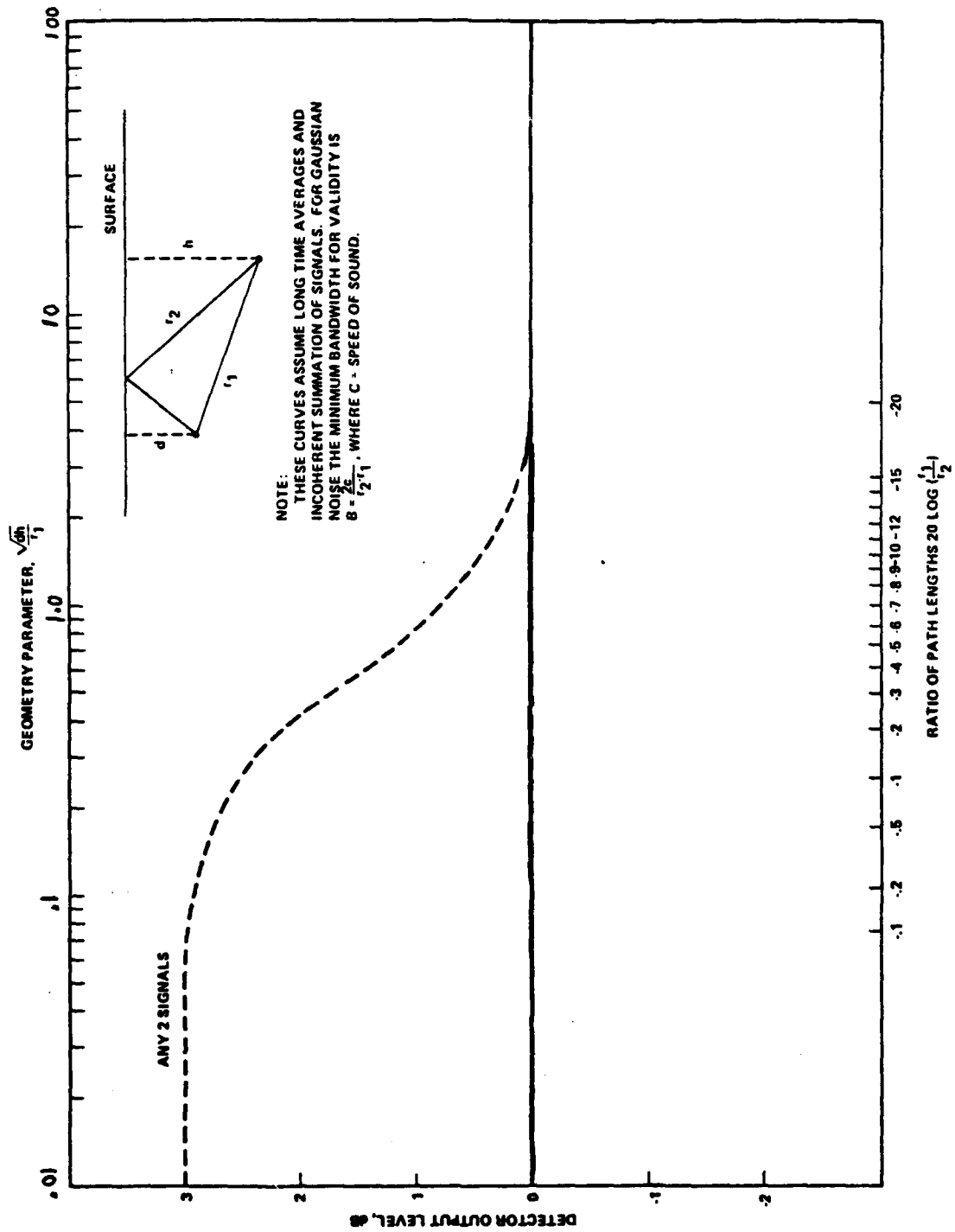


Figure 2. Increase in mean level of wideband noise signals due to surface reflected sound as a function of geometry (square-law detector assumed).

λ_0 is the wavelength of sound of frequency f_0 . In the case of scattering from a narrow beam of sound, α has a unique value. This is the case usually treated in the literature. However, in the case of an omnidirectional source, sound is scattered at all angles from a rough surface. Nevertheless, we ^{can} retain the specular-reflection value for α in the latter case. The justification for this is that α is always the angle from which most of the sound will be reflected on a time-average basis, and angles within, say, 10 percent of α will usually cover a large portion of the scattered sound pressure (3). Therefore the Rayleigh parameter will be retained with the above extension of its definition implied in the case of an omnidirectional source.

If the sea surface is flat, equation (2) applies, for any band of frequencies centered at f_0 . But if we assume a very rough surface, such that $R > 10$, it is clear that the reflected ray will be uncorrelated with respect to the direct ray, regardless of the value of B. In other words, even with $B=0$, equation (3) will apply when R is large.

5. Both B and R affect the correlation factor. It seems likely that they both affect it to the same degree, because both are dimensionless ratios of lengths, the limiting values are the same, and they are both conservative: they only affect the received phase; there is no amplitude loss. From the above considerations we infer a combined expression for the correlation factor of the form:

$$g = \frac{\sin (\pi B T + R)}{\pi B T + R} . \quad (4)$$

It is clear that the effects of B and R are additive, because when one term is small and the other large, the large one dominates. It also seems reasonable that both B and R have equal weight in determining the correlation factor, g .

Therefore a general expression for the received mean square sound pressure from an omnidirectional point source and receiver under a rough sea surface may be written

$$\langle p^2 \rangle_t = \frac{p_o^2 r_o^2}{r_1^2} \left[1 + \frac{r_1^2}{r_2^2} - \frac{2r_1}{r_2} \frac{\sin(\pi B T + R)}{\pi B T + R} \cos 2\pi f_o T \right] \quad (5)$$

AVERAGE OVER A FINITE-SIZE SOURCE

Equation (5) may be extended further to include the effect of spatial averaging in a vertical dimension caused by a source of finite size. This situation occurs, for instance, in the case of a cavitating propeller on a surface ship, where the collapsing cavitation bubble is extended in depth and radiates sound across this extended region.

In this case the depth-averaging term has a form that is identical to the Rayleigh parameter, except that the rms wave height s is replaced by the rms vertical source width d :

$$Z = \frac{2 \pi d \sin \alpha}{\lambda} = \frac{2 \pi d f_o \sin \alpha}{c}$$

This is the correlation factor for spatial averaging in the vertical dimension. Clearly this factor is additive with the other factors. Therefore, the resultant image interference equation is obtained by adding all three factors:

$$g = \frac{\sin(\pi B T + R + Z)}{\pi B T + R + Z}$$

so that the resulting image interference equation becomes

$$\langle p \rangle_t^2 = \frac{p_o^2 r_o^2}{r^2} \left[1 + \frac{r_1^2}{r_2^2} - \frac{2r_1}{r_2} \frac{\sin(\pi BT+R+Z)}{\pi BT+R+Z} \cos 2\pi f_o T \right] \quad (6)$$

This model of the image interference anomaly has been implemented in a BASIC-language program for the Hewlett-Packard 9845 computer. A listing is included in Appendix B. The program uses conventional 1/3-octave frequency bands and can accept up to 4 receiver depths in a vertical array, with two commonly-used methods of averaging the data from different receivers.

Appendix A. Derivation of Image Interference Term
for a Band of Frequencies

Equation (1) applies only to the case of a single frequency f_0 , whereas it is more usual to measure noise in a band of frequencies $B = f_2 - f_1$. In this case the third term in equation (1) must be averaged over frequency:

$$I = \frac{1}{2\pi BT} \int_{f_1}^{f_2} \cos 2\pi fT \, df.$$

Defining $f_0 = \frac{f_1+f_2}{2}$, $\theta_1 = \pi f_1 T$ and $\theta_2 = \pi f_2 T$, we obtain

$$\begin{aligned} I &= \frac{1}{2\pi BT} \left[\sin 2\pi f_2 T - \sin 2\pi f_1 T \right] \\ &= \frac{1}{2\pi T(f_2 - f_1)} \left[\sin 2\pi f_2 T - \sin 2\pi f_1 T \right] \\ &= \frac{1}{2(\theta_2 - \theta_1)} \left[\sin 2\theta_2 - \sin 2\theta_1 \right] \\ &= \frac{1}{\theta_2 - \theta_1} \left[\frac{\sin 2\theta_2}{2} - \frac{\sin 2\theta_1}{2} \right] \\ &= \frac{1}{\theta_2 - \theta_1} \left[\sin \theta_2 \cos \theta_2 - \sin \theta_1 \cos \theta_1 \right] \\ &= \frac{1}{\theta_2 - \theta_1} \left[(\cos^2 \theta_1 + \sin^2 \theta_1) \sin \theta_2 \cos \theta_2 - (\sin^2 \theta_2 + \cos^2 \theta_2) \sin \theta_1 \cos \theta_1 \right] \\ &= \frac{1}{\theta_2 - \theta_1} \left[\sin \theta_2 \cos^2 \theta_1 \cos \theta_2 - \sin^2 \theta_2 \cos \theta_1 \sin \theta_1 - \cos^2 \theta_2 \sin \theta_1 \cos \theta_2 \right. \\ &\quad \left. + \cos \theta_2 \sin^2 \theta_1 \sin \theta_2 \right] \\ &= \frac{\sin \theta_2 \cos \theta_1 - \cos \theta_2 \sin \theta_1}{\theta_2 - \theta_1} \left[\cos \theta_1 \cos \theta_2 - \sin \theta_1 \sin \theta_2 \right] \end{aligned}$$

$$= \frac{\sin (\theta_2 - \theta_1)}{\theta_2 - \theta_1} \cos (\theta_1 + \theta_2)$$

$$= \frac{\sin \pi B T}{\pi B T} \cos 2\pi f_o T.$$

```

10 | LLOYDD          LLOYD-MIRROR INTERFERENCE FOR 1/3-OCTAVE MEASUREMENTS
20 | PAUL ARVESON          REVISED JUNE 2, 1983
30 | DATA STORAGE VERSION OF LLOYDP
40 | BASED ON FORTRAN PROGRAMS BICENT (CCPAP), PSM (CCPAM), AND OTHER WORK
50 | This program generates anomaly in propagation loss due to surface
60 | image interference as well as anomalies due to hydrophone direction-
70 | ality, absorption loss, and detector type. Options are available
80 | to account for averaging due to a vertical source width
90 | and hydrophone averaging method (average of dB levels or average of
100 | powers before dB conversion).
110 | The program does not account for sometimes significant effects
120 | due to averaging over range during sample time, refractive anomalies,
130 | or bottom reflections.
140 | OPTION BASE 1
150 | PRINTER IS 16
160 | GCLEAR
170 | PRINT PAGE
180 | DIM D2(10),Freq(41),P(10),Asum(41),Dbsum(41),Db(10,41)
190 | DIM Fre(41),A(10,41),Akyds(21),X(41),Y(41),P$(6),C$(80)
200 | SHORT Xsum(34)
210 | DATA .0053,.0068,.0085,.104,.13,.164,.215,.293,.415,.604,.9,1.36,2.07
220 | DATA 3.14,4.73,7,10.1,14.1,18.8,23.9,29
230 | MAT READ Akyds
240 | RESTORE 210
250 | Fmax=34          | UPPER FREQUENCY IS 20,000 Hz
260 | Msus1$=":"
270 | Det=1
280 | PRINT "PROPAGATION ANOMALY DATA"
290 | BEEP
300 | INPUT "SQUARE LAW DETECTORS ARE ASSUMED; IF LINEAR ENTER 1",L$
310 | IF L$="1" THEN Det=PI/4
320 | BEEP
330 | INPUT "ENTER LENGTH OF HYDROPHONE ELEMENT IN INCHES",Hyl
340 | Hyd=Hyl/12
350 | BEEP
360 | INPUT "ENTER OCEAN WAVE HEIGHT IN FEET",Wh
370 | BEEP
380 | INPUT "ENTER MEAN SOURCE DEPTH IN FEET",D1
390 | BEEP
400 | INPUT "ENTER SOURCE VERTICAL WIDTH IN FEET",Dx
410 | IF D1>Dx THEN GOTO 460
420 | BEEP
430 | DISP "ERROR -- SOURCE NOT FULLY SUBMERGED"
440 | WAIT 1500
450 | GOTO 370
460 | BEEP
470 | INPUT "ENTER HORIZONTAL RANGE IN YARDS",Cpay
480 | BEEP
490 | INPUT "HOW MANY HYDROPHONES ARE AVAILABLE?",Nhyd
500 | IF Nhyd<>0 THEN GOTO 550
510 | BEEP
520 | DISP "BAD INPUT, TRY AGAIN"
530 | GOTO 480
540 | MAT D2=(0)
550 | FOR I=1 TO Nhyd
560 | BEEP
570 | INPUT "ENTER DEPTH OF HYDROPHONE IN FEET",D2(I)
580 | NEXT I
590 | | START OF COMPUTATIONS - - - - -
600 | Cpa=3*Cpay
610 | Cpaq=Cpa^2
620 | C=5000          | Sound speed in feet per second
630 | Avg1=1
640 | Avg2=0
650 | DISP "WAIT A MINUTE -- I'M THINKING"
660 | FOR I=1 TO Nhyd | - - - - - 13 - - HYDROPHONE DEPTH LOOP - - - - -

```



```

670 Sum=D1+D2(I)
680 Diff=D1-D2(I)
690 Rsq=Cpaq+Diff^2
700 Rrsq=Cpaq+Sum^2
710 R=SQR(Rsq)           | Source to hyd. distance
720 Rr=SQR(Rrsq)        | Image to hyd. distance
730 P(I)=SQR(D1+D2(I))/R | Geometry parameter for surface reflections
740 Theta1=PI/2
750 Theta2=PI/2
760 RAD
770 IF Cpa>0 THEN Theta1=ATN(Diff/Cpa) | Angle source to hyd.
780 IF Cpa>0 THEN Theta2=ATN(Sum/Cpa) | Angle image to hyd.
790 Angle(I)=ABS(Theta1+180/PI)
800 W=R/Rr
810 T=(Rr-R)/C
820 FOR F=1 TO Fmax !- - - - - FREQUENCY LOOP - - - - -
830 Freq=10*10^(.1*(F-1))
840 Fre(F)=DROUND(Freq,3)
850 E1=E2=1           | Absorption loss negligible below 1 KHz.
860 Lambda=C/Freq
870 IF F<21 THEN GOTO 910
880 Alpha=Akyds(F-20)/60000 | Divide by 3000*20 to give exp. loss per foot
890 E1=10^(-Alpha*R)       | Absorption loss factor for R
900 E2=10^(-Alpha*Rr)      | Absorption loss factor for Rr
910 Dir1=FNDirect(Theta1,Lambda,Hyd)
920 Dir2=FNDirect(Theta2,Lambda,Hyd)
930 C1=E1*Dir1
940 C2=E2*Dir2
950 Sina=Sum/R           | Sine of angle from image to hyd.
960 B=.2316*Freq         | Bandwidth in hertz
970 Z1=PI*B*T           | Bandwidth integral
980 Z2=2*PI*Dx*Sina/Lambda | Integral over source width (NEW VERSION)
990 Z3=2*PI*Hh*Sina/Lambda | Integral due to surface roughness (Rayleigh)
1000 X=Z1+Z2+Z3
1010 Corr=SIN(X)/X
1020 A(I,F)=C1^2+(W*C2)^2-2*W*C1*C2*Corr*COS(2*PI*Freq*T) | Lloyd mirror eqn.
1030 Db(I,F)=10*LGT(A(I,F)*Det)
1040 NEXT F
1050 Avg1=Avg1+Angle(I)
1060 Avg2=Avg2+Angle(I)
1070 NEXT I
1080 Avg1=Avg1^(1/Nhyd) | Average angle computed as harmonic mean
1090 Avg2=Avg2/Nhyd     | Average angle computed as ordinary mean
1100 FOR F=1 TO Fmax   | Compute hydrophone data averages two ways
1110 Asum(F)=0
1120 Dbsum(F)=0
1130 FOR I=1 TO Nhyd
1140 Asum(F)=Asum(F)+A(I,F)*Det
1150 Dbsum(F)=Dbsum(F)+Db(I,F)
1160 NEXT I
1170 Asum(F)=10*LGT(Asum(F)/Nhyd) | Asum = AVERAGE OF POWER VALUES IN DB
1180 Dbsum(F)=Dbsum(F)/Nhyd     | Dbsum = AVERAGE OF DB VALUES
1190 NEXT F
1200 DISP
1210 Plotdone=0
1220 Store: | STORE ASUM VALUES ON DISK WITH SUPPORT DATA
1230 BEEP
1240 Yesno=0
1250 INPUT "STORE COMPUTED VALUES ON DISK? (CONT=NO, 1=YES)",Yesno
1260 IF Yesno=0 THEN GOTO Print
1270 BEEP
1280 EDIT "ENTER MASS STORAGE UNIT SPECIFIER",Mausi$
1290 MASS STORAGE IS Mausi$
1300 BEEP
1310 INPUT "ENTER NEW FILE NAME",Name$
1320 SS=" " | CREATE SUPPORT DATA STRING

```

```

1330 FIXED 1
1340 H1$=VAL$(H1)
1350 Wh$=VAL$(Wh)
1360 Sd$=VAL$(D1)
1370 Su$=VAL$(Dx)
1380 Hr$=VAL$(Cpay)
1390 Hd1$=VAL$(D2(1))
1400 Hd2$=VAL$(D2(2))
1410 Hd3$=VAL$(D2(3))
1420 Hd4$=VAL$(D2(4))
1430 C$=Name$&S$&"HL="&H1$&S$&"WH="&Wh$&S$&"SD="&Sd$&S$&"SW="&Su$&S$&"HR="&Hr$
1440 C$=C$&S$&"HD="&Hd1$&S$&Hd2$&S$&Hd3$&S$&Hd4$
1450 PRINT C$
1460 FOR K=1 TO 34
1470 Xsum(K)=Asum(K)
1480 NEXT K
1490 CREATE Name$,1
1500 ASSIGN #1 TO Name$
1510 MAT PRINT #1;Xsum
1520 PRINT #1;C$
1530 ASSIGN #1 TO *
1540 PRINT "LLOYD-MIRROR DATA STORED IN FILE ";Name$
1550 Print:  ! - - - - - PRINT OUTPUT - - - - -
1560 BEEP
1570 Hc=0
1580 INPUT "PRINTED DATA FOLLOWS; WANT HARDCOPY? (1=YES)",Hc
1590 IF Hc=1 THEN PRINTER IS 0
1600 PRINT "PROPAGATION ANOMALY VERSUS HYDROPHONE DEPTH AND FREQUENCY"
1610 PRINT
1620 PRINT "FROM FILE ";Name$
1630 PRINT
1640 IF L$<>"1" THEN PRINT "SQUARE LAW DETECTORS ASSUMED"
1650 IF L$="1" THEN PRINT "LINEAR DETECTORS ASSUMED"
1660 PRINT "VERTICAL LENGTH OF HYDROPHONE ELEMENT = ";H1;" INCHES"
1670 PRINT "OCEAN WAVE HEIGHT = ";Wh;" FEET"
1680 PRINT "MEAN SOURCE DEPTH = ";D1;" FEET"
1690 PRINT "SOURCE VERTICAL WIDTH = ";Dx;" FEET"
1700 PRINT "HORIZONTAL RANGE = ";Cpay;" YARDS"
1710 PRINT LIN(3)
1720 PRINT "HYDROPHONE DEPTH (FEET) AND ANGLE (DEG.)"
1730 IMAGE 12X,4(DDDD,4X),"PWR AVG. DB AVG."
1740 PRINT USING 1730;D2(1),D2(2),D2(3),D2(4)
1750 IMAGE 13X,6(DD.D,4X)
1760 PRINT USING 1750;Angle(1),Angle(2),Angle(3),Angle(4),Avg1,Avg2
1770 PRINT "FREQUENCY"
1780 PRINT
1790 FOR F=1 TO 10
1800 IMAGE DDDDD.D,3X,6(SDD.D,3X)
1810 PRINT USING 1800;Fre(F),Db(1,F),Db(2,F),Db(3,F),Db(4,F);Asum(F);Dbsum(F)
1820 NEXT F
1830 FOR F=11 TO Fmax
1840 IMAGE 2X,DDDDDD,3X,6(SDD.D,3X)
1850 PRINT USING 1840;Fre(F),Db(1,F),Db(2,F),Db(3,F),Db(4,F);Asum(F);Dbsum(F)
1860 NEXT F
1870 IF Hc=1 THEN PRINT PAGE
1880 PRINTER IS 16
1890 Yn=0
1900 BEEP
1910 INPUT "WANT PLOT? (1=YES)",Yn
1920 IF Yn<>1 THEN GOTO Lastline
1930 Pic:  ! GENERAL DATA AND CURVE PLOTTING, CARTESIAN COORDINATES
1940 ! GRAPH SETUP DATA
1950 Ymin=-30
1960 Ymax=10
1970 Xmin=1
1980 Xmax=41
1990 Nvert=0

```

```

2000 Nhorz=40
2010 Xlabel$="FREQUENCY BAND, Hz"
2020 Ylabel$="ANOMALY, dB"
2030 Xsp=ABS(Xmax-Xmin)/Nhorz
2040 Ysp=ABS(Ymax-Ymin)/Nvert
2050 Ygap=ABS(Ymax-Ymin)*.005
2060 Plotgraph:      ! GENERAL GRAPH SETUP * * * * *
2070 PRINT PAGE
2080 PLOTTER IS "GRAPHICS"
2090 GRAPHICS
2100 FRAME
2110 SETGU
2120 LOCATE 12,118,16,93      ! Defines graph area within 100 X 123 frame
2130 SETUU
2140 SCALE Xmin,Xmax,Ymin,Ymax
2150 LINE TYPE 3
2160 GRID 10,5,1,-30
2170 LINE TYPE 1
2180 AXES 1,5,Xmin,Ymin
2190 AXES 1,5,Xmax,Ymax
2200 ! LABEL GRAPH * * * * *
2210 DEG
2220 LDIR 90
2230 LORG 8
2240 CSIZE 2.4
2250 FOR I=1 TO 41           ! Label x-axis numbers
2260 MOVE I,Ymin-Ygap
2270 LABEL Fre(I)
2280 NEXT I
2290 LDIR 0
2300 LORG 8
2310 FOR J=Ymin TO Ymax STEP Ysp      ! Label y-axis numbers
2320 MOVE Xmin,J
2330 LABEL J
2340 NEXT J
2350 SETGU
2360 CSIZE 3.3
2370 MOVE 65,2
2380 LORG 5
2390 LABEL Xlabel$          ! Label x-axis title
2400 MOVE 3,50
2410 DEG
2420 LDIR 90
2430 LORG 4
2440 LABEL Ylabel$        ! Label y-axis title
2450 LORG 1
2460 LDIR 0
2470 MOVE 110,1
2480 CSIZE 2.4
2490 LABEL "LLOYD"
2500 SETUU
2510 UNCLIP
2520 Plotdata: ! PLOTS DATA FROM UP TO 6 FILES USING 6 DIFFERENT SYMBOLS
2530 Ps(1)="+"
2540 Ps(2)="*"
2550 Ps(3)="X"
2560 Ps(4)="O"
2570 Ps(5)="@"
2580 Ps(6)="~"
2590 FOR I=1 TO Nhyd
2600 SETUU
2610 LORG 5
2620 CSIZE 2.4
2630 FOR J=1 TO Fmax
2640 X(J)=J
2650 Y(J)=Db(I,J)

```

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2660 IF Y(J)>Ymax THEN Y(J)=Ymax
2670 IF Y(J)<Ymin THEN Y(J)=Ymin
2680 IF X(J)>Xmax THEN X(J)=Xmax
2690 IF X(J)<Xmin THEN X(J)=Xmin
2700 MOVE X(J),Y(J)
2710 LABEL P*(I)
2720 NEXT J
2730 SETGU
2740 MOVE 40+10*I,98
2750 LABEL P*(I)
2760 MOVE 40+10*I,95
2770 LABEL D2(I)
2780 NEXT I
2790 Finish: !
2800 WAIT 4000
2810 BEEP
2820 Copy=0
2830 INPUT "WANT HARDCOPY? (1=YES)",Copy
2840 IF Copy=1 THEN DUMP GRAPHICS
2850 Plotdone=1
2860 PRINT PAGE
2870 Lastline: !
2880 END
2890 !
2900 DEF FNDirect(Theta,Lambda,Hyd)
2910 ! HYDROPHONE VERTICAL DIRECTIVITY FUNCTION
2920 Arg=ABS(PI*Hyd*SIN(Theta)/Lambda)
2930 Direct=1
2940 IF Arg>0 THEN Direct=SIN(Arg)/Arg
2950 RETURN Direct
2960 FNEND
2970 END

```


REFERENCES

1. Fortuin, L., "Survey of Literature on Reflection and Scattering of Sound Waves at the Sea Surface," Journal of the Acoustical Society of America, Vol. 47, pp. 1209-1228 (1970).
2. Clay, C.S. and Medwin, H., "Dependence of Spatial and Temporal Correlation of Forward-Scattered Underwater Sound of the Surface Statistics," Journal of the Acoustical Society of America, Vol. 47, pp. 1412-1429 (1970).
3. Huang, J. C., "Analysis of Acoustic Wave Scattering by a Composite Rough Surface," Journal of the Acoustical Society of America, Vol. 49, pp. 1600-1608 (1971).

Note: An extensive survey of the literature on surface scattering as it may apply to ship acoustical trials was conducted by Applied Hydro-Acoustics Research, Inc. under contract to DTNSRDC in 1974. The survey was published in a final report No. TR 116. This survey included 72 reports and various related literature on the subject. This report includes some of the findings of that survey.