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A Study of Low Frequency Sound Propagation in Shallow Water Ducts

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PREFACE

This work was done under NUSC J.O. No. A62200, the Shallow Water Sonar Initiative (SWSI), P. D. Herstein, Principal Investigator, under the Surface Ship ASW Advanced Development Program (SASWAD), D. Ashworth, NUSC Program Manager. The work was sponsored by E. Plummer, NAVSEA 06UR1.

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13. ABSTRACT ***(Maximum 200 words)***

An analysis of sound propagation conditions found in 10 shallow water locations found that, on a yearly basis, some form of ducting or channeling occurs in most locations a majority of the time. A modeling study is conducted to determine typical cutoff frequencies and the impact of in- and below-duct source/receiver geometries. The results are examined with respect to previous work (F. B. Jensen and W. A. Kuperman, J. Acoust. Soc. Am., 73(3), 813-819, 1983).

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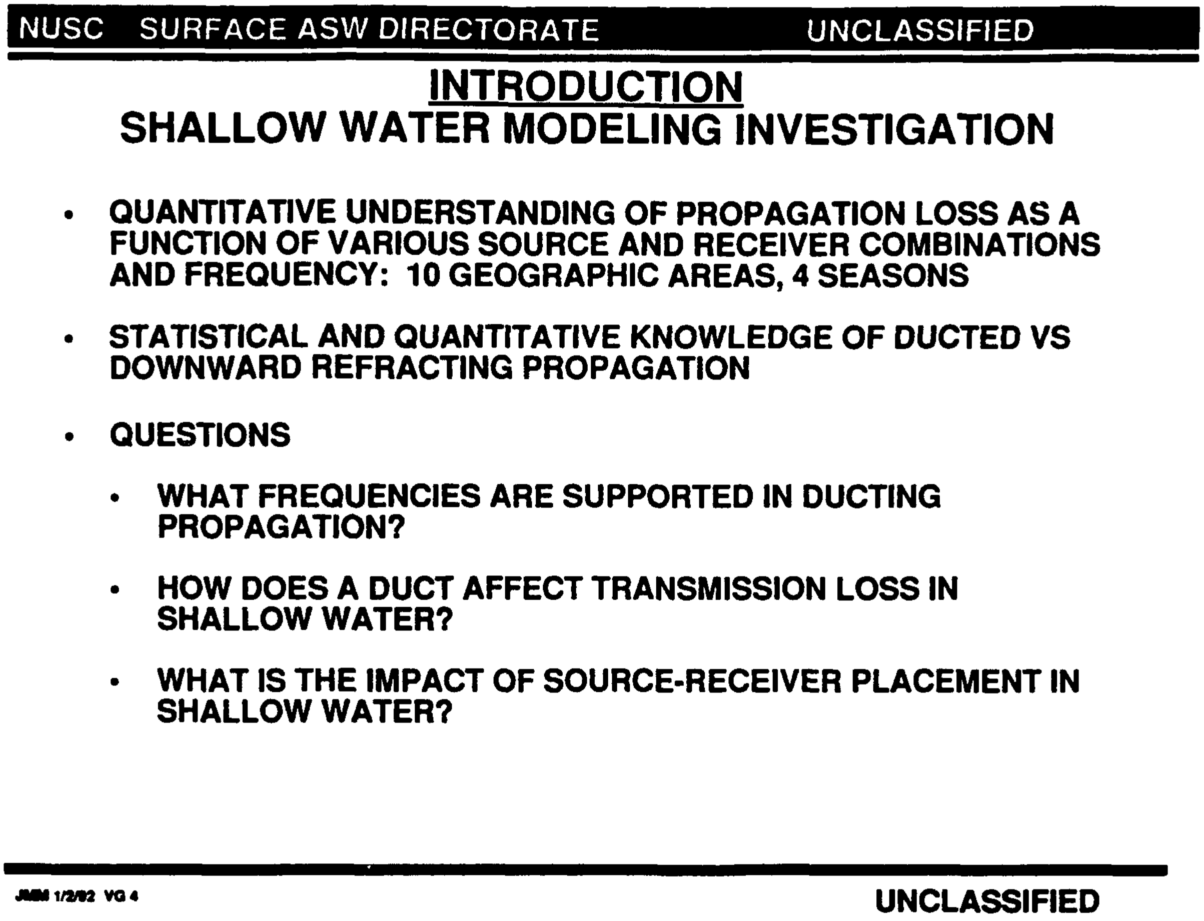

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INTRODUCTION
SHALLOW WATER MODELING INVESTIGATION

- QUANTITATIVE UNDERSTANDING OF PROPAGATION LOSS AS A FUNCTION OF VARIOUS SOURCE AND RECEIVER COMBINATIONS AND FREQUENCY: 10 GEOGRAPHIC AREAS, 4 SEASONS
- STATISTICAL AND QUANTITATIVE KNOWLEDGE OF DUCTED VS DOWNWARD REFRACTING PROPAGATION
- QUESTIONS
  - WHAT FREQUENCIES ARE SUPPORTED IN DUCTING PROPAGATION?
  - HOW DOES A DUCT AFFECT TRANSMISSION LOSS IN SHALLOW WATER?
  - WHAT IS THE IMPACT OF SOURCE-RECEIVER PLACEMENT IN SHALLOW WATER?

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Figure 1.

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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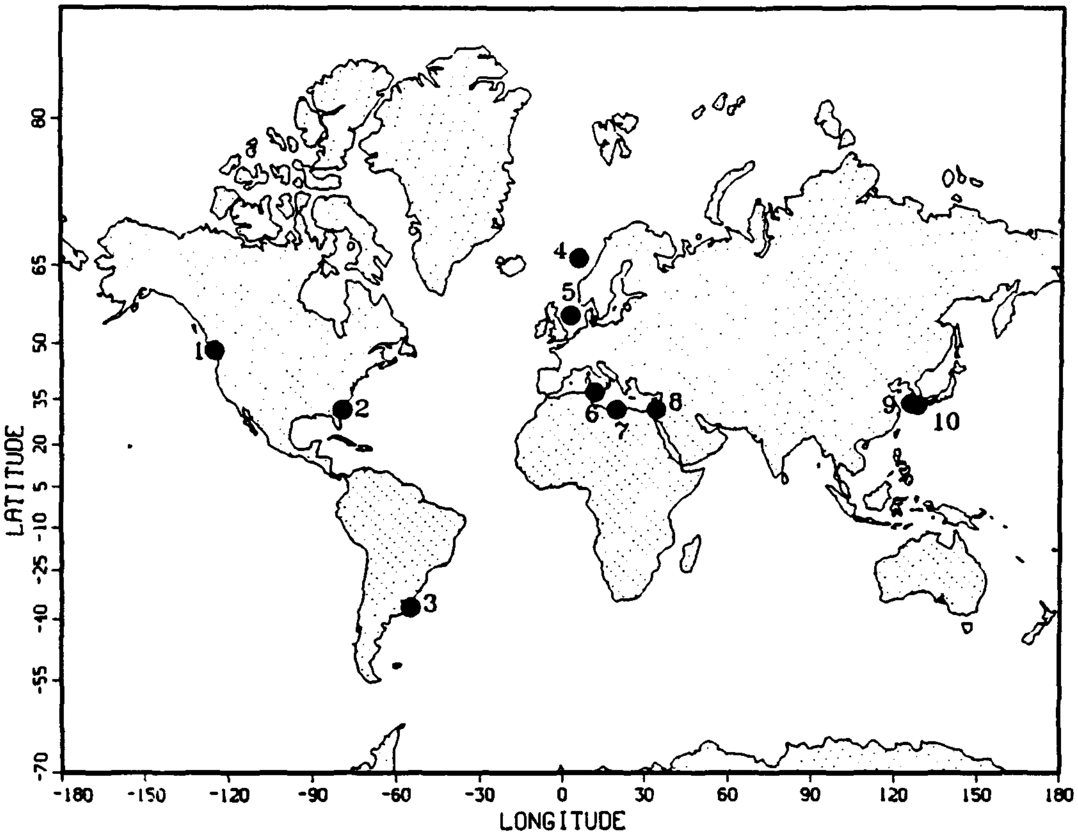
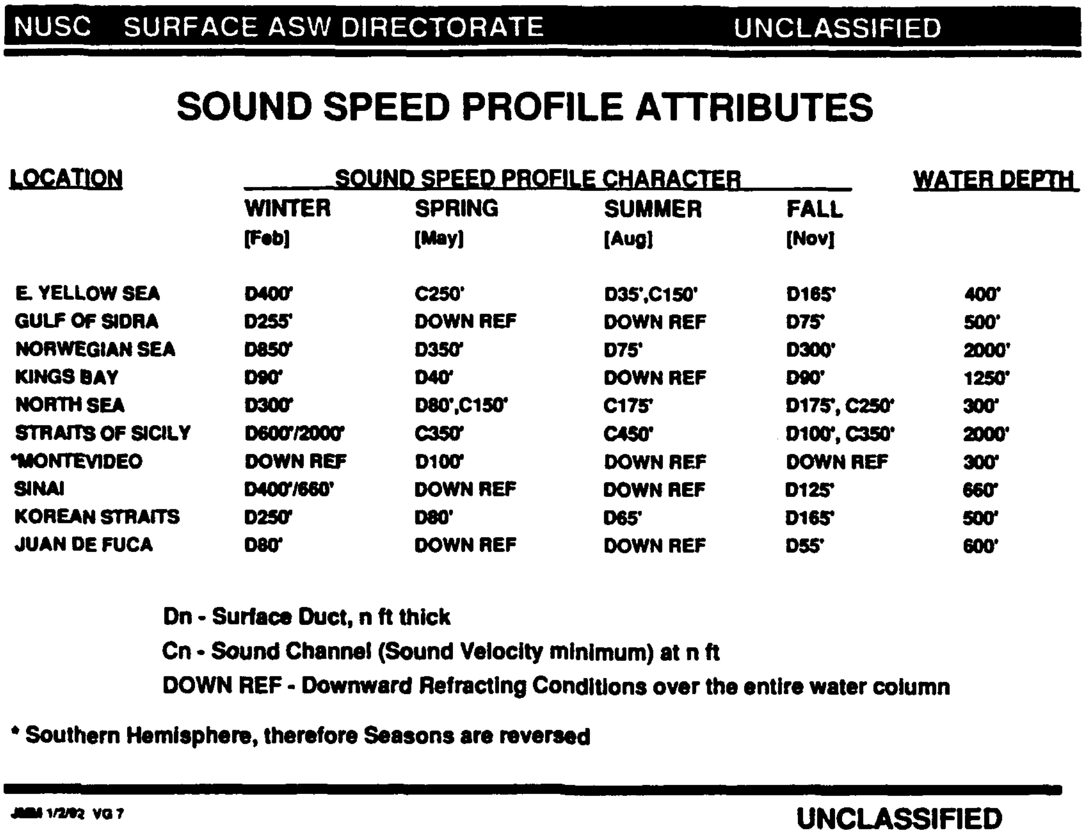
SHALLOW WATER LOCATIONS



SWSI Locations 11/25/91 VG 1 **UNCLASSIFIED**

Figure 2.

To obtain an adequate representation of shallow water environments, 10 geographic locations were chosen for this investigation based on their physical and acoustic attributes. These locations are shown here: 1. the Strait of Juan de Fuca, 2. King's Bay, 3. Montevideo (Southern Hemisphere), 4. the Norweigan Sea, 5. the North Sea, 6. the Strait of Sicily, 7. the Gulf of Sidra, 8. Sinai, 9. the East Yellow Sea, 10. the Korean Strait. Water depths for these locations range from approximately 300 to 2000 ft. 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 noted, the hallmark is variability.



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SOUND SPEED PROFILE ATTRIBUTES

LOCATION	SOUND SPEED PROFILE CHARACTER				WATER DEPTH
	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

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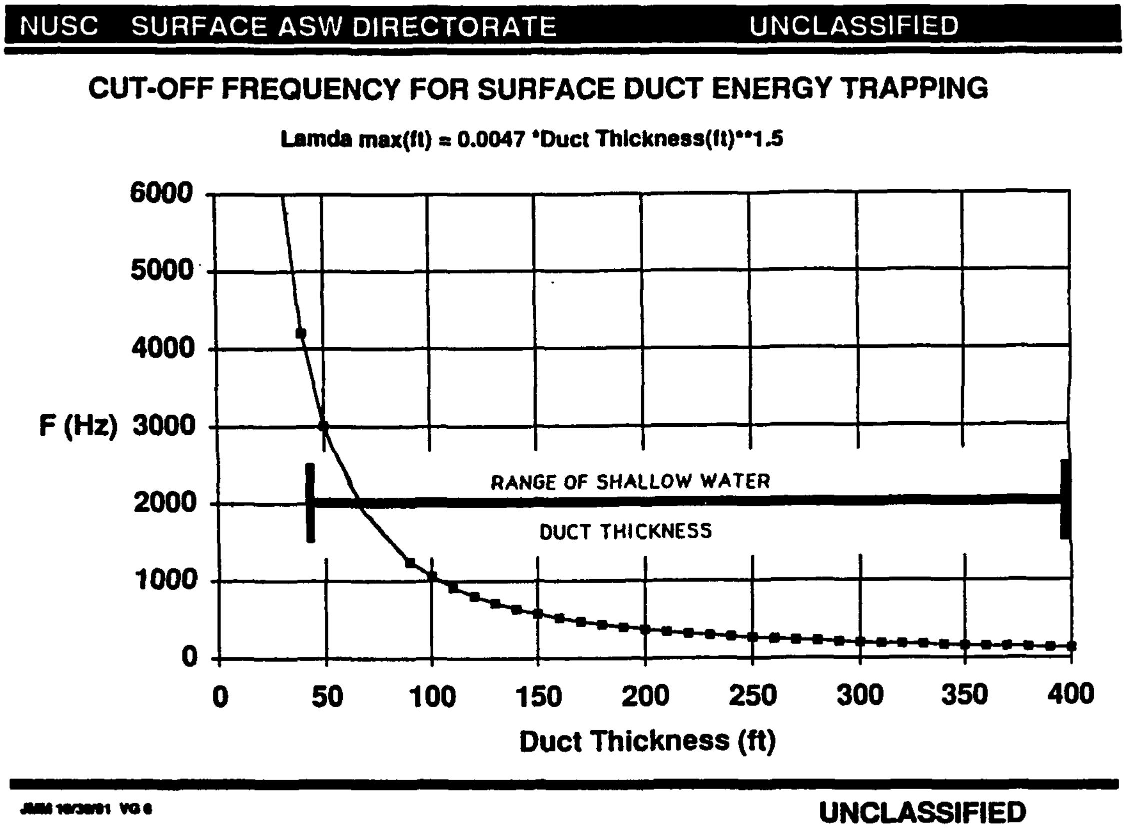
Figure 3.

Shown here are 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 ft in this matrix of 40 environmental conditions. For approximately 75 percent of this matrix, a surface duct or sound channel exists; for the other 25 percent, the sound speed profile is purely downward refracting. 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. This leads to the observation that bottom characteristics and bottom loss are important not only for modeling shallow water propagation but also for modeling sea surface characteristics and surface loss.



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CUT-OFF FREQUENCY FOR SURFACE DUCT ENERGY TRAPPING

Lamda max(ft) = 0.0047 *Duct Thickness(ft)1.5**

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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 is shown here along with the corresponding cutoff frequency.[1] The functional relationship is that the maximum trapped wavelength is directly proportional to the duct thickness to the 1.5 power. The X and Y axis show duct thickness which ranges from 0 - 400 ft and frequency from 0 - 6000 Hz, respectively. 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.

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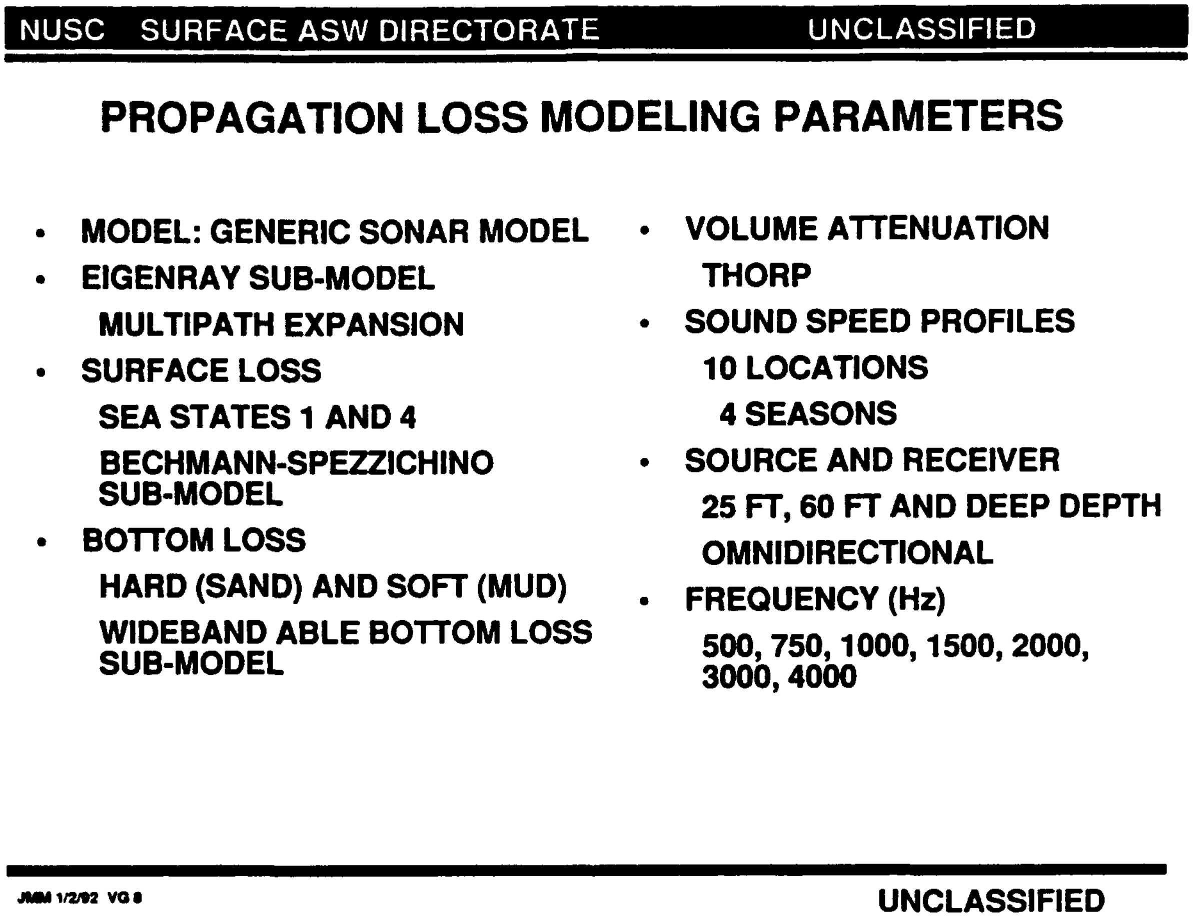
[1] Principles of Underwater Sound," 2nd ed., R. J. Urick, 1975, p. 139



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PROPAGATION LOSS MODELING PARAMETERS

- 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
  - 25 FT, 60 FT AND DEEP DEPTH
  - OMNIDIRECTIONAL
- FREQUENCY (Hz)
  - 500, 750, 1000, 1500, 2000, 3000, 4000

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Figure 5.

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 called Wideband ABLE.[2] 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 ft, 60 ft, 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 Thorp model.

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[2] "Wideband ABLE: A Total Energy Bottom Loss Model for Frequencies from 500 to 3500 Hertz," Thaddeus G. Bell, Report BLO-0501-003, Sonalysts Inc., 18 October 1990.

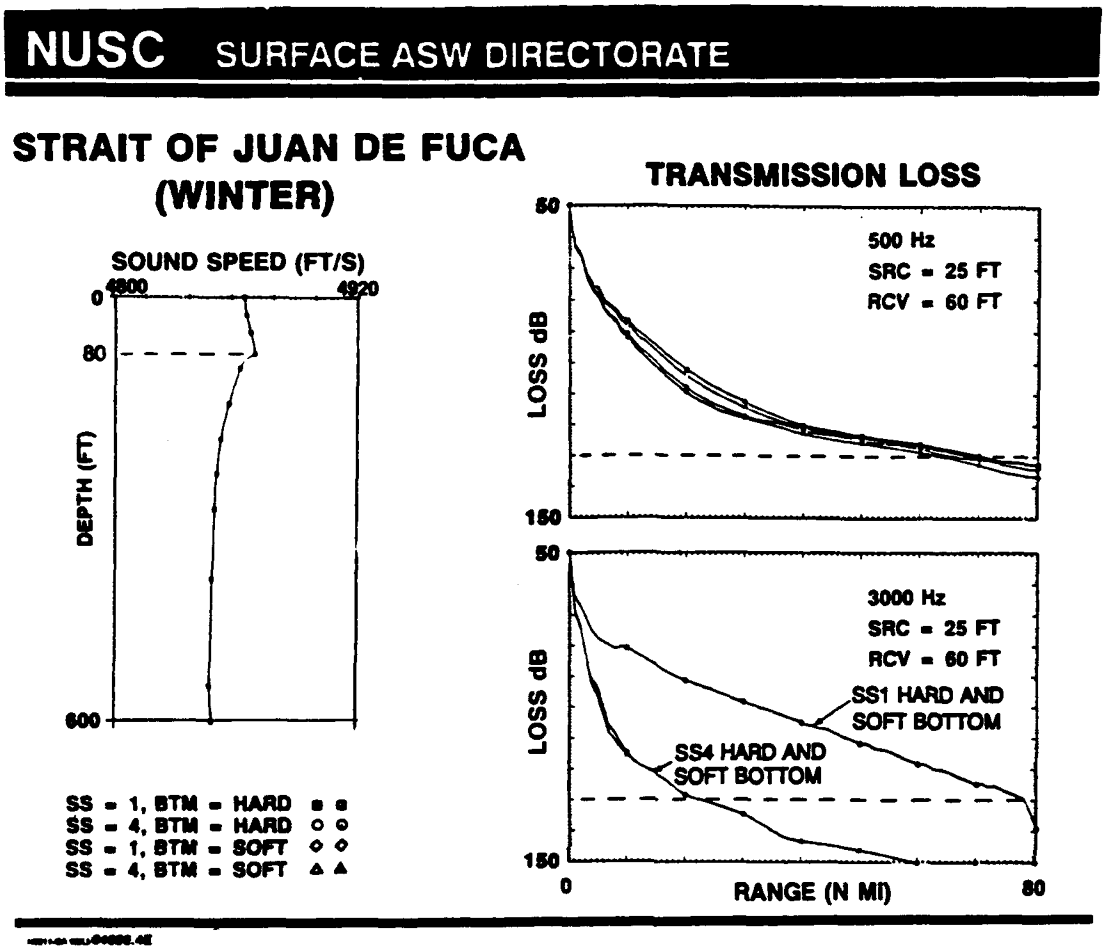

Figure 6.

Shown here are one-way transmission loss vs. range curves and the associated sound speed profile for the Strait of Juan de Fuca in winter. The sound speed profile (left graph) has an 80 ft-thick surface duct, which theoretically can support ducted (fully trapped) propagation at 1500 Hz and higher. The two sets of transmission loss curves (on the right) have axes of 50 to 150 dB and range from 0 to 80 nmi. The top set of curves is for 500 Hz, the bottom set, 3000 Hz. Source and receiver are placed in the duct at 25 and 60 ft, respectively, for both frequencies. Each plot consists of four transmission loss curves with parametric variation over sea state and bottom type. As a reference point, the dashed line represents a transmission loss value of 130 dB. At 500 Hz, there is very little dependence on propagation loss with sea state or bottom type. The two top curves at 3000 Hz represent sea state 1 for hard and soft bottom compared to the lower two curves which represent SS4 for both bottom types. Also, SS1, 3000 Hz propagation for hard and soft bottom exhibits less loss than all four 500 Hz cases. This is the result of energy trapping within the duct at 3000 Hz. By comparison, at 3000 Hz and SS4, the sensitivity of trapped energy to an absorptive (lossy) boundary are demonstrated. These figures clearly show the effect of acoustic energy trapping and leakage in a duct.

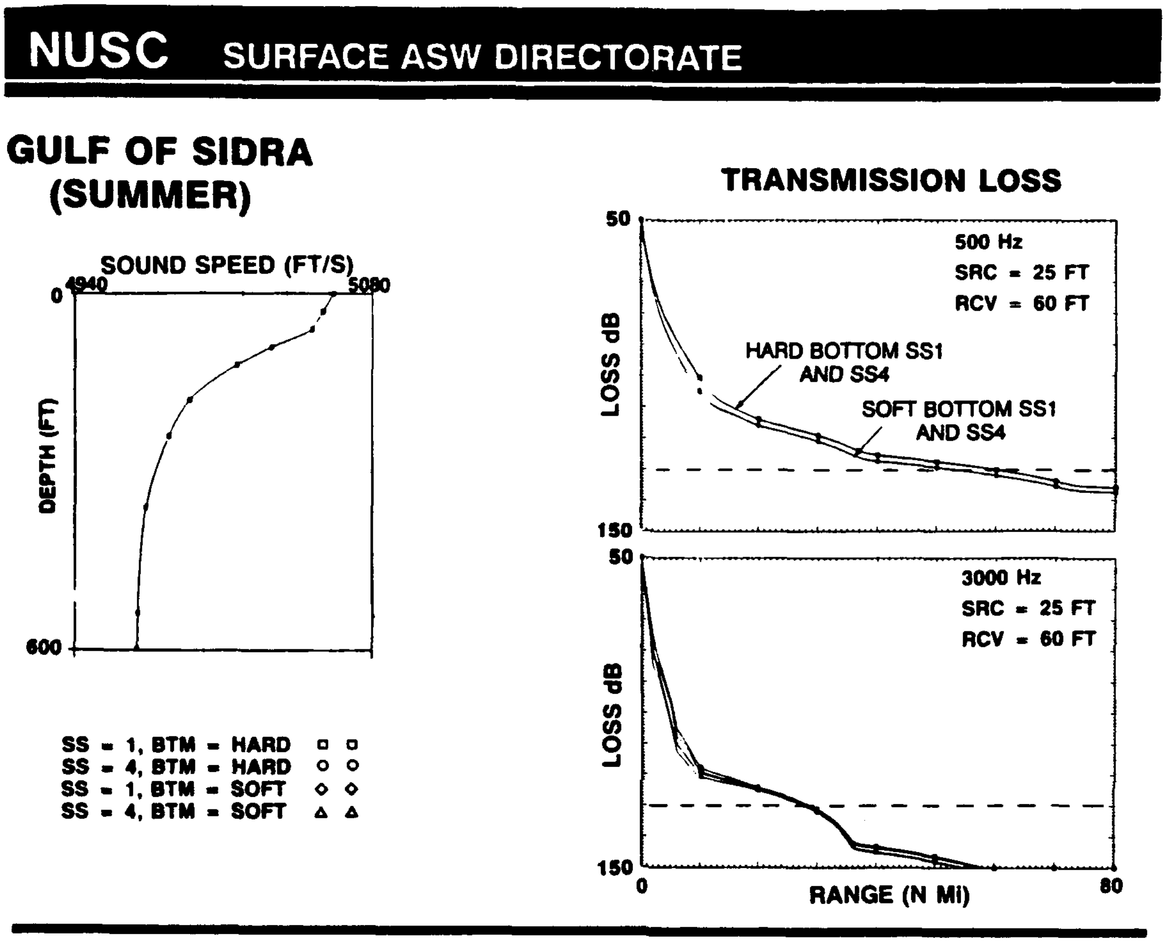

Figure 7.

In contrast, the Gulf of Sidra in summer is shown here. The sound speed profile is downward refracting. Similar to the previous figure, one-way propagation loss for a source at 25 ft and a receiver at 60 ft for frequencies of 500 and 3000 Hz are shown in the top and bottom right hand figures, respectively. 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.

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TRANSMISSION LOSS
STRAIT OF JUAN DE FUCA (WINTER)

SEA STATE = 1 BOTTOM = HARD

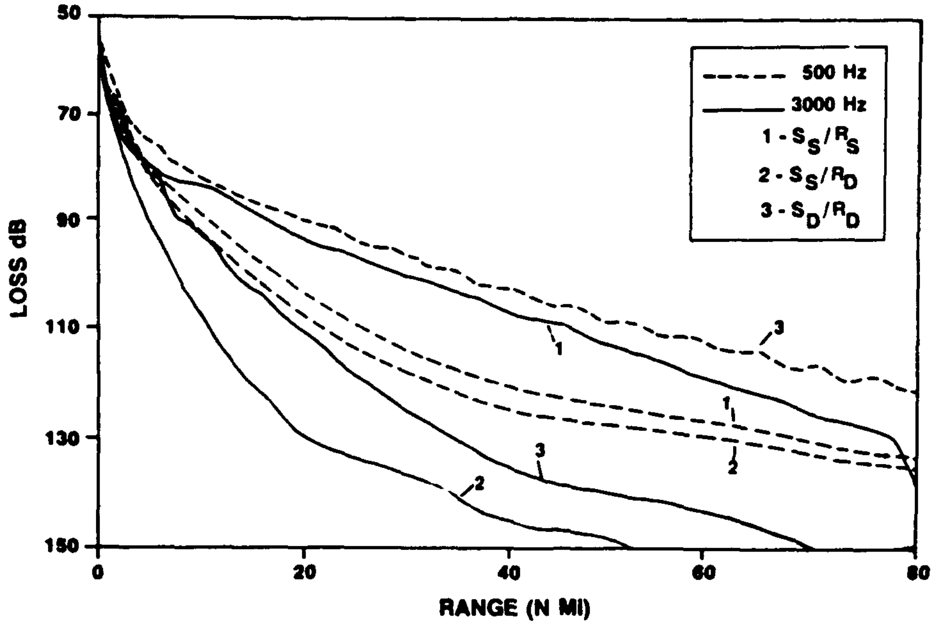

Figure 8.

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. Frequencies are 500 and 3000 Hz. 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 ft. Receiver shallow depth is 60 ft and deep depth is 275 ft. 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[3] 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.

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

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TRANSMISSION LOSS
GULF OF SIDRA (SUMMER)

SEA STATE = 1 BOTTOM = HARD

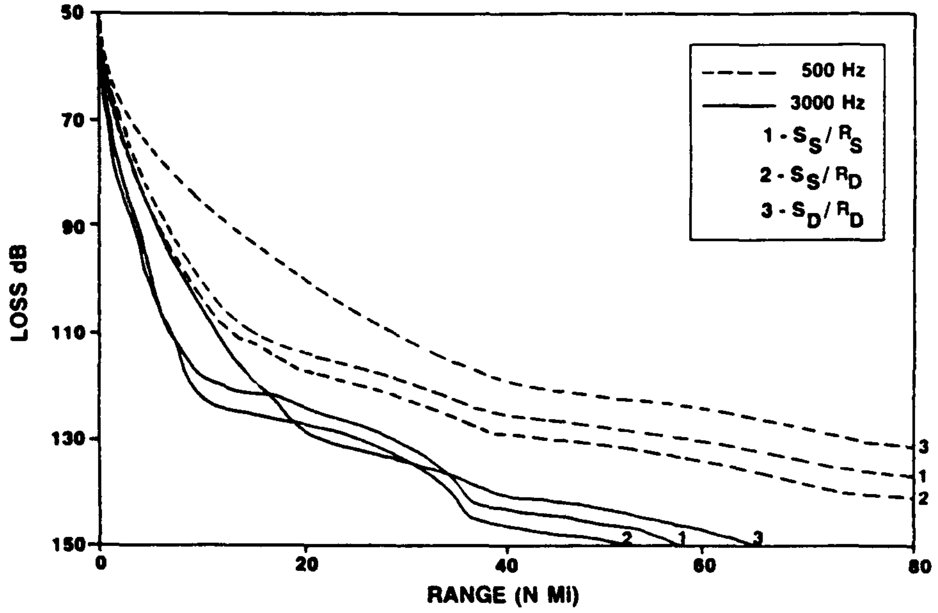
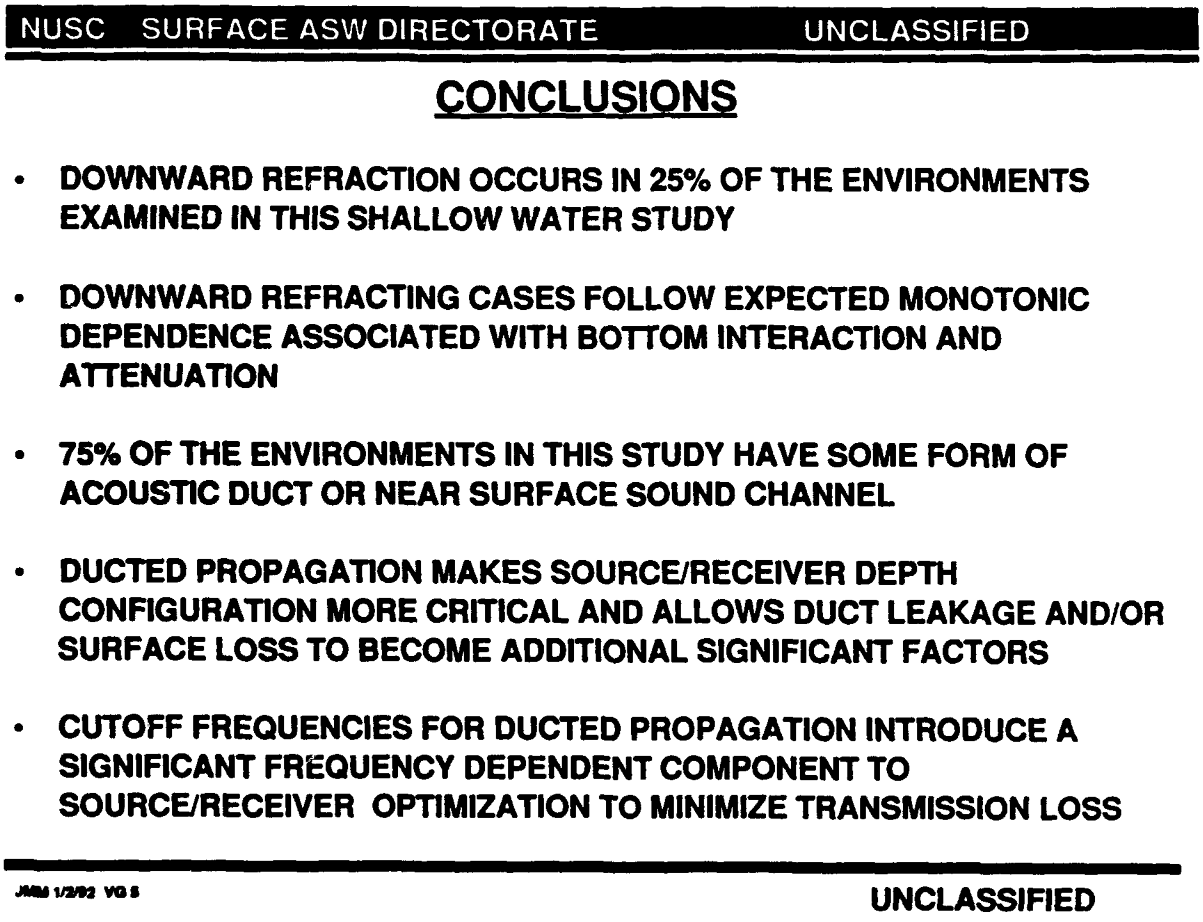


Figure 9.

By comparison to figure 8, here we have 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.



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CONCLUSIONS

- 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

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Figure 10.

The conclusions for this shallow water transmission loss modeling investigation are shown here. Of the 40 environments chosen (10 geographic locations, four seasons), only 25 percent were dominated by downward refracting conditions. These conditions follow expected monotonic frequency dependence associated with bottom interaction and attenuation. Alternately, 75 percent of the environments chosen have some form of surface duct or sound channel. These propagation conditions make source/receiver depth configuration more critical and allow duct leakage and/or surface loss to become additional significant factors. Finally, cutoff frequencies for ducted propagation introduce a significant frequency component to source/receiver optimization.

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