ENVIRONMENTAL IMPACT ON MOBILE SONAR SHALLOW WATER OPERATIONS

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Abstract Shallow Water operations provide unique challenges for mobile sonars. In many cases propagation conditions can be optimized - our studies have shown that sound channeling can occur in approximately 75% of the strategic shallow water scenarios studied (10 geographic locations, 4 seasons) - if sensors (and targets) are at proper depths. However, at low frequencies (500 - 4000 Hz) we must consider how significant leakage will be; this can be either an asset or a liability. Even in strongly downward refracting conditions the situation can be improved by placing sensors below the thermocline. The need to lower frequency to increase detection range must be balanced against increased reverberation and noise, and ultimate system performance. The ideal optimization based on our analysis of propagation conditions for various source and receiver configurations will be compared with what is practical.

1. Introduction

We are all aware of the increased interest in shallow water and that sound propagation conditions in shallow water can be "different" than in deep water. This paper presents results from a recent investigation of shallow water propagation loss for low frequencies (500-4000 Hz). Shallow water is defined in this context as a location where acoustic energy has numerous boundary interactions. This definition leads to both physically shallow and not-so-shallow sites. The objectives of this investigation are: first, to gain a quantitative understanding of propagation loss as a function of source/receiver placement and frequency for numerous shallow water environments, in this case, for 10 geographic areas across all four seasons; second, to gain quantitative information of surface duct versus downward refracting propagation by using a statistical approach; and third, to address questions concerning frequencies which are supported in ducting propagation, effects of duct transmission loss in shallow water, and the impact of source/receiver placement in shallow water.

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2. Survey

To get an understanding of the general propagation conditions that might be encountered in shallow water we chose to do an analysis of 10 typical geographic locations for each of the four seasons, a total of 40 scenarios. These locations are shown in Figure 1. They are: 1. Strait of Juan de Fuca, 2. King's Bay, 3. Montevideo (Southern Hemisphere), 4. Norwegian Sea, 5. North Sea, 6. Strait of Sicily, 7. Gulf of Sidra, 8. Sinai, 9. East Yellow Sea, 10. Korean Strait. Water depths for these locations range from approximately 300 to 2000 feet. Propagation conditions range from completely upward to completely downward refracting. Wind speeds generally range from sea state 1 to sea state 4. Bottom properties range from hard, low bottom loss, generally good reflectors, to soft, high bottom loss, good attenuators. As can be seen, this is a broad spectrum of environmental parameters over which to attempt to understand propagation. Welcome to shallow water acoustics for which, as R. J. Urick (1979) noted, the hallmark is variability.

The most challenging part of the survey was to determine what parameters (Figure 2) to use for the modeling analysis. We wanted to cover a broad frequency range (500-4000 Hz) which, of course, had a significant impact on what could be used for environmental inputs, particularly bottom loss.

For this shallow water modeling investigation, the Generic Sonar Model is used with Multipath Expansion, which is a wave theoretical model, as the eigenray submodel. In this model, surface and bottom interaction are treated as a loss per bounce with no sub-bottom penetration. The surface loss submodel was Bechmann-Spezzichino, which has both frequency and grazing angle dependence. Sea states 1 and 4 were modeled. Bottom loss was modeled as hard (low loss) and soft (high loss), using a recently developed bottom loss model by Bell (1990) called Wideband ABLE. This model was used because of its frequency and grazing angle dependence and the two regimes of bottom loss it has -- hard and soft. Even though this is a shallow water investigation, very little information on shallow water bottom loss was available in a comprehensive format across the band of interest: 500 - 4000 Hz. Therefore, a deep water bottom loss model was selected for this initial investigation. Propagation loss runs were done for source and receiver depths: 25 feet, 60 feet, and a deep depth determined by the sound speed profile. Source and receiver are all modeled as omnidirectional. Volume attenuation (i.e., seawater absorption) was also taken into account, using the Thorp model.

We also wanted to bracket the realistic environmental conditions that may be encountered without examining an infinite number of cases. Therefore, this paper will have two objectives:

a. To present the results of a shallow water propagation loss analysis and the implications for mobile sonars; and

b. To discuss the assumptions, compromises, and choices we made in modeling propagation in the shallow water environment.

3. Analysis

A summary of the 40 sound speed profiles used in this investigation are given in figure 3. Figure 3 shows the 10 geographic areas and the dominant sound speed profile for each of the four seasons: winter (February), spring (May), summer (August), and fall (November). The three attributes shown are surface ducting (D), near surface sound channel (C), and downward refracting (Down Ref). The depths of the surface duct and axis of the near surface sound channel are shown. The surface duct layer ranges from 40 to more than 400 feet in this matrix of 40 environmental conditions. It should also be noted that these percentages apply to this total combination of 10 locations and four seasons. As is clearly evident, there are individual locations that have different percentages. An example of this is Montevideo, which has downward refracting conditions for three of the four seasons. Surprisingly, considering the great interest in strongly downward refracting conditions in shallow water, approximately 75% of the profiles have some form of channeling. (We use channeling as the most general term with a duct being a subset - a surface duct therefore can be considered a half-channel). This leads to the observation that bottom characteristics and bottom loss are important for modeling shallow water propagation as well as sea surface characteristics and surface loss.

The channels prove to be both a blessing and a curse. On one hand, if the source (assuming a frequency above the cut-off frequency of the channel) and receiver are both in the duct we would have good propagation conditions, however, if the source doesn't cooperate, propagation in and out of ducts can be complicated.

Since we mentioned the cut-off frequency it would be worthwhile to recall the frequency dependence of duct trapping and/or leakage as shown by Urick and others. A typical relationship is shown in Figure 4. In the high frequency limit, the surface duct can be viewed as a waveguide trapping energy within it, so that the only loss variables are cylindrical spreading, sea water absorption, and surface loss. However, as frequency decreases, acoustic wavelength increases, and the duct is no longer able to contain all the originally trapped energy, that is, energy leaks out of the duct as range from the source increases, and propagation loss versus range will fall off more rapidly for this "leaky waveguide" condition. A simple mathematical expression relating surface duct thickness to the maximum wavelength trapped in the duct by Urick (1975) is shown in Figure 4 along with the corresponding cutoff frequency. The functional relationship is that the maximum trapped wavelength is directly proportional to the duct thickness to the 1.5 power. Superimposed on this curve is the range of shallow water duct thickness for this investigation, which is based on the previous figure. For the range of surface ducts present, frequencies as low as 100 Hz can be expected to be trapped in the duct.

Initially we see that, as expected, we encounter considerable variability in shallow water. The key question is what assumptions do we make to model it?

4. Environmental choices.

These assumptions are divided into two categories we refer to as "easy" and "hard":

A. Easy Choices
For the frequency range of interest (500-4000 Hz), we felt that the generic sonar model multipath expansion was a reasonable choice, as well as Thorp attenuation and Bechmann-Spezzichino surface loss.

B. Hard Choices
Two inputs required difficult and somewhat arbitrary decisions. First was the selection of source and receiver depths. We chose realistic depths of 25 and 60 feet and a third "deep" depth below the thermocline which varied for each sound speed profile and location. The second input was the most difficult: which bottom loss to use. Since our lowest frequency was 500 Hz, there might not be a great frequency dependence over our range. Ideally we would have liked to have measured bottom loss data for all frequencies and locations, but a search for such data proved entirely frustrating.

We finally settled for a recent analysis of the extensive deep water data base by Bell (1990), which resulted in the frequency dependent "ABLE" bottom loss curves for two bottom types: "hard" and "soft" (Figure 5).

We found that these curves gave results in agreement with other bottom loss curves in most cases. In a few cases, however, there was a significant difference. We were concerned that this might be due to low grazing angles. The "ABLE" curves had to be extrapolated to low angles because, in practice, no low angle deep water results were in the data base. A simple extrapolation of the trend at higher angles would not show a sharp change at the critical angle (Figure 6) as Urick suggests. An analysis of the limiting grazing angles at the bottom for our locations did indicate that we have to consider some cases with low angles (Figure 7) and that these were the ones causing trouble. Therefore, a linear extrapolation from the critical angle loss shown in Figure 6 value to 0 dB loss at 0 degrees was used. We chose, therefore, to modify the "ABLE" bottom loss curves (Figure 8) by linearly extrapolating from the value at 10 degrees down to zero at 0 degrees. This has resulted in a reasonable agreement in all comparisons of modeled propagation loss so far.

5. Results

Shown in Figure 9 is the winter profile from the strait of Juan de Fuca, which is illustrative of shallow water ducting, with an 80 foot surface duct, which would correspond to a cut-off frequency of approximately 1500 Hz. In Figure 9 you can see one-way transmission loss results for two frequencies (500 Hz - top figure, 3000 Hz - bottom figure) with the source at 25 feet and the receiver at 60 feet. Comparisons are made between "hard' and "soft" bottom loss and surface loss for sea states (SS) 1 and 4. At 500 Hz, for this configuration, there is very little dependence on either sea state or bottom type. At 3000 Hz, there is a strong dependence on sea state. As a reference point, the dashed line represents a transmission loss value of 120 dB. These figures clearly show the effect of acoustic energy trapping and leakage in a duct.

For the same location we present (Figure 10) a comparison (dashed - 500 Hz, solid - 3000 Hz) for various source and receiver configurations. One-way transmission loss vs. range for Juan de Fuca - winter, SS1 and low bottom loss (hard bottom) are shown here for various source-to-receiver configurations. Source-receiver configurations are shallow source - shallow receiver indicated by the number 1; shallow source - deep receiver, 2; and deep source - deep receiver, 3. Shallow source depth corresponds to 25 ft, deep depth, 350 feet. Receiver shallow depth is 60 feet and deep depth is 275 feet. Numbers 1, 2 and 3 correspond to in-, cross- and below-layer, respectively. Upon examining the 3000 Hz propagation loss curves, it is evident that the source/receiver in-layer case, number 1, has substantially less loss than the cross- and below-layer cases. By comparison, at 500 Hz, the optimal propagation is with source and receiver, both deep below the duct. Also, at 500 Hz, the case of source and receiver, both in the duct, exhibits more loss than the 3000 Hz case. Therefore, for a source and receiver located within this duct, it appears that higher frequencies can experience less transmission loss than lower frequencies when a surface duct is present (the upper boundary is highly reflective) and energy trapping occurs. Previous work by Jensen and Kuperman (1983) bounded transmission loss optimum frequency variability due to source/receiver configuration by placing both source and receiver in the middle of the water column. Our study investigates the sensitivity of optimum frequency to varying source/receiver configurations, particularly for the case of ducted propagation. Consequently, the optimum frequency could be much higher, particularly when both source and receiver are in the duct. This demonstrates the impact of both the surface duct and deeper channel. For example, the higher frequency does well in the surface duct but relatively poorly in a cross-duct configuration. Conversely the lower frequency does relatively well in a cross-duct situation but poorer in the surface duct.

A similar comparison can be made for downward refracting conditions in the Gulf of Sidra (Figure 11). For the same configuration as shown previously (source at 25 feet, receiver at 60 feet) there is little sensitivity to either bottom type or sea state. At 500 Hz, propagation loss appears to have a dependence on bottom type, not sea state, with the hard bottom SS1 and SS4 curves exhibiting about 3 dB less loss than the SS1 and SS4 soft bottom cases. At 3000 Hz, all four cases are tightly grouped. Clearly, for downward-refraction-dominated propagation, the lower the frequency, the better the propagation, as shown here, because bottom loss and volume attenuation are both decreasing as frequency decreases.

By comparison to Figure 10, Figure 12 has the same quantities plotted, but for the Gulf of Sidra summer downward-refracting conditions. Here 500 Hz has less transmission loss than 3000 Hz for all cases of source/receiver placement. Also, the optimum placement for minimizing transmission loss at source and receiver is deep (3) at both frequencies. Therefore, when there is no duct, the entire water column is the channel, and as frequency decreases, so does bottom loss, so transmission loss gets better as frequency decreases.

6. Active Sonar System Impact

With forty different environmental situations (10 geographic locations, 4 seasons) what would be the composite result? Perhaps surprisingly, the result is quite orderly. We can summarize our results by the following cumulative diagrams. For mobile active sonar systems, one of the fundamental drivers is two-way propagation loss. Once again, since in shallow water environmental variability is the norm, a statistical approach was taken. Figures 13 - 16 illustrate cumulative two-way propagation loss vs. percent occurrence across 80 different acoustic environments (10 geographic locations, 4 seasons, 2 windspeeds, and 1 average bottom loss) for a shallow target (60 ft) and a deep target depth at various source and receiver combinations, and a range of 10 nmi. Figure 13 clearly shows that at 500 Hz against a shallow target the optimum placement to minimize propagation loss is with source and receiver both shallow (Ss/Rs) and the source and receiver both deep (Sd/Rd) would have approximately 10 dB more loss. Also, if we assume an active sonar system performance could withstand 200 dB of propagation loss, then 90% of the environments would be covered. In Figure 14 the same scenario is present, but now the target depth is deep. Here the optimum source/receiver placement is both deep (Sd/Rd) and has 25 dB less loss than the shallow source/receiver (Ss/Rs), which was optimum against the shallow target. Here, approximately 85% of the environments would be covered.

Figures 15 and 16 are the 3000 Hz cases of Figures 13 and 14, respectively. The source/receiver placement is the same, as is the propagation loss difference between the optimum and worst case. The fundamental difference between 500 and 3000 Hz is the percentage of the environments which would be covered: 85-90% at 500 Hz vice 40-50% at 3000 Hz.

For a deep target the advantage of both source and receiver deep is shown. It is advantageous to have everything on the same side of the thermocline.

7. Conclusions.

The conclusions for this shallow water propagation loss investigation are listed below.

- Downward refraction occurs in 25% of the environments examined in this shallow water study
  - Downward refracting cases follow expected monotonic dependence associated with bottom interaction and attenuation
- 75% of the environments in this study have some form of acoustic duct or near surface sound channel
  - Ducted propagation makes source/receiver depth configuration more critical and allows duct leakage and/or surface loss to become additional significant factors
- Cutoff frequencies for ducted propagation introduce a significant frequency dependent component to source/receiver optimization to minimize transmission loss
- Deep target detection is critical in shallow water, and will be difficult in some environments
- Modeling of 1-way and 2-way transmission loss for 80 environments [10 locations X 4 seasons X 2 windspeeds] shows that better approaches to deep target detection incorporate either: a) deep receiver adjunct to current hull mounted systems, or b) deep source and deep receiver
- Through knowledge of the environment it is possible to minimize propagation loss by source/receiver configuration in shallow water

References

[1] Bell, T. G., 18 October 1990: "Wideband ABLE: A total energy Bottom Loss model for Frequencies from 50 to 3400 Hertz". Memo BL0-0501-003, Sonalysts, Inc., Waterford, Connecticut.

[2] Jensen, F. B. and W. A. Kuperman, JASA 73(3), 813-819, 1983

[3] Urick, Robert J., "Sound Propagation in the Sea," DARPA, Washington, DC, 1979.

[4] Urick, R. J., "Principles of Underwater Sound", 2nd ed., 1975, p. 139

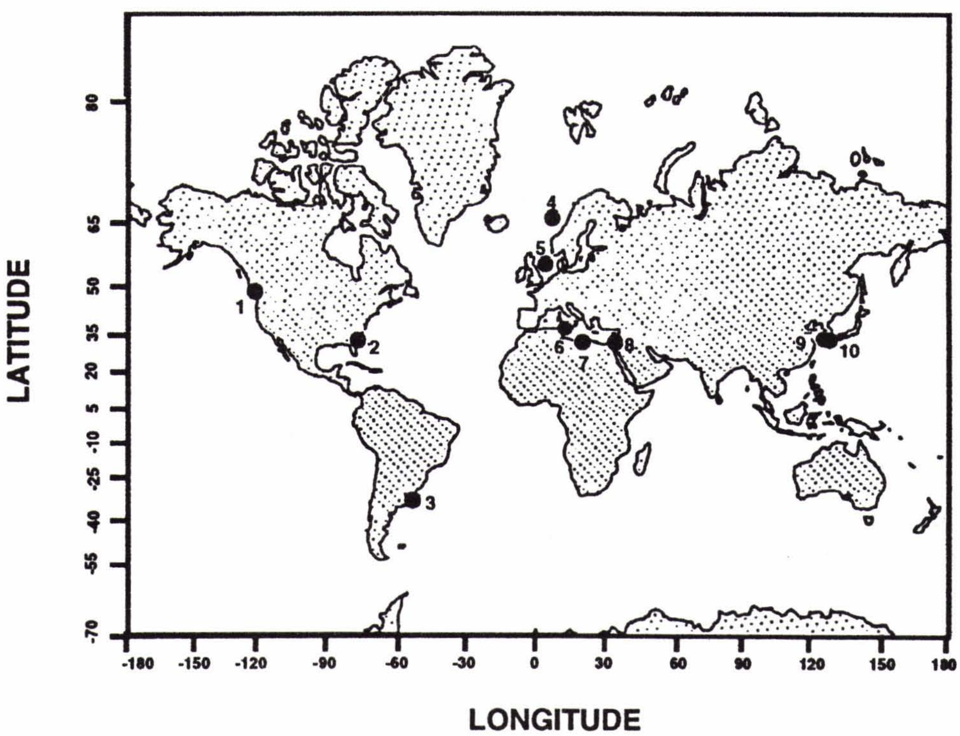

Figure 1. Shallow water geographic locations for propagation loss modeling investigations

- **MODEL: GENERIC SONAR MODEL**
- **EIGENRAY SUB-MODEL**
  -MULTIPATH EXPANSION
- **SURFACE LOSS**
  -SEA STATES 1 AND 4
  -BECHMANN-SPEZZICHINO SUB-MODEL
- **BOTTOM LOSS**
  -HARD (SAND) AND SOFT (MUD)
  -WIDEBAND ABLE BOTTOM LOSS SUB-MODEL
- **VOLUME ATTENUATION**
  -THORP
- **SOUND SPEED PROFILES**
  -10 LOCATIONS
  -4 SEASONS
- **SOURCE AND RECEIVER**
  -DEPTH:25 FT, 60 FT AND DEEP
  -OMNIDIRECTIONAL
- **FREQUENCY (Hz)**
  -500, 750, 1000, 1500, 2000, 3000, 4000

Figure 2. Propagation Loss Modeling Parameters.

LOCATION	SOUND SPEED PROFILE CHARACTER				WATER DEPTH (ft)
	WINTER [FEB]	SPRING [MAY]	SUMMER [AUG]	FALL [NOV]	
E. YELLOW SEA	D400	C250	D35 , C150	D165	400
GULF OF SIDRA	D255	DOWN REF	DOWN REF	D75	500
NORWEGIAN SEA	D850	D350	D75	D300	2000
KINGS BAY	D90	D40	DOWN REF	D90	1250
NORTH SEA	D300	D80 , C150	C175	D175 , C250	300
STRAITS OF SICILY	D600 /2000	C350	C450	D100 , C350	2000
*MONTEVIDEO	DOWN REF	D100	DOWN REF	DOWN REF	300
SINAI	D400 /660	DOWN REF	DOWN REF	D125	660
KOREAN STRAITS	D250	D80	D65	D165	500
JUAN DE FUCA	D80	DOWN REF	DOWN REF	D55	600

Dn - Surface Duct, n ft thick
Cn - Sound Channel (Sound Velocity minimum) at n ft
DOWN REF - Downward Refracting Conditions over the entire water column

* Southern Hemisphere, therefore Seasons are reversed

Figure 3. Shallow water sound speed profile attributes.

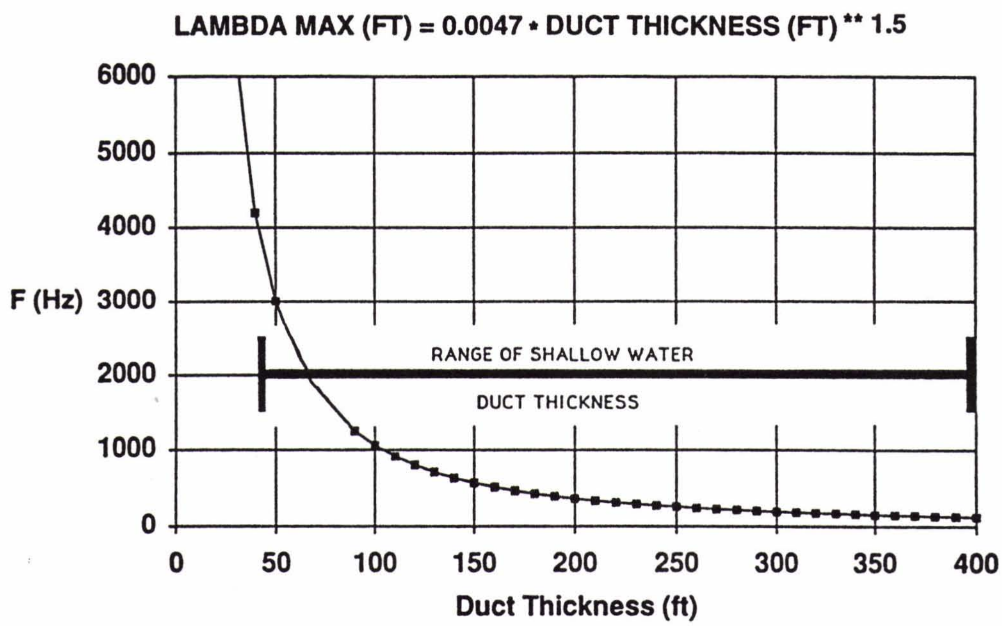

Figure 4. Cut-off frequency for surface duct energy trapping.

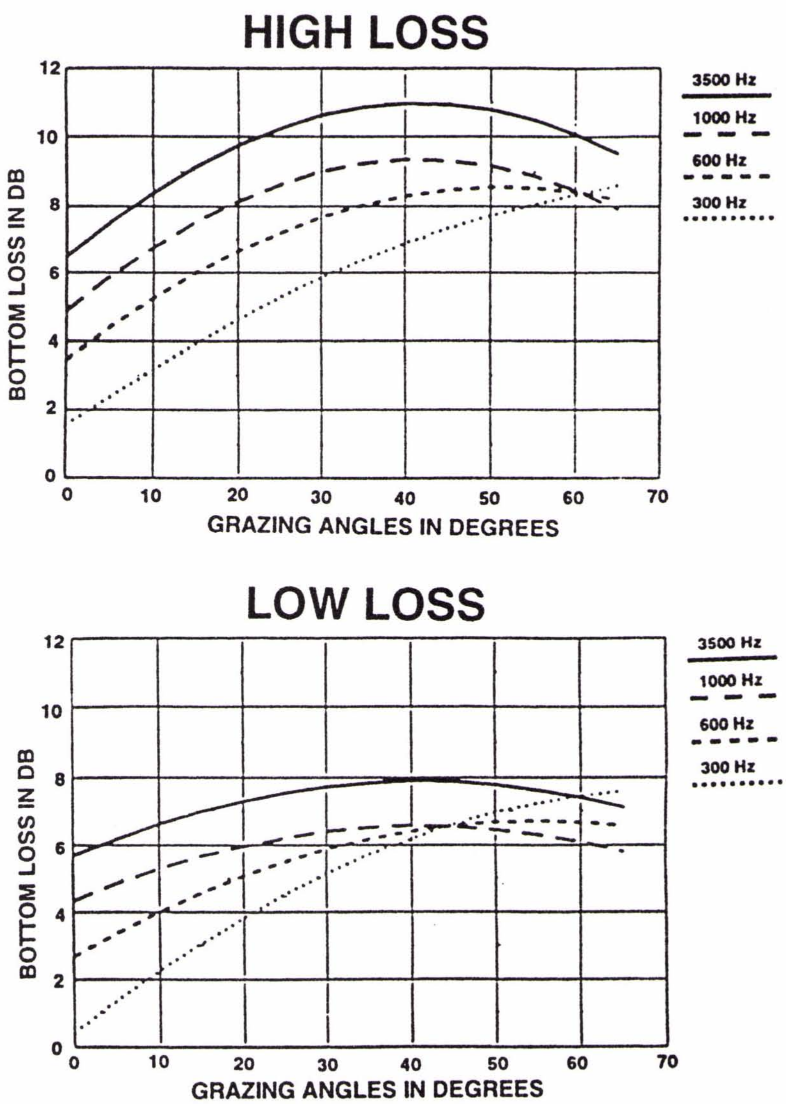

Figure 5. Wideband ABLE Bottom Loss curves.

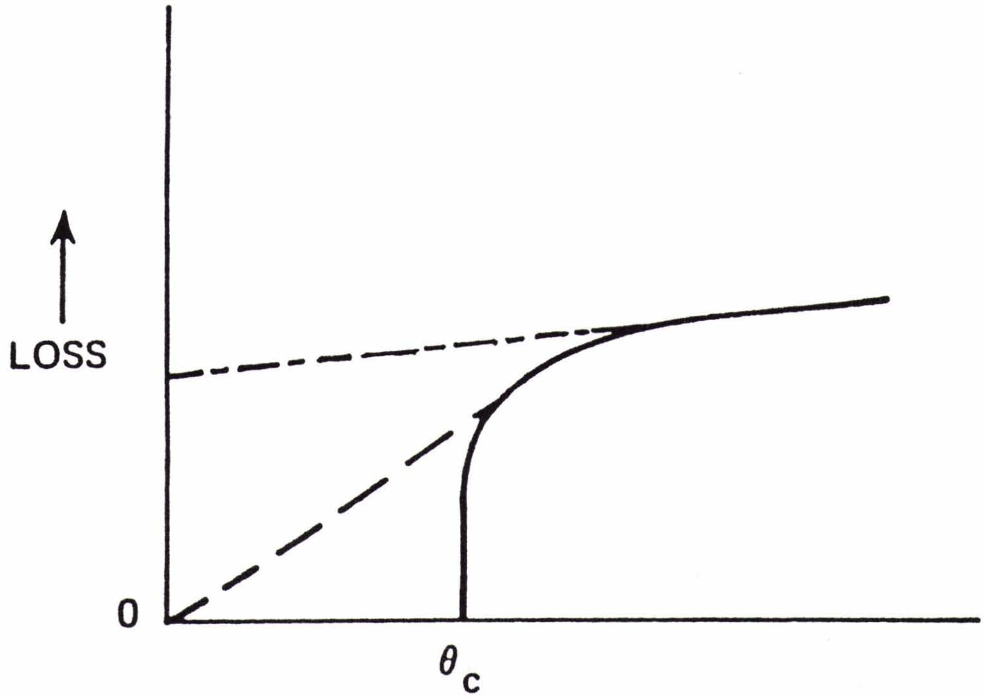

Figure 6. Bottom Loss versus Grazing Angle.

SUMMER PROFILES - DOWNWARD REFRACTING
RECEIVER ON BOTTOM
RANGE = 20 NMI

LOCATION	SOURCE = 25 FT	SOURCE = "DEEP"
GULF OF SIDRA	10 - 11°	1 - 2°
KOREA STRAIT	11°	4 - 10°
STRAIT OF SICILY	9 - 11°	0 - 4°
JUAN DE FUCA	9°	0 - 3°
MONTEVIDEO (FEB)	13°	1 - 2°
NORWEGIAN SEA	11 - 12°	9 - 12°
EAST YELLOW SEA	11°	0 - 1°
KINGS BAY	15°	7 - 8°
NORTH SEA	11 - 12°	0 - 1°
SINAI	11 - 12°	2 - 3°

Figure 7. Bottom grazing angle versus source depth.

MODIFIED WIDEBAND ABLE LOW LOSS [HARD] BOTTOM LOSS MODEL

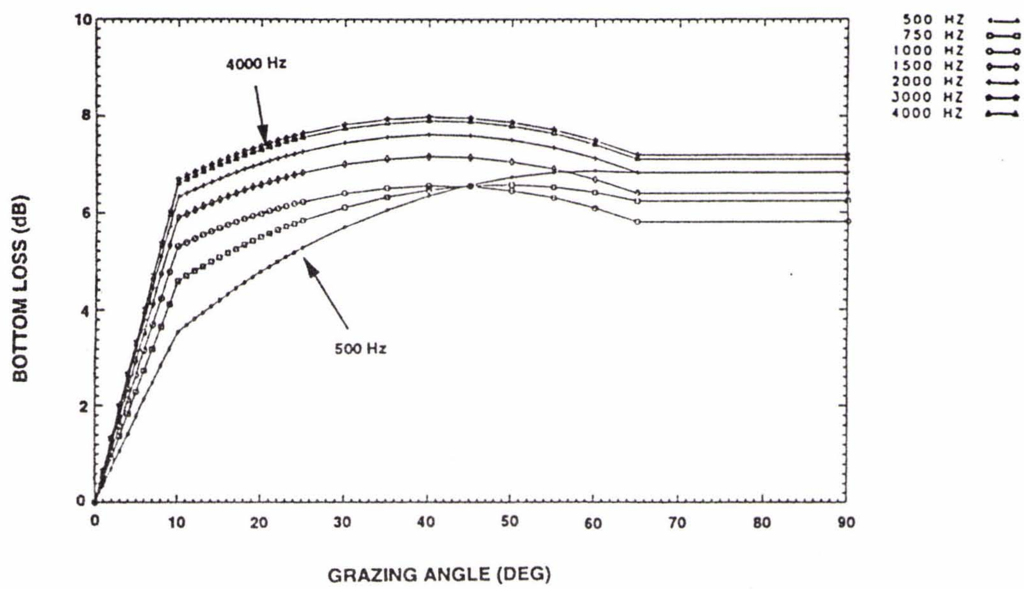

Figure 8. Bottom Loss versus grazing angle

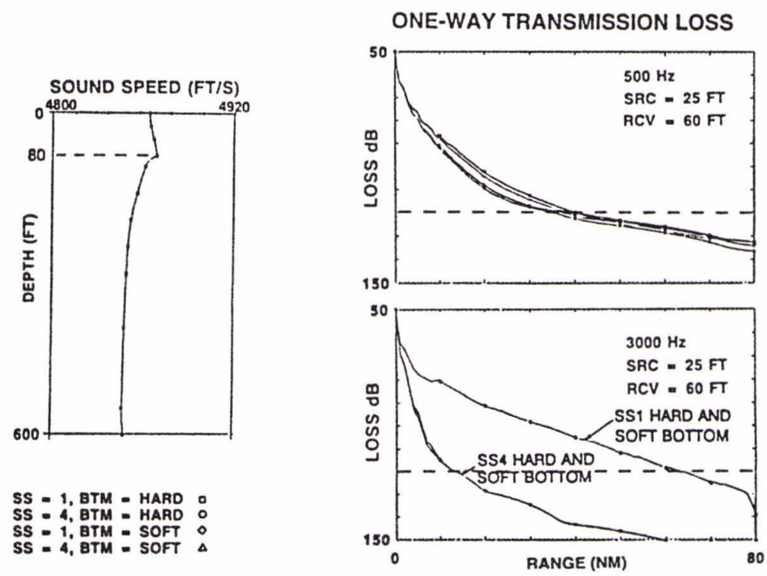

Figure 9. Strait of Juan de Fuca Winter SVP and 1-way propagation loss

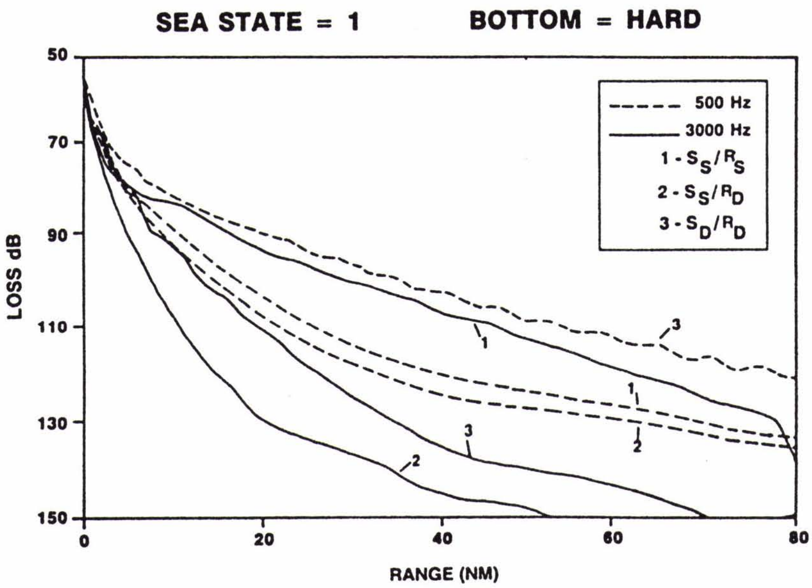

Figure 10. Strait of Juan de Fuca propagation loss versus frequency versus source/receiver placement

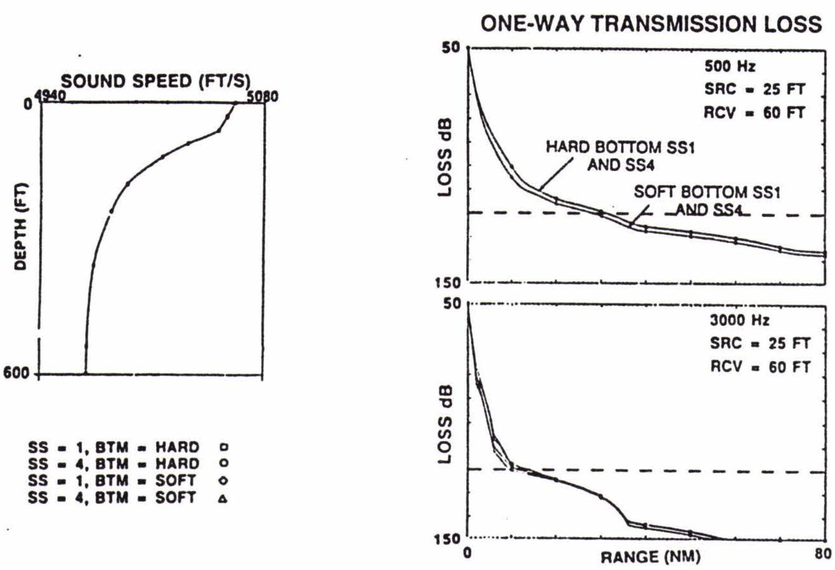

Figure 11. Gulf of Sidra Summer SVP and 1-way propagation loss.

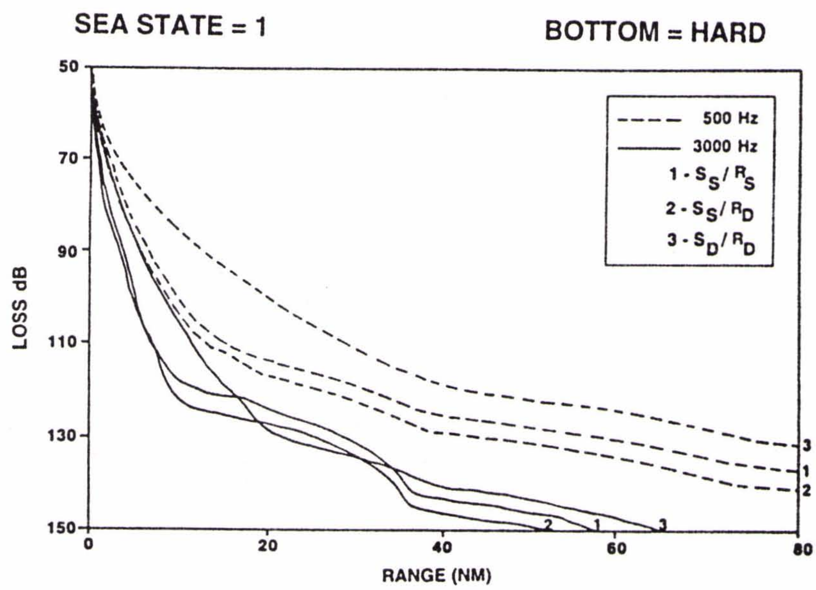

Figure 12. Gulf of Sidra propagation loss versus frequency versus source/receiver placement.

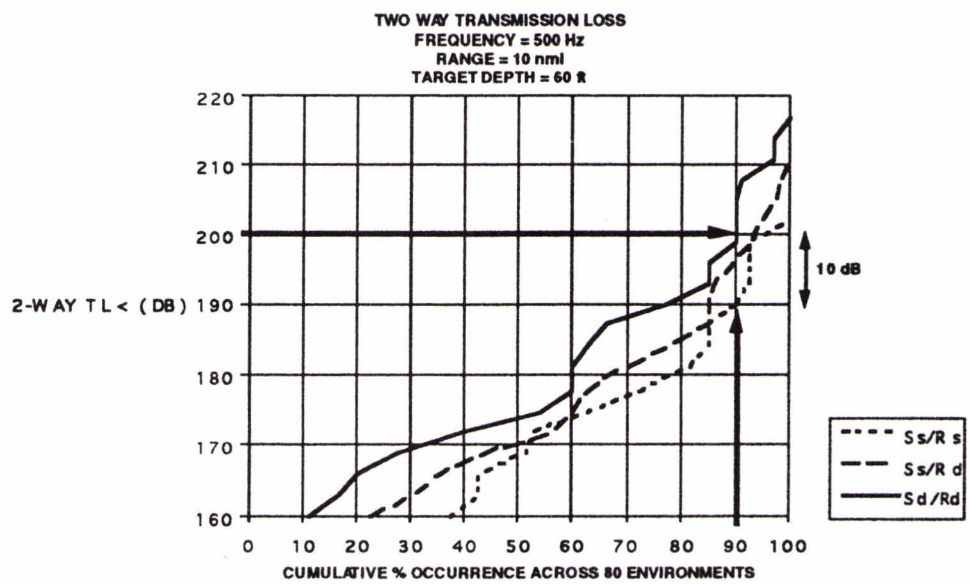

Figure 13. 2-way transmission loss cumulative percent occurence versus source/receiver placement; shallow target, 500 Hz.

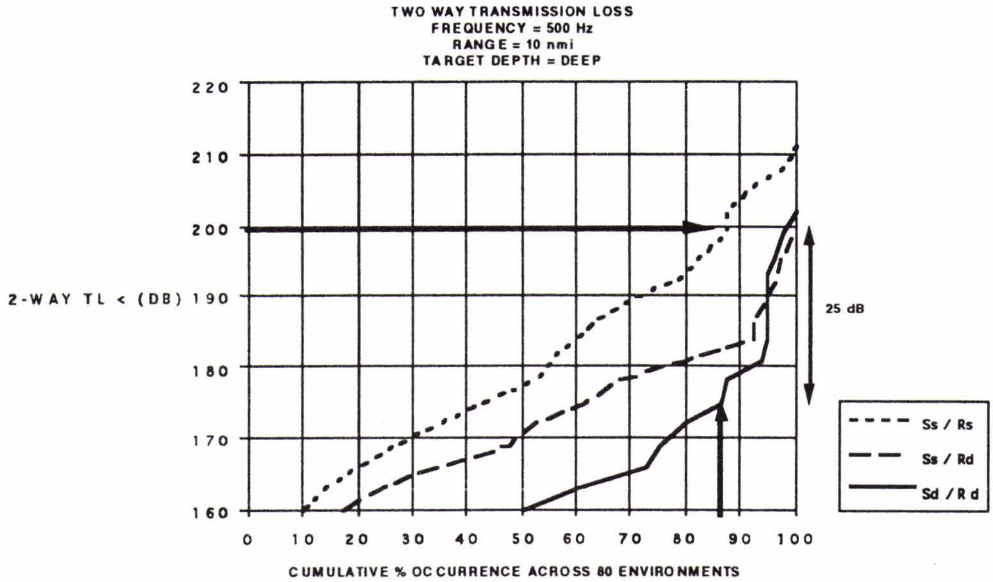

Figure 14 2-way transmission loss cumulative percent occurence versus source/receiver placement; deep target, 500 Hz.

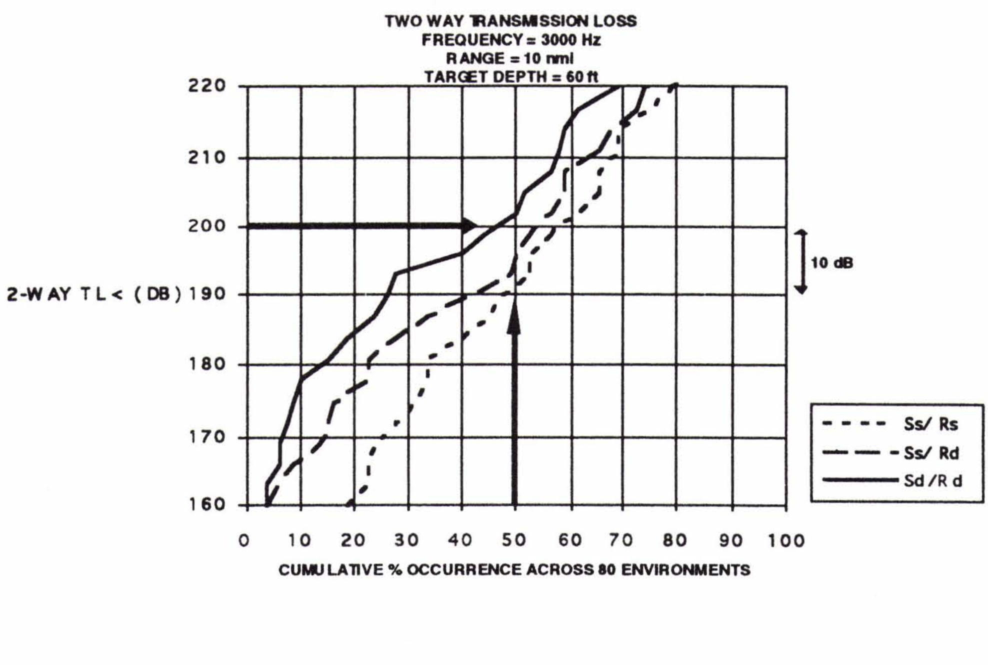

Figure 15 2-way transmission loss cumulative percent occurence versus source/receiver placement; shallow target, 3000 Hz.

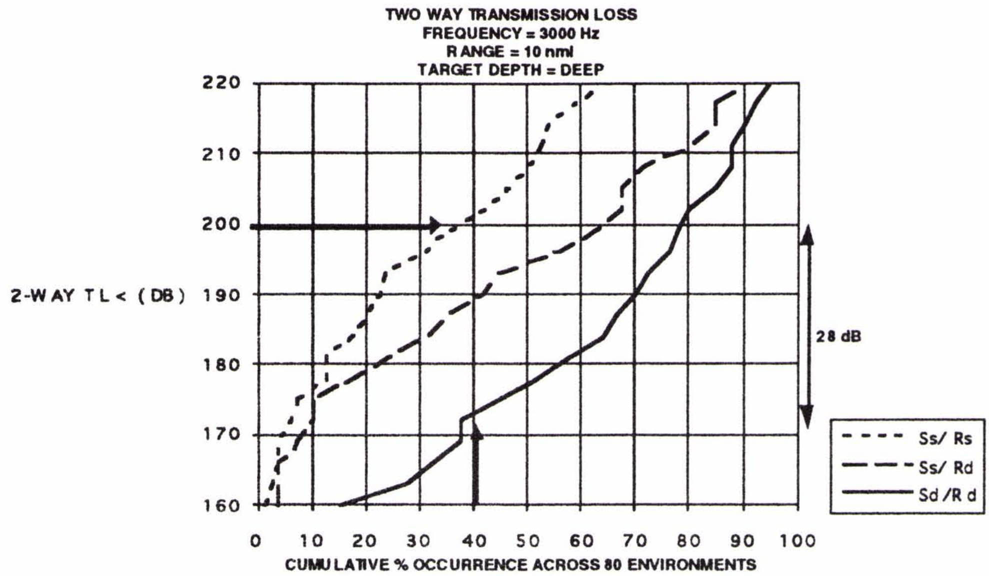

Figure 16 2-way transmission loss cumulative percent occurence versus source/receiver placement; deep target, 3000 Hz.