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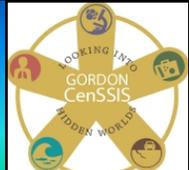
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Calibrated bistatic Rayleigh-Born bottom reverberation model for fluctuating and range-dependent continental shelf environments



(to be submitted to the *Journal of the Acoustical Society of America*)
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Abstract

Analytic and numerical models are developed for reverberation from volumetric inhomogeneities in the sea bottom in range dependent ocean waveguides using the Rayleigh-Born approximation to Green's theorem. The expected reverberation intensity depends on the statistical moments of the fractional changes in compressibility and density, which scatter like monopoles and dipoles respectively, and the coherence volume of the inhomogeneities. The model is calibrated using data acquired with a long range sonar on the New Jersey continental shelf during the 2003 Main Acoustic Experiment of the ONR Geoclutter Program. An approach for distinguishing moving clutter from statistically stationary background reverberation in long range sonar imagery is developed. Geoacoustic parameters needed for the calibration are either derived from previous geophysical surveys of the region or estimated from reverberation data. Analysis with the model indicates that the scattering strength of the bottom on the New Jersey shelf is approximately -37±1 dB re 1m². An approximate but computationally efficient numerical approach is also developed to simulate reverberation over wide areas for operational sonar systems. The numerical model employs the Navy standard range-dependent propagation model based on the parabolic equation, RAM, and can be readily incorporated into current Navy systems. Model is applied to minimize bottom reverberation and enhance biological detection for OAWRS imaging of fish.

Theory – Reverberation model

Scattered field from volume inhomogeneity

First-order Rayleigh-Born approximation to Green's Theorem

Monopole term

$$\Psi_s(\mathbf{r}|\mathbf{r}_0, \mathbf{p}_t, f) = Q(f)(4\pi)^2 \iiint_V \left(\frac{k^2 \Gamma_\kappa G(\mathbf{r}|\mathbf{r}_0, f) G(\mathbf{r}|\mathbf{r}_t, f)}{+\Gamma_d \nabla G(\mathbf{r}|\mathbf{r}_0, f) \cdot \nabla G(\mathbf{r}|\mathbf{r}_t, f)} \right) dV_t$$

Dipole term

$$\Gamma_d = \frac{d_t - d}{d_t} \quad \Gamma_\kappa = \frac{\kappa_t - \kappa}{\kappa}, \quad \kappa = dc^2$$

Expected Reverberation Intensity

Total intensity Coherent Intensity Incoherent Intensity

$$\langle |\Psi_s(\mathbf{r}|\mathbf{r}_0, \mathbf{p}_t, f)|^2 \rangle = \langle |\Psi_s(\mathbf{r}|\mathbf{r}_0, \mathbf{p}_t, f)|^2 \rangle + \text{Var}(\Psi_s(\mathbf{r}|\mathbf{r}_0, \mathbf{p}_t, f))$$

Mean field

$$\langle \Psi_s(\mathbf{r}|\mathbf{r}_0, \mathbf{p}_t, f) \rangle = Q(f)(4\pi)^2 \iiint_V \left(\frac{k^2 \langle \Gamma_\kappa \rangle \langle G(\mathbf{r}|\mathbf{r}_0, f) G(\mathbf{r}|\mathbf{r}_t, f) \rangle}{+\langle \Gamma_d \rangle \langle \nabla G(\mathbf{r}|\mathbf{r}_0, f) \cdot \nabla G(\mathbf{r}|\mathbf{r}_t, f) \rangle} \right) dV_t$$

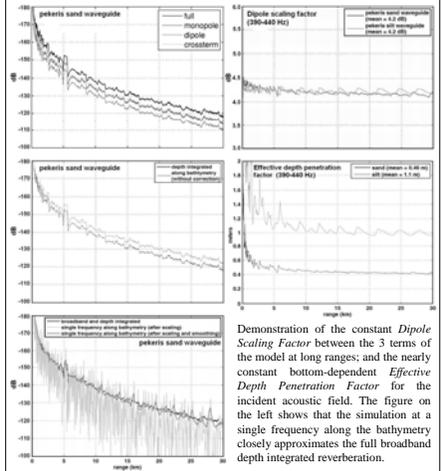
Incoherent intensity

Coherence volume Monopole term Dipole term Cross term

$$\text{Var}(\Psi_s(\mathbf{r}|\mathbf{r}_0, \mathbf{p}_t, f)) = |Q(f)|^2 (4\pi)^2 \iiint_V \left(\begin{aligned} &k^4 \text{Var}(\Gamma_\kappa) \langle |G(\mathbf{r}|\mathbf{r}_0, f)|^2 |G(\mathbf{r}|\mathbf{r}_t, f)|^2 \rangle \\ &+\text{Var}(\Gamma_d) \langle \nabla G(\mathbf{r}|\mathbf{r}_0, f) \cdot \nabla G(\mathbf{r}|\mathbf{r}_t, f) \rangle^2 \\ &+k^2 \text{Cov}(\Gamma_\kappa, \Gamma_d) \langle 2\text{Re} \{ G(\mathbf{r}|\mathbf{r}_0, f) G(\mathbf{r}|\mathbf{r}_t, f) \nabla G(\mathbf{r}|\mathbf{r}_0, f) \cdot \nabla G(\mathbf{r}|\mathbf{r}_t, f) \} \rangle \end{aligned} \right) dV_t$$

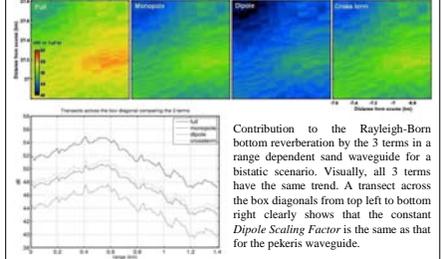
Approximations for efficiency

Monostatic reverberation in a Pekeris waveguide (390-440 Hz)



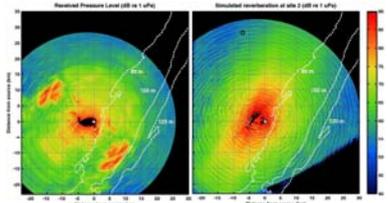
Demonstration of the constant Dipole Scaling Factor between the 3 terms of the model at long ranges; and the nearly constant bottom-dependent Effective Depth Penetration Factor for the incident acoustic field. The figure on the left shows that the simulation at a single frequency along the bathymetry closely approximates the full broadband depth integrated reverberation.

Bistatic reverberation in a range dependent sand waveguide (390-440Hz)

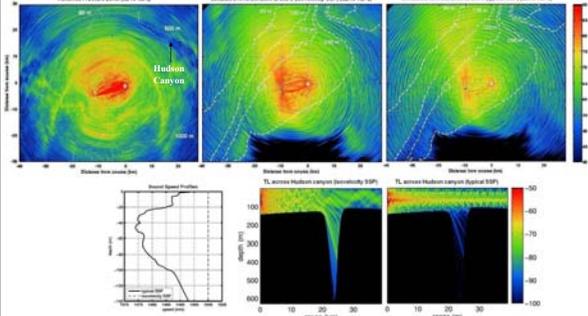


Contribution to the Rayleigh-Born bottom reverberation by the 3 terms in a range dependent sand waveguide for a bistatic scenario. Visually, all 3 terms have the same trend. A transect across the box diagonals from top left to bottom right clearly shows that the constant Dipole Scaling Factor is the same as that for the Pekeris waveguide.

Wide area simulations near the New Jersey shelf

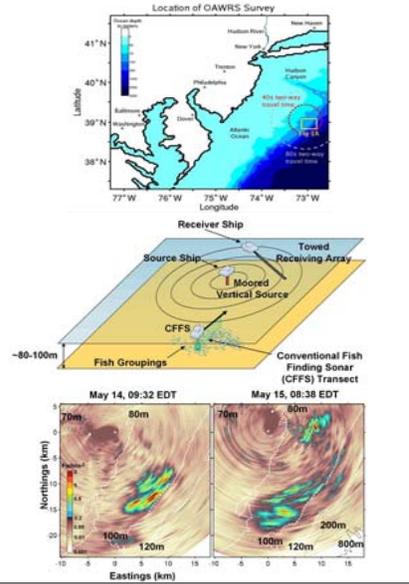


(Above) An approximate but fast simulation done for site 2 of the New Jersey continental shelf. Results are shown after beamforming with an array having a range resolution of 15 meters and a length of 94 meters. The source level is the same as that used in the experiment. The small black box in the upper left corner indicates the location used for calibrating the model (it is the same box shown for the bistatic case in the section on approximations). Background levels estimated by the simulation are comparable to the actual data shown on the left. It is clearly evident that the high levels in the data that stand 20 dB above the background cannot be due to sea bottom reverberation and must be caused by other reasons like scattering from fish shoals or euphausiids.

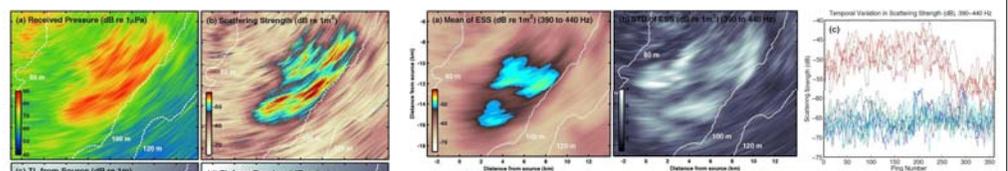


(Above) Wide area reverberation simulated for site 3 of the New Jersey continental shelf for two different sound speed profiles. In the isovelocity environment, the illumination is more uniform in depth and the geology of the Hudson canyon shows up due to backscatter from the canyon walls. But for an actual environment with a typical sound speed profile the geology is not visible suggesting that the feature seen near the Hudson canyon in the Geoclutter data image on the left could actually be due to scattering from biological formations along the walls of the canyon like spawning fish schools or resident zooplankton and phytoplankton.

Ocean Acoustic Waveguide Remote Sensing (OAWRS)

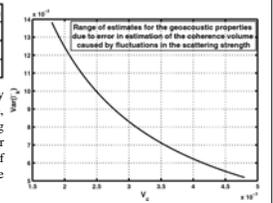


Model Calibration with OAWRS data collected on May 14th, 2003 at the New Jersey shelf (390 to 440 Hz)



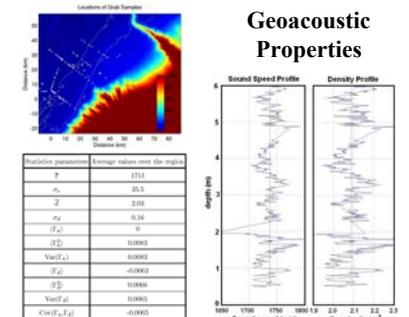
(Above) Spatial and temporal variations in scattering strength. (a) Mean and (b) Standard deviation of the Effective Scattering Strength computed from 361 instantaneous scattered field images which were converted to scattering strength. (c) Temporal variation in the Effective Scattering Strength at various locations in these images. Hot colored lines correspond to moving clutter like fish schools. Cool colored lines correspond to the stationary background which is used for calibrating the reverberation model.

Frequency	mean SS	Coherence Volume Vc Estimate	Correlation Length (Lc)
390 to 440 Hz	-67.5	0.003 m ³	0.18 m
875 to 975 Hz	-65.0	0.0023 m ³	0.185 m
1250 to 1400 Hz	-62.5	0.0021 m ³	0.191 m

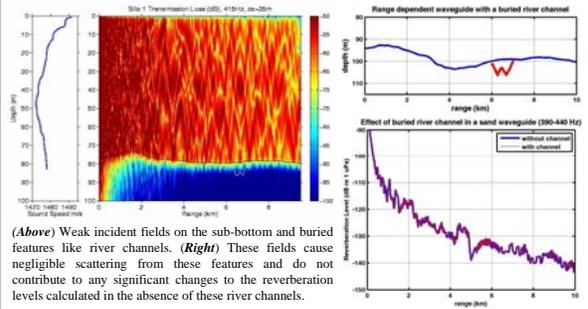


(Above) Model calibration results for different frequency bands showing estimates of the Effective Scattering Strength, Coherence volume Vc and Correlation length Lc (assuming inhomogeneities are isotropic and spherical). Estimates for Vc at the three frequency bands have the same order of magnitude as expected. Coherence lengths estimated are within the range of values obtained from core measurements.

Geoacoustic Properties



Buried river channels not a major source of clutter



(Above) Weak incident fields on the sub-bottom and buried features like river channels. (Right) These fields cause negligible scattering from these features and do not contribute to any significant changes to the reverberation levels calculated in the absence of these river channels.

References

Ref1: Makris et al., "Fish population and behavior revealed by instantaneous continental shelf-scale imaging", Science, Feb 2006.
Ref2: J.A.Goff et al., "Seabed characterization on the New Jersey middle and outer shelf: correlativity and spatial variability of seafloor sediment properties", Marine Geology, May 2004.