Critical Angle and Seabed Scattering Issues for Active-Sonar Performance Predictions in Shallow Water

Donald R. Del Balzo, James H. Leclere and Mona J. Collins

U.S. Naval Research Lab (7183)
Stennis Space Center, MS 39529-5004, USA
delbalzo@nrlssc.navy.mil

Abstract

Active sonar performance predictions (0.75 to 3 kHz) are examined in summer shallow-water environments to quantify the impact of variable seabed and watermass properties on detection. Scattering is computed with an environmentally sensitive modified Lambert's Law. The results show a) unmodified Lambert's Law yields optimistic performance by a factor of up to 30 in coarse sand, and b) with environmentally-sensitive scattering, performance is poor for sands (high reverberation) and clays (high TL) and optimum for silty areas.

1. Introduction

Naval operations in the post cold-war era are moving away from traditional, deep-water, fairly stable environments and into littoral regions where the water is shallow, complex and dynamic. The littoral environment presents significant new challenges in both (a) direct functions like sensor performance and tactics, and (b) supporting functions like environmental and sensor predictions, and environmental data surveys. Two mission areas of undersea warfare which are heavily influenced by local environmental conditions are Anti-Submarine Warfare (ASW) and Mine Counter-Measures (MCM). Most of the capability to perform ASW and MCM is with acoustic sensors (sonar) and associated systems at frequencies below 10 kHz for ASW and above 30 kHz for minehunting. For the analysis here, environmental influences on acoustic signals at ASW frequencies are considered in two categories; first, water-mass, as defined by water depth and sound-speed profiles, and second, the seabed sediment, as defined primarily by grain size and density. Future work will be directed toward the higher frequencies associated with minehunting.

In deep water, the effects of oceanography (e.g. internal waves, thermal fronts and eddies) on acoustic propagation and coherence can be significant but the physical processes and their impact on sonar performance are well understood and mostly predictable. However, in shallow water other processes, like tidal currents, fresh-water river outflows, solitons and surf waves may have significant influence on acoustic systems, by altering 4-D sound-speed structures. The space-time character of these water-mass processes is not well understood, nor easily predictable.

In deep water the sea bottom may not be a dominant factor in determining acoustic signal properties because upward refraction in the water column can reduce acoustic interaction with the bottom. However, in shallow-water areas most ASW operations involve significant acoustic interactions with the seabed which can have significant impact on sensor performance. Some mechanisms affecting performance at the seabed are transmission and reflection at the boundary (often described by bottom reflection loss), refraction and attenuation in the sediment, shear wave conversion in the bottom, creation of interface waves, and scattering (both forward and backward) at the interface and in the sediment. These phenomena are understood to varying degrees and their impact on acoustic signal properties are now being incorporated into advanced (research) models.

This analysis is focused on the ASW problem for tactical active sonars in shallow water. A fundamental question is addressed concerning the need to model low grazing angle energy with an adequate scattering kernel and the impact on reverberation over various sediment types as compared to using the environmentally insensitive Lambert's Law approach.

2. Scenario

This paper reports a simulation assessment of environmental impacts on active sonar performance in shallow-water, characterized by conditions found in the Strait of Sicily during the summer, when thermal conditions cause downward refraction and significant bottom interaction. Although the work is based on archival environmental information from a specific region, the data span a large set of bottom and water conditions which could apply at many other areas. The assessment is based on the predicted impact of variable environmental conditions on system performance, in terms of detection area.

The analysis has implication on actual tactical ASW operations because the sensor descriptions and scenarios are realistic (although generic). Specifically, the scenario involves notional sonars at 0.75 and 3 kHz operating at 50 m depth in 100 m water-depths against a zero-Doppler submarine with target strengths of 0 to 10 dB operating at 50 m depth. The source is modeled as a Hann-weighted 5-element vertical array, horizontally steered, with an intensity of 230 dB re μPa and a vertical beamwidth of 28 deg. The Hann weighting significantly reduces vertical sidelobes and undesirable reverberation. The receiver is modeled as a horizontal towed array with a broadside beamwidth of 10 deg which yields a 3-D directivity against omnidirectional noise of 13.6 dB. The sonar signal is a 100 ms CW pulse and the processor assumes incoherent integration over 3 pulses. The signal processing assumes a signal differential of 1.8 dB against noise and 9.5 dB against reverberation and a probability of false alarm of 10^{-4}.

2.1 Bottom Sediment Properties

Figure 1 shows the distribution of sediment types for the Strait of Sicily [1]. There is significant spatial variability, as seen by the localized regions with coarser grains (sands, silts without clay, gravel, pebbles, shells, and rock fragments) and larger regions with finer-grain material (sands and silts with clay in the northwest and around Sicily and fine silty-clays in the southeast).

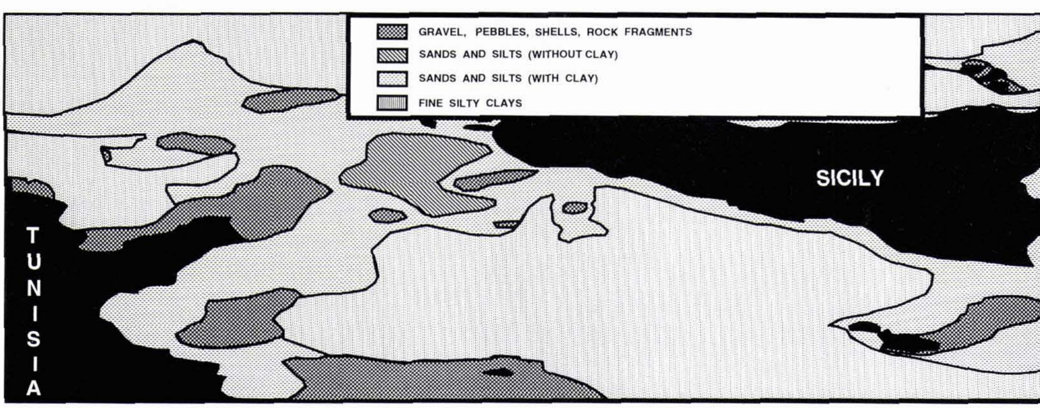

Fig. 1 Bottom properties in the Strait of Sicily.

A set of geophysical and geoacoustic descriptions, based on the sediment types shown in Fig. 1 and consistent with Hamilton's analyses [2], were constructed for this study. The sediments, which are considered to be thick (50 m) and upward refracting, are referred to by their phi-values (inversely related to their grain sizes, δ, as $\delta = [1/2]^{\phi}$). The six sediment types used here are coarse sand (ϕ=1), fine sand (ϕ=3), silty sand (ϕ=4.5), sand-silt-clay (ϕ=6), clayey silt (ϕ=7), and silty clay (ϕ=8.5). Standard geoacoustic properties (sound speed, density and attenuation profiles) were determined. There is a discontinuity in sound speed at the water-sediment interface which determines critical angles for bottom reflection. These discontinuities (in per cent) are 20, 13, 9, 3, 0.6, and -1 for coarse sand through silty clay, respectively, which give rise to critical angles (in deg) of 33.9, 27.9, 23.0, 13.6 and 6.3. Since the sound speed for silty clay is less than the water sound speed at the bottom, there is no critical angle, i.e.; there is penetration at all angles and there exists an angle of intromission at 9 deg where extremely high loss occurs. The sediment properties are listed in Table 1.

Sediment	Grain Size (mm)	Phi	Interface Discontinuity	Critical Angle (deg)
Coarse sand	0.500	1	20.5	33.9
Fine sand	0.125	3	13.2	27.9
Silty sand	0.044	4.5	8.6	23.0
Sand-silt-clay	0.016	6	2.9	13.6
Clayey silt	0.008	7	0.6	6.3
Silty clay	0.003	8.5	-1.1	----

Table 1. Sediment properties used in the analysis.

2.2 Water Sound Speed and Geoacoustic Profiles

Archival water sound speed profiles (SSPs) were extracted from the Master Oceanographic Observation Data Set (MOODS) during the summer season from the area shown in Fig. 1. Three profiles were constructed and smoothed for use in the simulations. One represents the mean water conditions and the other two represent extremes corresponding to +/- 2-standard deviations from the mean.

The 3 water SSPs are shown in Fig. 2, along with the geoacoustic profiles for each sediment type. All 3 water SSPs are downward refracting for a source at 50-m depth. The warmest condition (SSP max) produces the greatest amount of downward refraction and therefore the most bottom interaction.

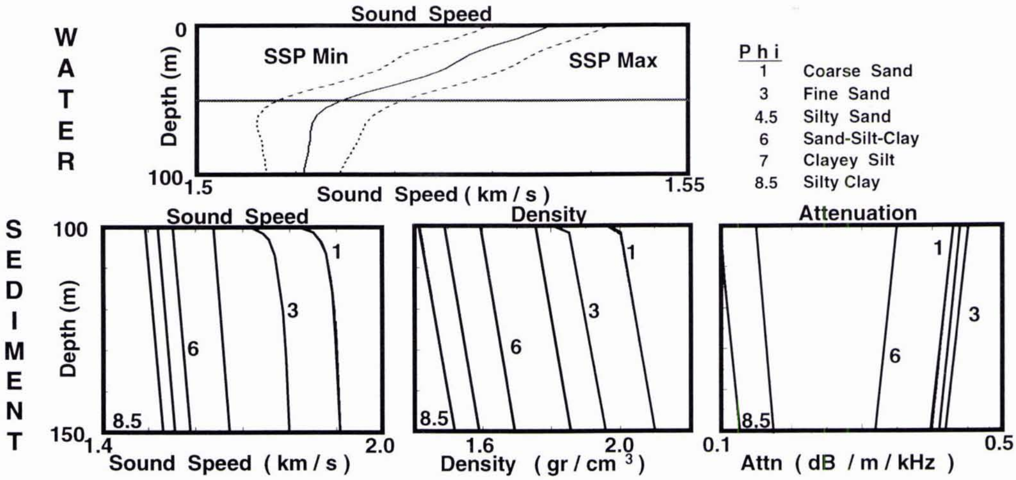

Fig. 2 Profiles of water sound speed (min, mean and max) for summer in the St. of Sicily and representative sediment geoacoustic properties from coarse-sand to silty-clay.

2.3 Bottom Reflection Loss

For each of the six bottom types, the corresponding geophysical / geoacoustic descriptions were converted into curves of bottom reflection loss (BRL) as a function of grazing angle. These are shown in Fig. 3 for the mean water SSP at 3 kHz. The water-sediment SSP discontinuity was assumed to be the same for each of the three water conditions; therefore the sediment geoacoustic profiles shown in Fig. 2 were adjusted slightly for each water condition to maintain the discontinuity. This gave rise to 18 BRL curves for each of the two frequencies, one for each combination of water condition and bottom type. The frequency dependence in BRL results from the frequency dependence of sediment attenuation.

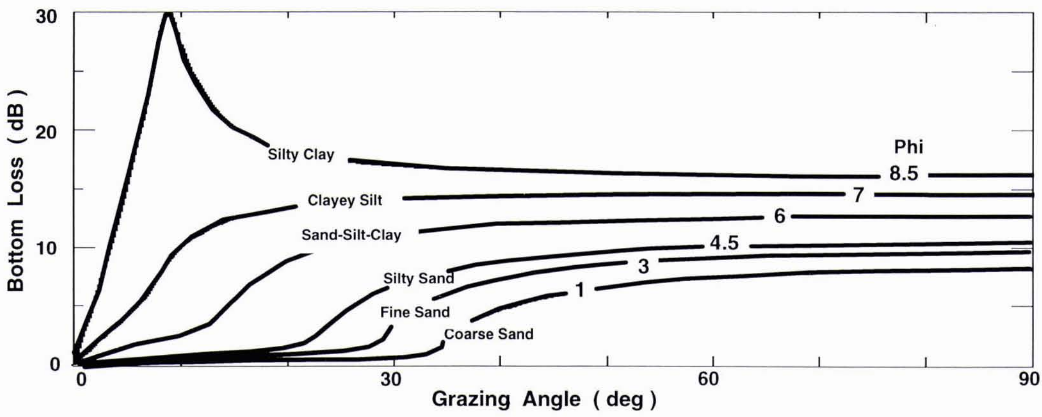

Fig. 3 Bottom reflection loss curves computed from geoacoustic properties.

2.4 Backscattering Strength and Reverberation

As acoustic energy propagates in shallow water, there are at least three scattering components (sea surface, volume and bottom) which redistribute energy in all directions. The first order effect of scattering on sonar system performance is backscattering and reverse propagation to the receiver. This produces reverberation, against which targets are to be detected. The analysis reported here includes calculations of backscattered reverberant energy from all three mechanisms. The total reverberation level is calculated and used in determining detection performance. In all cases considered the bottom component dominates.

2.4.1 Sea Surface Scattering

The amount of scattering at the pressure-release sea surface depends on the acoustic wavelength, the incident angle and on interface roughness, which is often characterized by sea state and waveheight. In low-wind conditions, the surface is nearly flat and the backscattered energy is usually negligible. For this study, surface reverberation is calculated using the Chapman-Harris empirical model [3]; however, the wind speed is assumed to be only 1 kt so that surface reverberation is small.

2.4.2 Volume scattering

The amount of scattering from volume inhomogeneities (primarily fish and fish schools) depends on frequency and the biologic distribution and density. These are so dependent on location, time of day, and season that a simple generic model which assumes a sparse marine-life population, is used.

2.4.3 Bottom scattering

The amount of scattering from the seabed depends primarily on the grazing angle and the type of material and secondarily on the frequency. The frequency dependence is not well understood, is probably insignificant in the band of interest (0.75 to 3 kHz) and is therefore not considered in this analysis. For many years, a simple sine squared (Lambert's Law) approach to diffuse scattering at the bottom has been adopted, with the normal incidence coefficient empirically determined to be -27 dB by Mackenzie [4] for deep-water sites. The formulation is simply

$$\mathrm{BBSS} = 10 \log (\mu \sin^2 \theta), \tag{1}$$

where BBSS is bottom backscattering strength in dB, θ is the grazing angle of the acoustic energy at the bottom and 10 log μ is the Mackenzie coefficient. To simplify terminology this approach will be labeled LM, for Lambert-Mackenzie. One deficiency with this simple LM formulation is that BBSS is independent of the bottom characteristics.

Another problem with the simple LM approach is that BBSS approaches negative infinity as the grazing angle approaches zero. Recent experimental evidence (e.g. from the Critical Sea Test (CST) Program [5] from 300 to 1500 Hz) is that BBSS does not become vanishingly small at low grazing angles. On the contrary, there exists a scattering-strength plateau caused by scattering inside the sediment rather than from the water-sediment interface which depends on the type of bottom material. This plateau and its dependence on the type of sediment has been analyzed [6]. One approach to deal with the low grazing angle scattering issue is to assume an "omnidirectional" scattering kernel proportional to the sine of the grazing angle and to adjust μ. This often provides a better "fit" to data from 10 to 30 deg, but it fails to describe the plateau at very low angles. To be consistent with CST and other data a new model for BBSS is proposed and used in this analysis. It is formulated as

$$\mathrm{BBSS} = 10 \log [\alpha(\phi) + \mu(\phi) \sin^2 \theta], \tag{2}$$

where α is the low grazing angle plateau and where both α and μ are functions of the environment through the grain-size parameter, ϕ. This modified Lambert's Law will be labeled ALM to indicate the α plateau at low angles.

A graphical representation of the proposed ALM approach for BBSS is shown in Fig. 4 for all 6 environments along with the standard Lambert's Law with a -27 dB coefficient. For coarse sand and fine sand Lambert's Law underestimates scattering (reverberation levels) at all angles. For the other environments Lambert's Law overestimates scattering above 15 deg and underestimates scattering below about 5 deg. From 5 to 15 deg (where one could expect the most interaction) the comparison depends on the exact sediment type.

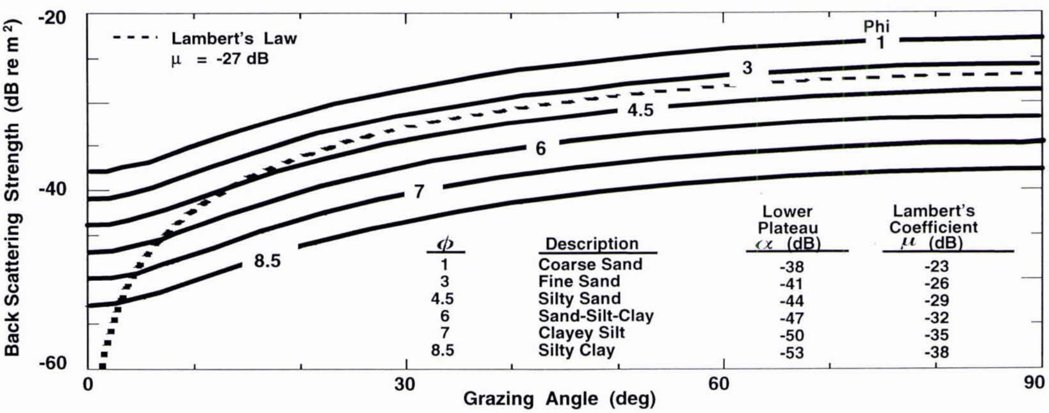

Fig. 4 Proposed ALM bottom backscattering strength curves (solid) with standard LM curve (dotted).

3. Transmission Loss and Reverberation

Transmission loss (TL) was calculated for all combinations of range-independent environments and frequencies. An example for a soft, ϕ=7, clayey-silt environment is shown in Fig. 5 as acoustic intensity vs. depth and range in the summer for a 50-m source in 100-m water using the Extended Finite Element Parabolic Equation approach [7]. The left and right columns correspond to the minimum (-2σ) and maximum (+2σ) SSPs for the area and the upper and lower rows are for 750 and 3000 Hz, respectively. In this case, the water conditions appear to have a major effect on propagation at both frequencies. In the maximum (max) SSP condition, the increased downward refraction causes significant penetration and attenuation in the sediment, compared to the minimum (min) SSP condition. The effect of warm water and sediment attenuation on transmission loss is much larger than the effect of changing the frequency.

In order to assess the relative importance of water conditions to sediment type, curves of TL vs range at a 50-m receiver depth for min and max SSPs were overlaid in Fig. 6 for ϕ = 1, 6, 7, and 8.5. The softer sediments (ϕ=7 and 8.5) on the top row show a large transmission loss and a significant difference between min and max SSP conditions, compared to the harder sediments (ϕ = 1 and 6) in the bottom row. The TL is so large for the softer sediments that sonar performance may be expected to be poor. The TL is much lower in the harder sediments so that one may anticipate good sonar performance, however hard interfaces (especially ϕ = 1 to 3) have high scattering strengths which increase reverberation and decrease detection range. The relative amounts of TL and reverberation must be considered in order to understand sonar performance.

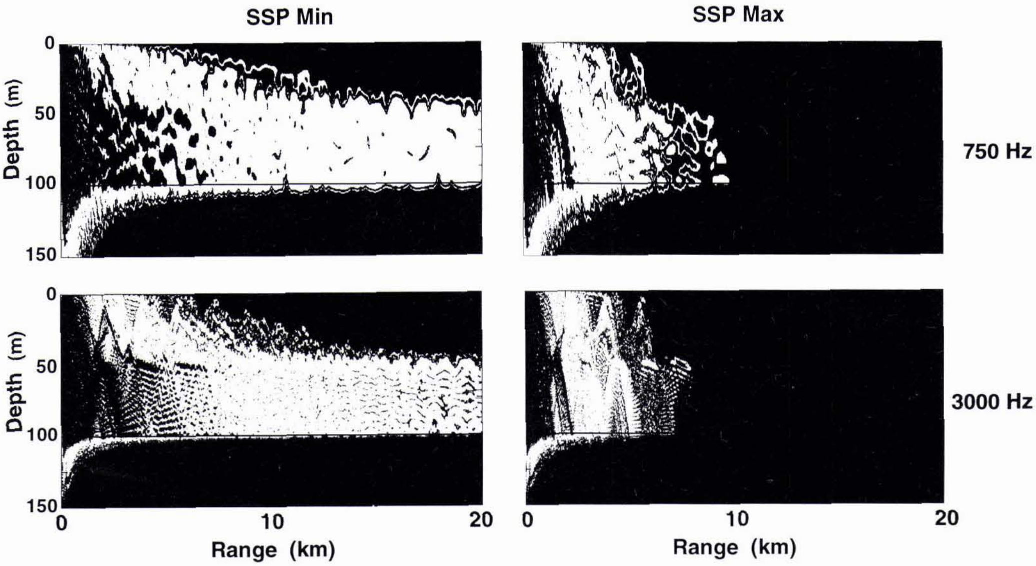

Fig. 5 Range-depth transmission loss contours for extreme water SSPs in the summer (min left and max right) for 750 Hz (upper) and 3000 Hz (lower). TL is computed with EFEPE using source depth = 50 m, water depth = 100 m and a soft, clayey-silt bottom sediment. Scale is defined by dark red at 53 dB and deep blue at 110 dB.

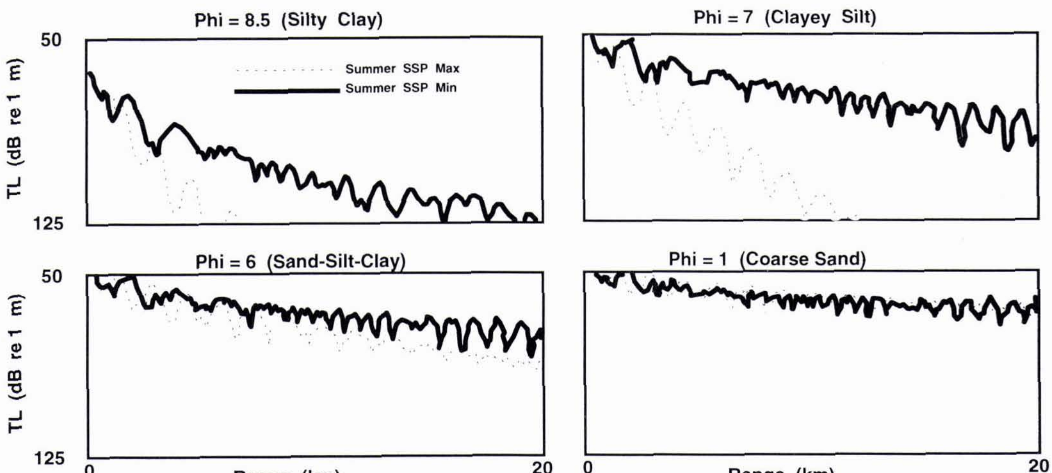

Fig. 6 TL at 3000 Hz for min and max water SSPs over 4 bottom sediment types. TL computed with EFEPE using source depth = 50 m, water depth = 100 m and receiver depth = 50 m.

Another observation from Fig. 6 is that in hard sediments (especially ϕ == 1 and 3) varying water conditions do not have a significant effect on TL. This is because hard sediments have high critical angles and little acoustic penetration. On the other hand, soft sediments have low critical angles and greater penetration. In this case the additional downward "ray bending" by the max SSP increases the acoustic angles at the sediment and this allows more penetration and attenuation and higher TL. Clearly, changes in either the water or bottom conditions can cause significant variation in TL, depending on the situation.

Reverberation levels also depend on water SSPs and sediment conditions through the scattering-strength curves shown in Fig. 4. The detailed results are not shown here because they have already been summarized; i.e. hard (soft) sediments produce high (low) reverberation. The important result is the balance between TL and reverberation through the sonar equation and the resulting detection performance in various environments, which is discussed in the next section.

4. Detection Performance

The ASW sonar scenario described in Section 2 is addressed here using a ray approach to computing TL and reverberation. Parallel EFEPE computations were performed to determine the efficacy of the ray-trace results. In some environments there were differences (e.g. the ray-based TLs were too high in soft sediments at 750 Hz) but the average differences were insignificant (less than 2 dB) out to maximum detection ranges. Most detections were against bottom reverberation even though realistic noise levels (from heavy shipping and low wind) were used. In a few cases corresponding to $\phi = 7$ and 8.5 the detections were noise limited at the maximum ranges. All calculations are for range-independent environments to simplify analysis and to allow generalization.

Some representative results of performance are given in Fig. 7 for the mean water SSP in all bottom sediments for a 750 Hz (top) and 3 kHz (bottom) notional sonar against a 0 dB (left) 10 dB (right) target strength. The circles result from assuming LM scattering and the triangles correspond to using the proposed ALM set of environmentally sensitive BBSS curves. The overall results for 0 dB target strength are about an order of magnitude worse than for the 10 dB target strength. The detailed results for LM and ALM are about the same for the 2 softest sediments; i.e. either scattering kernel is adequate because TL (not reverberation) dominates detection in these sediments. From $\phi = 6$ to 1 there is a monotonic increase in the difference between the 2 results because bottom scattering (not TL) dominates. The greatest differences in detection area occur in the hardest sediments. In all 3 sand areas the LM approach underestimates reverberation and predicts normalized detection areas from 3 to 30 times higher than the ALM approach. Separate calculations were made to isolate the impact of the low grazing angle plateau compared to the rest of the scattering. It was determined that in almost all cases the α plateau rather than the μ coefficient was the dominant parameter. This is consistent with the understanding that only low grazing angle energy propagates to long ranges since the steeper energy is absorbed by the sediment.

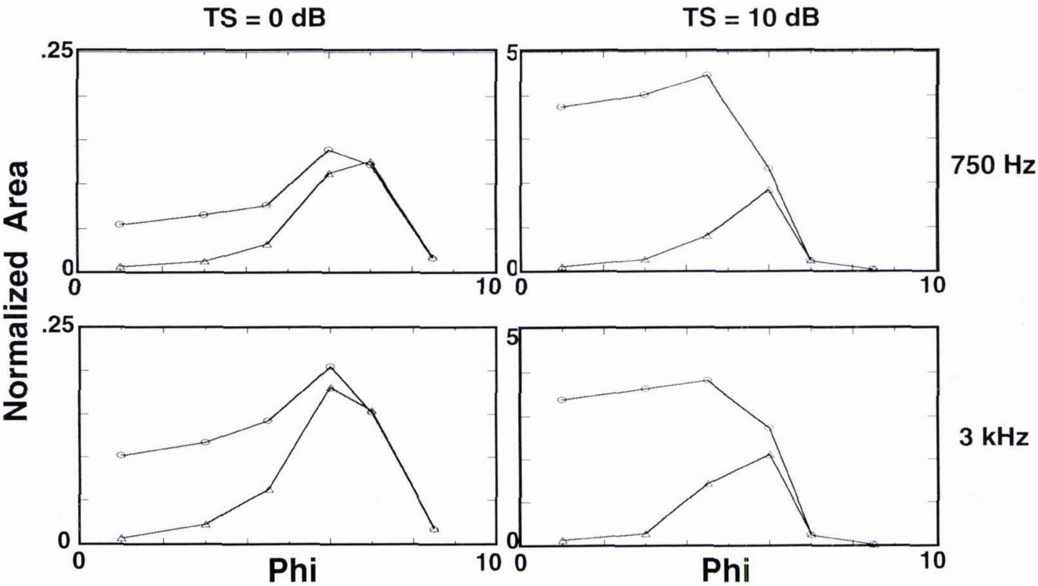

Fig. 7 Normalized detection area for 750 Hz (upper) and 3 kHz (lower) against a 0 dB (left) and 10 dB target in average water SSP conditions in all 6 bottom sediment types. The circles result from standard Lambert's Law / Mackenzie's Coefficient scattering and the triangles result from the proposed environmentally sensitive scattering kernel.

In all cases, the ALM detection performance is poor in the silty clay soft sediment (ϕ = 8.5) because TL is high and also poor in the coarse to fine sand hard sediments (ϕ = 1 to 3) because predicted reverberation from low grazing angles is large when the α plateau is applied. The proposed ALM approach shows a natural peak for optimum performance centered at the sand-silt-clay sediment.

Clearly, correct modeling of bottom scattering and bottom loss is essential to obtain accurate performance predictions. In addition, the water-mass properties must be carefully considered since they affect interface critical angles and ray trajectory angles, which has a significant impact on TL (see Figs. 5 and 6). An analysis was performed with these environmental-acoustic data to assess the relative impact of incorrect descriptions of water mass compared to bottom type in the regime of conditions considered in the St. of Sicily. Using detection area as a measure of effectiveness, it was found that correct bottom descriptions were about 5 times more important than correct water SSPs in this summer, downward refracting, shallow water situation. This result should be considered strategic rather than tactical. The implication is that for planning active acoustic ASW operations using archival environmental data, correct bottom descriptions are essential, whereas correct water SSPs are less important. However, during a tactical on-scene mission, the local details of the water mass can be extremely important due to dynamic changes in mixing layers and ducts which can affect choices to optimize sonar performance, like best source and receiver depth.

5. Summary

Based on a set of shallow-water geoacoustic descriptions and archival water sound speed information from the St. of Sicily, active sonar performance calculations were made for 750 Hz and 3 kHz in separate range-independent environments with water depth = 100 m. Performance against 0 to 10 dB targets at 50 m depth were compared in various possible environmental conditions using 2 approaches to modeling the scattering kernel; a) the standard Lambert's Law / Mackenzie Coefficient approach and b) Lambert's Law with the addition of environmentally sensitive Mackenzie's coefficient for moderate to high grazing angles and a low angle plateau. It was found that high transmission loss in soft sediments (with significant amounts of clay) caused poor detection performance. Further, high levels of bottom backscattering from hard sandy sediments limited detection areas when using the environmentally sensitive scattering function. Performance results were overly optimistic (by a factor of 3 to 30) when using the standard Lambert's Law / Mackenzie Coefficient. For intermediate sediments (grain sizes between sand and clay) detection performance was enhanced and optimized by a combination of only moderate TL and reverberation when the low angle plateau was employed.

6. Acknowledgements

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