Modeling of Mid-Frequency Reverberation in Very Shallow Water: A Green's Function Approach and Application to TREX2013 Data Analysis

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Contents

Abstract

The long-term goals of this research are to better understand and accurately model low- to mid-frequency reverberation in shallow water environments. Specific goals are to develop a model of reverberation for conditions (1–10 kHz, ~ 20 m water depth, ~ 10 km range) corresponding to the ONR Target and Reverberation Experiment performed in spring 2013 (TREX2013), develop a code and conduct computer simulations with environmental inputs typical for the chosen location, and apply this model to analysis of available TREX2013 data. This report presents a Green's function modeling approach that allows fast estimations of volume reverberation in complex shallow water environments. A simplified first-order version of the approach is considered to show how far-field scattering solutions obtained for free space can be incorporated into reverberation in complicated bounded, range-dependent, and stratified environments. A higher-order modification of this approach is considered as well, using a MFSB (Multiple Forward Single Backscatter) approximation. Application to TREX2013 reverberation data and tentative model–data comparisons are presented.

Objectives

The long-term goals of this research are to better understand and accurately model low- to mid-frequency propagation and reverberation in shallow water environments. This would result in development of a robust model (potentially a tool) for prediction and interpretation of reverberation in complex (range-dependent, potentially 3D-dependent) waveguides. This report presents a Green's function modeling approach that allows fast estimations of propagation and reverberation in shallow water. The approach also addresses a basic science question: how scattering solutions obtained for free space (or measured in direct-path, short-range conditions) can be incorporated into long-range reverberation in bounded and complicated environments, such as shallow water or deep-water waveguides, where effects of multiple interactions with boundaries and volume heterogeneities must be taken into account, providing both sufficient accuracy and speed of calculations.

Specific goals of this research are to develop a model of reverberation for conditions (1–10 kHz, ~ 20 m water depth, ~ 10 km range) corresponding to the ONR Target and Reverberation Experiment performed in spring 2013 (TREX2013), develop a code and conduct computer simulations with environmental inputs typical for the chosen location, and apply this model to analysis of available TREX2013 data [see TREX13 website, *TREX13 Workshops* (2012, 2013, 2014)]. This report demonstrates the capabilities of codes developed based on a Green's function modelling approach to provide extremely fast predictions of reverberation in a very shallow water environment, gives numerical examples for several relevant scenarios, discusses possibilities for a quantitative interpretation of reverberation data, presents tentative TREX2013 data–model comparisons, and suggests implications for future research.

Project Background

A proposal for this project was written in response to the ONR call for suggestions and comments in the *White Paper* (2011) “Mid-frequency reverberation measurements with full companion environmental support,” which defined conditions for approaching reverberation experiments in very shallow water (~ 20 m depth). Scattering mechanisms to be addressed were specified as well: sea surface and bottom roughness, heterogeneity in the water column (near surface bubbles, fish schools) and sediments (e.g., large shells and mud inclusions). The *White Paper* emphasized, however, the importance to address applicability of this study to more general environments. In addition to the general problem of reverberation, specific basic science issues to be addressed were defined: (1) Mid-frequency sound scintillation index and coherent field, (2) evolution of mid-frequency spatial coherence as a function of range from source, (3) sediment sound speed and attenuation as a function of frequency, (4) effects of spatial variability of bottom scattering strength, and (5) impact of sediment ripple fields on waveguide propagation and sediment volume scattering.

The proposal for this project, “Modeling of mid-frequency reverberation in very shallow water,” submitted in 2012, can be summarized as follows. The main goal of the project was to enhance the modeling component of the upcoming experiment, and to contribute to the development of non-traditional approaches to shallow water reverberation, i.e., to support the idea expressed in the *White Paper* (2011) that a new area of investigation for WPRM (Wave Propagation in Random Media) in shallow water should be suggested. The proposal mentioned, however, that for such very shallow water and to support this specific experiment, the focus of the investigation should be broader than or even different from the one in the *White Paper*, where effects of only internal waves were emphasized in this connection. This project suggested that the investigation most relevant to very shallow water environments, where sediment is a critical part of the propagation channel, should be focused on the effect of 3D variability of the sediment properties along with corresponding effects of propagation and 3D refraction within the seafloor.

It was assumed that in such complicated conditions some multiple scattering effects may be important, and suggested addressing these effects by exploiting an approach developed by *De Wolf* (1971) and then successfully used by Ishimaru, Tatarskii, and others to describe electromagnetic propagation and multiple scattering in a turbulent atmosphere. Particularly, the approach is applicable to a description of the so-called backscattering enhancement effect, known also as “weak localization” and “coherent backscatter” effects. This approach is well recognized in the WPRM community, and called the MFSB (Multiple Forward Single Backscatter) approximation. While similar terminology appears often in the underwater acoustics literature, such an approach for conditions of shallow water reverberation has not yet been adequately developed, although experimental observations exist (*Sabra*, 2010).

For a description of multiple-scattering effects in acoustics of marine sediments, the MFSB approach was used by *Ivakin* (1999), and then it was reformulated for the case of reverberation in a shallow-water waveguide by *Ivakin* (2008). The main complication in this case (in comparison with previous work) appears because of the multi-path conditions for propagation in a waveguide. Recent developments suggest treating this complication by directly considering both the heterogeneous sediment and water column as parts of the ocean waveguide (*Ivakin*, 2011 and 2012). In this research, the approach was developed further for a very shallow water environment. In particular, it was suggested to perform numerical modeling for several typical scenarios that include the water column and seabed as possible mechanisms of reverberation to better understand their relative effects.

One important direction of this research is development, using both analytical and numerical modeling, of practical relationships between reverberation and environmental parameters, with a specific goal to evaluate the sensitivity of measured reverberation intensity to these parameters, to determine which environmental parameters or mechanisms of scattering are critical for reverberation in chosen acoustic and environmental very shallow water scenarios. This may help to reduce the number of parameters needed to be measured or taken into account to provide “full environmental support” of the field experiment proposed in the *White Paper* (2011). Another important application of this modeling would be evaluation of the possibility for inferring environmental parameters from reverberation data. New inference techniques and algorithms were expected to be developed.

This project was proposed for a two-year period, FY2013 and FY2014. During the first year, a simplified version of the reverberation model was developed, with a focus on bottom scattering mechanisms to facilitate developing codes and conducting pre-test computer simulations, and to help plan the acoustic experiment and environmental ground truth measurements. Results of this work were presented in *Ivakin* (2013) and *Hefner et al*. (2013a and 2013b). During the second year, FY2014, a more general model of reverberation was developed and applied to TREX2013 data based on available acoustic and environmental inputs. Also, it was suggested to consider analytical expressions for reverberation, methods of its inversion for environmental parameters, and applicability of results obtained in specific TREX2013 conditions to more general shallow water scenarios. Some results of this work are presented in *Ivakin* (2015a) and *Hefner et al*. (2015a and 2015b).

Modeling Approach

This report presents a Green's function modelling approach that allows fast estimations of reverberation in shallow water. The approach also addresses a basic science question: how far-field scattering solutions obtained for free space can be incorporated into reverberation in bounded and complicated environments, such as shallow water or deep-water waveguides, where effects of multiple scattering and interaction with boundaries and volume heterogeneities must be taken into account.

A basic approach, its simplified first-order version and initial results, are based on models discussed in *Ivakin* (2010, 2011, 2012, and 2013). A higher-order modification of this approach exploits ideas of a MFSB (Multiple Forward Single Backscatter) approximation developed by *De Wolf* (1971) for studying electromagnetic propagation and multiple scattering effects in a turbulent atmosphere. To describe such effects in marine sediments acoustics, the MFSB approach was applied in *Ivakin* (1999), and reformulated for the case of reverberation in a shallow water waveguide in *Ivakin* (2008). Its further development is presented in *Ivakin* (2015a).

A first-order Green's function approach

Consider the total field (acoustic pressure) as a sum of the unperturbed field and a first-order (single-scattered) field expressed through correspondent components of the full-field Green's function,

$$p = p_0 + p_1 = AG = A\left(G_0 + G_1\right) \tag{1}$$

with a coefficient, A, introduced so that Green's function near the source represents a spherical wave of the unite magnitude, i.e., $\left|\vec{r} - \vec{r}''\right| G(\vec{r}, \vec{r}'') \xrightarrow[\vec{r} \to \vec{r}'']{} 1$. Analytical results and numerical solutions for zeroth-order Green's function are currently available for rather complicated background (or unperturbed) media, such as range-dependent shallow water or deep water waveguides, and are based on various propagation models, such as PE, normal modes, wave number integration, or various ray based approximations.

A solution for the single-scattered field is known, e.g., *Ivakin* (2008, 2010, 2011, 2012, and 2013), which then results in an integral expression (*Ivakin*, 2011 and 2012)

$$\begin{aligned} \left\langle I_1(\vec{r}', \vec{r}'') \right\rangle &= |A|^2 \int \left(\rho_0(\vec{r}') / \rho_0(\vec{r})\right)^2 M_V(\vec{r}) \left| G_0(\vec{r}, \vec{r}') G_0(\vec{r}, \vec{r}'') \right|^2 d^3 r = \\ &= |A|^{-2} \int M_{Vef}(\vec{r}) I_0(\vec{r}, \vec{r}') I_0(\vec{r}, \vec{r}'') d^3 r \end{aligned} \tag{2}$$

where $I_{0,1} = \left|p_{0,1}\right|^2$ are the zeroth- (unperturbed) and first-order (scattered) intensities, $\rho_0(\vec{r})$ is the density in an unperturbed medium, $M_{Vef} = \left(\rho_0(\vec{r}') / \rho_0(\vec{r})\right)^2 M_V$, and M_V is a volume scattering coefficient, or the scattering cross-section per unit volume. Limitations of Eq. (2) result from the assumption that the spectrum of heterogeneity is a smooth enough function, neglecting bistatic scattering effects by ignoring the difference in wave vectors in the stratified environment with both down-going and up-going waves (*Ivakin*, 2011 and 2012). Despite its simplicity, Eq. (2) is general and can be applied to scattering near marine boundaries, seabed or sea surface, or near an arbitrary reference interface within the marine environment using a general procedure described in *Ivakin* (2012).

A specific expression for M_V can be obtained from a far-field solution for scattering in free space with a specified type of heterogeneity, continuum or discrete. For backscatter from continuum heterogeneity caused by local spatial fluctuations of the density and sound speed, we have (*Ivakin*, 2011 and 2012),

$$M_V = 2\pi k^4 \Phi_{2\vec{k}}(\varepsilon_{\rho c}) \tag{3}$$

where $\varepsilon_{\rho c} = (\rho c)/(\rho_0 c_0) - 1$ are relative fluctuations of the impedance, and Φ is their power spectrum at the backscattering Bragg's wave vector. In the case of discrete scatterers, such as particles and objects of various kinds, a general expression for the incoherent volume scattering strength of randomly distributed objects is of the form (*Ivakin*, 2012),

$$M_V = C_V \langle \sigma / v \rangle \tag{4}$$

where σ and v are the individual scattering cross section of the object and its volume, their ratio is averaged (given a fixed volume) over other parameters, such as size, shape and orientation, and $C_V << 1$ is the total volume concentration of the objects.

Therefore, the approach provides a simple way for calculations of reverberation as follows. An integral expression for the backscatter intensity, given by Eq. (2), has a factorized integrand comprised of two kernels, the two-way propagator and the scattering kernel. The propagator is a product of two local intensities, each being defined along one of the two ways of propagation. For rather complicated environments, generally depth–range-dependent, the local intensity can be calculated using available models and codes, e.g., PE, normal modes, ray based, or other approximations.

The scattering kernel is defined as a local volume scattering coefficient and exploits simple first-order solutions for far-field scattering from a heterogeneous volume in free (unbounded) space. It can be specified for the water column and seabed with continuum heterogeneity, such as spatial fluctuations of density and sound speed, and/or discrete randomly and sparsely distributed targets, such as gas bubbles, fish, shells, lens-like inclusions, oil droplets, solid hydrate particles, and others (*Ivakin*, 2011 and 2012).

Moreover, the scattering kernel can include a component due to the contribution of roughness at an arbirary number of interfaces at depths $z = z_j$ as follows

$$M_{Vef}(\vec{r}) = m^{-2} M_V + \sum_j M_{Rj} \delta(z - z_j) \tag{5}$$

$$M_{Rj} = \frac{k_o^4}{4} D_j^2 \, \Phi_{2\vec{k}}^{(R)}(\zeta_j) \tag{6}$$

$$D_j = \left(\frac{n_j}{m_j} - \frac{n_{j+1}}{m_{j+1}} \right) \left(n_j + n_{j+1} \right) \tag{7}$$

where $m = \rho / \rho_0$ and $n = c_0 / c$ are relative density and refraction index of the background medium, M_{Rj}, $\Phi^{(R)}$, and D_j are the roughness scattering coefficient, the power spectrum, and a contrast factor at *j-th* interface, respectively. In more detail, this case is described in *Ivakin* (1998 and 2015c).

Note that this approach provides estimations of bottom reverberation without calculations of the equivalent surface scattering strength, although may include it as a particular case (*Ivakin*, 2012, 2013, and 2015a). The approach is applicable, generally, for an arbitrary distribution of scatterers defined by their volume scattering coefficient M_V, and roughness scattering coefficient M_R (Eqs. 3–5). Therefore, it allows a fast estimation of potential contributions of different scattering mechanisms with arbitrary strengths and locations.

A modified higher-order approach

Integral expression (2) for the reverberation intensity can be generalized by treating the propagating kernel stochastically and accounting for multiple forward-scatter effects, using the MFSB approximation developed by *De Wolf* (1971). According to this approach, the total field is presented as a sum of a multiple forward-scattered field and a single backscattered field, or through correspondent components of the full Green's function,

$$p = p_f + p_s = AG = A\left(G_f + G_s\right) \tag{8}$$

Then one obtaines the integral expression

$$\begin{aligned} \left\langle I_s(\vec{r}_1, \vec{r}_2) \right\rangle &= |A|^2 \int \left\langle M_{Vef}(\vec{r}) \left| G_f(\vec{r}, \vec{r}_1) G_f(\vec{r}, \vec{r}_2) \right|^2 \right\rangle d^3 r = \\ &= |A|^{-2} \int \left\langle M_{Vef}(\vec{r}) I_f(\vec{r}, \vec{r}_1) I_f(\vec{r}, \vec{r}_2) \right\rangle d^3 r \end{aligned} \tag{9}$$

where $I_{f,s} = \left| p_{f,s} \right|^2$ are the multiple forward- and single back-scattered intensities.

Despite an apparent similarity to the first-order expressions (1, 2), Eqs. (8 and 9) represent a substantial modification and improvement. The modified approach takes into account such multiple scattering effects as the scintillations of propagated intensity, the two-way propagation coherence, and the related "backscattering enhancement" known also as "coherent backscatter" and "weak localization."

To show how and where this improvement appears and can be used, recall an important energy conserving advantage of the forward scattering propagator, resulting in $\left\langle I_f \right\rangle \approx I_0$. Then for the backscatter from uniform scatterer distributions one obtains

$$\langle I_b \rangle = \langle I_s(\vec{r}_1, \vec{r}_1) \rangle \approx |A|^{-2} \int M_{Vef}(\vec{r}) I_0^2(\vec{r}, \vec{r}_1)[1 + K_I(\vec{r}, \vec{r}_1)] d^3 r \tag{10}$$

where K_I is the scintillation index. The effect of backscattering enhancement appears here automatically because $K_I > 0$.

Consider now applicability of this modified approach to analysis of the seabed reverberation in complicated conditions, such as in the TREX13 environment, where marine sediments have a substantial lateral variability. To apply Eq. (9), a general procedure can be used similar to that described in *Ivakin* (2012). Consider spatial variables of integration in (9) of the form $\vec{r} = (\vec{r}_\perp, \xi),\ \vec{r}_\perp = \vec{r}\big|_{\xi=0}$, and introduce normalizing functions, for example, as incident forward propagation wave functions on the bottom surface, $G_{0f}(\vec{r}_\perp, \vec{r}_2)$, so that $G_f(\vec{r}, \vec{r}_{1,2}) = G_{0f}(\vec{r}_\perp, \vec{r}_{1,2}) g_{1,2}(\vec{r})$. Then Eq. (9) can be presented in the form

$$\langle I_s(\vec{r}_1, \vec{r}_2) \rangle = |A|^2 \int \langle M_R(\vec{r}_\perp) \rangle \left\langle \left| G_{0f}(\vec{r}_\perp, \vec{r}_1) G_{0f}(\vec{r}_\perp, \vec{r}_2) \right|^2 \right\rangle d^3 r \tag{11}$$

where M_R is a local equivalent interface scattering cross section, or dimensionless bottom scattering strength,

$$M_R = \int (\rho_1 / \rho)^2 |g_1 g_2|^2 M_V d\xi \tag{12}$$

Eqs. (9–12) can be used for analysis of volume reverberation in a complex TREX13 environment taking into account heterogeneity of both the water column and the seabed. For instance, TREX13 sediments were heterogeneous, and had a substantial lateral variability of sediment type and composition, mostly due to variations in mud and shell content (*Hefner and Tang*, 2014).

The observed variability of sediment composition (e.g., change from well-sorted medium sand to muddy or shelly sand) may result in noticeable variations in sound speed and attenuation. Particularly important in this case are changes in local critical angle, affecting local reflection, penetration, and scattering properties. For instance, alternations of the sediment type along the propagation paths may have a strong accumulation effect on the propagator kernel in (9–11), resulting in the propagation intensity scintillations and corresponding backscattering enhancement (10). The alternations across the path result in an effective averaging of the scattering kernel in (11) given by the local bottom scattering strength M_R, which is very sensitive to changes in sediment type, especially at shallow grazing angles (below the critical angle). Therefore, such lateral variability may significantly affect reverberation at long ranges. A quantitative analysis of the effect based on this approach is planned as part of future work.

Numerical Examples

Examples here are to demonstrate capabilities of the first-order Green's function modeling approach to provide fast estimations of reverberation, to show three critical steps in the algorithm of these estimations, and to help analyze potential contributions of different mechanisms of scattering in shallow water environments (heterogeneous water column, rough and heterogeneous bottom). Several scenarios with different types of a layered mud/sand bottom are considered, which are applicable to very shallow water, as well as to more general shallow water environments [see *ONR Workshop* (2015)]. Input parameters for the bottom are chosen to be representative and typical for mud and sand sediments.

Environmental scenarios and input parameters

In the following numerical examples Green's function magnitude, as a function of range and depth (specified for a given very shallow water range-independent environment), was calculated using a PE code (*Tang*, 2014), with input parameters as follows:

Frequency – 3.5 kHz
Water depth – 20 m
Source/receiver depth – 19 m

Three bottom scenarios were chosen to represent sand/mud sediments with different thickness of the mud layer (h) placed above sand halfspace:

(1) sand halfspace ($h=0$)
(2) 0.5 m of mud above sand halfspace
(3) 3.5 m of mud above sand halfspace

Calculations for the penetration field within the bottom were made for depths down to 5 m below the bottom surface.

Acoustic parameters for water, mud, and sand are taken as follows:

	water	mud	sand
Sound speed [m/s]	1530	1500	1670
Density [g/cm^3]	1.0	1.6	2.0
Attenuation (loss tangent), δ	0	0.002	0.01

Numerical simulations in steps

The algorithm of fast estimations of shallow water reverberation includes three critical steps. The first step, according to Eq. (2), is to evaluate the propagation kernel as a function of locations of the source/receiver and scattering point. For this, the Green's function magnitude should be pre-calculated in the waveguide of interest. Importantly, the algorithm requires calculations only at one (central) frequency. These calculations are illustrated in Figures 1–3.

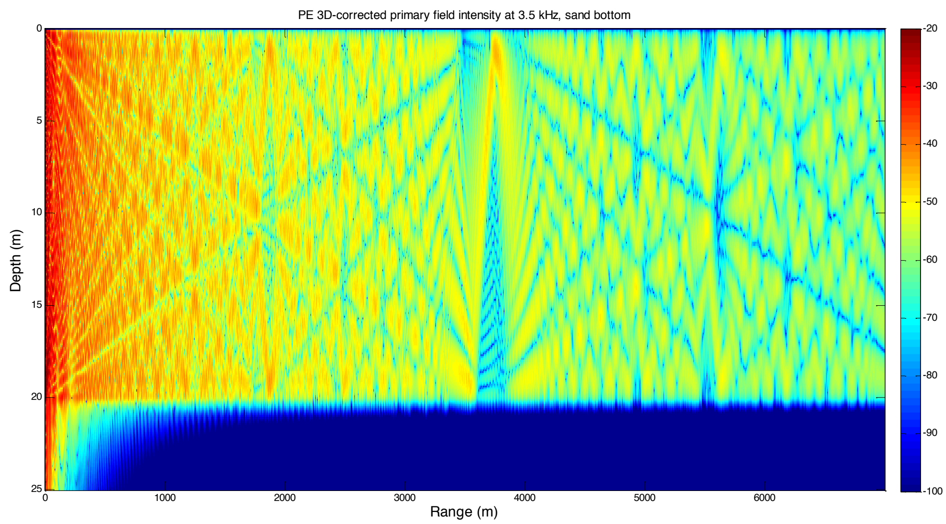

Figure 1: Intensity of 3.5-kHz PE-propagation field in shallow water (20 m depth) with sand bottom. The source is 1 m above the bottom.

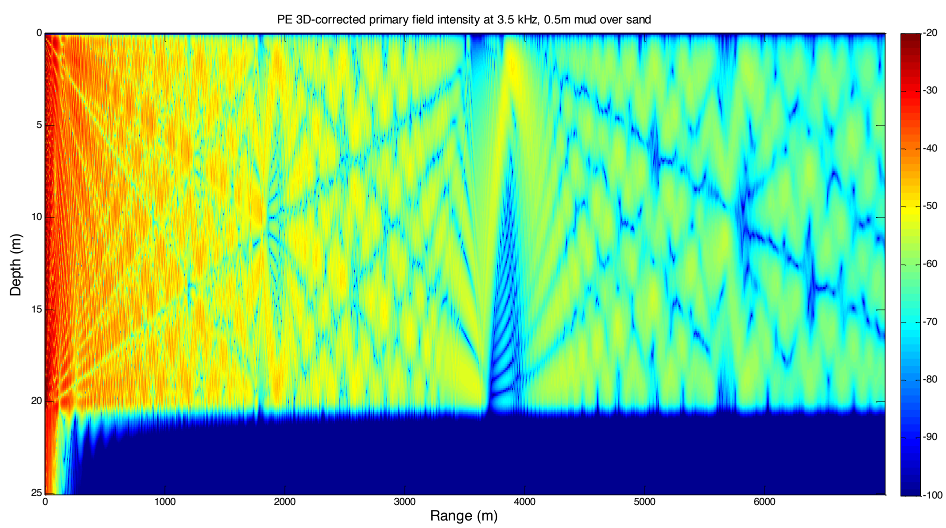

Figure 2: Intensity of 3.5-kHz PE-propagation field in shallow water (20 m depth) with a two-layer, 0.5 m of mud over sand, bottom. The source is 1 m above the bottom.

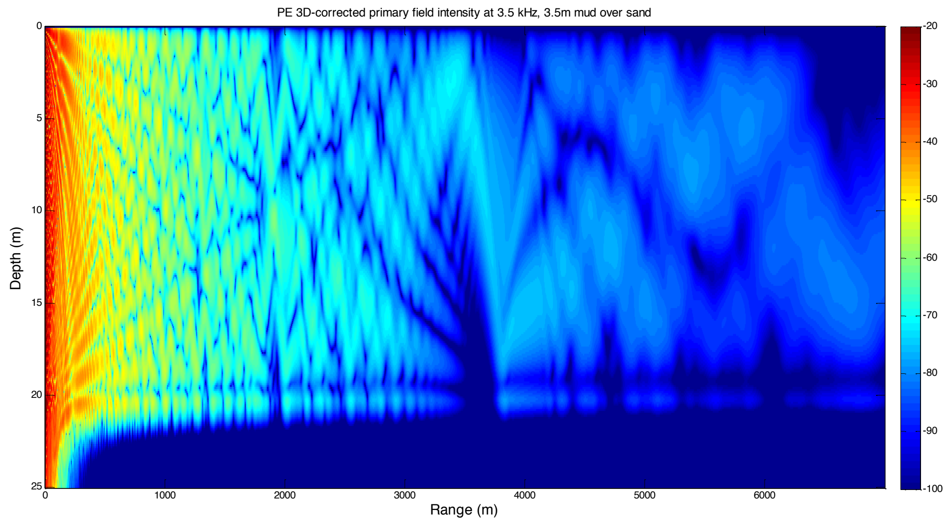

Figure 3: Intensity of 3.5-kHz PE-propagation field in shallow water (20 m depth) with a two-layer, 3.5 m of mud over sand, bottom. The source is 1 m above the bottom.

The second step of the algorithm is illustrated in Figures 4–6. The range-dependence of the propagation intensity on the bottom surface, which is important for estimation of bottom reverberation, is a strongly oscillating function (Figure 4). For further analysis, such calculations require a kind of smoothing. For a particular kind, results are shown in Figure 5, where the smoothing was performed for a fixed range span $L = 100$ m. A simple rationale for such smoothing may result from possible uncertainty in ranges/depths, which can be substantial in some measurement techniques, e.g., in the case where source or/and receiver locations are not fixed. For instance, such a technique was used in the TREX propagation measurements with a fixed vertical array at mid-water (9–15 m depth) and a CW-source moving (i.e., not fixed) at a 10 m depth, so that a range dependence of the transmission loss (TL) was measured. It was noticed that for regions with sand bottom covered by a mud layer (about 20 cm thick) and regions with sand bottom (free of mud), TL is essentially the same. This effect is easy to see in Figure 6, where even a 50-cm mud layer is not sufficient to affect propagation intensity averaged over 100-m ranges and 9–15 m depths. Another reason for smoothing over a range span will be discussed in connection with TREX reverberation data analysis.

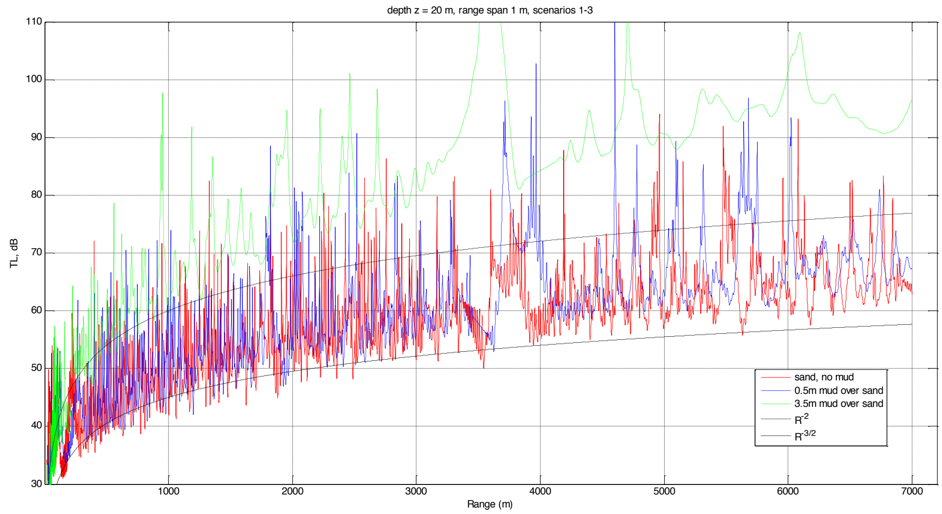

Figure 4: Range dependence of transmission loss at the bottom surface (20 m depth), 3.5-kHz PE-propagation field for three different types of bottom: sand half-space (red), 0.5 m of mud over sand (blue), and 3.5 m of mud over sand half-space (green). The source is 1 m above the bottom. Also shown are $R^{3/2}$ and R^2 range-dependences.

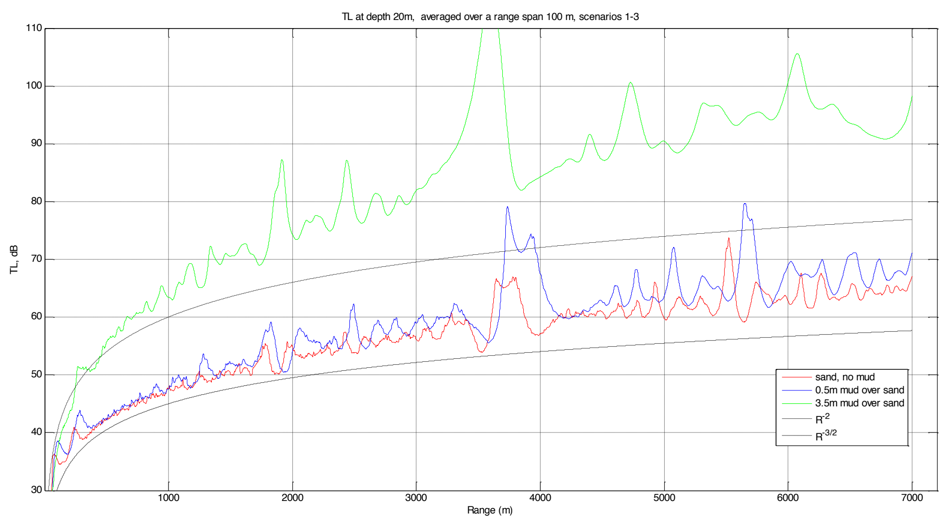

Figure 5: Smoothed 100-m span range-dependence of transmission loss at the bottom surface (20 m depth), 3.5-kHz PE-propagation field for three different types of bottom: sand half-space (red), 0.5 m of mud over sand (blue), and 3.5 m of mud over sand half-space (green). The source is 1 m above the bottom. Also shown are $R^{3/2}$ and R^2 range-dependences.

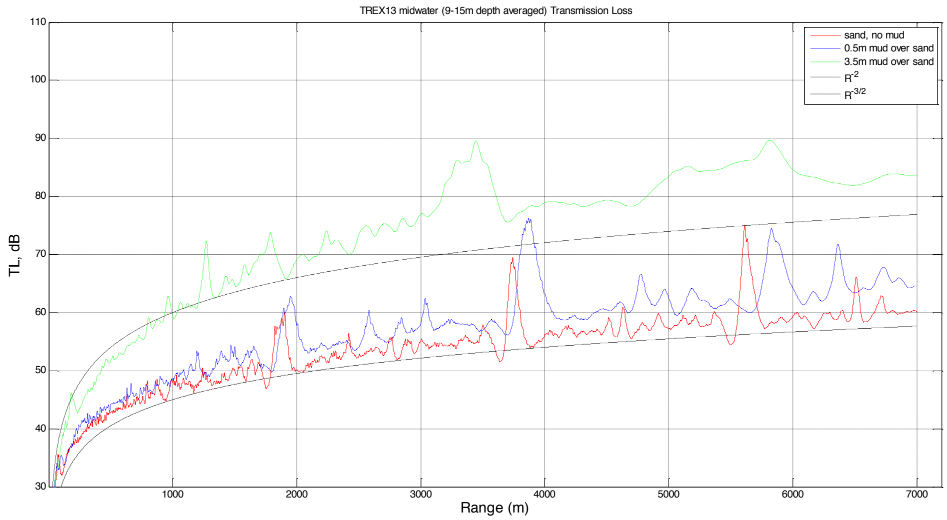

Figure 6: Range-dependence of transmission loss in mid-water, averaged (smoothed) over 100-m span and over 9–15-m depths, 3.5-kHz PE-propagation field in shallow water (20 m depth) for three bottom types: sand half-space (red), 0.5 m of mud over sand (blue), and 3.5 m of mud over sand half-space (green). The source is 1 m above the bottom. Also shown are $R^{3/2}$ and R^2 range-dependences.

The third step of the algorithm provides extremely fast evaluation of reverberation in a shallow water waveguide using the pre-calculated range-depth dependence of single-frequency Green's function intensity for this waveguide. The effect of the frequency bandwidth is considered at this step. According to Eq. (2), the integration should be performed over a horizontal cross-section of the scattering (ensonified) volume, which assumes a span of azimuthal angles, $\Delta\varphi$, (to account for possible azimuthal directivity, e.g., for horizontal arrays, such as FORA). Also, the integration over scattering area presumes another span of ranges, Δr, which may be significantly different from the above mentioned smoothing scale *L*. The span Δr is related to a span of double (two-way) propagation time, and can be defined (although only approximately) the same way as in a direct-path (short-range) scenario, through the frequency bandwidth, Δf, or through the pulse duration, τ, as follows: $\Delta r = c\tau/2 = c/\Delta f/2$. In the following calculations, input parameters needed are: $\Delta f = 100\,\text{Hz}$, $\Delta\varphi = 2.6°$. This yields an estimate $\Delta r = 8\,\text{m}$.

At this step, reverberation caused by bottom volume heterogeneity and rough interfaces, as well as volume reverberation from scatterers in the water column, can be calculated, generally, for an arbitrary distribution of scatterers defined by their volume scattering coefficient M_V, and roughness scattering coefficient M_R (see Eqs. 3–7). Therefore, this allows fast estimation and comparison of relative contributions of different scattering mechanisms, with different natures, strengths, and locations.

Results for chosen bottom scenarios are presented in Figures 7–11, showing reverberation caused by different types of scatterers: heterogeneities of the water column (Figure 7), bottom volume (Figures 8 and 9), and bottom interface roughness (Figures 10 and 11), using representative values for input parameters, M_V and M_R.

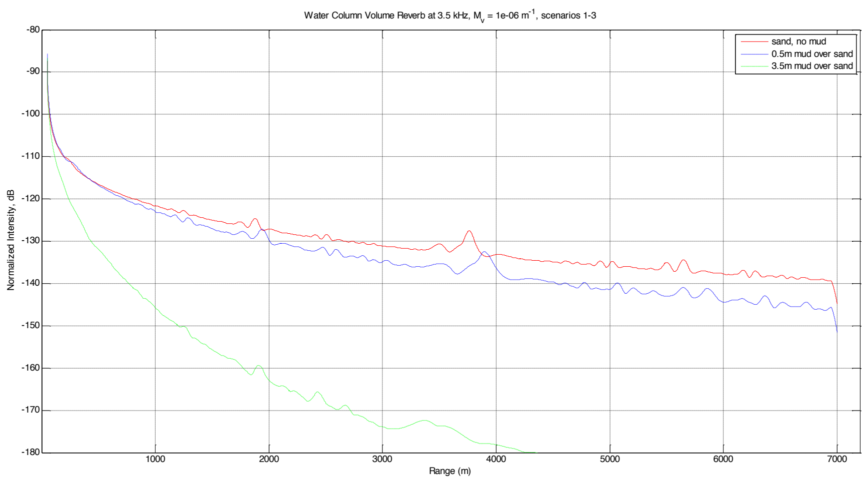

Figure 7: Normalized intensity of reverberation, RL–SL, at 3.5 kHz, caused by volume scattering in the water column with $M_V = 10^{-6}$ m $^{-1}$. Shallow water (20m) with three different types of bottom: sand half-space (red), 0.5 m of mud over sand (blue), and 3.5 m of mud over sand half-space (green). The source is 1 m above the bottom.

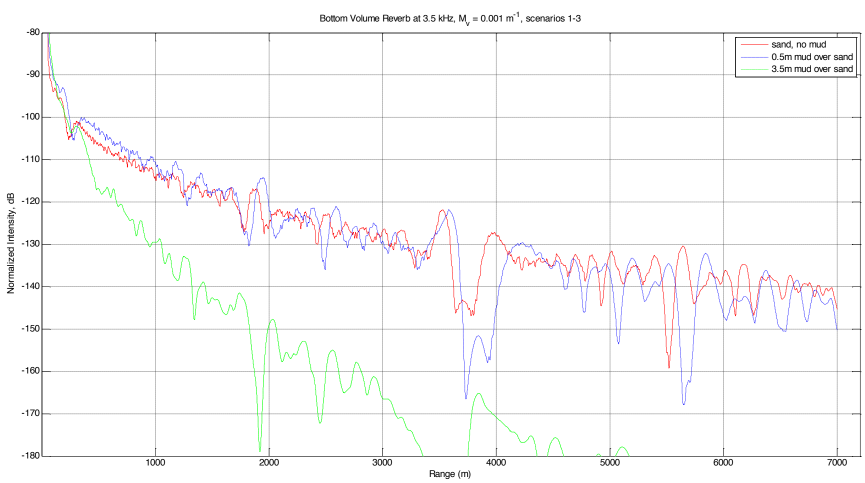

Figure 8: Normalized intensity of reverberation, RL–SL, at 3.5 kHz, caused by sediment volume scattering with $M_V = 10^{-3}$ m $^{-1}$. Shallow water (20 m) with three different types of bottom: sand (red), 0.5 m of mud over sand (blue), and 3.5 m of mud over sand (green). The source is 1 m above the bottom.

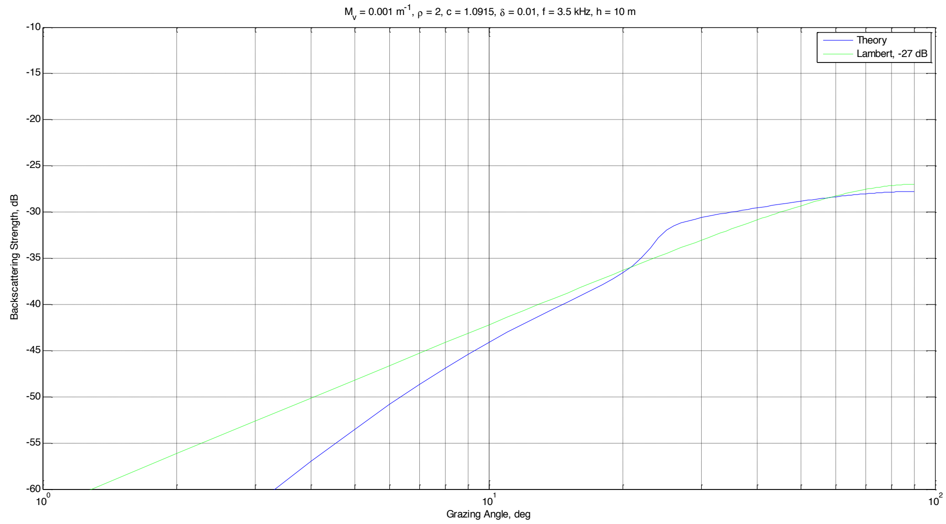

Figure 9: Angular dependence of bottom scattering strength (normalized short-range reverberation intensity), RL–SL, for 3.5 kHz, sand bottom with the same (typical) scattering strength per unit sediment volume used in Figure 8, $M_V = 10^{-3}$ m $^{-1}$. Also shown (in green) is the Lambert law at –27 dB.

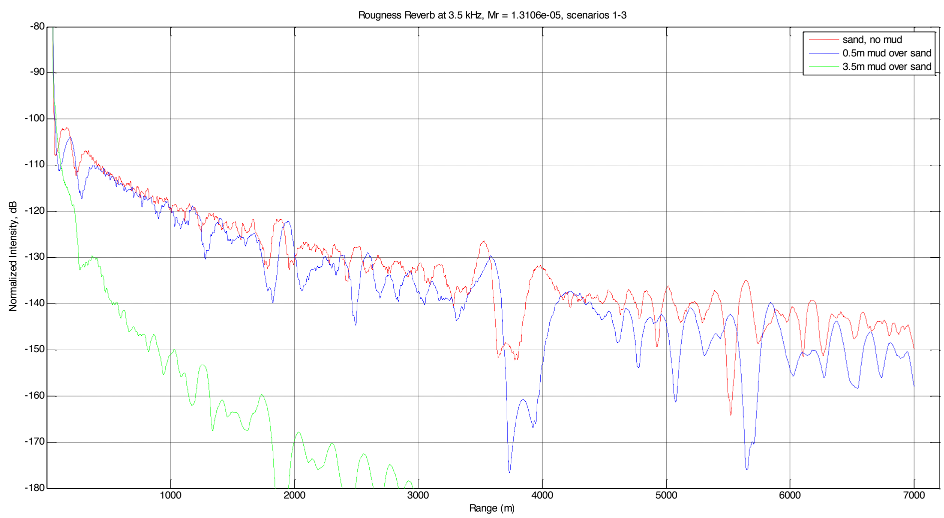

Figure 10: Normalized intensity of reverberation, RL–SL, at 3.5 kHz, caused by bottom interface roughness, with $M_R = 1.3 \times 10^{-5}$. Shallow water (20 m depth) with three different types of bottom: sand half-space (red), 0.5 m of mud over sand (blue), and 3.5 m of mud over sand half-space (green). The source is 1 m above the bottom.

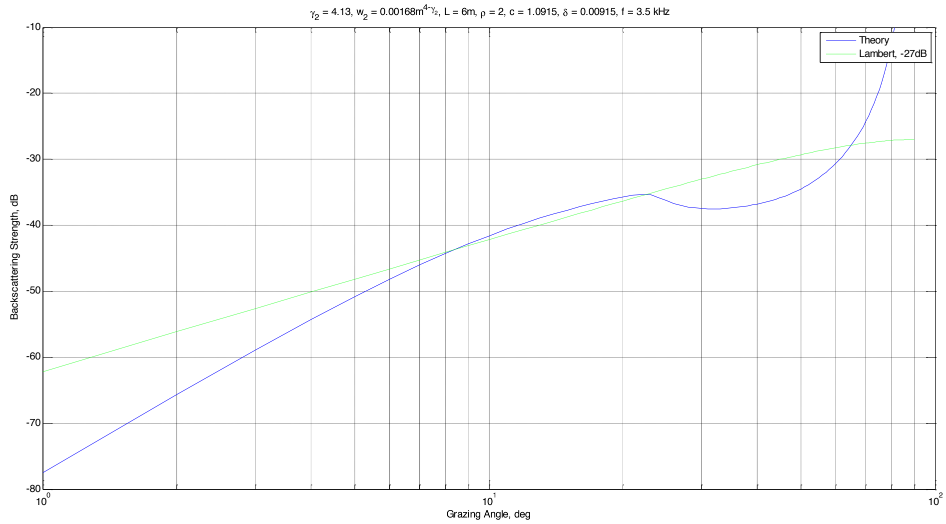

Figure 11: Angular dependence of bottom scattering strength (normalized short-range reverberation intensity), RL–SL, at 3.5 kHz, sand bottom with a roughness scattering coefficient used in Figure 10, $M_R = 1.3\times10^{-5}$. Also shown (in green) is the Lambert law at –27 dB.

Application to TREX Data Analysis

The approach described in the previous sections was refined and specified for the TREX13 environment, geometry, and other input parameters.

TREX environmental scenario and input parameters

As in previous examples, Green's function magnitude was calculated using a PE code (*Tang*, 2014), but for a slightly different configuration and parameters corresponing to a Pekeris waveguide with a sand bottom. Parameters for these calculations were chosen as most relevant to TREX13 conditions and available from the acoustic data (*Tang*, 2015):

Central frequency – 3450 kHz
Frequency bandwidth – 100 Hz
Water depth – 19 m
Source depth – 17.8 m
Receiver (FORA) depth – 16.9 m
Azimuthal beamwidth – 2.6 deg
Source Level (SL) – 200 dB

Calculations for the penetration field within the sand bottom were made for depths down to 2 m below the bottom surface.

Acoustic parameters for water and sand are taken as follows:

	water	sand
Sound speed, (m/s)	1525	1630
Density (g/cm^3)	1	2.0
Attenuation (loss tangent), δ	0	0.01

TREX-specified algorithm for numerical simulations

The algorithm for calculations of reverberation, specified for the TREX scenario, also includes three steps, but with some distinctions from those described previously in this report. The first step, in contrast with previous examples, considers a more general case of bistatic geometry, i.e., according to Eq. (2), now the propagator is to be calculated considering different locations of the source and receiver. For this, the Green's function magnitude was pre-calculated for refined input parameters, given above. Again, it is important that the algorithm requires calculations only at one (central) frequency.

The second step of the algorithm was also refined taking into account the fixed–fixed source–receiver geometry of the TREX13 reverberation measurements and a broadband frequency filter (100 Hz) chosen for the TREX13 reverberation data processing (*Yang et al*., 2014). This case requires a technique for smoothing strong oscillations of the propagation intensity, which differs from that used in previous examples. It takes into account range-dependent scales in interferencial structure of the broadband field in shallow water waveguides. In this case the range span for the smoothing is range dependent as well, and, in contrast with previous numerical examples, is defined as follows: $L = r\Delta f / f$. More details on this technique are described in *Ivakin* (2015b).

The third step of the algorithm provides extremely fast evaluation of TREX13 reverberation using range–depth dependence of single-frequency Green's function intensity pre-calculated for this environment and smoothed in correspondence with the above-described technique. The integration, according to Eq. (2), was performed over a horizontal cross-section of the scattering (ensonified) volume, with a span of ranges, Δr, and a span of azimuthal angles, $\Delta\varphi$, defined in the same way as in previous examples, i.e., $\Delta\varphi = 2.6°$ and $\Delta r = 8\,\text{m}$.

TREX reverberation: Tentative model–data comparison

For further analysis, reverberation caused by bottom volume heterogeneity, as well as volume reverberation from scatterers in the water column, was calculated and a tentative model–data comparison for a subset of TREX reverberation data was performed. The data subset used here is limited to a published example of TREX reverberation data (*Hefner and Tang*, 2014), presented in some more detail in *Yang et al*. (2014) (see TREX13 website). This example includes only one frequency sub-band (f =3400÷3500 Hz), one azimuthal look angle, $\varphi = 129°$, and only two runs, Run #17 (23 April 2013) and Run #79 (9 May 2013). The data are shown in Figure 12, where a normalized reverberation intensity, reverberation level (RL) corrected for source level (SL), i.e., RL – SL, is presented.

It is seen that the data shown in Figure 12 are somewhat different. This difference might represent an effect of environmental changes resulting from a storm that occurred in the area around 1 May 2013. The following calculations and results of model–data comparisons, presented in Figures 13–19, give a tentative interpretation of this effect.

The model suggests that reverberation is caused by volume scattering either in the water column or in the sediment. The contribution of bottom roughness can be considered in a way similar to that shown in previous numerical examples and is not included in this report. A separate paper, *Ivakin* (2015c), which discusses this case in detail, is in preparation. Typical values for the only free parameter of the model, M_V, were used to provide a reasonably good fit between model results and the data.

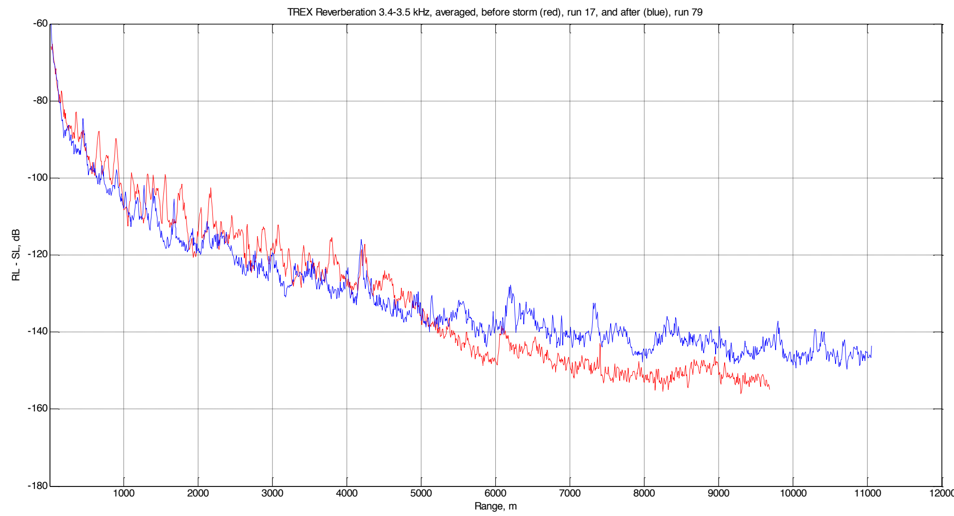

Figure 12: TREX13 normalized reverberation intensity, RL–SL, at 3.4–3.5 kHz, for two runs, before (red) and after (blue) a storm.

First, reverberation from that water column was considered. The results for before storm model–data comparison are shown in Figure 13. Generally, it shows that scattering in the water column can provide a good fit to data at long ranges (more than 6 km). However, to fit the data level, volume scattering strength in the water column should be somewhat higher than typical. Unfortunately, there is no available TREX ground truth data for scattering in the water column at these ranges.

The next case to consider is volume scattering in the sediment. As an initial step, the bottom volume scattering coefficient was assumed to be range-independent. The results are shown in Figure 14. Then a possibility of a smooth range-dependence of $M_V(r)$ was considered to reduce the model–data difference. This resulted in estimated/inferred range-dependence $M_V(r)$ shown in Figure 15. The corresponding corrected reverberation model–data comparison is shown in Figure 16.

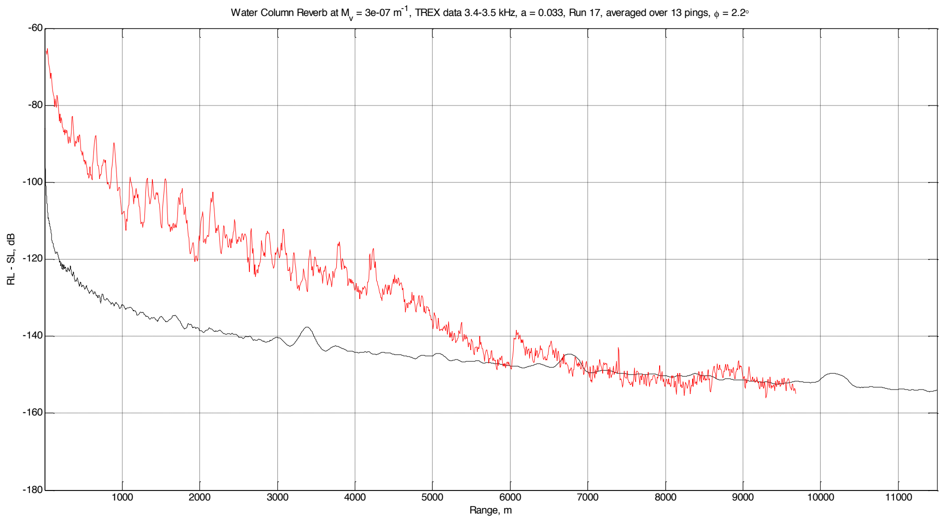

Figure 13: TREX13 normalized reverberation intensity, RL-SL, at 3.4–3.5 kHz, measured before storm (red), compared to model result calculated for scattering in the water column with volume scattering coefficient $M_V = 3\times10^{-7}$ m^{-1}.

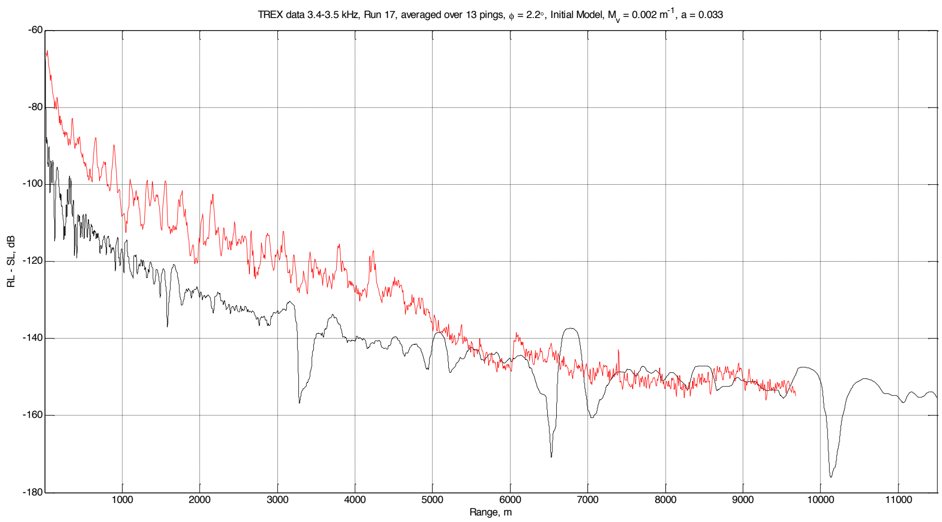

Figure 14: TREX13 normalized reverberation intensity, RL–SL, at 3.4–3.5 kHz, measured before storm (red), compared to that calculated for volume scattering in a sand bottom (range-independent) with $M_V = 0.002$ m^{-1}.

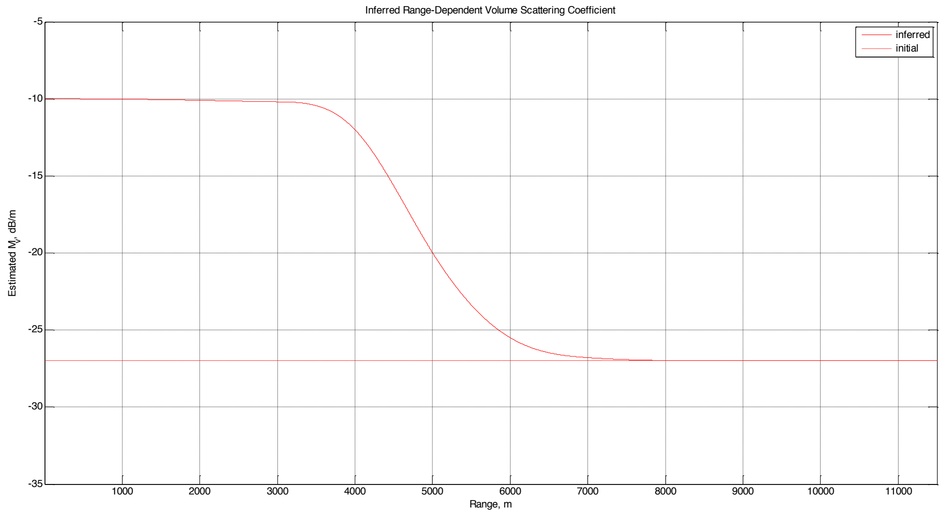

Figure 15: A correction made for range-dependence of local volume scattering strength in the TREX13 sand bottom before a storm.

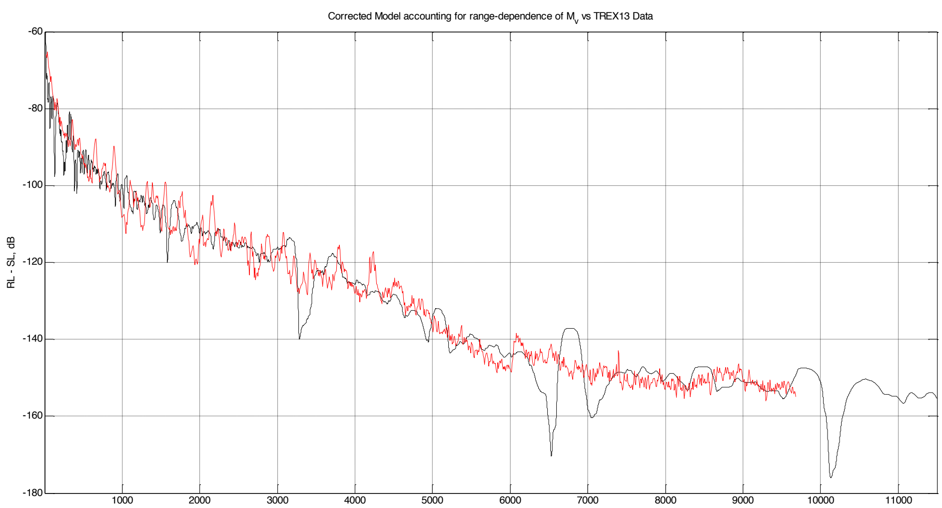

Figure 16: TREX13 normalized reverberation intensity, RL–SL, at 3.4–3.5 kHz, measured before storm, compared to that calculated for volume scattering ina sand bottom with corrected range-dependent volume scattering strength shown in Figure 15.

A similar procedure was performed for analysis of after storm reverberation. The results of the initial model–data comparison (for range independent M_V) are shown in Figure 17. It shows only a slight discrepancy at small ranges, which was easily compensated by a correspondingly slight range-dependence of sediment volume scattering coefficient shown in Figure 18. Then the model–data comparison, shown in Figure 19, becomes reasonably good.

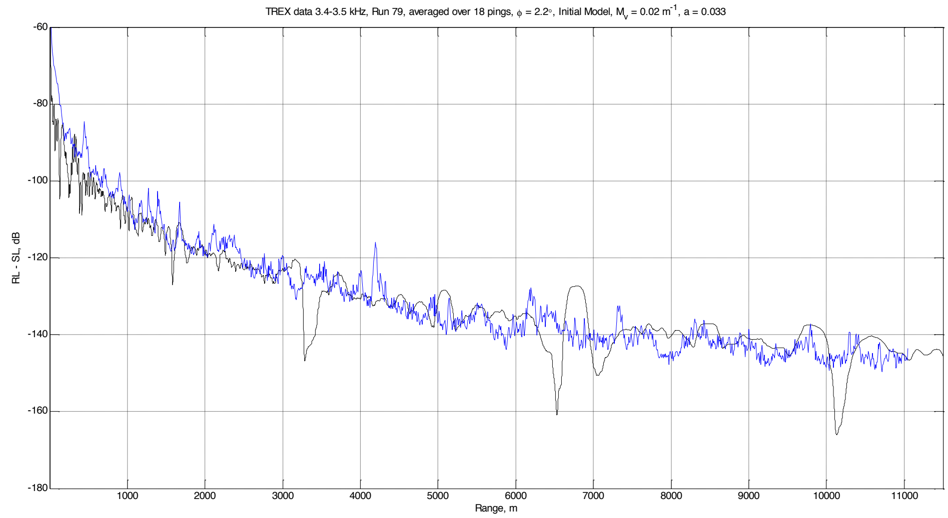

Figure 17: TREX13 normalized reverberation intensity, RL-SL, at 3.4–-3.5 kHz, measured after storm (blue), compared to that calculated for volume scattering from sand bottom (range-independent),) with $M_V = 0.02$ m $^{-1}$.

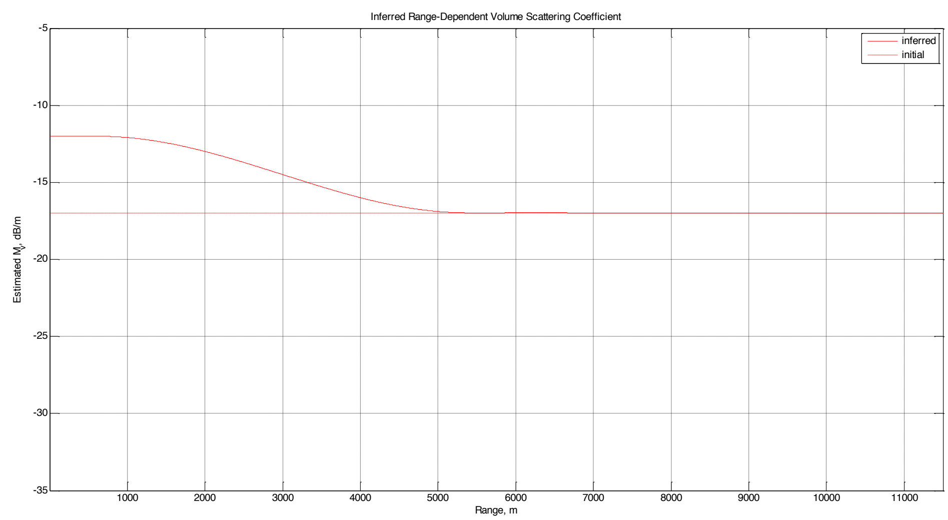

Figure 18: A correction made for range-dependence of local volume scattering strength in TREX13 sand bottom after storm.

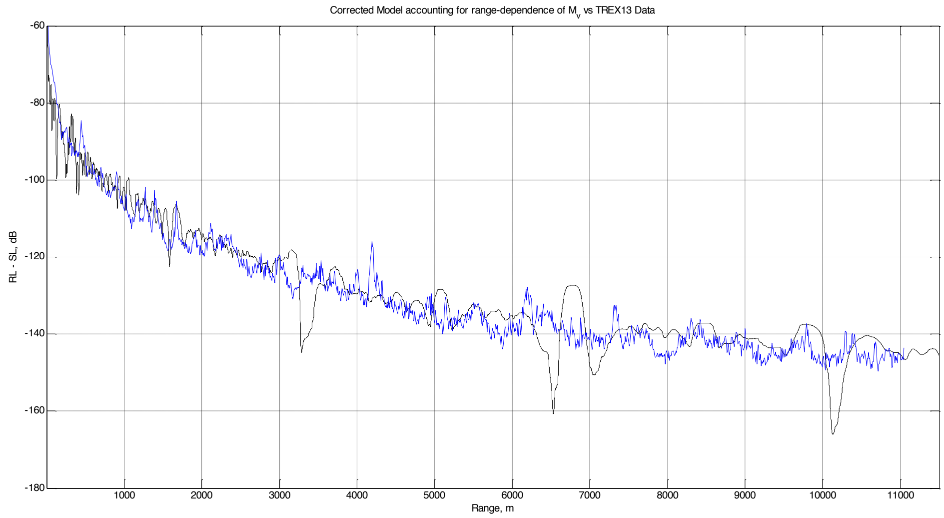

Figure 19: TREX13 normalized reverberation intensity, RL-SL, at 3.4–3.5 kHz, measured after storm (blue), compared to that calculated for volume scattering in sand bottom with corrected range-dependent local volume scattering strength shown in Figure 18.

The comparison of Figure 15 and Figure 18 aid understanding of the nature of the environmental impact of the storm in the area that significantly affected reverberation. Such an impact could result from dynamical mixing of the sediment and consequent smoothing of the range dependence of the strength of surficial sediment heterogeneity along the observation path. Importantly, the same conclusions would be reached if the range-dependence of local roughness scattering is considered using Eq.(5). In more detail, this will be described in a separate paper (*Ivakin*, 2015c).

In addition, to ensure that the two runs, #17 and #79 (Figure 12), used here for model–data comparisons are indeed representative of a more comprehensive data set, reverberation data from five more runs that became available recently (*Tang*, 2015) were considered. They are added to the previous two runs (Figure 20) and confirm the general effect of the storm (Figure 12). This suggests that the model–data comparison, as well as conclusions based on this comparison, will remain reasonable for a more comprehensive TREX13 data analysis.

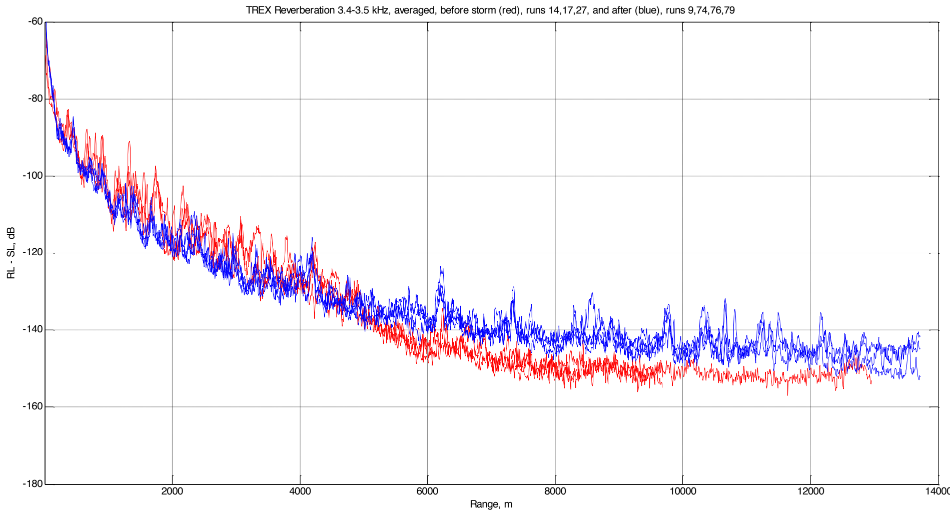

Figure 20: TREX13 normalized reverberation intensity, RL–SL, at 3.4–3.5 kHz, measured before (red) and after (blue) storm. Five more runs added to Figure 12, showing that the previous two runs are typical.

Concluding Remarks and Implications for Future Research

This report has presented a modeling approach that allows fast estimations of volume reverberation in complex shallow water environments. Computer simulations with environmental inputs typical for shallow water have been conducted. Capabilities of this modelling approach and developed codes to provide a reasonable interpretation of TREX2013 reverberation data are demonstrated and discussed.

Based on these results, future research may address several science issues, which appeared to be important for better understanding TREX2013 data:

- To account for sediment lateral variability, mud patches/strips, using more advanced PE codes for Green's function (here only the case of a Pekeris waveguide was considered)
- To analyze environmental and acoustic data to get inputs describing variability of shell content, sub-bottom interface spectra, heterogeneity in mud
- To extensively support TREX13 data analysis, including data obtained for whole mid-frequency range, 1–10 kHz, and all other azimuthal angles (here only a subset of data at 3.4–3.5 kHz and one azimuthal direction was considered)

Several journal papers are in preparation to be submitted in the near future based on results of this research and briefly discussed in this report (*Ivakin*, 2015c, 2015d, and 2015e). One of them, *Ivakin* (2015b), to be submitted soon, includes results shown in Figures 12–19 of this report and uses data currently available on the TREX2013 website (Figure 12).

Publications

A.N. Ivakin (2013), "Volume scattering and reverberation in shallow water: A simplified modeling approach," *J. Acoust. Soc. Amer.*, 134 (5, Pt.2), p. 4208.

B.T. Hefner, D.R. Jackson, A.N. Ivakin, and G. Wendelboe (1913), "Physics-based inversion of multibeam sonar data for seafloor characterization," *J. Acoust. Soc. Amer.*, **134**(4), Pt.2, p. 4240.

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Ivakin A.N. (2015d), "Scattering from discrete heterogeneity of marine sediments," in preparation.

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14. ABSTRACT
The long-term goals of this research are to better understand and accurately model low-to mid-frequency reverberation in shallow water environment. Specific goals are to develop a model of reverberation for conditions (1-10 kHz, ~20m water depth, ~10 km range) corresponding to the ONR Target and Reverberation Experiment performed in the spring 2013 (TREX2013), develop a code and conduct computer simulations with environmental inputs typical for the chosen location, and apply this model to analysis of available TREX2013 data. This report present a modeling approach that allows fast estimations of volume reverberation in complex shallow water environments. A simplified first-order version of the approach is considered to show how far-field scattering solutions obtained for free space can be incorporated into reverberation in complicated bounded, range-dependent, and stratified environments. A higher order modification of thie approach is considered as well, using a Multiple Foward Single Backscatter (MFSB) approximation. Application to analysis of shallow water reverberation measured during the TREX2013 is discussed.

15. SUBJECT TERMS
Underwater reverberation, volume scattering, mid-frequency acoustic data inversion, TREX13, backscatter intensity, Green's function, continuum and discrete heterogeneity, multiple scattering effects, scintillations, backscattering enhancement

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