AURALIZATION OF SOUND FIELDS BY WAVE FIELD SYNTHESIS

Diemer de Vries * and Jan Baan
Laboratory of Acoustic Imaging and Sound Control
Delft University of Technology
P.O.B.5046
2600 GA Delft
The Netherlands

ABSTRACT

Berkhout [1] showed that, for a given source position, the sound field in a hall can be acquired with full temporal and spatial information by recording or calculating impulse responses along an array of microphone positions. As an implementation of this concept, an array of loudspeakers is fed with these impulse responses such that the sound field can be auralized.

INTRODUCTION

The main goal of consultancy in architectural acoustics is to predict the acoustic quality of a hall before it is built. Various calculation programs are available to simulate the (approximated) impulse responses of a hall design. On the one hand, physical parameters can be derived from these impulse responses which are supposed to predict the quality of perceptual cues as clarity, spaciousness, reverberance etc. On the other hand, local or binaural impulse responses are convolved with anechoic signals and made audible through headphones or a pair of near field loudspeakers in order to give a listener a perceptual impression of the hall acoustics; for a survey of common methods of this so-called *auralization* procedure, see Naylor et al. [2]. The main shortcoming of these methods is that they give only local information. Besides, sound reproduction through headphones often leads to 'in-head localization' such that good assessment of spatial cues becomes impossible. In order to solve these problems, in this paper a new method for auralization is proposed, based on the reproduction of multi-channel impulse responses by wave field synthesis, a concept introduced by Berkhout [3]. This method, when implemented with all its potentials, enables the perceptual assessment of the complete hall design without the use of headphones, i.e., including all temporal and spatial cues. The method can also be applied to impulse responses measured in an existing hall. This way, the acoustics of a certain hall can be reproduced elsewhere, to be perceptually analyzed or to reproduce speech or music with the acoustics of that hall.

MULTI-CHANNEL RECORDING, CALCULATION AND PROCESSING

Berkhout et al. [1], [4] have shown that multi-channel recording or calculation of impulse responses in an enclosed space along an array of microphone positions gives much insight in the temporal and spatial structure of the wavefield. An example is given in figure 1, showing the impulse responses measured in the Amsterdam Concertgebouw along an array of microphone positions, with interspacing 0.05m, over the full width of the hall at a distance of 12m from the stage front, the omnidirectional source being placed at the center of the stage front. The vertical axis represents the traveltime coordinate t

which equals zero when the pulse leaves the source. The horizontal axis gives the lateral microphone position x, the so-called offset, *re* the center of the array which in this case coincides with the center of the hall. The responses are given in terms of sound pressure. Since the measurements were done with an omnidirectional microphone, this dataset allows no discrimination in the elevation plane around the microphone array: wave fronts from front, back, above and below are all projected in the same offset-traveltime plane. Nevertheless, by taking the hall geometry into account, the origins of many reflected or diffracted wave fronts can be identified.

When not only the sound pressure is recorded, but also the three spatial components of the particle velocity - which can be done simultaneously by using a Soundfield SPS 422 microphone, on each microphone position a directional microphone can be *simulated* by post-processing, as described by De Vries et al. [5]. This simulated microphone can be rotated around the microphone array under each azimuthal angle with the array between -90 and +90 degrees, such that wave components incident on the array under different elevation angles can now be discriminated. Figure 2 shows the decomposition of the dataset of figure 1 for the elevation angles 0 (front), 90 (upward), 180 (back) and 270 (downward) degrees.

Using wave field extrapolation techniques as developed for seismic extrapolation purposes (Berkhout [6]), from a multi-channel recording along one array the responses at the position of any other array in the hall can be estimated. Figure 3 shows the dataset of figure 2c (i.e., the waves arriving at the original array from the rear) after inverse (backward) extrapolation over 2.4m distance. The result is an approximation of this wave subset when measured along a microphone array at 14.4m distance of the stage front. It is seen that at this position one of the rows of chairs comes into focus (see arrow): it is the row just near the array, the seats of which start to generate diffracted waves when hit by the primary wave after ab. 45 ms - corresponding with the time needed to travel 14.4m. Note that the chairs are displayed as sources of diffractional acoustic pressure. Their properties can be changed, they can be removed, a screen can be placed instead etc, whereafter the wave field can be extrapolated back to the original array position and the differences with the original response (i.e., the influence of the changes made) can be investigated. In principle, by combining the techniques of wave field extrapolation and directional microphone synthesis described above, one array measurement gives ample 3D information on the acoustics of the hall. Taking aspects of spatial resolution into account, it becomes clear that, in addition to recording or calculation along an array over the width of the hall, data acquisition along an array with front-to-back orientation and a vertical array improves this resolution.

AURALIZATION BY WAVE FIELD SYNTHESIS

Multi-channel datasets as discussed in the previous section can be physically analyzed in many ways, which yields much insight in the generation and propagation of sound fields in enclosed spaces [1]. On the other hand, the responses recorded or calculated at (or extrapolated to) a microphone array, can be auralized by feeding them 'one to one' to an array of loudspeakers with the same interspacing. Basically, the ultimate configuration for this purpose would be a 3D space of concert hall dimensions of which all boundaries are covered with closely sampled arrays of individually driven loudspeakers. Then, the acoustic field in any hall could be simulated or reproduced and listeners within that space could walk around and perceive the acoustic conditions at any place with correct temporal and spatial properties. This, however is not realizable for several reasons, among which computational power is the most serious one. Therefore, the authors propose to aim at optimal auralization in the horizontal earplane by surrounding the listeners with a rectangular configuration of four linear loudspeaker arrays which correctly synthesize the wave field components recorded or calculated by four microphone arrays at the same positions. By the front array, only the components traveling from that array into the listening area, as identified by the technique of the simulated directional microphone discussed above, are generated, by the righthand array only the components coming from the right, etc. It is obvious that components incident on the listening area from a front-right direction are generated by the front and righthand array together.

Vertically incident wave components are now 'projected' in the horizontal plane, which is not physically or perceptually correct. Since, however, the vertical component of a sound field in a hall is usually relatively weak due to the absorbing floor (seat, audience) area, this could be a minor drawback. If perceptual experiments reveal the necessity, the strongest ceiling reflections can be added by a linear array above the listening area.

The dimensions of the auralization studio that the authors have to their disposition affords a horizontal array configuration of 6m x 4m at maximum. This means that only a part of the wave field in a large hall can be auralized at a time. However, different parts can be auralized subsequently.

STATE OF THE ART

During the Tonmeistertagung in 1998 in Karlsruhe, Germany, a demonstration has been given by the authors, where the central 4m of the multi-channel recording of figure 1 was auralized by one array of 32 loudspeakers with 0.125m interspacing. The difference in interspacing with the microphone array (0.05m) was corrected for by appropriate interpolation. No separation was made between components with different elevation angles, such that the listeners in fact perceived the acoustics of the Concertgebouw through a narrow slit while wave components which should arrive from behind were projected to the front. The recording was convolved in real time with anechoic cello music. In spite of the many restrictions mentioned, there was a general perception of a cello 'rehearsing' in a large, empty concert hall, with natural spaciousness and depth. As a comparison, the convolved central impulse response was auralized through 32 loudspeakers as a plane wave; the impression of spaciousness and depth immediately disappeared.

Using the technique of the simulated directional microphone, the authors have separated the wave components from front and back in the central part of the recording of figure 1, and auralized the two data sets by two (front and back) arrays. Global listening tests have shown that the spatial impression strongly improves.

Also, parts of the wave fields recorded in different concert halls (the Amsterdam Concertgebouw and "De Doelen" in Rotterdam) have been auralized and compared: perceptual differences are quite significant and should be further specified. The same holds for comparison of recorded and calculated multi-channel responses. The extension of software and hardware necessary to do 'full-size' experiments as proposed in the previous section is now under design.

CONCLUSIONS

1. Multi-channel recordings or calculations of impulse responses in halls, acquired along an array of microphone positions, can be auralized by feeding them to corresponding loudspeaker arrays.
2. This approach enables perceptual evaluation of the sound field in a volume of the hall (instead of at one local position) without the use of headphones, i.e., with natural temporal and spatial cues. This may yield a major step forward in room acoustic consultancy practice.
3. By applying processing techniques as developed for seismic exploration purposes, from one array measurement ample 3D information on the acoustics of a hall can be obtained. Also, the influence of interior design modifications (removal or renovation of chairs, addition of screens etc) on the acoustic field can be evaluated physically and perceptually.
4. Introductory experiments show that the approach has promising practical potentials.

REFERENCES

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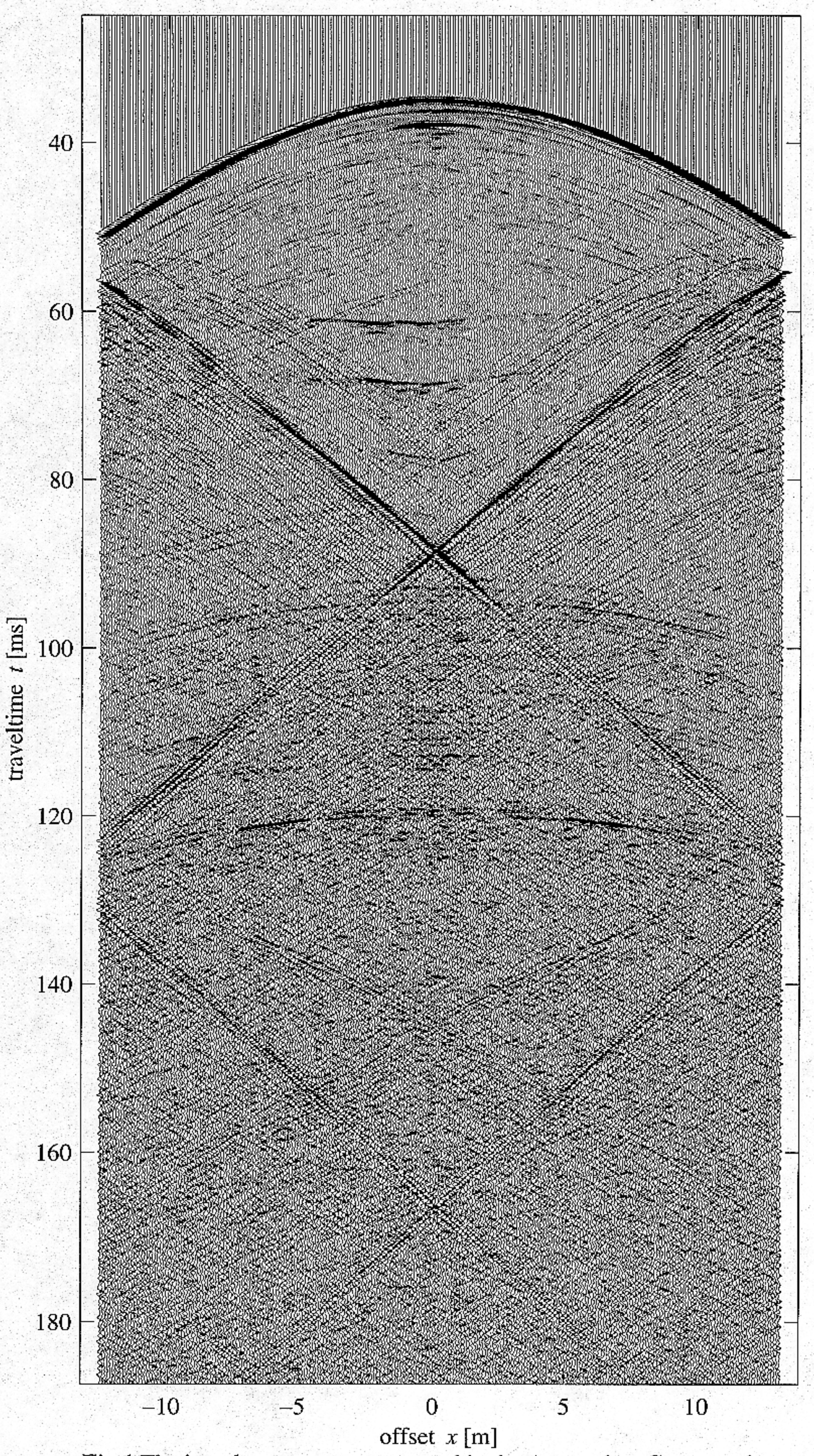

Fig 1 The impulse responses measured in the Amsterdam Concertgebouw.

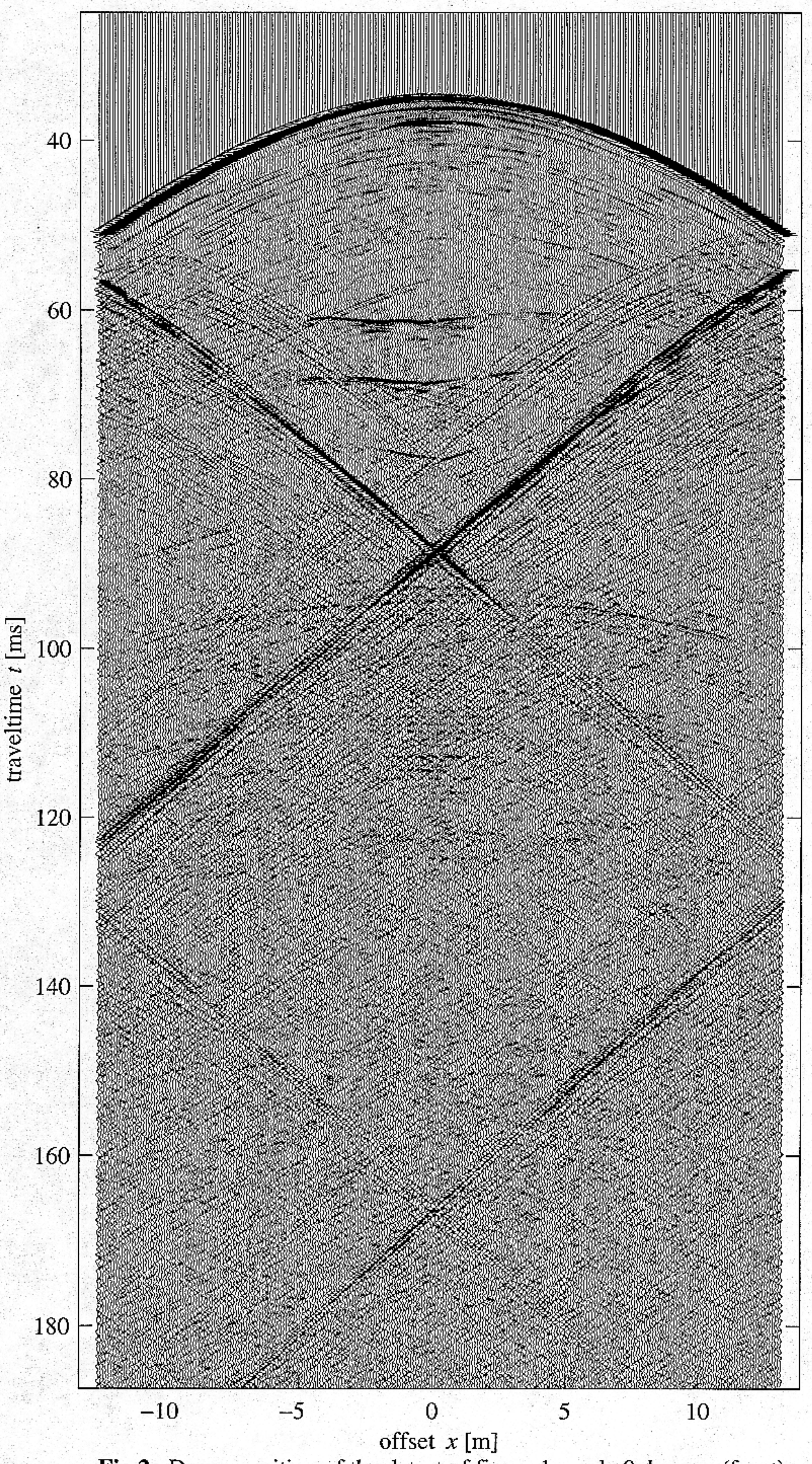

Fig 2a Decomposition of the datset of figure 1, angle 0 degrees (front).

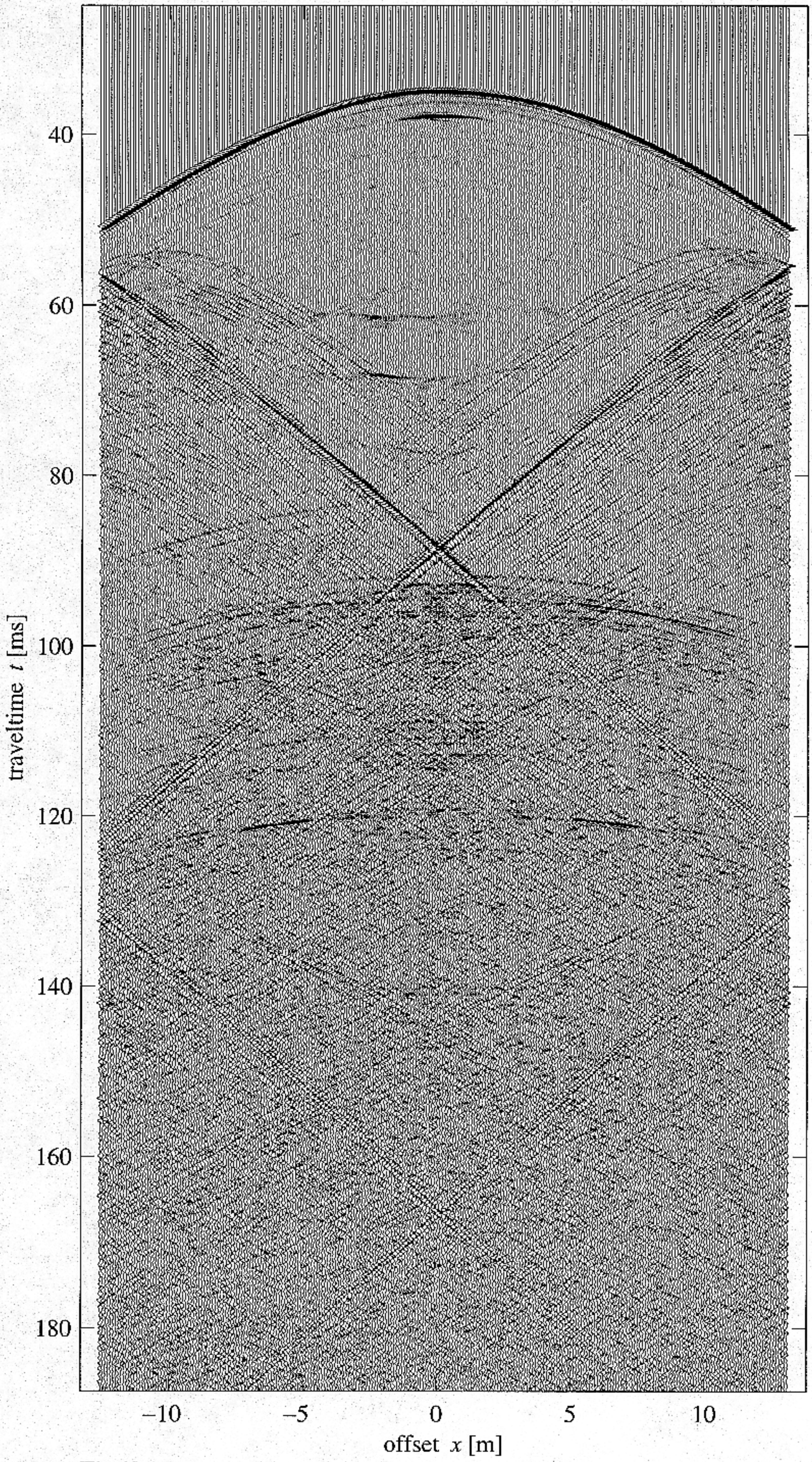

Fig 2b Decomposition of the datset of figure 1, angle 90 degrees (upward).

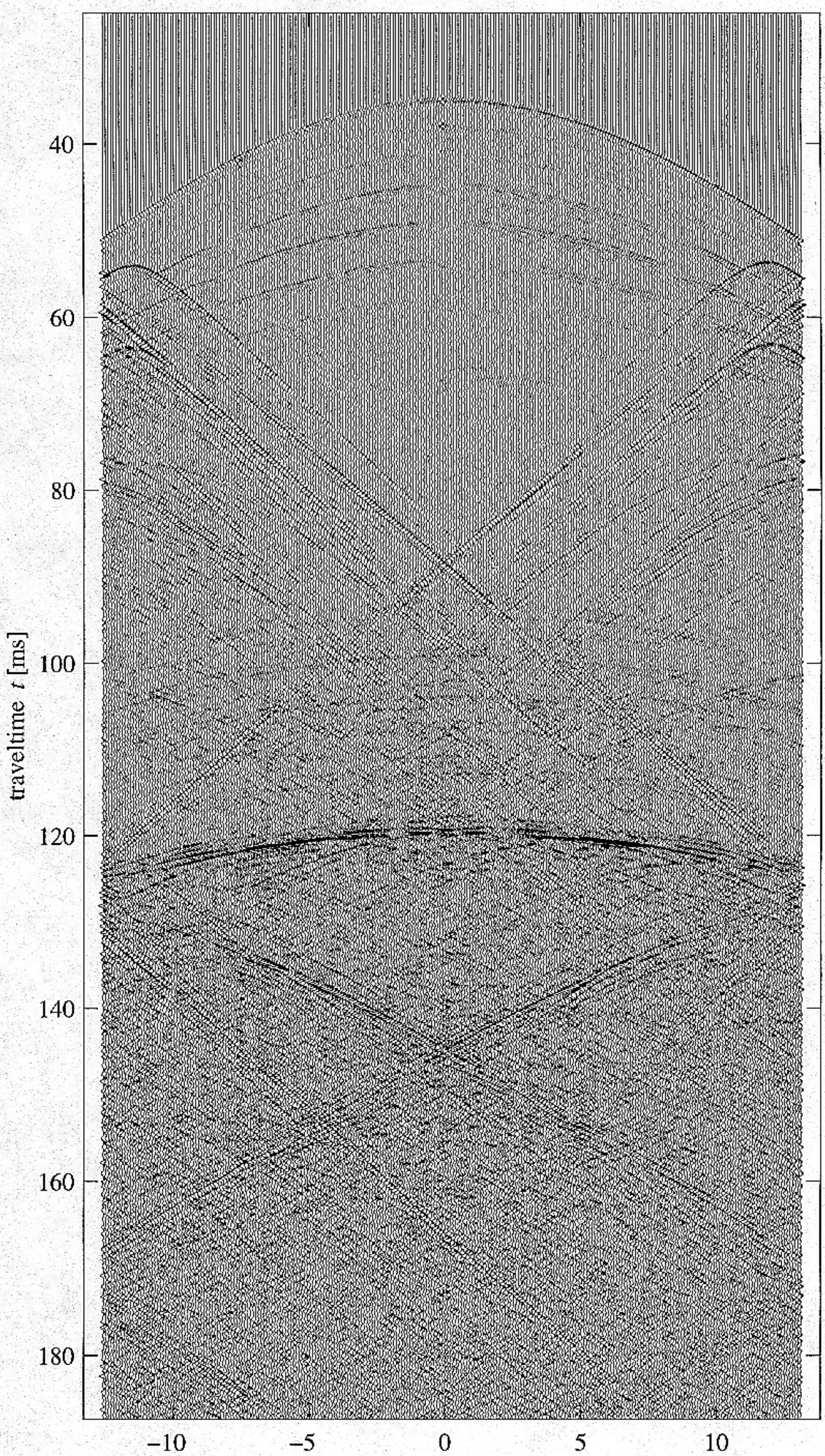

Fig 2c Decomposition of the datset of figure 1, angle 180 degrees (backward).

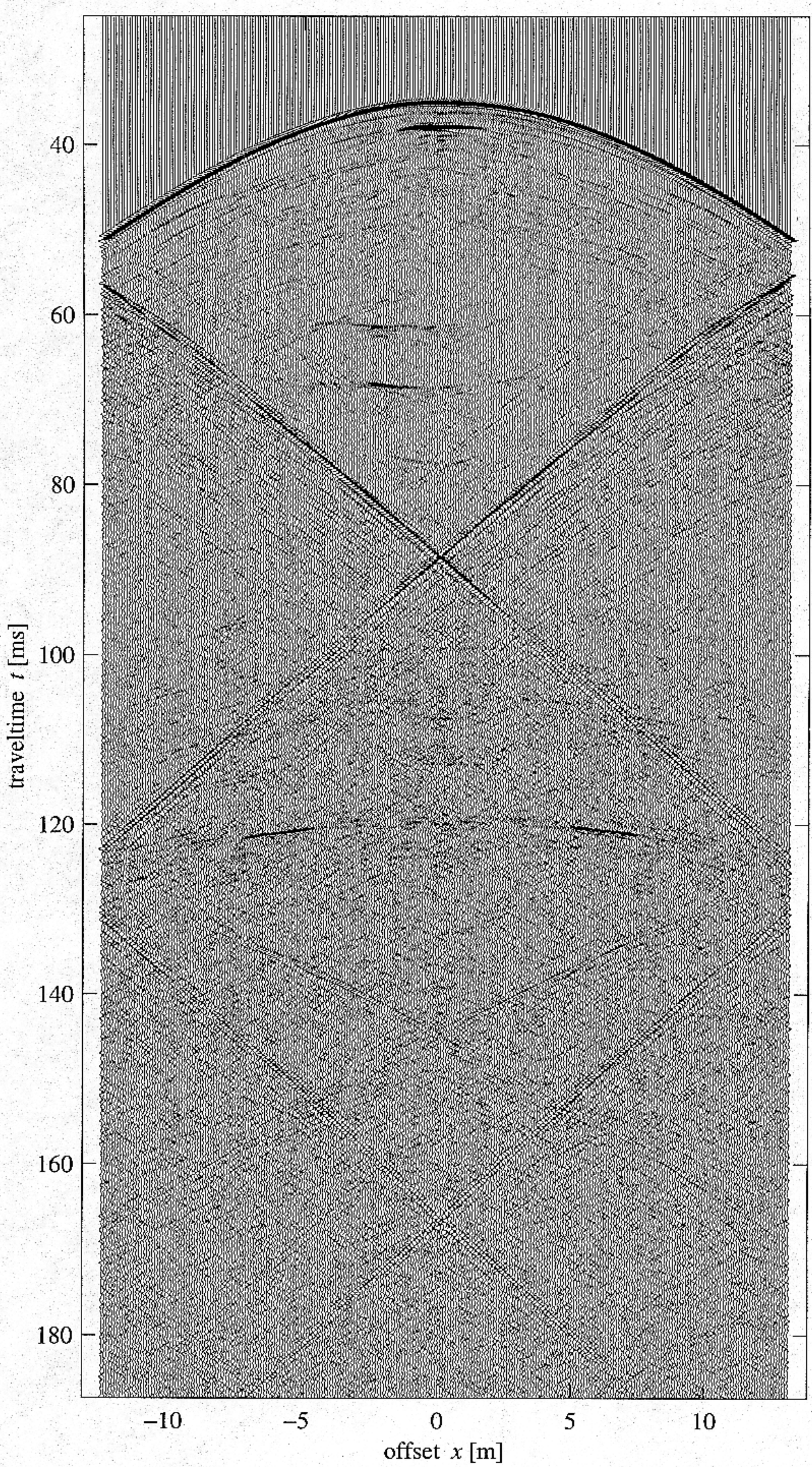

Fig 2d Decomposition of the datset of figure 1, angle 270 degrees (downward).

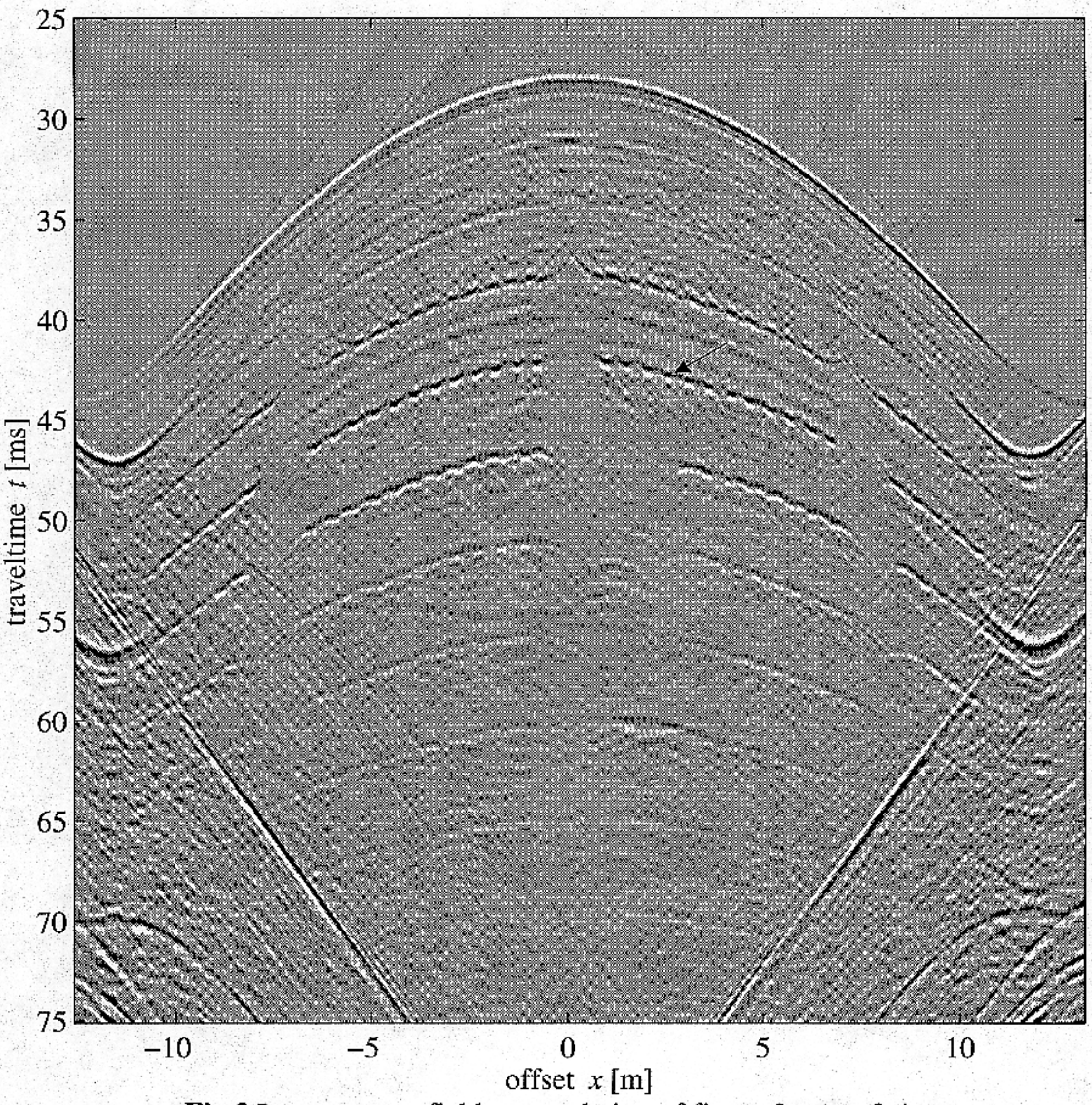

Fig 3 Inverse wave field extrapolation of figure 2c over 2.4 meter