REVERBERATION MODELLING WITH INSIGHT

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1. INTRODUCTION

Because of current trends towards the use of low frequency active sonar, reverberation modelling has recently been the subject of much research effort [1, 2], with a number of numerical models currently under development for predicting reverberation level vs time. If the signal level (i.e. target echo) is also known, or modelled, as a function of time, then a signal-to-noise (S/N) vs time curve can be predicted. Often, what is required by sonar assessors is S/N vs *target range* rather than vs *time*; the need to remove the unwanted parameter (time) from the calculations leads to a variety of possible compromise solutions which are discussed in Sec. 3. This is followed in Sec. 4 by a discussion of backscattering strengths, and comparisons with results from Ref. 18; comparisons have also been made with other models [3, 4], with similar agreement.

First, though, in Sec. 2 we provide a brief overview of the INSIGHT propagation model [5], used as the kernel for subsequent S/N predictions. A compromise S/N vs target range curve is developed in Sec. 3, followed by a discussion of appropriate backscattering strengths (Sec. 4). Section 4 also includes a number of S/N predictions using INSIGHT. A monostatic geometry is assumed throughout. Note that we use the short hand "S/N" strictly to mean separate signal and reverberation levels, and not a signal to noise *ratio*.

2. INSIGHT OVERVIEW

The kernel of INSIGHT is a fast transmission loss module, based on a components approach [5]; each component (e.g. bottom reflection, surface duct etc) has an analytical formula for its contribution to the total field [6]. For example the bottom reflected and bottom refracted components are calculated using a stationary phase method [7, 8], with a simple correction for refraction in the water [9]. Despite the analytical nature of the calculation, a completely arbitrary sound-speed profile is catered for, as well as a vertical beam pattern, and a non-zero bandwidth [10]. A systematic comparison with a set of benchmarks, for frequencies 50Hz to 10kHz and water depths 100-4,000m, can be found in Ref. 11. The accuracy (rms errors typically around 3dB and mean errors less than 1dB) is sufficient for many applications, and because no numerical modelling is involved, the INSIGHT prediction is virtually instantaneous, irrespective of frequency.

3. S/N vs RANGE

We now address the question of how best to remove the unwanted dependence on time of both signal and reverberation.

3.1 Signal Level

For a target at horizontal range r_T and depth z_T, we denote the time variation of the one-way (source to target) pressure by $p(r_T, z_T; t)$. It is customary [12,13] to remove the time dependence by averaging the power over the pulse, so that for a reference pressure p_0 (at 1m from the source), we obtain

$$P(r_T, z_T) = \frac{\int |p(r_T, z_T; t)|^2 dt}{\int |p_0|^2 dt}. \tag{3.1}$$

The corresponding echo level EL (in dB) can then be computed vs target range as

$$EL(r_T) = \text{source level} + 20\log_{10} P(r_T, z_T) + \text{target strength}. \tag{3.2}$$

3.2 Reverberation Level

Having removed the time dependence from the signal, the next task is to do the same for the reverberation, or "noise". It is acknowledged that, for the signal and noise calculations to be truly compatible, a more detailed knowledge of the signal processing is required. We proceed nonetheless, in the hope that signal processing effects can be treated as an add-on to, for example, the detection threshold.

Three approaches are considered in all. The first, and most obvious, is to repeat the trick used for the signal, and integrate over time; unfortunately the end result is then independent of target range and therefore not very useful. The second approach is to compute that part of the reverberation intensity which originates from the same horizontal range as the target; the answer is thus linked directly with the target range, and this method works well in shallow water, where there is little distinction between travel time (× sound speed) and target range.

In deep water, though, the echo from a target at range r_T will often arrive significantly before (say) the bottom reverberation from scatterers at the same range, because of the extra delay from travelling to the bottom and back. For the example of Fig. 1, the appropriate bottom reverberation intensity (that part of it which arrives at the same time as the echo) clearly originates from scatterers at horizontal range r_B, given from simple geometry by

$$r_B^2 = r_T^2 + (d_s - d_T)^2 - (H - d_s)^2 = r_T^2 - (H - d_T)(H + d_T - 2d_s). \tag{3.3}$$

Our third method, then, valid for deep water as well as shallow, is to compute the reverberation intensity originating from the range r_B. In other words, the bottom reverberation level RL_B for a backscattering strength BBS is

$$RL_B(r_T) = \text{source level} - 20\log_{10} P(r_B, H) + BBS + 10\log_{10} A \tag{3.4}$$

where A is the scattering area, given by (for a horizontal beamwidth Φ_H and pulse length τ)

$$A = \Phi_H r_B c\tau/2. \tag{3.5}$$

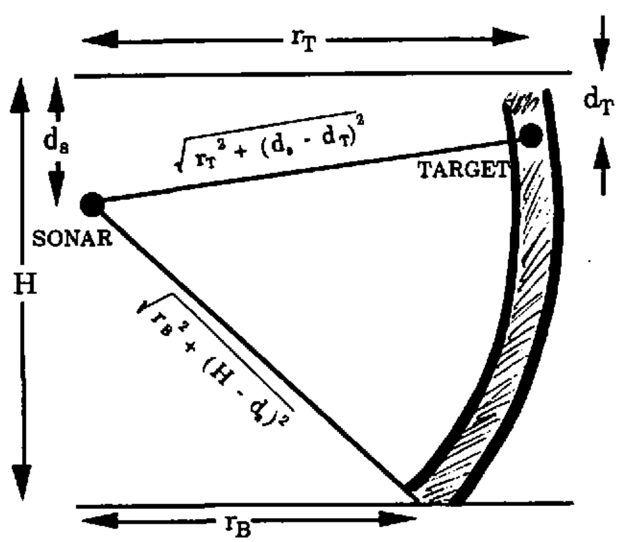


Figure 1 - Geometry for bottom reverberation

Equation (3.4) is a compromise; having integrated over time, it cannot possibly contain all the information required to analyse multipaths in the time domain. Nevertheless, it retains much of the character of RL vs time curves (including the first fathometer return for example, but not subsequent ones), and is used by INSIGHT for computing S/N vs r_T curves, along with similar equations for surface and volume reverberation.

The angle dependence implicit in the BBS term (as well as the appropriate sonar beam pattern) is incorporated into the propagation term 20logP.

4. BACK-SCATTERING STRENGTHS

4.1 Surface Backscattering Strength

The surface backscattering strength (SBS) formula in most common use, at least for LFAS frequencies and near grazing incidence, is probably that due to Chapman and Harris [14]. For angles θ close to normal incidence, a facet scattering model is more appropriate, and a formula valid for all angles is therefore (following Ellis and Crowe [15], and defining $\sigma_S = 10^{SBS/10}$)

$$\sigma_S(\theta) = \sigma_{CH}(\theta) + \frac{\operatorname{cosec}^4\theta}{8\pi\,\Sigma_S^{\,2}} \exp\left[-\frac{\cot^2\theta}{2\,\Sigma_S^{\,2}}\right] \tag{4.1}$$

where Σ_S is the facet slope, given for a wind-speed v in m/s [16, 17], by

$$\Sigma_S^{\,2} = 0.003 + 0.00512v\,, \tag{4.2}$$

and the CH subscript denotes the Chapman-Harris scattering strength formula. Eq. (4.1) is implemented in INSIGHT, with the Ogden-Erskine formula [18] as an alternative option.

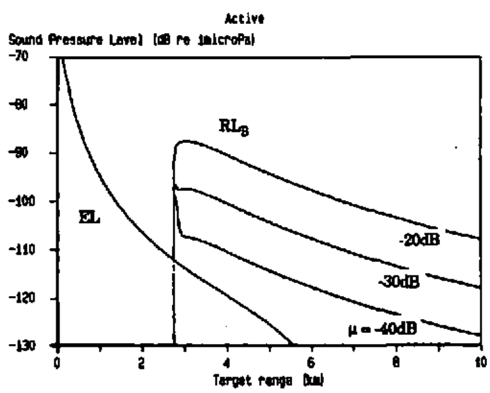
For completeness, relationships between wind speed and wave height for two commonly used surface wave spectra are provided in the Appendix, correcting some small numerical errors in other sources.

4.2 Bottom Backscattering Strength

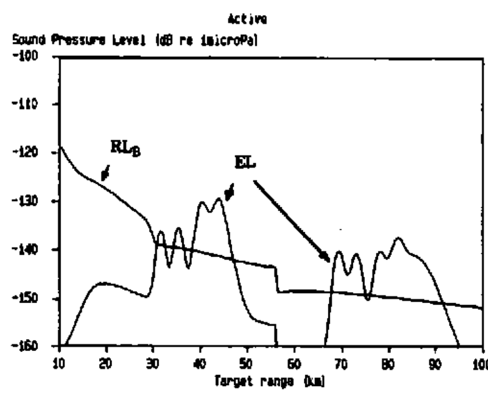
In principle, the bottom backscattering strength (BBS) can be parametrised in terms of a boundary roughness and sediment inhomogeneity [19] in much the same way as the wind speed represents the surface roughness. However, the necessary bottom data are rarely available and it is more common to assume Lambert's law [12], with an empirical multiplying constant μ. This latter approach is followed below, together with a facet scattering term as for the surface (defining $\sigma_B=10^{BBS/10}$)

$$\sigma_B(\theta) = \mu \sin^2\theta + R\frac{\operatorname{cosec}^4\theta}{8\pi\,\Sigma_B^{\,2}}\exp\left[-\frac{\cot^2\theta}{2\,\Sigma_B^{\,2}}\right]. \tag{4.3}$$

Note the extra factor of R in the facet term here compared with Eq. (4.1). It is the power reflection coefficient at normal incidence, and given approximately by $(\rho-1)^2/(\rho+1)^2$ where ρ is the sediment specific gravity. Strictly, a similar factor should appear in the surface facet strength, but in Eq. (4.1) above we have assumed that all energy incident on the sea surface is reflected.



a) 0 to 10km, showing first fathometer return



b) 10 to 100km, showing detection opportunities at the two convergence zones

Fig. 2 - Echo and bottom reverberation levels vs range for zero wind speed. The parameters are taken from Schneider's Fig. 16. [20].

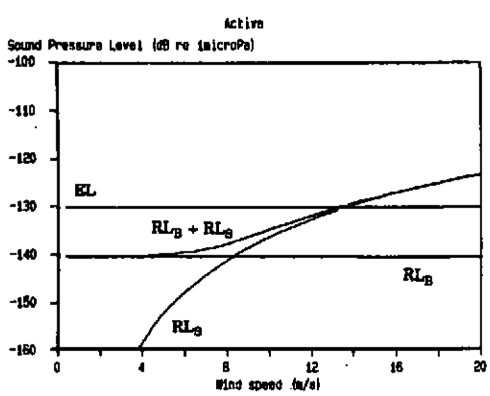


Fig. 3 - Echo and reverberation levels vs wind speed at 40km.

Figure 2(a) shows signal and noise levels vs target range for a facet slope Σ_B of 0.1, and three values of Lambert's constant ($\mu=10^{-4}$, 10^{-3}, 10^{-2}). The bottom reverberation ("RL$_B$") clearly masks the target echo ("EL") beyond the fathometer return at 2.8km. A target strength of 20dB and depth 100m have been assumed; other parameters (e.g. water depth 3km, sonar depth 250m, frequency 100Hz and source level 0dB) have been taken from Schneider [20]. At longer ranges [Fig. 2(b)], there are further detection opportunities from convergence zone returns around 40km and 80km. Figure 2(b) was evaluated with $\mu=10^{-3}$ and is directly comparable with Schneider 's Fig. 16, except that for clarity we have suppressed interference by performing the calculations incoherently. For higher wind speeds, the signal will be partially obscured by surface reverberation [Fig. 3], and potentialy also by ambient noise.

5. SUMMARY AND DISCUSSION

We have presented predictions of surface and bottom reverberation level (RL) vs target range using the sonar performance model INSIGHT. Comparisons with other models have shown that good agreement is found for some features, but not others. Potential sources of disagreement are many (scattering strengths, boundary losses, treatment of multiply-scattered paths, conversion from time to range etc) and there is a clear need for establishing a set of tried and tested reverberation level benchmarks.

An important feature of INSIGHT is its speed. The predictions presented in Figs. 2, 3 took a few seconds each on a 486 PC, enabling rapid assessment of sensitivity to the various sonar design parameters.

6. ACKNOWLEDGEMENTS

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APPENDIX - SEA SURFACE DESCRIPTORS

Commonly used parameters to describe the sea surface include [18]: wind speed (v), usually at a height of 10m above the sea; significant and average wave heights ($H_{1/3}$ and $\overline{H}$ respectively); and rms roughness σ. There is a surprising lack of care in the literature in adequately defining and distinguishing between the various descriptors [21, 22]. The purpose of this Appendix is to derive relationships between the above 4 parameters (see Ref. 23 for definitions), based on the original work of Longuet-Higgins [24]; and to point out errors made elsewhere. The sums are done for both the Neumann-Pierson [25] and Pierson-Moscowitz [26] surface wave spectra. We calculate the rms roughness from the frequency distribution $S^2(\omega)$ [22]

$$\sigma^2 = \int_0^\infty S^2(\omega)d\omega \, , \tag{A.1}$$

and then use the relationships [24]

$$\overline{H}/\left(2\sqrt{2}\sigma\right) = \pi^{1/2}/2 \tag{A.2a}$$

$$H_{1/3}/\left(2\sqrt{2}\sigma\right) \approx 1.416 \, . \tag{A.2b}$$

The factors $\sqrt{2}$ and 2 in the left-hand-side denominator are to convert, respectively, from rms roughness to rms amplitude, and from amplitude to (crest-to-trough) wave height.

Using subscripts NP and PM to denote the two spectra, we have [25, 26]

$$S_{NP}^2(\omega) = (C_{NP}/2\omega^6)\exp\left[-2(g/v\omega)^2\right] \quad \text{(A.3a)}$$

$$S_{PM}^2(\omega) = (C_{PM}g^2/\omega^5)\exp\left[-0.74(g/v\omega)^4\right] \quad \text{(A.3b)}$$

where g is the acceleration due to gravity and C_{NP}, C_{PM} are empirically determined constants

$$C_{NP} = 4.80\ \mathrm{m^2s^{-5}} \quad \text{(A.4a)}$$

$$C_{PM} = 8.10\times10^{-3}\,. \quad \text{(A.4b)}$$

Applying Eq. (A.1) above and making use of the standard integrals

$$\int_0^\infty x^4 e^{-x^2}dx = 3\pi^{1/2}/8 \quad \text{(A.5a)}$$

$$\int_0^\infty x\, e^{-x^2}dx = 1/2, \quad \text{(A.5b)}$$

we find that

$$\sigma_{NP}^2 = 3\,C_{NP}\,(\pi/2^{13})^{1/2}\,(v/g)^5 \quad \text{, and} \quad \text{(A.6a)}$$

$$\sigma_{PM}^2 = (C_{PM}/2.96)\,(v^2/g)^2\,. \quad \text{(A.6b)}$$

Substituting for g=9.80ms^{-2} and using Eqs. (A.2) above we obtain the following table for the two spectra.

	Neumann-Pierson	Pierson-Moscowitz
σ	$1.77\times10^{-3}\,v^{5/2}$	$5.34\times10^{-3}\,v^2$
$\overline{H}$	$4.43\times10^{-3}\,v^{5/2}$	$1.34\times10^{-2}\,v^2$
$H_{1/3}$	$7.07\times10^{-3}\,v^{5/2}$	$2.14\times10^{-2}\,v^2$

Table A.1 - rms roughness σ, average wave height $\overline{H}$ and significant wave height $H_{1/3}$ vs wind speed v for Neumann-Pierson and Pierson-Moscowitz spectra. Units are m/s for wind speed and m for roughness and wave height.

Comparing the table with other sources, we note first of all the agreement with the careful work of Kuo [22], which we have largely followed, adding the significant wave height here for completeness. There are discrepancies, though, with three other publications as follows. Marsh et al [27] use the expression (in imperial units of feet, knots) $\sigma_{NP}^2 = 2.42 \times 10^{-6} v^5$, which in SI units becomes

$$\sigma_{NP} = 2.49 \times 10^{-3} v^{5/2} . \qquad (A.7)$$

As pointed out by Kuo [22], Eq. (A.7) is in error by a factor $\sqrt{2}$.

The other two discrepancies appear in the formulae (again in Imperial units): $\overline{H} = 0.0026 v^{5/2}$ quoted by Schulkin and Shaffer [28] for the NP spectrum; and for the PM spectrum, $H_{1/3} = 1.82 \times 10^{-2} v^2$ quoted by Neumann and Pierson [23]. Recasting in SI units these are, respectively,

$$\sigma_{NP} = 1.66 \times 10^{-3} v^{5/2} \qquad (A.8)$$

and

$$\sigma_{PM} = 5.22 \times 10^{-3} v^2 . \qquad (A.9)$$

Although the errors are numerically small (6% and 2% compared with Table A.1), their consequencies are potentially serious. This is on the one hand because of their widespread use (they are both quoted by Urick [12]; see pages 157 and 270), and on the other because the error is sometimes amplified by raising the coefficients to high powers (2 to 4) in practical applications [21, 29].

Of the two spectra, PM is now in most common use for research purposes [30], but the NP spectrum is still important for the interpretation of early work.

As a final aside, we note that for wind speeds close to 10m/s, very similar wave heights are predicted by the two spectra. The equivalence is exact for a wind speed (found by equating σ_{NP} with σ_{PM}) of 9.13m/s, corresponding to an rms roughness σ = 0.445m.

REFERENCES

[1] D D Ellis, J R Preston and H G Urban (Eds.), 'Ocean Reverberation', Kluwer, Dordrecht, (1993).

[2] Reverberation and Scattering Workshop, 2-6 May 1994, Gulfport, MS, USA.

[3] '1985 Baseline Active RAYMODE Propagation Loss Prediction Computer Program Performance Specification', NUSC Technical Document 7803B, December 1987.

[4] D D Ellis, 'A shallow-water normal-mode reverberation model', SACLANTCEN Report SR-196, September 1992.

[5] M N Packman, C H Harrison and M A Ainslie, 'INSIGHT - A Fast, Robust, Propagation Loss Model with Physical Intuition', IOA Acoustics Bulletin 17(4), pp21-24 (1992).

[6] C H Harrison, 'Simple techniques for estimating transmission loss in deep water', 13th ICA, Volume 5, Sea Acoustics Satellite Symposium, pp169-172 (1989).

[7] M A Ainslie and C H Harrison, 'Diagnostic tools for the ocean-acoustic modeller', *in* Computational Acoustics: Seismo-Ocean Acoustics and Modeling (Lee et al, eds), pp107-130, North-Holland, Amsterdam (1990).

[8] M A Ainslie, 'Stationary phase evaluation of the bottom interacting field in isovelocity water', J. Acoust. Soc. Am. 94, 1496-1509 (1993).

[9] C H Harrison, 'Refraction Corrections in Range and Angle for a Simple Transmission Loss Model', YARD Report 3293/2/TR/5 (1989).

[10] C H Harrison and J A Harrison, 'A simple relationship between frequency and range averages for broadband sonar, J. Acoust. Soc. Am. (accepted for publication).

[11] M A Ainslie, 'INSIGHT: A Systematic Comparison with SPWG Transmission Loss Benchmarks', BAeSEMA Report 5109/TR-2 (1992).

[12] R J Urick, 'Principles of Underwater Sound', 3rd edition, McGraw-Hill, New York (1983).

[13] R J Urick 'Generalized form of the sonar equations', J. Acoust. Soc. Am. 34, 547-550 (1962)

[14] R P Chapman and J H Harris, 'Surface backscattering strengths measured with explosive sound sources, J. Acoust. Soc. Am. 34, 1592-1597 (1962).

[15] D D Ellis and D V Crowe, 'Bistatic reverberation calculations using a three-dimensional scattering function', J. Acoust. Soc. Am. 89, 2207-2214 (1991).

[16] C Cox and W Munk, 'Measurement of the roughness of the sea surface from photographs of the Sun's glitter', J. Opt. Soc. Am. 44, 838-850 (1954).

[17] R P Chapman and H D Scott, 'Surface backscattering strengths measured over an extended range of frequencies and grazing angles, J. Acoust. Soc. Am. 36, 1735-1737 (1964).

[18] P M Ogden and F T Erskine, 'Surface scattering measurements using broadband explosive charges in the Critical Sea Test experiments', J. Acoust. Soc. Am. 95, 746-761 (1994).

[19] P D Mourad and D R Jackson, 'A model/data comparison for low frequency bottom backscatter', J. Acoust. Soc. Am. 94, 344-358 (1993).

[20] H G Schneider, 'Surface loss, scattering, and reverberation with the split-step parabolic wave equation model', J. Acoust. Soc. Am. 93, 770-781 (1993).

[21] A I Eller 'Implementation of rough surface loss in sonar performance models', NORDA Rev., pp31-35 (1986).

[22] E Y T Kuo, 'Sea surface scattering and propagation loss: review, update and new predictions', IEEE J. Oceanic Eng. 13(4), 229-234 (1988).

[23] G Neumann and W J Pierson, 'Principles of Physical Oceanography', Prentice-Hall, Englewood Cliffs, NJ (1966).

[24] M S Longuet-Higgins, 'On the statistical distribution of the heights of sea waves', J. Marine Res. XI(3), 245-266 (1952).

[25] G Neumann and W J Pierson, 'A detailed comparison of theoretical wave spectra and wave forecasting methods', Deut. Hydrogr. Z. 10(3-4), 73-92, 134-146 (1957).

[26] W J Pierson and L Moscowitz, 'A proposed spectral form for fully developed wind seas based on the similarity theory of S A Kitaigorodskii', J. Geophys. Res. 69(24), 5181-5190 (1964).

[27] H W Marsh, M Schulkin and S G Kneale, 'Scattering of underwater sound by the sea surface', J. Acoust. Soc. Am. 33, 334-340 (1961).

[28] M Schulkin and R Shaffer, 'Backscattering of sound from the sea surface', J. Acoust. Soc. Am. 36, 1699-1703 (1964).

[29] D E Weston and P A Ching, 'Wind effects in shallow water acoustic transmission', J. Acoust. Soc. Am. 86, 1530-1545 (1989).

[30] S T McDaniel, 'Sea surface reverberation: A review', J. Acoust. Soc. Am. 94, 1905-1922 (1993).