INTERACTION OF NON-LINEAR ACOUSTICS WITH SEDIMENTS

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1. INTRODUCTION

This tutorial will consider the use of parametric arrays for sea-bed-penetrating sonars mainly for small scale applications and will be mainly practical in tone. It will start by describing some of the problems in using sonar for looking into the sea-bed and how the parametric sonar can help to alleviate them. It should be stated, however, that the parametric array is not the only technology available in most cases and other options should not be ignored.

Later sections describe how the beam from a parametric array has particular properties if propagating from water into a sediment with a higher velocity of sound. The normal critical angle effects are modified to enhance propagation into the sediment at angles larger than critical, though at low levels.

Finally, some commercial equipments which use the parametric array to penetrate sediments will be reviewed.

2. SONAR PROBLEMS PROPAGATING INTO AND THROUGH SEDIMENTS

2.1 The Interface

In most circumstances propagation of a compressional wave from water into sediment incurs a loss at the interface, (lossless propagation occurs at the angle of intromission). This loss is because some of the energy is reflected or translated from the compressional wave into a wave of another type in the sediment. The particular properties of the parametric array have little effect until the incident angle on the sediment is beyond the plane-wave critical angle. However the narrowness of the beams that can be generated with a parametric array cause diffraction effects near to the critical angle. These topics will be discussed later.

2.2 Absorption

Absorption in sediments is much higher than in sea-water. Table 1 compares the absorption at 100kHz in sea-water and sand respectively.

	Sea-water	Fine Sand
100kHz	0.003	24
10kHz	0.0007	2.4

Table 1. Attenuation (dB.m^{-1}) in Sea-water and Sand

Suppose for example that an object buried by 1m was to be detected by a beam refracted to an angle of 60° to the vertical in the sediment. The two-way path in the sediment would be 4m in length and the absorption at 100kHz is 24dB x 4 = 96dB . Whether absorption is a problem depends on the application. For example, a sub-bottom profiler with a narrow, vertical beam may be viable because the sub-bottom echoes suffering high absorption can be separated temporally from the stronger echoes at shallower depth and can be amplified by TVG. Suppose, however, that the sub-bottom profiler was developed into a swath-sounder. Now it is probable that, at large angles of incidence, the sub-bottom echo and the bottom reverberation would be insonified by the beam simultaneously. Now, temporal separation would be impossible and the absorption must be reduced if the sub-bottom echo is to be seen.

Empirically, absorption of sound in sediments varies approximately as the first power of frequency. This is shown in Figure 1 from Hamilton [1] which is a synthesis of many absorption measurements. It is obvious that the losses within the sediment can be reduced by a reduction of frequency, say by ten times. The absorption loss then becomes more acceptable at about 3dB. It is also obvious that reducing the frequency must not introduce other detrimental effects.

2.3 Reverberation

As stated above, sub-bottom echoes are often have to be detected against a background of reverberation, either from the interface or from the volume of the sediment itself. The limited amount of published data shows reverberation from the sea-bed to reduce or at least to stay constant with reduction in frequency. Figure 2 (from McKinney and Anderson [2]) illustrates this for sand. Assuming that the signal/noise ratio is sufficient, the necessity is therefore, to minimise reverberation whilst operating at a low frequency to reduce absorption. This implies reducing the beam-width and pulse length to maximise the wanted echo whilst minimising the insonified volume causing reverberation.

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2.4 Advantages of the Parametric Array

It is in this respect that the parametric array has advantages.

Firstly, it can generate narrow beams at low frequencies. These can also be pencil beams to give maximum temporal separation of targets from the reverberation.

Secondly, the band-width of the primary frequencies is translated to the low-frequency band where it is relatively large allowing short pulses to be transmitted.

As always there is a price to be paid. In addition to the well known inefficiency of the parametric array, there is the disadvantage of having high resolution in the parametric transmitter and low resolution in the conventional receiver. This necessitates transmitting and receiving many beams independently which is time consuming compared to a multi-beam receiver operating with a wide-beam transmitter.

To summarise the chief advantages of the parametric array lie in the reduction of absorption in the sea-bed possible by operating at low frequencies whilst retaining good signal/reverberation ratio by virtue of the narrow beams and short pulse-lengths which are possible. A secondary advantage is the ability to generate narrow pencil beams from small apertures which can further reduce reverberation or allow temporal separation of the target echo from the bottom reverberation.

3.PROPAGATION OF SOUND ACROSS THE SEDIMENT INTERFACE

3.1 Introduction

I will introduce the effects of a parametric array on propagation across the interface slowly by considering firstly plane waves

propagating across a flat interface into a lossless, liquid sediment, then adding, in turn, absorption and narrow beams.

3.2 Plane Waves

The transmission coefficient between two liquid media depends only on their acoustic impedances (ρc) and the angle of incidence (θ_I) .

$$\sin\theta_R = \frac{C_R}{C_I}\sin\theta_I \qquad (1)$$

$$W = \frac{2\rho_R c_R \cos\theta_I}{\rho_R c_R \cos\theta_I + \rho_I c_I \cos\theta_R} \qquad (2)$$

These equations predict a critical angle for total reflection beyond which there are no bulk waves within the sediment. This can be a serious limitation to a sonar system.

3.3 Effect of Attenuation

Beyond the critical angle, an evanescent wave propagates in the sediment which diminishes rapidly with depth into the sediment with attenuation coefficient (α_E).

$$\alpha = k_I\sqrt{\sin^2\theta_I - \eta^2} \qquad (3)$$

Because of the absorption in the sediment, energy is lost by this wave and total reflection does not occur at any angle. Nevertheless, the evanescent wave only penetrates very shallowly into the sediment and therefore is of little use for detecting objects.

3.4 Narrow Beams

The propagation of narrow beams into the sediment has been studied by two approaches.

3.41 The Diffraction Approach. Tjotta and Tjotta [3] considered the sharp spot projected by a narrow beam onto the sediment. They showed analytically that such a spot would diffract into the sediment, even at angles beyond the critical angle.

3.42 The Plane-wave Spectrum Approach. The alternative approach is probably easier to understand physically. This involves the decomposition of the narrow beam into a spectrum of plane waves. Jensen and Schmidt[4] used this approach numerically by means of the SAFARI computer model. Figure 3a from their paper [4] shows the plane-wave spectra for three beams of decreasing width, at a grazing angle of 30°. It can be seen that as the beam-width narrows the spectrum widens. Referring to figure 3b showing the reflection from a lossless sediment with a critical angle of 30°, it can be seen that part of the plane-wave spectra can propagate into the sediment as bulk waves before the critical angle. Compare this to the plane-wave case where only on evanescent wave is possible. Figure 4 shows Jensen and Schmidt's result from the same paper for a very narrow beam (2.5λ in width) at critical grazing angle and at 5° either side of it. A weak beam can be seen even at 5° beyond critical.

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4. DIFFERENCES WITH PARAMETRIC ARRAYS

4.1 Nature of Truncated Parametric Array

The main feature of the parametric array is that it generates narrow beams at low frequency. These correspond in many respects to those considered by Jensen and Schmidt. However, in the parametric array the acoustic sources are distributed throughout the interaction volume and, particularly when the sources are near to the interface, it is necessary to consider their influence on the sound field in the sediment. This problem was studied by Wingham [5,6], drawing on previous work by Pace and Ceen [7,8] and by Berktay and Moustafa [9].

4.2 Effective Acoustic sources

Figure 5 shows a parametric array incident on a sediment interface. The primary frequency beam (assumed to be collimated) is intercepted by the interface which prematurely truncates the 'virtual end-fire array' which generates the difference frequency. Attenuation in the sediment rapidly reduces the amplitude of the primaries in the sediment, effectively stopping difference frequency generation at the interface. It was shown by Pace and Ceen that this truncation acts as a second, radiating 'aperture' in addition to the transducer. This 'aperture' at the truncation causes the differences between the propagation into sediments of beams from parametric arrays and those from conventional arrays. These differences are only significant at and beyond the critical angle. At smaller angles of incidence, the effect of the truncation is masked by the radiation from the transducer; at larger angles penetration is limited by the directivity resulting from the phase variation across the 'aperture'.

4.3 Propagation Paths

Figure 5 shows the Snell's Law path from the transducer, the path associated with the truncation and the path of the evanescent wave from the transducer already mentioned in section 3.3. The effect of these three paths can be seen in results by Wingham[10]. Figures 6 presents theoretical and experimental contour plots of the sound pressure within the sediment for a pre-critical beam. These may be compared with Figure 7 which is for a post-critical beam. In the pre-critical case, a well-formed beam is apparent which is similar to that from a conventional array. When the beam is post-critical, as expected, the situation is more complex. The slowly varying contours to the left of the plots are associated with the conventional post-critical beam from the transducer. They are horizontal because the transducer is some way off to the left of the plot and they relate to a plane-wave, spectral components well off the array axis. The greatest levels are in a narrow beam in the centre between the interface and line dipping at an angle of about 25°.

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This beam occurs when the field points are within the directivity of the truncation 'aperture'. The truncation arrival interferes with the transducer arrivals; near the interface the truncation suffers less spherical spreading and dominates, at greater depths, the transducer takes over but at a low level. Very close to the interface, in the region of the truncation, the truncation arrival also interferes with the evanescent wave. The asymmetry of the beams demonstrates that part of the incident beam has been reflected as shown by the plane-wave decomposition in section 3.42.
This interpretation of these figures is confirmed by pulsed experiments which are able to distinguish the paths by time-of-flight. Figure 8, again from Wingham [10] (using a technique developed by Pace and Ceen), shows the theoretical and experimental times of arrival for pulses travelling along the three paths as the angle of incidence is varied. The geometry is as in Figure 5. At the smallest angles, the Snell's law arrival and a small evanescent wave are seen. Their arrival times should not vary as the angle changes. As the angle increases, the amplitude of the Snell's Law arrival diminishes and that of the evanescent arrival peaks as the beam passes over the hydrophone. The truncation arrival separates from the Snell's Law arrival because its path becomes longer as the truncation moves away from the Snell's law path. This arrival also peaks once the truncation has passed over the hydrophone.

4.4 Limitations in Practice
The effects described result from the truncation and from the phasing of the effective 'aperture' created by it. Therefore the array must be truncated correctly. It can be shown theoretically that the parametric array acts like a conventional array if the truncation is at a distance greater than $R_0\pi\omega_0/\omega$, where R_0 is the Rayliegh distance of the primaries and ω_0 & ω are the primary and secondary frequencies. In practice, the effects are dying away at half this distance. The complicated nature of the post-critical field in the sediment makes it hard to give guidelines to performance apart from noting the advantages of narrow primary beams and the limitation to truncation distance.

5. APPLICATIONS OF PARAMETRIC ARRAYS TO SEDIMENT PENETRATION

5.1 Parametric Sub-bottom profilers
The parametric array has a potential for sub-bottom profiling that was realised early in its history. Whilst it offers increased resolution, there does not appear to have been much of a market for the few systems that have been offered. This may be because good resolution is not essential for many applications. The parametric systems are more complex than conventional ones (Not only is the parametric array itself is complex, but

systems probably needs stabilisation to give the best resolution). They also have poorer efficiency leading to shorter ranges. Two systems will be outlined.

5.11. One of the earliest parametric arrays and still among the largest to have been built was the 'TOPS' by Konrad. This was a very large low-frequency echo sounder designed for very deep sounding or sub-bottom profiling. It had an large array (1.8m x 0.53m) with primaries centred at 23kHz which generated secondaries at 1kHz - 6kHz. The primary power was 40kW generating a source level of 209 -230dB re. 1μPa at 1m.

5.12. A more modest commercial system is offered by Ulvertech. The Non-linear Sub-bottom Profiler uses a 30cm circular array with a centre frequency of 200kHz. This is modulated with square waves to generate difference frequencies between 5kHz and 20kHz with maximum efficiency. A pulse-compression mode is available in an effort to recover more of the poor parametric-array efficiency by signal-processing gain. A long FM pulse is transmitted and detected by a replica-correlator receiver.

5.2 Buried-object Detection

The possibility of detecting buried objects by parametric sonar was recognised equally early but obviously requires a much more complex system than a sub-bottom profiler. A single-beam sonar is sufficient to detect sub-bottom layering (or even pipe-lines) . Detecting a small, isolated object requires a sonar with a wider swath to be practical. Other considerations are also important. The nature of the sea-bed determines whether the critical-angle effects discussed above will occur. Depending on the application these might restrict the swath width. Swath width and/or rate of advance may also be restricted by parametric-array directivity being in the transmitter. (Parametric receivers are not suited to scanning applications). When the directivity is in the receiver it is possible, at the cost of increased complexity, to form several beams for each transmission which increases the search rate. With directivity in the transmitter, each resolution cell on the sea-bed must be insonified individually and the echoes received must be separated temporally. This is obviously more time consuming and requires compromises between resolution, rate of advance, complexity etc.

5.21 A few experimental buried-object detection systems have been reported in the military field but little detail has been released in the open literature. In the commercial field a range of systems is available from Bentech with primary frequencies of either 18kHz or 40kHz and difference frequencies of 0.5kHz - 5kHz and 1kHz - 7kHz respectively. The higher frequency system uses a 0.5m x 0.7m array with 16 staves to scan a 4° beam over a ±45°sector in steps of between 1° and 6°. All the systems operate well within the critical angle.

6. CONCLUSIONS

6.1 Sub-bottom sonar systems must contend with high absorption in the sea-bed which reduces echoes relative to the bottom and sub-bottom reverberation.

6.2 The ability of a parametric array to generate narrow acoustic beams at low frequency and with a wide band-width makes it a possible contender for sonar systems which have to penetrate into marine sediments. Absorption is lower at low frequencies. Echo/reverberation ratio can be improved by narrow beams and wide-band pulses either by reducing the insonified volume or by allowing temporal separation.

6.3 If a parametric array is truncated by the sea-bed, there is an additional propagation path into the sediment from a second 'aperture' at the truncation. At angles near to and beyond the critical angle this path becomes significant as the amplitude of the beam propagated from the transducer diminishes. Even at these angles the effects are only significant at shallow depths and at moderate post-critical angles.

7. REFERENCES

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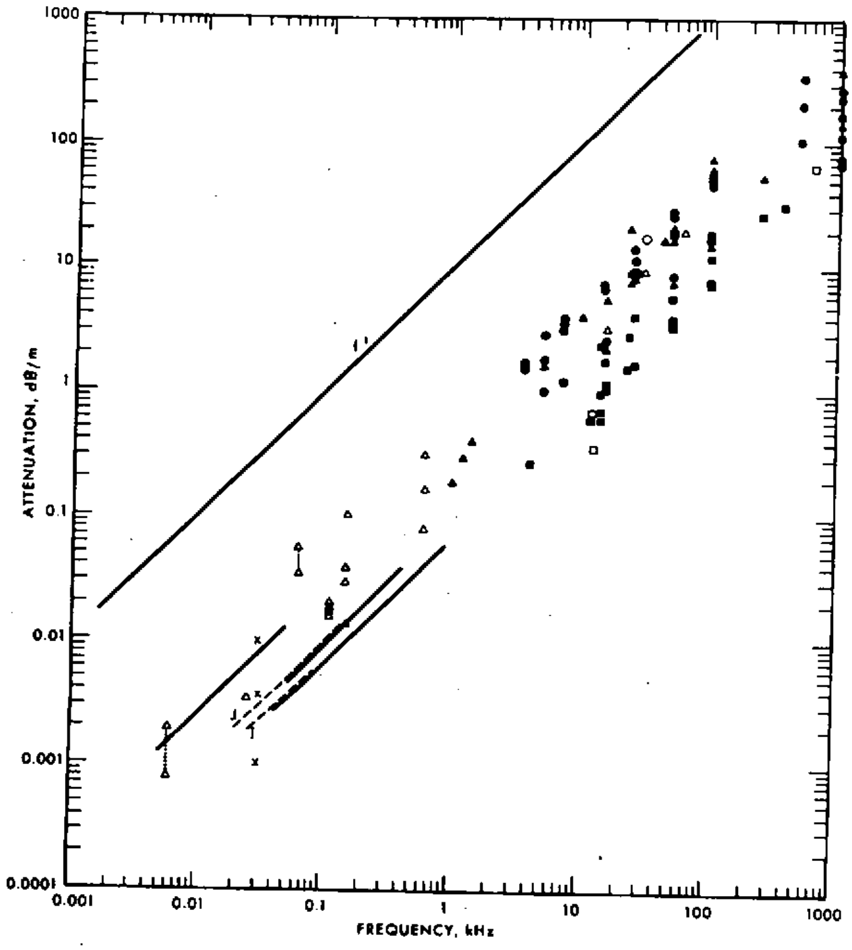

Figure 1. Attenuation in marine sediments v. frequency. (reprintes from J.Acoust. Soc. Am.)

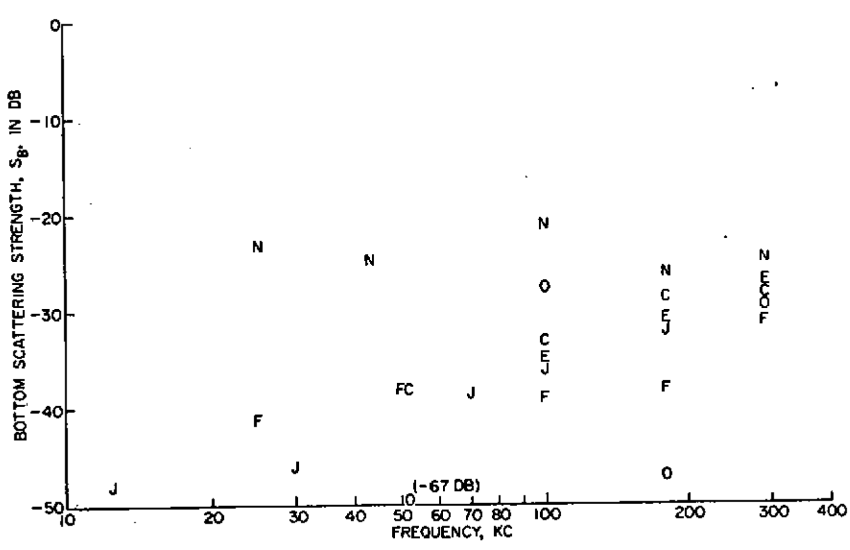

Figure 2. Bottom-backscatering strength v. frequency. (Reprinted from J. Acoust.Soc. Am.)

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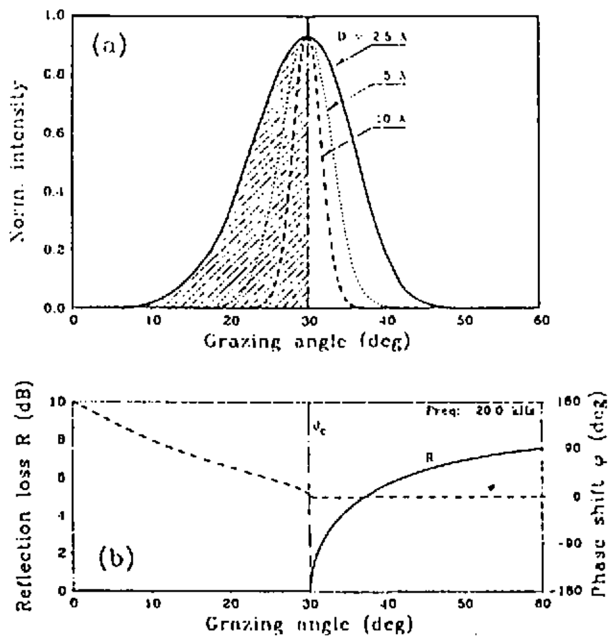

Figure 3. Plane-wave spectra for 3 beam-widths. (reprintes from J.Acoust. Soc. Am.)

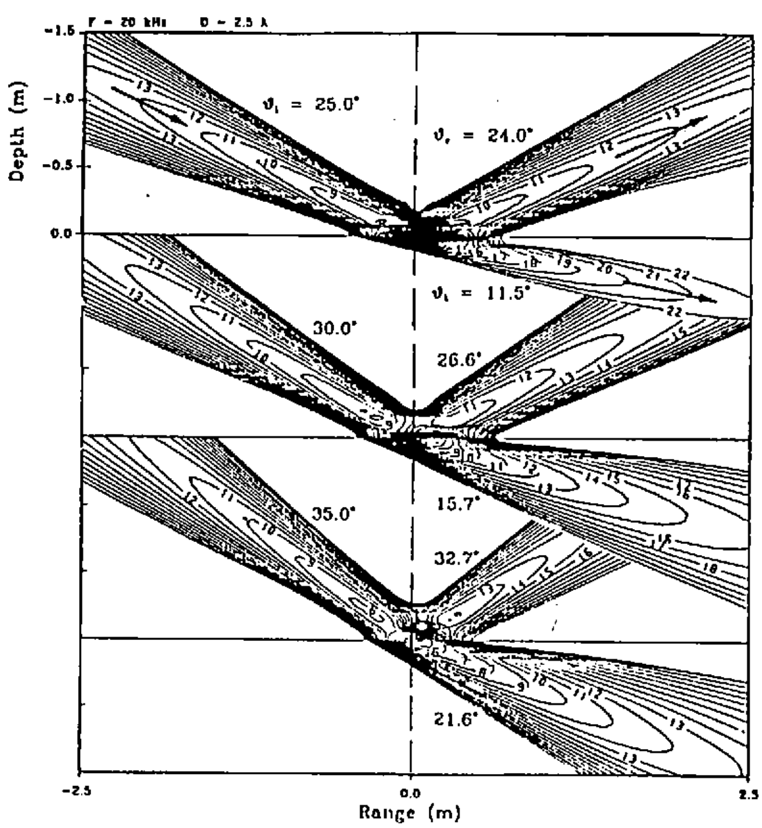

Figure 4. Reflection and transmission at a water-sediment interface computed by SAFARI, Critical Grazing angle = 30°

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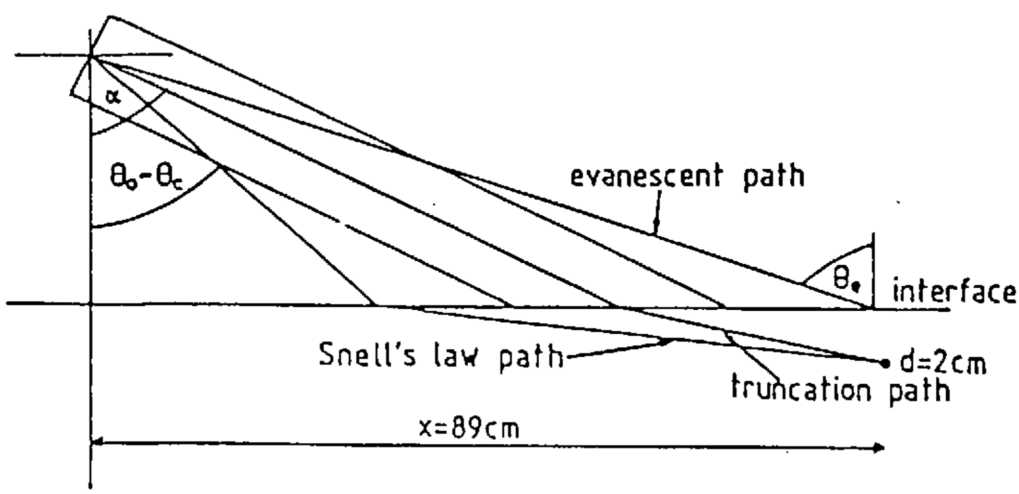

Figure 5. The geometry of the truncated parametric array and the three possible raypaths.

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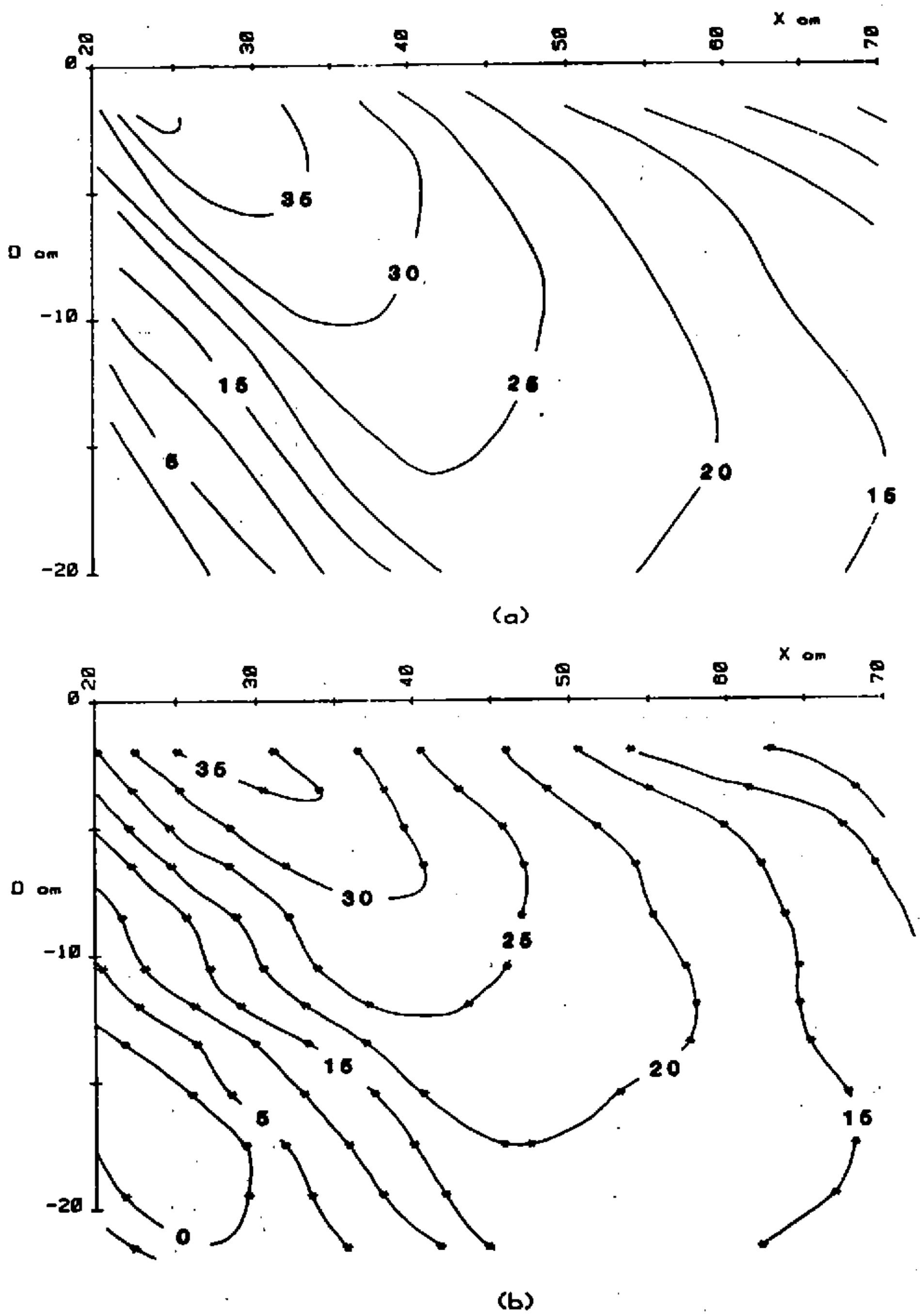

Figure 6. The sound field within the sediment for a truncated parametric array incident at less than the critical angle.(Upper =theoretical, lower = experimental).

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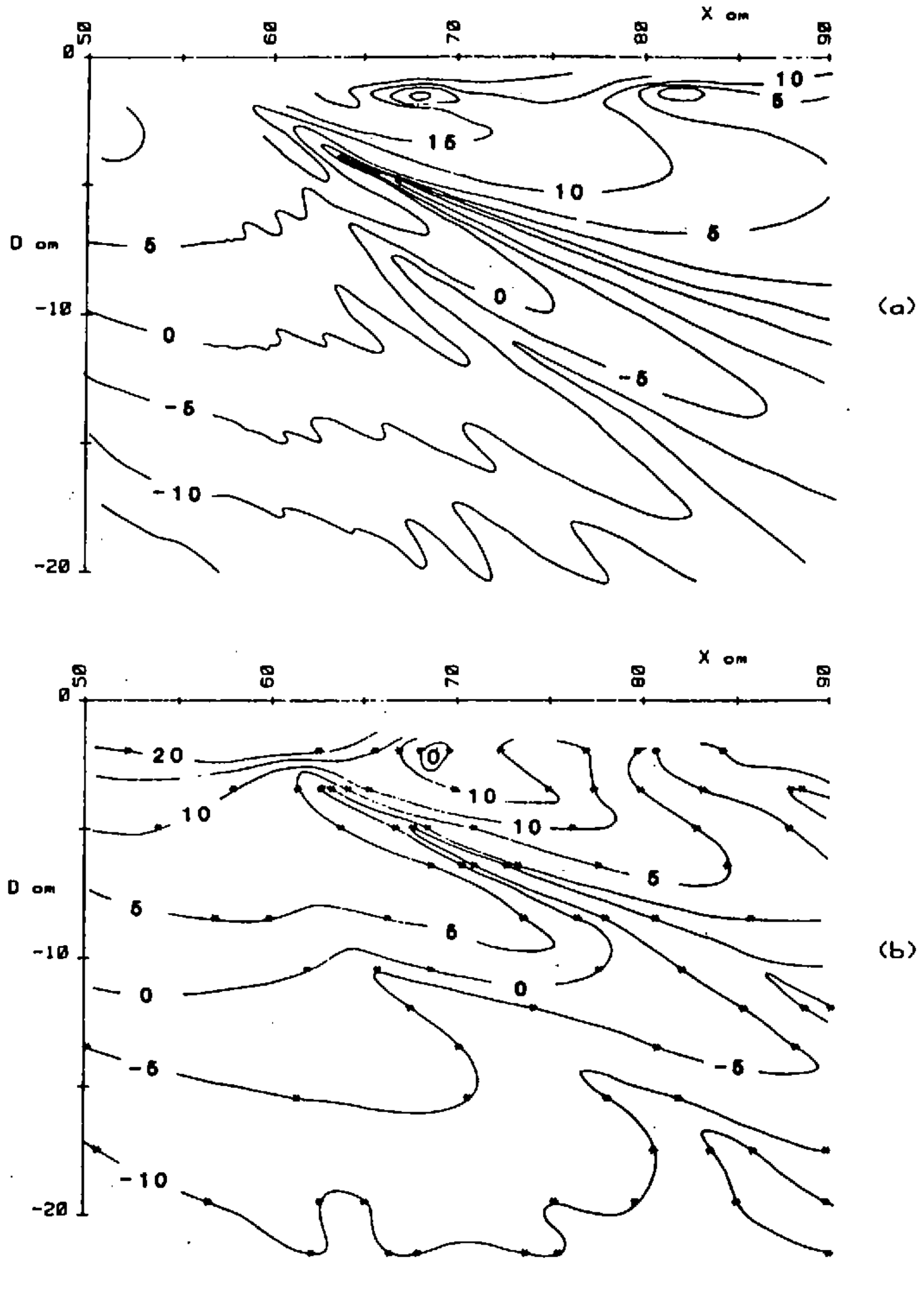

Figure 7. The sound field within the sediment for a truncated parametric array incident at greater than the critical angle.(Upper =theoretical, lower = experimental).

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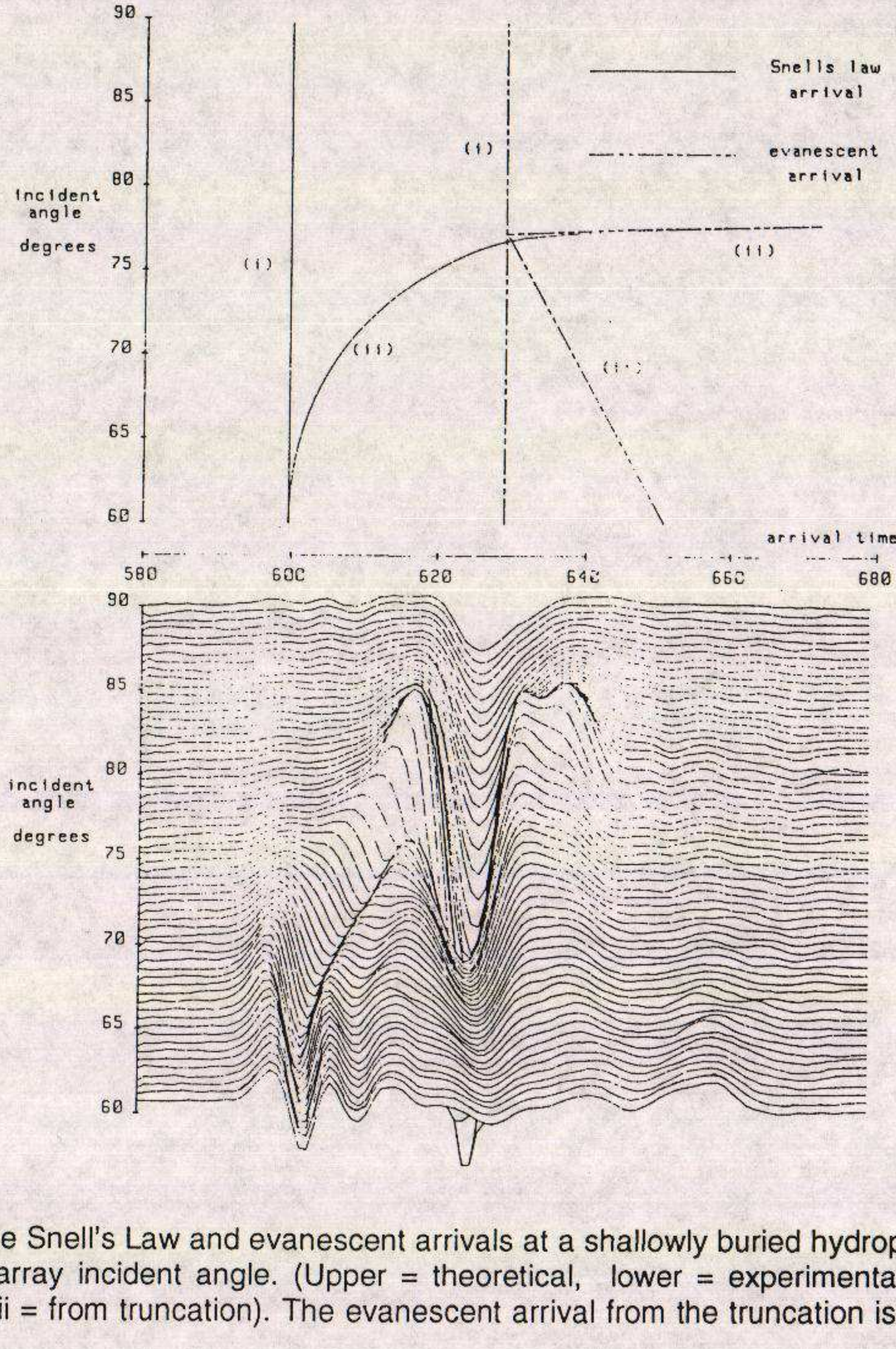

Figure 8. The Snell's Law and evanescent arrivals at a shallowly buried hydrophone as a function of array incident angle. (Upper = theoretical, lower = experimental; i = from transducer, ii = from truncation). The evanescent arrival from the truncation is not seen.