# PROPAGATION AND INVERSION OF AIRGUN SIGNALS IN SHALLOW WATER OVER A LIMESTONE SEABED

Li Fan[a], Alec J Duncan[b], Alexander Gavrilov[b]

[a] Institute of Acoustics, Chinese Academy of Science, Beijing, China.
[b]Centre for Marine Science and Technology, Curtin University of Technology, Western Australia.

Alec J Duncan, Centre for Marine Science and Technology, Curtin University of Technology, GPO Box U1987, Perth, Western Australia, 6845, Fax +61 8 9266 4799, a.duncan@cmst.curtin.edu.au

***Abstract:*** *Limestone seabeds with thin or non-existent coverings of unconsolidated sediment are common around the southern Australian continental shelf and often provide strong coupling between the sound wave in the water and the shear wave in the seabed. Sound reflection from such seabeds is very weak except at the p-wave critical angle, which results in the acoustic energy transmitted to long range in the water column being dominated by high-speed Head waves. The characteristics of acoustic propagation in such an environment have considerable practical importance for the propagation of the sound produced by marine seismic surveys and are investigated in this paper, which compares measured signals from a commercial seismic survey with the results of numerical modelling. Techniques for inverting for the geoacoustic parameters of the seabed are also considered.*

***Keywords:*** *Acoustic, propagation, limestone, calcarenite, geoacoustic inversion*

## 1. INTRODUCTION

Most of the southern and western continental shelf of Australia is capped by calcarenite, a relatively soft type of limestone formed during past sea level low-stands when unconsolidated sediments with a high proportion of calcium carbonate were exposed to fresh water [1]. The fresh water partially dissolved the calcium carbonate, which then re-solidified, bonding the sediment grains together. There are few rivers of any significance along this coastline and those that do exist bring very little sediment to the ocean. The result is that over the majority of the shelf the calcarenite is covered by only a thin veneer (typically less than 1m) of unconsolidated sediment of mainly marine origin.

Calcarenite is a highly variable material, but the geoacoustic properties given in Table 1 appear to be typical [2].

The plane wave reflection coefficients of calcarenite seabeds covered by various thicknesses of sand are plotted in Fig. 1. Of particular note is the very rapid reduction in reflection coefficient with increasing angle that occurs for small grazing angles when there is no sand cover. This is due to the conversion of incident acoustic energy into shear waves in the calcarenite. This dip is progressively filled in as the thickness of the sand layer increases.

| Material | Calcarenite | Sand |
|---|---|---|
| Density ($kg.m^{-3}$) | 2400 | 1800 |
| Compressional wave speed ($m.s^{-1}$) | 2800 | 1700 |
| Compressional wave attenuation (dB/wavelength) | 0.1 | 0.8 |
| Shear wave speed ($m.s^{-1}$) | 1400 | - |
| Shear wave attenuation (dB/wavelength) | 0.2 | - |

*Table 1: Geo-acoustic parameters used for reflection coefficient calculation.*

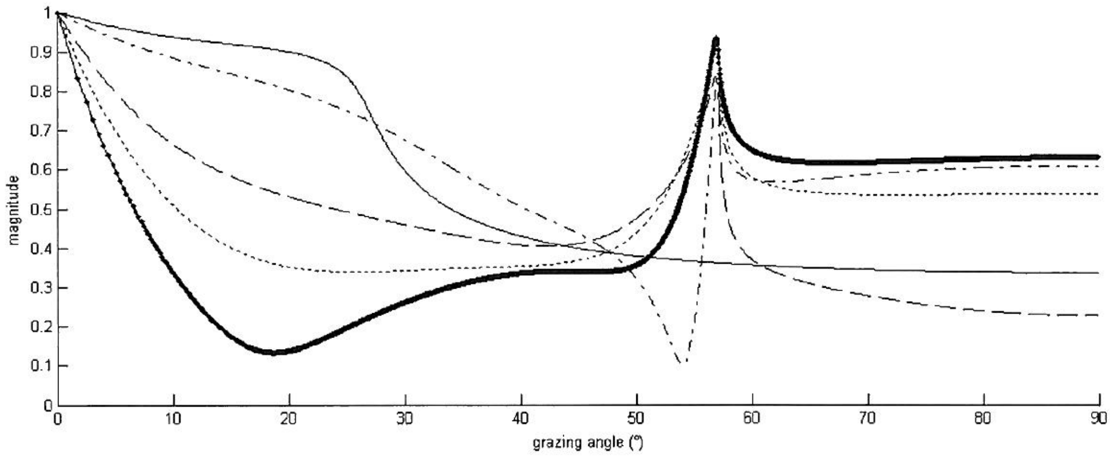


Fig. 1. Magnitude of plane wave reflection coefficient vs. grazing angle for seabeds comprising a calcarenite halfspace covered by sand of thickness 0λ (thick line), 0.1λ (dotted line), 0.2λ (broken line), 0.5λ (dash-dot line), and ∞ (thin solid line). λ is compressional wave wavelength in the sand layer, geoacoustic parameters are given in Table 1.

Another important feature of this plot is the sharp peak at 57°, which corresponds to the p-wave critical angle at the calcarenite interface. Sound incident at grazing angles fractionally less than this will propagate along the interface at the calcarenite compressional wave speed, re-radiating into the water column. Such waves are called Head or lateral waves and are discussed in detail in [3].

The following sections present a comparison between measured data and modelling results for acoustic signals recorded in a shallow water environment with a seabed of this type.

## 2. COMPARISON BETWEEN MEASURED DATA AND MODEL OUTPUT

The measured data presented here were recorded during a commercial two-dimensional seismic survey that was carried out off Dongara, Western Australia, centred on 29°10'S, 114°45'E, in water depths ranging from 10m to 45m. The receiving system was a bottom mounted autonomous acoustic recording system that was left in-situ for the duration of the survey (12 days). A total of 27478 airgun array signals (shots) were recorded by this receiver during the survey, but only shots close to the 40m bathymetry contour have been included in the analysis to facilitate using the range independent wavenumber integration propagation model SCOOTER [4] for the comparison. The source depth was 4m and a total of 15001 shots were analysed with source -receiver separations varying from 1 km to 16 km. The Centre for Marine Science and Technology's airgun array model was used to obtained the source spectrum of the array in the direction of the receiver, and this was combined with the narrowband spectrum of the received signal to obtain the transmission loss as a function of range and frequency.

An initial Head wave arrival time analysis [5] was carried out in order to obtain a starting point for a geoacoustic model for the seabed. The Head waves from the higher speed layers were well defined, but the identification of a Head wave from the sediment layer was uncertain. The resulting geoacoustic model is given in Table 2. Compressional wave speeds and layer thicknesses are from Head wave analysis, shear speeds were taken as 50% of compressional wave speeds for elastic layers. Other parameters are typical values for sediments with similar compressional wave speeds. SCOOTER was then run to obtain transmission loss as a function of frequency and range to compare with the modelled data.

A comparison between measured and modelled results is shown in Fig. 2. At frequencies below 120 Hz there is a pronounced horizontal banding in the measured data, which is even more pronounced in the model results. This is similar to the effect expected from shearwave resonances in an upper sediment layer [6], however, the presence of the banding in the modelled data, which does not include an upper sediment layer, indicates that this is not the explanation in this case.

The model results capture the general characteristics of the measured data very well, including the broad maximum in the transmission loss that occurs at all ranges at just over 100 Hz, and the wedge shaped region of much lower transmission loss at higher frequencies, with its characteristic modal interference patterns.

An expanded view of the low frequency portion of the plot is given in Fig. 3. This shows good agreement between the frequencies of the lowest frequency horizontal bands, but progressively poorer agreement at higher frequencies. SCOOTER also predicts sharper, more distinct bands extending out to longer range than those seen in the data.

| Layer | Water column | Calcarenite | Limestone basement |
|---|---|---|---|
| Thickness (m) | 42.5 | 448 | $\infty$ |
| Density ($kg.m^{-3}$) | 1024 | 2400 | 2400 |
| Compressional wave speed ($m.s^{-1}$) | 1523 | 2426 | 3550 |
| Compressional wave attenuation (dB/wavelength) | 0 | 0.15 | 0.15 |
| Shear wave speed ($m.s^{-1}$) | - | 1213 | 1770 |
| Shear wave attenuation (dB/wavelength) | - | 0.3 | 0.3 |

*Table 2: Geoacoustic parameters used for model comparison with measured data.*

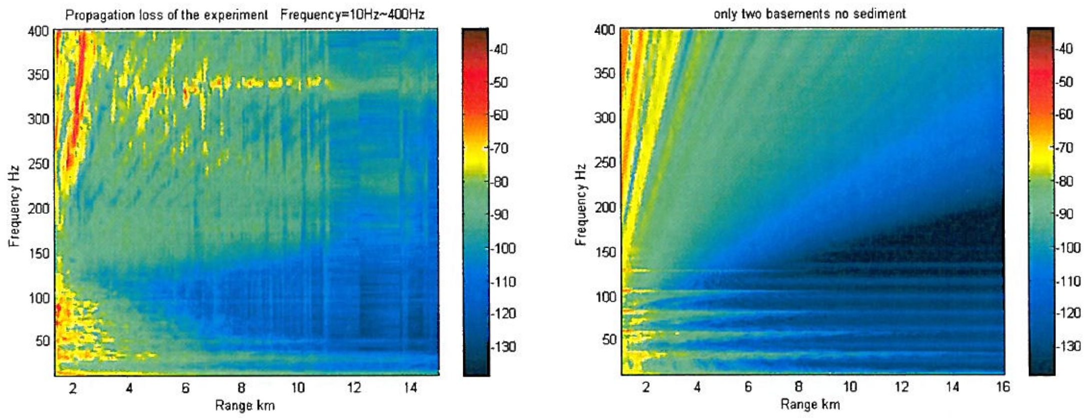


Fig. 2. Transmission loss in dB as a function of range and frequency from measured data (left) and propagation modelling (right).

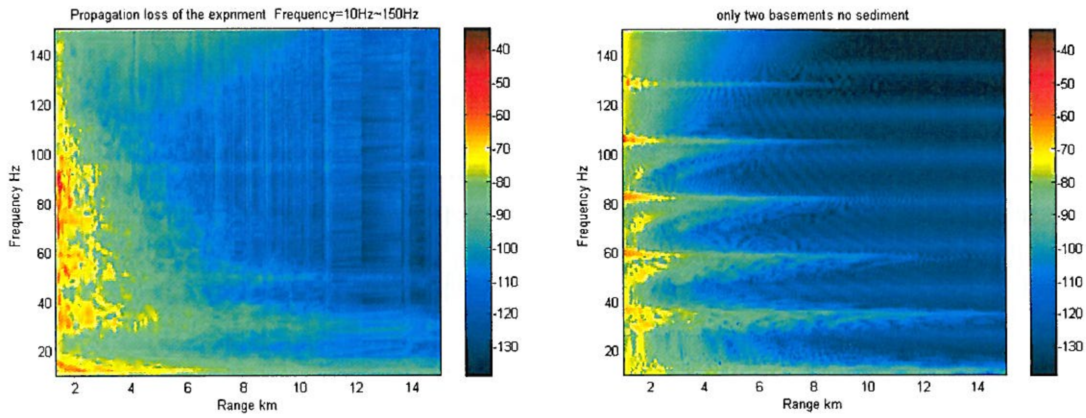


Fig 4. Expanded view of low frequency portion of Fig. 2.

## 3. DISCUSSION

The striking features of the transmission loss plots shown in the previous section can be explained in terms of the calcarenite halfspace reflection coefficient plot given in Fig. 1.

The horizontal bands occur at the frequencies where the in-water modes have grazing angles at the seabed that correspond to the sharp spike in the reflection coefficient at the compressional wave critical angle. The lowest frequency band occurs when mode 1 satisfies this condition, the second band when mode 2 satisfies it, etc. At these frequencies there is reinforcement between the in-water modes and the Head waves, and strong Head wave arrivals are observed.

As frequency is increased, the seabed grazing angle for a given mode reduces, so the mode can be thought of as traversing the reflection coefficient curve in Fig. 1 from right to left.

At low frequencies all the modes have substantial grazing angles and, because of the sharp dip in the reflection coefficient are strongly attenuated unless one happens to be at the compressional wave critical angle. At frequencies above about 120 Hz the grazing angle of the lowest order mode has reduced to the point where its reflection coefficient is high enough to allow it to make a noticeable contribution to the received field. As the frequency is increased further, the mode 1 reflection coefficient continues to increase, as do the reflection coefficients of the higher order modes so that they also start to contribute significantly to the received signal, giving rise to the modal interference patterns seen above about 170 Hz.

The reasons for the differences between model results and data for the frequencies, spectral width and strengths of the horizontal bands require further investigation, but could include variations in water depth and geoacoustic parameters with range.

### 3.1. Implications for geoacoustic inversion

The very different transmission loss regimes evidenced by this type of seabed present both challenges and opportunities for geoacoustic inversion. The prominent low frequency banding potentially provides useful information to aid the inversion process, but because of its narrowband nature, would be very easy to miss if inversion was carried out on the basis of a small number of discrete, pre-determined frequencies. For a simple calcarenite halfspace seabed, the frequencies of the horizontal bands correspond to the modal cut-off frequencies and can therefore be used to directly calculate the compressional wave speed in calcarenite. However, when this method was applied to the data presented here it was only found possible to match the frequencies of a few of the bands (Fig. 3). Further work is required to generalise this method to more complicated seabeds.

At higher frequencies more traditional geoacoustic inversion methods based on a comparison between modelled and measured transmission loss at a subset of frequencies should be effective and would be expected to be sensitive to at least some of the properties of the upper sediment layer.

## 4. CONCLUSIONS

The propagation of sound in shallow water over calcarenite seabeds typical of much of the southern and western sections of Australia's continental shelf displays two distinct frequency regimes. Low frequency propagation occurs in a number of narrow frequency bands determined by the requirement that the grazing angle of a mode at the seabed corresponds to the calcarenite compressional wave critical angle. Much of this energy propagates through the seabed as Head waves. Through-water propagation corresponding to modes with much smaller grazing angles becomes more important at higher frequencies. These different regimes can potentially be exploited to aid the process of geoacoustic inversion, but this requires further work.

## 5. ACKNOWLEDGEMENTS

Dr Li Fan's visit to the Centre for Marine Science and Technology to work on this project was funded by the Australian Academy of Science. The authors wish to acknowledge the support of Roc Oil Company Ltd. and its partners in exploration permit WA-286-P for providing the details of the seismic survey analysed in the case study, and also for funding the recording system deployment and data extraction.

## REFERENCES

[1] **E C F Bird**, Geomorphology of the sea floor around Australia, In *Australia's Continental Shelf,* J R V Prescott (editor), Nelson, 1979, pp 1-21, ISBN 0 17 005397 0..

[2] **A J Duncan, A Gavrilov and T Hu,** *Using offshore seismic surveys as acoustic sources of opportunity for geoacoustic inversion,* Proceedings, Acoustics '08, Paris, June 29 to July 08, 2008.

[3] **L Brekovskikh and Y Lysanov**, *Fundamentals of Ocean Acoustics*, 3rd Ed., Springer-Verlag NY, 2003, ISBN 0-387-95467-8.

[4] **M B Porter**, *Acoustics Toolbox,* Available from http://oalib.hlsresearch.com/FFP/index.html (2007)

[5] **M V Hall**, *Measurement of seabed sound speeds from Head waves in shallow water,* IEEE J. Oc. Eng., 21 (4), pp.413-422, October 1996.

[6] **M A Ainslie,** *Conditions for the excitation of interface waves in a thin unconsolidated sediment layer,* J. Sound and Vibration, 268 (2003), pp 249-267.