Modelling acoustic reflection loss at the ocean surface for small angles of incidence

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***Abstract*-This paper investigates the performance of available models of acoustic surface loss for small grazing angles of incidence, and for lower wind speeds for which bubble formation is less likely to play a role. In order to investigate the expected importance of shadowing for these scenarios, a wave-type model has been run with a deterministic simulation of the surface profile, for a number of situations for which transmission has been confined to small angle arrivals. This modelling includes, implicitly, the effects of diffraction into the shadowed regions, and the effects of the varying levels of intensity of insonification in accord with the different surface slopes. The surface loss values inferred from these simulations are compared with those from the other models, and to the extent possible, with the apparent effects observed with available at sea data. In this work, attention has been paid to the angles of incidence at the surface which dominate the loss effects. To the extent possible, conclusions are drawn on the apparent accuracy of the various models, and the need for further work to ascertain their appropriateness at small grazing angles.**

I. Introduction

A description of the reflection of underwater sound incident upon a real ocean surface boundary is a necessary component of an acoustic transmission model. For predictions of signals received at medium-to-long ranges (10 km to 30 km or more), especially for oceans with an isothermal surface duct or for shallow oceans, the acoustic interaction at small angles of incidence (about 10° and less) is particularly relevant. Descriptions of surface loss for such situations are needed for matters relating to detection of either submerged or surface vessels, and in relation to the impact of underwater acoustic signals on marine fauna.

At low frequencies, the sea surface may be regarded as smooth, with total reflection of intensity at the specular angle. At mid-frequencies (over about 1 kHz), this is no longer the case and an intensity reduction must be included to account for the sound scattered from the surface at non-specular angles. For all but low sea states, the root-mean-square slope of the ocean surface is of the order or greater than the incident grazing angle of significant components of the transmitted sound. As a result, some areas of sea surface are shadowed, and are insonified by diffracted sound, only. Other practical complications include whether roughness alone causes the acoustic loss effects, or whether near-surface bubbles play a role. Also, the reflection of sound occurs over a surface patch with two-dimensional characteristics, and so a one-dimensional description of the surface profile may be inadequate. Lastly, it may be necessary to consider whether the sound reflected in the specular direction consists entirely of a coherent component, or whether an incoherent, or diffuse, component is assumed to exist as well. Due to the existence of these complexities in the relevant phenomena, and the non-uniformity of the surface state, the modelling of surface loss remains an area yet to be mastered.

In response to this unresolved situation, the Defence Science and Technology Organisation (DSTO), Thales Australia and the Centre for Marine Science and Technology (CMST) at Curtin University have investigated the different models of surface loss available to them and have compared the performance of these models. In addition, the output of these models has been compared with that obtained from a small-slope approximation model [1] made available by the Applied Physics Laboratory of the University of Washington, Seattle. These comparisons have been made, firstly, at the level of predictions of surface loss per bounce, and secondly, at the level of predictions of transmission loss (*TL*) based on the use of these models, for scenarios for which at-sea measurements of *TL* are available.

This paper extends earlier work [2], [3] by investigating the small angle performance of the available models. In order to investigate the expected importance of shadowing for these scenarios, a wave-type model has been run with a deterministic simulation of the surface profile, for a number of situations for which transmission has been confined to small angle arrivals. This modelling includes, implicitly, the effects of diffraction into the shadowed regions, and the effects of the varying levels of intensity of insonification in accord with the different surface slopes. The surface loss values inferred from these simulations are compared with those from the other models, and to the extent possible, with the apparent effects observed with available at sea data. In this work, attention has been paid to the angles of incidence at the surface which dominate the loss effects. To the extent possible, conclusions are drawn on the apparent accuracy of the various models, and

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the need for further work to ascertain their appropriateness at small grazing angles.

The paper commences with consideration of the issues under investigation, and then a brief description of the surface loss models considered. Section IV then considers the transmission loss effects which can be expected from surface loss models of two basic forms, for both isovelocity shallow oceans and isothermal surface ducts. This leads to a re-analysis of some of the results of Williams et al [1] and a consideration of the extent to which that work may be considered to highlight differences between surface loss models. Section V describes the techniques used in this study for the determination of coherent surface reflection loss using a wave-type transmission model with random replications of a surface boundary displacement. Results obtained are shown, and discussed in the context of the models considered earlier. Next, at-sea *TL* measurements are shown compared with predictions based on the use of various surface loss models. Lastly, conclusions are drawn from the completed work.

II. Surface Loss Issues

The literature relating to acoustic loss at the ocean surface is vast. One of the more recent studies involving the development and demonstration of a surface loss model for use at mid-frequencies is that of Williams et al. [1]. This paper includes a re-examination of some of the findings of that work in the context of transmission scenarios involving a mixed layer surface duct.

A. Implications of Williams et al. Study

A surprising implication from the William et al. [1] work is that a surface loss model as simple as the Gaussian-roughness Kirchhoff gave results for *TL* nearly the same as modelling which was much more sophisticated, from a physics viewpoint. That work included a deterministic modelling of the effects of a roughened sea surface by the use of a parabolic equation (PE) transmission model with a sea surface boundary profile derived from appropriately correlated random realizations of surface height adhering to the Pierson-Moskowitz wave spectrum. The modelling included, implicitly, effects such as shadowing of the sea surface and diffraction into the shadow zones. Surprisingly, the *TL* results from the deterministic PE modelling were matched closely by the Gaussian-roughness Kirchhoff model used with ray modelling of transmission. The authors of the present paper were surprised by this result and the apparent lack of a need to consider shadowing, so commenced the study for which early results are presented below. In this paper, the Williams et al. scenarios of 5 m/s and 10 m/s wind speed at 3.2 kHz are considered.

B. Sea Surface Shape and Shadowing

The common parameters used for studying sea surface roughness in the context of surface acoustic loss are as shown in Fig. 1. For convenience, most models of surface loss simplify the description of the sea surface to a statistical profile which is then described by a single length parameter. It is common to assume a relationship between the statistical profile and the wind speed, and thus the sea surface shape is represented solely by a wind speed value *w*.

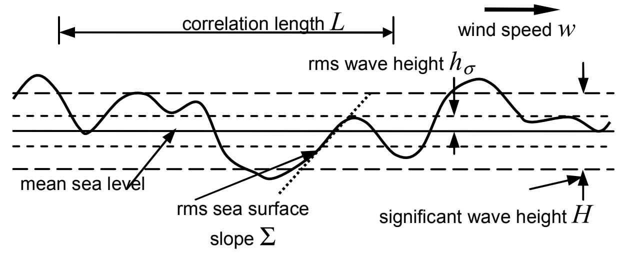

Figure 1. Common Parameters for Sea Surface Roughness

For simulations conducted in this study, the relationship used is from the Pierson-Moskowitz spectrum (e.g. section 13.1 of Medwin and Clay [4]

$$h_\sigma \approx 5.3\times10^{-3} w^2 \qquad (1)$$

where rms wave height h_σ and wind speed w are in metres and m/s, respectively. (Note: w is usually taken to be at 19.5 m above sea level.) For wind speeds used in this study, values of h_σ are 0.13 m (5 m/s wind) and 0.53 m (10 m/s wind).

Values of rms sea surface slope Σ are not used within this study directly, but an expression of Cox and Munk [5] is reproduced as it is quoted frequently. The usual expression quoted from [5] is the mean square slope formed from the sum of the measured mean square slope contributions in crosswind and up/downwind directions, as

$$\Sigma^2 \approx 0.003 + 5.12\times10^{-3} w \pm 0.004 \qquad (2)$$

where w was measured at 12.5 m above sea level. This suggests relatively large rms slopes for 5 m/s and 10 m/s wind speeds, but is relevant to much smaller spatial scales at the surface than applicable to the mid-frequency range of interest. Regardless, it was considered feasible that acoustic shadowing (e.g. Wagner [6]) of the surface might be an issue for shallow grazing angles (about 5° and less) considered in this study.

III. Surface Loss Models Studied

The surface loss models considered include the Kirchhoff, Beckmann-Spizzichino and the small-slope model from the Applied Physics Laboratory of the University of Washington, Seattle [1].

A. Kirchhoff

As stated by Williams et al. [1] (section V), the Kirchhoff surface loss model is based on the rms wave height h_σ whether this is obtained using a wave spectrum model in which the sea surface is described in either one or two surface dimensions. The standard form of the Kirchhoff model, for a surface with a Gaussian distribution of surface height is well known:

$$R_{coh} = -e^{-0.5\Gamma^2} \quad (3)$$

where $\Gamma = (4\pi f h_\sigma \sin\beta)/c_w$ (Rayleigh roughness parameter); f is cyclic frequency, Hz; β is grazing angle at the surface, radians; c_w is speed of sound in seawater, m/s; R_{coh} is the coherent sound pressure reflection coefficient.

This arises from the Kirchhoff approximation to scattering. It is noteworthy that the result does not depend on a spatial correlation with range (e.g. Brekhovskikh and Lysanov [7]). Lurton [8] section A.3.3 describes the derivation of this model for a one-dimensional, Gaussian, surface profile. The loss results from phase cancellation of the phase separated components reflected from the entire insonified area, thus representing a coherent loss component. The key feature of the surface is the rms height h_σ and the probability distribution for the surface heights. The Reflection Loss (*RL*) resulting from (3) is

$$RL = -20\log_{10}\left(e^{-0.5\Gamma^2}\right) \text{ dB.} \quad (4)$$

This is not the only "Kirchhoff" model that may be postulated, as a non-Gaussian surface profile will yield a different loss result. It may be noted that this model assumes that the entire ocean surface is insonified with uniform intensity. As the grazing angles become of the same order as the rms wave slope, this assumption is clearly in error.

As part of this study, similar models have been derived for each of a symmetrical triangular-shaped and a sinusoidal-shaped surface, using a surface description in one-dimension. The values of reflection loss obtained are as follows:

$$\text{triangular-shaped } RL = -20\log_{10}\left[\frac{\sin\left(\sqrt{3}\Gamma\right)}{\sqrt{3}\Gamma}\right] \text{ dB} \quad (5)$$

$$\text{sinusoidal-shaped } RL = -40\log_{10}\left(1-\Gamma^2/4\right) \text{ dB} \quad (6)$$

where, in the case of (6), it may be shown that the expression is limited to values of roughness parameter no greater than $\Gamma \approx \pi/\left(2\sqrt{2}\right)$. It may be easily shown that each these forms becomes identical to (4) for small roughness Γ.

It may be shown that the peak wave heights (peak-to-peak) are $2\sqrt{3}\,h_\sigma$ for the triangular-shaped surface and $2\sqrt{2}\,h_\sigma$ for the sinusoidal. Note that the length scale of these profiles, and hence the rms wave slopes, are irrelevant to (4), (5) and (6).

Determinations of surface loss, based on these expressions, are shown in Figs. 2 and 3 for the wind speeds of interest for 3200 Hz. Note that values of Γ for the maximum angle shown (10°) are 0.61 for 5 m/s wind and 2.46 for 10 m/s wind. The closeness of surface loss values is interesting, bearing in mind the quite different probability distributions for these surface types, indicating the importance of the rms wave height.

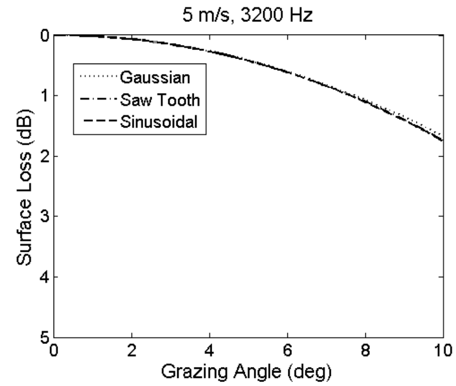

Figure 2. Surface Loss per bounce for Kirchhoff model, wind speed 5 m/s, 3200 Hz

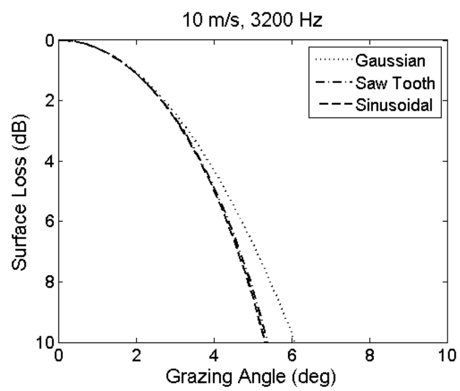

Figure 3. Surface Loss per bounce for Kirchhoff model, wind speed 10 m/s, 3200 Hz

The surface height distributions, $p(x)$, where x is height value, are of the form: $p(x) = \text{constant}$ for symmetrical triangular shape; $p(x) = \left(A^2 - x^2\right)^{-1/2}/\pi$ for sinusoidal shape; $p(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-x_0)^2/2\sigma^2}$ for Gaussian shape (e.g. [9]). Of these three forms of surface of identical rms height h_σ, the Gaussian has the least number of large values - this probably being the reason it causes the least loss in Fig. 3. The surface height distributions for the deterministic simulations of sea surface discussed in Section V are Gaussian, and so the model in (4) will be valid apart from complicating factors (shadowing, etc.) due to small angle incidence and finite amplitude wave heights.

B. Beckmann-Spizzichino

Each of DSTO and Thales Australia uses implementations of the "Beckmann-Spizzichino" model of surface loss. This model has a long history of use and its origins are in the 1960s (e.g. Jones et al [2, 3]). The RAYMODE Beckmann-Spizzichino model is described in two NORDA documents (Lauer [10], McGirr [11]), with some of the links to the underlying theory being clarified by Jones et al [2, 3]. The algorithms of the RAYMODE version are outlined below. Williams et al [1] compared their models to the GRAB implementation of Beckmann-Spizzichino.

Reflection loss *RL* dB per bounce is given by the sum of two terms: SL_1, a "high frequency loss"; SL_2, a "low frequency loss" (Lauer [10]). The "high frequency loss" component is drawn from the theory of Beckmann-Spizzichino:

$$SL_1 = -20\log_{10}\left[(1-v_3)\right]^{1/2} \text{ dB} \tag{7}$$

where v_3 is the maximum of $\left[\sin\beta - \frac{e^{-\left[a\beta^2/4\right]}}{(\pi a)^{1/2}}\frac{\sin\beta}{\beta}\right]$ and $(\sin\beta)/2$, and $a = \left[2\left(0.003 + 5.1\times10^{-3}\, w\right)\right]^{-1}$ where from (2) a is the reciprocal of twice the mean-square slope of the surface. The value v_3 is limited to 0.99. The term SL_1 is claimed to be relevant to losses under large roughness and is determined solely by grazing angle and mean-square slope, and not by frequency. From (7), numerical values of SL_1 for scenarios of present interest may be shown to be small.

The "low frequency loss" SL_2 is shown in Deavenport's equation (3B-7) (Lauer [10]) in terms of frequency and average wave height *H*. By substituting for wave height in terms of wind speed using an expression attributed to Eugene Podeszwa (Lauer [10]), the "low frequency loss" becomes

$$SL_2 = -20\log_{10}\left(0.3 + \frac{0.7}{1+6.0\times10^{-11}\, w^4 f^2}\right) \text{ dB}. \tag{8}$$

As pointed out by the authors [2], the original derivation of (8) from the work of Marsh et al [12] simplified the dependence of surface loss upon grazing angle by fixing the surface duct depth at 60 m, for which the limiting ray has an angle at the surface of 2.13°. Thus (8) is relevant to this angle only. Further, the authors [2] postulated that the constants "0.3" and "0.7" originated as a means of limiting the value of SL_2 to the maximum observed in a set of at-sea data, this being about 10.5 dB loss per bounce, noting that $-20\log_{10}(0.3) \approx 10.5$ dB. It is believed that various implementations of Beckmann-Spizzichino differ from the above RAYMODE form (i) in the expression used for the high frequency loss SL_1; (ii) in the constant multiplied by the term $w^4 f^2$, thus changing the wind speed-frequency combination at which the maximum value for SL_2 of 10.5 dB is approached.

C. Small Slope Model of Williams et al.

Williams et al. [1] published details of a small-slope approximation model, and a perturbation analysis model. These models have been made available to the lead author for the purposes of the present comparison. Each model describes the coherent surface reflection coefficient due to surface roughness with a Pierson-Moskowitz surface wave spectrum.

Williams et al [1] simulated received intensity with the GRAB Gaussian beam model run with (i) their surface loss models, (ii) the GRAB-version Beckmann-Spizzichino model, (iii) a Kirchhoff model for a Gaussian surface.

D. Surface Loss Predictions

For the models considered in this study, Reflection Loss for a single bounce for frequency 3200 Hz was computed as a function of grazing angle for wind speeds of 5 m/s and 10 m/s. The rms surface height h_σ for the Kirchhoff model was obtained using (1). Labelling in Figs. 4 and 5 is as follows

R-BS	RAYMODE Beckmann-Spizzichino (7) + (8)
W SS	Williams et al small slope model
Kirchhoff	Gaussian roughness Kirchhoff model (4)
RAVE	Beckmann-Spizzichino of Thales Australia

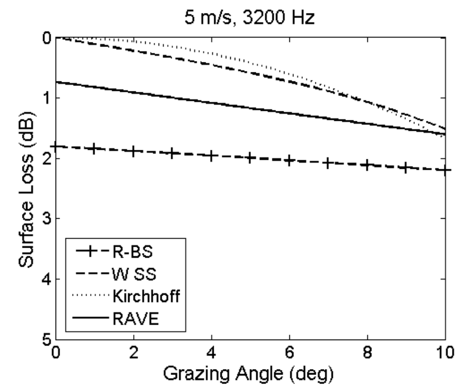

Figure 4. Surface Loss per bounce for wind speed 5 m/s, 3200 Hz

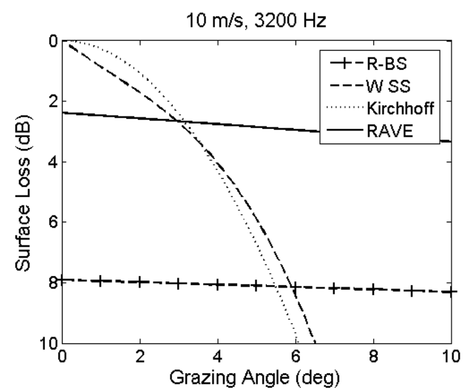

Figure 5. Surface Loss per bounce for wind speed 10 m/s, 3200 Hz

From (8), the RAYMODE Beckmann-Spizzichino term SL_2 has no grazing angle dependence. The small variation with grazing angle is due to the SL_1 term in (7). From (4), the Gaussian roughness Kirchhoff model gives a dependence on the square of grazing angle. The Williams et al. small slope model gives a linear dependence on grazing angle for small angles, increasing more rapidly with angle at about 6° for 5 m/s wind, or 3° for 10 m/s wind. The loss from the Gaussian roughness Kirchhoff model is close to that from the Williams et al small slope model at all but very small angles for which the former returns lower loss values. It may be noted that none of these models implicitly includes the effects of shadowing of the surface. Such effects might be expected to increase the loss for small grazing angles and rough surfaces. The RAYMODE (and RAVE) Beckmann-Spizzichino data in Figs. 4 and 5 may be considered to represent this effect (finite loss at grazing angle 0.0°) but from its origins this does not appear to have been overtly intended.

For isothermal surface ducts of depth 150 m and less, the grazing angle of limiting rays is less than about 3.3°, and so all ducted transmission is confined to rays with angles shallower than this.

IV. Significance of Surface Loss Including Comments on Williams et al. Scenario

The scenario modelled by Williams et al. [1] (their figure 1), is an isovelocity (1500 m/s) shallow ocean of constant 50 m depth. The seafloor was modelled as an absorbing fluid half-space of uniform properties, with a smooth bottom surface. Seafloor density was twice that of the ocean, sound speed 1600 m/s and attenuation 1.0 dB/λ. The source was at 25 m depth, and had a Gaussian-shaped beam-pattern (down by $1/e$ (4.3 dB) at ±10° [13]) directed upward at 10°. Received intensity at 3200 Hz was modelled to a range of 20 km.

A. *Simplified Boundary Losses for Wind Speed 5 m/s*

The bottom loss (*BL*) determined for this seafloor may be shown to be as in Fig. 6.

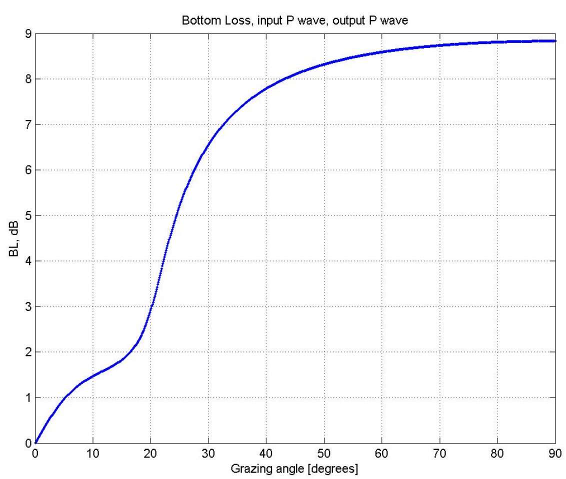

Figure 6. Bottom Loss for Williams et al. scenario, 3200 Hz

As is well known (e.g. Jones et al. [14]), a suitable approximation at small angles β is for the bottom loss per bounce to be assumed proportional to angle, as $F\,\beta\,\mathrm{dB}$. Data in Fig. 6 show that this is a reasonable approximation for grazing angles less than about 10°, if not to higher grazing angles. From this data, a value of $F \approx 11$ dB/radian may be obtained. From figure 6 of Williams et al. [1], it may be seen that the coherent surface loss per bounce for their small slope model has, likewise, a near linear variation in grazing angle, and a value of $F \approx 6.6$ dB/radian may be deduced for 3200 Hz and wind speed 5 m/s. If the total losses from both boundaries are assumed to occur at one boundary only, the total boundary losses may then be approximated by their summation, as 17.6 dB/radian, at that boundary. It may be noted that the seafloor losses dominate the total boundary losses.

B. *Transmission Description for Wind Speed 5 m/s*

For an isovelocity ocean with boundary losses of the form $F\,\beta\,\mathrm{dB}$ per bounce, for omni-directional source and receiver, if all significant arrivals are summed at each range, the transmission loss may be shown to be (see, e.g. Weston [15])

$$TL \approx 15\log r + 5\log hF - 7.2 + \alpha r\ \mathrm{dB} \qquad (8)$$

where r is horizontal range and h is ocean depth in metres; F is total boundary loss per bounce, dB/radian, α is in-water absorption, dB/m.

For this situation, the angular distribution of arrival energy may be shown to be of Gaussian form (e.g. Jones et al [16]), with a variation of the form $10^{-\frac{rF\beta^2}{20h}}$. It follows that the 1/e point for the angular distribution corresponds with

$$\beta_{1/e} = \pm\sqrt{\frac{20\,h}{r\,F\ln 10}}\ \text{radians} \qquad (9)$$

and for the scenario in question, the $1/e$ point then occurs at $\beta_{1/e} = \pm 2.1°$. (It may be shown that the angular spread corresponding with ±σ for the Gaussian angular distribution of arrival energy is $\beta_\sigma = \sqrt{20\,h/(r\,F\ln 10)} \sim \pm 1.5°$.) The beam pattern of the channel response is then much narrower than that of the signal source by the factor $2.1°/10° = 0.21$, with the effect that the signal energy directed at much greater angles is heavily attenuated. The result is that the signal received at 20 km may be seen to be very approximately the same as if the source was omni-directional with a source strength $1/e$ of the true source, that is, the source response at the horizontal. The approximated transmission loss, TL_S, incorporating source directivity is then

$$TL_S \approx 15\log r + 5\log hF - 2.9 + \alpha r\ \mathrm{dB}. \qquad (10)$$

From (9), even at 2500 m range, the spread of arrival energy imposed by the channel is merely $\beta_{1/e} = \pm 5.6°$, whereas at 1000 m range the angular spread is $\beta_{1/e} = \pm 9.0°$, and the approximation of *TL* according to (10) is no longer valid.

Some confirmation of the appropriateness of (10) for the 5 m/s wind speed case with the Williams et al. small slope model is given by the fact that the *TL* increase from 2.5 km range to 20 km range shown in Williams et al. figure 7 [1] is in accord with $15\log r$ expected from (10), this being a 13.5 dB increase. Confirmation of the approximation of the boundary losses being in accord with $F\,\beta\,\mathrm{dB}$, with $F \approx 17.6$ dB, is also shown by the vertical variation in received amplitude at 20 km range shown in Williams et al. figure 8 [1]. The expression for vertical amplitude variability shown by Jones et al. [16] for an isovelocity shallow ocean with boundary losses $F\beta\,\text{dB}$ is $\Delta x_y \approx 0.14\lambda\sqrt{rF/h}$. For the present case, $\Delta x_y \approx 11.7\lambda \approx 5.5$ metres, being consistent with the vertical scale at 20 km range in Williams et al. figure 8 [1].

A consequence of this analysis is that the effect of zero surface loss may be easily estimated. From (10), the impact on *TL* of zero surface loss ($F \approx 11$ dB/radian), versus with surface loss from the small slope model ($F \approx 17.6$ dB/radian), is not great, being merely 1.0 dB more at each range value.

C. RAYMODE Beckmann-Spizzichino Surface Loss for Wind Speed 5 m/s

It is not known to the authors if the Beckmann-Spizzichino model used by Williams et al. is the same as the RAYMODE version described by Lauer [10] and McGirr [11], for which loss values per bounce for 3.2 kHz are included in Fig. 4. In this case the loss may be approximated, roughly, as constant at about 2 dB per bounce. For small arrival angles, this exceeds the bottom loss shown in Fig. 6, so the total boundary loss will be assumed 2 dB per bounce irrespective of grazing angle.

For this shallow isovelocity ocean, with boundary loss *G* dB per bounce independent of grazing angle, the distribution of arrival intensity with grazing angle may be shown to have an exponential form $e^{-rG\beta\ln 10/(20h)}$. Now, knowing that the equivalent width of an exponential $e^{-|x|}$ is 2 (e.g. Table 8.3 of Bracewell [17]), that is, the span $\pm x$ where $x = 1$, the number of arrivals contributing within the relevant angular spread may be estimated and *TL* determined by modelling spherical spreading along each. In this way, so long as the loss *G* is not very small, it may be shown that the *TL* for an isovelocity shallow ocean with boundary loss independent of grazing angle is

$$TL \approx 20\log r + 10\log G - 9.4 + \alpha r \text{ dB}. \qquad (11)$$

By comparing *TL* values computed from (8) and (11), using $F = 17.6$ dB/radian in (8) representing total boundary loss with the Williams et al. small slope surface loss, and $G = 2$ dB in (11) representing use of the RAYMODE Beckmann-Spizzichino surface loss, the value of *TL* at 20 km is about 7 dB greater at 20 km range for the scenario with the latter surface loss model. The relativity between the respective *TL* plots in Williams et al. figure 7 is similar at about 5 dB difference, however these may be based on a different implementation of Beckmann-Spizzichino. A feature of the data for the Beckmann-Spizzichino model in Williams et al. figures 7 and 9 is that the rise in *TL* between ranges 2.5 km and 20 km is in accord with the $20\log r$ expectation (18.1 dB increase) of (11).

D. Transmission Description for Wind Speed 10 m/s

From figure 6 (b) of Williams et al. [1], the small-angle straight line segment of the small slope model for surface loss per bounce may be extrapolated to give a loss function of 48 dB/radians. By combining with the seafloor loss of 11 dB/radian, a total boundary loss function of 59 dB/radian is obtained, with the surface losses being dominant. The expected effect on *TL*, in comparison with the 17.6 dB/radian total boundary loss for the 5 m/s wind speed, is small at only 2.6 dB extra *TL* at each range value ($5\log(59/17.6)$). The intensity values shown in Williams et al. figures 7 and 9 do appear to show this amount of extra loss for *TL* determined using their small slope model.

From (9), at 20 km range, the angular distribution of arrivals imposed by the shallow water channel is extremely small, with $\beta_{1/e} = \pm 1.1°$.

E. Expected Implications of Surface Duct Scenario

For transmission in an isothermal surface duct of depth *D*, such as shown in Fig. 7, unless bottom-reflected energy exists, the propagating rays are confined to a very small angular spread, and the performance of surface loss models at small grazing angles is expected to be crucial.

In an isothermal duct, sound rays undergo a surface reflection at a regular spacing related to the skip distance, this well known to be $2\beta c_w/g$ m, where β is the angle subtended at the surface by a ray, *g* is sound speed gradient ≈ 0.017 s^{-1} and c_w is the speed of sound in seawater. For a surface loss function of the form $F\beta\,\text{dB}$ per bounce, it follows that the rate of loss due to surface interactions is $Fg/(2c_w)$ per metre. This implies that the loss per unit range is independent of grazing angle, which has the result that the angular distribution of arrivals is unchanged with range throughout the zone of cylindrical spreading. This differs from the case with the isovelocity ocean for which arrival structure imposed by the channel was in accord with (9).

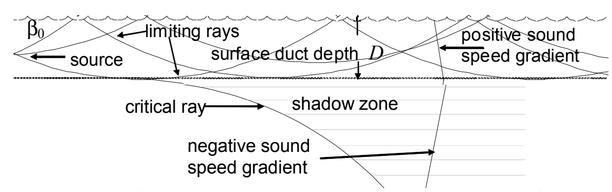

Figure 7. Sea surface interaction in mixed layer, isothermal, surface duct

Depth-averaged *TL* will have the form of spherical spreading to a transition range r_t, with cylindrical spreading beyond plus added surface loss. For a surface loss function of the form $F\beta\,\text{dB}$, the *TL* may be shown to be

$$TL \approx 10\log r_t + 10\log r + F\,g\,r/(2c_w) + \alpha r \text{ dB}. \qquad (12)$$

In the case of wind speeds 5 m/s and 10 m/s, the total loss due to surface interaction at 20 km range is expected to be 0.7 dB ($F \approx 6.6$ dB/radian corresponding with 5 m/s wind), 5.4 dB ($F \approx 48$ dB/radians for 10 m/s wind). Clearly, doubling the wind speed from 5 m/s gives almost twice the extra loss effect than the 2.6 dB in the isovelocity case.

Using a ray approximation to transmission, each ray will undergo multiple surface bounces in transmission to a long range, and for each bounce the angle of grazing is the same as for every other bounce. If the surface loss has a value *G* dB independent of grazing angle (the RAYMODE Beckmann-Spizzichino model has the form, very approximately), the total loss to range *r* for a ray that has reflections at the surface at angle β may be shown to be $G\,g\,r/(2\beta c_w)$ dB. Clearly, the energy for rays with the shallower angles is stripped from the duct, so the total surface loss integrated over duct depth exceeds $G\,g\,r/(2\beta_0\, c_w)$ dB where β_0 is the grazing angle for the limiting ray (Fig. 7). Obtaining a closed form solution to the total loss is not feasible, and for convenience the depth averaged *TL* is estimated by using the loss associated with the limiting ray as

$$TL \approx 10\log r_t + 10\log r + G\,r\sqrt{g/(8\,D\,c_w)} + \alpha r \text{ dB}. \quad (13)$$

In the case of the isovelocity scenario with surface loss values $G = 2$ dB and 8 dB, respectively, according to 5 m/s and 10 m/s wind speed (Figs. 4, 5), from (11) the total loss due to surface interaction at 20 km range is expected to be $10\log(8/2) \approx 6$ dB greater at the higher than at the lower wind speed. (Note that the RAYMODE Beckmann-Spizzichino surface loss per bounce is much greater that the seafloor loss, so the latter may be neglected.) From (13), for an isothermal duct of depth 50 m, the total surface loss to 20 km becomes 20.2 dB greater for wind speed 10 m/s than for wind speed 5 m/s – a much greater difference than for the isovelocity case.

F. Implications of Shallow Isovelocity Scenario

From the above, it is obvious that the ocean scenario chosen for study by Williams et al [1], the 50 m depth shallow ocean with selected seafloor, gave rise to effects from the choice of surface loss model which would differ from those relevant to a surface ducted scenario. Further, the isovelocity scenario gave rise to much lower amounts of total surface loss than would a surface ducted scenario, thereby reducing, rather than highlighting, effects due to differences between models at small grazing angles. Further mathematical statement of the differences imposed by the two types of scenarios are given below.

For an isovelocity ocean of depth *h* with a surface loss of the form $F\beta$ dB, where *F* is a constant and β is grazing angle, the surface loss attenuation function of the scenario may be shown to be of the form $B_\beta \approx r\,F\,\beta^2/(2\,h)$ dB, where B_β dB is total surface loss to range *r* corresponding with a ray at grazing angle β. From (12), for an isothermal surface duct, the corresponding expression, which is independent of grazing angle, is $B \approx F\,g\,r/(2\,c_w)$ dB. In the case of a surface loss of the form *G* dB, where *G* is independent of grazing angle, the corresponding expressions are $B_\beta \approx r\,G\beta/(2\,h)$ dB for the isovelocity ocean and $B_\beta \approx G\,g\,r/(2\beta c_w)$ dB for a surface duct of sound speed gradient *g*. Clearly, the total surface losses for the two scenarios have quite different characteristics.

Due to the fact that the Williams et al. isovelocity scenario limited the visibility of model differences relative to a surface ducted transmission, it does appear that there was a limited ability to draw conclusions about the suitability of the Kirchhoff model for small angles of incidence. Additionally, it does appear that conclusions related to the results for the 5 m/s wind speed were compromised by the dominance of seafloor losses for that scenario.

V. Deterministic Modelling of Sea Surface

Values of coherent surface reflection loss were determined by the CMST at Curtin University through a numerical simulation of transmission in an ocean with a sea surface boundary displaced vertically according the Pierson-Moskowitz wave spectrum. By using a PE transmission code (RAMSurf as implemented by CMST [18]) the modelling included forward transmission effects due to acoustic shadowing of segments of the sea surface and diffraction of sound into shadowed zones. For practical purposes, a one-dimensional sea surface was described and transmission simulated cylindrical symmetry. A similar PE transmission scheme was used by Williams et al. [1].

In practice, the CMST simulation generated sea surface height values with a spatial correlation determined by the Pierson-Moskowitz wave spectrum, and a surface height distribution, $p(x)$, which was Gaussian, with rms wave height h_σ related to wind speed according to (1). The grid sizes used for the simulations were 0.1λ vertically, and 2λ horizontally, where λ is acoustic wavelength. The acoustic field was computed to a range of 30 km in each case. For each scenario, the field was computed first using a description of a flat, smooth surface, then with the surface described as rough, as above. For each scenario, a large number (typically 40) of replications of the sea surface was generated and the coherent field determined for each. The total loss of coherent transmission was determined by subtracting the mean of the coherent fields obtained for the roughened surface from the field obtained with the smooth surface.

In order to determine a coherent surface reflection loss per surface bounce, scenarios were selected so that each consisted of a surface duct of uniform gradient over an isovelocity ocean layer of 110.3 m thickness, under which was placed an absorbing lower boundary. The (omni-directional) source was placed 5 m above the lower boundary of the surface duct, to ensure that all surface reflections occurred at grazing angles that were known, these being close to those expected from ray theory. Combinations of duct depth and gradient were selected to ensure good duct trapping (frequency well above duct trapping frequency) and a sufficient number of surface bounces to 30 km range. Surface loss per bounce was determined by dividing total coherent loss in dB as determined within the duct, by the number of surface skips. Fig. 8 shows an example of this work for wind speed 5 m/s, 3200 Hz, for a

150 m surface duct of gradient 0.20 s^{-1}, for which the following may be obtained from ray theory: grazing angle for limiting ray 11.5°, duct trapping frequency 28 Hz, skip distance 3 km. Fig. 8 shows values of coherent loss as a function of range at (i) duct mid-depth, (ii) receiver depth equal to source depth. A similar loss per bounce is evident, at each depth, as are each of the surface bounces. The coherent surface loss per bounce at 11.5° follows as 1.4 dB.

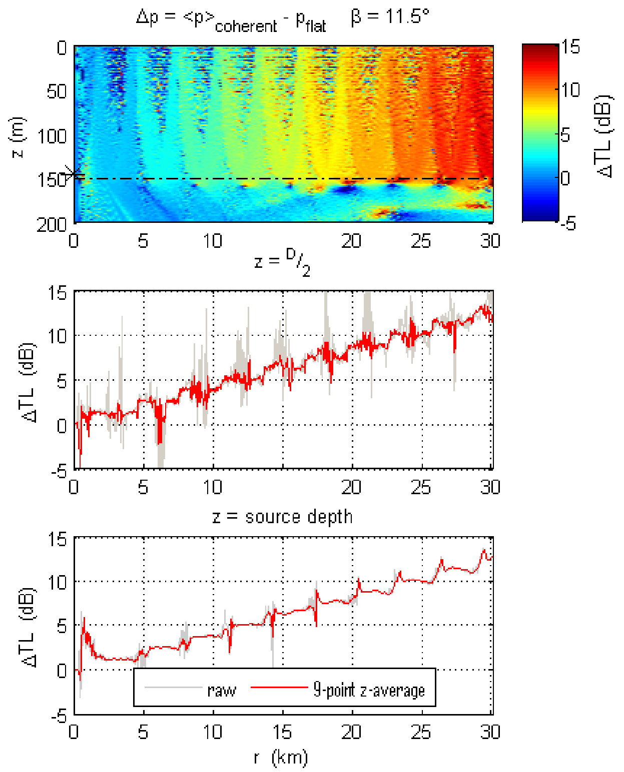

Figure 8. Overall coherent loss for ducted transmission scenario, surface skips at 11.5° grazing angle, wind speed 5 m/s, 3200 Hz

Values of coherent surface reflection loss determined are shown in Table I. This shows features of each scenario: surface duct depth and sound speed gradient; number of surface skips that occurred in the 30 km range available for the simulation. In general, a more reliable result is achieved if there is a greater number of surface bounces in the simulation, and if the loss per bounce is not very small.

A result from this data is that the values in Table I are closer to the Williams et al. small slope model than to the Gaussian Kirchhoff model at the smaller angles. There is little evidence of effects due to surface shadowing, for which surface loss values in excess of the Williams et al. small slope model were expected. For the present deterministic modelling, the distribution of surface slopes was Gaussian, with rms surface slope values 2.3° (5 m/s wind) and 6.3° (10 m/s wind). Whilst the small rms slope for the lower wind speed is not likely to result in significant shadowing, such effects might be expected with the 10 m/s wind speed, yet none was evident across the range of grazing angles 1.5° to 5.7°.

TABLE I
DETERMINATIONS OF COHERENT SURFACE REFLECTION COEFFICIENT
3200 Hz

Grazing angle	Coherent loss per bounce		Scenarios	
	Wind speed		No. of surface skips	Surface duct depth, sound speed gradient
	5 m/s	10 m/s		
1.5°	0.23 dB	1.8 dB	1	100 m, 0.005 s^{-1}
1.75°	0.16 dB	1.6 dB	3	70 m, 0.01 s^{-1}
2.1°	0.18 dB	1.9 dB	5	60 m, 0.017 s^{-1}[
2.7°	0.25 dB	2.9 dB	4	100 m, 0.017 s^{-1}
3.0°	0.25 dB	2.7 dB	4	100 m, 0.02 s^{-1}
3.1°	0.25 dB	2.5 dB	8	45 m, 0.05 s^{-1}
3.6°	0.28 dB	3.1 dB	7	60 m, 0.05 s^{-1}
4.7°	0.38 dB	4.6 dB	6	100 m, 0.05 s^{-1}
5.7°	0.52 dB	6 dB	5	150 m, 0.05 s^{-1}
11.5°	1.4 dB	large	10	150 m, 0.2 s^{-1}

VI. AT-SEA DATA

Transmission Loss (*TL*) data, for several upward-refracting shallow water environments in the Australian region, were obtained by DSTO in a series of trials carried out in 1993. One of these series (Track Q) was carried out for a wind-speed (4.6 m/s) which closely corresponded with the 5 m/s considered in this study. In these trials, data were obtained by a receiver located at 18.3 m depth from a surface buoy, while small explosive charges were deployed from a ship as it moved away. Each charge was set to detonate at 18.3 m depth. The source to receiver range extended to 20 km. More details of the data collection were made available by Jones et al. [19], [2]. The *TL* was determined within 1/3rd octave bands by summing the acoustic energy over the duration of the received transient signal, typically 0.15 to 0.5 seconds, and referring this to an assumed emitted energy. The measurement process was unable to distinguish between coherent and diffuse energy components received within the time-window of the analysis, so the measured *TL* values shown below do not necessarily relate to coherent transmission.

Sea surface and wind conditions were recorded on an hourly basis. The wind velocity was measured with the ship's anemometer, and the wave height and direction were estimated visually. The "swell height" data is an estimate of crest to trough distance for the swell component of the waves, but does not necessarily relate to other wave features. The recorded directions of wind and swell are the directions from which they originate.

A. Track Q Description

Water column and sea surface conditions for ocean track Q are listed in Table II. The periodic data are not included, however, the range of these observations, and the chronological order are shown. A ray diagram is shown in Fig 9 for 11 rays over ± 2½ degrees.

TABLE II
WATER COLUMN AND SEA SURFACE DATA FOR OCEAN TRACK Q

Ocean Track		Track Q
ocean depth (m)		64
depth of upward refracting layer (m)		64
average sound speed gradient in upward layer (m/s per m)		0.018
minimum no. surface skips to hydrophone		2
wind speed (m/s)		5 – 4
wind direction (°T)		40 -50
swell	Height (m)	0.5
	period (seconds)	6
	direction (°T)	120 - 110

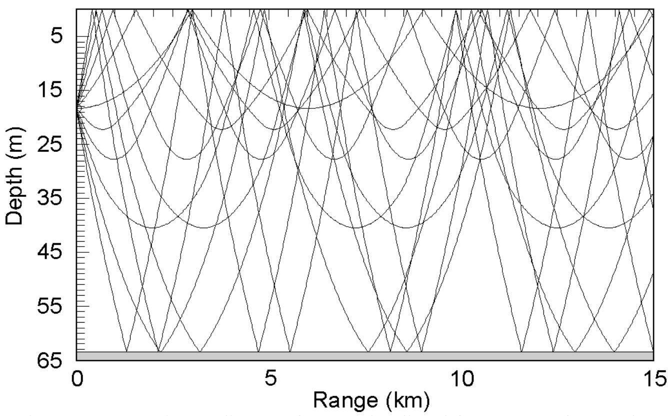

Figure 9. Acoustic ray diagram for sound radiated from source for Track Q, 11 rays over ± 2½ degrees

Seafloor data were collected at the site. The lithographic description was "shelly medium-sand" s and mean grain size ϕ of 0.8 at track start and 1.1 at track end, where $\phi = -\log_2 d \approx -1.44 \ln d$, where d is the diameter of the material grains in mm. Each of RAVE, BELLHOP and the Gaussian beam model at DSTO used different seafloor models but these were each of essentially the same type: complex Rayleigh, for which the seafloor was modelled as an absorbing fluid: compressional speed 1817 m/s; compressional attenuation 0.886 dB/λ; density 1845 kg/m^3. This results in a very small bottom loss equivalent to about 2 dB/radian, so that boundary losses will be dominated by surface losses.

B. Transmission Loss Data and Predictions

TL calculations all assume an omni-directional transmitter and an omni-directional receiver each located at 18.3 m depth. Comparisons were made between the measured *TL*, and *TL* predicted by models incorporating the different surface loss sub-models: (i) Gaussian beam model at DSTO using the RAYMODE Beckmann-Spizzichino surface loss model described by (7) and (8); (ii) RAVE model at Thales Australia using the Thales implementation of Beckmann-Spizzichino; (iii) BELLHOP model at CMST using the Gaussian roughness Kirchhoff model, (iv) Gaussian beam model at DSTO using Williams et al. [1] small slope surface loss model. The RAVE model was developed by Thales Pty. and some descriptions were provided by Jones et al [20].

Fig. 10 shows the *TL* measured at-sea at 3150 Hz, and predicted *TL*. Fig 11 shows data captured at the same time (from the same explosive detonations) at 1000 Hz, together with a corresponding set of *TL* predictions.

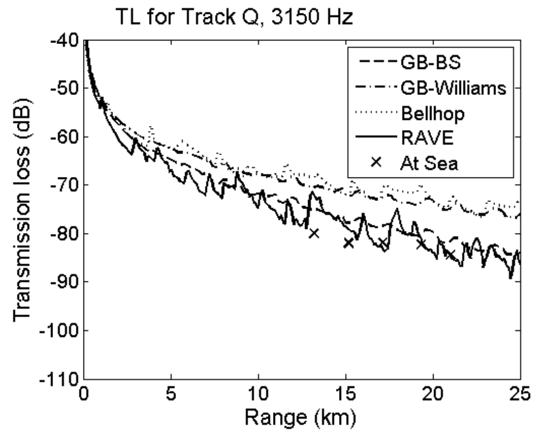

Figure 10. *TL* for Track Q, wind speed 4.6 m/s, 3150 Hz

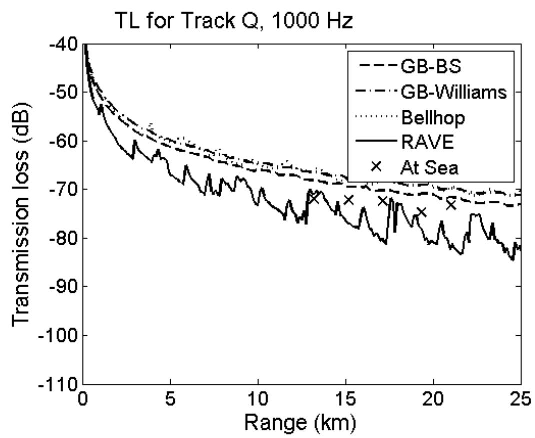

Figure 11. *TL* for Track Q, wind speed 4.6 m/s, 1000 Hz

C. Discussion

Taken at face value, the data in Fig. 10 imply that the Williams et al. small slope and Gaussian-roughness Kirchhoff models produce the poorest fit to the at-sea data and that the two Beckmann-Spizzichino models produce a closer result. This would be surprising, based on the results of the deterministic modelling in Section V, as the former models produced loss values closer to the numerical determinations than the latter models. Due to the difficulties in obtaining finely toleranced absolute measurements of *TL*, it is expected that the relativity of the measured *TL* at the two frequencies (Figs. 10 and 11) is more robust than the absolute data. Clearly, the only model to follow the correct relative trend is the RAYMODE Beckmann-Spizzichino, as predictions based on the Williams et al. small slope and Gaussian-roughness Kirchhoff models do not change sufficiently with frequency. Further data for 5000 Hz [3] confirm these conclusions.

VII. CONCLUSIONS

A study has been made of some of the issues relevant to the loss imposed on transmitted acoustic signals upon reflection from a rough sea surface at the specular angle, for small angles of grazing. A brief review, and comparison of numerical results, has been made of some of the available surface loss models, including the small slope model of Williams et al [1], several models of the Kirchhoff type, and Beckmann-Spizzichino type models. These models are quite varied in nature, with Beckmann-Spizzichino models trending to a finite loss at zero grazing angle, whereas the other models have forms that trend to zero loss. By studying the effects imposed by different surface loss functions on transmitted signal energy, it was shown that loss effects at medium to long range were greater for surface ducted scenarios than for shallow water isovelocity environments. In particular, the isovelocity scenario used by Williams et al. would not be expected to highlight transmission effects due to surface loss models.

Numerical simulations of the loss per surface bounce were generated successfully using the RAMSurf PE code combined with random replications of the sea surface that satisfied the Pierson-Moskowitz wave spectrum. Values of loss per bounce were generated for grazing angles ranging from 1.5° to 11.5° for wind speeds 5 m/s and 10 m/s at 3200 Hz. In the data generated, adherence to the form of the Williams et al. small slope model has been found to be good across this range of angles for the wind speeds and frequency studied. No effects that could be attributed shadowing of the sea surface were evident, even for small grazing angles for the higher wind speed for which the rms surface slope was 6.3°.

Transmission Loss (*TL*) measured in an upward refracting environment was compared with *TL* obtained using the various surface loss models, for a wind speed (4.6 m/s) and frequency (3150 Hz) similar to that used in the numerical studies. At-sea *TL* data collected simultaneously at 1000 Hz showed a significant reduction compared to that at 3150 Hz, implying additional surface loss at the higher frequency, yet the only surface loss model to cause predicted *TL* to do likewise was the RAYMODE Beckmann-Spizzichino. This is perplexing, given that that model was vastly different from the loss values per bounce from the numerical simulations. Further work which may clarify the situation includes comparison with additional at-sea data sets, and the study of the effects of bubbles in the water column.

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