EVALUATION OF EXPERIMENTAL TECHNIQUES FOR DETERMINING THE PLANE WAVE REFLECTION COEFFICIENT AT THE SEA FLOOR

Henrik Schmidt and Finn B. Jensen
SACLANT ASW Research Centre
I-19026 La Spezia, Italy

ABSTRACT

One of the most commonly used techniques for determination of the geoacoustical properties of the sea bed is the measurement of plane wave reflection coefficients at the ocean bottom. An incident field is produced by either an explosive source or a beam generating device and the reflected field is then detected by means of an array of hydrophones. The associated angles of incidence have traditionally been determined by simple geometrical considerations. However such simple interpretations give results that in some cases depend on the actual experimental geometry. For example critical angles can appear far away from the correct values or not be present at all. Here an exact numerical model is used to examine the different experimental techniques. The observed discrepancies are explained, both for the point and beam source experiments. In addition, guidelines are given for interpretation of results obtained by the different experimental techniques.

INTRODUCTION

The importance of the sea bed geoacoustic properties for shallow water sound propagation is well established, and reliable transmission loss predictions obtained by means of numerical propagation models therefore require accurate knowledge of the sea bed properties. The traditional raytrace propagation models require a plane wave reflection coefficient at the bottom in order to account for the bottom loss. More recent wave theory models like those based on normal modes, the full wavefield fast field programs (FFP) and the parabolic equation models (PE), require a more detailed knowledge of the wave speeds, attenuations and densities in the sea bed. These parameters could in principle be obtained from samples, but due to the fact that the low-frequency acoustic waves penetrate deeply, very deep and expensive boreholes would be required. Further, and often more important, the de-pressurisation and change of temperature, unavoidable in the core sampling process, tend to deteriorate the mechanical and chemical bondings in the sediment material, and thus heavily influence the properties, shear in particular.

The geoacoustic properties therefore primarily have to be determined from in-situ propagation experiments. One of the most common experimental techniques is the determination of the plane wave reflection coefficient at the sea floor. This approach has two advantages: the results can be used directly by the raytrace models, and the plane wave reflection coefficient is needed as an input parameter in most inverse schemes for the determination of bottom properties [1].

Several experimental techniques have been devised with the objective of determining the reflection coefficients directly. They are all based on the detection, by hydrophones, of the bottom reflected part of the field produced by a sound source placed in the water column. The source has been either an omnidirectional explosive source or a device producing a narrow beam of sound directed towards the sea floor at a variable angle of incidence. However, several authors have shown that the results obtained are usually not directly interpretable as plane wave reflection coefficients.

Here we will use the full wavefield SAFARI model [2,3], to demonstrate how these discrepancies arise, and to show how numerical models are not restricted to interpretational purposes, a traditional application in underwater acoustics, but can also be used for the design and planning of experimental setups.

EXPLOSIVE SOURCE EXPERIMENTS

The most common experimental technique for determination of plane wave reflection coefficients uses an explosive omnidirectional source to generate a transient field. The hydrophone array used as a detector may be either horizontal or vertical, moving or fixed (Fig. 1).

By assuming that the source and receivers are so far apart that the bottom-interfering eigenrays can be considered plane waves when hitting the bottom, a very simple interpretation technique has been used. First the nominal specular reflection angle at the bottom is determined for each receiver by means of simple raytracing. Then the received signals are split into a direct part and a bottom reflected part by inspection. After correction for different travel paths, the reflection coefficient is found simply by dividing the frequency spectrum of the reflected signal by that of the direct signal.

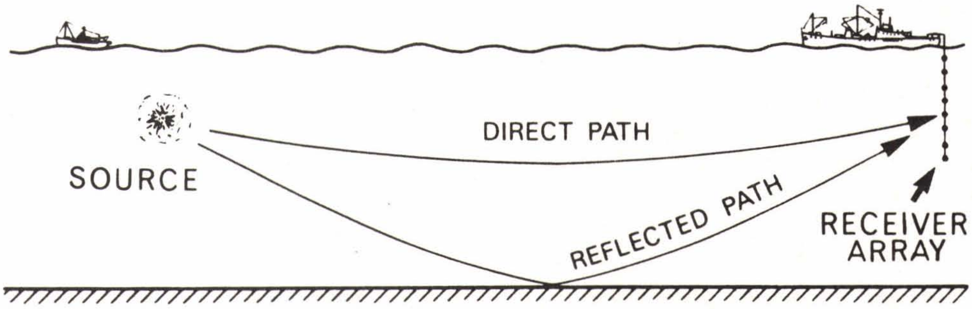

Fig. 1 Experimental set up for bottom reflection-loss measurements by means of an explosive source and a vertical hydrophone array.

The obvious advantage of the explosive source experiments is the possibility of separating the different arrivals in the time domain, and hence to eliminate unwanted surface multiples. Further, the experiments are cost-effective because they do not require any specialized equipment. As pointed out by several authors, however, the simple interpretation technique outlined above is only rarely applicable. Stickler [4] and Santaniello et al [5] demonstrated that the simple interpretation technique will give wrong reflection coefficients when the bottom is upward refracting or has deeper, reflecting interfaces, because of the interference between the different arrivals. Non-physical effects like negative bottom loss and source/receiver position-dependent results arise. The critical angle shift pointed out by Stickler [4] is due to the same effect. Even in the case of an isovelocity bottom with a sound speed higher than that of the ocean, the headwave formation will give rise to the same phenomenon. The simple interpretation technique can be applied only in the rather unusual case of a purely downward refracting or homogeneous bottom with a sound speed less than that of water.

We will here illustrate the limitations of the simple interpretation principle by simulating an explosive source experiment in a very simple ocean environment by means of the SAFARI full-wavefield model. The sound speed profile is shown in Fig. 2. The water is characterized by an upward refracting profile close to the bottom, and surface multiples of no present interest are avoided by replacing the ocean above -800 m by an isovelocity halfspace. The fluid bottom is upward refracting to 30 m below the seabed. Below this depth it is represented by an isovelocity halfspace. In order to more clearly illustrate the phenomenon, the bottom is considered lossless. Thus the reflection loss is identically zero for grazing angles less than the critical 14.6° onto the water-bottom interface.

An explosive source is assumed to be placed 400 m above the bottom and the radiated pressure pulse has a duration of 10 ms and a centre

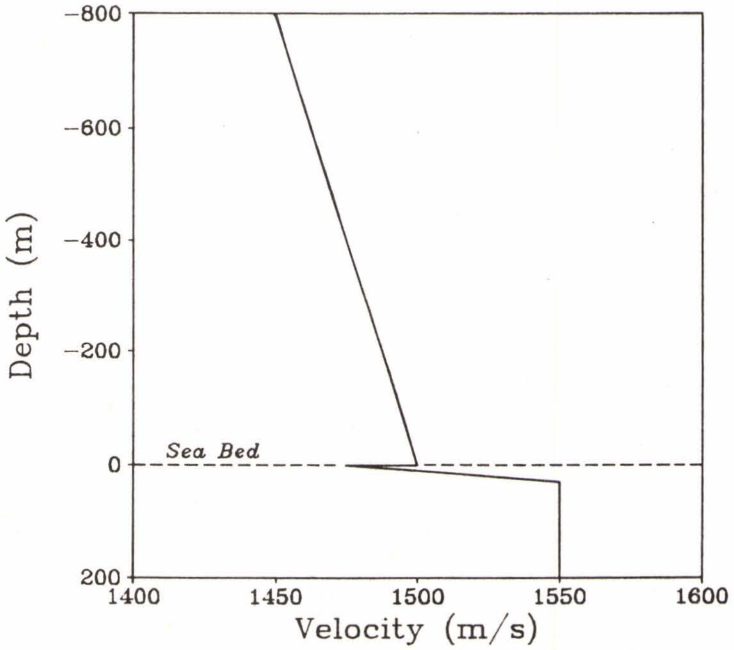

Fig. 2 Sound speed profile for simulation of experiment. Depth 0 m refers to the sea bed.

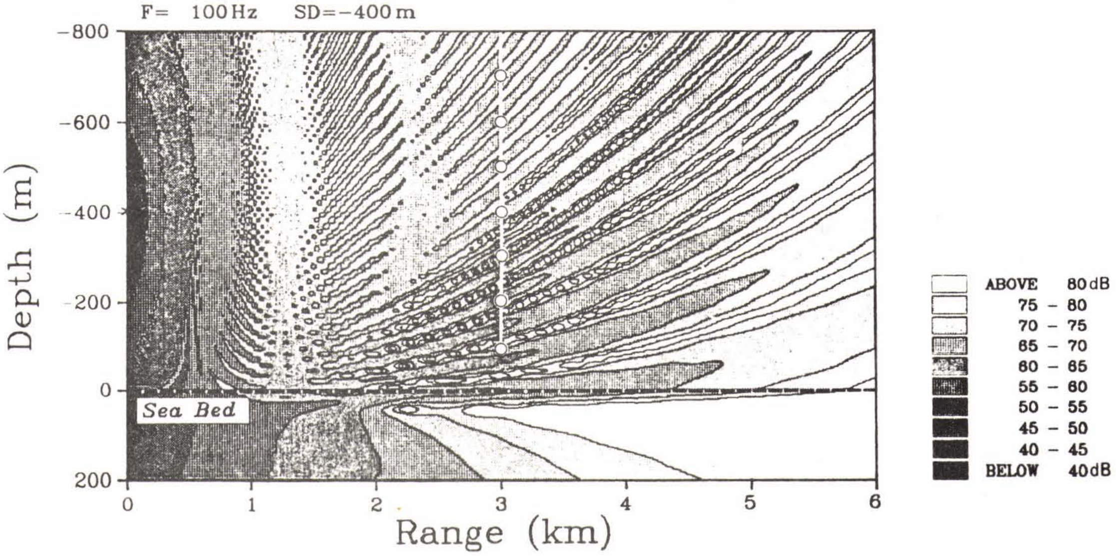

Fig. 3 Transmission loss contours at 100 Hz for a point source 400 m above the bottom. Hydrophone array used for pulse calculations is indicated by o.

frequency of 100 Hz. Figure 3 shows the transmission loss contours in depth and range at the centre frequency (black indicating highest intensity). The Lloyd-mirror pattern due to the interference between the direct and the bottom reflected fields is evident and illustrates the complexity of the sound field even in this very simple case.

A vertical array of 7 hydrophones with 100 m spacing is placed 3 km from the source as indicated in Fig. 3. The synthetic hydrophone signals for this array are shown in Fig. 4, with each trace being identified by the nominal specular angle of the reflected signal at the ocean bottom, as separated from the reflected parts, which, however, do not clearly

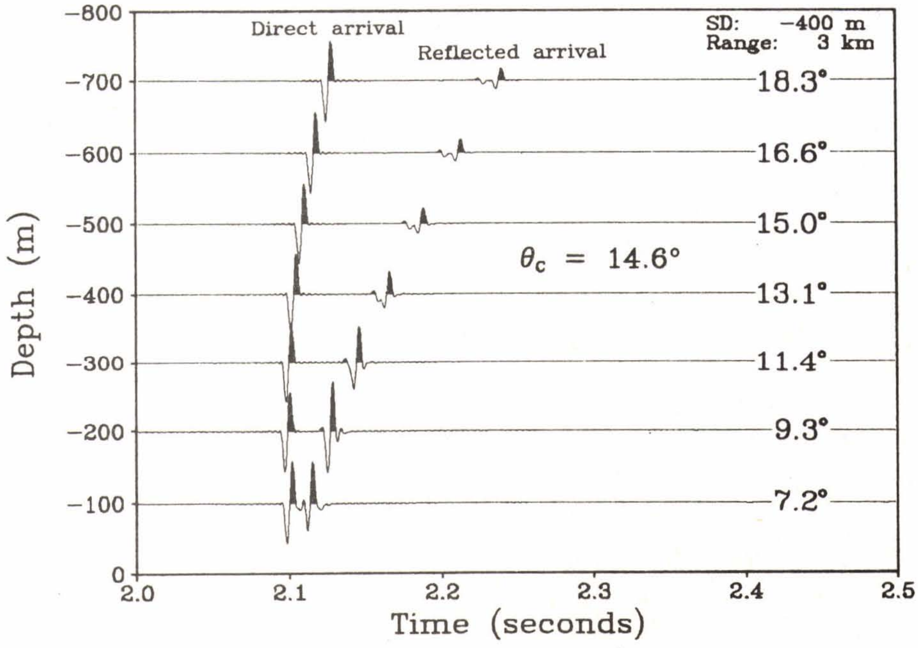

Fig. 4 Synthetic hydrophone signals for vertical array at 3 km range. Each trace is identified by its corresponding nominal specular reflection angle.

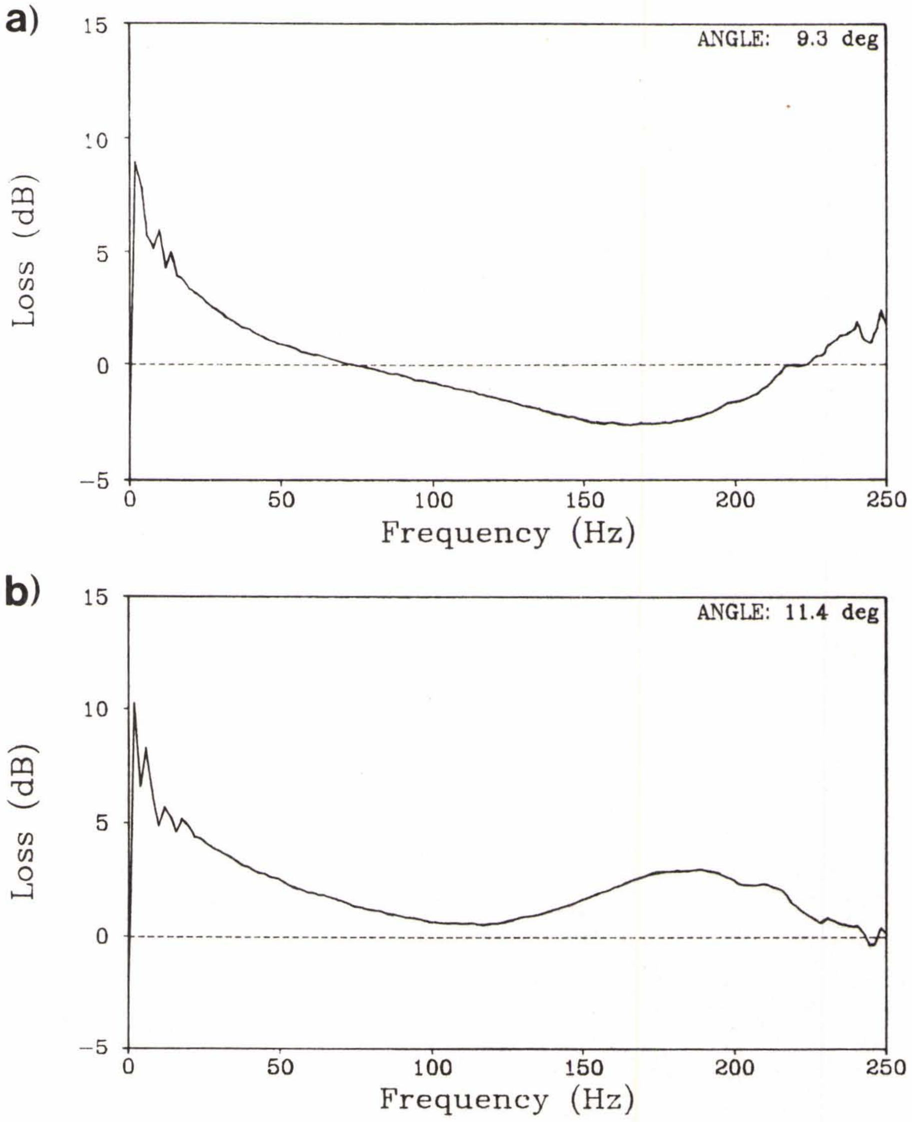

Fig. 5 Reflection coefficients determined by deconvolution of synthetic signals: a) 9.3°, b) 11.4°

indicate the critical angle of 14.6°. Further, the trace corresponding to 9.3° indicates an apparent negative bottom loss. These properties are also indicated by the reflection coefficients obtained by the simple deconvolution principle for the grazing angles 9.3° (Fig. 5a) and 11.4° (Fig. 5b) respectively. Both angles are less than critical; therefore the reflection loss should be zero in both cases. The "ringing" at low and high frequencies is due to the very low energy content of the source pulse at these frequencies, but even in the central frequency interval errors of several dB are obtained.

Figure 6 outlines the different travel paths yielding errors in the reflection coefficients obtained by the simple technique. The possibility of multiple paths, due to headwaves (1), upward refracting profiles (2) or reflecting interfaces (3), yields results which are dependent on whether the different arrivals are interfering constructively or destructively, which is again dependent on the source-receiver positions. As is also clear from Fig. 6, the multiple arrivals do not correspond to the same angle as the nominal specular reflection angle at the water-bottom

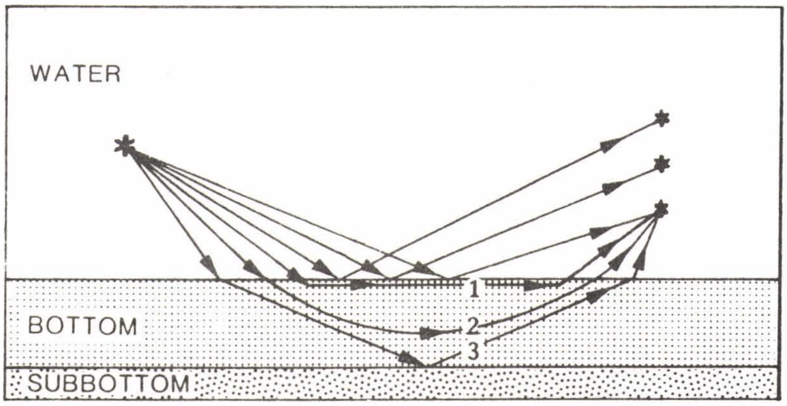

Fig. 6 Additional arrivals obstructing simple deconvolution. 1) Headwaves, 2) Upward refracted arrivals, 3) Deep reflection.

interface. The field detected by each hydrophone is therefore not a single plane wave component, as is assumed when the simple interpretation technique is used, but a complicated interference between several different components.

This phenomenon directly leads to the conclusion that in order to obtain the plane wave reflection coefficient from explosive source experiments, some kind of beamforming, or plane wave decomposition, has to be applied to the received signals. In principle this could be done by using towed arrays. However, at the low grazing angles, often of main interest, this technique requires very long arrays because the bottom refracted signals travel a long distance before re-entering the water column, and the whole reflected field has to be covered by the array. Therefore, a synthetic aperture technique, as proposed by Frisk et al [6], is often more convenient than the use of a towed array.

BEAM EXPERIMENTS

In contrast to the omnidirectional explosive source described above, a source that generates an approximate plane wavefield would provide the opportunity to directly measure the plane wave reflection coefficients. This is the philosophy behind the use of beamed sources, as shown schematically in Fig. 7. A beam is directed towards the water-sediment interface at a nominal angle of incidence, and the reflected beam is measured in the specular direction by means of a hydrophone.

It is well known, however, that very wide beams are required in order to simulate plane wave behaviour. This is due to the fact that a beam of finite width has a finite angular spectrum, whereas for a plane wave the angular spectrum is infinitely narrow [3]. For practical reasons this technique has therefore not been a realistic alternative to the explosive source experiments until the development of the parametric transducer [7]. In principle, this transducer generates a virtual endfire-array that is the source of a highly directional beam which can be used for measurement of plane wave reflection coefficients [8]. In practice, however, the virtual array will have a finite length, and thus results in the beam having a finite angular spectrum.

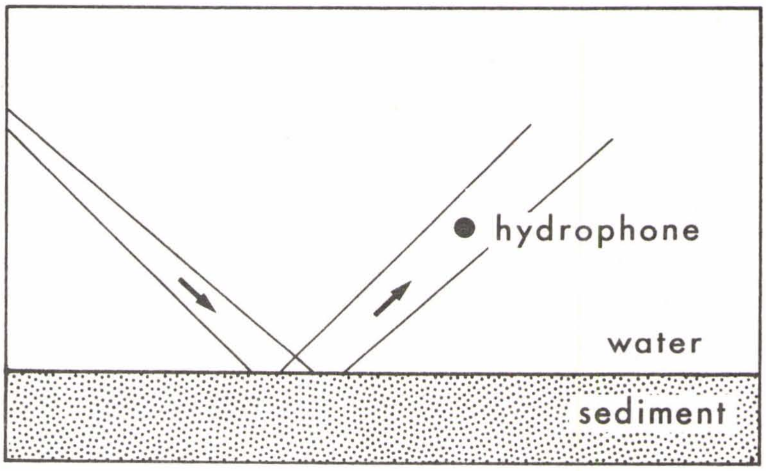

Fig. 7 Reflection of a narrow beam from the sea bed.

We will here use the SAFARI model to demonstrate how a velocity profile in the ocean close to the bottom influences the reflection of a realistic, narrow beam at low grazing angles. The environment shown in Fig. 2 is also used for this study. A vertical source array of 61 elements at half-wavelength spacing, placed 400 m above the bottom is used to generate a narrow beam, 6 wavelengths wide at the sea bed, measured between the 3-dB down points. The array is phased to yield a nominal grazing angle of 2.5°, 5° and 10° at the sea bed.

The resulting fields are shown in Fig. 8 (black indicating highest intensity). The contour interval is 2 dB, but the actual dB values are arbitrary. Obviously the beams are not specularly reflected. At the two smallest grazing angles, Figs. 8a and 8b, a clear beam splitting occurs, and the reflected beam with highest amplitude has a much smaller grazing angle than the incident beam. A comparison with Fig. 3 shows that the directions of the split beams correspond to those of the lowermost lobes of the Lloyd-mirror pattern in the point source field. This indicates that the angular spectrum of the beam is apparently so wide that the interference between the direct, but upward refracted, purely waterborne arrivals and those reflected off the bottom is important. This assumption is supported by the calculated angular spectrum of the 5° beam at the bottom, shown in Fig. 9. The beam is seen to contain significant energy at grazing angles in the interval of 1° through 12°. Figure 8c indicates that the splitting effect due to the interference decreases for higher grazing angles, as expected, but although the energy is here concentrated in a single beam, a significant widening of the beam cross-section has occured. Even at this relatively high grazing angle, a single hydrophone in the specular direction would not yield the right value of the reflection coefficient; instead it would indicate too high a reflection loss.

Even in the ideal case of an isovelocity water column over a homogenous bottom, it was shown by Muir et al [8], that narrow parametric beams could penetrate into the bottom at grazing angles less than critical. This problem has been treated theoretically by several authors. Tjotta and Tjotta [9] presented a wide beam approximation showing the effect qualitatively. Schmidt and Jensen [3] used the SAFARI model to simulate the experiments in which extremely narrow beams, not covered by the approximate theory, were used. The reported beam cross-section at the bottom interface was simulated by means of a focusing linear array.

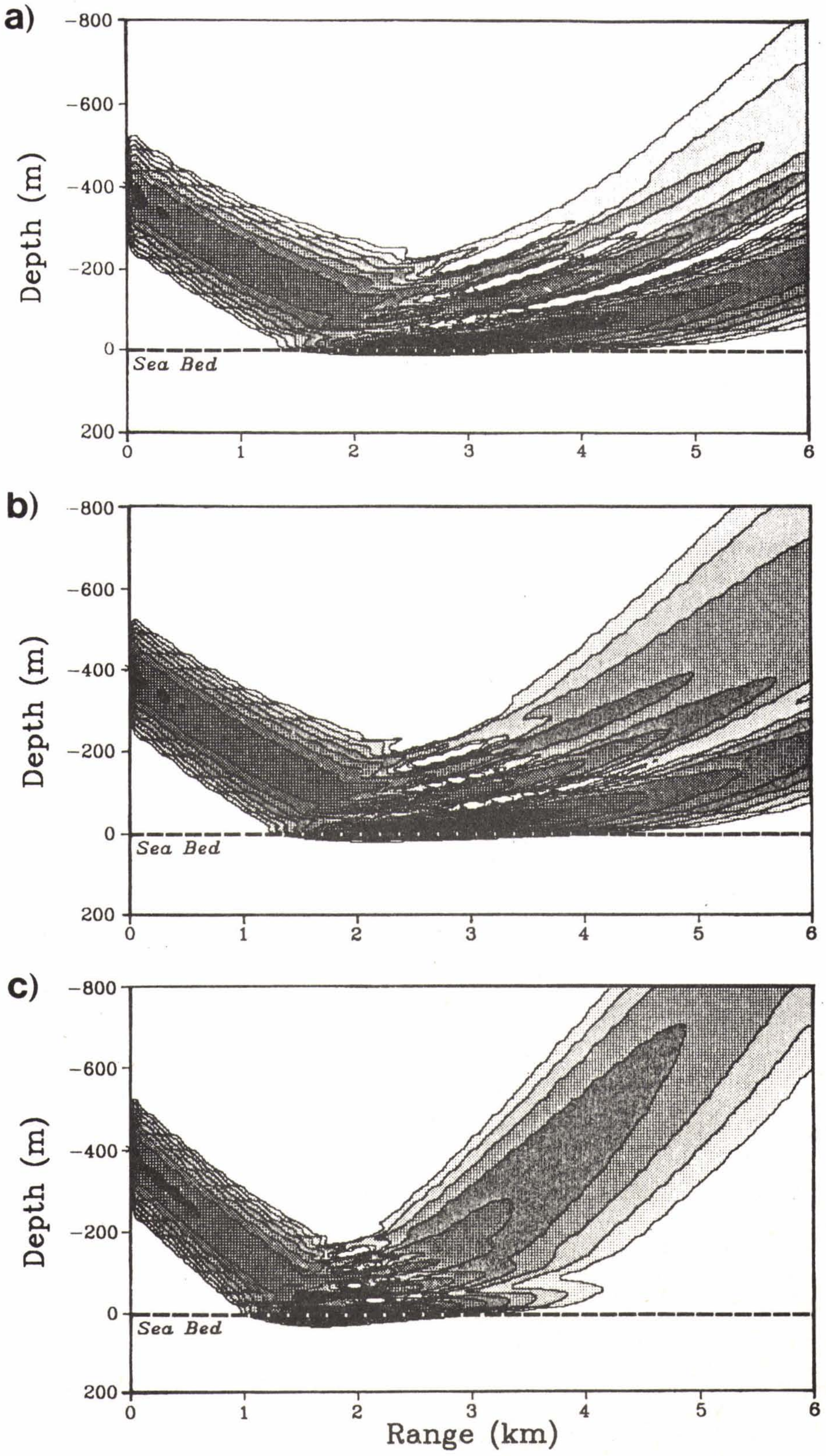

Fig. 8 Field contours at 100 Hz for an incident beam of 6 wavelengths width at 3 nominal grazing angles: a) 2.5°, b) 5° and c) 10°. (Contour interval = 2 dB).

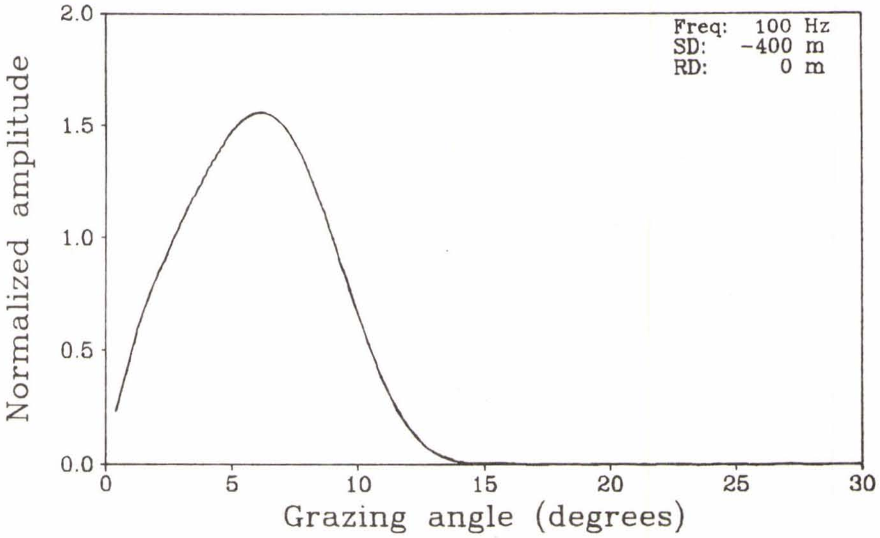

Fig. 9 Angular spectrum of beam at the ocean bottom for nominal grazing angle of 5°.

The results demonstrated that subcritical penetration is a simple consequence of the basic physical principle that a narrow beam has a wide angular spectrum. Thus the narrow beam may contain energy that propagates at grazing angles greater than critical although the nominal angle of incidence is subcritical. The results further showed that, for the same reason, the reflected beam was not specular, but shifted towards a smaller grazing angle. In conclusion, the parametric beams in practice are narrow and not highly directional as often stated, and hence they are a poor approximation to a plane wave.

To summarize, the use of beam sources does not yield the possibility of measuring the plane wave reflection coefficients directly by means of a single hydrophone. As was the case for the explosive sources, plane wave decomposition has to be applied to the reflected field. However, the advantage of using beam sources is that smaller arrays or synthetic apertures can be used because only a limited part of the angular spectrum is activated by the beam.

CONCLUSION

A full wavefield numerical model has been used to demonstrate that neither explosive source techniques nor narrow beam techniques yield the plane wave reflection coefficients directly. It has been demonstrated, that the narrow beams are not highly directional, and thus do not behave like plane waves. Therefore, both experimental techniques require the application of either plane wave decomposition or beamforming to the reflected field in order to correctly determine the plane wave reflection coefficients.

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