Model Development to Support Analysis of Acoustic Buried Target Data

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LONG-TERM GOAL

The work reported here makes use of scattering models to understand the high sub-critical-grazing-angle target detection performance initially observed at the SAX99 field test using NSWC PC's synthetic aperture sonar (SAS) system. In this test, cylindrical targets buried as much as 50 cm in a fairly uniform sand bottom with minor roughness on the surface were detected robustly at grazing angles low enough (e.g., below the critical grazing angle) and frequencies high enough that detection would normally be expected to be very difficult. The long-term goal is to identify the mechanism and relevant environmental parameters responsible for detection and use this information to formulate models that reliably predict sonar detection and classification/identification performance against buried mines.

OBJECTIVES

The work performed this year follows up on work begun in previous years to use buried target scattering models to predict and explain the performance of synthetic aperture sonar (SAS) for imaging cylindrical targets buried in a sand bottom. Current models are configured to account for scattering by elongated targets (e.g., a finite cylinder) buried in an attenuating bottom with a rippled upper interface. A continuing objective has been to use these models to check that ripple diffraction correctly accounts for enhanced sound transmission and target backscatter at shallow sonar grazing angles by comparing their predictions with laboratory measurements. Another objective this year has been to use the validated scattering models to look at evanescent wave effects, which have become of interest lately as developmental sonar have been fielded for buried target detection at lower frequencies.

APPROACH

As in previous years, the investigations performed used comparisons between model predictions and data collected in controlled measurements with buried targets to validate ripple scattering as a mechanism for enhancing backscatter by buried targets. For simple target shapes, the model predictions are generated from high-fidelity acoustic scattering solutions based on the transition (T) matrix method [1] to account for free-field scattering within the sediment, layered-medium basis functions to account for propagation to and from the scatterer [2], and Rayleigh-Rice perturbation theory to account for transmission across interface roughness in the basis functions [3]. For target shapes that the T matrix approach has difficulty with, PCSWAT is updated and verified against the simpler shapes accessible to the T matrix and then PCSWAT is used to compare with data collected using more complex shapes. Controlled data was collected in NSWC PC's freshwater pond facility by J. Lopes with support from a separate ONR project (document #N0001407WX20546).

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14. ABSTRACT

The work reported here makes use of scattering models to understand the high sub-critical-grazing-angle target detection performance initially observed at the SAX99 field test using NSWC PC?s synthetic aperture sonar (SAS) system. In this test, cylindrical targets buried as much as 50 cm in a fairly uniform sand bottom with minor roughness on the surface were detected robustly at grazing angles low enough (e.g., below the critical grazing angle) and frequencies high enough that detection would normally be expected to be very difficult. The long-term goal is to identify the mechanism and relevant environmental parameters responsible for detection and use this information to formulate models that reliably predict sonar detection and classification/identification performance against buried mines.

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WORK COMPLETED

Last year a free-field spheroidal-basis transition matrix developed by G. Sammelmann was incorporated into the buried target scattering models that, in the past, were limited to near spherical targets [4]. Ripple above the target is modeled with a sinusoidal interface and the effect of this interface is accounted for using small-amplitude, Rayleigh-Rice perturbation theory. As with the models for near-spherical targets, multiple scattering between the scatterer and the ripple interface is ignored. The resulting scattering solution was coded in C++. Publication of this work has been pursued this year with a manuscript written for journal submission detailing the derivation and demonstration of the arbitrary-order perturbation theory used [5]. Another manuscript incorporating this formulism into the spheroidal-basis T-matrix scattering solution for a buried elongated scatterer is in progress.

The spheroidal-basis T-matrix code was also exercised to compare its predictions against both laboratory data collected with a buried aluminum (Al) cylinder in NSWC PC's freshwater pond facility and predictions of PCSWAT. In the T-matrix formulism, the cylindrical shape is modeled by encoding the target as a superspheroid. By increasing the order of the superspheroid, its shape approaches that of a flat-endcapped cylinder. However, even with the use of spheroidal basis functions, stability of the T-matrix code is best and convergence fastest for this target shape when the aspect ratio is not too extreme. To keep calculation times reasonable (i.e., limited to overnight runs), we concentrated on comparisons with the 2ft long Al cylinder, which had an aspect ratio of 2. This provided an important check on the fidelity of the algorithms in PCSWAT as well on the basic physics built into models to explain observations for very nonspherical targets.

A study was also initiated to look at the consequences of scattering by a buried sphere at shallow grazing angles and low enough frequencies that evanescent waves are important. The impetus for this study was to help understand observations from mid-frequency (1-10 kHz) field data (Florida Atlantic University's Bottom Object Search Sonar (FAU BOSS)) suggesting that buried objects illuminated at grazing angles shallower than 20° on a sand bottom are undetectable. T-matrix calculations were run to clarify when evanescent scattering dominates the scattering and to predict signal-to-noise (SNR) expected for these angles and frequencies. Cases were also calculated to assess the potential for higher signal-to-noise in bistatic scattering configurations when evanescent scattering is important.

RESULTS

Transition Matrix Predictions for the 2ft Al cylinder: In recent controlled sonar measurements, data was taken with Al cylinders buried shallowly in NSWCPC's Acoustic Test Pond Facility 383 [6]. Two 1 ft diameter cylinders were used that were either 2 ft or 5 ft long. To assess the ripple diffraction mechanism for explaining the data as well as check the fidelity of the modeling, a comparison between T-matrix and PCSWAT predictions with measured signal levels was carried out. An example of a comparison for the 2 ft long cylinder is given in Fig. 1. In the Facility 383 measurement setup for this target, the cylinder was buried in sand under sinusoidal surface ripple of 75 cm wavelength and 2.46 cm amplitude. The ripple wave vector was directed at an angle of 101° from the direction of the track along which the sonar moved. The cylinder was buried at a range of 10.75 m from the track of the sonar, 27.94 cm deep (from the ripple median to the center of the cylinder), and the cylinder axis paralleled the track. For the case considered here, data were collected in the 15-45 kHz band at a 20° grazing angle on the bottom over the target and processed to form SAS images of the bottom. In the model results, the following parameters were assumed: water sound speed, 1500 m/s; water density,

1.0 g/cm^3; Al compressional speed, 6568 m/s; Al shear speed, 3149 m/s; Al density, 2.7 g/cm^3; sediment density, 2.0 g/cm^3; sediment sound speeds, (1650.0, -10.0) m/s and (1668.0, -16.8) m/s. Note that the sand sediment is treated as an attenuating fluid. In both the PCSWAT and T-matrix results, second-order Rayleigh-Rice perturbation theory was used to represent the transmission effects of the surface. Multiple scattering between the spheroid and the surface is expected to be a minor contribution to the backscatter and ignored in the calculations. In the T-matrix calculations, the cylinder is represented as a super-spheroid of order 10. Calculations were terminated below 34 kHz due to decreasing precision at the pre-set T-matrix truncations.
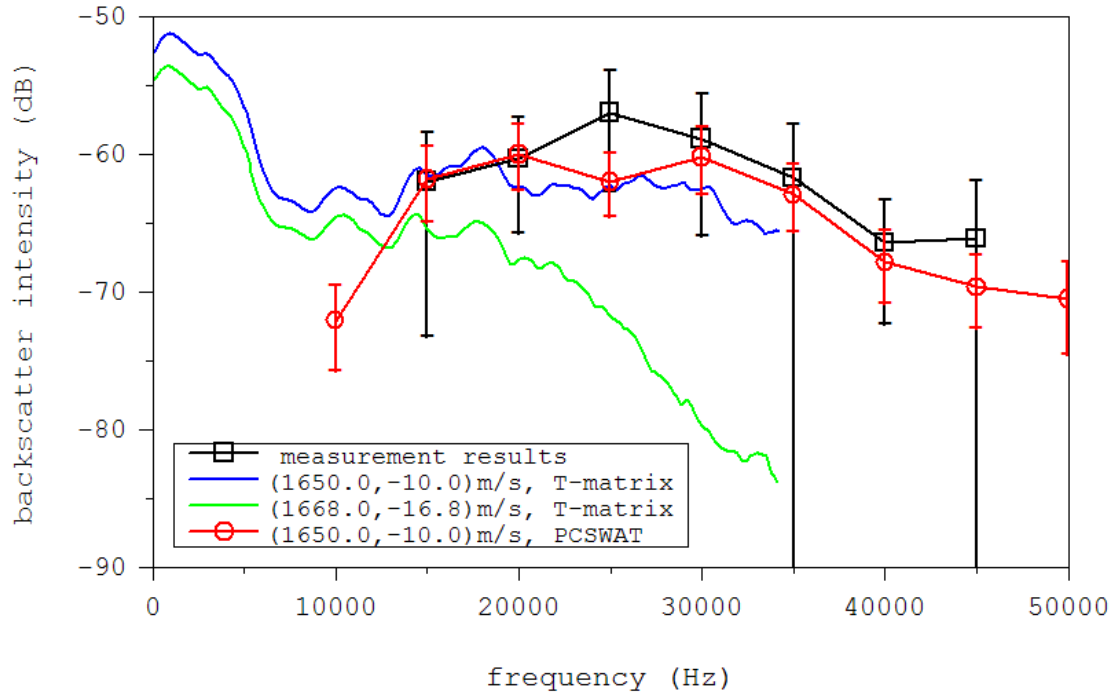

***Figure 1. Comparison of backscatter signal intensity predictions
from spheroidal-basis T-matrix and PCSWAT with measured levels.***

The measured backscatter signal levels in Fig. 1 (black boxes) were deduced from SAS images processed from the data collected. To calibrate the signal level of the image relative to the unit amplitude plane wave assumed in the calculated results, it is scaled using a source level recorded at a hydrophone near the target. Likewise, the predicted signal levels from PCSWAT (red circles) were deduced from the signal levels observed in simulated images. Error bars in both of these curves account for the uncertainty inherent in estimating the signal levels when reverberant bottom noise is present. The two T-matrix calculations (blue and green lines) are computed without noise contamination included but they have been smoothed by averaging the computed spectra with a 5 kHz moving window. This is meant to account for spectral averaging that occurs as part of the SAS beamforming process.

A couple of comments can be made in regard to the comparisons in Fig. 1. First, good agreement between modeled and measured signal levels is exhibited as a function of frequency provided sediment parameters associated with the lower attenuation range of measured values is assumed. This has been

noted before in model-measurement comparisons using a buried oil-filled spherical shell [3] in the Facility 383 pond. The need to choose different sediment sound speeds for particular measurements to facilitate agreement with model predictions suggests the sediment experiences an unknown amount of settling each time a target is buried and the sand around it reconfigured. The reason for this has not been correlated with any noticeable difference in how the measurement set-up is prepared but remains a potential source of error in future comparisons due to the apparent sensitivity exhibited by the predicted curves in Fig. 1.

Another observation worth mentioning is the relative disagreement between T-matrix and PCSWAT predictions at 10 kHz. This discrepancy may be caused by not accounting for the evanescent wave properly in PCSWAT because evanescent wave and ripple penetration effects appear to interfere at this frequency. This possibility will be investigated further in future work.

Evanescent Wave Predictions: Sonar operating in the mid-frequency band is capable of penetrating sand sediments at subcritical grazing angles to detect targets within 0.5 m of the surface using evanescent waves. However, the lack of detections reported below 20° grazing by developmental systems (e.g., FAU's BOSS) on known buried targets prompts one to ask why. To investigate this issue, a number of T-matrix calculations were performed using spheres buried under a flat sand bottom, illuminated from several grazing angles. In one set of calculations, the source/receiver is assumed to be 17.78 m (horizontal range) from a 35.56 cm-diameter sphere, flush-buried in a sand bottom. The grazing angle desired is used to set the vertical height of the source receiver, from 1.56 m at 5° to 10.27 m for 30°. The following target and environment parameters were assumed: water sound speed, 1543 m/s; water density, $1.0 g/cm^3$; steel compressional speed, 5773 m/s; steel shear speed, 3100 m/s; steel density, $7.975 g/cm^3$; oil sound speed, 1004.0 m/s; oil density, $0.97 g/cm^3$; sediment density, $2.0 g/cm^3$; sediment sound speed, (1735.875, -17.35875) m/s. To account for bottom reverberation, small-scale random roughness typical of medium sand was assumed, as specified by University of Washington Applied Physics Laboratory (APL-UW) researchers [7].

Figure 2 provides a sample of the calculations performed to assess the potential SNR when mid-frequency sonar is used to detect flush-buried spherical targets at 4 grazing angles: 5°, 10°, 20°, and 30°. Three types of sphere are considered: an enhanced target strength (nominally -10 dB) oil-filled steel shell of 0.98% thickness, a solid steel sphere, and a rigid, immovable sphere. The noise level of the bottom needed to determine SNR was determined using APL-UW's perturbative small-scale roughness model [7] assuming a reverberant patch size suitable for FAU's BOSS. The results show that at 30°, which is above the critical grazing angle, SNR is in excess of 10 dB. However, at all the other grazing angles, which are sub-critical, SNR is mostly negative except for the oil-filled sphere (ofs) between 2 and 4 kHz. Still, this indicates that targets of higher target strength should be detectable even with deeper burial. Note that as the grazing angle drops from 10° to 5° the SNR does not change significantly. This is a result of the noise level and signal level falling off at comparable rates as a function of grazing angle. This occurs if one assumes that SAS processing maintains the same reverberant patch size at different grazing angles. Whether this is a proper assumption will be assessed as comparisons with measurements are considered in future study.
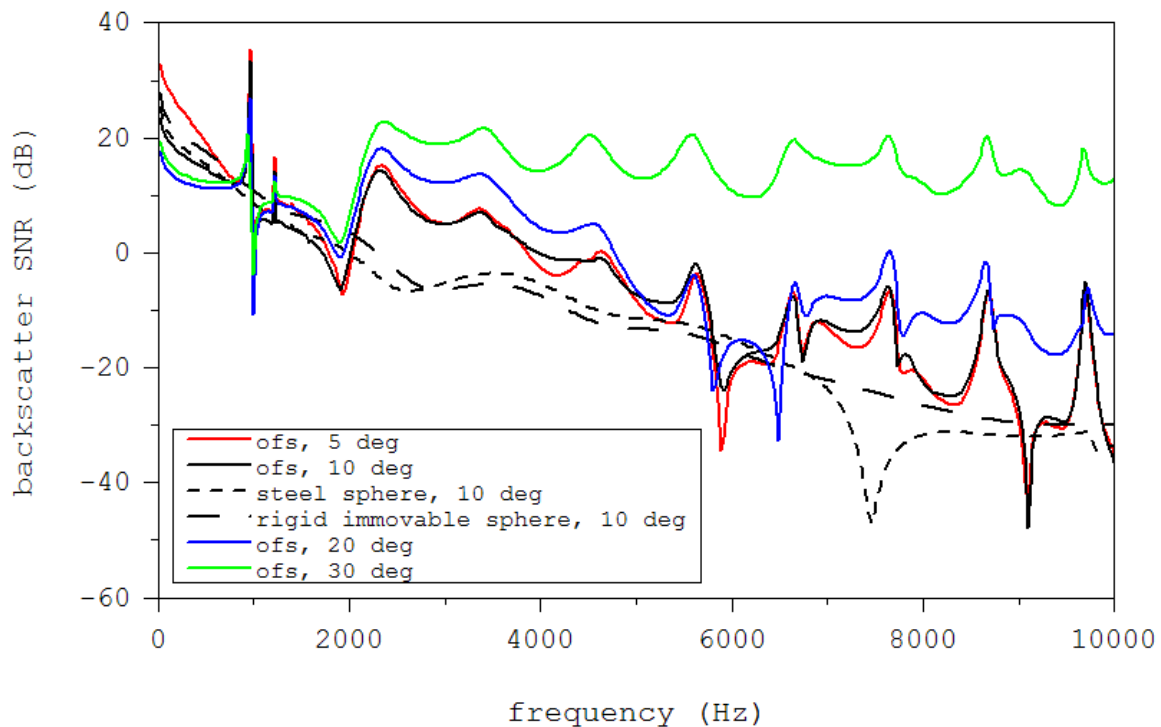
Figure 2. Comparison of SNR predictions for flush-buried spheres at 4 grazing angles.

IMPACT/APPLICATIONS

This research extends our understanding of how sound penetrates a rough ocean bottom and interacts with buried targets, especially at shallow grazing angles. This will lead to improved sonar systems that can detect and identify targets buried over extended ranges in littoral environments.

TRANSITIONS

These results are being used to predict signal-to-noise levels in tests carried out this year and next year with support from ONR's Buried Mine Program (POC: R. Manning) and to update NSWC PC's PC compatible Shallow Water Acoustic Toolset (PCSWAT) with support from SERDP's Munitions Management Program (POC: Anne Andrews) and ONR's Buried Mine Program.

RELATED PROJECTS

The present research is closely coordinated with theoretical and experimental efforts ongoing at APL/UW (E. Thorsos and K. Williams) and at NSWC PC (J. Lopes, D. Burnett) under support from ONR Codes 321OA, 321OE, 321MS, and SERDP to resolve bottom target (mines and UXO) detection issues. D. Burnett is developing a numerical approach based on finite elements to model acoustic scattering and radiation by complex three-dimensional objects near boundaries. The work reported here will play an important role in verifying the resulting models. G. Sammelmann (NSWCPC) is also continuing to update PCSWAT with algorithms to account for buried targets under support from SERDP. Related efforts also exist elsewhere. H. Schmidt (Massachusetts Institute of Technology) and coworkers use modifications of the OASES program to predict multi-static scattering by proud and

buried targets. This has undoubtedly been used to help interpret data collected at field tests performed in collaboration with the NATO Undersea Research Centre (NURC) research facility such as GOATS 98. J. Fawcett (DRDC-Atlantic, Canada) is using a variety of techniques to develop models of target scattering in layered ocean environments. Other researchers at NURC (A. Tesei, M. Zampolli, Finn Jensen, et al.) are also testing acoustic propagation and scattering models by comparing predictions with data from buried targets and with other benchmark calculations provided at acoustic computation workshops hosted by NURC.

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