Proceedings of the Seventh European Conference on Underwater Acoustics, ECUA 2004
Delft, The Netherlands
5-8 July, 2004

BISTATIC SCATTERING FROM BURIED TARGETS IN SHALLOW WATER - EXPERIMENT AND MODELING

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The joint SACLANTCEN-MIT GOATS experiments have provided rich datasets for developing a fundamental understanding of the bistatic scattering from partially and completely buried seabed targets in the mid-frequency regime, thus providing the foundation for the development of new low-frequency, bistatic synthetic aperture processing approaches for mine countermeasures in very shallow water, concurrently detecting and classifying targets by tracking the spatial and temporal structure of the 3-D acoustic scattering, using AUVs as bistatic receiver platforms. The analysis has led to the development of a hybrid modeling framework for scattering from partially and completely buried elastic targets in shallow water waveguides.

1. INTRODUCTION

The Generic Ocean Array Technology Sonar (GOATS) is an AUV-based, multistatic sonar concept for coastal mine countermeasures (MCM), intended for concurrent detection and classification of proud and buried seabed targets. To achieve bottom penetration [1, 2], and optimally explore the acoustic signatures of the targets the sonar concept uses frequencies in the 1-20 kHz regime where both geometric and resonant target scattering are significant [3]. In addition multistatic configurations may significantly improve the detection of targets which are stealthy to mono-static sonars. A key objective of the GOATS joint research effort between MIT and SACLANTCEN is to develop a fundamental understanding of the associated 3D, mid-frequency (1-20 kHz) acoustic environment and to develop efficient physics based propagation and scattering models incorporating aspect-dependent targets and seabed features, and the waveguide multipath effects. The goal is a consistent physics-based modeling framework for high-fidelity simulation of bi-and multistatic sonar configurations for VSW MCM.

The GOATS'98 and '2000 experiments provided extraordinarily rich mono- and bistatic acoustic data sets using a parametric source for insonification, and a suite of fixed arrays and an AUV as a mobile bistatic receiving platform. The results to date include a unique

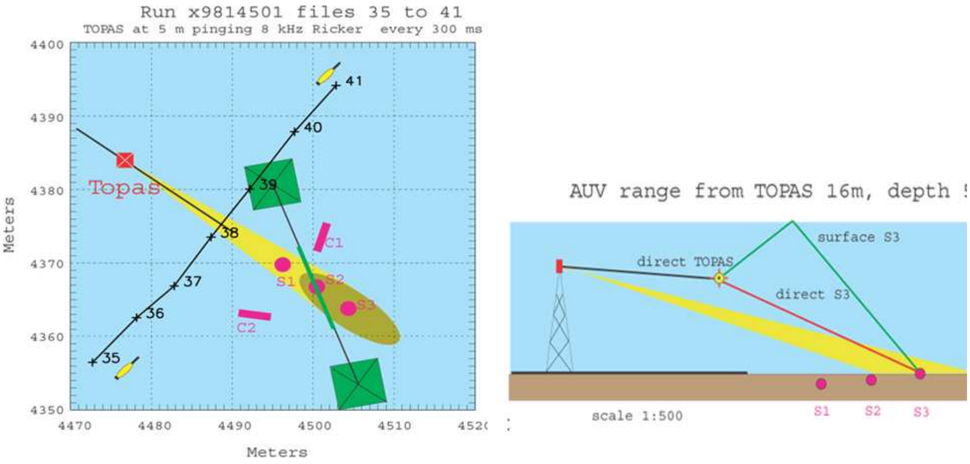

Figure 1: Bistatic sonar geometry. A parametric source is insonifying the seabed with a footprint of approximately 5 × 10 *, centered on the half-buried spherical target S3. The Spherical target S2 i flush buried.*

demonstration of sub-critical detection of buried targets by bistatic SAS from an AUV [4], and the demonstration of the autonomous detection of aspect-dependent targets by capturing their bistatic enhancement. In terms of target scattering physics it has been demonstrated that scattering models using the single-scatter approximation are excellently capable of representing the elastic components of the scattering from a spherical shell, proud as well as buried, as long as they were insonified above the critical angle of the seabed [5]. However, the existing models based on the single-scatter approximation have turned out to be incapable of capturing the correct physics of subcritical scattering from buried targets. This paper describes the latest experimental analysis of the bistatic data, and the development of a new hybrid modeling capability which incorporate multiple scattering between the target and the seabed.

2. BISTATIC SCATTERING EXPERIMENTS

In the GOATS'98 experiment an AUV and a suite of fixed arrays were used for mapping the 3-D scattering from proud and buried targets and explore the potential of bistatic synthetic aperture processing. Figure 1 shows the bistatic sonar geometry of the experiment. A parametric source is insonifying the seabed with a footprint of approximately 5 × 10 m, here centered on the half-buried spherical target S3. The spherical target S2 is flush buried.

In addition to the AUV-array, a 128-element horizontal array was suspended over the target field, as indicated in Fig. 1, for measuring the bistatic scattering. In a bistatic configuration the counter-clockwise and clockwise elastic waves revolving around the shell in opposite directions have different travel times and are being launched at different grazing angles toward the receiver. This phenomenon makes the bistatic scattering problem significantly more complex than the mono-static equivalent.

For the flush-buried sphere being insonified below the seabed critical angle, the time-series and associated time-frequency response for a receiver in the backscatter direction at 30° bistatic angle, is shown in Fig. 2. The left frame shows the experimental result while the right frame shows the corresponding *single-scatter* modeling result by OASES-3D. The geometrically expected arrivals times of the circumferential longitudinal Lamb waves

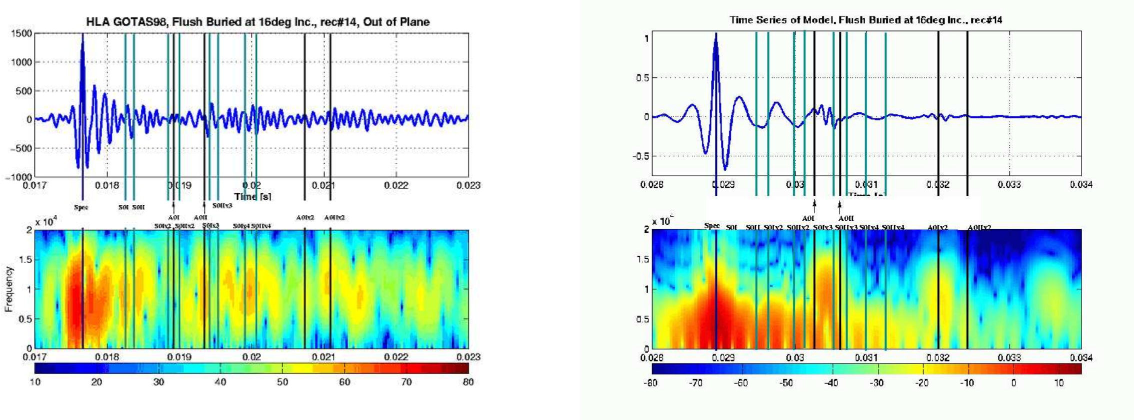

Figure 2: Timeseries and associated time-frequency spectrum of bistatic, elastic scattering from buried spherical shell under evanescent insonification. a) GOATS'98 experiment; b) OASES-3D single-scatter model .

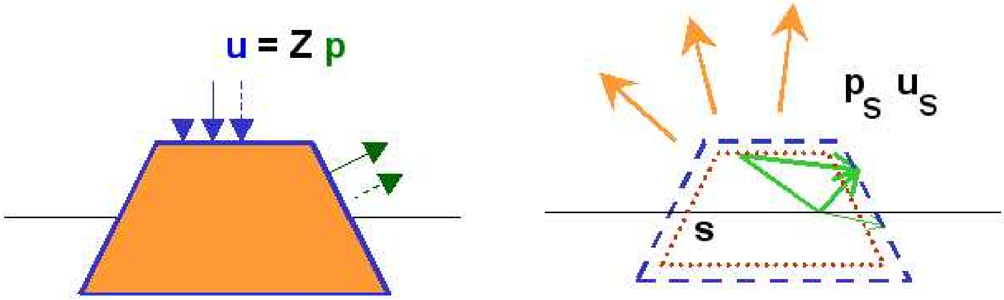

Figure 3: Virtual source approach. The elastic target with surface admittance matrix Z is replaced by the stratified background medium, with a distribution of virtual sources **s**. *The total field on the surface of the target volume satisfies the same admittance condition as the target,* $\mathbf{u} = \mathbf{Z}\ \mathbf{p}$

are indicated by the vertical blue lines in Fig. 2, while the black lines indicate the flexural wave arrivals. The lines appear in pairs corresponding to the two opposite circumferential directions.

Previous analysis of the super-critical monostatic data [5] achieved excellent agreement between model and experiment, and clearly identified the individual arrivals associated with the circumferential Lamb waves. As is evident from Fig. 2 the same agreement could not be achieved for the bistatic, sub-critical insonification. It is hypothesized that the discrepancy is associated with the single-scatter approximation being inadequate for partially and flush-buried targets, which has led to the development of the new modeling capability described in the following, incorporating multiple scattering between the target and the seabed.

3. TARGET SCATTERING MODEL

The OASES-3D modeling framework for targets in stratified media [2, 3] has been expanded to incorporate multiple scattering between partially buried targets and the seabed. The multiple scattering is incorporated using a generalization of the virtual source, or internal source density approach [6], in combination with the Fourier-Bessel representation of the waveguide multipath Green's function [7]. It is fundamentally a wavefield superposition approach, replacing the target by a distribution of acoustic sources placed in the background medium, inside the volume occupied by the target, and of unknown magnitude and phase. These virtual source strengths are then found from the condition that the superposition of their generated field with the incident field on the surface of the volume occupied by the target must satisfy the boundary conditions associated with the true target.

This simple superposition principle is illustrated schematically in Fig. 3. The plot to the left shows an arbitrarily shaped object in a stratified ocean, possibly penetrating interfaces. The stratification can include fluid as well as elastic layers, but it is here for simplicity assumed that the layers containing the target are isovelocity fluid media. In the plot to the right, the target is removed and replaced by a continuously stratified medium with a discrete distribution of N simple point sources, the unknown, complex strengths of which are represented by the vector $\mathbf{s}$. This source distribution is assumed to generate a field which is identical to the scattering that would be produced by the target.

If the surface of the target is discretized in N nodes, the total pressure $\mathbf{p}$ and normal displacement $\mathbf{u}$ at the nodes are decomposed into the known incident field contribution $\mathbf{p_i}, \mathbf{u_i}$, and the scattered field, $\mathbf{p_s}, \mathbf{u_s}$, with the scattered field generated by the virtual source distribution $\mathbf{s}$,

$$\mathbf{p_s} = \mathbf{Ps} \tag{1}$$

$$\mathbf{u_s} = \mathbf{Us} \tag{2}$$

Here $\mathbf{P}$ and $\mathbf{U}$ are NxN matrices containing the the pressure- and normal displacement Green's functions, respectively, between the N virtual sources and the N surface nodes, incorporating the reflection and transmission process at the seabed.

The total field on the virtual target surface must now satisfy the boundary conditions associated with the real target. Thus, the field inside the true target must satisfy Green's theorem, providing a unique relation between the pressure and normal displacements on the surface. In a discrete representation with N surface nodes, this relation can be expressed in terms of a frequency-dependent, dynamic admittance matrix $\mathbf{Z}$,

$$\mathbf{u} = \mathbf{Zp} \tag{3}$$

Combining Eqs. (1)-(3) and the superposition principle, then leads to a matrix representation for the virtual source strengths.

$$\mathbf{s} = [\mathbf{U} - \mathbf{ZP}]^{-1}[\mathbf{Zp_i} - \mathbf{u_i}] \tag{4}$$

The scattered field now follows anywhere in the external medium by superposition, using the Green's function for the continuous medium, in this case the stratified ocean waveguide.

The virtual source approach implemented in OASES-3D has been validated by comparison with the SACLANTCEN FESTA finite-element model [8]. For example, Fig. 4 shows in a polar dB-diagram the computed scattered field (+ 20 dB) in the vertical plane at 1 m distance from the center of the spherical target used in GOATS, i.e. a spherical steel shell of inner diameter 1m, half-buried in a seabed with sound speed 1700 m/s, but without density contrast. The admittance matrix for the spherical shell is here computed exactly in terms of spherical harmonics, but it could be computed using any applicable method, such as finite elements, which is obviously important for targets of more complex shape. The OASES-3D result is shown by the solid, blue curve, while the FESTA results are represented by a red, dashed curve. The diagram to the left shows the results for

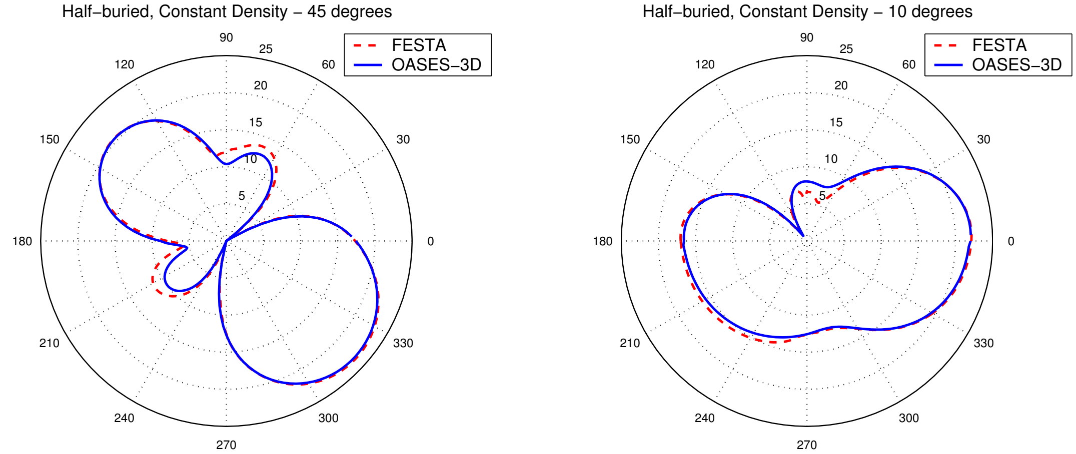

Figure 4: Comparison of virtual source and FEM computation of scattered field 1 m from from half-buried spherical shell, insonified at (a) supercritical (45°), and (b) subcritical (10°) angles. Seabed sound speed 1700 m/s, no density contrast. Blue, solid curve: Virtual Source Approach; Red, dashed curve: FESTA.

super-critical, 45° incidence, while the diagram to the right shows the comparison for a sub-critical 10° incidence. It should be noted that the virtual source results for these cases are achieved two orders of magnitude faster than the FESTA results, while also computing the scattered field out to distances of several water depths.

The new modeling capability is currently being applied in the continued analysis of the experimental data, but it has already been used to demonstrate theoretically the importance of incorporating multiple scattering in the modeling for targets at shallow burial depth. [7].

The fact that the target in the virtual source approach is described entirely by its surface admittance matrix has made it straightforward to develop a hybrid modeling framework where the admittance matrix is computed by FESTA, and subsequently used in OASES-3D for handling the waveguide propagation physics for both the incident and scattered fields. Several coupling approaches are being investigated, including the use of FESTA solely for computing the admittance matrix. Another approach is a 'scattering chamber' approach, where OASES is still applied for the computation of the incident and scattered fields, but where the finite element analysis incorporates part of the surrounding fluid. This approach is advantageous when investigating mutual scattering of multiple, adjacent targets [9]. On the other hand it requires a separate finite element analysis for each insonification and target burial scenario, in contrast to the present 'admittance matrix' approach.

4. CONCLUSION

The GOATS experiments have provided unique datasets for developing new low-frequency, bistatic synthetic aperture processing approaches for mine countermeasures in very shallow water. By exploring the bistatic enhancement such approaches have significant potential for detection of buried, stealthy objects beyond the critical bottom penetration range of traditional high-frequency sonars, and may provide concurrent detection and classification of such targets by tracking the spatial and temporal structure of their 3-D acoustic scattering. A comprehensive modeling framework, combining wave-theory waveguide propagation modeling with a generalized virtual source approach has provided a new and highly efficient approach to modeling of the scattering from partially and completely buried elastic targets.The new modeling capability has been verified by comparison to a general finite element model. Further, a hybrid framework has been developed where the target admittance matrix for an arbitrarily shaped elastic target is computed *a priori*, e.g. using finite elements, and coupled into the waveguide model using the virtual source approach, allowing the scattered field to be modeled out to ranges of tens or hundreds of water depths very efficiently, for a wide variety of burial and insonification scenarios with only a single computationally intensive finite element computation.

5. ACKNOWLEDGMENT

The collaboration in the GOATS'98 experiment with A. Maguer, E. Bovio, W. Fox, B. Miaschi, P. Guerrini, P.A. Sletner, and others of SACLANTCEN, is highly appreciated. This work is supported by the Office of Naval Research and SACLANTCEN.

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