3rd EUROPEAN CONFERENCE
ON UNDERWATER ACOUSTICS
Heraklion, Crete, Greece
24-28 June, 1996

Using inversion techniques to extract bottom scattering strengths and sound speeds from shallow-water reverberation data

Dale D. Ellis* and Peter Gerstoft**

*Defence Research Establishment Atlantic, P.O. Box 1012, Dartmouth, NS, B2Y 3Z7 Canada
**SACLANT Undersea Research Centre, Viale San Bartolomeo 400, 19138 La Spezia, Italy

The determination of scattering strengths in shallow water is difficult due to multipath effects. A method is described based on global inversion of reverberation data, which allows both the bottom scattering strength and geoacoustic parameters (bottom loss) to be determined simultaneously. The data are sub-kilohertz reverberation measurements from a shallow-water site north of Elba in the Mediterranean Sea. The forward model uses a computationally-efficient reverberation method based on normal modes, ray-mode analogies, and Lambert rule scattering. The global inversion technique uses genetic algorithms to compare model predictions with the data, and extract bottom scattering strengths and bottom sound speeds.

1. INTRODUCTION

In recent years several authors ([1–3], and references therein) have had reasonable success in matching normal-mode reverberation-model predictions with shallow-water reverberation data. They have usually noticed a strong dependence of the reverberation on the bottom properties (bottom loss). There has also been considerable progress in using global inversion techniques ([4], and references therein) to extract environmental properties from acoustic propagation data. In this paper we combine the two and describe a technique to extract bottom parameters and scattering strengths from reverberation data.

A number of authors indicate that bottom reverberation data are very useful in determining bottom parameters and have used reverberation data to extract both bottom loss and scattering information. Kamminga *et al.* [5] used an inversion procedure similar to the one used in this paper, parameterizing the scattering functions and bottom loss, but using a simple ray-based model in a deep-water environment. Bishop *et al.* [6] used a least-squares inversion with similar parameters on data from the continental shelf. Jin and Zhang [7] used simulated data and a stochastic inverse to obtain reflection loss and backscattering strength as a function of grazing angle. We use broadband data from shallow water, and look at the frequency dependence of the extracted bottom properties.

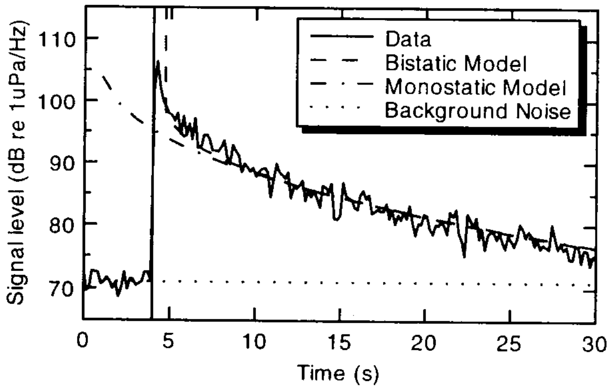

Figure 1: Reverberation vs time in 631 Hz band: data and model predictions.

2. FORWARD MODELLING WITH KNOWN GEOACOUSTIC MODEL

The bistatic normal-mode reverberation model OGOPOGO [2–3], used as the forward model, is an extension of the method of Bucker and Morris [8]. The propagation is described in terms of normal modes; the specific normal-mode compute engine is the DREA normal-mode model PROLOS [9]. The scattering is assumed to occur at the water-sediment interface and is determined by empirical scattering functions and ray-mode analogies; the scattering function is the Mackenzie-Lambert rule $\mu \sin\theta \sin\phi$, where θ and ϕ are the incident and scattered grazing angles, and μ is the adjustable Lambert coefficient. The environmental inputs required by the model include: the sound speed profile in the water, the geoacoustic model for the seabed (a series of isovelocity layers), the source-receiver separation, source-receiver depths, and the Lambert coefficient.

In June 1991 the SACLANT Undersea Research Centre conducted a reverberation experiment in a reasonably flat shallow-water area north of the island of Elba off the west coast of Italy. The sources were explosives (approximately 1-kg) detonated at a depth of 60 m, and the receiver was a horizontal array towed at a nominal depth of 60 m. The average water depth was 130 m, and the bottom was primarily clay, mixed with some sand and silt. There was a typical summer downward-refracting sound speed profile, with a mixed surface layer to about 35 m depth (see Refs [2–3]). Winds were light, about 5 knots, and the sea state was 1, so bottom reverberation dominated. The source and receiver were separated in range, making the geometry bistatic, but a monostatic model can be used once the direct arrival has decayed.

The hydrophone time series were sampled at 3000 Hz, and spectrally analyzed using 512-point FFTs, Hann weighted and non-overlapped, giving reverberation estimates every 0.17 s. The FFT bins were combined into approximate one-tenth-decade bands, from 25 to 1000 Hz. Ambient noise was fairly high due to nearby shipping, but data above 300 Hz had sufficient signal-to-noise to be used in the inversion process. The solid line of Fig. 1 shows a reverberation time series in the 631-Hz band and a source-receiver separation of 6 km; time zero corresponds to the instant of the detonation. The ambient noise level before the main blast is extrapolated (dotted line) for the duration of the shot to show that the reverberation is more than 5 dB higher than the background to about 30 s.

Frequency (Hz)	Source level (dB)	Lambert coefficient (dB)
316	198.8	−35
400	198.5	−36
501	196.4	−35
630	196.3	−35
794	195.5	−36
1000	192.8	−36

Table 1: Lambert coefficient using source levels shown and 1600 m/s bottom sound speed.

Figure 1 shows a comparison of the OGOPOGO calculation (dashed line) with the bistatic data, for a source-receiver separation of 6 km, and at a frequency of 631 Hz. The seabed model is a simplification of Jensen's [10] model based on fitting SACLANTCEN propagation loss data: it is a half-space with sound speed 1600 m/s, relative density 1.8, and attenuation of 0.09 dB/m-kHz. Since the reverberation is proportional to the Lambert coefficient, it is sufficient to do a single reverberation run with an arbitrary value for the coefficient, then by inspection of the model and data time series to re-adjust the Lambert coefficient to provide a reasonable overall fit to the data.

Table 1 shows Lambert coefficients for 6 frequencies using OGOPOGO with the geoacoustic half-space described above. The coefficients were adjusted to the nearest dB to provide a reasonable fit to the data. The source levels used for the frequency bands are also given in the table; any error in source levels or in the calibration of the data would be reflected in an equal but opposite shift in the Lambert coefficient. The Lambert coefficients are about 10 dB lower than the classical Lambert coefficient of −27 dB, indicating that the scattering in this region is relatively weak.

3. INVERSION FOR GEOACOUSTIC AND SCATTERING PARAMETERS

The bistatic reverberation model OGOPOGO was simplified into a computationally-efficient monostatic version for the inversion procedure and is incorporated into the efficient global optimization/inversion code SAGA [4]. Figure 1 includes a monostatic reverberation calculation (dash-dot line); note that the monostatic and bistatic calculations converge at 9 s, about 5 s after the main blast.

For the initial inversions, the seabed was assumed to be a bottom half-space. The parameters chosen for the inversion were bottom sound speed and Lambert scattering coefficient. The other parameters were as in the previous section. The data between 10 and 30 s (120 points) were used for the inversion. From Fig. 1, this is the region between the bistatic domain and ambient noise contamination. The model-data comparisons were made in dB, using a cost function with L_2 norm. For the first example the inversion was done independently for each frequency and used 1000 forward runs, taking from 2 to 15 minutes for each frequency on a DEC Alpha 600 workstation.

Table 2 (left side) shows the extracted Lambert coefficients and the sound speed in the bottom half-space. Note that the Lambert scattering gets stronger with frequency, and is accompanied by a sound speed that decreases with frequency. The results clearly

	Single-frequency inversion		Multi-frequency inversion
Frequency (Hz)	Lambert coefficient (dB)	Sound speed (m/s)	Lambert coefficient (dB)
316	−36.2	1610	−34.2
400	−37.3	1615	−35.1
501	−36.2	1610	−35.0
630	−32.3	1580	−34.6
794	−26.1	1545	−33.3
1000	−24.5	1540	−34.6

Table 2: Results of global inversion, using either the data from the single frequencies individually or combining the data from all the frequencies simultaneously.

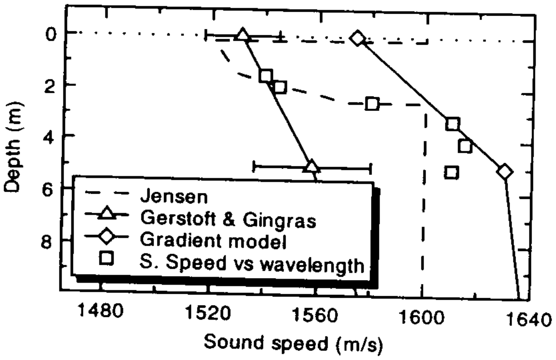

Figure 2: Sound speed vs depth, compared with geoacoustic profiles obtained by other authors.

show that a high sound speed is associated with a weak scattering coefficient, and vice versa. The rate of decay of the reverberation curve is determined by the bottom loss (sound speed and attenuation coefficient), while the overall level of the reverberation is determined by the Lambert coefficient and the sound speed. Since the sound speed should be independent of frequency, we believe there is a sound-speed gradient in the bottom and this is an artifact of the half-space assumption of the model.

We attempted to estimate this sound-speed gradient by inversion using a multilayer bottom. For single frequencies there did not seem to be a consistency in the inverted gradients, so the information from all the frequencies were combined into one single inversion. The inverted parameters were the Lambert scattering coefficients for each frequency as well as a single sound speed profile in the sediment for all frequencies. The disadvantage of this is that now we have to estimate more parameters in one inversion. This will in general require more forward modelling runs, and each forward run requires the field to be determined for all 6 frequencies. We modelled the profile by a gradient down to 5 m and another gradient down to 20 m, and estimate the sound speed at the bottom, at 5 m and at 20 m. The attenuation was fixed at 0.09 dB/m-kHz. The result of this inversion for the Lambert scattering coefficients is shown in Table 2 (right side), and the estimated

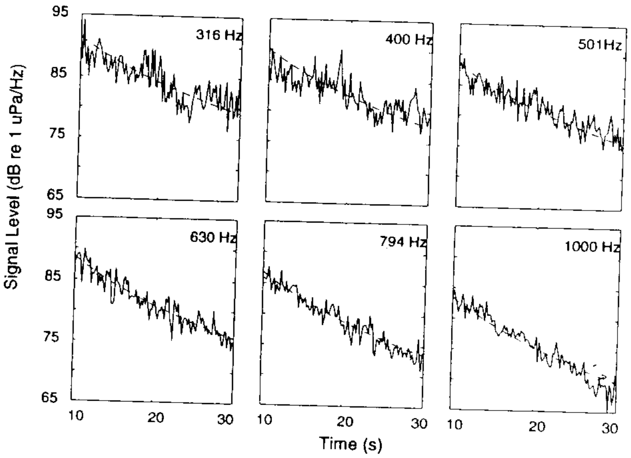

Figure 3: Fits to data at all 6 frequencies using multi-frequency inversion.

sound speed profile is plotted in Fig. 2. Figure 3 shows the comparison of the fits with the data over the 10 to 30 s time frame. The agreement is better than the manual approach and constant geoacoustic model used for Figure 1, but the fit is not as good as the ones obtained when inverting for each frequency separately (not shown).

Figure 2 shows some other seabed sound speed profiles for the area. Jensen's [10] geoacoustic model used a 2.5 m sediment layer over a halfspace of speed 1600 m/s, relative density of 1.8, attenuation of 0.094 dB/m-kHz. The sediment layer was assigned a relative density of 1.75, attenuation of 0.08 dB/m-kHz, and a sound speed profile ranging from about 1520 m/s to 1570 m/s (aside from a thin 1600 m/s layer near the surface). Ellis [2–3] simply used Jensen's basement throughout. Gerstoft and Gingras [11] fitted propagation data along a similar track by inverting over 6 frequencies between 170 and 330 Hz in a range-dependent environment. Their best fit has a gradient in the bottom and is shown in Figure 2, with error bars. The other parameters used in the upper portion of the seabed are relative density 1.5 and attenuation 0.08 dB/m-kHz. Our extracted profile for the gradient model has somewhat higher sound speeds than the other seabed models. An intriguing comparison is to plot in Fig. 2 our extracted sound speeds (Table 2, left side) at a depth of one wavelength. The depth scale should only be interpreted qualitatively; perhaps one should multiply it by a factor that could be frequency dependent. However, it illustrates the effect of mode functions penetrating into the seabed, and follows the trend of Jensen's profile.

We are pursuing inversions with other parameters; however, a few words of caution are in order. Reverberation data are clearly more noisy than data used with state-of-the-art matched-field inversion techniques. Thus it is expected that less information can be extracted from this type of data. Our data do not include the phase, the area is neither uniform nor flat, the scattering function assumes a Lambertian grazing angle dependence, and the scattering may be coming from the sub-bottom and not the interface. However, Jin and Zhang [1] indicate that the reverberation intensities are not very sensitive to the actual form of the scattering function.

4. SUMMARY

The procedure enables one to invert for bottom parameters and scattering parameters simultaneously. The inversion for scattering strength is sensitive to bottom parameters—sound speed in particular. Though further investigations are needed, these initial results suggest that there is a sound speed gradient in the bottom, and that the scattering strengths are almost independent of frequency.

The procedure is computationally efficient, depends on only a simple source and hydrophone receiver, and could be the basis for a quick assessment of the propagation and reverberation characteristics in an unknown but uniform area. In a non-uniform area, directional beam patterns would help in determining the spatial variability, though a range-dependent reverberation model would likely be necessary.

REFERENCES

[1] G. Jin and R. Zhang, "The numerical simulation of average reverberation intensities in shallow water," Chinese J. Acoustics, **9**, 36–44 (1990).

[2] D.D. Ellis, "Shallow water reverberation: normal-mode model predictions compared with bistatic towed-array measurements," IEEE J. Oceanic Engineering, **18**, 474–482 (1993).

[3] D.D. Ellis, "A shallow-water normal-mode reverberation model," J. Acoust. Soc. Am., **97**, 2804-2814 (1995).

[4] P. Gerstoft, "Inversion of acoustic data using genetic algorithms and a posteriori probability distributions," J. Acoust. Soc. Am., **95**, 770–782, (1994).

[5] S.D. Kamminga, D.D. Ellis, and P. Gerstoft, "Extraction of both bottom backscattering strength and reflection loss by inversion of reverberation measurements," J. Acoust. Soc. Am., **94**, 1844. (1993). Abstract only.

[6] J.L. Bishop, M.T. Sundvik, and D.W. Grande, "Inverting sea bed acoustic parameters from reverberation data," in O. Diachok *et al.* (eds.), *Full Field Inversion Methods in Ocean and Seismio-Acoustics*, (Kluwer, Dordrecht, NL, 1995), pp. 401–406.

[7] G. Jin and R. Zhang, "Inversion of shallow water reverberation for bottom reflection and scattering coefficients," in *Proceedings of 15th International Congress on Acoustics*, Trondheim, Norway, 26–30 June, 1995, pp. 257–260.

[8] H.P. Bucker and H.E. Morris, "Normal-mode reverberation in channels or ducts," J. Acoust. Soc. Am. **44**, 827–828 (1968).

[9] D.D. Ellis, "A two-ended shooting technique for calculating normal modes in underwater acoustic propagation," DREA Report 85/105, September 1985.

[10] F.B. Jensen, "Comparison of transmission loss data for different shallow water areas with theoretical results provided by a three-fluid normal-mode propagation model," in O. F. Hastrup and O. V. Olesen, *Sound Propagation in Shallow Water*, SACLANTCEN Conference Proceedings CP-14, November 1974, pp. 79–92.

[11] P. Gerstoft and D.F. Gingras, "Parameter estimation using multi-frequency range-dependent acoustic data in shallow water," to appear, J. Acoust. Soc. Am. (1996).