Acoustics 2008
Geelong, Victoria, Australia 24 to 26 November 2008

Acoustics and Sustainability:

How should acoustics adapt to meet future demands?

Modelling acoustic reflection loss at the ocean surface – an Australian study

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ABSTRACT

The reflection of underwater sound from the ocean surface boundary is one of the critical phenomena which must be described within models of sonar transmission and reverberation at mid-frequencies (up to about 5 kHz), yet it has not been studied within Australian organisations for a considerable time. Some of the algorithms which are frequently referenced are based on simplistic theoretical assumptions of roughness, whereas others are based on studies which are quite old. In order to address the issue in the Australian context, and with reference to modern sonar models, commonly referenced models of surface reflection loss are compared with each other and with at-sea time series sonar data obtained by DSTO within the Australian region.

INTRODUCTION

The phenomenon of reflection of underwater sound at the sea surface is simple for low acoustic frequencies, and for a flat sea surface. Under these circumstances, incident sound is reflected underwater at the specular angle, with a negligible loss due to transmission into the air, and with a phase change of π radians due to the near-perfect pressure release at the surface. The situation for mid-frequency sound (about 1 kHz to 10 kHz) and for realistic oceans with roughened surfaces is, however, much more complex. Here, at least some of the incident sound is scattered at angles other than specular, 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.

For mid-frequencies, acoustic wavelengths are of the order of the length scales of ocean surface features, the waves are in motion, and, at higher wind speeds, whitecaps occur which add bubbles to the sea surface and the region beneath. In addition, the surface waves have a complex structure, with a "swell" originating from a large distance adding to the local wind-induced wave effects. Ocean swell usually has a coherent form, and a noticeable direction, this not necessarily being the same as the local wind direction. A sonar transmission model intended for mid-frequency application must be able to describe the acoustic effects of these phenomena in a practical manner. For ease of computation, it has become commonplace for the effect of the sea surface on underwater sound to be described by a loss value, in dB, accounting for the component of an acoustic signal which is lost to scattering to non-specular angles. This paper is concerned with a review of the surface loss models in use in several Australian organisations, including the origins of these models, and includes comparisons between these models and with at-sea measurements of transmitted sound for circumstances for which the sea surface loss effects were significant.

SIGNIFICANCE OF SURFACE LOSS

The roughness of the sea surface is relevant to sound travelling underwater for those circumstances for which the transmitted signal is incident on the sea surface. Practical ocean scenarios, for which acoustic interaction with the sea surface is significant include (i) shallow oceans, (ii) mixed surface layer ducts in either deep or shallow oceans, as shown in Figures 1 and 2 respectively.

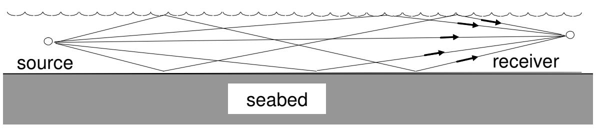

Figure 1. Sea surface interaction in shallow ocean

The shallow ocean scenario in Figure 1 shows a ray diagram for the isovelocity case, but this would also be representative of oceans with various levels of refraction. For such an ocean, the sound undergoes reflection at both the surface and seafloor. In general, the nature of the seafloor will not be well known and at mid-frequencies it may be expected that effects of seafloor roughness may be as significant as surface roughness. For example, Jones et al (2006) studied transmission of signals from small underwater explosives and found that the reduction in peak level due to seafloor interaction appeared to be greater than that from surface interaction.

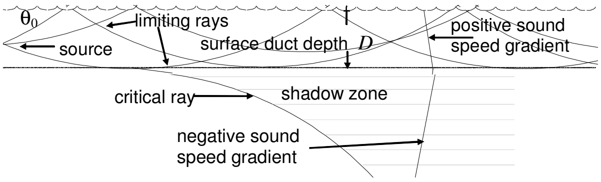

Figure 2. Sea surface interaction in mixed layer surface duct

The surface duct scenario of Figure 2, which is typical of winter conditions, or conditions following a period of moderate or high wind speed, involves a surface reflection on each sound "skip". The number of skips per unit range is dependent on the sound speed gradient, the depth of the mixed surface layer *D*, the source depth and launch angle of the radiated sound. The relevant theory is well known (eg. Urick 1983) and it follows that, for practical surface duct scenarios, the angle of incidence at the surface is less than about 3 degrees. For the shallow ocean scenario of Figure 1, however, or for deep ocean scenarios with a deep sound source or receiver, relevant angles of incidence at the ocean surface will be greater as bottom-reflected sound may be significant.

SURFACE LOSS MODELS

There appears to be no readily accepted surface loss model in use. This is probably the case as the problem is one for which there is no single, definable, set of input parameters. This situation is little changed from when reviewed by Eller (1985) in which it was stated that in some cases surface loss modelling was a "weak link" in a modelling package. Due to the large extent of information on the subject, and the absence of a consensus on a satisfactory solution, the approach taken in the present study has been a pragmatic one in which models in use within Australia have been compared with each other, against at-sea data, and against a well-known model for reflection from a generalised rough surface. This work then forms a preliminary study in the intended progress towards the examination of more recent analyses (eg. Williams et al (2004)) and the adoption of an improved model of surface loss. Any new model, of course, must not have excessive numerical complexity, as is likely to be the case with some more recent models.

Both DSTO and Thales Australia have versions of the Beckmann-Spizzichino surface loss model, and have experience in using this type of model within sonar performance models. These models are compared below, together with a different model used by Curtin University.

Gaussian roughness model

Curtin University implemented the following expression used to describe a randomly rough surface (Jensen et al 2000):

$$R_{coh} = -e^{-0.5\Gamma^2} \tag{1}$$

where $\Gamma = 2kh\sin\theta$ (Rayleigh roughness parameter, eg. Etter (2003), page 66), k is wavenumber, h is rms surface roughness, and θ is grazing angle, radians.

This arises from the Kirchhoff approximation to scattering and assumes a Gaussian probability of surface elevations of standard deviation *h*, but under these assumptions the result does not depend on the surface spatial correlation function (eg. Brekhovskikh and Lysanov 2003). As the Kirchhoff approximation is assumed, with the effect that acoustic wavelength « radius of curvature of wave features, this is a high frequency model. Lurton (2002) section A.3.3 presents a simplified description of this model, in which the amplitude reduction results from the phase cancellation of the phase separated components reflected from the entire insonified surface area. The Rayleigh parameter Γ may be shown (Lurton 2002) to describe the standard deviation of the phase variation amongst reflected components. The model is valid for phase fluctuations $\Gamma < \pi/2$, at which $R_{coh} = -e^{-\pi^2/8} \approx 0.3$, $h = \lambda/(8\sin\theta)$, and the reflection loss per surface bounce $RL \approx 10.7$ dB. For example, for a limiting ray in a surface duct of thickness 60 m, for which the grazing angle at the surface may be shown to be 2.1°, this implies that this model is appropriate only if rms surface roughness $h < 3.41\lambda$, where λ is wavelength of the acoustic signal. For 1 kHz, the validity limit on *h* is then 16.7 ft, whereas for 3.15 kHz and 5 kHz it is 5.2 ft and 3.3 ft, respectively.

In this paper this is named the "Gaussian roughness model". It is worth noting that this model is the same as the "Kirchhoff" model discussed by Williams et al (2004) equation (14), and is the same as the term for the coherent reflection shown by Medwin (1968) in his equation (8). Williams et al (2004) also show that this expression is derived as one term of the more complete "small slope" analysis.

For small grazing angles, from Equation (1), the reflection loss per bounce becomes $RL \approx 160\pi^2 \left(f\,h\theta/c_w\right)^2 / \ln 10$ dB, where f is cyclic frequency, Hz, and c_w is speed of sound in seawater. In terms of the units used in the remainder of this paper:

$$RL \approx 2.83\times10^{-5}\ h^2\ f^2\ \theta^2 \ \text{ dB loss per surface bounce} \tag{2}$$

where *h* is rms wave height in ft. It is satisfying to see that, for the aforementioned limiting cases (eg. frequency 5 kHz, grazing angle 2.1°, maximum rms roughness 3.3 ft), the approximate Equation (2) returns 10.3 dB – very near to the 10.7 dB from the original Equation (1). For this study, Curtin University used a well known relationship to estimate a value of rms roughness *h* from measured wind speed. This expression (Equation (15) below) is considered later, but it is instructive to now obtain a form of Equation (2) in terms of wind speed by making the substitution from Equation (15):

$$RL \approx 6.0\times10^{-10}\ \nu_k^{\,4}\ f^2\ \theta^2 \ \text{ dB} \tag{3}$$

where ν_k is wind speed in knots.

As with most models of surface loss, Equation (1) describes the specularly reflected component, with the remaining components being assumed to be scattered at both non-specular and specular angles and, in the former case, absorbed by the seafloor before reaching ranges of interest. It is most likely, however, that some components scattered at non-specular angles will also be transmitted at shallow angles and will also reach the receiver. Equation (3), in its realm of validity, will thus tend to be an over-prediction of loss per bounce in dB.

Beckmann-Spizzichino model

Each of DSTO and Thales Australia use a different implementation of what is known as the "Beckmann-Spizzichino" model. As pointed out by Eller (1985), this name is, strictly, not appropriate as the model contains two components, one being derived from a combination of at-sea data with the model of Marsh, Schulkin and Kneale (1961), and the other being drawn from the theory of Beckmann and Spizzichino (1963) [although the actual link to the latter is by no means clear from inspection of the models]. Published information about the algorithms in the various "Beckmann-Spizzichino" implementations is scarce, however, details of the implementation in the RAYMODE model are available. Some descriptions of the RAYMODE are given by Etter (2003), however, much more complete information about the RAYMODE propagation loss model, and the RAYMODE "Beckmann-Spizzichino" surface loss model in particular, is available in several NORDA documents (Lauer1982, McGirr 1990).

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

$$SL_1 = -20\log_{10}\left[(1-v_3)\right]^{1/2} \text{ dB} \tag{4}$$

where v_3 = maximum of $\left[\sin\theta - \frac{e^{-\left[a\theta^2/4\right]}}{(\pi a)^{1/2}}\frac{\sin\theta}{\theta}\right]$ and $\frac{\sin\theta}{2}$

and $a = \left[2\left(0.003 + 2.6\times10^{-3}\,\nu_k\right)\right]^{-1}$ where ν_k is wind speed in knots, θ is grazing angle, radians. McGirr (1990) states that a is related to the mean-square slope $(1/2)\tan^2\beta_0$ of waves by the relation $1/(2a) = \tan^2\beta_0$. 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. (Note: units of ft. and knots are used in this paper, so that the links to the origins of the Beckmann-Spizzichino model might be better understood.)

From Deavenport (Lauer1982), the "low frequency loss" component, SL_2, is based on the surface duct scattering work of Marsh and Schulkin (1962), and thus on the analysis of Marsh et al (1961) considered separately below. This term is dependent on frequency and wave height (and hence upon wind speed), but is independent of grazing angle. From Deavenport's equation (3B-7), this loss term is

$$SL_2 = -20\log_{10}\left(0.3 + \frac{0.7}{1+\left(f\,H/10^4\right)^2}\right) \text{ dB} \tag{5}$$

where *H* is average wave height in feet. By substituting for wave height *H* in terms of wind speed, using an expression attributed to Eugene Podeszwa ($H = 2.04\times10^{-2}(\nu_k)^2$), the surface loss term becomes (Lauer1982)

$$SL_2 = -20\log_{10}\left(0.3 + \frac{0.7}{1+4.2\times10^{-12}\,\nu_k{}^4\,f^2}\right) \text{ dB} \tag{6}$$

From examination of pages 46-49 including Figure 8 of the Marsh and Schulkin report (1962) it is clear that Equation (5) is an adaptation of equation (3.8) of Marsh et al (1961) to fit a limited number of at-sea measurements. The inclusion of constants "0.3" and "0.7" can be explained as a means of limiting the value of SL_2 to the maximum value in that data, this being about 10.5 dB, noting that - $20\log_{10}(0.3) \approx 10.5$ dB.

In making the adaptation from the original Marsh et al paper (1961), the grazing angle dependence included in equation (3.8) of Marsh et al was neglected and instead the data in Figure 3 of March et al was used, this being relevant to an isothermal surface duct of 200 ft (61 m) depth, for which the limiting ray has an angle at the surface of 2.13°. Thus Equations (5) and (6) above are, strictly, relevant to this angle only. It is worth noting here that the Marsh et al surface loss expression (1961) is appropriate to combinations of the product $f\,H$ no greater than about $8\,\text{kHz}\cdot\text{ft}$, however, the adaptation leading to Equations (5) and (6) assumes relevance to $f\,H \approx 100$ kHz ft.

By making approximations based on $4.2\times10^{-12}\nu_k{}^4 f^2 \ll 1$, and making the substitution $\log_{10}(1+x) \approx 0.434x$, for small x, the term SL_2 may be approximated as

$$SL_2 = 26\times10^{-12}\nu_k{}^4 f^2 \text{ dB} \tag{7}$$

This form of SL_2, which returns values similar to Equation (6) up to a few dB, is similar in form to Equation (3), apart from the θ^2 term. For grazing angle $\theta = 2.13°$, it is clear that SL_2 is greater than *RL* from Equation (3) by a factor of 31. For $\theta = 1.5°$, which corresponds with the limiting ray in an isothermal surface duct of depth 30 m, the relative difference in prediction of surface loss per bounce is about a factor of 63. As SL_2 is hard-limited to 10.5 dB, the loss from the Gaussian roughness model will "catch up" at large wind speed – frequency combinations.

According to Fortuin (1970), the Marsh method is a generalisation, to a random surface, of the Rayleigh method for scattering from a sinusoidal boundary. The Marsh method then applies to a surface for which the acoustic wavelength and roughness scales are of the same order and for which diffraction is relevant. Kuo (1988) describes the method of Marsh et al as a perturbation method. Due to the dependence of the "Beckmann-Spizzichino" model on the work of Marsh et al, it is worth considering this model and re-visiting the determination of surface loss.

Marsh model

Marsh et al (1961, 1962) obtained an acoustical intensity surface reflection coefficient, Ω, which is:

$$\Omega = 1 - 0.485\left(f_{\text{kHz}}\,H\right)^{3/2} H^{1/10}\sin\theta \tag{8}$$

where *H* is the average wave crest to trough height (ft) and f_{kHz} .is acoustic frequency in kHz The expression in terms of frequency *f* in Hz for surface loss for small angles θ radians then becomes

$$RL \approx -10\log_{10}\left[1 - 1.53\times10^{-5}\left(f\,H\right)^{3/2} H^{1/10}\theta\right] \text{ dB}\,. \tag{9}$$

Some manipulation of Equation (9) may be postulated to attempt to derive an equivalent form of Equation (5). If the negative term inside the brackets is assumed small, and if the "0.3" and "0.7" terms are introduced to limit the value of *RL* to $20\log_{10}(0.3) \approx 10.5$, it may be shown that we get

$$RL \approx -20\log_{10}\left[0.3 + \frac{0.7}{1+10.9\times10^{-6}\left(f\,H\right)^{3/2} H^{1/10}\,\theta}\right] \text{dB} \tag{10}$$

It may be shown that for small angles θ and values of $f\,H$, less than about $8\,\text{kHz}\cdot\text{ft}$, Equation (10) returns about the same value as the original Marsh et al Equation (8). Equation (10) is, however, not the same as Equation (5), and so Equation (6), although purported to be based on Marsh et al (Lauer1982), appear to not follow directly from that work.

By using the substitution $\log_{10}(1+x) \approx 0.434x$, for small x, in Equation (9), we get

$$RL \approx 6.6\times10^{-5}\left(f\,H\right)^{3/2} H^{1/10}\,\theta\;\text{dB}\,. \tag{11}$$

where units of f, H and θ are Hz, ft, radians, respectively, and it may be noted that the exponents of the parameters are different than for the Gaussian roughness model, Equation (2). The linear variation of surface loss in dB with grazing angle in Equation (11) has the result that the rate of surface loss with range is the same for all rays, regardless of grazing angle θ at the surface. This follows as the ray skip distance r_s is a linear function of θ ($r_s = 2\theta c_w/g$ where c_w is speed of sound in seawater, m/s, and g is sound speed gradient, s^{-1}), so that the number of surface bounces for a ray varies inversely with grazing angle.

Kuo (1988) developed an analysis based on perturbation methods, and compared this against a re-evaluation of the analysis of Marsh, as well as others. According to Kuo, Marsh et al (1961) made errors in their analysis and a more correct form of Equation (8) is as follows:

$$\Omega = 1 - 0.165\left(f_{\text{kHz}}\,H\right)^{3/2} H^{1/10}\sin\theta \tag{12}$$

where units are as for Equation (8). Using an expression based on the Neumann-Pierson wave spectrum for wind speed in terms of wave height (see, also, following section), Kuo obtained from Equation (12) the following form of the acoustical intensity surface reflection coefficient:

$$\Omega = 1 - 4.2\times10^{-10}\, f^{\,3/2}\, \nu_k^{\,4}\,\theta \tag{13}$$

where f is cyclic frequency, Hz, ν_k is wind speed in knots, θ in grazing angle, radians. It follows from Equation (13) that

$$RL \approx 1.8\times10^{-9}\, f^{\,3/2}\, \nu_k^{\,4}\,\theta\;\text{dB}\,. \tag{14}$$

For a test case presented by Kuo (1988), of 3.5 kHz, 15 knot wind, Neumann-Pierson wave spectrum and average wave height $H = 2.4$ ft, Equation (14) returns values similar to those obtained from Kuo's own analysis (1988), so may be regarded as an expression which can be used for low loss situations of up to a few dB per bounce.

Equation (14) may not be compared directly with either of Equations (3) or (7), as the frequency exponent is different, however comparison of values for a grazing angle θ of 2.13° have been made. For frequency 5 kHz, the loss from (14) is just 20% higher than from (3) but a factor of 27 smaller than from (7). For 3.15 kHz, the loss from (14) is 43% higher than from (3) and 22 times smaller than from (7).

Williams et al (2004) show how a model based on perturbation theory originates from their small slope analysis. In their figure 6, their perturbation and small slope surface loss models agree with each other up to grazing angle about 3 degrees, and for their 10 m/s wind speed case, may be shown to give similar reflection loss as Equation (14). Both their perturbation and small slope models have the same linear dependence of loss in dB with grazing angle as shown in Equation (14).

sea surface description

The surface loss models described above all depict the state of the sea surface with merely a single parameter. The Gaussian roughness model uses rms surface roughness, whereas the RAYMODE Beckmann-Spizzichino model, as usually implemented, uses wind speed. The at-sea sonar data used in this study was obtained coincident with observations of wind speed, sea state and wave height, and each in turn was used as the input parameter for the sonar models. The Gaussian beam transmission model used by DSTO is implemented to use one of wind speed, wave height, or sea state as the single input, with the surface loss model ultimately run using wind speed as the input, following an internal conversion from the different parameter. The same situation applies in the case of the RAVE model used by Thales Australia. In the case of the RAVE model and the Gaussian beam model retained by DSTO, the default conversions within the models were used in this study. In the case of the Gaussian roughness model implemented by Curtin University, a well known conversion between wind speed and rms wave roughness was used so that the BELLHOP model might be run using wind speed data. Some description of these data conversions is necessary, and this is given below.

The well known relationship between sea state and wind speed (eg. Table 2.2 of Etter (2003)) is shown in Table 1.

Table 1. Relationship between sea state and wind speed

Sea State	Description	Wind Speed (kt)
0	calm, glassy	under 1
1	calm, rippled	4 – 6
2	smooth wavelets	7 – 10
3	slight	11 – 16
4	moderate	17 – 21
5	rough	22 – 27

Source: (Etter 2003)

There have been numerous algorithms used for conversion between wind speed and wave roughness dimensions. Mostly these are linked to various assumptions of the spectrum of the sea surface roughness, and the assumption that a given wind speed results in a given roughness spectrum. This is considered, briefly, below, using the units of ft and knots to maintain consistency with the models.

Lurton (2002), section 3.5.1, for example, points out that the mean-square wave height h^2 is given by the normalised integral of the surface spatial spectrum. (This relationship is, of course, true for any spectrum.) Due to the ease of observation, however, the form of wave spectrum usually considered is in terms of wave frequency, eg. Figure 12.11 shown by Pond and Pickard (1983). A complicating factor is the fact that the wave spectrum will have a unique form depending on the length of time the wind has blown from different directions. In practice, a wave spectrum for a fully-developed sea is used mostly, with the Neumann-Pierson and Pierson-Moskowitz spectra being common choices.

The relationship used by Curtin University in this study is from the Pierson-Moskowitz spectrum (eg. section 13.1 of Medwin and Clay (1998)):

$$h \approx 0.46\times10^{-2}\,\nu_k^{\,2} \tag{15}$$

where rms wave height h and wind speed ν_k are in ft. and knots, respectively. The rms wave height was estimated to be ¼ of the wave peak to trough height H, so that

$$H \approx 0.0185\,\nu_k^{\,2}\,. \tag{16}$$

AT-SEA SCENARIOS

At-sea acoustic data were recorded by DSTO using a ship-based technique. The ship in question was a hydrographic vessel of the Royal Australian Navy. For each track, the data were obtained using a suitable 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 range values extended to the order of 20 kilometres. The data collection is described in more detail by Jones et al (2006). The transmission loss (*TL*) was determined by summing the acoustic energy over the duration of the received transient signal, typically 0.15 to 0.5 seconds, and referring this received energy to that emitted, based on a model of the explosive source. In this way, the *TL* values shown below included the effects of both coherent and incoherent energy components received within the time-window of the analysis.

Sea surface and wind conditions were recorded on the ship's quartermaster's bridge log, being entered 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 sea state was also recorded and provides a more complete description of the sea surface. The recorded directions of wind and swell are the directions that they come from. Water column and sea surface conditions as recorded for ocean tracks Q, T and V are listed in Table 2. Periodic (approximately hourly) data are not included, however, the range of these observations, and the chronological order are shown.

Table 2. Water column and sea surface data for shallow water tracks

Data for Ocean Track		Q	T	V
ocean depth (m)		64	79	42
depth of upward refracting layer (m)		64	45	42
average sound speed gradient (m/s per m)		0.018	0.022	0.032
minimum no. surface skips to hydrophone		2	3	5
wind speed (kt)		10 – 8	30 - 28	27 - 26
wind direction (°T)		40 -50	60 - 95	80 - 65
sea state		3	5	6
swell	height (m)	0.5	2	2
	period (s)	6	5	6
	direction (°T)	130 - 85	60 - 80	80

For each of tracks Q, T and V, the ocean was almost completely upward refracting, with gradients shown in Table 2. Sound speed profiles for the tracks are shown in Figure 3.

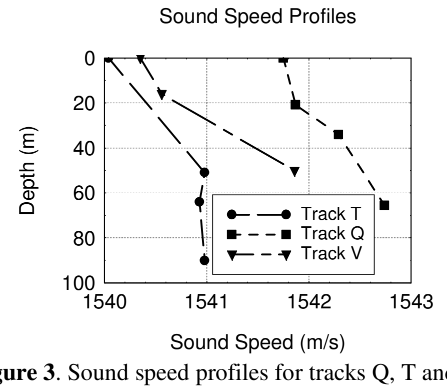

Figure 3. Sound speed profiles for tracks Q, T and V

For these tracks, 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 2. These values are based on ray plots, Figures 4 to 6.

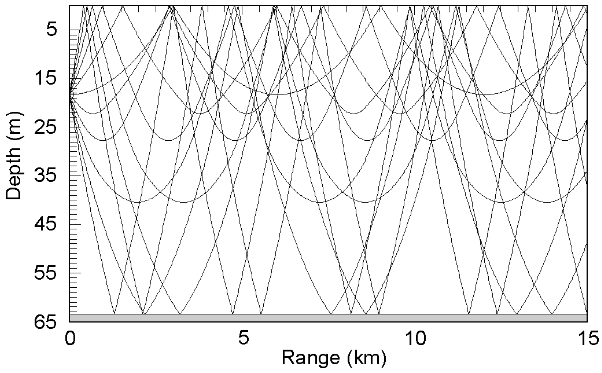

Figure 4. Acoustic ray diagram for sound radiated from source for Track Q, 11 rays over ± 2½ degrees

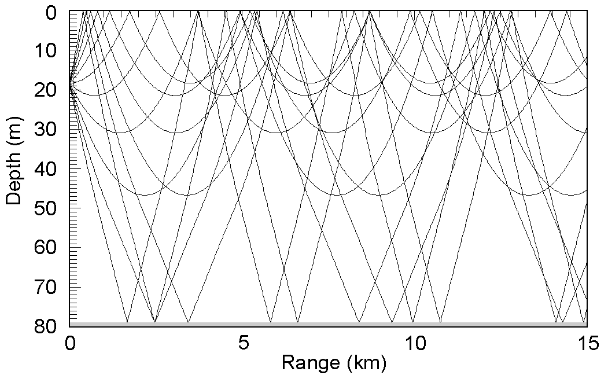

Figure 5. Acoustic ray diagram for sound radiated from source for Track T, 11 rays over ± 2½ degrees

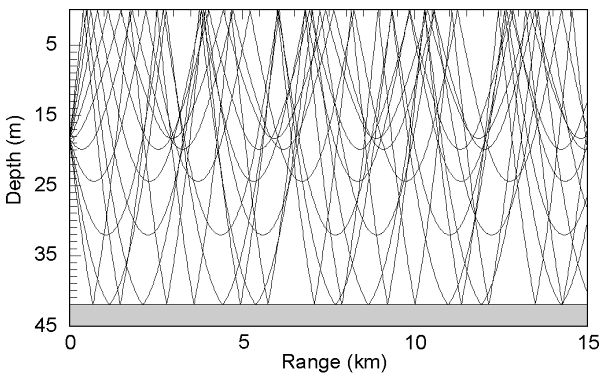

Figure 6. Acoustic ray diagram for sound radiated from source for Track V, 11 rays over ± 2½ degrees

As already stated, the models of surface loss considered in this study used merely a single input parameter. This single parameter approach takes no advantage of some of the sea surface descriptors which are available, such as wind direction, swell direction and period.

TRANSMISSION LOSS PREDICTIONS

Comparisons were made between the measured *TL*, and *TL* predicted by models incorporating different surface loss models: Gaussian beam model at DSTO using an implementation of Beckmann-Spizzichino surface loss; RAVE model at Thales Australia using a different implementation of Beckmann-Spizzichino; BELLHOP model at Curtin University using their implementation of the Gaussian roughness model. The RAVE model was developed by Thales Pty. and some description has been provided by Jones et al (2008).

The need to use a single parameter as input to each of the surface loss models created an issue as conversions of observed sea state and observed swell height to wind speed did not give consistent wind speed values, and did not give the same values as those obtained directly from the ship's anemometer. For this reason, according to whether each *TL* model permitted the alternative input, predictions of *TL* were repeated using (i) wind speed as the origin of the input; (ii) sea state as the origin; (iii) wave height as the origin. The actual input parameter values used by the models for the three tracks are shown in Table 3 in bold type. From the data in Table 3 for inputs to BELLHOP, and with reference to the earlier section on the Gaussian roughness model, it may be seen that the value for rms roughness *h* for which the Gaussian roughness model is valid is exceeded only for the case of the wave height value being based on the wind speed for Tracks T and V, and then by a small amount, only.

Previous studies (Jones et al 2008) have shown that the three transmission models gave similar transmission losses when the same boundary losses were used as inputs. Therefore it is considered that the differences in the modelled transmission losses shown in this paper are mainly due to the differences in the surface loss determinations.

Table 3. Inputs used for model runs

	Input Parameter Type	Q	T	V
Gaussian Beam model at DSTO	**wind speed ν_k (kt)**	**9**	**30**	**27**
	sea state **effective ν_k (kt)**	3 **13.8**	5 **24.8**	6 **30.3**
	wave height *H* (ft) **effective ν_k (kt)**	1.6 **13.2**	6.6 **23.0**	6.6 **23.0**
RAVE model at Thales Australia	**wind speed ν_k (kt)**	**9**	**30**	**27**
	sea state **effective ν_k (kt)**	3 **14**	5 **24**	6 **30**
BELLHOP model at Curtin	wind speed ν_k (kt) **effective rms height *h* (ft)**	9 **0.37**	30 **4.3**	27 **3.4**
	wave height *H* (ft) **effective rms height *h* (ft)**	1.6 **0.41**	6.6 **1.6**	6.6 **1.6**

Track Q

For Track Q, Figures 7, 8 and 9 show the values of *TL* versus range, for source and receiver both at 18.3 m depth, predicted by all three models, with observed wind speed as the source of the input parameter, for 1 kHz, 3.15 kHz and 5 kHz. At-sea measured *TL* data are also shown. Figures 10, 11 and 12 are corresponding figures for which observed sea state was the source of the input parameter. Here, there is no corresponding prediction from BELLHOP.

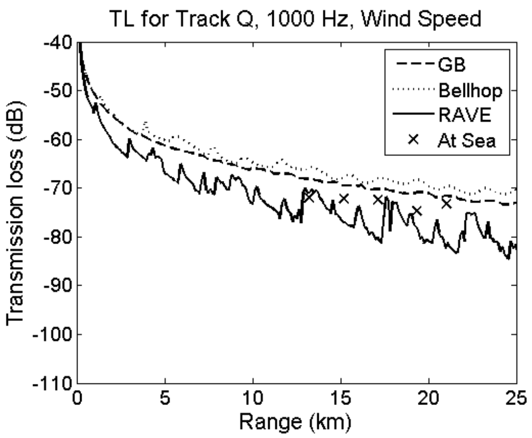

Figure 7. *TL* for Track Q, wind speed 9 kt, 1000 Hz

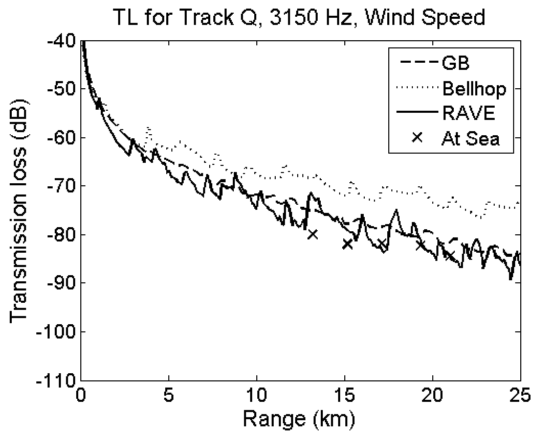

Figure 8. *TL* for Track Q, wind speed 9 kt, 3150 Hz

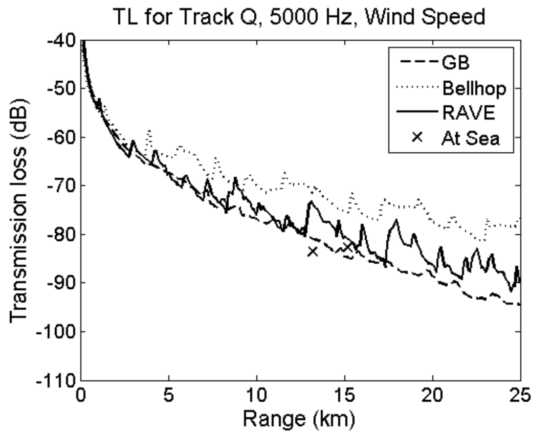

Figure 9. *TL* for Track Q, wind speed 9 kt, 5000 Hz

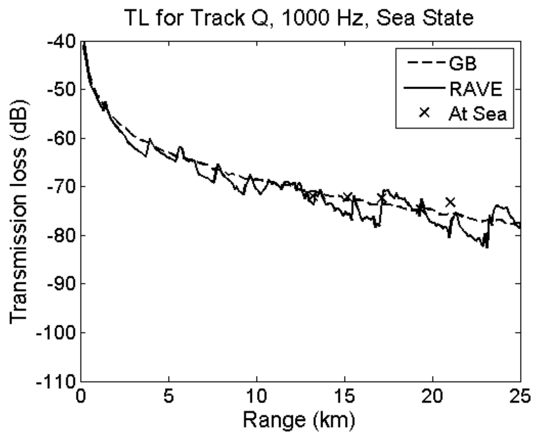

Figure 10. *TL* for Track Q, sea state 3, 1000 Hz

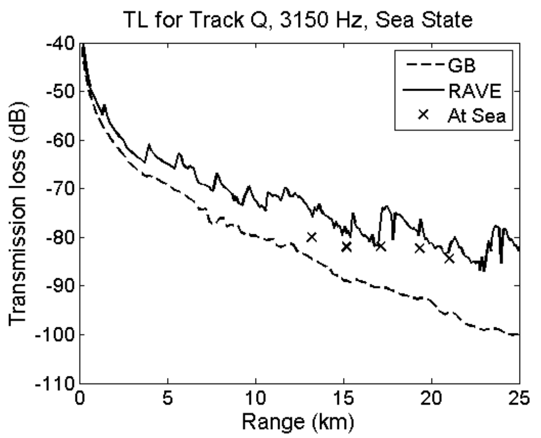

Figure 11. *TL* for Track Q, sea state 3, 3150 Hz

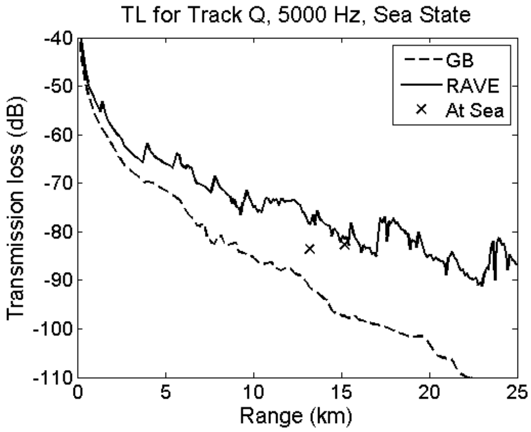

Figure 12. *TL* for Track Q, sea state 3, 5000 Hz

Track T

For Track T, Figures 13, 14 and 15 show the *TL* predicted by all three models, with observed wind speed as the input parameter, for 1 kHz, 3.15 kHz and 5 kHz. At-sea measured *TL* data are also shown. Corresponding figures for which observed sea state was the source of the input parameter are shown in Figures 16 and 17 for 1 kHz and 3.15 kHz.

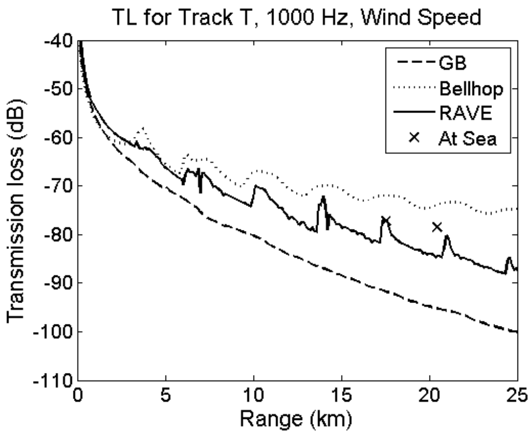

Figure 13. *TL* for Track T, wind speed 30 kt, 1000 Hz

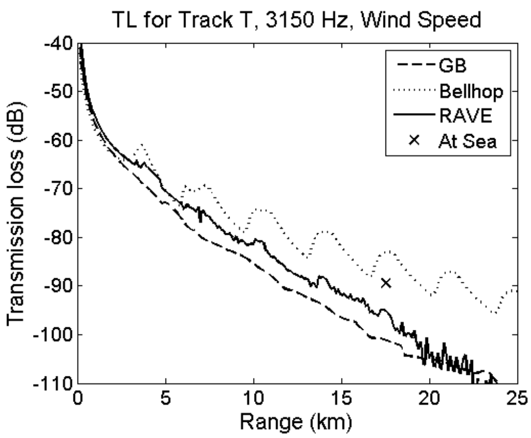

Figure 14. *TL* for Track T, wind speed 30 kt, 3150 Hz

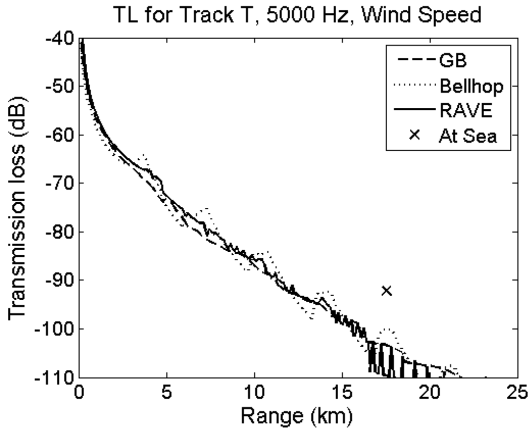

Figure 15. *TL* for Track T, wind speed 30 kt, 5000 Hz

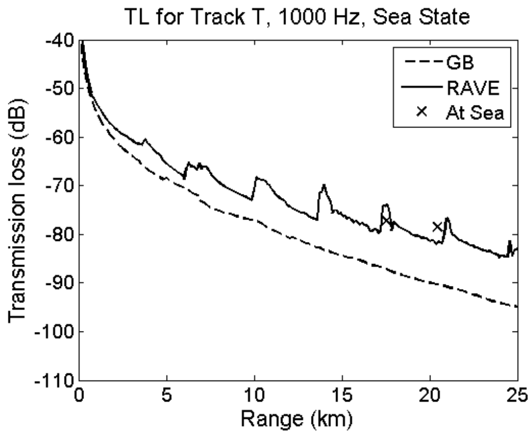

Figure 16. *TL* for Track T, sea state 5, 1000 Hz

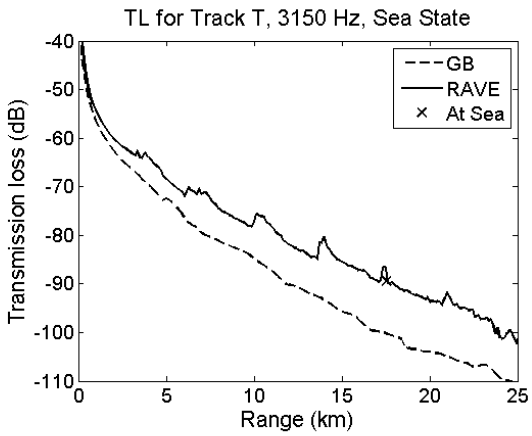

Figure 17. *TL* for Track T, sea state 5, 3150 Hz

Track V

For Track V, Figures 18 and 19 show the at-sea measured *TL* and *TL* predicted by all three models, with observed wind speed as the input parameter, for 1 kHz and 3.15 kHz. There is no at-sea data at 5 kHz. Since the effective wind speed based on the sea state observations, 30 kt, is close to the observed wind speed of 27 kt, the "sea state-based" *TL* predictions are not shown, as minimal difference was obtained.

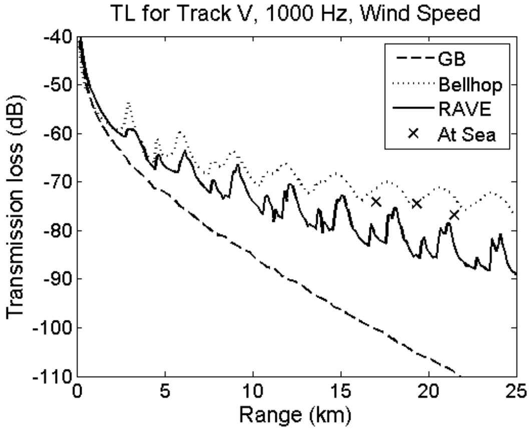

Figure 18. *TL* for Track V, wind speed 27 kt, 1000 Hz

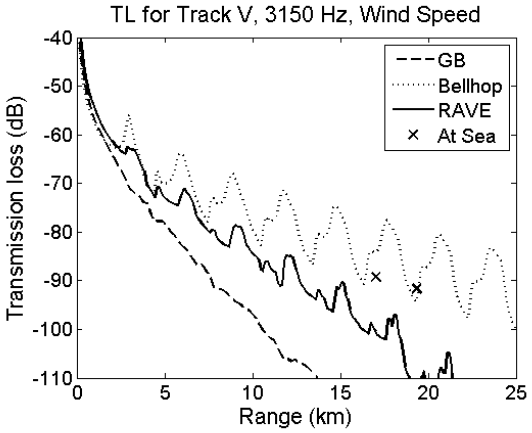

Figure 19. *TL* for Track V, wind speed 27 kt, 3150 Hz

DISCUSSION

The comparisons of measured *TL* to predictions made using the models considered in this study are limited in extent, however some consistency is apparent in the results.

For the track with the lowest wind speed (Track Q with 9 kt), the Gaussian beam model retained at DSTO, and RAVE, gave predictions close to the measured data. At 3.15 and 5 kHz, BELLHOP, with the Gaussian roughness model, under-predicted loss at 20 km range by about 10 dB, in comparison with the other models and at-sea data, when wind speed was the source of the parameter input. For this wind speed, low loss was expected from the Gaussian roughness model as Equation (3) gives just 0.12 dB loss per surface bounce for grazing angle 2° at 5 kHz.

For Tracks T and V (wind speeds 30 kt and 27 kt, respectively), when wind speed was the input parameter, the Gaussian beam model with its version of Beckmann-Spizzichino model, over-predicted surface loss at 20 km by about 10 dB and 30 dB, respectively. RAVE, with its different implementation of Beckmann-Spizzichino, was closer to the measured data, but also tended to over-predict surface loss. BELLHOP, with the Gaussian roughness model, tended to under-predict loss relative to the other models, but was generally less than 5 dB from the measured data. When sea state was used as the source of input parameter, the Gaussian beam model still over-predicted loss by at least 10 dB, whereas RAVE improved its fit to the at-sea data. Although not shown here, it was found that if wave height was used as the source of input parameter, the Gaussian beam model over-prediction was reduced, whereas BELLHOP, with the simple Gaussian roughness model, under-predicted more severely.

At the higher wind speeds (Tracks T and V), the over-prediction of surface loss by the Beckmann-Spizzichino model implemented in the DSTO-retained Gaussian beam *TL* model is a consistent feature. It has been noted that the use of a version of Beckmann-Spizzichino surface loss in the study of Williams et al (2004) also gave an over-estimation of surface loss.

CONCLUSIONS

This brief study has compared estimates of transmission loss made using the underwater acoustic surface loss models in use within Australia and has shown that there is a significant disparity between them. A brief review of the theoretical background of these models showed that differences were to be expected. It is reasonable to suggest, however, that the nature of the roughness, and reflection of sound, for a real sea surface, requires a multiple parameter description, and so the single-parameter models considered in this study were, in hindsight, destined to be inadequate. Consideration is then needed for a surface loss modelling method that exploits more of the available information, including remotely sensed and *in-situ* observed data.

ACKNOWLEDGEMENT

The authors acknowledge the efforts of DSTO staff members who collected, processed, archived and documented the data used in this paper, in particular, Dr. M. V. Hall.

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