Using offshore seismic surveys as acoustic sources of opportunity for geoacoustic inversion

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Commercial offshore seismic surveys involve the use of powerful acoustic sources consisting of arrays of airguns. These sources produce frequent, loud, impulsive sounds at precisely timed intervals, at accurately known positions during surveys that may last for several months. By deploying a low-cost acoustic receiving system in the vicinity of such a survey scientists can acquire high quality data for geoacoustic inversion experiments in an extremely cost-effective manner. This paper discusses the various factors that must be considered when using such data for geoacoustic inversion, including the prediction of source spectra and array directionality, and provides some examples

1 Introduction

Geoacoustic inversion experiments involving active sources are usually complicated and expensive to mount. However, in many parts of the world the imperative of finding more reserves of oil and gas has resulted in a great deal of seismic exploration. This exploration requires the use of powerful, low frequency acoustic sources with accurately known characteristics, that are very precisely navigated, during surveys that often last for several months. These sources have one particularly desirable characteristic for the underwater acoustics researcher - someone else is paying for them!

Section 2 of this paper describes the characteristics of typical offshore seismic survey sources, and Section 3 provides an example of the use of a seismic survey as a source of opportunity for a geoacoustic inversion experiment.

2 Seismic source characteristics

The vast majority of commercial offshore seismic surveys are carried out using acoustic sources comprising horizontal planar arrays of airguns. When electronically triggered, each airgun releases high-pressure compressed air into the water column, resulting in a sharp, impulsive sound, followed by a decaying oscillation due to successive expansions and contractions of the air bubble. The acoustic signal produced by a small (0.33 litre) airgun is shown in Fig. 1.

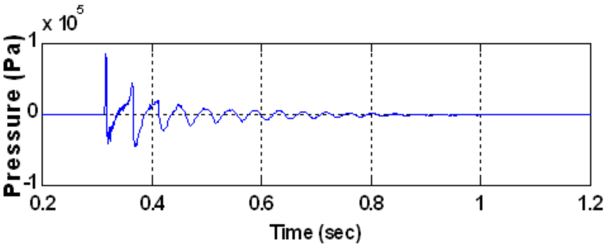

Fig. 1 Acoustic signal recorded 0.87m from a 0.33 litre (20 cui) airgun operating at 10 MPa.

For the purposes of seismic exploration, the initial impulse is a desirable signal, whereas the signal due to the oscillating bubble is undesirable. Seismic arrays use two main methods of suppressing the bubble signal:

1. Guns of different volumes are used in the array. The bubble oscillation frequency depends on the bubble volume so the bubble signals from different sized guns tend to cancel.

2. The array is towed very shallow - typically 4 m to 10 m below the water surface. The sea-surface reflected signal is inverted with respect to the direct signal so, in the vertically downward direction (which is of most interest to the seismic community), the relatively long period bubble pulse destructively interferes with its reflection, whereas the very short initial impulse is still time-separated from its reflection.

As can be seen from Fig. 2, these measures can be very effective and produce waveforms with highly desirable characteristics for seismic exploration.

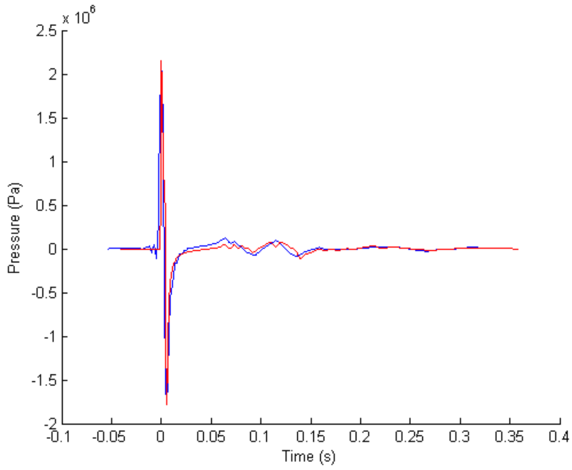

Fig. 2 Comparison of two different simulations of the signal produced by a commercial airgun array with a total volume of 28.8 litres. Plot is for the vertically downward direction and includes the effect of the surface reflection.

However, in geoacoustic inversion experiments it is the near-horizontal propagation of sound that is of most interest, and it is therefore the horizontal plane characteristics of the source signal that are required. These can be predicted in a straightforward way by considering the individual airguns to be omni-directional sources and then appropriately delaying and summing their waveforms to produce the effective array source signal in any desired direction. This is the approach taken in the Centre for Marine Science and Technology's (CMST's) airgun array model, which uses a modification of the free-bubble oscillation method given in [1] to predict the acoustic signals produced by the individual guns.

The results of applying this model to a typical commercial airgun array are shown in Fig. 3, which shows the source spectral level of the array in the horizontal plane as a function of azimuth and frequency. At frequencies below 100 Hz this array is close to omnidirectional, whereas it becomes increasingly directional at higher frequencies.

The large amount of high-frequency energy emitted in the array broadside direction (azimuths of 90° and 270°) is typical of commercial seismic arrays, and is very apparent in recordings of seismic sources passing stationary receivers.

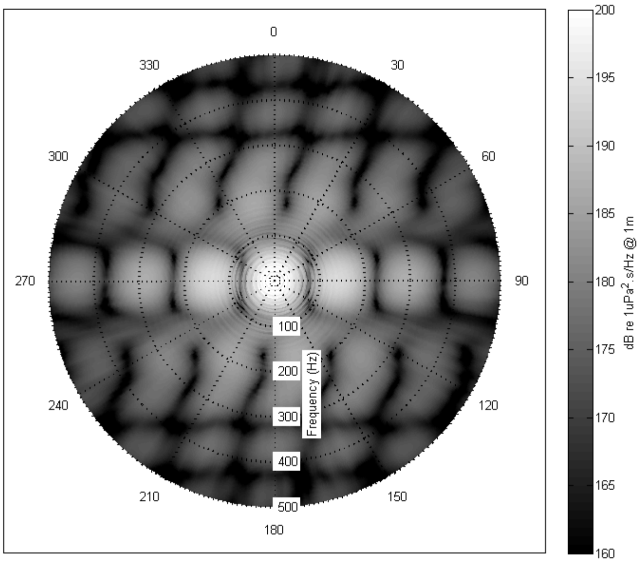

Fig. 3. Modelled horizontal plane beam pattern for a commercial airgun array. Frequency increases radially from the centre. Gray-scale represents source spectral level. An azimuth of 0° corresponds to the tow direction. Surface reflection is not included.

As can be seen in Fig. 4, the horizontal, planar geometry of the array results in a weak dependence of source spectral level on elevation angle for angles near horizontal. This simplifies the modelling process for geoacoustic inversion applications as, in most cases, the vertical directionality of the array can be ignored.

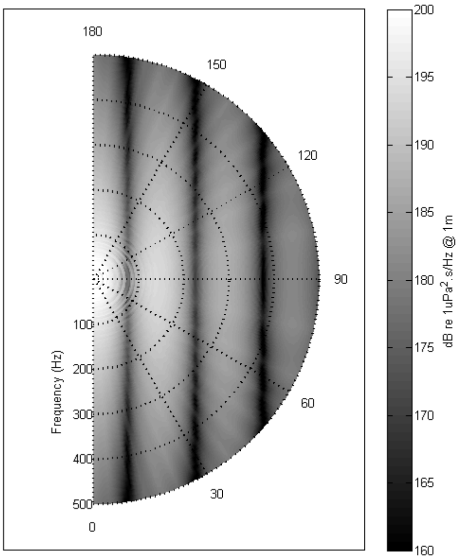

Fig. 4. Modelled vertical plane beam pattern for the same array as Fig. 3 in the array broadside direction (90° azimuth). An elevation of 0° is vertically downward. Surface reflection is not included.

3 Case study

The example considered here relates to a commercial two-dimensional seismic survey carried out off Dongara, Western Australia (see Fig. 5). Three autonomous acoustic recording systems were deployed during the survey, each with a bottom-mounted hydrophone. These systems are small enough to be deployed and retrieved from a fishing vessel and were left in-situ for the duration of the survey (12 days). Only data from one of the recording systems (1) is considered here.

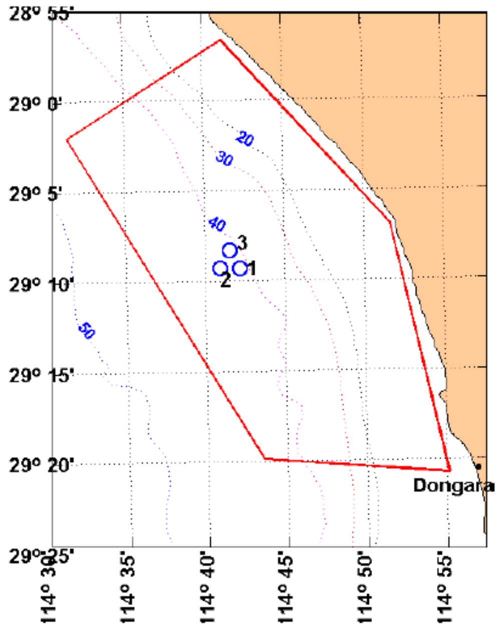

Fig. 5 Case study seismic survey location. Solid lines indicate boundary of seismic survey, dotted lines are depth contours with depths given in metres. Circles show locations of autonomous recording systems. Data from recording system 1 were used for this study.

A total of 27478 airgun array signals (shots) were recorded by this receiver during the survey. Fig. 6 shows the range and bearing of the receiving system relative to the seismic array for each shot, calculated from the survey navigation data provided by the seismic contractor. Signals were recorded at ranges that varied from less than 1 km to more than 30 km.

With this wealth of data one can afford to be choosy, so it was decided to only use data from propagation paths parallel to the bathymetry contours in the inversion. This allowed the wavenumber integration program, SCOOTER [2] to be used for forward modelling. Although slower than other methods, wavenumber integration produces accurate results at low frequencies in shallow water with seabeds of arbitrary complexity, including layers with significant shear [3]. Apart from speed, its only limitation is that it is strictly range independent.

In order to restrict the analysis to signals with a high signal to noise ratio, it was decided to only use shots at ranges of less than 10 km. Shots 25165 to 25525 were found to meet both these criteria and were chosen for analysis.

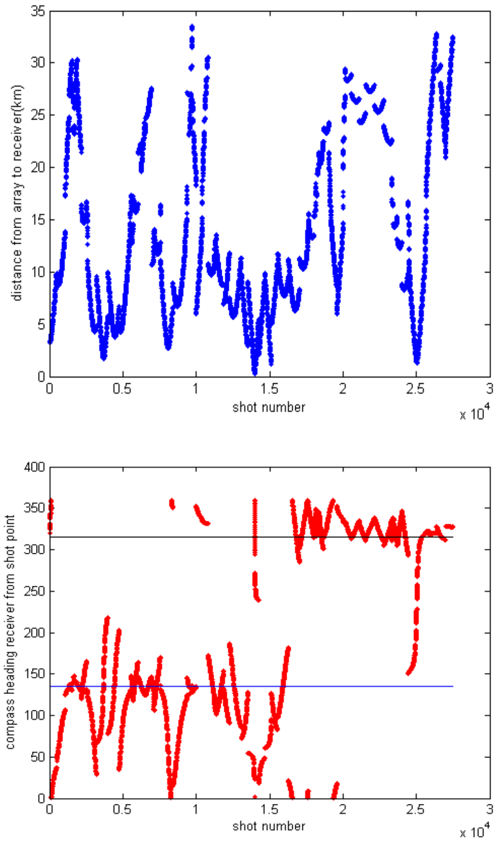

Fig. 6. Top plot shows range of recording system from seismic source for all shots recorded during the survey. Bottom plot shows compass bearing of receiving system from seismic source for all shots. Horizontal lines correspond to azimuths that are parallel to the bathymetry contours.

The inversion process was carried out in the following steps:

1. An appropriate geoacoustic model of the seabed was chosen. The few rivers on Australia's western coast discharge very little sediment, so seabeds on the continental shelf typically consist of limestone pavements overlain by thin layers (typically no more than a few metres) of unconsolidated sediment, usually coarse sand.

2. The received signals from the chosen airgun shots were analysed to compute the integrated squared pressure in 1/3 octave bands with centre frequencies of 10, 12.5, 16, 20, 25, 32, 40, 50, 63, 80, and 100 Hz.

3. The survey navigation data were used to compute the azimuth of the receiver relative to the seismic array for each shot. CMST's seismic array model was then used to compute the far-field horizontal plane source spectrum corresponding to this azimuth, which was then integrated over the same 1/3 octave bands to obtain source levels.

4. The 1/3 octave band source levels were then combined with the receive levels to obtain the transmission loss in each band.

5. Forward modelling was carried out using SCOOTER, which was run at a number of frequencies in each 1/3 octave band. Five frequencies were used for bands with centre frequencies up to 25 Hz, 11 frequencies for bands from 32 Hz to 63 Hz, and 20 frequencies from 80 Hz to 100 Hz. The average transmission loss in each band was calculated by averaging the squared pressure amplitude from the runs at all frequencies in the band.

6. A measure of the difference between the modelled and measured transmission loss results (known as a cost function) was obtained by taking the mean square dB difference between modelled and measured transmission losses. The mean was calculated over both range and 1/3 octave bands.

7. The simulated annealing algorithm described in [4] was then used to find the set of seabed parameters that minimised the cost function.

Two separate runs of the optimisation routine were carried out, which resulted in somewhat different parameter values with very similar final costs. The results are summarised in Table 1.

Parameter	**Range**	**Run 1**	**Run 2**
Sediment layer:			
Thickness (m)	0.1 - 8	1.2	1.1
Density (kg.m^{-3})	1500 - 2200	1870	1580
p-wave speed (m.s^{-1})	1600 - 2100	1785	1910
p-wave attenuation (dB/.λ)	0.01 - 1	0.39	0.46
s-wave speed (m.s^{-1})	0 - 800	262	600
s-wave attenuation (dB/.λ)	0.01 - 1	0.22	0.8
Basement:			
Density	2000 - 3000	2400	2300
p-wave speed	1800 - 3600	2683	2906
p-wave attenuation	0.01 - 7	0.12	0.35
s-wave speed	900 - 1800	1268	1769
s-wave attenuation	0.01 - 7	0.02	0.28
Final cost (dB^2)		24.6	25.6
Root mean square difference between measured and modelled TL (dB)		5.0	5.1

Table 1 Optimisation parameters and results.

A comparison of measured transmission loss vs. range, with modelled results calculated using the two different optimised parameter sets, revealed that in each case there was good agreement at some frequencies, but relatively poor agreement at others. The frequencies at which good agreement was obtained differed between the parameter sets, indicating that the two sets represent different local minima of the cost function.

Fig. 7 shows some representative plots from Run1, in which very good agreement was obtained for frequency bands centred at 25, 32, 63, and 100 Hz, moderate agreement at 12.5, 16, 50 and 100 Hz, and poor agreement at 10, 20 and 40 Hz. Comparing measured and modelled results using the Run 2 parameters, there was very good agreement at 10, 32, 40 and 50 Hz, moderate agreement at 16, 25, and 63 Hz, and poor agreement at 12.5, 20, 80 and 100 Hz.

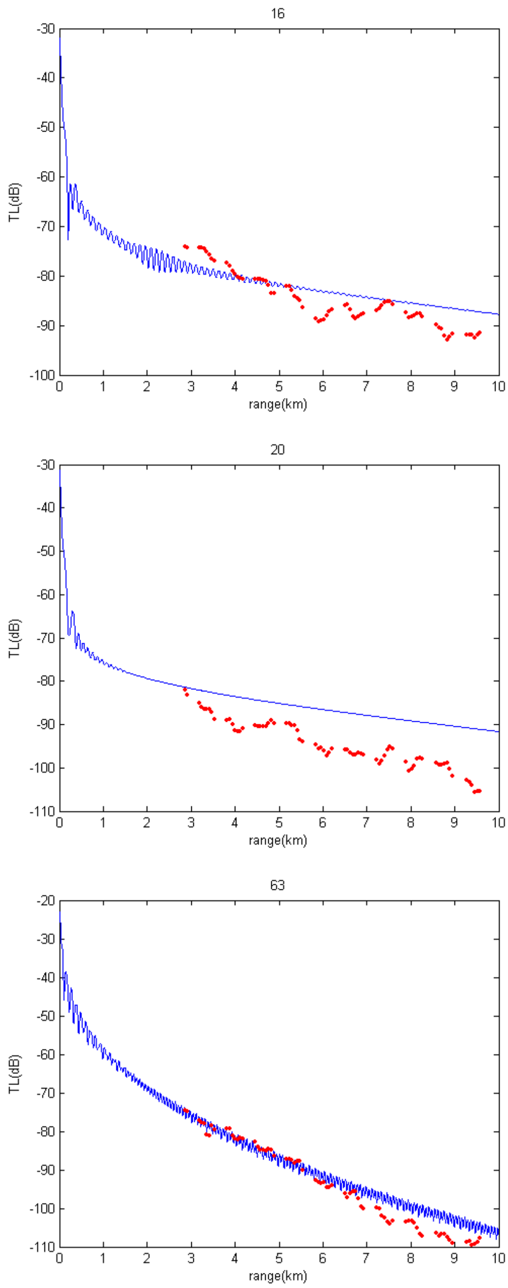

Fig. 7 Measured (points) and modelled (line) transmission loss vs. range for optimised parameters from run 1 for frequencies of 16 Hz (top), 20 Hz (middle) and 63 Hz (bottom).

There are a number of possible reasons for the inability of the inversion procedure to find a set of parameters that provided a good match between modelled and measured data in all frequency bands. These are still being investigated, but include:

1. Insufficient search of the parameter space. In retrospect, inverting for all eleven parameters was probably an unwise thing to do, and the available computational time could have been better utilised by fixing at nominal values the parameters that were likely to have a relatively minor influence on the received signals (eg. layer density, shear speed and attenuation). The optimisation algorithm would then be able to carry out a more thorough search of the lower dimensionality parameter space, with the same number of cost function evaluations.

2. A mismatch between the assumed geoacoustic model and reality. A preliminary analysis was carried out of the Head waves associated with the received signals [5]. Head waves are signals arriving at the receiver in advance of the through-water pulse after travelling via seabed-refracted paths. This analysis showed the likely presence of a deep basement with a compressional sound speed of about 3800 $m.s^{-1}$, commencing at a depth of approximately 1000 m. The presence of this deep basement may have had a significant effect on the received signals in the lowest frequency bands.

3. Range dependence of geoacoustic properties. This analysis has assumed the geoacoustic properties of the seabed are strictly range independent, and that any variations in bathymetry in the chosen propagation direction is insignificant. The validity of both these assumptions is yet to be tested.

4. Source modelling errors. Some discrepancies have been noted between the spectra of source signals produced by the CMST airgun model and a reference signal provided by the seismic contractor. The possible impact of these discrepancies on the inversion process needs to be investigated.

5 Conclusion

Commercial seismic surveys provide a very useful sound source for geoacoustic inversion studies and together with small, autonomous receiving systems, open up the possibility of carrying out a wide range of experiments at a very modest cost.

Although requiring significantly more work to refine, the case study presented here demonstrates the potential of this approach.

Acknowledgments

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