

# The Influence of the Sea Surface and Fish on Long-Range Reverberation

Roger Gauss, David Fromm, Kevin LePage, Joseph Fialkowski, and Redwood Nero\*

*Acoustics Division, Naval Research Laboratory, Washington, DC 20375-5350, USA*

*\* Acoustics Division, Naval Research Laboratory, Stennis Space Center, MS 39529-5004, USA*

**Abstract.** Acoustic detection for active sonars involves identifying target signatures in the presence of environmental effects, such as acoustic scattering from the ocean boundaries and fish. The Naval Research Laboratory has recently developed 3D broadband models that provide physics-based estimates of the dependence of scattering from the sea surface, bubble clouds and near-boundary fish (including boundary-interference effects) on the incident and scattered angles, and physical/biological descriptors of the environment. In this paper, these models and a surface-loss model are used as kernels in reverberation models, which in turn are used to assess the sensitivity at 3.5 kHz of long-range reverberation to environmental variables. It is shown that the acoustic field in shallow water waveguides could be quite sensitive to the values of sea surface (wind speed) and fish (density, size, depth) parameters, and that physics-based models are needed for accurate field characterization.

## INTRODUCTION

Reverberation is a major source of interference for active sonar systems that is caused by the interaction of acoustic energy with environmental features at or near the ocean boundaries. In low-to-moderate sea states, the seafloor, the rough air-sea interface, and fish contribute to the acoustic reverberation. When wave breaking is significant, air becomes entrained in the near-surface zone in the form of subsurface bubbles. Under these conditions, bubble clouds also contribute to the acoustic reverberation.

Recently, the Naval Research Laboratory (NRL) has developed broadband, bistatic physics-based formulas that predict the dependence of surface and near-boundary fish scattering strengths on the incident and scattered angles, the acoustic frequency, and environmental variables [1]. It has been demonstrated that the acoustic Scattering Strength (SS) can depend quite strongly on the environmental features [1,2]. In this paper, we use these formulae 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 both sea surface (wind speed) and fish (density, size, depth) parameters.

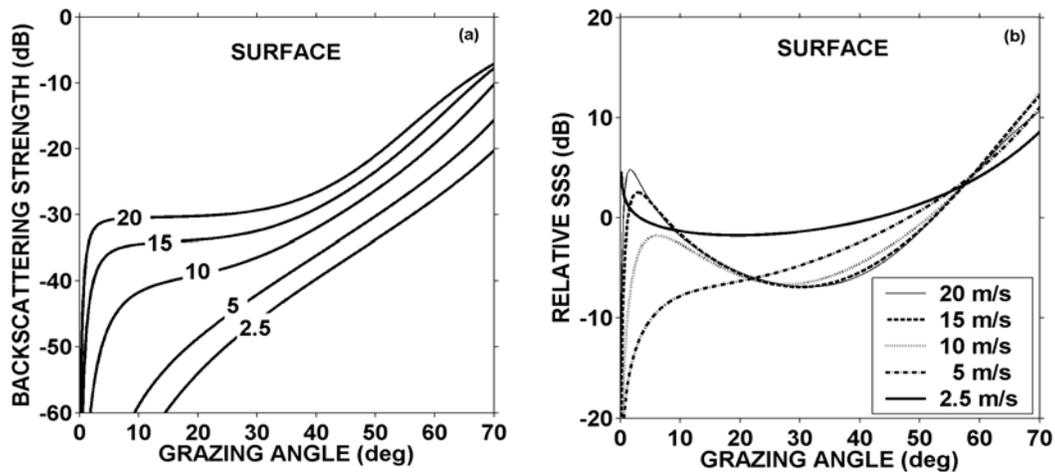
A range-independent waveguide of 150 m depth was assumed. Two bottom half spaces were used in the study: very fine sand and rock (basalt). The assumed geoacoustic values come from Hamilton [5-6]; for sand and rock respectively: density

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. The resulting bottom losses are shown in Fig. 1b of [7]. Two sound speed profiles were considered (Fig. 1a of [7]), a near-isospeed “winter” profile and a downward-refracting “summer” profile. For these profiles, the p-wave (compressional) critical angles are at  $\sim 27$  and  $\sim 73$  deg for sand and rock respectively, while the s-wave (shear) critical angle for the rock is at  $\sim 56$  deg. For this paper, the assumed bottom roughness values [7] are  $\gamma_2 = 3.2$  and  $w_2 = 0.001 \text{ m}^4$ .

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  $\mu\text{Pa}$  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.

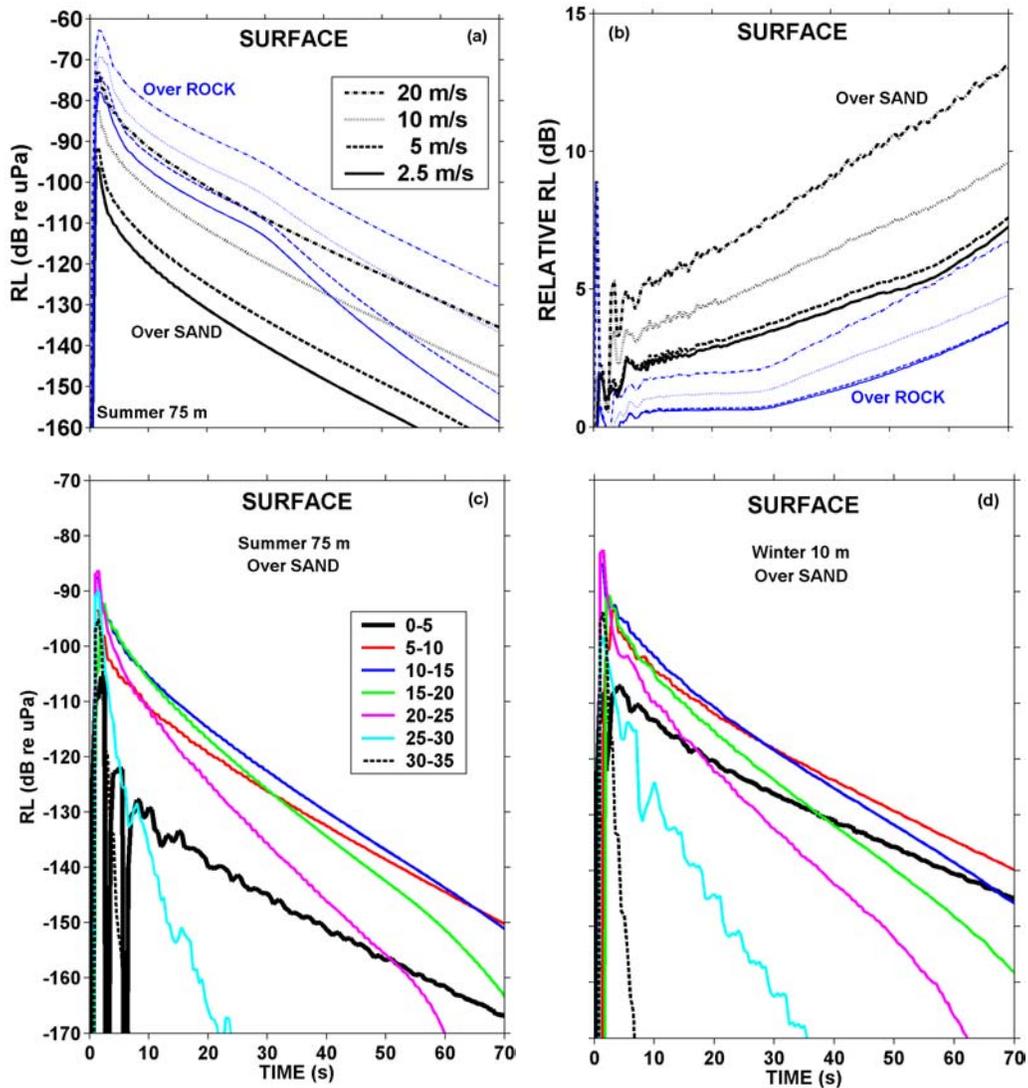
## SURFACE REVEBERATION

The surface scattering strength formula relies on lowest-order small-slope theory for scattering from the rough air-sea interface and a stochastic volume theory for scattering from the bubble clouds [1]. Model fits to open ocean data yielded a formula that environmentally depends only on the wind speed (measured at an elevation of 10 m). By its semi-empirical nature, the discrete nature of bubble clouds and attenuation effects are embedded in the effective surface-scattering formula. Figure 1a shows predicted sea surface backscattering strengths vs. grazing angle at 3.5 kHz for a set of wind speeds. At low scattering angles, bubble cloud backscattering is the dominant SS mechanism (when wave breaking is significant), and the rough air-sea interface at high scattering angles.



**FIGURE 1.** Predictions of monostatic surface backscattering strength at 3.5 kHz as parameterized by wind speed at 10 m (m/s): (a) NRL model and (b) the difference of two model predictions, NRL’s minus Chapman-Harris’s.

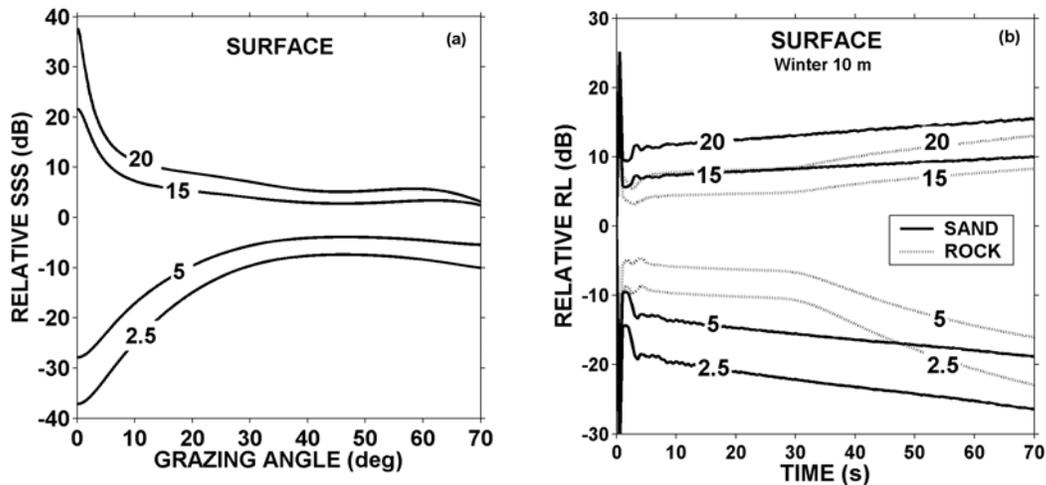
Figure 2 illustrates how long-range surface reverberation can depend not only on wind speed, but also on the waveguide characteristics (bottom type, sound speed profile) and geometry (S-R depth). Figure 2a shows significant differences in Reverberation Level (RL)—15 to 25 dB at 20 km (~26 s)—depending on whether the seafloor is sand or rock. The significantly longer decay times for a rock seafloor compared to a very fine sand seafloor are a function of how much energy propagates to a given range, a result of the lower bottom loss and higher critical angle for rock [7]. As illustrated in Fig. 2b, RL exhibited more sensitivity to the sound-speed profile and S-R depth when the seafloor was sand.



**FIGURE 2.** Predictions of monostatic surface reverberation at 3.5 kHz. (top) As parameterized by wind speed  $U$  for both sand and rock seafloors, (a) RL vs. time for the summer profile/75 m S-R case, and (b) relative enhancement in RL in going from the summer profile/75 m S-R case to the winter profile/10 m S-R case. (c-d) RL contributions by mean grazing angle in 5-deg bins when  $U = 10$  m/s for two scenarios.

The latter effect is explored in Fig. 2c-d. Using BiRASP's ability to deconstruct the reverberation by average grazing angle, it is seen that in the downward-refracting conditions of the summer profile/mid-water S-R case (left), the higher-angle energy is more quickly stripped away and lower-angle interactions more shielded compared to the mild ducting conditions of the winter-profile/shallow S-R case (right). The relative absence of this effect for a rock seafloor over this time window is due to rock's higher critical angle, coupled with lower bottom loss (cf. Fig. 4 in Ref. [7]).

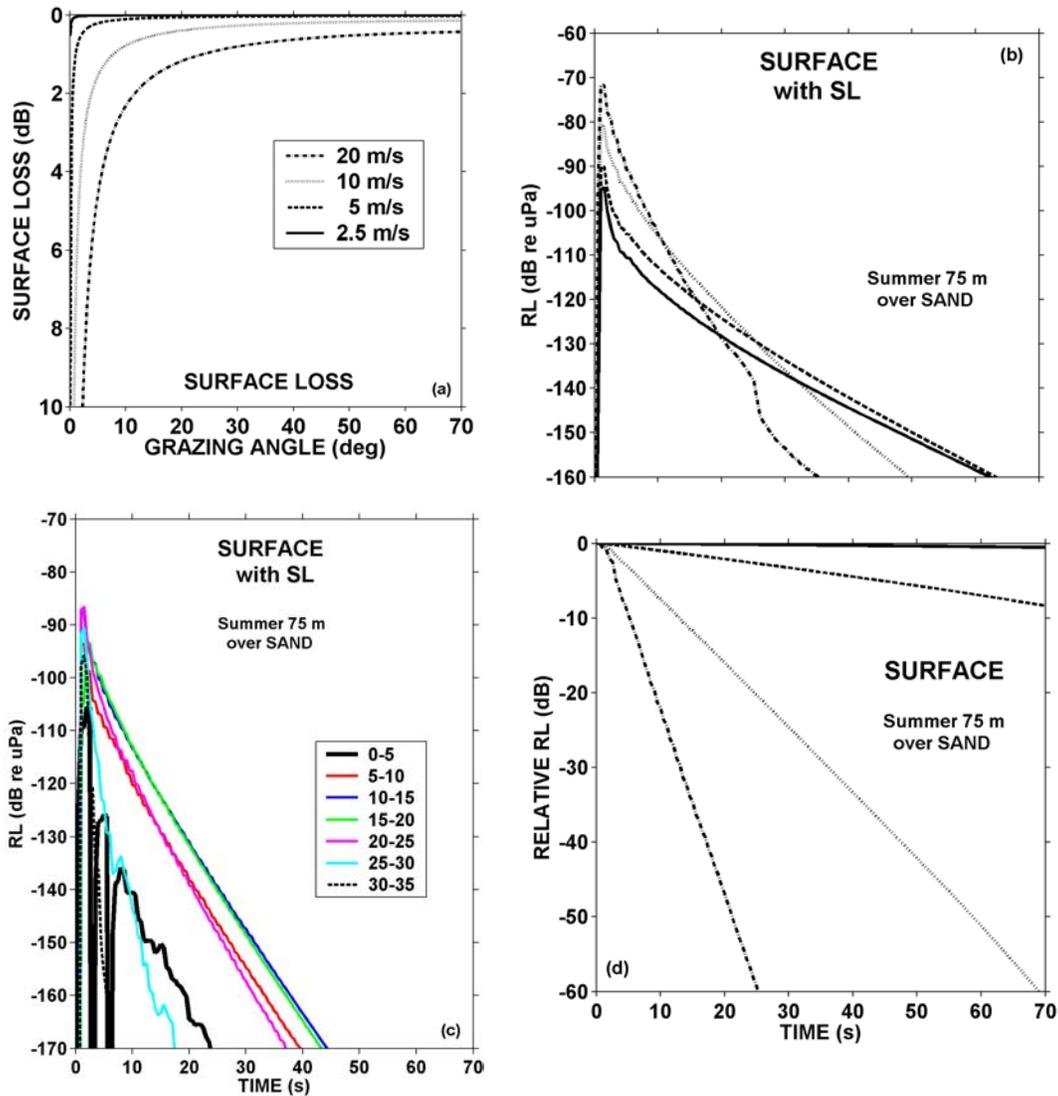
Figure 2a suggests that RL grows increasingly sensitive to wind speed  $U$  with increasing range (time), i.e. as lower and lower grazing angle backscattering dominates the reverberation. This is made more apparent in Fig. 3, which presents SS (left) and RL (right) *relative* to their values at  $U = 10$  m/s. It is seen that the biggest RL differences occur at the lower wind speeds.



**FIGURE 3.** At 3.5 kHz for four wind speeds  $U$  relative to the  $U = 10$  m/s case: (a) surface scattering strengths and (b) surface RL over sand and rock for the winter profile, S-R at 10 m case.

## SURFACE LOSS

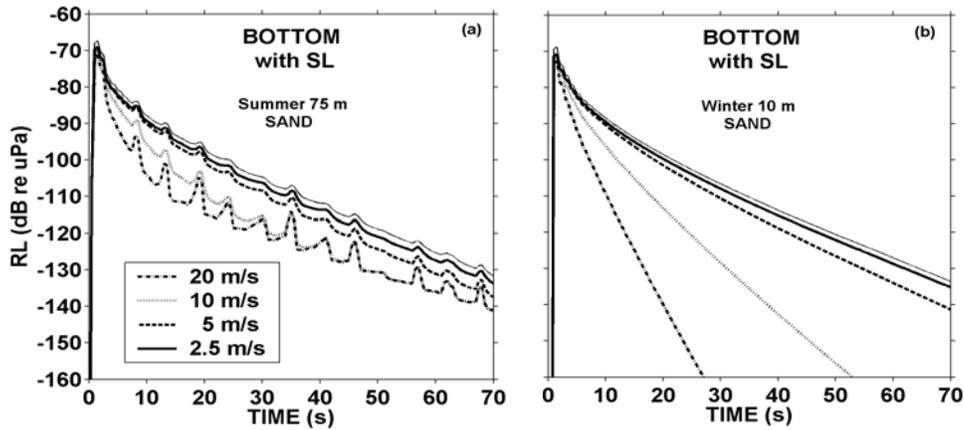
The above RL predictions (and all those in Ref. [7]) ignored the effects of surface loss on the propagation. In this section, we incorporate the incoherent high-frequency Surface Loss (SL) model of APL/UW [9-10] (extrapolated down to 3.5 kHz) into the propagation calculations of BiRASP. Figure 4a shows predictions of SL vs. grazing angle at 3.5 kHz for four wind speeds. It is seen that the losses per bounce are largest at low grazing angles, especially at high wind speeds. (Bubble attenuation is the primary surface loss mechanism [10].) Incorporating this SL model in the BiRASP runs significantly reduced the predicted RL at long range as demonstrated by comparing the curves in Fig. 4b,c with the corresponding curves for sand in Fig. 2a,c. To make the impact clearer, Fig. 4d displays the characteristic reduction in RL when SL is included as a function of wind speed. Only for the 2.5- and 5-m/s wind-speed cases are the reductions not large.



**FIGURE 4.** 3.5-kHz predictions at four wind speeds  $U$ : (a) SL vs. grazing angle. For the summer profile / S-R at 75-m over a sandy seafloor case: (b) surface RL including SL; (c) reverberation contributions to the  $U = 10$  m/s case of (b) by mean grazing angle in 5-deg bins; and (d) the reduction in surface reverberation when SL is included in the propagation calculations.

Figure 5 includes SL in predictions of bottom reverberation for two scenarios. The assumed bottom scattering strengths are described in Ref. [7] ( $\gamma_2 = 3.2$ ,  $w_2 = 0.001 \text{ m}^4$  case). Marked differences between the scenarios are apparent, with SL having relatively little impact at long range in the summer profile/75 m S-R case, but a significant impact in the winter profile/10 m S-R case where there are significantly more low-angle surface interactions (cf. Fig. 2c-d).

These runs stress the importance of surface loss on reverberation, whether it be from the bottom, sea surface, or fish and, so, the importance of having accurate SL models. (Small changes in dB-per-bounce values can have major cumulative effects on long-range reverberation levels at mid-frequencies.)



**FIGURE 5.** Effects on bottom reverberation of including surface loss in the propagation modeling for a sand bottom for two scenarios: (a) summer profile with S-R at 75 m and (b) winter profile with S-R at 10 m. The topmost curve (thin solid line) in each plot corresponds to a zero wind speed [7].

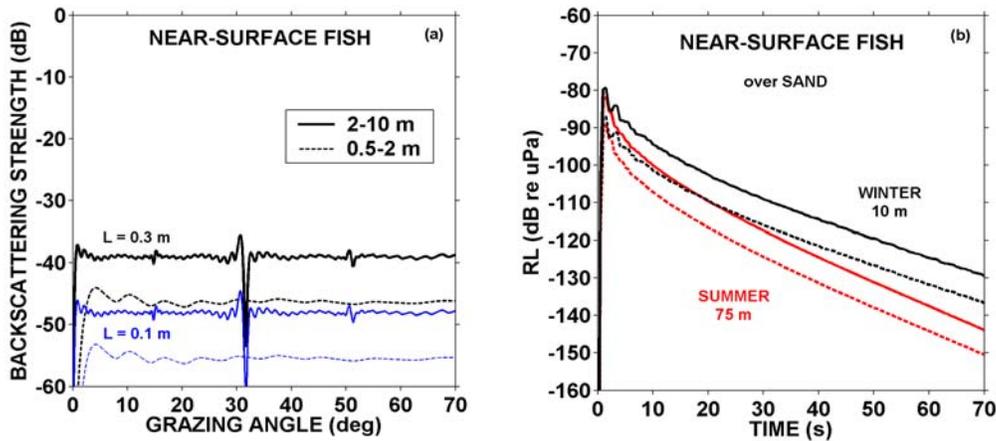
## REVERBERATION FROM FISH

The primary physical drivers of the acoustic response of fish are their density, and size and depth distributions [11]. When fish are near the ocean surface or bottom, boundary-interference effects must also be accounted for. In Refs. [1-2], the fish target strength model of Love [11] was extended by convolving a Lloyd-mirror model with fish density and target strength over their depths to yield a formula effectively equivalent to surface scattering algorithm (allowing a simple implementation in reverberation models). For fish near the bottom, bottom properties are also important (but not the roughness parameters) [1]. This paper assumes the fish are uniformly distributed throughout the layer and ignores fish-attenuation effects. The RL calculations in this section assume flat boundaries and ignore SL effects.

Figure 6a shows predictions of fish backscattering strength vs. grazing angle at 3.5 kHz for mean fish lengths of 0.3 and 0.1 m, and for layer depths of 0.5-2 and 2-10 m below the sea surface. (The density was fixed at 0.01 fish per  $m^3$ . Changing fish density by a factor of  $k$  raises or lowers such curves by  $10\log_{10}(k)$  dB.) It is seen that at these depths, the scattering response is basically flat with grazing angle.

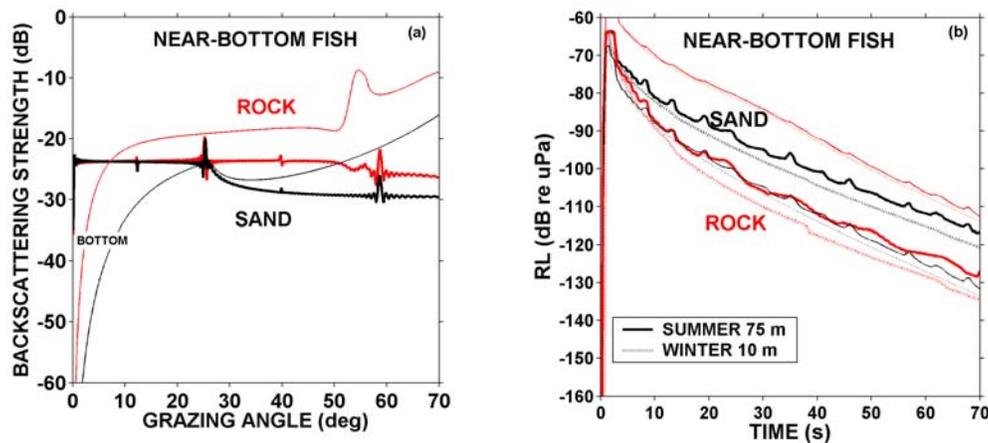
Figure 6b shows the sensitivity of near-surface fish reverberation to fish depth and scenario. A noticeable dependence on scenario is seen with levels up to 10 dB higher at 20 km ( $\sim 26$  s) in the winter profile/10 m S-R case. As expected given the flat dependence of scattering strength on grazing angle, the reverberation differences for different layer depths for a given scenario are basically range independent.

A comparison of Fig. 6a with Fig. 1a suggests that whether the sea surface or fish dominates near-surface reverberation can depend on grazing angle and a number of environmental factors: wind speed and fish density, sizes, and depths. For example, comparing Fig. 6b with Fig. 2a shows that for the chosen fish parameters, near-surface fish reverberation is dominant over surface reverberation at low wind speeds and comparable to surface reverberation at high wind speeds. Recall changes in fish density can raise or lower the RL curves. (Frequency is another consideration.)



**FIGURE 6.** At 3.5 kHz for fish in layers 0.5-2 and 2-10 m below a flat sea surface at a density of  $0.01 \text{ m}^{-3}$ : (a) monostatic backscattering strength vs. grazing angle for two fish sizes, 0.3 and 0.1 m, and (b) near-surface fish reverberation for two scenarios over sand.

Similarly, for fish near the bottom, their scattering strength response with angle is basically flat (Fig. 7a), and whether the bottom or fish dominates the bottom-zone reverberation depends on the grazing angle, and fish sizes, depths and densities. This is illustrated in Fig. 7b, where for the particular parameter values chosen, near-bottom fish can easily dominate bottom reverberation from a sandy seafloor, but can be easily dominated by bottom reverberation from a basalt seafloor. Near-bottom fish reverberation was relatively insensitive to scenario, with  $\sim 5$  dB differences at 20 km.



**FIGURE 7.** At 3.5 kHz for 0.3-m-long fish 0-25 m above flat rock and sand seabeds at a density of  $0.1 \text{ m}^{-3}$ : (a) monostatic backscattering strength vs. grazing angle for fish over rock and sand (thick curves). Also shown are corresponding bottom backscattering strengths at 3.5 kHz (thin curves). (b) Comparison of near-bottom fish (thick curves) and bottom (thin curves) RL for rock and sand for two scenarios.

In real shallow-water environments, fish are not uniformly distributed in space. Hence, RL curves would exhibit range and azimuth dependence beyond such as that shown in Figs. 6 and 7 (e.g., fish echoes may only be seen at particular ranges in a

limited set of beams). An additional complication is that fish exhibit a variety of temporal (short-term, day/night and seasonal) behavior.

## DISCUSSION

The model studies in this paper suggest that the sea surface and near-boundary fish could have a significant impact on reverberation levels, and moreover those levels could be quite sensitive to geometry, and oceanographic (wind speed, sound speed profile), geoacoustic, and biological (fish depth, size and density) variables. As the latter are generally unknown for a given environment, there is a particular need to assess the local fish populations (e.g., perhaps via echosounders) coupled with models such as these to estimate their contribution to the reverberation. Knowledge of fish behavior (e.g., typical day/night depths) can then help optimize sonar settings to minimize their impact.

## ACKNOWLEDGMENTS

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## REFERENCES

1. Gauss, R. C., Gragg, R. F., Nero, R. W., Wurmser, D., and Fialkowski, J. M., "Broadband Models for Predicting Bottom, Surface, and Volume Scattering Strengths," NRL/FR/7100—02-10,042, Washington, DC: Naval Research Laboratory, September 30, 2002.
2. Gauss, R. C., Fialkowski, J. M., and Wurmser, D., "Assessing the Variability of Near-Boundary Surface and Volume Reverberation Using Physics-Based Scattering Models," in *Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance*, edited by N. G. Pace and F. B. Jensen, Dordrecht: Kluwer Academic, 2002, pp. 345-352.
3. Fromm, D. M., Crockett, J. P., and Palmer, L. B., "BiRASP – The Bistatic Range-dependent Active System Performance Model," NRL/FR/7140—95-9723, Washington, DC: Naval Research Laboratory, September 30, 1996.
4. LePage, K. D., "Monostatic Reverberation in Range Dependent Waveguides: The R-SNAP Model," SACLANT Undersea Research Centre SR-363, La Spezia, Italy, 2002.
5. Hamilton, E. L., "Geoacoustic Modeling of the Sea Floor," *J. Acoust. Soc. Am.* **68**, 1313-1319 (1980).
6. Essen, H.-H., "Scattering from a rough sedimental seafloor containing shear and layering," *J. Acoust. Soc. Am.* **95**, 1299-1310 (1994).
7. Gauss, R. C., Fromm, D. M., LePage, K. D., and Gragg, R. F., "The Dependence of Long-Range Reverberation on Bottom Roughness," in *High Frequency Ocean Acoustics Conference*, edited by M. B. Porter, T. M. Siderius, and W. A. Kuperman, San Diego, CA, March 2004.
8. Jensen, F. B., Kuperman, W. A., Porter, M. B., and Schmidt, H., *Computational Ocean Acoustics*, AIP Press, 1994, p. 38.
9. Thorsos, E. I., "Surface Forward Scattering and Reflection," APL-UW 7-83, Applied Physics Laboratory, University of Washington, May 1984.
10. Dahl, P. H., "Revisions and Notes on a Model for Bubble Attenuation in Near-Surface Acoustic Propagation," APL-UW TR 9411, Appl. Physics Laboratory, University of Washington, July 1994.
11. Love, R. H., "Resonant Acoustic Scattering by Swimbladder-Bearing Fish," *J. Acoust. Soc. Am.* **64**, 571-580 (1978).