Modelling the acoustic reflection loss at the rough ocean surface

Adrian D. Jones (1), Janice Sendt (2), Alec J. Duncan (3), Paul A. Clarke (1) and Amos Maggi (3)

(1) Defence Science and Technology Organisation, P.O. Box 1500, Edinburgh, SA 5111, Australia
(2) Thales Australia, 274 Victoria Road, Rydalmere, NSW 2116, Australia
(3) Centre for Marine Science & Technology, Curtin University of Technology, GPO Box U1987, Perth WA 6845, Australia

ABSTRACT

A description of the reflection of underwater sound incident upon a real ocean surface boundary is a necessary component of a sonar transmission model. 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 2 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. Complications include whether roughness alone causes the acoustic loss effects, or whether near-surface bubbles play a role. In addition, it may be necessary to consider whether the sound reflected in the specular direction consists entirely of a coherent component, or whether an incoherent component is assumed to exist. Due to these complexities in the relevant phenomena, and the non-uniformity of the surface state, the modelling of surface loss remains as an area yet to be mastered. In response to this unresolved situation, DSTO, Thales Australia and the Centre for Marine Science and Technology at Curtin University have compared the performance of surface loss models in their possession, both against each other and against at-sea data for a number of ocean scenarios, including several for which data have not been published previously. In addition, the output of these models has been compared with that obtained from a small-slope approximation model made available for this purpose by the Applied Physics Laboratory of the University of Washington, Seattle. Here, comparisons have been made of the various predictions of surface loss per bounce, as well as comparisons between predictions of transmission loss based on the use of these surface loss models, including comparisons with at-sea measurements of transmission loss. This paper discusses aspects of these surface loss models and the differences between them which have been revealed.

INRODUCTION

The reflection of underwater sound at the sea surface is a complex phenomenon for all but smooth ocean surfaces, but must be modelled, nonetheless, for predictions of transmission of sonar signals to be made for mid-frequencies (over about 2 kHz). Upon reflection at a roughened surface, at least some of the incident sound is scattered at angles other than specular, some is scattered at angles out of the vertical plane of the multipath arrivals, and a loss of acoustic energy is perceived to have occurred for the transmitted, specularly reflected, signal. In addition, the signal scattered at the specular angle may contain both coherent components and diffuse, or incoherent components. As is discussed, models used as part of sonar performance prediction purposes typically include the coherent specular component, only. The specular incoherent component, and the non-specular and out-of-plane energy, is then neglected in modelling. Also, most models of surface loss exclude detailed descriptions of the surface shape, with statistical representations being used.

This paper is concerned with a comparison of some of the surface loss models retained by each of DSTO, Thales Australia and the Centre for Marine Science and Technology (CMST) at Curtin University, together with a model made available by the Applied Physics Laboratory of the University of Washington, Seattle. The present work is an extension of that reported earlier (Jones et al 2008), in which the significance of surface loss issue was outlined, the origins of some components of some of the models were examined and predictions of *TL* (transmission loss) obtained by each of DSTO, Thales Australia and CMST, using the various surface loss models, were compared with each other and against at-sea measurements for three tracks in shallow ocean areas in the Australian region.

In the present paper, the surface loss models under investigation are introduced, and then compared in their ability to describe the loss upon a single reflection from the surface. Predictions of *TL*, based on the models of surface loss being incorporated with transmission models, are then compared with the at-sea data presented in the earlier study (Jones et al 2008) plus at-sea data for two additional ocean tracks.

SURFACE LOSS MODELS

The surface loss models considered include the RAYMODE Beckmann-Spizzichino model (Lauer1982, McGirr 1990), a different implementation of the Beckmann-Spizzichino model used by Thales Australia, a Kirchhoff model based on a Gaussian surface profile, a model devised by DSTO based on the work of Kuo (Kuo 1988) and a small-slope model from the Applied Physics Laboratory of the University of Washington, Seattle (Williams et al 2004). Some descriptions of these models are given below. The extent of these descriptions is appropriate to the ease by which the relevant information may be found in the literature.

Common Roughness Parameters

It is instructive to state the parameters in common use for describing a rough sea surface in relation to acoustic surface loss. These are shown in Figure 1.

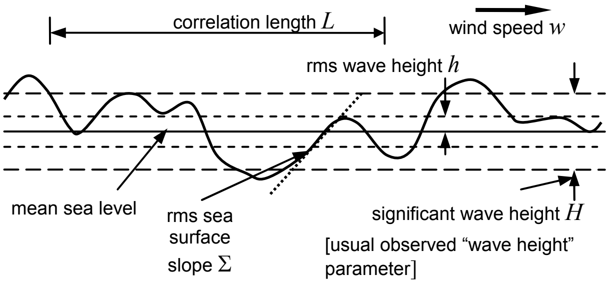

Figure 1. Common parameters for rough sea surface

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 parameter of length. It is common to assume a relationship between the statistical profile and the wind speed, and thus the sea surface shape may be represented solely by a wind speed value *w*. This approach does not usually include an ability to describe a surface for which the sea state is developing, or for which there is a directional feature, for example, an ocean swell of distant origin.

Beckmann-Spizzichino Model

Each of DSTO and Thales Australia has used implementations of the "Beckmann-Spizzichino" model of surface loss. This model has a long history of use and its scientific origins are in the 1960s (Jones et al 2008). In spite of its frequent use (e.g. Williams et al (2004) compared their models to the GRAB implementation of Beckmann-Spizzichino), descriptions of the Beckmann-Spizzichino model are scarce. The RAYMODE Beckmann-Spizzichino model is described in two NORDA documents (Lauer1982, McGirr 1990), with some of the links to the underlying theory being clarified by Jones et al (2008). The algorithms are outlined below.

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 (Lauer1982). The "high frequency loss" component is drawn from the theory of Beckmann-Spizzichino, and is given by

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

where v_3 is the maximum of $\left[\sin\theta - \dfrac{e^{-\left[a\,\theta^2/4\right]}}{(\pi a)^{1/2}}\dfrac{\sin\theta}{\theta}\right]$ and $(\sin\theta)/2$, and $a = \left[2\left(0.003+5.1\times10^{-3}\,w\right)\right]^{-1}$ where *w* is wind speed in m/s, θ is grazing angle, radians. McGirr (1990) states that *a* is the reciprocal of twice the mean-square slope (Σ^2 in Fig. 1) of the surface waves. The value v_3 is limited in magnitude to 0.99. The term SL_1 is relevant to losses under large roughness and is determined solely by grazing angle and mean-square slope, and not by frequency.

For grazing angles relevant to limiting rays in even the deepest isothermal surface duct (e.g. grazing angle is 3.7° in surface duct of depth 180 m), for even the highest wind speeds (e.g. 15 m/s), the value of $\left[\sin\theta - \dfrac{e^{-\left[a\,\theta^2/4\right]}}{(\pi a)^{1/2}}\dfrac{\sin\theta}{\theta}\right]$ will be negative, so that the value of v_3 returned will be $(\sin\theta)/2$. From Equation (1), for a surface duct of depth 180 m, SL_1 is just 0.14 dB per surface bounce. The surface loss from the term SL_1 is then small for medium-range ducted propagation, but will be relevant to scenarios for which sound is incident at the ocean surface at steeper angles.

From Deavenport's equation (3B-7) (Lauer 1982), the "low frequency loss" component, SL_2, is

$$SL_2 = -20\log_{10}\left(0.3+\frac{0.7}{1+1.07\times10^{-7}(f\,H)^2}\right) \text{ dB} \qquad (2)$$

where f is cyclic frequency, Hz; *H* is average wave height, metres. By substituting for wave height *H* in terms of wind speed using an expression attributed to Eugene Podeszwa, the surface loss term is shown as (Lauer 1982)

$$SL_2 = -20\log_{10}\left(0.3+\frac{0.7}{1+6.0\times10^{-11}\,w^4\,f^2}\right) \text{ dB} \qquad (3)$$

where *w* is wind speed m/s, *f* is frequency Hz.

As pointed out by Jones et al (2008), in the derivation of Equation (2) from the work of Marsh et al (1961), the dependence of the surface loss upon grazing angle was simplified by assuming the surface duct depth was always 60 m, for which the limiting ray has an angle at the surface of 2.13°. Thus Equation (3) is relevant to this angle only. Further, Jones et al (2008) postulated that the constants "0.3" and "0.7" originated as a means of limiting the value of SL_2 to the maximum value in the originating data, this being about 10.5 dB, noting that $-20\log_{10}(0.3)\approx 10.5$ dB.

For low surface loss scenarios, with $6.0\times10^{-11}w^4 f^2 \ll 1$ in Equation (3), and substituting $\log_{10}(1+x)\approx 0.434x$ for small *x*, the term SL_2 may be approximated as

$$SL_2 = 3.7\times10^{-10}\,w^4\,f^2 \text{ dB}. \qquad (4)$$

Kirchhoff Model

CMST implemented the following expression used to describe a randomly rough surface (e.g. Jensen et al 2000):

$$R_{coh} = -e^{-0.5\Gamma^2} \qquad (5)$$

where $\Gamma = 2kh\sin\theta$ (Rayleigh roughness parameter, e.g. Etter (2003) page 66); k is wavenumber; h is rms surface roughness, metres; θ is grazing angle, radians; R_{coh} is sound pressure reflection coefficient.

This arises from the Kirchhoff approximation to scattering and the assumption of a Gaussian probability of surface elevations of standard deviation *h*. The result does not depend on a spatial correlation with range (e.g. Brekhovskikh and Lysanov 2003). Lurton (2002) section A.3.3 describes this model, for which the loss results from phase cancellation of the phase separated components reflected from the entire insonified area. The Reflection Loss resulting from (5) is

$$RL = -20\log_{10}\left[e^{-0.5\Gamma^2}\right]. \qquad (6)$$

This is not the only "Kirchhoff" model that may be postulated, as a non-Gaussian surface profile will yield a different loss result. Further, this model assumes that the entire ocean surface is insonified with uniform intensity. Shadowing effects (e.g. Wagner 1967), in which parts of the surface have a slope greater than the angles of ray arrivals, are ignored.

For small grazing angles θ, from (6), the Reflection Loss per bounce is $RL \approx 160\pi^2 \left(f h \theta / c_w\right)^2 / \ln 10$ dB, where c_w is speed of sound in seawater. The Reflection Loss becomes

$$RL \approx 3.0\times10^{-4}\ h^2\ f^2\ \theta^2 \ \text{dB loss per surface bounce} \qquad (7)$$

with h in metres, f in Hz, θ in radians. This expression yields values close to (6) for loss values up to about 10 dB.

CMST assumed a relationship between rms wave height h and wind speed w that was in accord with a Pierson-Moskowitz wave spectrum (e.g. section 13.1 of Medwin and Clay (1998), and as shown in the section below), and so for loss values to about 10 dB, Reflection Loss is

$$RL \approx 8.6\times10^{-9}\ f^2\ w^4\ \theta^2 \ \text{dB loss per surface bounce} . \qquad (8)$$

Kuo Model

Kuo (1988) developed an analysis based on perturbation methods, and compared this against the analysis of Marsh et al (1961), as well as others. According to Kuo, Marsh et al made errors in their analysis and a corrected form of the acoustical intensity surface reflection coefficient, Ω, they derived is as follows (ref. equation (11) of Kuo (1988)):

$$\Omega = 1 - 3.5\times10^{-5}\ f^{3/2}\ H^{8/5}\sin\theta \qquad (9)$$

where H is in metres, f in Hz, θ in radians. The surface Reflection Loss is $RL = -10\log_{10}\Omega$ dB. By substituting rms wave height $h = H / \left(1.77\times\sqrt{2}\right)$, Kuo obtained a form of the Marsh et al expression (ref. equation (13) of Kuo (1988))

$$\Omega = 1 - 1.5\times10^{-4}\ f^{3/2}\ h^{8/5}\sin\theta . \qquad (10)$$

Kuo's analysis utilised the Neumann-Pierson wave spectrum, as did Marsh et al, so it is appropriate to use that wave spectrum to substitute for rms wave height h m in (10) in terms of wind speed w m/s. From the Neumann-Pierson spectrum, e.g. Kuo's equation (21), $h \approx 1.77\times10^{-3} w^{5/2}$ and equation (10) above becomes

$$\Omega = 1 - 5.9\times10^{-9}\ f^{3/2}\ w^4\sin\theta . \qquad (11)$$

Reflection Loss follows as $RL = -10\log_{10}\Omega$. Alternatively, using the substitution $\log_{10}(1+x) \approx 0.434x$ in (11), gives

$$RL \approx 2.6\times10^{-8} f^{3/2}\ w^4\ \theta \ \text{dB} . \qquad (12)$$

In the work that follows, the Reflection Loss obtained from (11) will be described as the "Kuo model", although, strictly, it is the Marsh et al model corrected by Kuo.

APL-UW Models

Williams et al (2004) 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 (2004) simulated TL 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. For a rough surface, the TL predicted using the GRAB-version Beckmann-Spizzichino model was higher than obtained with the other models (figure 7 of Williams et al (2004)).

Comparison of Models for Single Reflection

For the surface loss models which are the subject of this study, Reflection Loss for a single surface bounce was computed, as a function of grazing angle, for wind speed examples relevant to two of the scenarios described later: 4.6 m/s (Track Q), 14.4 m/s (Track O). The labelling in the figures shown below is in accord with models as follows

- R-BS RAYMODE Beckmann-Spizzichino surface loss from (1) and (3)
- RAVE Thales Australia implementation of Beckmann-Spizzichino surface loss model
- Kirchhoff Gaussian roughness Kirchhoff model (6)
- W SS Williams et al small slope surface loss model
- Kuo Kuo surface loss model from (11).

Figs. 2 and 3 show surface loss values for frequencies 3150 Hz and 5000 Hz for the lesser wind speed, and Figs. 4 and 5 show surface loss values for 1000 Hz and 5000 Hz for the greater wind speed. For the models described earlier, the wind speed and frequency dependence evident in Figs. 2 to 5 may be understood more readily by inspection of the expressions for RL derived for low loss cases.

From (4), the RAYMODE Beckmann-Spizzichino model has no grazing angle dependence. The small variation with grazing angle is due to the SL_1 term in (1). From (8), the Gaussian roughness Kirchhoff model gives a dependence on the square of grazing angle, and considering (4), has the same dependence on wind speed and frequency as the RAYMODE Beckmann-Spizzichino model. From (12) the Kuo model gives a linear dependence on grazing angle for small angles. From the figures it appears that, for low wind speed and small grazing angles, the Kuo model produces about half the loss provided by the Williams et al (2004) small slope method. Also, 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 Beckmann-Spizzichino model data in Figs. 2 to 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.

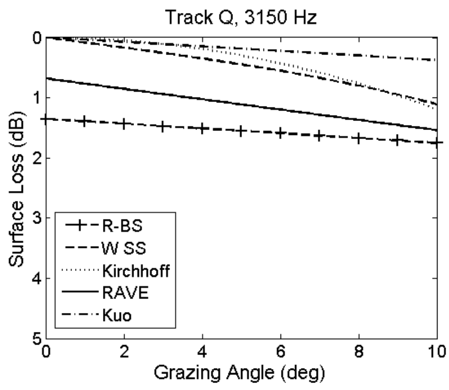

Figure 2. Surface Loss for wind speed 4.6 m/s, 3150 Hz

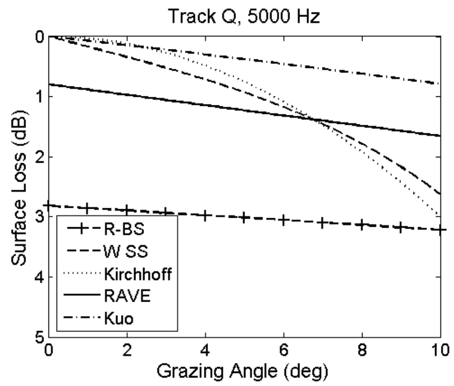

Figure 3. Surface Loss for wind speed 4.6 m/s, 5000 Hz

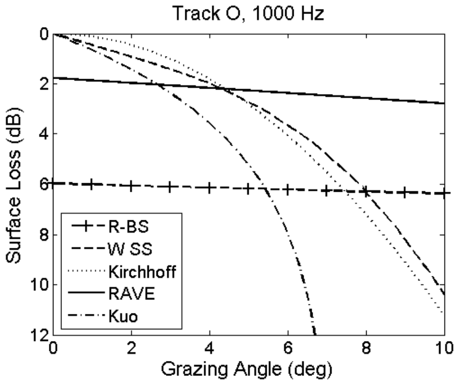

Figure 4. Surface Loss for wind speed 14.4 m/s, 1000 Hz

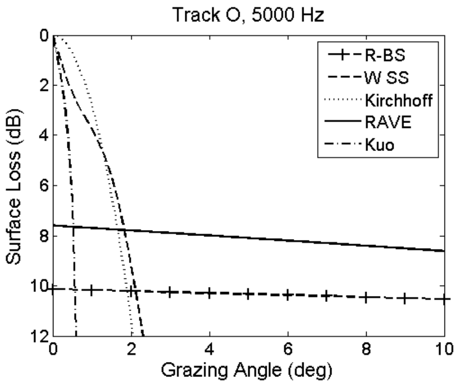

Figure 5. Surface Loss for wind speed 14.4 m/s, 5000 Hz

It may be noted that for surface ducts of thicknesses considered in this study (up to 65 m), the grazing angle of limiting rays is less than about 2.2°, and so all ducted transmission is confined to rays with shallower angles than this.

AT-SEA SCENARIOS

At-sea acoustic data were recorded by DSTO along five tracks in shallow ocean areas in the Australian region. For each track, 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. Typically, source to receiver ranges extended to 20 kilometres. The data collection is described in more detail by Jones et al (2006), and the particulars of the collection along tracks Q, T and V by Jones et al (2008). The *TL* was determined by coherently summing the acoustic energy over the duration of the received transient signal, typically 0.15 to 0.5 seconds, and referring this to that emitted, based on a model of the source. The *TL* values were thus determined after including both the coherent and any diffuse energy components received within the time-window of the analysis.

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. Water column and sea surface conditions for ocean tracks Q, T and V, were shown by Jones et al (2008). Corresponding data for tracks O and R are listed in Table 1. The periodic data are not included, however, the range of these observations, and the chronological order are shown. As already stated, the models of surface loss considered in this study each use a single input parameter, wind speed, to describe the sea surface, apart from frequency. This single parameter approach takes no advantage of some of the descriptors which are available, e.g. wind direction, swell direction and period. Sound speed profiles are shown in Figure 6.

Table 1. Water column and sea surface data for ocean tracks

Ocean Track		O	R
ocean depth (m)		145	65
depth of upward refracting layer (m)		61	65
average sound speed gradient in upward layer (m/s per m)		0.018	0.017
minimum no. surface skips to hydrophone		1	2
wind speed (m/s)		12.9–15.9	2.6 – 1.5
wind direction (°T)		120 - 110	130 - 100
swell	height (m)	1	0.25
	period (seconds)	5 - 4	6
	direction (°T)	120	120 - 110

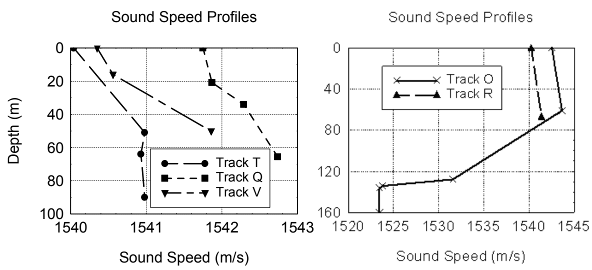

Figure 6. Sound speed profiles for all tracks

Ray plots corresponding with tracks O and R are shown in Figs. 7 and 8 (ray plots for other tracks were shown by Jones et al (2008)). It is reasonable to expect that the *TL* at long range is dominated by sound that travels by upward refraction and repeated surface skips. The minimum number of surface skips for sound travelling to the closest receiver used in this study, for each track, is shown in Table 1.

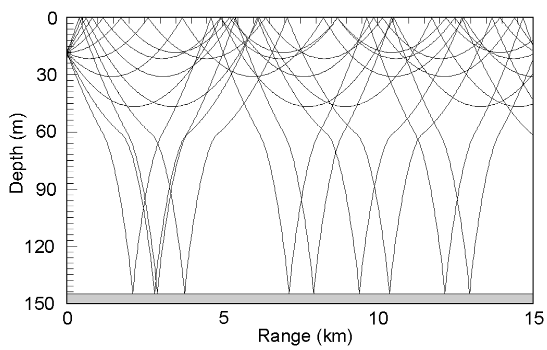

Figure 7. Acoustic ray diagram for sound radiated from source for Track O, 11 rays over ± 2½ degrees

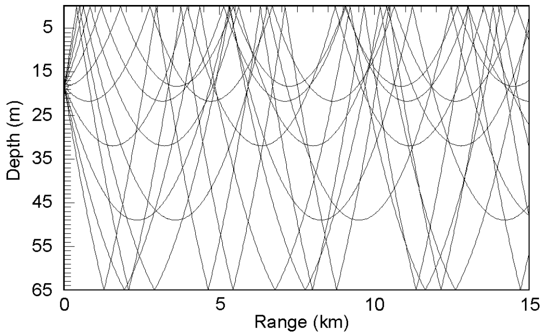

Figure 8. Acoustic ray diagram for sound radiated from source for Track R, 11 rays over ± 2½ degrees

Seafloor Descriptions

Seafloor data were collected at the sites, or was otherwise known from earlier measurements. The lithographic descriptions and mean grain size determinations are shown in Tables 2 and 3, where $\phi = -\log_2 d \approx -1.44 \ln d$, where d is the diameter of the material grains in mm.

Table 2. Seafloor Data for Shallow Water Tracks Q, T, V

Ocean Track	Q	T	V
lithology	shelly medium-sand	sand with gravel	sand with gravel
mean grain size (ϕ)	0.8 (start) 1.1 (end)	-1.1 (start) -0.3 (end)	1.1

Table 3. Seafloor Data for Shallow Water Tracks O, R

Ocean Track	O	R
lithology	Sandy silt with gravel	shelly medium-sand
mean grain size (ϕ)	4.6 (start) 4.1 (end)	-1.0 (start) 1.4 (end)

TRANSMISSION LOSS PREDICTIONS

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 (1) and (3); (ii) RAVE model at Thales Australia using a different 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 (2004) small slope surface loss model. The RAVE model was developed by Thales Pty. and some descriptions were provided by Jones et al (2007).

For each surface loss model, the characteristics of the sea surface were described by a value of observed wind speed, solely. These observed wind speed values did not necessarily correspond with the contemporaneous observations of sea state and swell height. This issue was considered by Jones et al (2008) and model runs were made with alternate inputs. For predictions of *TL* shown in this paper, wind speed values, alone, were used, with the values as shown in Table 4.

Table 4. Wind speed inputs used for model runs

Ocean Track	O	Q	R	T	V
wind speed w (m/s)	14.4	4.6	2.06	15.4	13.9

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. The bottom loss was then effectively independent of frequency. Seafloor data values were selected independently by each of DSTO, Thales and CMST, according to the descriptions in Tables 2 and 3. Derived data are shown in Tables 5, 6 and 7. Bottom loss values generated by the model used by DSTO, and used by the DSTO-retained Gaussian beam model, are shown in Fig. 9. For all tracks but O, these are indicative of low losses for the shallow angle arrivals which are responsible for most of the signal received at all but short ranges. *TL* calculations all assume an omni-directional transmitter and an omni-directional receiver each located at 18.3 m depth.

Table 5. Seafloor inputs for Gaussian Beam model at DSTO

Ocean Track	O	Q	R	T	V
Compressional speed c_s (m/s)	1551	1817	1927	2060	1887
Compressional attenuation α_λ (dB/λ)	1.178	0.886	0.894	0.93	0.898
density (kg/m^3)	1195	1845	2231	2492	2151

Table 6. Seafloor inputs for RAVE model

Ocean Track	O	Q	R	T	V
Compressional speed c_s (m/s)	1518	1817	1826	2060	1887
Compressional attenuation α_λ (dB/λ)	0.116	0.88	0.87	0.93	0.90
density (kg/m^3)	1387	1845	2059	2492	2151

Table 7. Seafloor inputs for BELLHOP model

Ocean Track	O	Q	R	T	V
Compressional speed c_s (m/s)	1575	1817.6	1650	2060.3	1887
Compressional attenuation α_λ (dB/λ)	1.0	0.88	0.80	0.93	0.90
density (kg/m^3)	1700	1845	1900	2492	2151

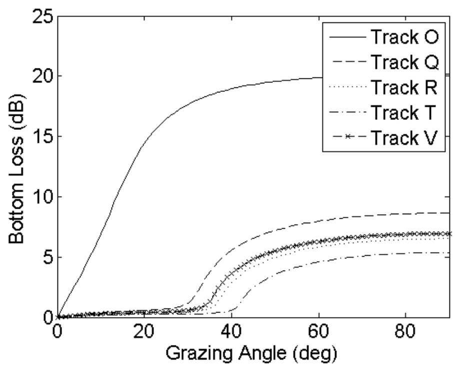

Figure 9. Bottom loss used by Gaussian beam model at DSTO (frequency independent)

TL predictions were also carried out with wind speed set to zero, so that underlying differences between the *TL* models might be revealed. In this paper, such a simulation is shown in Fig. 14 for Track Q for 3150 Hz. In order to account for the fact that the RAYMODE Beckmann-Spizzichino term SL_1 returns a non-zero loss for a wind speed of zero, the Gaussian beam model retained by DSTO was also run with the surface loss fixed at zero (labelled "mirror" in Figure 14), so that the difference between *TL* obtained with the surface modelled as completely smooth, and that obtained with the SL_1 term included, would be seen. These zero-surface roughness calculations may also be compared with those for which the sea surface was modelled as rough, so as to illustrate the impact of the roughened sea surface, as modelled, on the overall *TL*.

Track O

For Track O, Figures 10, 11 and 12 show *TL* versus range predicted by all models, for 1 kHz, 3.15 kHz and 5 kHz. At-sea *TL* data are also shown. Labelling is as follows:

- GB-BS Gaussian beam model at DSTO with RAYMODE Beckmann-Spizzichino surface loss from (1), (3)
- RAVE RAVE model with Thales Australia implementation of Beckmann-Spizzichino surface loss
- Bellhop BELLHOP model at CMST using Gaussian roughness Kirchhoff model
- GB-Williams Gaussian beam model at DSTO with Williams et al (2004) small slope surface loss model.

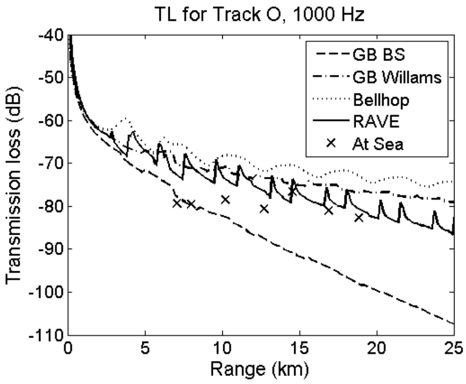

Figure 10. *TL* for Track O, wind speed 14.4 m/s, 1000 Hz

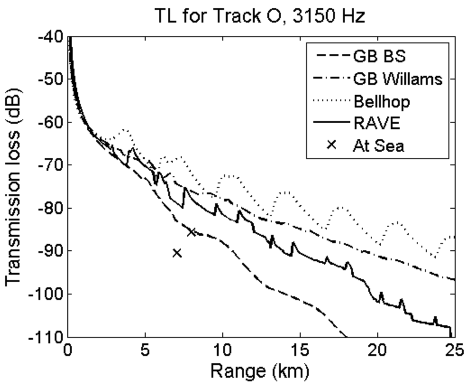

Figure 11. *TL* for Track O, wind speed 14.4 m/s, 3150 Hz

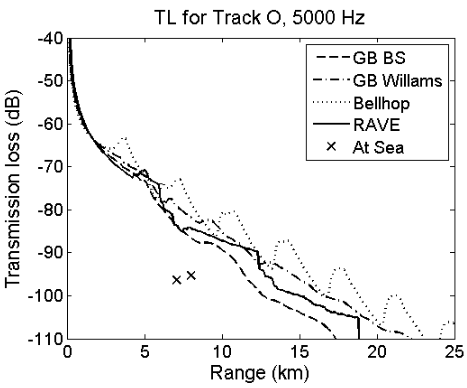

Figure 12. *TL* for Track O, wind speed 14.4 m/s, 5000 Hz

Track Q

For Track Q, Figures 13, 15 and 16 show *TL* versus range, for 1 kHz, 3.15 kHz and 5 kHz. Figure 14 shows the values of *TL* versus range predicted for 3.15 kHz with the wind speed input parameter set to zero in each of the three *TL* models, and with the surface loss fixed at zero in case of the data for the Gaussian beam model labelled "GB mirror". As the Beckmann-Spizzichino model in RAVE includes a slight surface loss with zero wind speed, similarly as for the RAYMODE version, the data for RAVE in Figure 14 should be compared with that for the DSTO-retained Gaussian beam model for the zero-wind input, "GB 0 wind" in the figure.

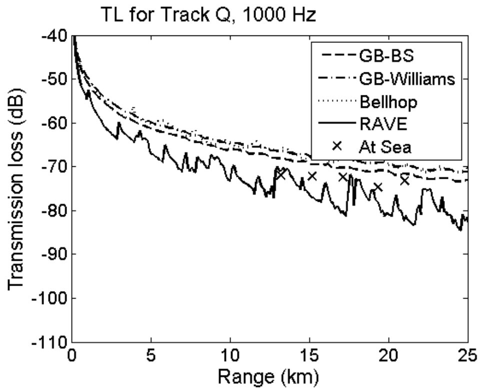

Figure 13. *TL* for Track Q, wind speed 4.6 m/s, 1000 Hz

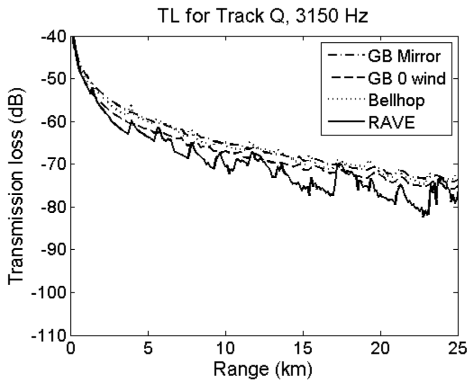

Figure 14. *TL* for Track Q, zero wind speed, 3150 Hz

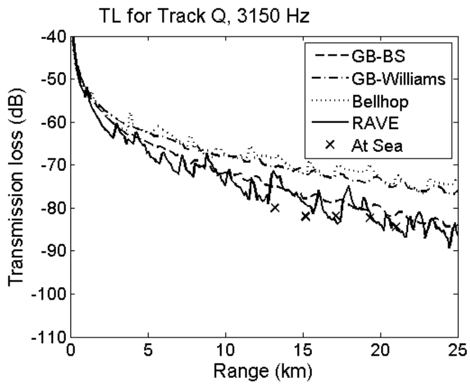

Figure 15. *TL* for Track Q, wind speed 4.6 m/s, 3150 Hz

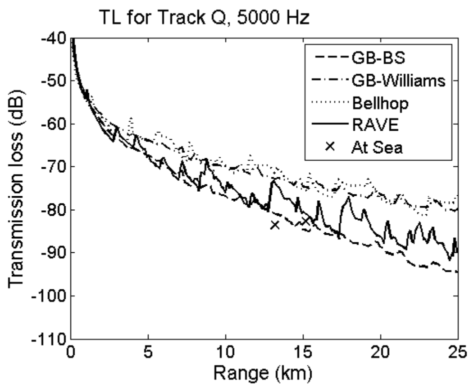

Figure 16. *TL* for Track Q, wind speed 4.6 m/s, 5000 Hz

Track R

For Track R, Figures 17 and 18 show the values of *TL* versus range, for 3.15 kHz and 5 kHz.

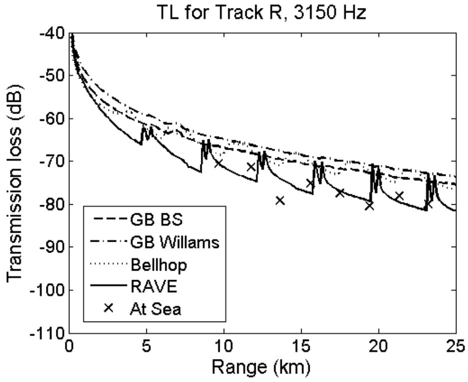

Figure 17. *TL* for Track R, wind speed 2.06 m/s, 3150 Hz

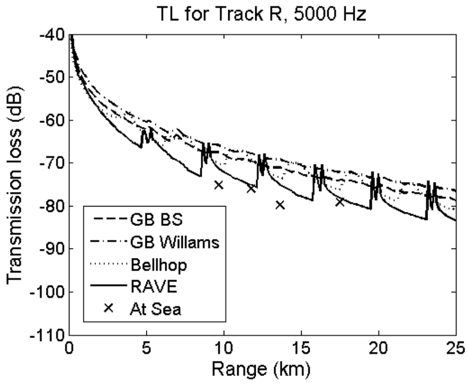

Figure 18. *TL* for Track R, wind speed 2.06 m/s, 5000 Hz

Track T

For Track T, Figures 19, 20 and 21 show *TL* versus range, for 1 kHz, 3.15 kHz and 5 kHz.

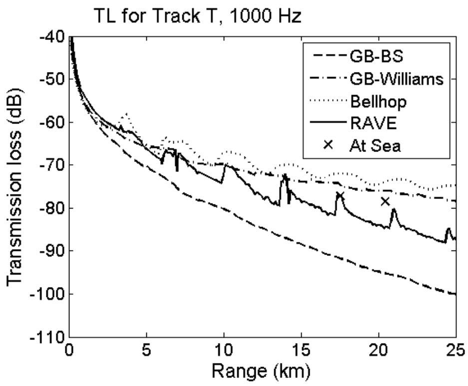

Figure 19. *TL* for Track T, wind speed 15.4 m/s, 1000 Hz

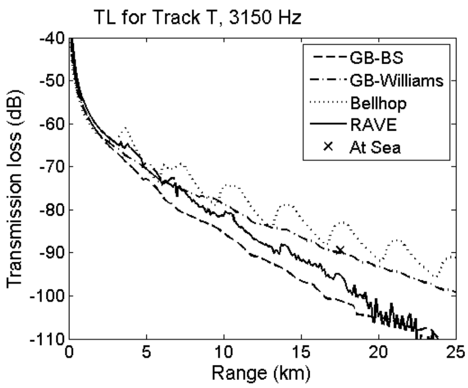

Figure 20. *TL* for Track T, wind speed 15.4 m/s, 3150 Hz

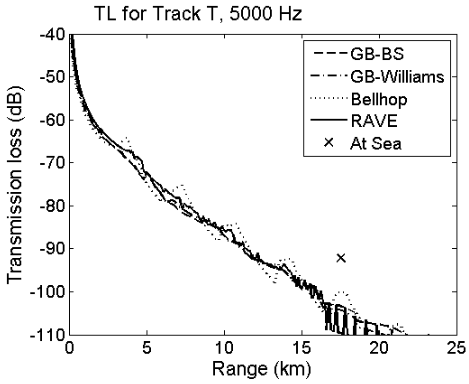

Figure 21. *TL* for Track T, wind speed 15.4 m/s, 5000 Hz

Track V

For Track V, Figures 22, 23 and 24 show *TL* versus range, for 1 kHz, 3.15 kHz and 5 kHz.

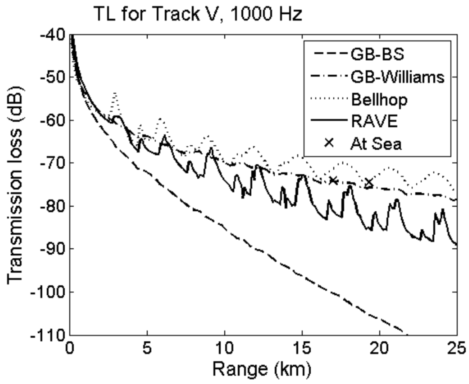

Figure 22. *TL* for Track V, wind speed 13.9 m/s, 1000 Hz

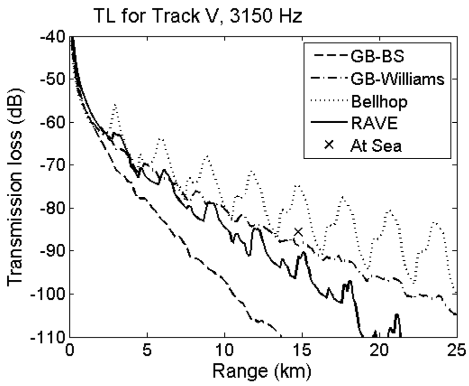

Figure 23. *TL* for Track V, wind speed 13.9 m/s, 3150 Hz

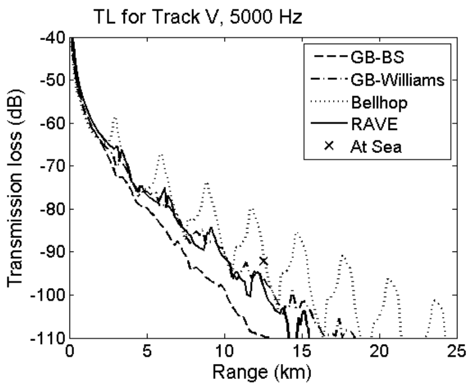

Figure 24. *TL* for Track V, wind speed 13.9 m/s, 5000 Hz

DISCUSSION

The at-sea data shown in Figures 10 to 13 and 15 to 24 are limited in extent in that data are not available at all range values at all frequencies, and no scenarios are included for a medium-strength wind speed. Also, the *TL* predictions are limited in potential accuracy due to practical limitations in the available knowledge of the ocean environments. Regardless, some statements of the effectiveness of the various models of surface loss are possible.

For the lowest wind speed scenario, Track R, for which surface loss values are least, the RAVE model returns a slightly higher value of *TL* than other models, but it is also closest to the measured data. For the next highest wind speed, 4.6 m/s (Track Q), RAVE is also close to the at-sea data, but so also is the DSTO-retained Gaussian beam model with the RAYMODE Beckmann-Spizzichino surface loss. The same Gaussian beam model with the Williams small slope surface loss, and BELLHOP with the Gaussian roughness Kirchhoff model both under-estimate the at-sea *TL* for Track Q, noticeably. From the zero-wind speed simulation in Figure 14, it may be seen that RAVE slightly over-predicted the *TL* in comparison with the corresponding zero-wind speed simulation with the Gaussian beam model, so that the apparent agreement by RAVE in Figs. 13, 15 and 16 may not necessarily be due to its surface loss model. Also apparent from the latter figures is that the *TL* from the Gaussian beam model with the RAYMODE Beckmann-Spizzichino surface loss increases considerably more with frequency that in the case of any other model – indicative of the much greater surface loss shown for this model in Figs. 2 to 5. The fact that the best agreement for Track Q is obtained when the two Beckmann-Spizzichino models are used does suggest that the surface loss values from the Williams small slope and Gaussian-roughness Kirchhoff models, for low loss cases (see Figs. 2 and 3), may be too low in value, or perhaps a finite loss needs to be included for the smallest grazing angles.

For the higher wind speed scenarios, and higher frequencies, there are few at-sea data points available for comparison, but these few values do show an increase in *TL* with wind speed and frequency. As expected from the data in Figs. 2 to 5, the RAYMODE Beckmann-Spizzichino model generates the highest surface loss for grazing angles relevant to ducted rays (angles 2.2° and less for duct thicknesses considered), and so gave rise to the highest predictions of *TL*. This is particularly so for Track O for 1000 Hz and 3150 Hz, Track T for 1000 Hz, and Track V for 1000 Hz and 3150 Hz. For cases of extreme roughness (5000 Hz for Tracks O, T and V), *TL* values from all models are tending to be similar. This may be understood with reference to Figure 5, as all the surface loss models used in *TL* estimations (the Kuo model is not used with a *TL* model in this study) have, very approximately, similar values of loss (7 dB to 11 dB) per reflection for grazing angles between about 1.5° and 2.2°, this span corresponding with most ducted rays. The agreement of the models with the at-sea data for these extreme cases is not particularly close, with both under-estimation of *TL* (Fig. 12) and over-estimation (Fig. 21).

CONCLUSIONS

This study has reviewed the origins of some models of surface loss, and has compared the loss obtained from them for a single surface reflection. The models are shown to be quite varied in origin and nature. The RAYMODE Beckmann-Spizzichino surface loss model, and an alternate version used by Thales, both give a finite loss value for zero grazing angle with the former returning the highest loss values for all models considered. The comparisons of *TL* obtained using these models show that the RAYMODE Beckmann-Spizzichino model gives rise to the greatest *TL* values, with the exception of high wind speed (about 15 m/s) and frequency (about 5000 Hz).

Considering the comparisons with the at-sea *TL* data presented, no single surface loss model can be considered the "winner", with the Thales Beckmann-Spizzichino and the William et al small-slope surface loss models providing the best overall match of *TL* values. Based on this study, additional at-sea data, particularly for wind speed values in the range 6 to 11 m/s, is needed for a more meaningful test of the models. Also, consideration needs to be given to the models themselves, and the underlying assumptions, which are various. The authors speculate that the loss values for very small angles may not tend to zero, and a study of shadowing phenomena, accounting for diffraction, may reap benefits.

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