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SEPARABILITY OF SCATTERING AND REFLECTION PARAMETERS IN REVERBERATION INVERSION

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Abstract: *A premise of reverberation inversion is that one can separate geoacoustic reflection properties from scattering properties since their effects on reverberation are distinguishable. Some doubt has been cast on this premise in the case of long range reverberation by the fact that simple theory suggests that the two are inseparable for many scattering laws, even in a refracting environment. Instead a recent paper* [Harrison, C.H., Nielsen, P.L., J. Acoust. Soc. Am., **121**, 108-119, (2007)] *has shown that by modifying the directionality of the source or receiver one can effectively alter the propagation in situ whilst leaving the scattering law unchanged. In particular, using a dipole directivity results in a different dependence of reverberation on range, and therefore provides an additional measurement. Dividing this 'dipole reverberation' by the usual 'monopole reverberation' yields a quantity that clearly does not depend on the strength of the scattering (although it does depend on its angle behaviour). One can therefore separate geoacoustic and scattering properties. This idea has been tested on experimental data and could, in principle be applied to dipole-steered horizontal triplet arrays.*

Keywords: *Reverberation, inversion, scattering, reflection.*

1. INTRODUCTION

The idea of simultaneously separating out reflection and scattering properties from reverberation has developed over 15 years or so and there is a substantial literature, see [1-4]. It has potentially important consequences for sonar performance since it can make predictions not only of both types of seabed property but predictions over a large area at considerable range from the source ship.

At first sight one might expect the effects of scattering strength and boundary reflection to be quite distinct and separable since the first is a simple multiplier while the second, one might think, produces a decay in range. However an earlier paper [5] considered isovelocity water combined with Lambert's law and showed, by using analytical techniques, that beyond a certain range, within the so-called mode-stripping region, no such separation should be possible since the reverberation intensity was proportional to $\mu\alpha^{-2}r^{-3}$ where μ is the Lambert constant, α is the reflection derivative with angle (for small angles), and r is reverberation range (i.e. corrected travel time). In other words, in this limit, one could only determine $\mu\alpha^{-2}$, not μ and α separately.

The formulas for the isovelocity case were extended to uniform sound speed gradient [6,7] and showed a more complicated behaviour with respect to α and μ although the tendency to inseparability was still manifest. Harrison and Nielsen [8] demonstrated that even with a uniform sound speed gradient an increase in μ can be approximately matched by changing α, and exactly matched by changing α and the sound speed gradient c' at the same time. The main point of this paper is to suggest an alternative and in Section 3 we propose a way of separating μ and α, still from measurements of reverberation alone, even at long range and possibly a single ping, depending on configuration. Because the propagation is directly dependent on the angle distribution of the multipath rays (or modes) it is affected not only by the scattering law (or kernel) angle dependence but also by the directivity of the source and receiver. Thus by changing one or both of these directivities one can modify the propagation range dependence *in situ*, and the result is a modified reverberation. Given a measurement of 'conventional' reverberation with a point source and receiver, and a measurement of 'modified' reverberation with some given directivity one can deduce α alone from the relative range laws.

Finally some experimental demonstrations with a steered line array are given in Section 4, and the reflection and scattering parameters extracted. The resulting values of α agree with other estimates and the μ is within expected bounds.

2. LAMBERT REVERBERATION WITH MONOPOLE SOURCE AND RECEIVER

Treating the eigenrays or modes as a continuum in angle their angle distribution is Gaussian and they decay exponentially with range. A formula for isovelocity reverberation is [5]

$$I = \frac{\mu \Phi p}{\alpha^2 r^3} \left\{ 1 - \exp\left(\frac{-\alpha r \theta_c^2}{2H} \right) \right\}^2 \tag{1}$$

where μ is the Lambert constant, α is related to the derivative of reflection loss with angle α_{dB} (dB/rad) through $\alpha = \alpha_{dB}/(10\log_{10}(\mathrm{e}))$, θ_c is critical angle, H and r are water depth and range, Φ is the horizontal beam width, and p is the spatial pulse length $p = c\ t_p /2$. At long range this becomes

$$I = \frac{\mu \Phi p}{\alpha^2 r^3} \tag{2}$$

and at short range, expanding the exponential to first order, we have

$$I = \frac{\mu \Phi p\ \theta_c^{\ 4}}{4 r H^2} \tag{3}$$

The transition from short- to long-range occurs when the exponential term becomes negligible.

$$r_o = \frac{2H}{\alpha \theta_c^{\ 2}} \tag{4}$$

The inseparability of μ and α at long range is seen explicitly in Eq. (2) where reverberation depends on μ / α^2.

3. MODIFIED REVERBERATION – LAMBERT WITH DIPOLE SOURCE AND RECEIVER

One might expect that during any one experiment in one locality the scattering law and the propagation would be given and fixed, therefore one has no control over the reverberation. In fact there are various controls, for instance, in a refracting environment the source and receiver depth alter the results. Similarly placing either source or receiver near the sea surface creates a dipole directionality which alters the propagation by introducing an extra square-of-grazing-angle term in one or both of the outward and return angle integrals. In general, the waveguide imposes a near-Gaussian angle distribution which is multiplied by the directivities at the two ends of each propagation leg, i.e. source and scatterer for outward, and scatterer and receiver for return. There are therefore many ways one could alter the propagation integral *in situ* given the locally fixed scattering law.

Harrison and Nielsen [8] investigated three possibilities, all involving some vertical aperture, reverting to the isovelocity environment for simplicity. Here we consider a source (or receiver) with a vertical dipole beam pattern. To track the changes we note that Eq. (1) could have been written in terms of the outward and return integrals L_O, L_R as

$$I = \frac{\mu \Phi p}{r H^2} L_O L_R \tag{5}$$

where

$$L_O = L_R = \int_0^{\theta_c} \theta \exp\left(-\frac{\alpha \theta^2 r}{2H} \right) d\theta \tag{6}$$

We now leave L_O unchanged and calculate the new L_R as required. Introducing the shorthand

$$X = \frac{\alpha \theta_c^{\ 2} r}{2H} \tag{7}$$

we write L_R as

$$L_R = \frac{\theta_c^{\ 2}}{2X}\left(1 - \mathrm{e}^{-X}\right) \tag{8}$$

Assuming the dipole to be composed of two unit monopoles a distance z apart, there is a gain factor of $k^2 z^2 \sin^2\theta$ which we approximate as $k^2 z^2 \theta^2$.

$$L_{RD} = k^2 z^2 \int_0^{\theta_c} \theta^3 \exp\left(-\frac{\alpha\theta^2 r}{2H}\right) d\theta = k^2 z^2 \theta_c^{\ 4} \left(\frac{1-(1+X)\exp(-X)}{2X^2}\right) \tag{9}$$

Thus the ratio of dipole to monopole reverberation F is

$$F = \frac{I_{dipole}}{I_{monopole}} = \frac{L_{RD}}{L_R} = k^2 z^2 \frac{\theta_c^{\ 2}\left(1-(1+X)\exp(-X)\right)}{X\left(1-\exp(-X)\right)} \tag{10}$$

For long range ($X > 1$)

$$F = k^2 z^2 \frac{2H}{\alpha r} \tag{11}$$

For short range ($X < 1$)

$$F = k^2 z^2 \theta_c^{\ 2} / 2 \tag{12}$$

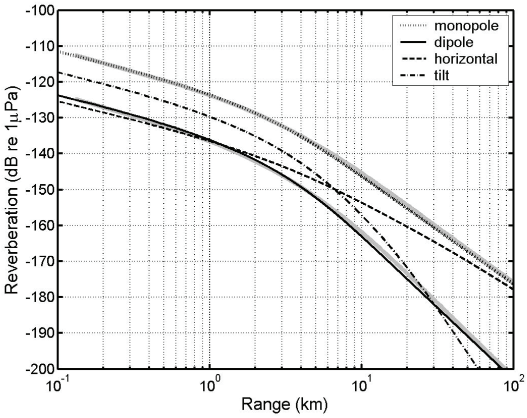

Fig. 1. Various reverberations: Monopole reverberation from closed-form solution (dotted black) and C-SNAP (thick grey); dipole reverberation from closed-form (solid black) and C-SNAP (thick grey); horizontal beam closed-form (dash black); tilted beam closed-form (dash-dot black).

The full behaviour is shown as the solid black line in Fig. 1 (suppressing the k^2z^2 term) for the baseline parameters ($H = 100$m, $\mu = 10^{-2.7}$, $\alpha_{dB} = 4$ dB/rad, $\theta_c = 20°$) and compared with conventional monopole reverberation (dotted line). The equivalent ratio F is shown in Fig. 2. The most important point is that because of Eq.(11) the range dependence is completely altered in a very simple way at long ranges. In fact, the ratio of this modified reverberation to conventional reverberation F *is independent of* μ at all ranges, as is clear in Eq.(10). If we plot $r \times F$ as shown in Fig. 3 we expect a long range plateau with value $2H/\alpha$. This means that if one measures monopole and dipole reverberation then α and μ are separable after all. In fact in this example the value of the plateau is 23.37 dB which leads to $\alpha_{dB} = 3.9977$ dB/rad and agrees with the input value. Having separated α one can deduce μ from long range monopole reverberation. Numerical confirmation of these findings for the monopole and dipole (using C-SNAP) is shown by the thick grey lines in Fig. 1 for the same parameters. Agreement is excellent.

The implications of adding extra information to a standard search inversion technique were investigated in [8]. First by examining a cost function using C-SNAP it was demonstrated that application of standard inversion techniques to conventional reverberation alone yielded poor estimates of α and μ . A dramatic improvement resulted from use of a joint cost function based on the two reverberation measurements. One could also argue from the point of view of Fig. 3 that there is no longer a need for a search at all.

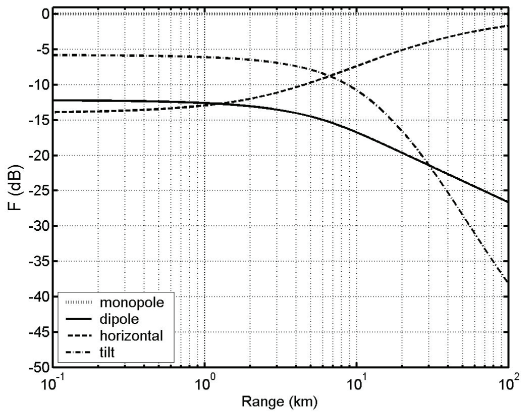

Fig. 2. The closed-form ratio of the quantities in Fig. (1) to monopole reverberation (i.e. F). Monopole (dotted); dipole(solid); horizontal beam (dash); tilted beam (dash-dot).

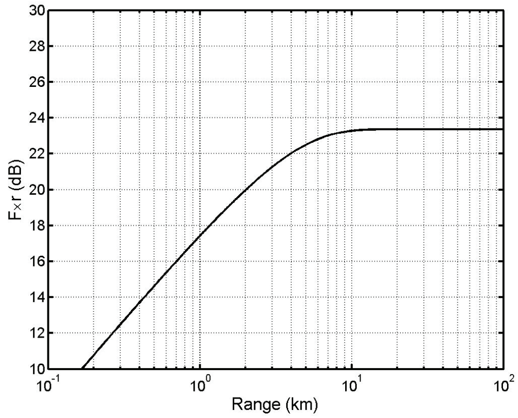

Fig. 3. The reverberation ratio multiplied by range (i.e. F × r) showing the plateau at long range.

4. EXPERIMENTAL DETERMINATION OF α FROM REVERBERATION RATIO

Here we use data gathered with a vertical array (VLA) to mimic a sine-squared beam since all beams are known. Of course, in this case, one could treat each vertical beam as a tilted beam, but the simplicity of the dipole formulas and the appeal of a dipole or triplet array compels us to demonstrate that approach. The data were collected at three sites on the Malta Plateau during BOUNDARY2003 (8th July 2003) and BOUNDARY2004 (17th and 20th May 2004). Each set consists essentially of monostatic reverberation on a gradual slope with the source and array in about 150 m water depth but with returns from water shallowing to about 80 m over some tens of kilometres. Given the smoothed beam responses it is an easy matter to sum over angles (monopole) or alternatively multiply by $\sin^2(\theta)$ then sum (dipole). The match-filtered response for the three dates extending out to about 25 km are shown in Figs. 4(a, b, c), and these can be compared with Fig. 1. The spike near 10 km on the 8th and the 20th is the Campo Vega oil rig and tender. From approximately 1 to 25 km in all cases one can see the expected divergence of the monopole and dipole curves. The weaker dipole curves tend to flatten off into ambient noise at a shorter range.

The equivalent of Fig. 3 for all cases is shown in Fig. 5. Now one can clearly see the effects of ambient noise beyond about 10 km, and the fall-off at short range, leaving a plateau in the middle at 23, 21, 21 dB respectively. If a flat bottom and Lambert's law were assumed with corresponding depths of 149, 143, 165 m we would arrive at α values of 1.49, 2.27, 2.62

rad^{-1}. Allowing for the fact that the dominant reverberation is from the shallow side of the array a more realistic average depth would be 100m, so the values of α would reduce to 1.00, 1.58,1.58 rad^{-1}.

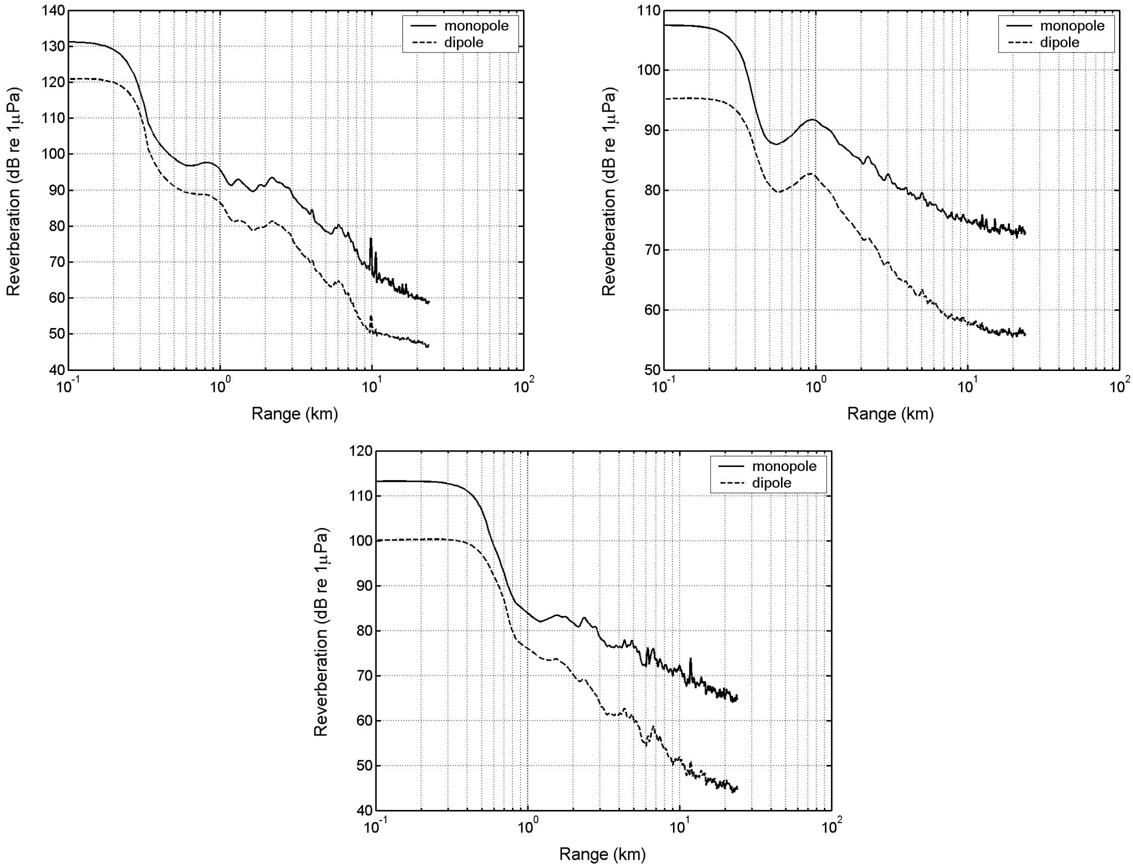

Fig. 4. Monopole (solid) and dipole (dashed) reverberation on the Malta Plateau for (a) 8th July 2003, (b) 17th May 2004, (c) 20th May 2004.

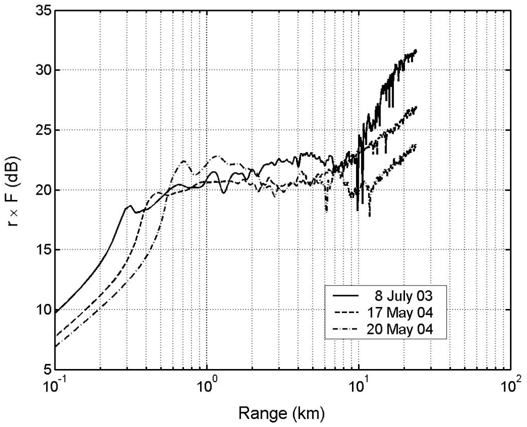

Fig. 5. The ratio of dipole to monopole reverberation multiplied by range for 8th July 2003 (solid), 17th May 2004 (dashed), 20th May 2004 (dash-dot).

Inserting $\alpha = 1.1$ rad^{-1} into Eq. (1) and taking the monopole reverberation value of 68 dB at range 10 km, with $\Phi = 2\pi$, $p = 1.87$ m (1.25 ms pulse), and vertical beam width 3.5°, we find $\mu = -33$ dB. This value is close to other measurements for the area for which there is a wide spread, and of course this evaluation depends on the sonar calibration, unlike the evaluation of α. In addition, for comparison purposes, long range measurements of μ that are immune from propagation uncertainty are hard to come by for the reasons central to this paper.

5. CONCLUSIONS

This paper has proposed an alternative geoacoustic inversion technique in which the reverberation is deliberately modified by biasing the propagation angles through a source or receiver beam (e.g. dipole), thus providing two separate measures of reverberation. The relative behaviour of these two measures then provides the required separability between scattering and geoacoustic parameters. The dipole reverberation combined with monopole (conventional) reverberation leads to some surprisingly powerful, simple, and robust results. For instance, from the ratio at long range we can find α directly and independently of other parameters (other than water depth). Having found α one can then deduce μ. The short range ratio is sensitive to critical angle and insensitive to μ and α. These deductions were confirmed [8] using a modified version of C-SNAP. The approach is robust to refraction and the derived α is relatively insensitive to the assumed scattering law. Separability of α and μ was demonstrated with experimental reverberation data from a vertical array. It ought also to be possible with a towed horizontal triplet array steered as a vertical dipole or monopole.

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