Aspects of modelling coherent acoustic reflection from a rough seafloor

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ABSTRACT

Acoustic energy incident at a roughened seafloor will result in a component scattered back into the water at non-specular angles, a component reflected coherently at the specular angle, and both coherent and incoherent components being transmitted into, and absorbed within, the seafloor. An initial expectation was that the total coherent reflection loss might be approximated by 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 perfectly reflecting surface. This hypothesis had been verified in limited earlier work, by comparing loss values obtained using this simple addition of model outputs with loss values obtained using the perturbation approach for rough surface scattering from stratified media described by Kuperman and Schmidt (JASA, 86, Oct. 1989). In new work, data obtained using Monte Carlo Parabolic Equation (PE) transmission simulations have been used as an added reference for further verification of the hypothesis.

1. INTRODUCTION

As is well known, the description of the coherent sound reflection from a rough surface of a defined profile is a mature area of research (e.g. Ogilvy, 1991). Most such past work, however, relates to scenarios for which the transmission media for the incident and the transmitted wave have vastly different values of characteristic acoustic impedance. For the underwater acoustic situation, the characteristic acoustic impedance of the seafloor will be greater than that of seawater, but not greatly so. In general, the issue of the reflection of sound incident upon an acoustically absorbing rough seafloor has not received much attention, whilst it is likely to be relevant to many sound transmission scenarios involving shallow oceans. Possibly, the lack of attention to the seafloor roughness has been due to the lack of adequate field data, and almost all work on seafloor acoustics relating to forward transmission has involved the description of the bulk properties of the seafloor material, for example, porosity, density, compressional sound speed, shear wave speed.

For acoustic frequencies in the range to about 10 kHz, Jones et al. (2016) used stochastic modelling based on Monte-Carlo runs of the Parabolic Equation (PE) transmission model RAMSurf (Collins n.d.) to illustrate that the small-slope approximation model (SSA) of coherent surface reflection from a rough surface (Williams et al., (2004)) provided accurate descriptions at a range of small grazing angles considered, including angles as small as 1°. This work also confirmed that the logarithmic form of coherent loss function for the rough surface, RL_{rough}, is close to linear for grazing angles less than particular values, leading to an approximation of the loss of the form $RL_{\text{rough}} \approx A\,\beta$ dB, where A is a constant with units dB/radian and β is grazing angle. As shown by Jones et al. (2016), for example, the form of A is dependent on mean-square surface height h_σ^2 and the form of the roughness spectrum $W(K_1)$, where K_1 is spatial wave number, m^{-1}.

It is well known that, for small angles less than critical, the logarithmic form of reflection loss for a smooth seafloor of particular geoacoustic properties, RL_{mat}, is also close to a linear function of grazing angle, with $RL_{\text{mat}} \approx F\,\beta$ dB (e.g. Etter's (2003) Equation 5.7, which is attributed by Rogers (1981) to A. I. Eller). Jones et al. (2013) hypothesised that a combination of the reflection loss attributed to a flat seafloor, the "material loss" RL_{mat}, plus the coherent loss due to the roughness scattering from a pressure release surface of identical profile, the "roughness loss" RL_{rough}, would approximate the overall coherent loss function for a rough seafloor RL_{total}, that is $RL_{\text{total}} \approx RL_{\text{mat}} + RL_{\text{rough}}$, and that $RL_{\text{total}} \approx (F+A)\beta$ dB. As reported by Jones et al. (2013) from work of limited extent, the overall coherent loss function RL_{total} was indeed very close to that obtained by adding the individual functions for "material loss" RL_{mat} and "roughness loss" RL_{rough}, and that the combined loss approximated the form $(F+A)\beta$ dB for small angles of incidence at the seafloor. For that work, Jones et al. (2013) obtained a "roughness loss" function using an SSA model, a "material loss" function using a Rayleigh model of reflection from a surface of specified parameters, and compared the sum of those loss functions to values obtained using the analysis of Kuperman and Schmidt (1989), that being a technique with which the coherent plane wave reflection may be determined for a rough-surfaced seafloor of stratified material of specified geoacoustic properties. However, it was considered that data from a Monte-Carlo PE method would provide an ultimate form of comparison, hence the present approach described by this paper.

It is simple to show that, in shallow oceans, coherent sound transmission is dominated by arrivals at small angle of incidence, as energy incident at steeper angles is readily absorbed into, or scattered from, the seafloor. Thus for many shallow water situations the only relevant values of overall coherent loss are those for small grazing angles. If these angles do not exceed those for which the overall coherent loss has the form $RL_{\text{total}} \approx (F + A)\beta$ dB, then many effects of transmission may be considered with simplified analyses and various insights obtained. As the individual loss effects may be readily determined if the roughness and material properties are known, there is an incentive to confirm the hypothesis that the overall loss may be obtained by summing the "material loss" and "roughness loss".

Further, values of the seafloor reflective loss obtained by acoustic inversion techniques which assume coherent transmission (e.g. Jones and Clarke (2010)) are inclusive of the overall coherent loss. In an area of an unknown seafloor, there can be no prior knowledge of whether an observed overall loss is due to roughness scattering, due to absorption into the seafloor material, or due to a combination of roughness and material losses, hence it is important to know how the individual loss effects combine to form the observed overall loss.

In an early analysis, Tolstoy and Clay (1987) derived an expression for the coherent reflection coefficient for a rough surface of a material which was described by its fluid properties. Their derived expression, their Equation (6.44b), was shown to be a product of (i) the Rayleigh reflection loss applicable to the differing fluid properties for seawater and for the seafloor, and (ii) what they termed the "coherence factor", where the latter was identical to the loss from the well-known Kirchhoff (KA) model of coherent reflection loss from loss-less surface. The overall loss function, in dB, resulting from Tolstoy and Clay's Equation (6.44b) is then the same as adding the relevant "material loss" in dB to the "roughness loss" in dB. However, as is well known, the KA model is erroneous at small grazing angles, and so the Tolstoy and Clay analysis was not used.

1.1 Rationale for stochastic modelling

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. Isakson and Chotiros did not make explicit determinations of the coherent loss function, however their use of Monte-Carlo modelling had similarities with the work of Jones et al. (2016) in which the Parabolic Equation (PE) model RAMSurf was used. As RAMSurf is expected to describe all relevant physics for forward transmission, and its results are expected to be definitive, it seemed to the authors of the present paper that an application of stochastic modelling using RAMSurf would be beneficial for the present problem. This subsequent work is the subject of this paper.

It is worth noting that Isakson and Chotiros (2011) concluded that the effects of seafloor roughness might be equated with the effects of increased attenuation of the compressional wave in the seafloor material. Now, it is well known that the effect of increased attenuation within a Rayleigh reflection model is to give an increase in the linear loss function *F* dB/radian for small grazing angles less than critical (e.g. fig. 1.22 (b) of Jensen et al., 2000), and so the conclusion of Isakson and Chotiros (2011) is not unexpected.

The initial study by Jones et al. (2013) included a description of a potential mechanism for a reflection loss greater than that given by a sum of the "roughness loss" and the "material loss". This was based on expectations based on Kirchhoff considerations. In particular it was argued that a component of coherent reflection loss would be caused by the acoustic path differences due to the different heights of presumed facets forming the seafloor surface, but that another component of loss might also arise due to the difference in the phase of the reflections from those facets at points of the same height on the rough seafloor surface, for which there will be a distribution of slopes, hence a distribution of sound incidence angles. If the loss is considered as arising from a phase-coherent combination of phasors, where each originates at a particular facet on the seafloor surface, the two phase effects might be considered to combine. The "roughness loss" as mentioned earlier, arises from the first of the two mechanisms described above, that is, the difference in surface heights, and is described by the KA model, or for angles below a certain value, by a "corrected" KA model (e.g. Chapman, 1983). This loss does not include a component due to the second mechanism, hence the expectation by Jones et al. (2013) that the total coherent reflection loss might exceed the sum of the "roughness loss" and "material loss" under some circumstances. The scenario chosen for the present study is one for which such an "extra" loss is expected, and the RAMSurf modelling was expected to account for this effect if it was relevant.

Lastly, it is reasonable to suggest that the method of Kuperman and Schmidt (1989) required some level of evaluation against PE-based stochastic modelling

2. STOCHASTIC MODELLING TECHNIQUE

The technique used for the present study is an adaptation of that described by Jones et al. (2016). In that work, RAMSurf was used to generate the coherent sound pressure field for each of many transmission scenarios for which the ocean surface simulated a particular random realisation of the displaced wind-driven sea surface shape. The coherent pressure values for each respective point in the field, for each of typically forty such realisations of the field, were averaged to obtain what was presumed to be the coherent result. The resultant amplitude values were compared with those for a coherent field in the case of a smooth sea surface, and bearing in mind the design of the scenarios, the coherent reflection loss was obtained at particular angles of sound incidence at the surface.

For the present work, the scenarios involve an ocean of uniform depth 30 m, a sound source at 3000 Hz at depth 5 m, and a uniform, downward refracting sound speed gradient that causes the signal launched horizontally to be incident at the seafloor at a chosen angle. The sound field was generated by RAMSurf, for each of many realisations of a very rough sea surface, with in turn, (i) a realisation of a rough seafloor of chosen geoacoustic properties, (ii) a smooth seafloor of the same geoacoustic properties, (iii) a realisation of a rough pressure-release seafloor, (iv) a smooth pressure-release seafloor. The real and imaginary sound pressure values for each range-depth field point, across each of these four series of realisations of the sound field, were coherently averaged, thus removing virtually all incoherent data. As the sea surface shape was selected to be very rough for each realisation, the resultant coherently averaged fields contained very little acoustic energy which had interacted with the surface, and the averaged field data was presumed to consist only of the energy reflected coherently from the seafloor. By suitable sampling of amplitude values within the averaged field data, the loss of coherent signal on each reflection from the seafloor was obtained. For each field realisation, a particular unique rough sea surface profile adhering to the Pierson-Moskowitz spectrum was generated, using a technique described by Jones et al. (2016). A wind speed of 15 m/s was simulated for all cases, in order to ensure a large loss of coherent signal.

2.1 Incidence at seafloor

For the 30 m shallow ocean scenario, ray modelling considerations were used to select the value of uniform sound speed gradient to be applied to RAMSurf for the Monte-Carlo modelling. In particular, the gradient was chosen so that the ray launched horizontally in an ocean with a smooth surface and seafloor was incident at the seafloor at the chosen angle. Fig 1 shows the fan of rays that have turning points either at or below the sea surface, for a particular case.

From well-known ray theory (for example, Tolstoy and Clay (1987) section 2.10), it is easy to show that the angle of incidence at the seafloor β_0 radians for a ray launched horizontally at depth *D* m at which the sound speed is c_w m/s, for a shallow ocean of uniform negative sound speed gradient *g* s^{-1} is

$$\beta_0 \approx \sqrt{-2Dg/c_w} \ . \qquad (1)$$

It is also simple to show that the skip distance r_s m between successive turning points for the ray, and the sound speed gradient required to cause sound incidence at a chosen angle β_0 radians, are as follows:

$$r_s \approx -2\beta_0 \, c_w / g \ . \qquad (2)$$

$$g \approx -\beta_0^{\,2} \, c_w / 2D \ . \qquad (3)$$

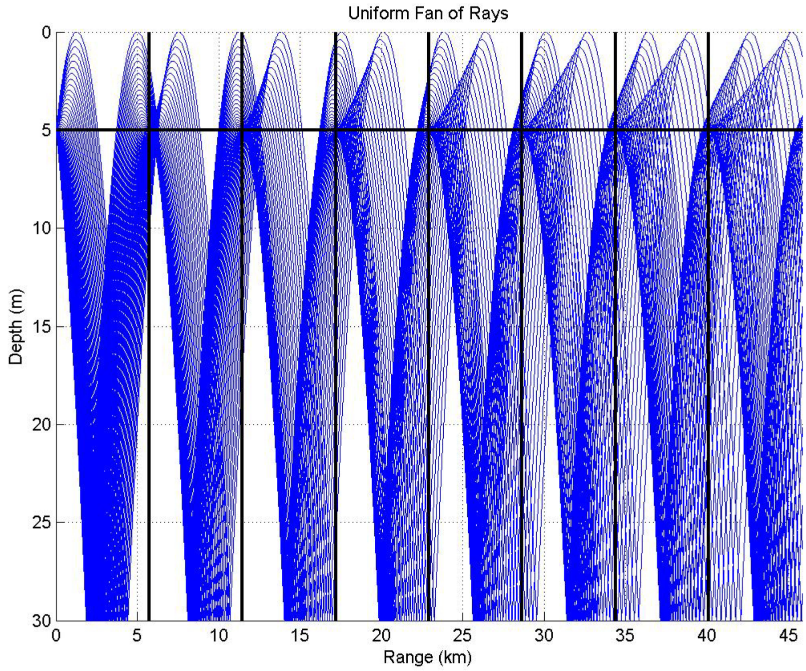

Figure 1: Ray plot showing all non-surface-interacting rays for scenario with source depth 5 m, water depth 30 m, sound speed gradient -0.00914 s^{-1}. For ray launched horizontally, angle of incidence at seafloor is 1°. Vertical lines show ranges for turning points of ray launched horizontally.

Fig. 1 shows a fan of non-surface-interacting rays, for an incidence angle $\beta_0 = 1°$ for the ray launched horizontally. From Equation (3), for a speed of sound 1500.2285 m/s at the source depth, the required gradient *g* is -0.00914 s^{-1} and from Equation (2) the skip distance is 5.73 km. It is clear that a fan of rays exists, with turning points at depths between 5 m and zero. For the ray grazing the surface, incidence at the seafloor is at 1.096°.

Note that the sound speed at the bottom of the water column for the case in Fig. 1 as modelled by RAMSurf is 1500 m/s, the water density is 1000 kg/m^3 and the geoacoustic properties of the seafloor are as used by Jones et al. (2013) for silt, but with the shear wave speed and attenuation set to zero. The remaining seafloor geoacoustic properties are: compressional speed 1550 m/s, compressional attenuation 0.78 dB/wavelength, density 1600 m/s. The resulting plane wave reflection loss and reflection phase variation with grazing angle are shown in Fig.2.

For the stochastic modelling, the Monte Carlo realisations of the rough seafloor boundary shape were modelled with the same technique that Jones et al. (2016) used for the rough ocean surface in that earlier work. For the present work, the rms displacement of seafloor heights h_σ was set to 0.16 m and the radial correlation length *L* was set to 4 m.

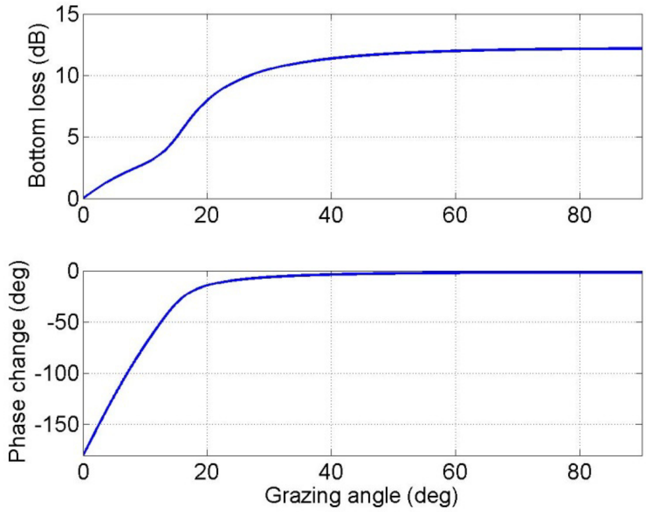

Figure 2: Reflection bottom loss & phase angle for flat surfaced silt half-space

2.2 Modelling of sample scenario

The scenario chosen for a set of Monte Carlo RAMSurf runs was that with the seafloor as described in the previous section, but for a nominal angle of incidence at the seafloor of 10°. From Equation (3) the required uniform sound speed gradient is -0.9279 s^{-1} and the sound speed at the source depth is 1523.20 m/s in order to fix the sound speed at the bottom of the water column at 1500 m/s. Note that the latter sound speed must be maintained across all potential sound speed gradient scenarios, so that the reflection amplitude and phase values are unchanged across such scenarios. It also follows from Equation (1) that the fan of rays that have turning points between depths between 5 m and zero, and thereby do not interact with the sea surface, have angles of incidence at the seafloor between 10° and 11.0°.

RAMSurf modelling was carried out for 2236 Monte Carlo realisations for each of the four cases: (i) rough seafloor of geoacoustic properties, (ii) smooth seafloor of geoacoustic properties, (iii) rough pressure-release seafloor, (iv) smooth pressure-release seafloor. Of course, for each realisation, the sea surface corresponded with a very rough profile as caused by a wind speed of 15 m/s. Each respective set of 2236 realisations of the coherent pressure field was averaged coherently.

Fig. 3 shows the resultant *TL* after coherent averaging of the 2236 realisations for the scenario with the very rough sea surface, for a rough seafloor of the geoacoustic properties described in the previous section. Fig. 4 shows the corresponding data for the scenario with the very rough sea surface, for a smooth pressure-release seafloor, and represents the "zero bottom loss" case against which the data in Fig. 3 may be compared to yield loss per reflection data. This process of comparison removes effects due to spreading with range, as such spreading effects are equal for the data in Figs. 3 and 4. Each figure illustrates the depth of the source and the range values at which the horizontally-launched ray has a turning point. In essence, the loss per reflection may be obtained by comparing amplitude data after each successive reflection from the seafloor, and as data in the vicinity of the turning points are relatively stable, these were extracted to determine loss per bounce. Note that the apparent variations in height of the ocean surface are an artifact of the averaging technique. As this occurred through a process of summation and division of each of real and imaginary sound pressure values, remnant values are shown which correspond with the extremes of surface displacement across the 2236 realisations, and have no material effect. Now, extreme sea surface excursions of $\pm 2h_\sigma$ and even $\pm 3h_\sigma$ may be expected. Using the rms surface height for a Pierson-Moskowitz sea surface of wind speed $w_{19.5}$ m/s measured at 19.5 m above the sea surface as $h_\sigma \approx 5.3\times 10^{-3}(w_{19.5})^2$ (for example, Jones et al., 2016), the sea surface excursions can be expected to be 2.4 m and 3.6 m respectively for a 15 m/s wind speed. These values are consistent with the excursions of sea surface shown in Figs. 3 and 4. Note also that each figure shows the acoustic field to the depth 55 m. This is, of course, not essential, however in the case of the fluid basement depicted in Fig. 3, the penetration within the basement is clear. For the pressure-release seafloor of the scenario of Fig. 4, of course there is no signal in the seafloor.

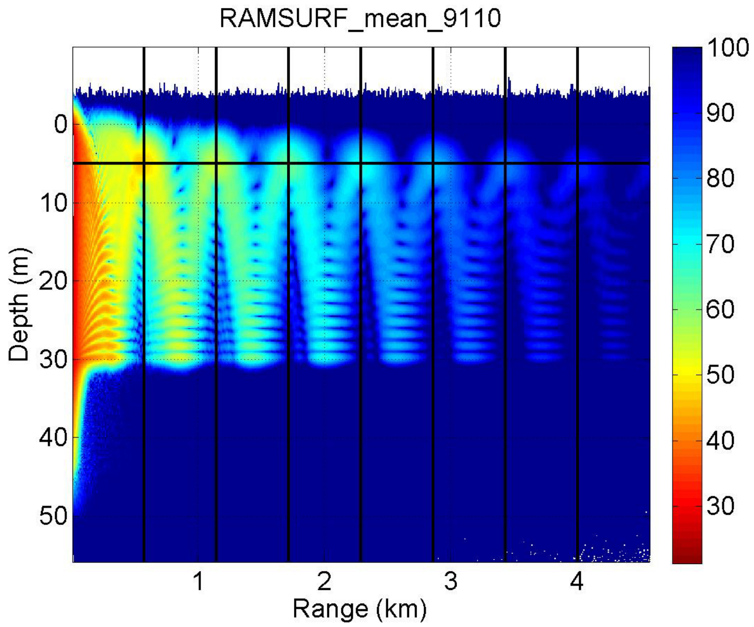

Figure 3: *TL* for rough seafloor of geoacoustic properties, as coherently averaged over 2236 realisations. Vertical lines show ranges for turning points of ray launched horizontally at 5 m depth.

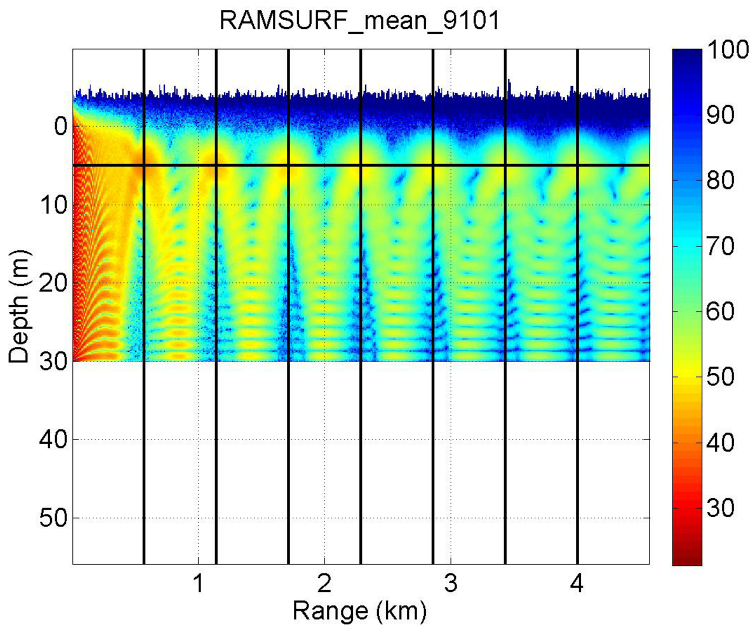

Figure 4: *TL* for smooth pressure-release seafloor, as coherently averaged over 2236 realisations. Vertical lines show ranges for turning points of ray launched horizontally at 5 m depth.

Each set of averaged field data produced in this work was sub-sampled to a matrix of 500 × 500 pixels, for which the value in each pixel then represents a space of 9.14 m length and 0.137 m height. Figs. 3 and 4 show the data obtained by this sub-sampling. In the vicinity of each turning point for the ray launched horizontally, amplitude data in dB form were then averaged arithmetically across a mesh of 21 × 21 pixels centred at the turning point. Loss per reflection data were then based on these averaged data.

3. SEAFLOOR REFLECTION RESULTS

The coherent reflection data from the stochastic modelling is shown in Fig. 5. This shows the loss per reflection obtained at the nominal incidence angle of 10° for the individual bounces out to and including the 6th

bounce. Loss values are shown for the following cases:

- "roughness loss" RL_{rough} from the comparison of data for the rough pressure-release seafloor with data for the smooth pressure-release seafloor
- "material loss" RL_{mat} from the comparison of data for the smooth seafloor of geoacoustic properties with data for the smooth pressure-release seafloor
- "total loss" RL_{total} from the comparison of data for the rough seafloor of geoacoustic properties with data for the smooth pressure-release seafloor
- A numeric sum of the dB values for "roughness loss" and "material loss".

It is apparent that the loss-per-bounce values are quite stable across the six bounces described by the simulations. This is, of course, expected to be the case if the stochastic modelling technique functions correctly. The data for the "material loss", curve B in the figure, may also be compared with the reflection loss value given in Fig. 2 for a grazing angle of 10°. Inspection of the data for that figure provides a value of 2.85 dB loss per bounce, which compares extremely well with the values in Fig. 5, for which the average over the six bounces is 2.93 dB.

It is also apparent that summation of the dB values for the "material loss" and for the "roughness loss" align very closely with the loss value obtained from the stochastic modelling for the rough seafloor of specified geoacoustic properties, the latter designated in the figure as the "total loss". For the data in Fig. 5, averaged over the six bounces the "roughness loss" is 1.95 dB, the summation of "material loss" and "roughness loss" is 4.88 dB, while the loss for the rough seafloor of geoacoustic properties (the "total loss") is 4.84 dB.

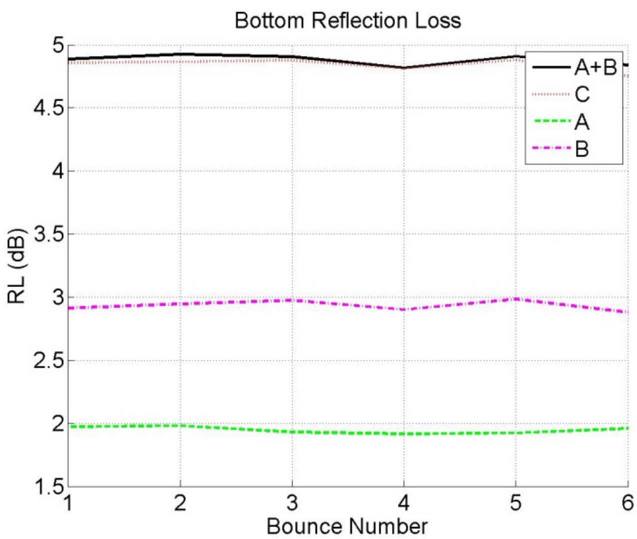

Figure 5: Coherent Reflection Loss per bounce from stochastic modelling for rough absorptive silt seafloor, rms surface height 0.16 m, correlation length 4 m, frequency 3000 Hz, incidence angle 10°: A "roughness loss" RL_{rough}, B "material loss" RL_{mat}, C "total loss" RL_{total}, A+B numeric sum of "roughness loss" and "material loss"

3.1 Discussion

The data derived for the single case for which stochastic modelling has been carried out is totally supportive of the hypothesis posed by Jones et al. (2013): that is, the coherent reflection loss at a rough seafloor of particular geoacoustic parameters RL_{total} dB may be closely estimated by adding the loss obtained for a smooth seafloor of the same material RL_{mat} dB to the coherent loss for a pressure-release surface of identical roughness RL_{rough} dB. The earlier work by the authors (2013) gave the same indication, however in that work the model used as the reference for the rough seafloor of geoacoustic properties (Kuperman and Schmidt, 1989) was itself potentially subject to evaluation against PE-based stochastic modelling. Also in that work, an SSA model was used to generate the "roughness loss" values, whereas in the present work they are generated by stochastic modelling. That SSA model was of a type satisfactorily validated by Jones et al. (2016) using PE-based stochastic modelling using RAMSurf. Lastly, for the earlier work, the "material loss" was determined using an implementation of Rayleigh reflection model retained by Curtin University whereas the data in Fig. 2 were determined using a Rayleigh reflection model retained by DSTG.

Fig. 6 shows data generated using the models used earlier by Jones et al. (2013) for the same parameters for the seafloor material, the seafloor roughness, and the water at the base of the water column, as used for the present work, and described in section 2. For an angles of incidence of 10°, the data in Fig. 6 indicate a "roughness loss" of 2.11 dB, a "material loss" of 2.83 dB, a "total loss" from the Kuperman and Schmidt model (1989) of 4.91 dB. Each of these values is very close to its corresponding average value obtained from the data plotted in Fig. 5. Significantly, the data from the Kuperman and Schmidt model differs from that obtained by the stochastic modelling described earlier by merely 0.07 dB.

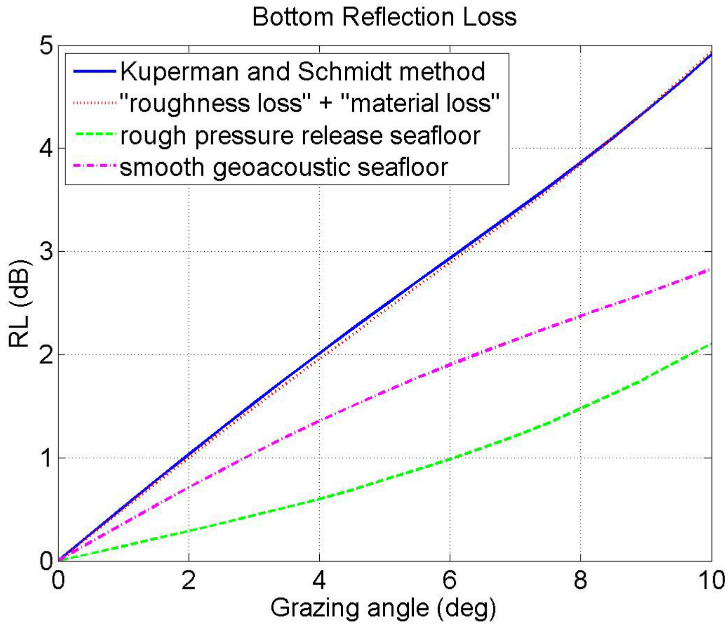

Figure 6: Coherent Reflection Loss per bounce for rough absorptive silt seafloor, rms surface height 0.16 m, correlation length 4 m, frequency 3000 Hz: blue line - Kuperman & Schmidt method (1989), cyan dashed line – "material loss" of smooth seafloor of geoacoustic properties, green dashed line – "roughness loss" SSA model loss for rough pressure-release boundary, red dotted line – "material loss" + "roughness loss"

The anticipation that the coherent loss for the rough seafloor of geoacoustic parameters RL_{total} dB, may be approximated by a function of grazing angle β in the form $(F+A)\beta$ dB, where the "roughness loss" $RL_{\text{rough}} \approx A\beta$ dB and the "material loss" $RL_{\text{mat}} \approx F\beta$ dB was, of course, not subject to confirmation by the stochastic modelling as the simulations were for one grazing angle only.

Lastly the expectation of an extra coherent loss component, due to the reflection phase differences associated with imagined surface facets for which the surface slope is different, was not at all supported by the stochastic modelling. If there was such a component of loss, the expectation was that the "total loss" would noticeably exceed the sum of the "roughness loss" and "material loss". In fact, the stochastic modelling showed that, for the scenario tested, the sum of the dB values of "roughness loss" and "material loss" was extremely close to the dB value for "total loss".

4. CONCLUSIONS

The coherent reflection loss per bounce for a simulated rough seafloor of particular geoacoustic properties, RL_{total} dB, was successfully obtained by a novel technique which is based on Monte-Carlo runs of the PE model RAMSurf. Additional Monte-Carlo runs of the PE model were used to obtain the coherent reflection loss per bounce RL_{rough} dB for a pressure-release surface of identical roughness in an otherwise identical ocean, and further Monte-

Carlo runs of the PE model were used to obtain the reflection loss per bounce RL_{mat} dB for a smooth seafloor of the geoacoustic parameters. An hypothesis, that the sum of the coherent reflection loss for a rough loss-less surface, and the loss for a smooth surface of specified geoacoustic parameters $RL_{\text{rough}} + RL_{\text{mat}}$ dB would closely approximate the coherent loss for the seafloor of the same roughness and geoacoustic properties RL_{total} dB was confirmed for the single case tested.

A comparison was made of the coherent reflection loss per bounce obtained by the stochastic modelling for the rough seafloor of geoacoustic properties with the result obtained by a model due to Kuperman and Schmidt. The agreement, for the particular rough seafloor, for a grazing angle of 10°, was extremely close.

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