An Initial Assessment of Effects of Seafloor Roughness on Coherent Sound Reflection from the Seafloor

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ABSTRACT

A roughened seafloor may be expected to scatter incident sound at non-specular angles, but also to reflect coherently at the specular angle, with some loss of amplitude attributed to the scattering and some loss attributed to sound transmission into, and absorption within, the seafloor. Our initial expectation was that a reasonable estimation of the total coherent reflection loss, at a given grazing angle, might be obtained simply from a combination of the loss attributed to a flat seafloor based on its geoacoustic properties, and the separate coherent loss due to the roughness scattering described for a pressure release surface. To test this hypothesis, loss values obtained using this simple addition of model outputs were produced for several seafloor material types with prescribed roughness profiles. These results are compared with loss values obtained using the perturbation approach for rough surface scattering from stratified media described by Kuperman and Schmidt (JASA, 86, Oct. 1989). The latter is a model which describes the coherent plane wave reflection from a rough surface of stratified material which has specified geoacoustic properties.

INTRODUCTION

As is well known, a considerable body of work has been devoted to the description of the coherent sound reflection from a rough surface of a defined profile. In underwater acoustics, the problem of sound reflection from the rough ocean surface has received much attention, and modelling solutions have been described for practical use (e.g. Williams et al. (2004), Ainslie (2005)). The problem of sound reflection from a rough seafloor has received much less attention, but is very relevant to many sound transmission scenarios involving shallow oceans. For acoustic frequencies in the range to about 10 kHz, Jones et al. (2012) used stochastic modelling based on Monte-Carlo runs of a Parabolic Equation (PE) transmission model to illustrate that the small-slope approximation model (SSA) of coherent surface reflection loss developed at the Applied Physics Laboratory of the University of Washington (APL-UW) provided accurate descriptions at a range of small grazing angles considered, including angles as small as 1°. This work also confirmed that the well-known Kirchhoff (KA) model of coherent reflection loss (e.g. Lurton, 2002, section A.3.3) from a surface with a Gaussian distribution of surface heights was a good approximation to the APL-UW small-slope model for grazing angles greater than a particular value. It needs to be noted that sound reflection from the rough sea surface requires consideration of the effects of near-surface bubbles induced by wind action (e.g. Ainslie (2005)), and that the above comments on the suitability of the SSA and KA models is on the basis of a correct description being obtained of the angle of incidence of sound at the mean plane of the surface.

The experience gained by the authors, in application of the SSA and KA models to the problem of coherent acoustic reflection at the rough sea surface, suggested that it would be reasonable to assess the suitability of modelling the reflection loss from a rough seafloor by a combination of the loss attributed to a flat surface based on its geoacoustic properties, and the separate coherent loss due to the roughness scattering described for a pressure release surface of identical profile. In particular, inasmuch as each of the logarithmic coherent loss functions for the smooth surface and rough surface has a form that is close to linear for small grazing angles, it is enticing to contemplate a very simple solution through addition of two functions each of the form $F\beta$ dB, where F is a constant with unit dB/radian and β is grazing angle. (The concept of a linear rise of logarithmic loss for a smooth seafloor as a function of grazing angle, for small angles less than critical, is well known, e.g. Etter's (2003) equation 5.7, which is attributed by Rogers (1981) to A. I. Eller. The trend of the coherent reflection loss from a rough pressure release surface to approximate a linear rise of logarithmic value for small angles of incidence is less known, but has been determined by Bartel (reported by Jones et al. (2012)) as the small angle limit of the SSA model.) A simple combination of separate loss effects offers the potential for ready inclusion within ray-type transmission models, and knowledge of the applicability of loss functions of the form $F\beta$ dB permits inclusion within simple depth-averaged models of transmission.

Isakson and Chotiros (2011) used a finite element model to study the Transmission Loss (*TL*) of a shallow water scenario for which the seafloor was assigned various levels of roughness. This modelling was carried out using a Monte-Carlo technique in which the sound fields obtained with each of many realisations of the rough surface were averaged to obtain a coherent resultant. (The Monte-Carlo modelling by Jones et al. (2012) is similar in concept.) From a limited study, Isakson and Chotiros (2011) concluded that the effects of roughness might be equated with the effects of increased attenuation of the compressional wave in the seafloor material. As the effect of increased attenuation within a Rayleigh reflection model is to give an increase in the linear loss function F dB/radian, at small grazing angles less than critical (ref. Etter's equation 5.7), the expectation of the authors was that the roughness effect might be modelled in such a simple way.

Kuperman and Schmidt (1989) developed a technique with which the coherent plane wave reflection may be determined for a rough-surfaced seafloor of stratified material of specified geoacoustic properties. Hence, in the present work, an implementation of this model was used as a reference against which more simple descriptions would be compared. In this initial study, the approach of Kuperman and Schmidt was implemented without, at this point, a detailed critique of its derivation. To provide an intuitive expectation of what might be expected for the coherent reflection from a rough absorptive seafloor, below an assessment is made of how a Kirchhoff type model of the phenomena might differ from the form of this model for a lossless surface.

KIRCHHOFF MODEL FOR ROUGH SURFACE OF SPECIFIED GEOACOUSTIC PROPERTIES

As stated earlier, techniques for modelling the coherent reflection from a rough sea surface are well-known. It is then reasonable to consider the changes made to these modelling approaches for the case in which the boundary does not present an extreme difference in impedance, that is in the case of the boundary being assumed neither pressure release nor rigid (zero or infinite impedance).

For a pressure release surface with a Gaussian distribution of surface heights, the well-known Kirchhoff (KA) model of coherent reflection loss (*RL*) for a single surface reflection, in terms of the Rayleigh parameter, is (e.g. Lurton, (2002) section A.3.3)

$$RL = -20\log_{10}\left(e^{-0.5\Gamma^2}\right)$$
$$= 10\Gamma^2 / \ln(10) \text{ dB per bounce.} \qquad (1)$$

where "ln" denotes natural logarithm, to base $e = 2.71828...$ and the acoustical roughness of the surface is given by the Rayleigh parameter $\Gamma = (4\pi f h_\sigma \sin\beta)/c_w$, where *f* is cyclic frequency, Hz; h_σ is rms height of the rough surface, metres; β is the acoustic grazing angle with the mean surface plane, radians; c_w is speed of sound in seawater, m/s. The coherent reflection is, of course, at the specular angle.

For a Gaussian distribution of surface heights, it may be shown that the Rayleigh parameter Γ is the same as the standard deviation of the phase variation (in radians) amongst the components scattered in the specular direction. For $\Gamma << 1$, the surface is considered acoustically smooth, and for $\Gamma >> 1$ the surface is considered acoustically rough.

The reflection loss from the KA model may be seen as simply due to the phase coherent combination, in the specular direction, of components which are scattered by sections of the sea surface at different heights. The loss results from path length differences, which cause phase differences. The loss from a rough pressure release surface, as described by the KA model, will be the same as the loss described for a rough rigid surface, as the relativity of phase difference between reflected components is the same in each case. The acoustic impedance of a surface of specified geoacoustic properties is, of course, neither infinite, nor zero. Considered in terms of reflection coefficient and phase, for a smooth seafloor of realistic geoacoustic properties, each of the reflection sound pressure amplitude and reflection phase angle is dependent on the incident grazing angle, while for either a pressure release or rigid surface, each is independent of grazing angle. Clearly a Kirchhoff model of roughness loss from a seafloor of realistic geoacoustic properties will not be the same as given by Equation (1). A key issue is the handling of the amplitude and phase of the scattered component. In the analysis of following sections, these are assumed to be in accord with that locally reflected due to the incidence angle on each respective facet. For sound at normal incidence to the mean surface plane, this will be a reasonable assumption, as the reciprocal arrangement, that is the situation with a swapping of the incidence and reflection directions, will result in identical angles of incidence on each facet. For small angles of incidence, however, the assumption of basing the scattered component on the amplitude and phase relevant to the angle of incidence on each facet does not satisfy reciprocity, although the degree of error caused is unknown.

For the example of a seafloor half-space consisting of silt (seafloor type A of Desharnais and Chapman (1999)), for which geoacoustic properties were assumed as shown in Table 1, and for seawater at the ocean bottom of density ρ_w = 1000 kg/m^3 and sound speed (i) c_w = 1496.15 m/s (ii) c_w = 1516.83, the reflection characteristics are as shown in Figure 1 (solid blue and red curves).

Table 1. Seafloor Properties for silt (after Desharnais and Chapman (1999))

Density (kg/m^3)	compres-sional speed c_p (m/s)	shear speed c_s (m/s)	compres-sional attn. α_p (dB/λ)	shear attn. α_s (dB/λ)
1600	1550	125	0.78	0.25

As is well known (e.g. see Weston (1971)), for sound incidence at less than the critical angle, a very good approximation to the bottom loss at the small grazing angles relevant to shallow water transmission may be made by assuming that the bottom loss function is $F\beta$ dB, where *F* dB/radian is the assumed "linear bottom loss function". The blue dashed line in the upper part of Figure 1 shows this assumed function, averaged over the first 10°, for the silt half-space example, for c_w = 1496.15 m/s, for which $F \approx 15$ dB/radian. The red dashed line shows the function for an alternative value of c_w = 1516.83 m/s, for which $F \approx 28$ dB/radian.

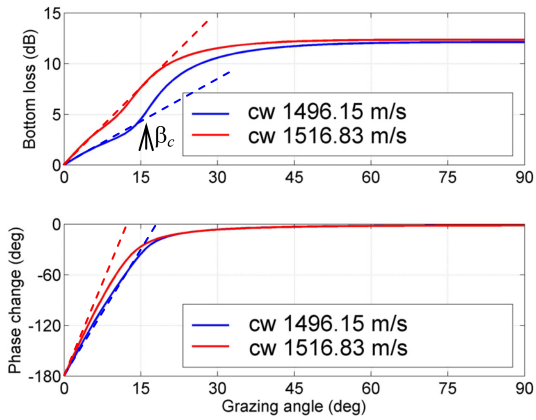

Figure 1. Reflection bottom loss & phase angle for flat surfaced silt half-space, - full description, - - - description based on *F*

Further, for a seafloor material of low shear speed, it may be shown (e.g. Jones et al. (2008)) that the reflection phase angle has a near-linear variation from $-\pi$ radians at 0° grazing to a phase angle of zero at $\beta_c = \arccos(c_w/c_p)$, where β_c is the critical angle. For the present example of silt, the critical angle β_c = 15.1° for c_w = 1496.15 m/s, and β_c = 11.9° for c_w = 1516.83 m/s. By making the assumption that the critical angle corresponds, very approximately, with a bottom loss value of some nominal amount (Jones et al. (2008) assumed 6 dB), the reflection phase may be approximated from, merely, knowledge of the bottom loss function F dB/radian. The blue and red dashed lines in the lower part of Figure 1 show these approximate functions of reflection phase for the two water sound speed values. If it is assumed that β_c is known, the approximated variation of reflection phase φ may be stated as

$$\varphi \approx -\pi + (\pi\beta)/\beta_c \text{ radians} \quad (2)$$

and the slope of the function of reflection phase φ in terms of incidence angle β is π/β_c. Using the assumptions stated above, of the relationship between a value of bottom loss of 6 dB and the critical angle β_c, the bottom loss function F dB/radian is then approximated as

$$F \approx 6/\beta_c \text{ dB/radian, i.e } \beta_c \approx 6/F \text{ radians.} \quad (3)$$

Based on these approximated functions for reflection loss in dB, and reflection phase angle, it now becomes easy to estimate the modifications required of a Kirchhoff-style model of coherent roughness loss. Here, the travel distance from each surface facet affects the phase of the specularly scattered component, and the local angle of incidence of each facet determines the amplitude of the specularly scattered component (e.g. Ogilvy (1991)). Of course, the reflection phase of the facet combines with the travel distance component to determine the total phase of the specularly scattered component.

Reflection from rough absorptive surface

The scattered components which, in the Kirchhoff approximation, contribute to the coherent reflection from either a rigid or pressure release surface, may be represented as in Figure 2. In the case of a Gaussian distribution of surface heights, the components may be represented by phasors all of equal amplitude but with phase values in accordance with a Gaussian distribution. As stated earlier, the Rayleigh parameter Γ is the same as the standard deviation of the phase variation.

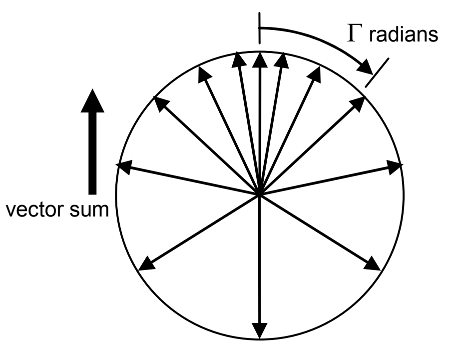

Figure 2. Phasor diagram for Kirchhoff components for rough surface either pressure release or rigid

The corresponding phasor diagram for an absorbing rough boundary, of specified geoacoustic parameters, is not necessarily straightforward to determine. While each particular surface height is associated with a known travel time, it cannot be associated with a particular surface slope, and must be associated only with a distribution of surface slopes. However, if the distribution of the heights of the rough surface is assumed Gaussian, a simplified analysis is possible, as follows.

Distribution of surface slopes

The average shape of a rough surface may be defined in terms of the rms displacement h_σ of heights z and the horizontal spatial scale L over which the surface heights are correlated to a nominal degree, taken here to be a correlation of $1/e$. Ogilvy (1991, p.22), for example, shows that for an isotropic surface with a Gaussian correlation function of surface height of the form $e^{-(x/L)^2}$ (where x is horizontal displacement), the rms surface slope s is

$$s = h_\sigma \sqrt{2}/L \text{ radians} \quad (4)$$

where the value of s is unrelated to the local value of height. Medwin and Clay's (1998, equ.13.2.10c) identical result confirms that the rms slope is the same for every value of surface height. As stated by Ogilvy (1991, p.21), for a Gaussian distribution of surface heights, the distributions of all higher order derivatives are also Gaussian, hence the surface slope values are Gaussian distributed. The distribution of surface slopes may then be seen to be the same for every value of surface height.

Ogilvy (1991, p.23) also considers the matter of the surface radius of curvature ρ, a key determinant in the validity of the Kirchhoff model. For small values of rms slope s, the values of radius of curvature are centred near $\rho \approx L^2/(2\sqrt{3}\, h_\sigma)$, or in terms of rms slope $\rho \approx L/(\sqrt{6}\, s)$. For small values of rms slope, the radius of curvature approximates the inverse of the second derivative of surface height, that is $\pm 1/(d^2z/dx^2)$ (as shown by Jones et al (2010) for example). This second derivative is Gaussian distributed, hence its inverse is not.

Loss expected due to distribution of slopes of absorbing surface

Returning to the matter of the phasor diagram of specularly scattered components from different points of height, we now know that for an absorbing rough boundary with Gaussian distribution of heights and a Gaussian spatial correlation function, on average the distribution of surface slopes is the same for every part of the surface, and hence the same for each height value of the surface. This will have the result that, for all points having a particular value of surface height, that is for all points contributing to a particular single phasor in Figure 2, there will be a distribution of sub-components relating to the distribution of values of surface slope. As this distribution is the same for all values of surface height, the resultant value of phase on reflection at every height of the surface will be the same, so that, after accounting for travel times from the different height components, the resultant phasors will have an identical relative angular distribution as in Figure 2. Further, as the resultant of the distribution of reflection events at each value of surface height is the same as at every other value of surface height, the resultant loss value from absorption by the geoacoustic seafloor material will also be the same at every height value of the surface, and every phasor in Figure 2 forming the coherent specular reflection has an identical attenuation. The vector sum is then of the form relevant to Figure 2, with a reduced amplitude, by A dB, equal to that imposed on every phasor. The Reflection

Loss for the rough surface, being the counterpart of Equation (1), then becomes

$$RL_{rs} = -20\log_{10}\left(e^{-0.5\Gamma^2}\right) + A$$
$$= A + 10\Gamma^2 / \ln(10) \text{ dB per bounce.} \qquad (5)$$

As outlined above, each phasor in Figure 2 is formed from a combination of the sub-components scattered from all points of the surface at a particular value of height, and for the points at each value of height there is a Gaussian distribution of slopes. The average value of slope is zero, for which the value of the dB loss is $F\beta$ dB, and the reflection phase is $\varphi \approx -\pi + (\pi\beta)/\beta_c$ radians, where F dB/radian is the assumed "linear bottom loss function" discussed earlier, and β is the angle of incidence of sound at the mean seafloor plane. With reference to Figure 3, for each value of rms slope $h_\sigma\sqrt{2}/L$, for each angle of incidence β, there is a distribution of sub-components in accord with the angles of incidence on the facets, with a value of reflection amplitude and phase for each of these angles, so that each phasor in Figure 2 may *itself* be seen to be comprised of a distribution of sub-components for which there is a vector sum, much like as in Figure 2, and as depicted in Figure 4. The distributions of reflection amplitude and phase of the sub-components that are illustrated in Figure 3 are as for the small angle forms of the bottom loss and reflection phase curves, discussed earlier. (This implies that the incidence angles on the facets are all less than the critical angle.) An analytical determination of the sum of the vectors shown in Figure 4 is not pursued here. However, as the function of reflection phase in terms of incidence angle on each facet is known (Equation (2)), the standard deviation of reflection phase of the sub-components may be stated as $\sqrt{2}\,\pi h_\sigma/(\beta_c L)$, as shown in Figure 3. From the argument presented earlier in terms of the KA model, it also follows that if

$$\frac{\sqrt{2}\,\pi h_\sigma}{\beta_c L} >> 1, \text{ i.e. } \frac{\sqrt{2}\,F\pi h_\sigma}{6L} >> 1, \qquad (6)$$

the phasors representing the sub-components will form a vector sum which involves phase cancellation and amplitude reduction with the result that the Reflection Loss for the rough surface RL_{rs} dB will be greater than obtained by adding RL dB from Equation (1) to the loss $F\beta$ dB appropriate to a smooth surface. If, however, the expression is << 1 there is relatively little spread of either reflection phase or amplitude values, and the Reflection Loss for the rough surface RL_{rs} dB may be expected to be virtually identical with the sum of RL dB from Equation (1) and $F\beta$ dB appropriate to a smooth surface.

Expression (6) is equivalent to $\sqrt{2}\,h_\sigma/L >> \beta_c/\pi$, that is the rms surface slope being much greater than β_c/π. For the example of silt described by Table 1 and Figure 1, for which the critical angle is 15.1°, the rms slope must then be much greater than 4.8° for the requirement to be met. Of course, the available span of reflection phase angles for the sub-components from the facets is over π radians, as reflection phase is -π at grazing angle of 0°, and is 0° at the incidence angles ≥ the critical angle. As the distribution of reflection phase of the sub-components is two-sided, an approximate maximum value for the standard deviation $\sqrt{2}\,\pi h_\sigma/(\beta_c L)$ can be seen to be π/2, when $\beta = \beta_c/2$. The corresponding rms slope then becomes $\beta_c/2$ for this maximum phase cancellation scenario.

As illustrated in Figure 3, the reflection loss of the sub-components, in dB, itself is normally distributed about $F\beta$ dB, with standard deviation $\sqrt{2}\,F h_\sigma/L$, that is, F times the rms slope. Assuming a value of, say, 0.2 radians (11.4°) for a maximum rms slope, this results in a maximum standard deviation of loss values for sub-components of 3.0 dB, for the silt material described in Table 1. It may be noted that the linear mean of a distribution which is symmetrically distributed on a logarithmic scale is not the same as the linear form of the mean of the logarithmic values. The low values within the distribution, below $F\beta$ dB, may be shown to add more reflected energy than the high loss values, above $F\beta$ dB, remove, so that, if there is not a spread of phase angles with resultant phasor cancellation, the expectation is that the reflected energy of the ensemble would be greater than for a flat surface.

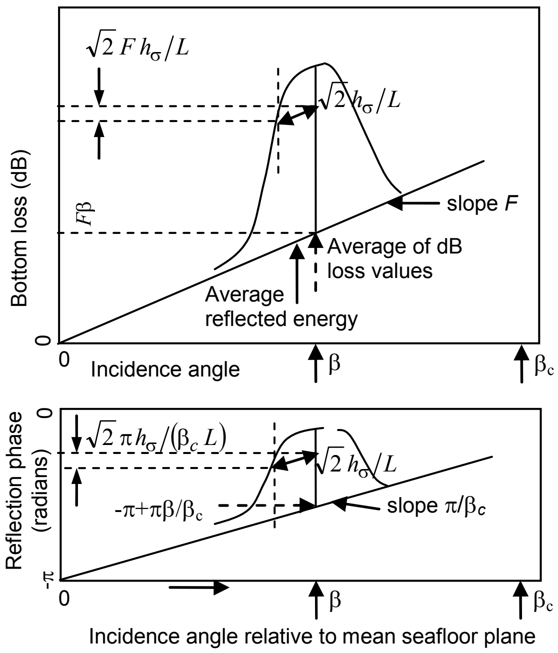

Figure 3. Reflection loss and phase angle fluctuations of sub-components due to Gaussian distribution of surface slopes of mean value β, for small β

If the standard deviation of reflection phase of the sub-components $\sqrt{2}\,\pi h_\sigma/(\beta_c L) \approx 1$, a phasor representation of the sum will resemble that in Figure 4. Here, the phasors representing the sub-components are distributed in angle in accord with the bottom sub-figure of Figure 3, and the amplitude values are in accord with the expectation from the top sub-figure of Figure 3. Although no proof will be pursued here, it does appear that the vector sum will be reduced, through phase cancellation, more than implied by $F\beta$ dB and that the vector sum is phase-shifted in the direction of a smaller phase angle φ than the value $-\pi + (\pi\beta)/\beta_c$ implied by the mean incidence angle β.

The above analysis is, of course, in terms of the Kirchhoff model of coherent reflection loss, but it may be presumed that the principles described above will be relevant to a "corrected Kirchhoff" model, such as the APL-UW small-slope approximation model (Williams et al (2004)).

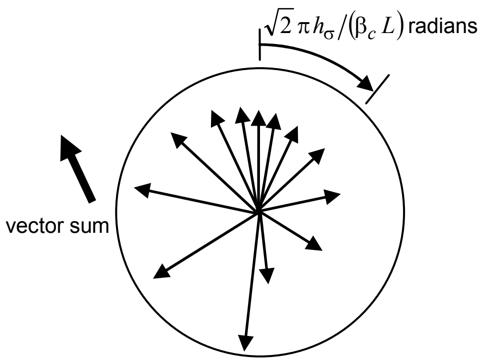

Figure 4. Phasor diagram for sub-components for each height value of the rough surface of specified geoacoustic properties

Practical aspects

The distribution of reflection phase and amplitude of the sub-components from the angled facets will not necessarily exist as implied by the approximate forms of the reflection amplitude and phase shown in Figure 1, and the assumptions carried through to Figures 3 and 4. There is a large range of possible situations. For seafloors other than lossy fluid types (for which the silt in Table 1 and Figure 1 is an example) the reflection phase functions do not resemble the form of Equation (2). Figure 5 shows data similar to that in Figure 1 for soft sedimentary rock (seafloor type F of Desharnais and Chapman (1999)), for which the geoacoustic properties are shown in Table 2, and the calculations for Figure 5 used water density of 1000 kg/m^3 and water sound speed 1500 m/s. This shows a much smaller phase variation over the span of grazing angles to about 15°, than for the silt material of Figure 1. Even with a large value of seafloor slope, for sound incidence angles to 10° and more, there will be little phase cancellation from sub-components. The implication of this, in terms of the above Kirchhoff-model arguments, is that the resultant coherent reflection loss of a rough surface will be expected to resemble the combination of the loss attributed to a smooth surface based on the geoacoustic properties, plus the separate coherent loss due to the roughness scattering from a pressure release surface.

Table 2. Seafloor Properties for soft sedimentary rock (after Desharnais and Chapman (1999))

Density (kg/m^3)	compres-sional speed c_p (m/s)	shear speed c_s (m/s)	compres-sional attn. α_p (dB/λ)	shear attn. α_s (dB/λ)
2100	2300	850	0.23	0.17

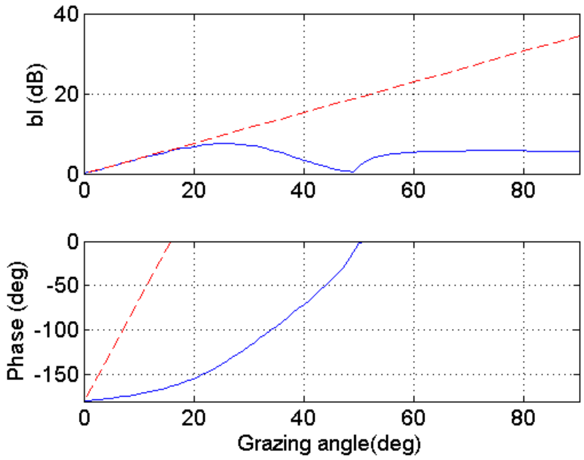

Figure 5. Reflection bottom loss & phase angle for flat surfaced soft sedimentary rock half-space, - full description, - - - description based on *F*

SIMULATIONS OF ROUGH ABSORBING SURFACES

An implementation of the second order, rotated coordinate, perturbation method for the determination of the plane wave coherent reflection coefficient for a rough seabed, as described by Kuperman and Schmidt (1989), was made in order to test the hypothesis of the present paper. The details of the implementation will not be described here. The implementation was used to generate values of coherent bottom loss per bounce, as a function of incident grazing angle, for a number of candidate seafloor half-space types and roughness parameters. Here the seafloor material was specified in terms of geoacoustic parameters. The roughness profile was described in terms of an rms height h_σ and a correlation length L, with either a power-law or Gaussian correlation function being used. In order to keep within the presumed requirements of a perturbation method, roughness parameters were chosen so that the Rayleigh roughness of the surface was < 1 for small grazing angles of interest. For computations used in this study, the Rayleigh roughness was confined to < 0.35. As stated by Ogilvy (1991, p.103), for example, several requirements for incidence angles β may be postulated for the validity of the Kirchhoff method. Firstly, a requirement for flatness of the surface segments assumed to be facets may be made in terms of the radius of curvature of the surface ρ, as $\sin\beta > \left(c_w/(f\rho)\right)^{1/3}$. Secondly, a requirement exists for the length extent of a facet, as projected onto the plane normal to the incidence angle β, to be larger than an acoustic wavelength. If the length of a facet is approximated as the correlation length L, this requirement may be stated as $\sin\beta > c_w/(f L)$. For the key scenarios considered below, the radius of curvature values ρ are centred near order 3.5 m, and the correlation length is 1 m, hence, for the frequency of interest (3000 Hz), the respective requirements are β > 32° and β > 30°. These are greater than the angles of incidence used, so inferences based on the Kirchhoff model will involve some error.

Simulations were carried out to determine the loss per bounce for several roughness profiles for several seafloor types, across a range of angles of incidence. The seafloor types included the silt seafloor of Table 1, for a water sound speed of 1516.83 m/s, and the soft sedimentary rock seafloor of Table 2.

Rough seafloor - silt

The coherent reflection loss per bounce was determined for the silt seafloor, for a range of grazing angles and for a range of roughness parameters, using the Kuperman and Schmidt (1989) method. The particular implementation was first checked for correctness by comparison against the example shown in Kuperman and Schmidt's Figure 3, with no error evident.

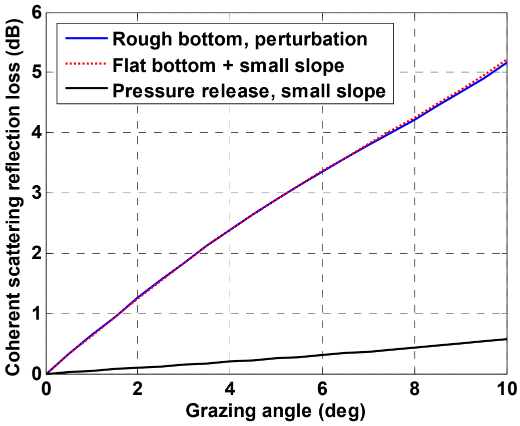

Figure 6. Coherent reflection loss per bounce for rough absorptive seafloor, silt, rms surface slope 6.5°, rms surface height 0.08 m, correlation length 1 m, frequency 3000 Hz, - Kuperman & Schmidt method, - flat surface loss plus SSA roughness loss for lossless boundary, - SSA roughness loss for lossless boundary

Figure 6 shows the Kuperman and Schmidt method result for the silt seafloor with an rms surface height $h_\sigma = 0.08$ m and (Gaussian) correlation length $L = 1$ m (giving an rms surface slope of 6.5°), for a source frequency of 3000 Hz. Figure 6 also shows the coherent loss function obtained by the SSA roughness loss model for a lossless (pressure release) surface with the same roughness profile, and shows the summation of this loss function with the loss function obtained for a flat silt surface. It is clear that the loss function derived by the Kuperman and Schmidt analysis is virtually identical with that obtained by summing the smooth surface loss function with the SSA loss function for a lossless surface.

For the silt seafloor for a water sound speed of 1516.83 m/s, the critical angle β_c is 11.9°. The anticipated standard deviation of reflection phase of the sub-components reflected from surface segments at different slopes is then $\sqrt{2}\,\pi h_\sigma/(\beta_c L)$, that is 1.71 radians. This is very close to the value π/2 expected to cause maximum cancellation among the sub-components reflected by the surface components of different slope, yet no effect is observed in Figure 6, as the Kuperman and Schmidt analysis produces virtually the same result as the summation of the flat surface loss with the roughness loss for a lossless surface. Stated in simple terms, for an angle of incidence with the mean seafloor surface of 6°, the rms slope of the surface of 6.5° will cause incidence angles of surface facets to vary from 0° to over 12°, yet no phase cancellation effects are apparent.

Rough seafloor – soft sedimentary rock

A similar set of comparisons was made for the example of a rough seafloor comprised of soft sedimentary rock, for which the reflection characteristics are shown in Figure 5. The results were the same as for the silt example, in that the Kuperman and Schmidt analysis gave virtually the same result as adding the smooth surface loss to the roughness loss for a lossless rough surface. The results for the same roughness parameters and acoustic frequency, as used for Figure 6, are shown in Figure 7.

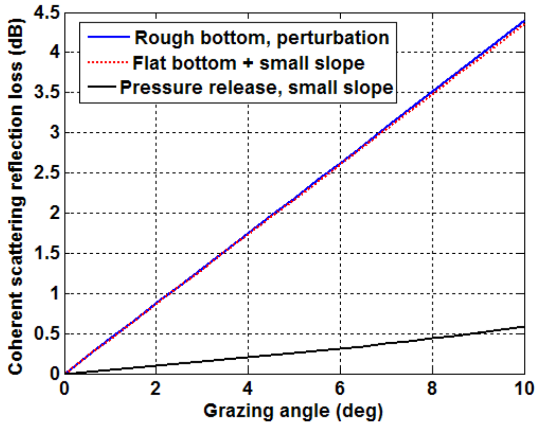

Figure 7. Coherent reflection loss per bounce for rough absorptive seafloor, soft sedimentary rock, rms surface slope 6.5°, rms surface height 0.08 m, correlation length 1 m, frequency 3000 Hz, - Kuperman & Schmidt method, - flat surface loss plus SSA roughness loss for lossless boundary, - SSA roughness loss for lossless boundary

Discussion

Other simulations for each of the silt and soft sedimentary rock materials which included both larger (2 m) and smaller (0.5 m) correlation length values, and a repetition of the simulations at 6000 Hz, but were otherwise identical, all showed that the coherent reflection loss from the Kuperman and Schmidt analysis gave virtually the same result as adding the smooth surface loss to the roughness loss for a lossless rough surface. It remains surprising to the authors that no cancellation effects, due to variations in the reflection phase at the facets, was evident. One issue with this work is that the roughness scenarios have been chosen so that the Rayleigh roughness parameter is < 0.35. Whilst it is desirable to test scenarios of greater roughness, it is considered that a perturbation method, such as used by Kuperman and Schmidt, will not be suitable to use as a benchmark. It is desirable to carry out some level of validation of results similar to those shown in Figures 6 and 7 through use of Monte Carlo simulations based on PE modelling, as these will be known to include all relevant physics. It is desirable that such Monte Carlo simulations include some seafloors of greater roughness, and also include scenarios which more closely adhere to the assumptions of the Kirchhoff method. If the results shown in Figure 6 and 7, and other simulations, are verified though Monte Carlo PE techniques, it would appear that the effects of seafloor roughness may be included within acoustic transmission models in a very simple manner.

For the examples considered, the resultant coherent loss function for the rough absorptive surfaces may be seen to be very close to linear in dB with grazing angle of incidence on the mean seafloor plane. This also has the potential to simplify certain analyses, for example in the same way that the bottom loss function F dB/radian has been used for a smooth absorptive seafloor.

CONCLUSIONS

Based on the considerations relevant to the simple Kirchhoff model of coherent reflection loss at a rough surface, an attempt was made to anticipate the coherent loss effect for a rough surface in the case of an acoustically absorbing seafloor material. For a surface with an rms slope value of the order of the angle of incidence of an acoustic plane wave, where the angle of incidence is small, it did appear that the differing reflection phase angles from the surface facets would result in an increased loss effect, but none was apparent when the coherent loss was determined for several seafloor examples using an analysis of Kuperman and Schmidt. If these indications from use of the Kuperman and Schmidt method are found to apply more widely, the inclusion of seafloor roughness effects within conventional sound transmission modelling would appear to be quite straight-forward, for small angles of incidence. In particular, the coherent reflection loss from a rough seafloor may then be estimated accurately by summing the dB loss obtained for a flat surface of the candidate seafloor material to the roughness loss obtained for a lossless surface of the same surface profile.

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