Models of scattering for remote acoustic sensing of the seafloor

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Abstract

Frequency-angular dependencies of the scattering strength for the sea bed with rough surface and volume heterogeneity contain some distinctive features. These can be used for remote acoustic sensing of the sediment, in particular, for identification of the sediment type and inversion of certain bottom parameters. However, the two mechanisms, volume and roughness scattering, can provide similar dependencies. To resolve possible ambiguities, the correlation method of separating and discriminating volume and surface scattering is proposed.

1. Introduction

Methods of remote acoustic sensing are usually based on certain models of sound interaction with the medium, acoustic propagation through and scattering from it. The models provide necessary relationships between parameters of the medium and characteristics of the acoustic field, and the methods of remote sensing exploit various possibilities of inverting those relationships with respect to medium parameters. A background for modelling of seabed scattering can be found in references [1-6]. Some experimental tests for the models and examples of their use for determination of certain seabed parameters are presented in references [4-11].

At high frequencies, only the top sediment layer is important because of strong absorption and small sound penetration into the bottom. In many cases, it permits several general simplifications in modelling of seabed scattering, which are used in this paper as well. First, the mean parameters of bottom medium are assumed to be depth-independent, that is the effects of sediment stratification, vertical gradients of mean acoustical parameters and discrete layering, are neglected. Secondly, the sediment is considered as a continuous medium, which ignores those effects of discrete microstructure of the sediment, porosity, grain scattering, etc, which cannot be included in effective acoustical parameters of the medium and their smooth spatial variations. Note, however, that these two simplifications are reasonable for high, but not too high frequencies, for which the wavelength becomes comparable to the discrete scatterer size or to the thickness of the water-sediment transition layer. Third assumption is that the effects of the sediment consolidation and shear elasticity can be neglected as well, that is the seabed medium is considered as a fluid. Some considerations, models and numerical examples beyond the mentioned assumptions can be found in references [1-4,12-15].

Two models of scattering from marine sediments are discussed in this paper, which can be used for high frequency acoustic sensing of the seafloor. The models take into account two different mechanisms of scattering: roughness of the seabed surface and volume inhomogeneities of the sediment (spatial fluctuations of the acoustical parameters). The models are based on a first-order theory of scattering in a fluid medium [1]. They provide the expressions for the roughness and volume scattering cross section per unit seabed surface, which are proportional to the energy spatial spectra of seabed random irregularities (roughness and volume inhomogeneities, correspondingly) with form-factors depending upon the mean parameters of the sediment. Numerical examples are presented for different types of sediments (sand, silt and gassy silt), for both monostatic and bistatic geometry configurations, and the role of various parameters of the models is analysed. It is shown, in particular, that angular dependencies of the seabed roughness and volume scattering strength contain some distinctive features, which can be used, in particular, for remote identification of the sediment type and inversion of certain bottom parameters.

The two mechanisms of seabed scattering, surface roughness and volume heterogeneity, can operate at the same time, and thus methods for their separate identification are of practical importance. The correlation method of separating and discriminating volume and surface components of the scattered field is proposed, which involves measurements of spatial coherence of the field with a linear array located near the source. It is shown that the correlation scales for the volume and surface components can be significantly different, and thus spatial filtration can be used for separating these components. This method would also permit separate measurement of the scattering strength per unit area of bottom surface, the scattering strength per unit volume and sound attenuation in the sediment.

2. Seabed Roughness Scattering

In the case, where effects of the sediment stratification can be ignored, which is usually assumed at high frequencies, the seabed roughness scattering coefficient, or scattering cross section per unit area of seabed rough surface, can be presented as follows [1,15]:

$$M_{sr} = F(\chi_i, \chi_s)\left|C_r(\chi_i, \chi_s, \phi_i - \varphi_s)\right|^2 k_w^4 \Phi_r(\vec{K}_s - \vec{K}_i), \tag{1}$$

where Φ_r is the spatial 2D-spectrum of roughness, $\vec{K}_i$ and $\vec{K}_s$ are horizontal components of the wave vectors of incident and scattered waves with $\chi_{i,s}$ and $\varphi_{i,s}$ being their grazing and azimuth angles in the water near water-sediment interface, $k_w = 2\pi f / c_w$ is the wave number in the water, F and C_r are the form-factors defined by the expressions:

$$F(\chi_i, \chi_s) = \left|1 + V(\chi_i)\right|^2 \left|1 + V(\chi_s)\right|^2, \tag{2}$$

$$2C_r(\chi_i, \chi_s, \phi) = \left(\frac{n^2}{m} - 1\right) + \left(1 - \frac{1}{m}\right)\left(\cos\chi_i \cos\chi_s \cos\phi - \frac{1}{m} P_i P_s\right), \tag{3}$$

$$P_{i,s} = P(\chi_{i,s}) = \sqrt{n^2 - \cos^2 \chi_{i,s}}, \tag{4}$$

$$V(\chi) = (m \sin\chi - P(\chi)) / (m \sin\chi + P(\chi)), \tag{5}$$

where $V(\chi)$ is the Frenel reflection coefficient, $m = \rho / \rho_w$ is the sediment-water density ratio and $n = n_0(1 + i\delta)$ is the complex refraction index of the sediment with $n_0^{-1} = c / c_w$ as the sediment-water sound speed ratio and δ as the loss parameter.

In this paper, three types of the sediment, sand, silt and gassy silt, were chosen with parameters presented in Table1. Note that "gassy silt" here is just a conditional name for the sediment with sound speed substantially less than in water. A possible reason for this can be presence of a small volume portion of micro-bubbles, which practically do not affect the sediment density, but significantly increase its compressibility and, correspondingly, reduce the sound speed.

Sediment Type	Density Ratio, m	Sound Speed Ratio, n_0^{-1}	Loss parameter, δ
1. Sand	1.8	1.05	0.01
2. Silt	1.4	0.97	0.005
3. Gassy Silt	1.4	0.8	0.01

Table 1. Parameters for different sediment types taken for numerical examples.

For the calculations below, the seabed roughness is assumed to be isotropic with the spectrum, which in a certain range, $K_1 < K < K_2$, has a form of the power law and can be defined as follows:

$$\Phi_r(\vec{K}) = A(k_0) k_0^{\gamma-4} \left(K^2 + K_1^2\right)^{-\gamma/2}, \quad K < K_2, \tag{6}$$

where k_0 is an arbitrary reference wave number introduced to yield a dimensionless roughness spectral strength, A, which, at $\gamma \neq 4$, depends on the choice of k_0. The spectral strengths for two different reference wave numbers are related as follows:

$$A(k_1) = A(k_0)(k_1 / k_0)^{4-\gamma}. \tag{7}$$

Introduction of the parameters K_1 and K_2 is needed at $\gamma \geq 2$ and $\gamma \leq 4$, respectively, for mean squared height and slope of roughness to be finite. Then one obtains

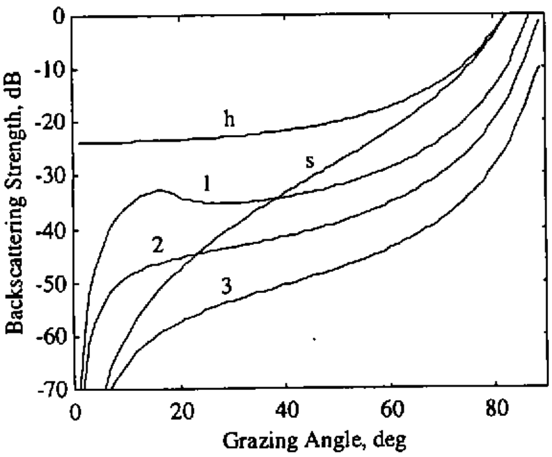
$$k_w^4 \Phi_r(\vec{K}_s - \vec{K}_i) = A(k_w)\left(u^2 + u_1^2\right)^{-\gamma/2}, \tag{8}$$

where $u_1 = (k_w L)^{-1}$ with $L = K_1^{-1}$ being the outer scale of roughness, and u is an angular dependent function defined as follows:

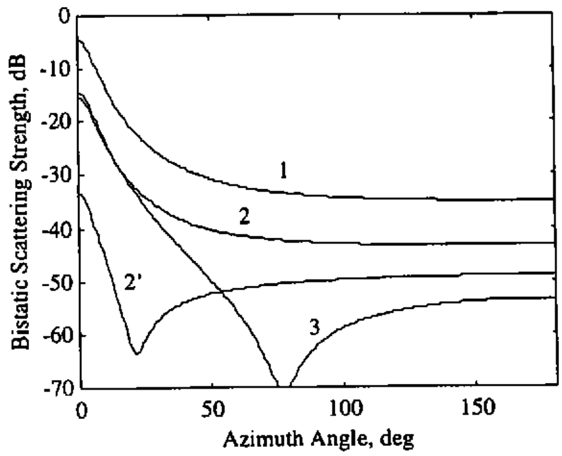
$$u^2 = \left(\frac{\vec{K}_s - \vec{K}_i}{k_w}\right)^2 = \cos^2\chi_i - 2\cos\chi_i \cos\chi_s \cos(\phi_i - \varphi_s) + \cos^2\chi_s. \tag{9}$$

Thus, to calculate the frequency-angular dependence of the seabed roughness scattering coefficient at given sediment type, only the two spectral parameters are needed, A and γ, for directions, which are not close to specular one. For near specular directions, the third parameter, $k_w L$, is needed.

For the calculations below, the following values of the parameters were used: $\gamma = 3.5$, $A(k_w) = 0.003$, and $k_w L = 10$. First two of them are close to available data [6,7], whereas the third one is assigned an arbitrary big but finite value just for scattering in near specular directions to be finite.In this case, the scattering strength slightly increases with frequency for all scattering directions, except those close to the specular direction, where it is strongly dependent on frequency and controlled by the parameter $k_w L$. In Figure 1, angular dependencies of the seabed roughness scattering strength, $SS = 10\log M_{sr}$, are shown for two different geometry configurations. Both are for the case where $\chi_i = \chi_s = \chi$, but the first one, monostatic or backscattering (a), corresponds to $\varphi_s - \varphi_i = \pi$ and shows dependence of the scattering strength on the grazing angle, χ, whereas the second, bistatic (b), shows the dependence on the azimuth angle, $\varphi = \varphi_s - \varphi_i$ at $\chi = 30°$, except curve 2' corresponding to $\chi = 10°$. For comparison, the backscattering strengths for hard and soft boundaries having the same roughness spectrum are shown as well.



(a)



(b)

Figure 1. Seabed roughness scattering strength for monostatic (a) and bistatic (b) configurations for different types of sediments with the same roughness spectrum: Sand (curves 1), Silt (2 and 2') and Gassy Silt (3). The backscattering strength for hard (h) and soft (s) boundaries are shown for comparison. In the bistatic case, the grazing angles are 30°(curves 1-3) and 10°(2').

Several effects can be mentioned here and possibly used for remote acoustic sensing of the seafloor. It is seen that the angular dependencies for different types of sediment can be very different and have certain distinctive features related to particular sediment types. First, the level of scattering, for the same roughness, is strongly influenced by the contrast of the acoustical parameters at the water-sediment interface, see (3). For example, for a water-silt interface, the level of scattering is much lower than for a water-sand interface, although for both types of the sediment this level is substantially higher than for an analogous (with the same roughness) soft boundary, e.g., the water-air interface, at small grazing angles. This effect is substantial and in principle, if the spectrum of roughness is known, can be used for remote determination of surficial sediment parameters. Second effect is seen in example of sands, where a pronounced feature is a "critical angle" (here at about 18°) defined by a higher sound speed in the sediment than in the water. Therefore, it can be used as a sign for high sound speed in the sediment. In the case of low sound speed (less than in water), another remarkable effect, in bistatic scattering, can be used. This effect is seen here in gassy silt case (curve 3, $\chi = 30°$) as a minimum at a certain azimuth angle (about 77°), but is not seen for silts at this grazing angle (curve 2). At given bistatic configuration, where $\chi_i = \chi_s = \chi$, the azimuth angle, $\varphi = \varphi_s - \varphi_i$, corresponding to this minimum can be determined from the expression

$$\sin^2(\varphi/2) = \frac{(m+1)}{2m}\left(1 - \cos^2\chi_p \big/ \cos^2\chi\right), \quad \cos^2\chi_p = \frac{m^2 - n_0^2}{m^2 - 1}, \tag{10}$$

where χ_p is the angle of total penetration into the sediment, which is about 50° for gassy silt and 15° for silt. This effect appears only for the following angles: $\chi < \chi_p$ $(\varphi_s \neq \varphi_i)$, or $\chi_s = \chi_i = \chi_p$ $(\varphi_s = \varphi_i)$. For gassy silt and taken grazing angles (30°), the minimum is remarkable, but for silt this effect can be seen only if grazing angles are less than 15°. The minimum is shown for silt by curve 2' at $\chi = 10°$ and appears at $\varphi \approx 20°$. The effect of "non scattering" at the angles defined by (10) can be considered as analogous to the effect of "non reflection" at the angle of total penetration. It is caused by the mutual compensation of two different types of "virtual" secondary sources, monopole and dipole, which appear as a result of the perturbation of the sediment interface, and which are represented by the two terms in (3). The effect is defined only by the mean sediment parameters and, thus, can be used as a sign or "classification clue" for low sound speed and high compressibility in the sediment related, for example, to presence of gas. Also, as it is easy to see from (10), if the minimum is measured for two different grazing angles, both the density and sound speed in the sediment can be determined.

3. Seabed Volume Scattering

Here we consider the same particular case as for roughness scattering, where effects of the sediment stratification were ignored. More general seabed volume scattering model is given in [1]. Also, it is assumed here that the vertical correlation scale of volume inhomogeneities in the sediments is smaller than both the thickness of the inhomogeneous layer, h, and the depth of sound penetration into the sediment, h_p. In this case, the scattering cross section per unit area of seabed surface, or the seabed volume scattering coefficient, can be presented as follows:

$$M_{sv} = Fm^{-2} M_v h_{ef}\,, \tag{11}$$

$$h_{ef} = h_p\left(1-\exp\left(-h/h_p\right)\right), \tag{12}$$

$$h_p = \left(4k_w P_2\right)^{-1},\ P_2 = \mathrm{Im}(P),\ P = (P_i + P_s)/2\,, \tag{13}$$

where M_v is the scattering cross section per unit volume of the sediment, which, in the case of continuous inhomogeneities, is defined as

$$M_v = 2\pi\,|k|^4\,\Phi_{ss}\left(\vec{Q}\right), \tag{14}$$

$$\vec{Q} = \mathrm{Re}\left(\vec{Q}_s\right) = \left(\vec{K}_s - \vec{K}_i, 2k_w P_1\right),\ \vec{Q}_s = \vec{k}_s - \vec{k}_i,\ P_1 = \mathrm{Re}(P), \tag{15}$$

$k = k_w n$ is the complex wave number in the sediment, $\vec{Q}_s$ is the complex scattering vector, $\vec{k}_i$ and $\vec{k}_s$ are the complex wave vectors of the incident and scattered fields in the sediment, Re and Im denote real and imaginary parts of a complex value, and Φ_{ss} is the energy spectrum of volume scattering or the spatial spectrum of a heterogeneity scattering function, ε_s, defined through the relative fluctuations (ratios of fluctuation of the parameter to its mean value) of the sound speed and density, ε_c and ε_ρ, as follows:

$$\varepsilon_s(\vec{r}) = \varepsilon_c(\vec{r}) + s\varepsilon_\rho(\vec{r}),\ s = Q_s^2/(2k)^2 = \sin^2\vartheta/2\,, \tag{16}$$

where ϑ is the angle between directions of scattered and incident waves in the sediment. Then the energy spectrum of scattering can be defined through the auto- and cross-spectra of the fluctuations:

$$\Phi_{ss}(\vec{Q}) = \Phi_{cc}(\vec{Q}) + 2\,\mathrm{Re}(s\Phi_{\rho c}(\vec{Q})) + |s|^2\,\Phi_{\rho\rho}(\vec{Q})\,, \tag{17}$$

$$\Phi_{\alpha\alpha'}(\vec{Q}) = (2\pi)^{-3}\int B_{\alpha\alpha'}(\vec{r})\exp(-i\vec{Q}\cdot\vec{r})d^3r\,, \tag{18}$$

where $B_{\alpha\alpha'}$ is the correlation function of the fluctuations, which are assumed to be statistically uniform:

$$B_{\alpha\alpha'}(\vec{r}) = \left\langle \varepsilon_\alpha(\vec{r}_0 + \vec{r}/2)\varepsilon^*_{\alpha'}(\vec{r}_0 - \vec{r}/2)\right\rangle,\ \alpha = c, \rho;\ \alpha' = c, \rho\,. \tag{19}$$

Consider the case where fluctuations of both sound speed and density are due to spatial variations of only one parameter, say density, and there is a certain relation between parameters given by a function $c = c(\rho)$. In this case, for the heterogeneity scattering function and its spectrum, one obtains

$$\varepsilon_s(\vec{r}) = a_\rho(s)\varepsilon_\rho(\vec{r}),\ a_\rho(s) = b + s,\ b = \frac{d\ln c}{d\ln\rho}, \tag{20}$$

$$\Phi_{ss}(\vec{Q}) = \left|a_\rho(s)\right|^2\Phi_{\rho\rho}(\vec{Q})\,. \tag{21}$$

It easy to see, that parameter b can have a strong effect on the angular dependence of bistatic scattering. In particular, in the case of anti-correlation between fluctuations of sound speed and density, where $b<0$, the energy spectrum of volume scattering has a minimum in directions defined as follows:

$$\sin\vartheta/2=\sqrt{-b}\,. \tag{22}$$

In these directions, the mutual compensation occurs for two different components of scattering, which are due to fluctuations of sound speed and density in (16).

To define a form of the spatial spectra, some assumptions are needed about the shape of inhomogeneities. This would permit, in its turn, to define relation of the 3D-spectra to the 1D-spectra of the inhomogeneities and to use, e.g., the core data. An assumption about isotropy of inhomogeneities, corresponding to their spherical shape (referring to surfaces of constant correlation in spatial lag space), is frequently used [5-7]. However, some examples, where the anisotropy of inhomogeneities is important, are known as well [2,4,10,12]. To take into account possible effects of anisotropy, consider a class of anisotropic fluctuations with spatial correlation functions of the form:

$$B(\vec{R},z)=B\left(\sqrt{R^2/\eta^2+z^2}\right), \tag{23}$$

where η is the aspect ratio of the inhomogeneities (ratio of their horizontal correlation scale to vertical). In this case, using (18), one can show that corresponding 3D (spatial) and 1D (vertical) spectra are related as follows

$$\Phi(\vec{K},q)=-\frac{\eta^2}{2\pi q'}\frac{d\Phi^{(1)}(q')}{dq'},\ q'=\sqrt{\eta^2K^2+q^2}\,. \tag{24}$$

Suppose the sediment inhomogeneity has the vertical spectrum, which in a certain range, $q_1<q<q_2$, obeys the power law. It can be taken in the form:

$$\Phi^{(1)}(q)=A(k_0)k_0^{\gamma-1}\left(q^2+q_1^2\right)^{-\gamma/2},\ q<q_2, \tag{25}$$

where k_0 is an arbitrary reference wave number introduced, as well as for roughness, to yield a dimensionless heterogeneity spectral strength, A, which, at $\gamma\neq 1$, depends on the choice of k_0. The spectral strengths for two different reference wave numbers are related as follows:

$$A(k_1)=A(k_0)(k_1/k_0)^{1-\gamma}\,. \tag{26}$$

Introduction of the parameters q_1 and q_2 is needed at $\gamma\geq 1$ and $\gamma\leq 3$, respectively, for the variances of the fluctuations and their gradients to be finite. Then one obtains

$$M_v/k_w=A(k_w)\eta^{-\gamma}\gamma|C|^2\left(u^2+u_1^2\right)^{-1-\gamma/2}, \tag{27}$$

$$C=n^2a_p(s)=bn^2+u^2/4+P^2, \tag{28}$$

$$u_1^2=(4P_1^2+k_w^{-2}l^{-2})\eta^{-2}, \tag{29}$$

where $l=q_1^{-1}$ is the vertical correlation scale of inhomogeneities. Then, taking into account that equation (11) can be presented in the form

$$M_{sv}=Fm^{-2}\left(1-\exp(-4k_whP_2)\right)(4P_2)^{-1}M_v/k_w, \tag{30}$$

one can see that, at given sediment type, this model requires a set of six dimensionless inputs, $A(k_w),\gamma,\eta,b,k_wl$, and k_wh, to provide calculations of frequency-angular dependence of the seabed volume scattering coefficient.

Format of this paper allows to discuss only some features of this model, which are illustrated in Figure 2. For a numerical example, the following values of input parameters were used: $A(k_w)=0.012$, $\gamma=1.5$, and $k_wl=1$. First two of them are close to available data [6,7], whereas the third one is assigned an arbitrary value to satisfy the assumption that the vertical correlation scale of volume inhomogeneities is smaller than both the thickness of the inhomogeneous layer, h, and the depth of sound penetration into the sediment, h_p. In this case, the scattering strength slightly decreases with frequency in cases where the scattering layer can be considered as a half-space, that is at not big grazing angles and at high enough frequencies, for which the penetration depth is smaller than the thickness of the inhomogeneous layer and the exponential term in (12) can be omitted. However, for bigger grazing angles and lower frequencies, the half-space model is automatically turns into the layer model, for which the scattering strength slightly increases with frequency. Parameter b was assigned different values for different types of sediments as follows: 0.1 (sand), –0.12 (silt), and –0.7 (gassy silt). There is no direct measurements of this parameter in sediments, but these values are in reasonable agreement with rough indirect estimations based on relations between mean parameters. The following values of two more parameters were used, $\eta=10$ (strong anisotropy) and $k_wh=2.5$ (thin inhomogeneous layer), except two curves in Figure 2a. One of them, curve 3', corresponds to isotropic inhomogeneities in gassy silt and its comparison with curve 3 shows the effect of anisotropy. Another one, curve 1', corresponds to infinitely thick inhomogeneous layer in sands (half-space model) and its comparison with curve 1 shows the strong effect of the parameter $k_w h$. It causes, in particular, appearance of the "critical angle" effect, which therefore exists for volume scattering from sand as well as for roughness scattering.

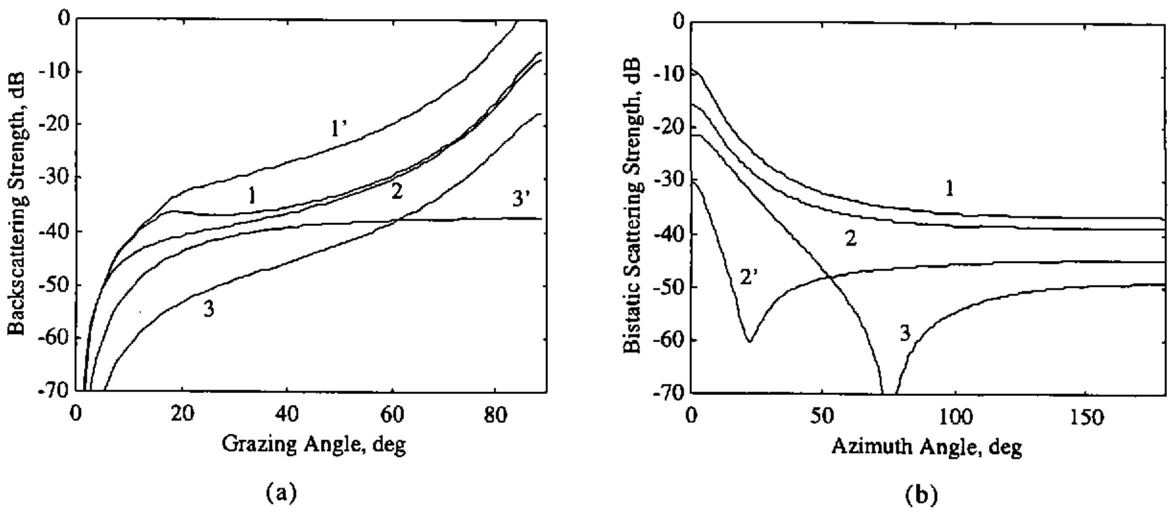


Figure 2. Seabed volume scattering strength for the same types of sediments and geometry, monostatic (a) and bistatic (b), as for roughness scattering (see Figure 1 and Table 1). The curves show scattering from a thin layer with anisotropic (1-3 and 2') and isotropic (3') inhomogeneities, and from halfspace with anisotropic inhomogeneities (1'). In the bistatic case, the grazing angles are 30° (curves 1-3) and 10° (2').

One more remarkable effect is seen in bistatic scattering for silt and gassy silt as a remarkable minimum at a particular azimuth angles defined in (22). This effect is caused by the same reason as in the roughness scattering case, that is by mutual compensation of the monopole and dipole scatterers. Therefore, this effect can be used as a sign for low sound speed in the sediment regardless the type of scattering, volume or roughness. Also, from comparison Figures 1 and 2, it becomes evident, that in certain cases it can be difficult to determine the type of scattering, volume or roughness, from measurements of scattered intensity, as the scattering strengths for these mechanisms of scattering can have very similar angular dependencies. Thus, if these components of scattering operate at the same time, which is usually the case, there is potential ambiguity in the resultant inversions of seabed parameters. To resolve this ambiguity and, in particular, to make possible separating and identification of the different components, not only intensity, but other characteristics of the scattered field should be measured.

4. Separating Roughness and Volume Scattering

Measurements of the spatial coherence of the scattered field can be used to separate contributions of volume and roughness components or, if there is only one component, to determine its type. For simplicity, consider the case, where the volume and roughness field components, p_v and p_r, are not correlated and, consequently, their intensities are additive:

$$I = \langle |p|^2 \rangle = I_r + I_v, \; p = p_r + p_v . \tag{31}$$

The spatial coherence coefficient is defined as follows:

$$N(r_1, r_2) = \frac{\langle p(r_1) p^*(r_2) \rangle}{\sqrt{I(r_1) I(r_2)}} . \tag{32}$$

In the far zone, where $L = |r_1 - r_2| \ll R$, with R being the distance between the scattering volume of sediment and receiving array, one obtains

$$N(L) = \frac{I_r}{I} N_r(L) + \frac{I_v}{I} N_v(L) . \tag{33}$$

It is easy to see that if the partial roughness and volume coherence coefficients, N_r and N_v, have significantly different coherence scales, L_r and L_v, e.g., $L_r \gg L_v$, then the intensities of these components can be determined separately using measurements of the spatial coherence of the total field at different values of L. In particular, at $L_r \gg L \gg L_v$, one obtains $N \approx I_r / I = 1 - I_v / I$. This is an illustration of a spatial "filtration", which in this case leaves only the roughness component of the scattered field and eliminates the volume component.

As an example, consider the vertical coherence of a spherical narrow band impulse of duration τ and period T, scattered nearly backward from the rough heterogeneous sediment volume with the same sound speed c as in the water (for simplicity) and attenuation coefficient $\beta = 2k\delta$. The expressions for the partial roughness and volume coherence coefficients, N_r and N_v, can be readily obtained [4,10]. For the roughness scattering component in the case of $\tau/2 << R/c$, we have

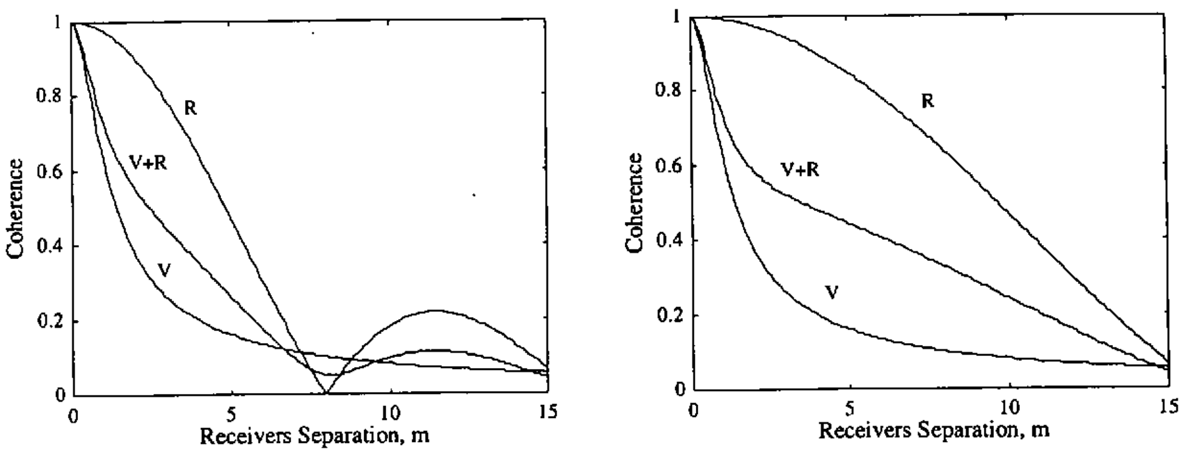
$$N_r(L) = \exp(ikL\sin\chi)\frac{\sin(L/L_r)}{(L/L_r)},\ L_r = \frac{2H(T/\tau)}{\pi\sin^2\chi}. \quad (34)$$

The roughness scatter spatial correlation appears to be independent of sediment parameters and is controlled by the duration of the incident signal. For the volume scattering component in the case of $1/\beta << R$ one obtains

$$N_v(L) = \exp(ikL\sin\chi)\frac{1}{1-i(L/L_v)},\ L_v = \frac{4H\delta}{\sin^2\chi}. \quad (35)$$

Thus, volume scatter spatial correlation is independent of signal duration and controlled by sediment parameters (sound attenuation). The condition $L_r >> L_v$ results in the requirement of a short enough, but still narrow-band, impulse such that $\pi\delta << T/\tau << 1$.

It is easy to see from the considerations above that measuring the coherence at different pulse duration can be used to determine the type of scattering, volume or roughness. If both types operate at the same time, the intensities of these components, and consequently the seabed roughness and volume scattering strengths, can be determined separately, as shown above. Measuring the coherence scale of volume component additionally permits the determination of the loss parameter, δ, and correspondingly, the attenuation coefficient, β. Then, using the model of volume scattering presented above, the scattering cross section per unit volume and the spectrum of heterogeneity can be determined.



(a) (b)

Figure 3. Magnitude of the coherence coefficient for two different pulse duration, $\tau = 10T$ (a) and $\tau = 5T$ (b).

As an example, in Figure 5, the spatial coherence for near backscattering directions at $H = 30$ m, $\chi = 60°$, $\delta = 0.005$ (silt) is shown for different relative contributions of volume and roughness components: only volume (V), only roughness (R), and their equal contributions(V+R). The ratio, 0.5, seems to be easy to invert from the evident two scale behaviour of the coherence with the shorter pulse. Note that spatial correlation scales of the scattered field in the far field zone are determined by the angular size of the scattering volume or surface "visible" from the viewpoint of the receiver. For roughness scattering, this angular size is defined by the insonified footprint at the seabed surface, which is proportional to the duration of the incident impulse. For volume scattering, the angular size is defined by the penetration depth, which is independent of the pulse duration. Thus, at sufficiently short pulses, the angular size for the scattering surface becomes much smaller than for the scattering volume. Correspondingly, this causes the difference in spatial correlation scales for roughness and volume components. The same considerations are valid for a horizontal array [4] and for other types of scatterers, e.g., discrete ones on the surface and in the volume of sediments.

5. Conclusions

In this paper, two models of scattering from marine sediments are presented and the possibilities of their use for remote acoustic sensing are discussed. The models take into account the different mechanisms of scattering: roughness of the seabed surface and volume heterogeneity of the sediment. The necessary equations are given for the analysis of both roughness and volume components of the seabed scattering strength. Their calculations as functions of scattering direction for monostatic and bistatic geometry configurations are presented for different types of sediments. It is shown that these dependencies contain some distinctive features, which can be used, in particular, for the identification of the sediment type and the inversion of the certain bottom parameters.

However, as it was shown, the difference between roughness and volume scattering can be insufficient for determining the type of scattering from measurements of seabed scattering strength. Thus, there is a potential ambiguity in subsequent inversions of seabed parameters, especially if various mechanisms of scattering are operating at the same time. The correlation method of separating and discriminating volume and surface scattering is proposed, which involves measurements of spatial coherence of the scattered field with a linear array located near the source. It is shown that correlation scales for the volume and surface components of the scattered field can be significantly different and, thus, spatial filtration can be used for separating these components. The correlation method would also permit separate measurement of the scattering strength per unit area of bottom surface, the scattering strength per unit volume and sound attenuation in the sediment.

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