Acoustic penetration of a sandy sediment

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Abstract

Measurements were made using a buried acoustic receiving array and a mobile sound projector, to study the underlying physical processes in the penetration of sound into sandy ocean sediments, particularly at shallow grazing angles. The experiments took place in a sandy sediment off the west coast of Florida, as part of the Sediment Acoustics Experiment (SAX99). The buried array was insonified by a wide band sound source carried on a remotely operated vehicle (ROV). Data were recorded at several positions and grazing angles over a period of 4 weeks. The discrimination between refraction and scattering processes was of particular interest. To this end, an array processing method was used that employed coherent superposition to distinguish between refracted and scattered signals. The latter should be incoherent. Variable focusing was used to sharpen the distinction between refraction from a distant source and scattered signals from scatterers in the near-field of the array. Sound waves entering the sediment at steep angles were clearly refracted. In the case of shallow grazing angles, the results were much more complicated. This is a component of a multi-disciplinary effort to study sediment acoustics.

1. Introduction

The penetration of sound into ocean sediments, particularly at shallow grazing angles, and the scattering of sound from the sediment, are two physical processes that are not well understood. Although a large number of measurements have been made in the past, including both *in situ* and laboratory experiments, and a number of hypotheses have been advanced, the underlying physical processes have not been determined with any confidence. The hypotheses may be roughly divided into two groups; one in which the sediment is approximated as an elastic fluid (e.g. Moe and Jackson [1]) or solid (e.g. Jackson and Ivakin [2]) and the other in which the sediment is treated as a poro-elastic medium according to Biot's theory (e.g. Stoll and Kan [3]).

With regard to penetration, there are two competing hypotheses for the penetration path at shallow grazing angles, (a) the Biot slow wave refraction and (b) scattering by surface and/or volume inhomogeneities. Within each there are a number of interconnected possibilities. The Biot slow wave path is applicable to a uniform sediment with a flat surface, but it may be enhanced by surface roughness and volume inhomogeneities through energy conversion between the slow and fast waves. The scattering path requires either surface roughness and/or volume inhomogeneities, but it is not known if the process may be adequately represented by an elastic medium approximation, or if it is necessary to resort to a Biot representation.

As for scattering, at the most fundamental level, it is desirable to determine if the process is single or multiple scattering. At the physical level, the scatterers need to be identified, and the likely candidates include (a) surface roughness, (b) volume inhomogeneities, and (c) the sand grains. The penetration study should reveal the acoustic paths by which the scatterers are insonified, but definitive tests are needed to distinguish between the different scattering mechanisms.

2. Acoustic measurements

In situ experimentation is an important component of the research effort, owing to the near impossibility of reproducing realistic ocean sediment conditions in the laboratory. Of particular note are the arrangement of grains under natural sediment deposition conditions, and the reworking of the sediment by hydrodynamic and biological processes. Although a number of measurements have been made in the past, both *in situ* (e.g. Richardson [4]) and in the laboratory (e.g. Simpson and Houston [5]), and a number of theories have been advanced, the underlying physical processes have not been determined with any confidence. The Sediment Acoustics Experiment (SAX99) was designed to address these issues [6]. There were two sets of high frequency sediment acoustic penetration experiments, one by the Applied Physics Laboratory at the University of Washington (APL/UW), and the other by the Applied Research Laboratories of the University of Texas at Austin (ARL:UT). This paper describes the latter experiments.

They involve a mobile sound source carried on a remotely operated vehicle (ROV) and tilted, rigidly supported, buried acoustic line arrays, as illustrated in Figure 1(a). An expanded view of the buried array is shown in Figure 1(b) which shows 3 receivers on the sediment surface, arranged in a triangle, and the buried receivers in a tilted line. Broad band signals, made possible by new transducer materials, were used in order to detect frequency dependent trends in both penetration and scattering. Cross-coupling between the elements were minimised by using absorptive backing material. Measurements in water were used to test for cross-coupling, and it was found that above 10 kHz the cross-coupling was insignificant. The projector beam width is approximately 20° between -3 dB points between 30 and 70 kHz. Outside this band, it changes in proportion to wavelength. The receivers had a beam width in excess of 40° at frequencies below 70 kHz.

In the period, 4 October to 14 November 1999, investigators from ARL:UT collected acoustic bottom penetrating and scattering data. Two buried arrays were deployed, and 25 ROV missions were flown to interrogate the buried arrays and collect backscattering and reflection data. In addition, diver cores and laser profiling data were collected over the ARL:UT site. A 0.5 ms chirp signal, from 10 to 100 kHz was used.

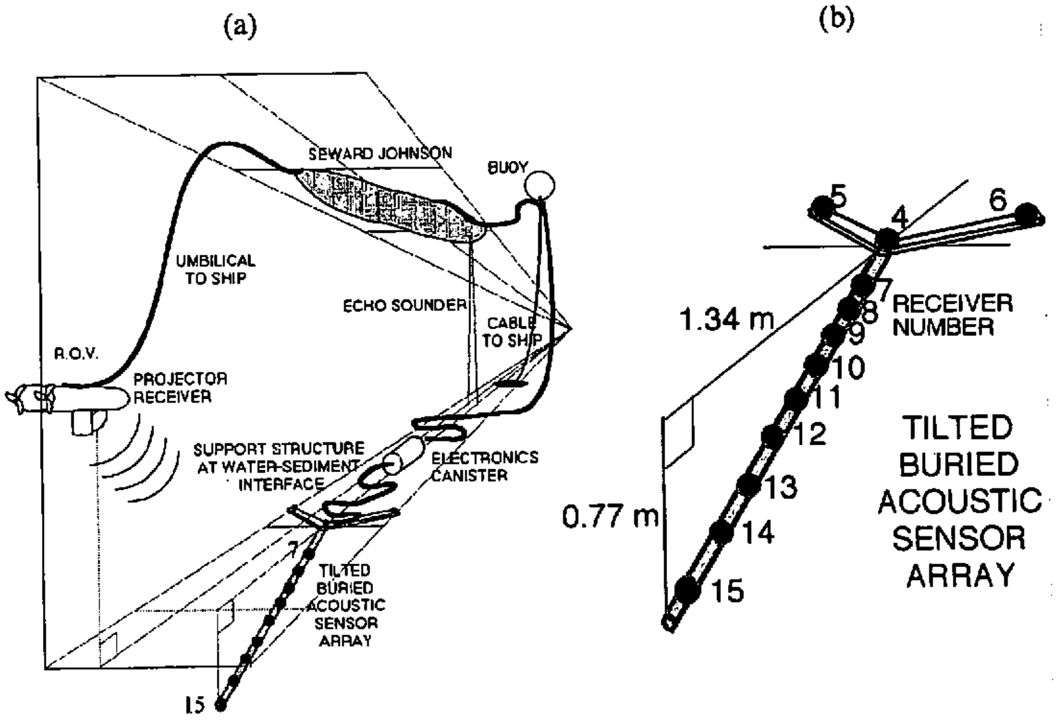

Figure 1. Illustration of experiment; (a) Layout and (b) buried array configuration

3. Data processing

3.1 Simple refraction modeling

A number of data analysis methods were considered, of which two will be described: (a) refraction modeling, and (b) ambiguity diagram analysis with variable focusing. In the former, a simple two-part medium was modeled. The upper medium was water with a known sound speed and density; it contained the sound source at a known location. The sediment contained the receiving array at a known location, and it was modeled as a uniform medium with a different sound speed. The sound paths and the corresponding travel times from source to each element of the buried array were computed for a range of sediment sound speeds, and the computed travel times were used to shift and sum the measured signals. If the sound paths were correctly modeled, the shifted signals would coincide and their coherent sum would reach its maximum output. This worked well at steep angles, as shown in the example in Figure 2. The ray paths that gave the maximum output are shown on the left. The corresponding superposition of the *in situ* signals is shown on the right. At shallow grazing angles, the coherence was greatly reduced, as shown in the example in Figure 3. In this case, the ray paths are sharply refracted at the point of entry. It is not difficult to see that the problem is ill-conditioned. A small perturbation of the interface could cause a large displacement in the point of the entry, and produce a correspondingly large perturbation in the travel time. With a rough surface, it is likely that there are several ray-paths from source to each receiver, each with a different travel time. These examples illustrate the difference in coherence above and below the critical angle.

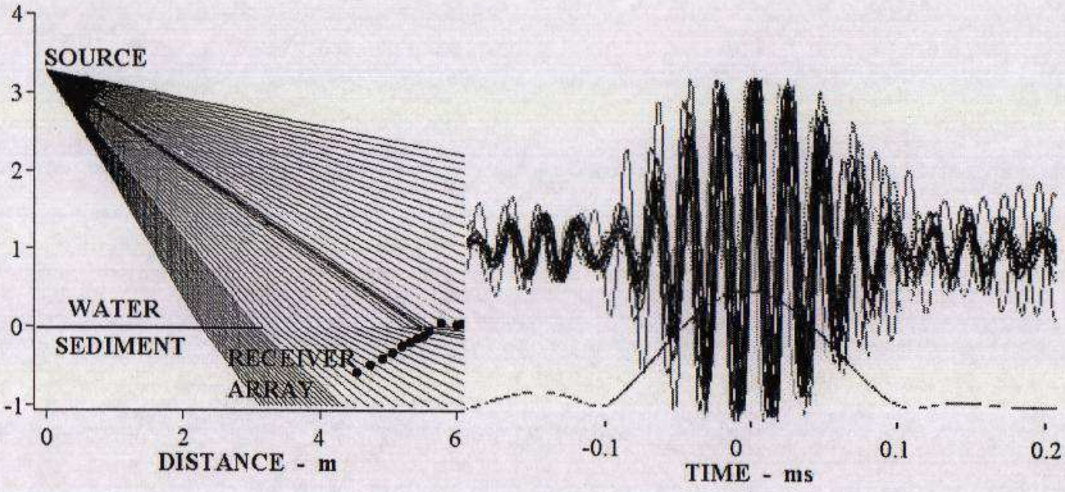

Figure 2. Illustration of refraction modeling: raypaths and superposition of experimentally recorded signals in the 40-50 kHz band at a grazing angle of 30° from SAX99; lower trace shows the amplitude of the coherent sum.

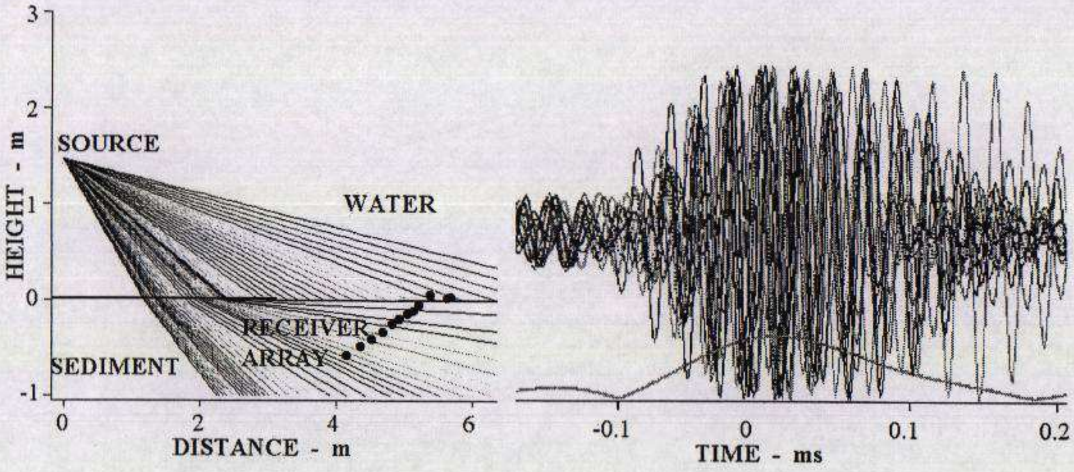

Figure 3. Illustration of refraction modeling: raypaths and superposition of experimentally recorded signals in the 40-50 kHz band at a grazing angle of 20° from SAX99; lower trace shows the amplitude of the coherent sum.

3.2 Ambiguity analysis with focusing

A different approach is needed that can distinguish scattered from refracted waves, and separate refracted waves of different wave speeds. A method was devised involving a speed and angle ambiguity diagram with variable focusing. It is designed to separate and identify coherent and incoherent wave components, based on direction, speed and wave front curvature. Unlike the refraction modeling, it does not require the source position as an *a priori* input, but knowing the source bearing reduces the dimensionality of the problem. Consider Figure 4, in which the buried array is shown on the left and the sound paths from source to receivers go from right to left. In this figure, a wave refracting into a faster medium would appear to arrive at a shallower depression angle from a source point (S_f) that is closer to the array and at a lower altitude than the true source position (S_o). Conversely, a wave refracted into a slower medium would appear to arrive at a steeper angle, from a point (S_s) that is further away and higher. These properties may be used to separate refracted waves of different speeds. Furthermore, a sound wave scattered by a single point at the water-sediment interface or within the sediment would appear to come from a point that is even closer. Scattering by a distribution of scatterers at the sediment interface or within the sediment would tend to randomize the signals at each receiver, causing a loss of coherence.

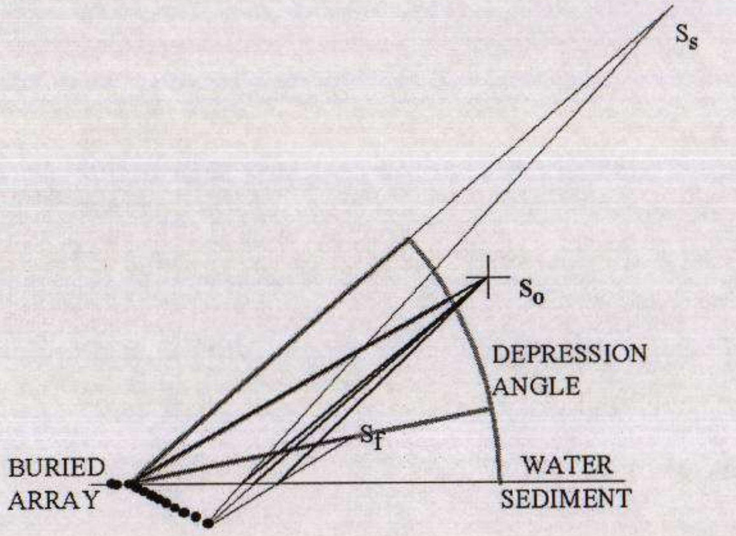

Figure 4. Illustration of the effect of refraction on the apparent height and range of the source point

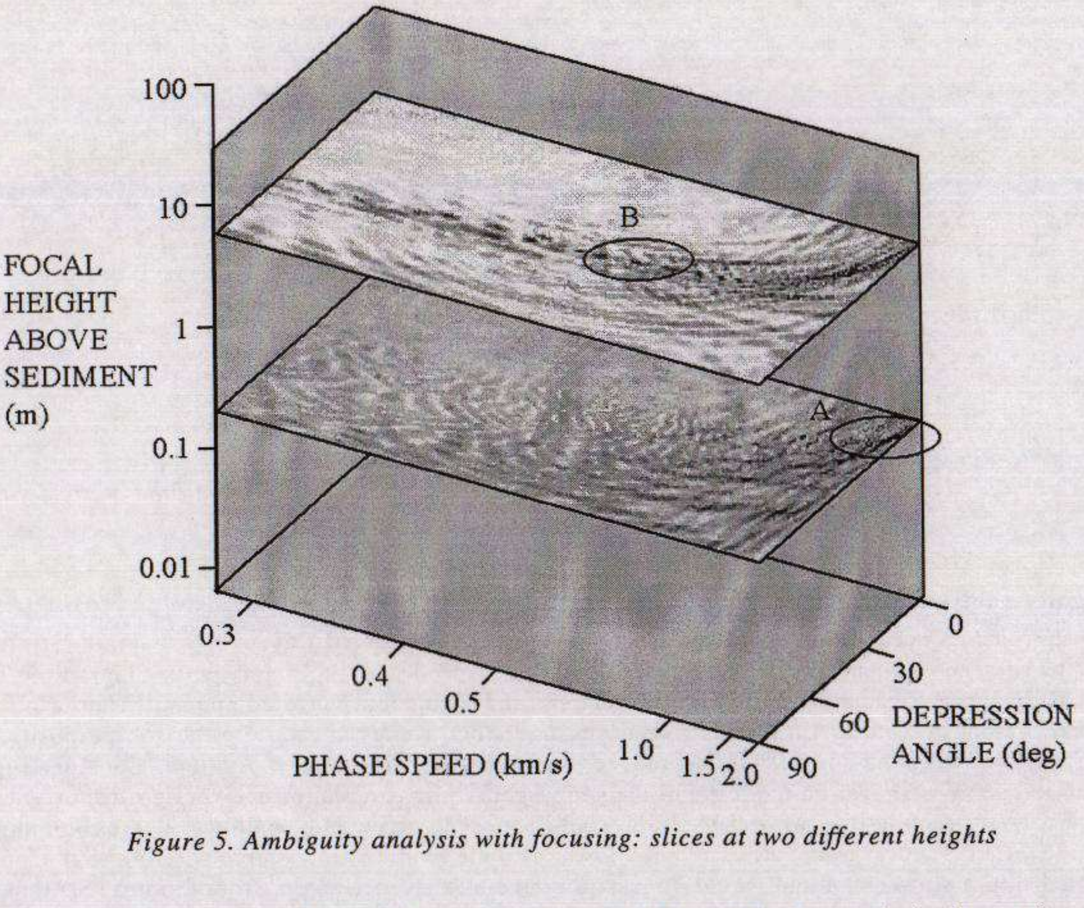

Figure 5. Ambiguity analysis with focusing: slices at two different heights

The process is essentially a time-delay and sum procedure [7] that searches for a spherical wave front through a 3-dimensional search space of elevation angle, wave speed and height. An example is shown in Figure 5. The three dimensions of the search space are depression angle, wave speed and source height. A couple of sections through the search space are shown as intensity coded images of the coherently summed signal magnitude. In this example, the true source height was 3.3 m and the depression angle, measured to receiver number 4 was approximately 30°, which is slightly greater than the critical angle. The lower slice, focused at a height of 0.3 m, contains a maximum, A, at a depression angle of 13° and a speed of 1.8 km/s, which corresponds to the sound speed in the sediment as measured by *in situ* probes. This fits the fast bottom category (S_f). The upper slice, focused at a height of 6 m, contains a number of maxima that are not present in the lower slice, of which the largest is labeled B. It occurs at a depression angle of 48° and a sound speed of 0.6 km/s.

The results may be summarized in a graphical form, as shown in Figure 6. The vertical axis of all the graphs is height above the sediment. The graph on the right shows that the peak level in each slice. The peaks A and B from the previous figure are identified. The middle graph shows the corresponding wave speed. The indicated height and distance on the left graph shows the apparent position of the source point.

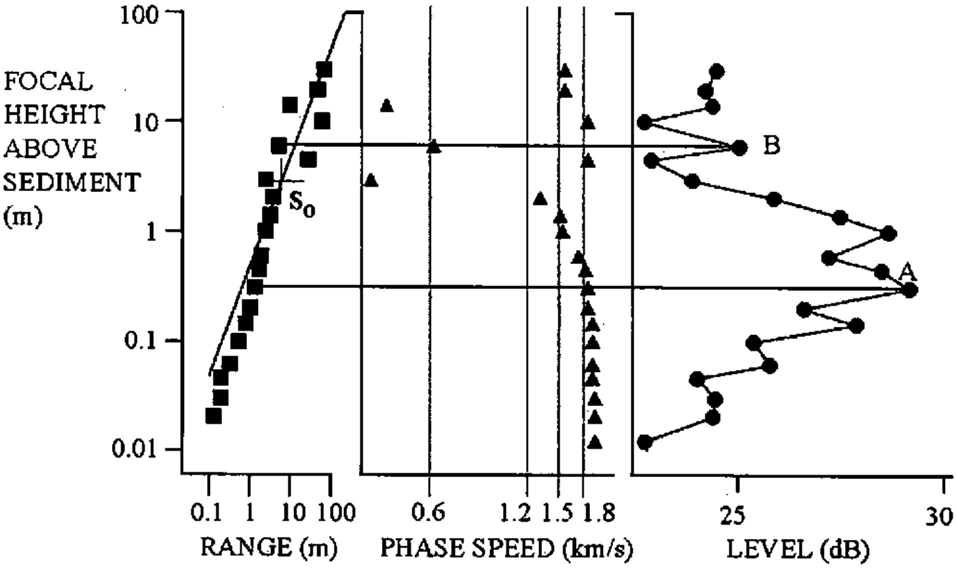

Figure 6. Ambiguity analysis with focusing: graphical summary

4. Discussion

This is work that is still in progress, and it is not possible to make definitive conclusions as yet. In addition to the acoustic measurements, there were numerous environmental measurements to support the acoustic modeling of the sediment, particularly the Biot theory approach, mainly by the Naval Research Laboratory (NRL). These included water-sediment interface roughness, sediment grain size distribution, porosity, permeability, and sound and shear wave speeds. These measurements will be applied to existing and improved models for comparison with the acoustic measurements

The experiment extended over a period of almost four weeks in which the conditions changed quite noticeably. The bottom changed from a rippled structure at the beginning of the period to a pockmarked structure at the end of the period. Therefore corresponding changes may exist in the character of the sediment penetrating signals. The data shown here are all from the first week. The orientation of the experiment was such that the sound path from projector to receiver array was approximately parallel to the ridges.

From the initial results, it is evident that coherent wave fronts were detectable. There are possibly more than one type of coherent wave, as indicated by the peaks A and B. The peak at A is very well defined and identifiable as the usual sound speed in water saturated sand, but the peak at B is more complicated. It is just the strongest of about half a dozen, spread out over a range of speeds and angles, covering the region where the Biot slow wave is expected. The fragmentation may be an indication of a slow refracted wave scattered by surface roughness or volume inhomogeneities. More analysis is needed to rule out other possibilities, but if this were the case then it would indicate that the Biot slow wave is an important part of the scattering process. Results from shallower angles showed more randomness over a greater range of heights indicating the presence of other forms of scattering.

5. Acknowledgements

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