Acoustic propagation over limestone seabeds

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ABSTRACT

The western and southern Australian continental shelf is mainly composed of a type of limestone called calcarenite, overlain by a thin veneer of unconsolidated sediment. The shear wave speed in calcarenite is slightly less than the sound speed in water, which leads to some important, and rather unexpected propagation effects that are of considerable practical importance for such tasks as predicting the performance of passive sonar, and modelling the environmental impacts of marine seismic surveys. This paper introduces the physics of propagation in such an environment and provides a comparison between modelled and measured data. The implications for common modelling tasks are also discussed.

INTRODUCTION

A large part of Australia's continental shelf consists of a type of limestone called calcarenite, overlain by a thin, patchy veneer of unconsolidated sediment. This paper provides an introduction to the physics of underwater acoustic propagation over such a seabed, which has unusual characteristics that are important to take into account when carrying out modelling for environmental impact assessments or defence applications.

The primary purpose of this paper is to make these characteristics more widely known, particularly as more acoustic consultants find themselves carrying out underwater acoustic propagation modelling, something that was previously the sole preserve of the specialist underwater acoustician.

GEOLOGICAL CONTEXT

Australia's southern and western continental shelf (Figure 1) is formed from sediments of marine origin which are composed primarily of the skeletal remains of marine organisms and are consequently high in calcium carbonate (Bird 1979).

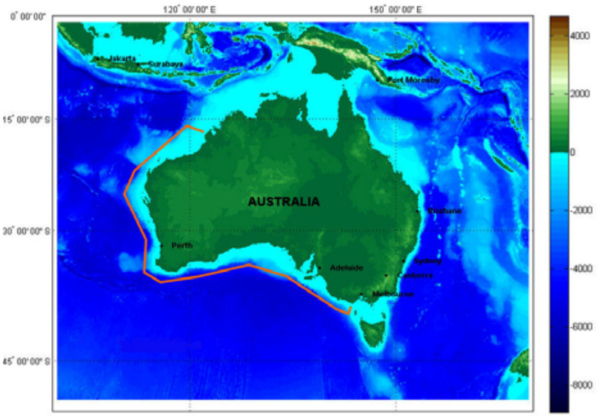

Figure 1. Map showing Australia's continental shelf and the approximate extent (orange line) of the sediment starved carbonate platform.

During past sea level low-stands the shelves were exposed to the atmosphere and to freshwater from rainfall, which dissolved the calcium carbonate. The calcium carbonate subsequently re-solidified, binding the sediment grains together and forming a type of limestone called calcarenite. The hinterland of this region is low-lying and arid, so that there is little sediment input from the land, and as a result there is only a thin (typically less than 1 m), patchy, veneer of unconsolidated marine sediment overlying the calcarenite.

GEOACOUSTIC PROPERTIES

Calcarenite is a variable material so its geoacoustic properties change from place to place. Typical values of geoacoustic characteristics are given in Table 1. As will be discussed later, from the point of view of underwater acoustic propagation, an important parameter is the shear wave speed which, at around 1400 ms^{-1} is slightly less than the water column sound speed of about 1500 ms^{-1}.

The table also lists some typical geoacoustic parameters for sand which will be used for comparison.

Table 1. Representative geoacoustic properties of calcarenite and sand.

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	-

Figure 2 compares the plane-wave pressure reflection coefficient of a calcarenite seabed with that of a sand seabed. To understand the marked differences between these two curves it is helpful to consider the ray diagrams shown in Figure 3.

The shear speed in sand varies between 250 and 350 $m.s^{-1}$ and is sufficiently low that it can usually be modelled as a fluid, which can transmit compressional waves, but not shear waves. (This isn't always true, see Ainslie 2003 for an example where this approximation breaks down.) Because the compressional wave speed in the seabed is higher than the sound speed in the water, the sound refracts upwards as it enters the seabed. If sound is incident on the interface at a steep grazing angle, part of the energy will be transmitted into the seabed and part will be reflected. If, however, the grazing angle is reduced sufficiently, refraction will result in the transmitted wave propagating along the interface as an evanescent wave. The evanescent wave does not remove energy from the interface and so all the incident energy is reflected - the acoustic equivalent of the total internal reflection that occurs in optics. The grazing angle at which total internal reflection first occurs is called the critical grazing angle. If there is no absorption of acoustic energy in the seabed, the reflection coefficient is unity for grazing angles less than the critical angle, however in practice there is always some absorption, so the reflection coefficient is less than unity.

The sand seabed reflection coefficient curve shown in Figure 2 is typical for a fluid seabed, in this case with a critical grazing angle of 28°.

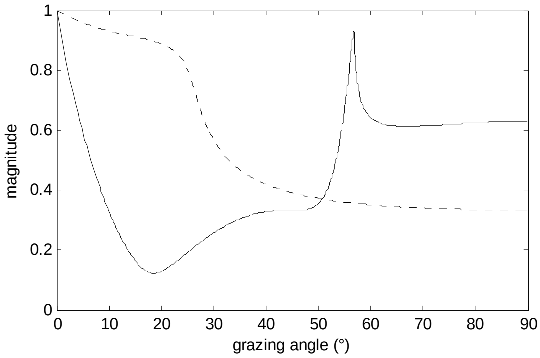

Figure 2. Magnitude of the plane-wave pressure reflection coefficient vs. grazing angle for a calcarenite seabed (solid line) and a sand seabed (dotted line).

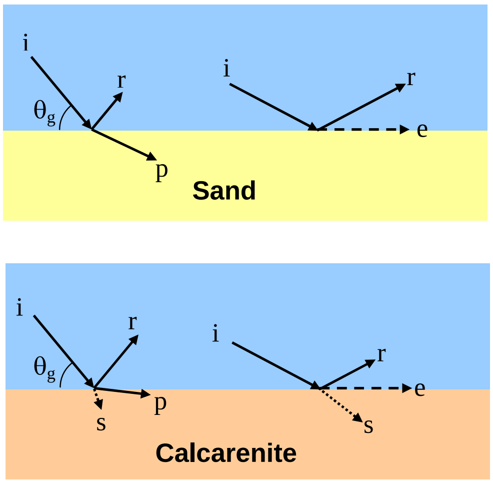

Figure 3. Ray description of acoustic reflection and transmission at sand and calcarenite seabeds for large (left) and small (right) grazing angles (θ_g). **i** is the incident ray, **r** is the reflected ray, **p** is the transmitted compressional wave, **e** is an evanescent wave travelling along the interface and **s** is the transmitted shear wave.

When sound is incident at a steep angle on a solid seabed such as one consisting of calcarenite, it will give rise to both a compressional wave and a shear wave in the seabed. The compressional wave will refract upwards as before, but because the calcarenite shear speed is slightly lower than the in-water sound speed, the shear wave will refract slightly downwards. Reducing the grazing angle below the critical angle will result in an evanescent wave as before, but there will still be a travelling shear wave removing energy from the interface. The reflection coefficient is therefore reduced below what it would be if there was no shear wave. In the case of calcarenite, there is a very good match between the sound wave in the water and the shear wave in the seabed, resulting in the dramatic dip in the reflection coefficient seen in Figure 2 at grazing angles less than 50°. The sharp peak in the calcarenite reflection coefficient at 58° corresponds to the critical grazing angle.

SHALLOW WATER PROPAGATION THEORY

In many acoustic propagation scenarios of interest the water depth is a sufficiently small number of acoustic wavelengths that it is necessary to consider waveguide effects. Normal mode theory is a particularly useful tool for this purpose, especially when the ranges of interest are much greater than the water depth and only the acoustic energy trapped in the waveguide is important.

Detailed mathematical treatments of normal mode theory can be found in a number of books on underwater acoustics, for example Jensen et. al. (2000), Brekovskikh and Lysanov (2003), however the diagrams shown in Figure 4 may be useful to readers unfamiliar with the concepts. These diagrams apply to an ideal, constant sound speed waveguide with a pressure release upper boundary, and a rigid lower boundary, however the same basic principles apply to the more complicated waveguides found in the ocean.

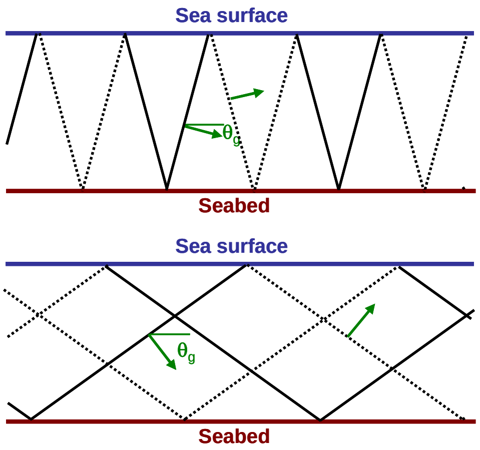

Figure 4. Diagram showing the first two normal modes of a shallow-water waveguide with a rigid seabed. Solid line represents a wave crest (pressure maximum), dotted line is a trough (pressure minimum). Green arrows show direction of propagation of wavefronts. Top plot is for mode 1, bottom plot for mode 2.

In these diagrams the straight black lines represent the acoustic wavefronts, either pressure maxima (solid lines) or pressure minima (dotted lines). The diagrams apply a long way away from the sound source, so multiple reflections from the seabed and sea surface result in pairs of upward and downward travelling waves. Note that the phase of the wave is reversed (maximum becomes a minimum and vice a versa) on reflection from the sea surface, but remains unchanged on reflection from the seabed.

The sea surface boundary condition for this waveguide is that the pressure must be zero, which requires a pressure maximum to always correspond with a pressure minimum. The seabed boundary condition is that the amplitude of the wave is a maximum, which requires either two maxima or two minima to correspond. For a given frequency (acoustic wavelength) there are only certain grazing angles, θ_g, for which both these boundary conditions can be simultaneously satisfied. The normal modes of the waveguide correspond to pairs of upward and downward travelling waves with these grazing angles. Figure 4 shows the first two normal modes of the ideal waveguide, and it can be seen that in both cases the top and bottom boundary conditions are being simultaneously met. When several modes exist at the same frequency they are said to be of different order, with the lowest order mode being the one with the smallest grazing angle.

At any given frequency, a shallow water waveguide with either an infinitely rigid or fluid seabed supports a finite number of normal modes: the higher the frequency the more modes will be present. If the frequency is lowered sufficiently, then no modes will exist and the waveguide is said to be "cut off", leading to rapid attenuation of the signal.

For any waveguide, the grazing angle of a particular mode will reduce as the frequency is increased. Alternatively, we can produce modes of different order, but the same grazing angle, by increasing the frequency (Figure 5).

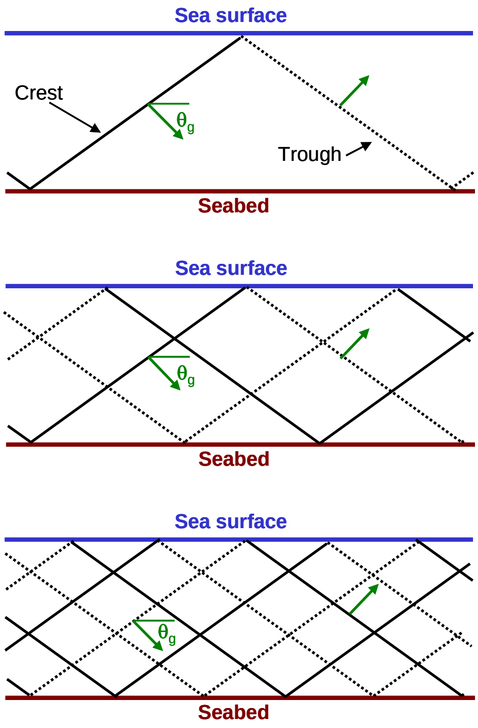

Figure 5. Modes of order 1 (top), 2 (middle) and 3 (bottom) with the same grazing angles but corresponding to different acoustic frequencies. Frequency is increasing from top to bottom.

SOUND TRANSMISISON CHARACTERISTICS

Sand seabed

Further insight into shallow water propagation can be obtained from the plots of transmission loss vs. range and frequency given in Figure 6. These plots were produced using the wavenumber integration program, SCOOTER (Porter 2007).

The upper plot in Figure 6 is for an infinitely thick sand seabed, modelled as a fluid. At high frequencies many modes exist, resulting in a complicated interference pattern superimposed on a gradual increase in transmission loss with increasing range. As the frequency is reduced the interference pattern becomes less and less complicated as the higher order modes progressively cut off. Finally, below the waveguide cut off frequency (20 Hz in this example) all modes are cut off and the transmission loss increases markedly. Note, however, that even below the waveguide cut-off frequency there is still some sound transmission, especially at frequencies just below cut-off.

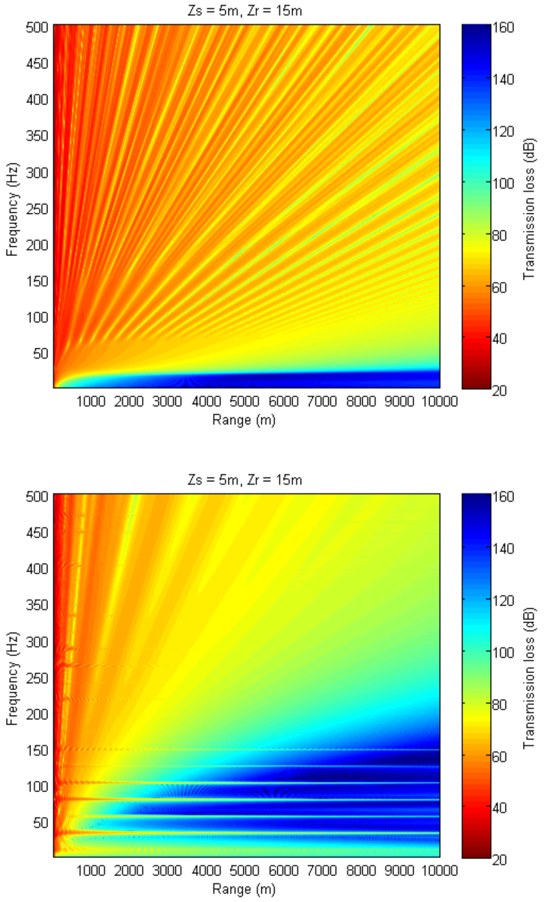

Figure 6. Modelled transmission loss vs. range and frequency for a 40m deep, isovelocity 1500 m/s water column. Top plot is for a sand seabed, bottom plot is for calcarenite. Source depth is 5 m, receiver depth is 15 m.

Calcarenite seabed

The lower plot in Figure 6 is for a calcarenite seabed and is very different from the sand seabed plot. The high frequency modal interference is much less distinct, there is a large wedge-shaped region of high transmission loss between 30 Hz and 150 Hz, and there are thin horizontal bands of low transmission loss that cut across this wedge. In addition, the transmission loss reduces at very low frequencies, the opposite of what happens in the sand seabed case.The last of these effects occurs because of a boundary wave called a Scholte wave, which propagates along a solid-liquid interface and decays exponentially either side of the boundary. Scholte waves travel slightly slower than the shear speed in the seabed and are important when the distances of the receiver and source from the seabed are comparable to the acoustic wavelength.

The other peculiar features of the lower plot in Figure 6 can be explained by a combination of normal mode theory and the calcarenite reflection coefficient curve shown in Figure 2 (Li et. al. 2009).

The thin horizontal bands of low transmission loss occur at the frequencies at which one of the normal modes has a grazing angle corresponding to the seabed critical angle. The low transmission loss is due to the sharp peak in the reflection coefficient curve that occurs at that angle. Bands at successively higher frequencies correspond to successively higher order modes meeting this criterion.

The wedge shaped, high transmission loss region is a result of the rapid drop in reflection coefficient with increasing grazing angle that occurs at small grazing angles. To understand its shape, recall that:

- for a given mode, the higher the frequency, the smaller the grazing angle, and
- at a given frequency, the higher the order of the mode, the larger the grazing angle.

At low frequencies, the grazing angle of the lowest order mode is relatively large and is in the low reflectivity region of the calcarenite reflection coefficient curve (Figure 2), resulting in a high transmission loss. As the frequency increases, the mode's grazing angle reduces, moving to a region of successively higher reflectivity and hence lower transmission loss. As the frequency is increased further, this process is repeated for successively higher order mode, further reducing the transmission loss and increasing the complexity of the interference field.

Layered sand/calcarenite seabed

Figure 7 plots the transmission loss vs. range and frequency for seabeds comprising various thicknesses of sand overlaying calcarenite. As the sand layer thickness increases, its effects become apparent at successively lower frequencies. Comparing figures 6 and 7, it can be seen that, at 500 Hz, even a 2 m thick sand layer is sufficient to screen out the effect of the underlying calcarenite, whereas this same layer has little effect on the transmission loss at frequencies below 100 Hz, which is very similar to that for the calcarenite seabed. This is to be expected because it is the thickness of the layer in acoustic wavelengths that determines its effect on the propagation.

As the sand layer thickness is increased further, the modal interference pattern extends to lower and lower frequencies, and the upper frequency limit of the high transmission loss wedge reduces. The horizontal bands corresponding to modes at the calcarenite critical angle persist, even for a 50 m layer thickness, but become closer together. This last effect is because the modes that cause these bands now span both the water column and the sand layer, which reduces their angular spacing. The band spacing is slightly smaller for the 2 m sand layer than for the 1 m layer, but the effect is too small to notice on these plots as it corresponds to only a 2.4% increase in the effective waveguide thickness (water column plus sand layer).

The plot for the 50 m layer thickness is very similar to the sand seabed plot in Figure 6, except that the waveguide does not completely cut off below 20 Hz: the calcarenite is providing an alternative propagation path for low frequency energy. Although a 50 m thick sand layer would be unusual on the Australian western and southern continental shelves, this result highlights the important effect that quite deep underlying geology has in modifying the behaviour of the waveguide at low frequencies.

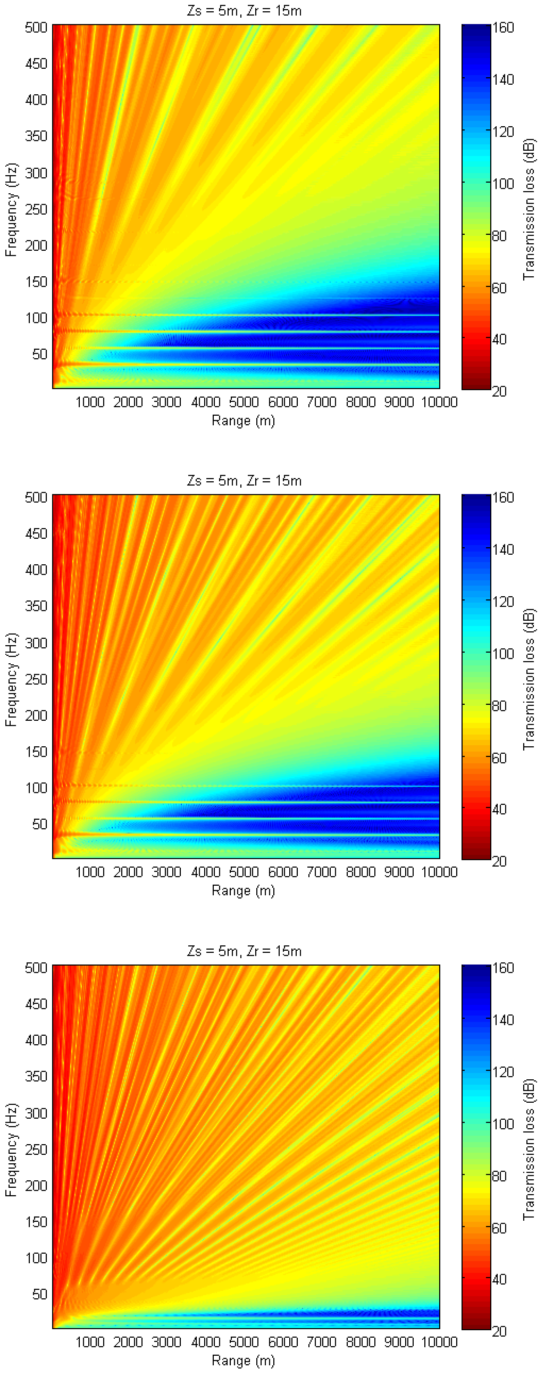

Figure 7. Modelled transmission loss vs. range and frequency for a 40m deep, isovelocity 1500 m/s water column with a seabed consisting of a layer of sand over calcarenite. Sand layer thicknesses are 1 m (top), 2 m (middle) and 50 m (bottom).

EXPERIMENTAL DATA

Figure 8 is a plot of transmission loss vs. range and frequency obtained from underwater sound recordings made during a commercial seismic survey in approximately 40 m of water off the Western Australian coast. Only shots close to the 40 m bathymetry contour were included in the analysis. Details of these measurements can be found in Li et. al. (2009).

Figure 8 shows many of the same characteristics as the calcarenite seabed propagation model result shown in Figure 6. The high transmission loss wedge is definitely present, as is the high-frequency modal interference pattern. There is also distinct horizontal banding at low frequencies, but it is more diffuse than that in the model result. The spreading of these bands is likely to be due to some range dependence in the real environment, particularly the bathymetry, which was not included in the model.

The low transmission loss region at about 340 Hz is likely to be an artefact due to a dip in the source spectrum at this frequency.

IMPLICATIONS FOR ACOUSTIC PROPAGATION MODELLING

The results presented above have a number of important implications:

- Except at very low frequencies, a bare calcarenite seabed will result in higher transmission loss, and hence lower received levels, than an infinitely thick sand seabed. What "very low frequencies" means in this context is the frequency range below the cut-off frequency for the waveguide with an infinite sand seabed, which depends on the water depth and the speed of sound in the sand. In this example it is 20 Hz. Modelling using an infinite seabed with the properties of the surficial sediment will therefore underestimate the transmission loss for frequencies above the sediment cut-off frequency, and overestimate it for frequencies below cut-off.

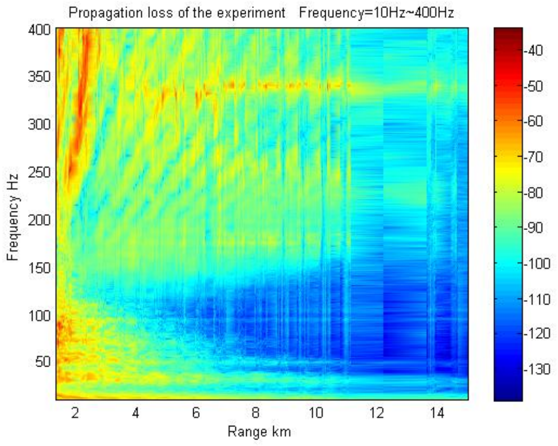

Figure 8. Measured transmission loss vs. range and frequency for a site off the Western Australian coast. Receiver was on the seabed in 42 m of water. Source was a commercial seismic survey.

- If the calcarenite is covered by sand, then the thickness of the sand layer will have a substantial influence on the transmission loss. The higher the frequency, the thinner the layer that affects the transmission loss. For example, at active sonar frequencies (about 10 kHz), the transition between the calcarenite and sand reflectivities occurs as the layer thickness increases from zero to a few tens of centimetres.

- Modelling the received energy represented by the low-frequency horizontal banding requires running a propagation model capable of dealing with elastic seabeds at small frequency intervals. (An interval of 1 Hz was used to generate the plots shown above.)

- At higher frequencies, the modal interference dominates and changes more gradually with frequency. It can be adequately modelled using larger frequency steps. It is often possible to further simplify the modelling in this frequency range by using a fluid propagation code with an "artificial" equivalent fluid seabed that provides a good match to the low grazing angle portion of the calcarenite reflection coefficient curve.

- The examples given in this paper were created using the wavenumber integration program SCOOTER (Porter 2007). This program can model seabeds comprising arbitrary fluid and elastic layers, but only when there is no change in water depth or acoustic properties with range. Most practical modelling scenarios involve some range dependence, the most common being the water depth, which rules out the use of this type of program.

  Parabolic equation (PE) codes are commonly used for modelling range dependent scenarios, with two of the most commonly used being RAM (fluid seabeds) and RAMS (elastic seabeds) (Collins 1993, Collins 2000). The authors have found that RAMS is stable and accurate when applied to a bare calcarenite seabed, but is unstable if a low (or zero) shear speed sand layer is placed on top of the calcarenite. It has therefore been necessary to adopt a hybrid approach to modelling propagation in range dependent environments over layered seabeds. This has involved using RAMS with a calcarenite seabed at frequencies considered low enough that the sand layer will have little influence, and then switching to RAM with a fluid seabed comprising sand over an equivalent fluid representation of calcarenite at higher frequencies. Choosing the best frequency to make the transition between the two models involves trading off errors introduced by ignoring the sand layer against errors due to ignoring elastic effects. The optimum transition frequency depends on the water depth and the detailed seabed properties, and in most cases requires a preliminary modelling effort to determine.

CONCLUSIONS

Much of Australia's continental shelf consists of a calcarenite seabed covered by a thin, patchy veneer of unconsolidated sediment, predominantly sand. Except at very low frequencies, the acoustic transmission loss over such a seabed is higher than it would be over a uniform sand seabed and is strongly dependent on the thickness of the sand layer. The presence of the calcarenite under the sand provides a path for low frequency sound propagation and so the waveguide does not cut off at low frequencies as it would for a uniform sand seabed.

Shallow water waveguides with calcarenite seabeds exhibit different propagation characteristics in different frequency ranges. At extremely low frequencies, transmission is by way of low-speed Scholte waves propagating along the interface between the calcarenite and the overlaying sediment or water. At slightly higher frequencies modes with grazing angles corresponding to the calcarenite critical angle dominate, giving rise to low transmission loss over narrow frequency bands. At still higher frequencies the main transmission mechanism is modes with very low grazing angles. In this high frequency region the transmission loss reduces, and starts to exhibit more pronounced modal interference, as the frequency is increased. The actual frequency ranges over which these different effects occur depend on the water depth and the detailed seabed properties.

The authors are continuing to investigate a number of other aspects of propagation over such seabeds. Of particularly interest are the effects of:

- Range dependence, especially on the narrow frequency bands.

- Shear waves in the sand layer. Although the shear speed is low, work by Ainslie (2003) has shown that it can still be significant for thin sand layers.

- A nonuniform water column soundspeed profile.

- Layers of calcarenite with different geoacoustic properties.

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