The Dependence of Long-Range Reverberation on Bottom Roughness

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Abstract. At long-range, shallow-water reverberation can be driven by sub-critical-angle scattering, i.e. by rough interface scattering. The Naval Research Laboratory has recently developed a small-slope model for elastic seafloors that provides physics-based estimates of the dependence of scattering on the incident and scattered angles, and physical descriptors of the environment. In this paper, this incoherent model is used as kernels in reverberation models, which in turn are used to assess the sensitivity at 3.5 kHz of long-range monostatic reverberation to the roughness of the water-sediment interface. It is shown that when sub-critical-angle scattering dominates, the acoustic field could be quite sensitive to the parameter values of the roughness, thus arguing for the need for regional in-situ methods for its estimation.

INTRODUCTION

Bottom reverberation is a major source of interference for active sonar systems in shallow water that is caused by the interaction of acoustic energy with environmental features at or in the seafloor. The rough water-sediment (and sediment-sediment) interfaces and the sediment volume contribute to the acoustic reverberation. Often at long ranges, low scattering angles prevail. Under these conditions, rough interface scattering can be a dominant scattering mechanism, particularly for non-soft bottoms.

Recently, the Naval Research Laboratory (NRL) has developed broadband, bistatic physics-based formulas that predict the dependence of scattering strength on the incident and scattered angles, the acoustic frequency, and environmental variables [1]. It has been demonstrated that the acoustic Scattering Strength (SS) of the bottom interface can depend quite strongly on the environmental features [1,2]. In this paper, we use the bottom-interface formula as kernels in two reverberation models, the ray-based BiRASP [3] and mode-based R-SNAP [4] to explore the sensitivity of long-range reverberation in shallow water at 3.5 kHz to the values of the interface-roughness parameters.

A range-independent waveguide of 150 m depth was assumed. Two bottom half spaces were used in the study: very fine sand and rock (basalt). The assumed geoacoustic values come from Hamilton [5-6], for sand and rock respectively: density ratios of 1.85 and 2.7, compressional speeds of 1708 and 5185 m/s, compressional attenuations of 0.12 and 0.02 dB/m/kHz, shear speeds of 100 and 2745 m/s, and shear attenuations of 25.0 and 0.07 dB/m/kHz. Two sound speed profiles were considered (Fig. 1a), a near-isospeed "winter" profile and a downward-refracting "summer" profile. For these profiles, the p-wave (compressional) critical angles are at ~27 and

~73 deg for sand and rock respectively, while the s-wave (shear) critical angle for the rock is at ~56 deg. The assumed bottom losses are also shown in Fig. 1b. For the sand, it is seen that the loss is very low at angles below critical. For the rock, the maximum loss is between its two critical angles, while below ~45 deg, the losses are very low.

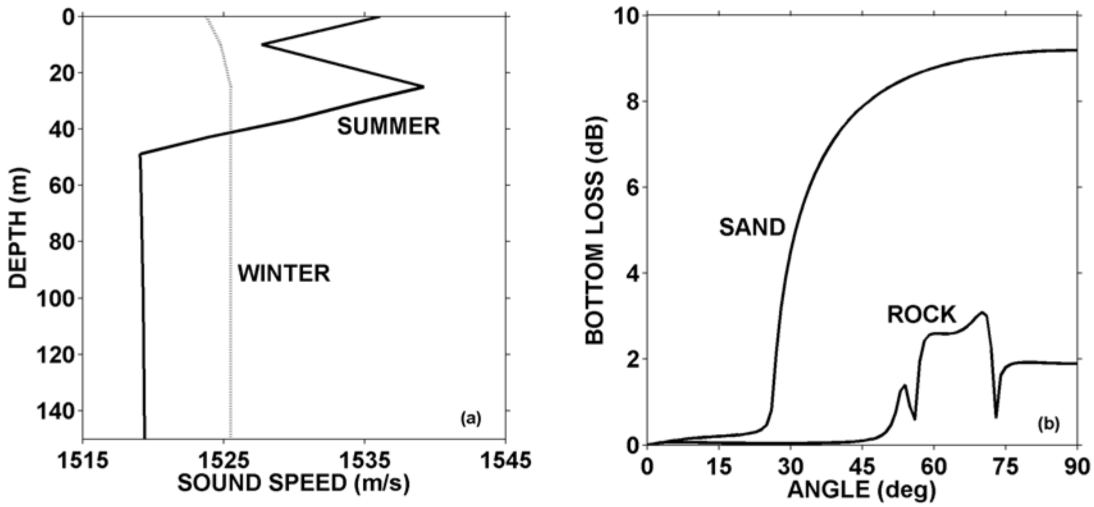

FIGURE 1. (a) Sound-speed profiles assumed in this study. (b) Bottom loss vs. angle at 3.5 kHz for rock and sand using REFLECT.

SCATTERING STRENGTH

The bottom scattering strength formula relies on lowest-order small-slope theory for scattering from the rough water-sediment interface [2] and a stochastic volume theory for scattering from the subbottom [7]. Figure 2 shows predicted monostatic bottom backscattering strengths vs. grazing angle at 3.5 kHz for very fine sand (left) and basalt (right) bottoms for three values of the bottom-interface roughness spectral exponent γ_2. In these plots, the other roughness parameter, the spectral strength w_2 was fixed at 0.001 m^4. In our reverberation model studies (next Section), we will also consider a w_2 value of 0.01 m^4, for a total of six cases.

Below the critical angle, the rough water-sediment interface is the dominant SS mechanism. At higher angles, the sediment volume contributes as well, especially when the bottom roughness is small; however, the particular volume model used predicts no sediment-volume scattering contribution below the critical angle. (This volume model ignores shear effects.)

Overlain in Fig. 2 are curves corresponding to the commonly-used (frequency-independent) Mackenzie's rule, i.e. Lambert's Law with μ = –27 dB. It shows significant differences, especially at low grazing angles (even if translated vertically, i.e. varying μ).

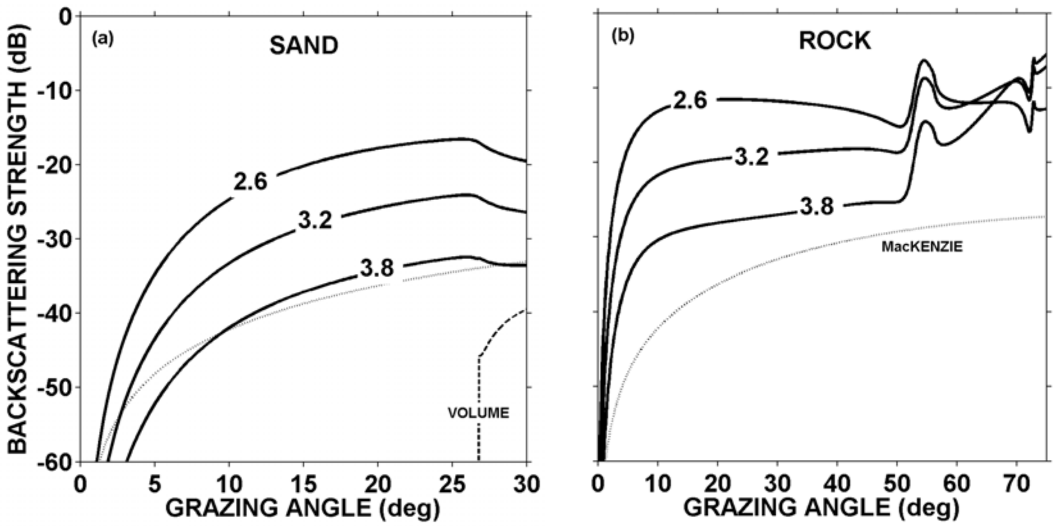

FIGURE 2. Monostatic bottom backscattering strength vs. grazing angle θ at 3.5 kHz for three values of the bottom roughness spectral exponent γ_2 for (a) sand to 30 deg and (b) rock to 75 deg. In each case, the bottom roughness spectral strength $w_2 = 0.001$ m^4. In (a), the solid curves represent the total (interface + volume) backscattering strength—the dashed curve shows the volume contribution. In (b), no volume contribution is included. For reference, the Mackenzie curve $\mu \sin^2\theta$ with $\mu = -27$ dB (dotted) is included in each plot.

LONG-RANGE REVERBERATION

To examine the sensitivity of long-range reverberation to environmental variables, the above scattering strength model was used as kernels in BiRASP and R-SNAP. The monostatic reverberation calculations assumed the co-located source and receiver (S-R) were at the same depths, with two depths considered: 10 and 75 m. A 0-dB source level and a 1-s (1-Hz-bandwidth) CW at 3.5 kHz were also assumed. (To obtain calibrated reverberation levels for a given source level, say, 200 dB re µPa at 1 m, simply add that number to the reverberation y-axis values.) Propagation included Thorp-based attenuation [8]. Noise was not included in the runs.

The reverberation predictions using the two models agreed very well, so for consistency this paper (and its companion, Ref. [9]) will present predictions from only those from one of the models, BiRASP. These runs also used monostatic scattering strengths as inputs. (We also did sets of bottom, surface and fish runs using bistatic scattering strengths as inputs in BiStaR, a bistatic version of R-SNAP. As expected for these simple monostatic scenarios, the results differed only slightly from the purely monostatic runs.)

Sensitivity Studies

Seasonal and geometry dependence are examined in Fig. 3a, where it can be seen the differences are very small (even at 70 s). A comparison of the rock and sand reverberation levels in Fig. 3a shows the significantly longer decay rates for the rock, e.g., over a 20-dB-higher Reverberation Level (RL) than for sand at most ranges. Such differences are not surprising given rock's higher scattering strengths (Fig. 2) and lower bottom losses (Fig. 1b) over more angles.

Sensitivity to roughness values is examined in Fig. 3b, using rock for the summer/ S-R at 75 m case as a representative example. Significant differences of up to 20 dB or more can be seen at all ranges. As after a few seconds sub-critical-angle scattering dominates, this argues that for such cases in the field, one needs to either acquire accurate estimations of the local roughness or measure in-situ the local backscattering strength over a range of grazing angles.

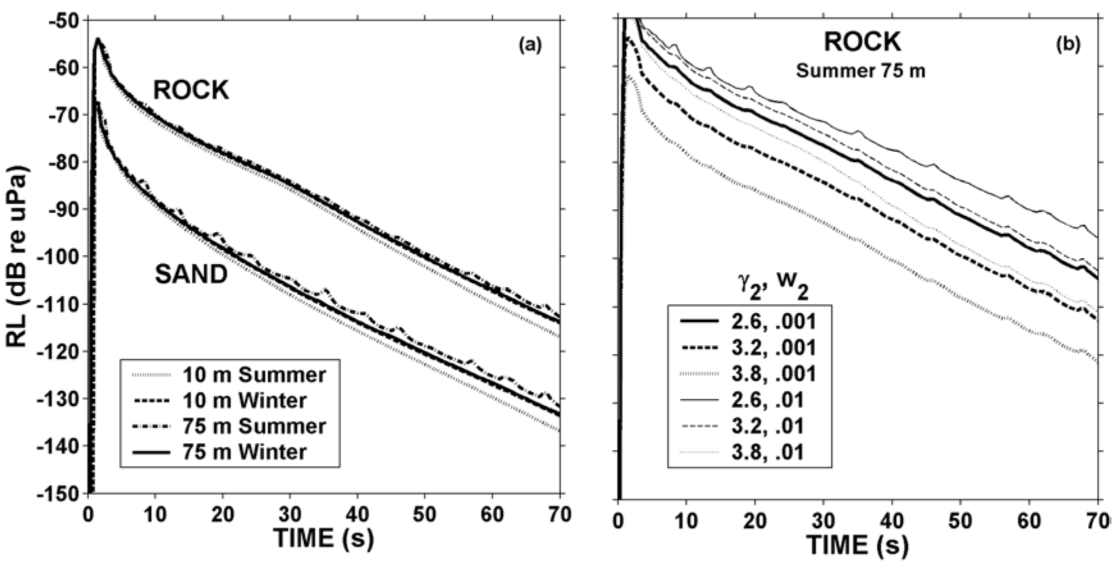

FIGURE 3. At 3.5 kHz: (a) RL for rock and sand for four scenarios for γ_2 = 3.2 and w_2 = 0.001 m^4; and (b) RL for rock for six pairs of roughness values for one scenario.

BiRASP's ability to deconstruct the reverberation by average grazing angle is illustrated for the summer profile/S-R at 75 m case in Fig. 4 for sand (a) and rock (b). (The corresponding RL curves in Fig. 3a are the sum of these curves.) It is seen that at 20 km (~26 s), angles up to 50 deg are still contributing in the rock case, but only angles up to 30 deg are in the sand case. This reflects both rock's higher critical angle(s) and lower bottom loss.

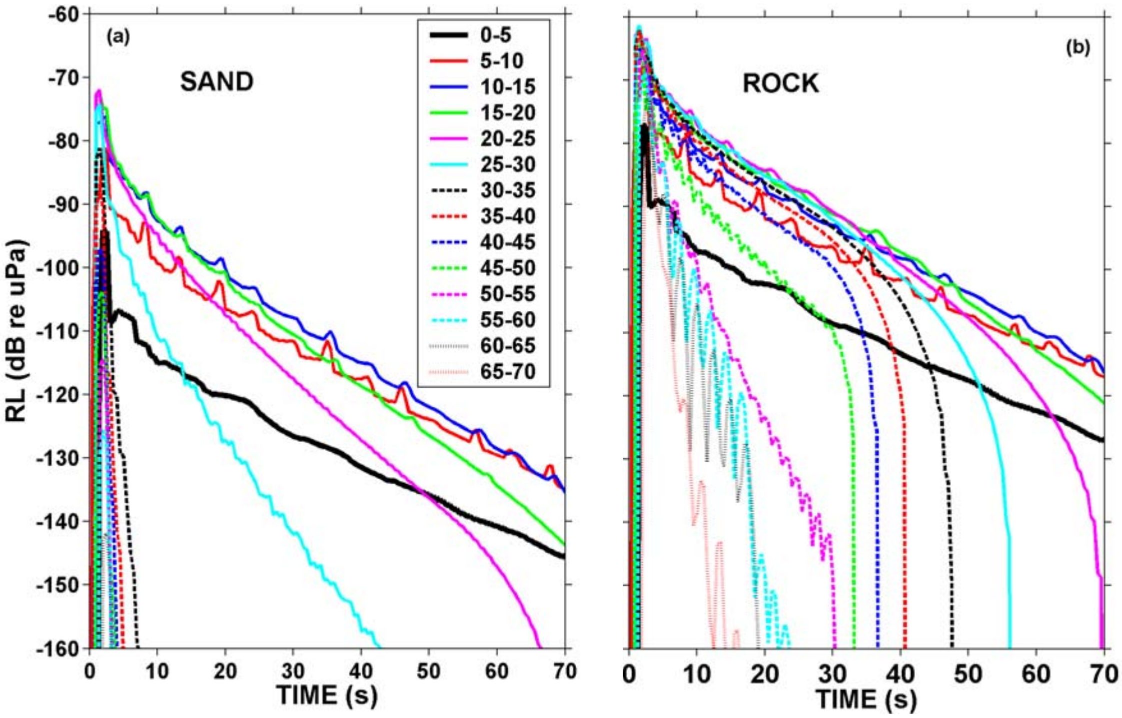

FIGURE 4. At 3.5 kHz for (a) sand and (b) rock: RL contributions by mean grazing angle in 5-deg bins for the $\gamma_2 = 3.2$ and $w_2 = 0.001$ m^4 case. Summer profile and S-R at 75 m.

To highlight the sensitivity of reverberation to the two bottom roughness parameters, Fig. 5 presents scattering strengths (top) and reverberation levels (bottom) for sand (left) and rock (right) *relative* to their values for the $\gamma_2 = 3.2$ and $w_2 = 0.001$ m^4 case.

For the scattering strengths, over the angles controlling the long-range reverberation, i.e. those below the p-wave critical angle for the sand and below the s-wave critical angle for the rock, the differences are generally fairly flat with angle (except above ~20 deg for the $w_2 = 0.01$ m^4 rock case), with generally increased backscatter in these cases the larger the w_2 (for a given γ_2) or the smaller the γ_2 (for a given w_2). (In general, increasing w_2 for a fixed γ_2, or decreasing γ_2 for a fixed w_2, will not always lead to stronger backscatter [2]—e.g., above the shear critical angle in Fig. 2b.) A non-obvious result is that the relative differences of the six cases are the same for rock and sand—note the different x-axis scales. This is because the scattering strength can be expressed as a product of two factors, one that depends on the bottom's material properties, but is independent of interface roughness (and frequency), and one that depends on the roughness (and frequency), but not the bottom properties [2]. So, when dividing by a reference case, the first factor is divided out, leaving a dependence only on the roughness parameters.

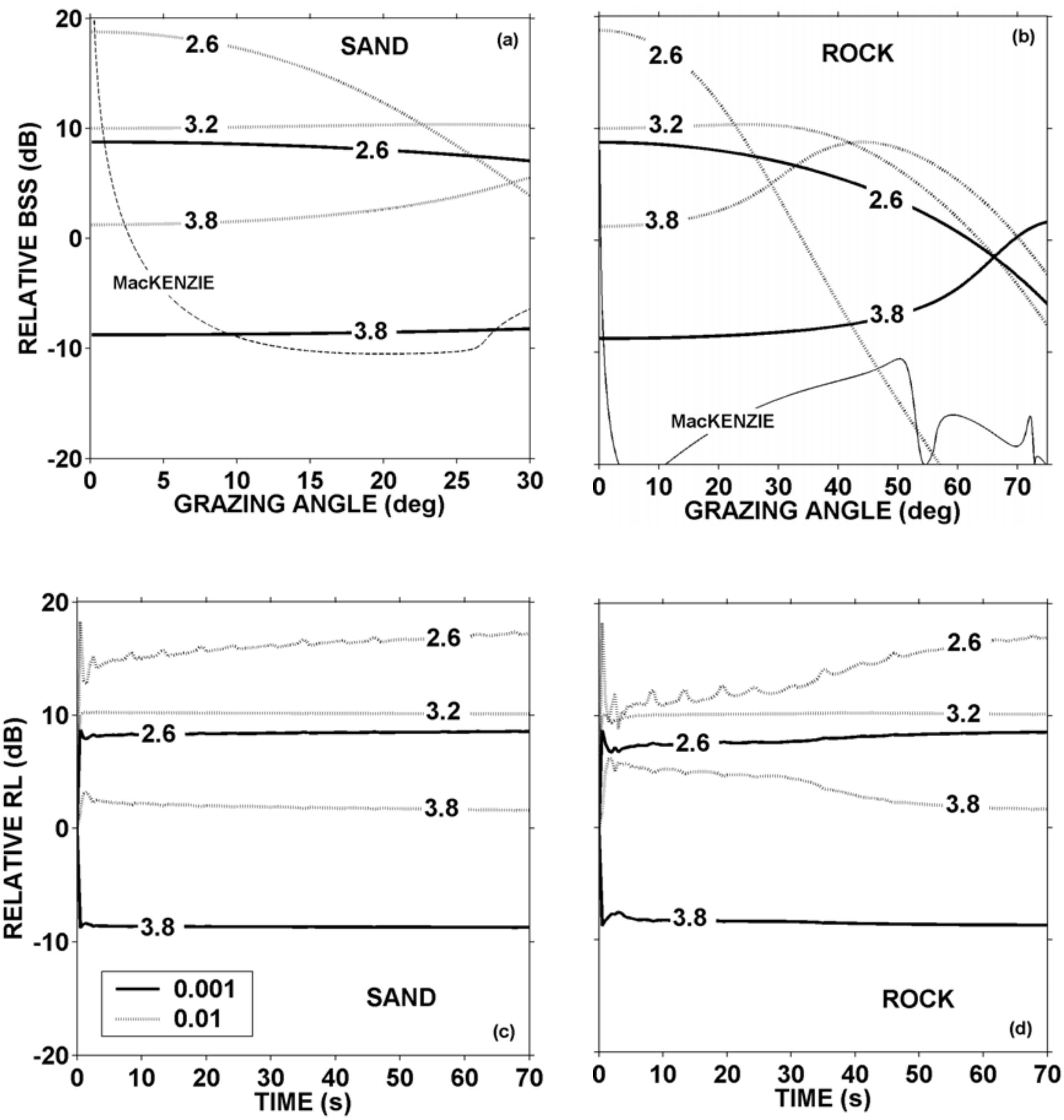

FIGURE 5. At 3.5 kHz for sand (left) and rock (right): scattering strengths (top) and reverberation levels (bottom) *relative* to the $\gamma_2 = 3.2$ and $w_2 = 0.001\ \text{m}^4$ case. Summer profile, S-R at 75 m. The solid and dotted curves correspond to w_2's of 0.001 and 0.01 m^4, respectively, with the γ_2's as shown.

For the reverberation, similar trends emerge. One difference that can be seen is the smaller spreads in the $w_2 = 0.01\ \text{m}^4$ rock values for times less than ~30s, a reflection of the complex γ_2 dependence at the higher angles (coupled with the range of contributing grazing angles for rock—cf. Fig. 4b).

SUMMARY AND DISCUSSION

Sub-critical-angle scattering, i.e. rough interface scattering, can drive shallow water reverberation. Application of an interface-scattering model for rough elastic seafloors in reverberation models suggests that the long-range acoustic field could be quite sensitive (up to 25 dB for the cases considered) to the parameter values of the roughness. As bottom roughness is a difficult quantity to accurately measure in the field even with state-of-the-art instrumentation, especially on regional scales, alternative methods for its in-situ estimation are needed. One method would be to use acoustic inversion with an elastic surface roughness model (as in [10]). A key feature of these scattering models is that the only frequency dependence is through the roughness spectral exponent γ_2 [2], arguing for multiple-frequency direct-path measurements to nail down its value. Given parameter values for the bottom, physics-based scattering strength models could then be used as kernels in reverberation models to predict the acoustic response at other frequencies and angles (especially bistatically).

This study also underscores the importance of the knowledge of the spatial and frequency dependence of the critical angle for predicting long-range reverberation. When considering sub-critical-angle scattering, a potential competing mechanism is near-bottom fish. As fish backscatter has a fairly flat grazing angle response, depending on their densities, sizes and depths, when present they can be significant low-angle scattering mechanism. See Ref. [9] for more details.

Finally, we note that for range-dependent environments, the presence of bathymetric features can excite higher angles at long range thus potentially enhancing reverberation variability at these ranges (especially if the feature is rock, i.e. of harder composition than the surrounding seabed).

ACKNOWLEDGMENTS

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