ON THE APPLICABILITY OF DISTRIBUTED MODE LOUDSPEAKER PANELS FOR WAVE FIELD SYNTHESIS BASED SOUND REPRODUCTION

Marinus M. Boone and Werner P.J. de Bruijn
Delft University of Technology, Laboratory of Acoustical Imaging and Sound Control
Lorentzweg 1, 2628 CJ Delft, The Netherlands

ABSTRACT

The applicability of distributed mode loudspeaker (DML) panels for Wave Field Synthesis based sound reproduction is investigated. For WFS a large number of closely spaced loudspeakers is necessary. DML panels are light-weight and can be placed directly on the walls. Results are reported of a research project to test the objective and subjective performance of these speaker panels for WFS.

0. INTRODUCTION

At TU Delft a new sound reproduction method has been developed, called Wave Field Synthesis. It consists of arrays of closely spaced loudspeakers which are fed with audio signals in such a way that a highly natural sound field is produced with wave front curvatures as would be obtained from real sources. In such a way an arbitrary number of so-called virtual sources can be reproduced simultaneously.

The applicability of distributed mode loudspeaker panels (DML) for Wave Field Synthesis based sound reproduction is investigated. DMLs have the benefit that they are light-weight and can be placed close to walls or even be integrated into walls. In sound for vision applications they can also be used as projection panels. Results are reported that were obtained in a research project to test the performance of these speaker panels for WFS. Emphasis is given to objective as well as subjective performance of the loudspeaker panels for this application. The objective performance is examined by measuring the multi-channel impulse responses of the reproduced sound field, thereby revealing the effects of the radiation behaviour of the DMLs in the reconstructed wave field.

1. WFS CONCEPT

In the late eighties a fundamentally new concept was proposed by Berkhout; see e.g. Berkhout [1] and Berkhout et al. [2]. In this new concept, wave theory plays an essential role and individual loudspeakers are replaced by loudspeaker arrays (or ‘loudspeaker-strips’) that generate wave fronts from true or notional sources. Unlike all existing methods, the wave front solution is a so-called volume solution that generates an accurate representation of the original wave field in the entire listening space (and not at one or a few listening spots).

In the ideal situation the listening area is surrounded by planes of loudspeakers, which are fed with signals so that they produce a volume flux proportional to the normal component of the particle velocity of the original sound field at the corresponding position.
For practical purposes, this method has been adapted to make use of linear loudspeaker arrays surrounding the listening area, rather than planes of loudspeakers. It can be shown [3] that for linear arrays the input signals of the loudspeakers are given by

$$E_i(\omega) = K\sqrt{jk}V_n(\mathbf{r}_i,\omega) \tag{1}$$

where $V_n(\mathbf{r}_i,\omega)$ equals the normal component of the particle velocity, virtually at the loudspeaker position $\mathbf{r}_i$, k is the wave number and K is a constant depending on the loudspeaker sensitivity, the distance between the loudspeakers and the desired sound pressure of the reproduction. In case of loudspeakers with a flat frequency response, K is frequency independent.
The WFS concept can be applied for the reproduction of virtual sources which can be behind or in front of the arrays, because WFS can simulate any wave field shape, with convex or concave wave fronts.

2. APPLICATION OF DML-PANELS

Because of the large number of loudspeakers needed for adequate wave field synthesis, and the fact that these loudspeakers should be positioned around the listening area, the use of small light-weight loudspeakers that need only a small back-volume is beneficial. Another point of concern is the cost of those loudspeakers. A main disadvantage of normal electro-dynamic loudspeaker drivers is that they need a housing with a relatively large volume to avoid the additional stiffness of the back-volume. Therefore efforts are taken to find alternatives that are cheap, light-weight and easy to mount directly on the wall surface.
This brought us to the idea to investigate the applicability of distributed mode loudspeaker panels (DMLs) that combine these advantages [4]. However, the distributed mode properties have their influence on the radiation characteristics, in temporal and spatial sense. Hence, the applicability of these panels for WFS, where the phase relations between the secondary sources (the loudspeakers) is so important is not evident from the beginning. For that reason, but mainly because of the many advantages of these panels, the applicability for WFS was tested.

3. MEASUREMENTS

To test the applicability of the DMLs we constructed a linear array of 9 rectangular NXT™ panels, with radiating surfaces of 0.18 x 0.125 m, which were mounted in shallow enclosures of 0.22 x 0.18 x 0.025 m. The panels were mounted side by side to form an array with a height of 0.18 m and a length of about 2 m. We started our experiments with an informal subjective evaluation. For that purpose, WFS-processed program material was reproduced by this array from several virtual source positions, with the virtual source at infinity (plane wave), behind the array and in front of the array, and it was found that the imaging quality was quite natural, giving results comparible to those obtained with normal direct radiation drivers. From these observations it was concluded that from a subjective point of view the amplitude and phase behaviour of these DMLs is adequate for WFS and it was decided to carry out a series of objective measurements. These measurements are divided into measurements on individual panels and measurements on the array of panels.

3.1 Measurements on individual panels

For WFS-application it is essential that the loudspeakers have consistent radiation behaviour. The general behaviour and similarity of three individual panels was examined by placing these panels in our anechoic room and measuring their impulse responses at a distance of 3 m for angles ranging from - 180 to + 180 degrees, with increments of 5 degrees, using a MLSSA-analyzer. Notice that, although these panels are meant for radiation in a 2π-space (by mounting directly to a wall), the measurements were carried out in a 4π-space, because of the anechoic test conditions at hand. A typical impulse response is shown in figure 1. The response consists of a direct pulse and a time distributed part related to the distributed modes of the panel. From the impulse responses we computed the frequency responses for each direction and averaged these over 1/12th octave bands with correction of the spectral slope introduced by this averaging (3 dB/octave).

Results are visualized in a two-dimensional presentation format as a function of the direction of radiation and the frequency bands, with a gray-scale representation of the amplitude responses. Results were obtained for three panels and are presented in figure 2.

For a better qualitative judgement of the results, figures 3 and 4 show the frequency responses of the three panels in a more conventional way, on-axis and for a direction under 30 degrees. The response curves are very well usable. Notice that general trends in the frequency characteristics can easily be corrected with a signal processing filter that can be combined with the $\sqrt{k}$-correction that is needed according to Eq. (1). Figure 5 shows the directivity patterns of panel 1 for 6 distinct frequencies. It is seen that the directivity pattern is more or less independent of frequency, as is expected from DMLs.

From figures 2, 3 and 4 it can be concluded that the three panels under test behave basically the same, but there are also differences. These differences may be due to the diffuse mode behaviour of the panels.

3.2 Measurements on an array of panels

The basic performance of the DMLs for WFS was tested by steering the 9 element array for plane wave synthesis (source at infinity). The multi-trace impulse responses were measured for that purpose at a distance of 3 m in front of the array. The results are shown in figure 6. This result clearly shows the correct synthesis behaviour of the individual responses, merging together to the desired wave. It can also be noticed that there remain responses from the individual transducers, especially at the left and right side of the figure. This is also quite natural and is caused by spatial aliasing: above a certain frequency the tails of the individual response curves do not interfere destructively, but remain visible as individual loudspeaker responses.

The synthesis behaviour of the DML-array is further tested for WFS by synthesis of a virtual source 1 m behind the array and measuring the multi-trace impulse responses again at a distance of 3 m in front of the array. This result is shown in figure 7 and behaves also as expected. The final test was to synthesize a virtual source 1 m in front of the array and to measure straight through the focus point, so also at a distance 1 m in front of the array. This result is presented in figure 8.

4. DISCUSSION AND CONCLUSIONS

The objective results on the DML-panels have shown that these loudspeakers are very well suitable for WFS-purposes. The benefit is that these panels are light-weight and can be easily mounted close to walls. The measurements show that the impulse responses of these panels are well suited for synthesis of secondary sources to form a desired wave front. Physical limitations of the synthesis principle occur in the same way as with conventional loudspeakers, with a characteristic difference, i.e. the spatial aliasing effects are more pronounced at larger angles. This can be understood from the fact that the DML-panels have a broader radiation characteristic at higher frequencies than conventional loudspeakers. From a physical point of view this may be seen as a disadvantage. However, by listening to the DML-array under practical conditions, no distracting effects could be observed. A reason for that might be that due to the distributed mode radiation, less interference occurs than with piston-type loudspeakers [5], [6], but further research is needed for evidence on that statement. Hence, it can be concluded that the DML-speakers are worth to be further investigated for WFS-applications. As already demonstrated by NXT™, DMLs are very well suited as projection screens. This makes the application of such loudspeakers for sound and vision such as home theaters and teleconferencing very attractive, especially when a combination can be made with WFS reproduction.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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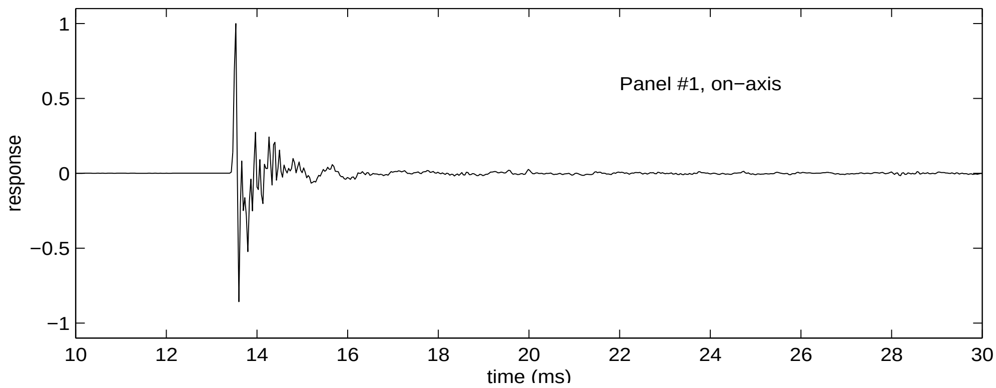

Figure 1: On-axis impulse response of a DML-panel.

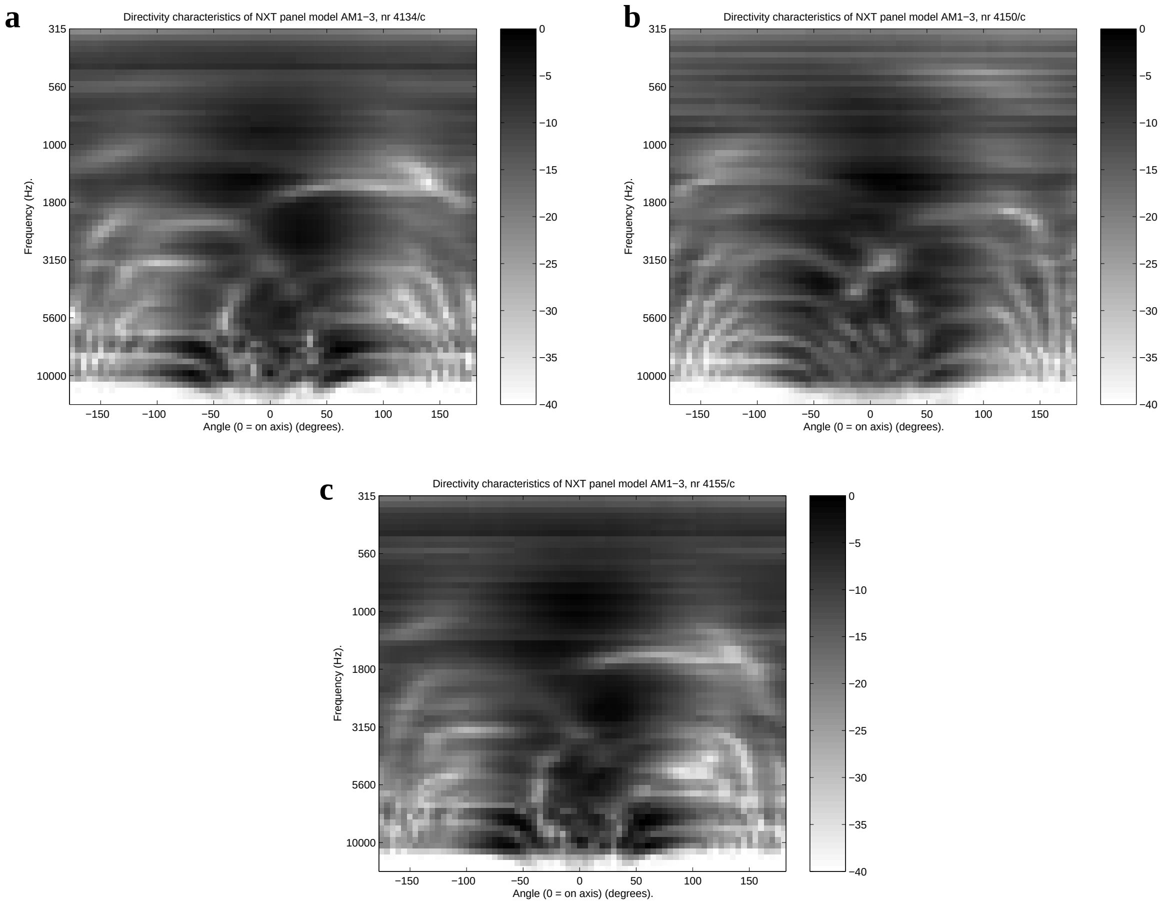

Figure 2: Gray-scale representations of amplitude responses as a function of frequency (1/12th octaves) and radiation angle, for 3 different panels.
The measurements are only valid below 10 kHz.

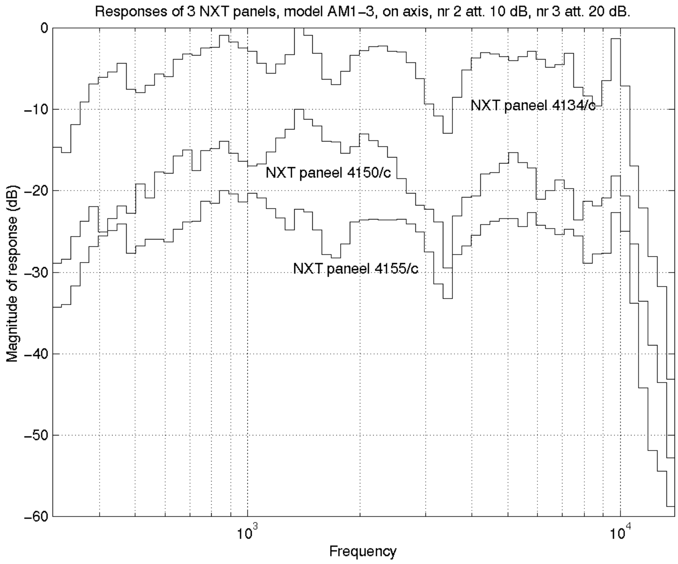

Figure 3: Frequency response curves of 3 panels at 0 degrees, valid below 10 kHz.

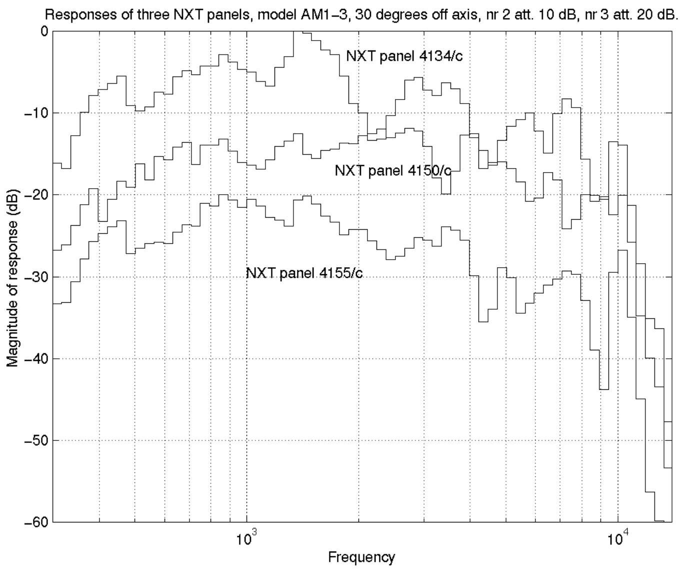

Figure 4: Frequency response curves of 3 panels at 30 degrees, valid below 10 kHz.

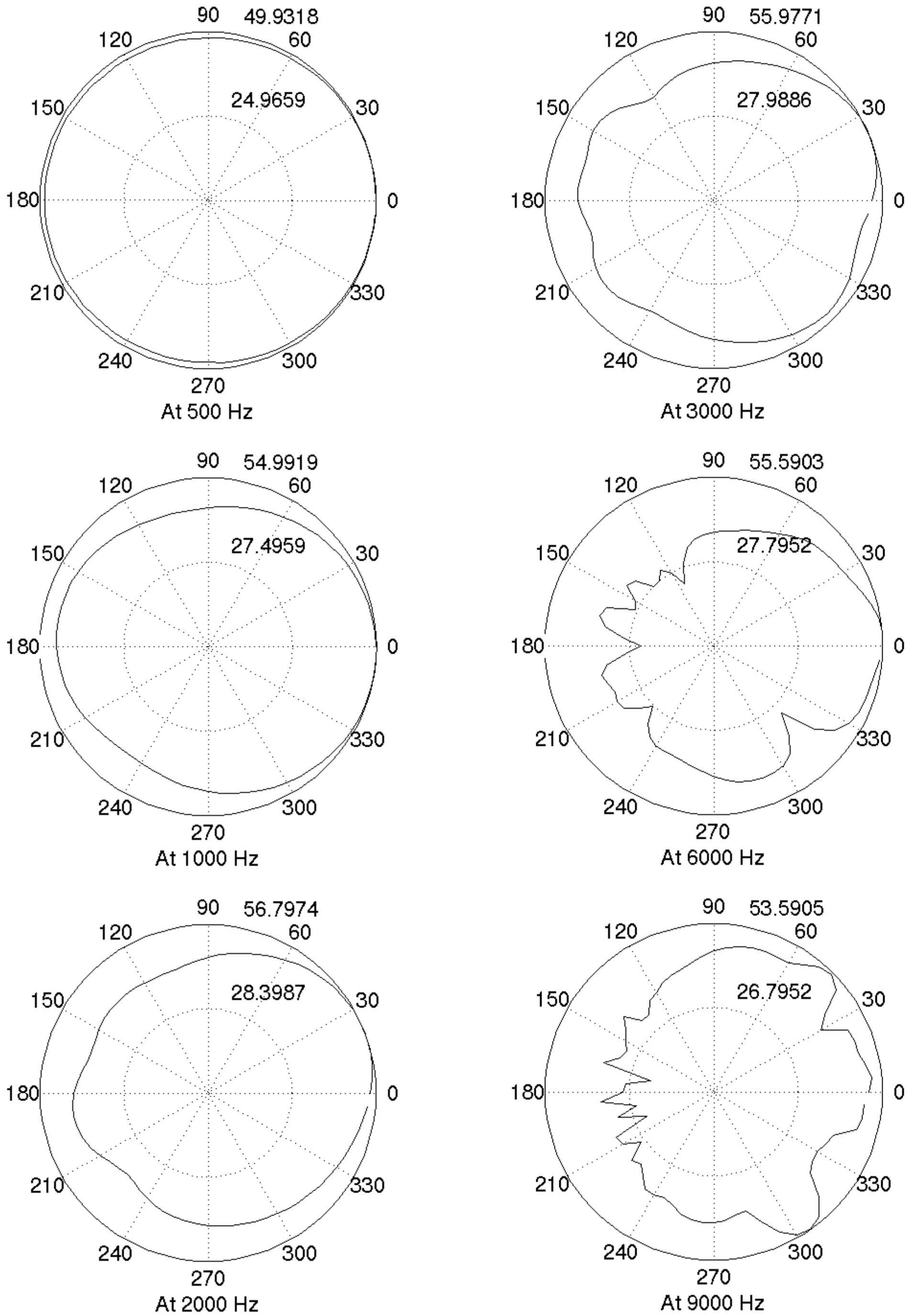

Figure 5: Directivity patterns of panel 1 for 6 different 1/12th octave bands.

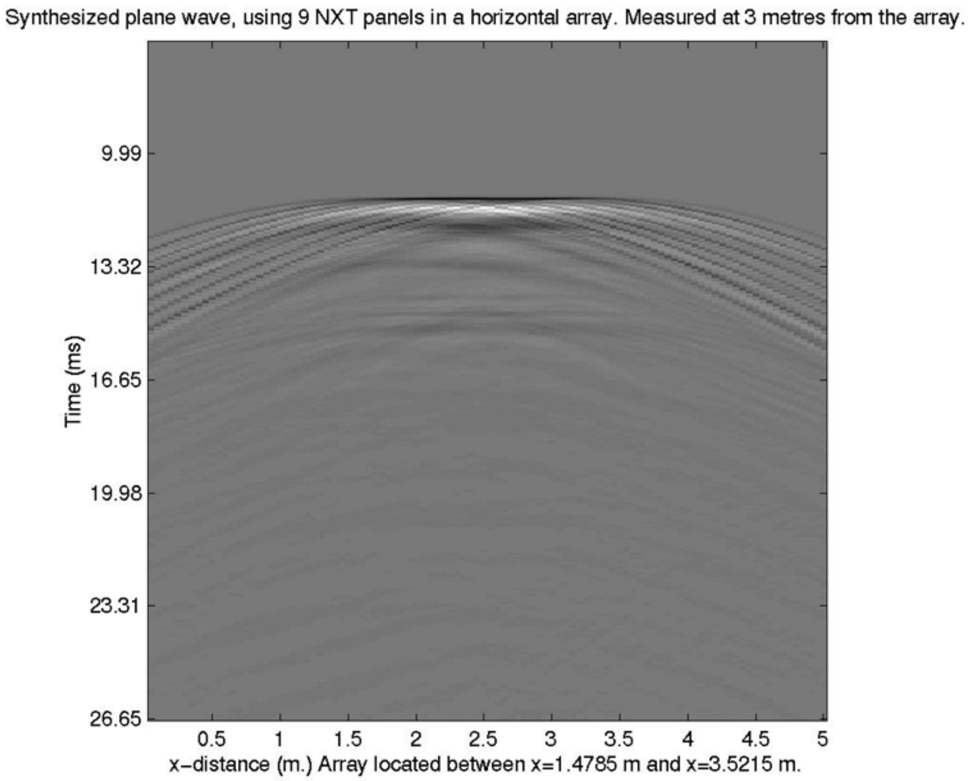

Figure 6: Multi-trace impulse response of 9 DML-panels, reproducing a plane wave with WFS.

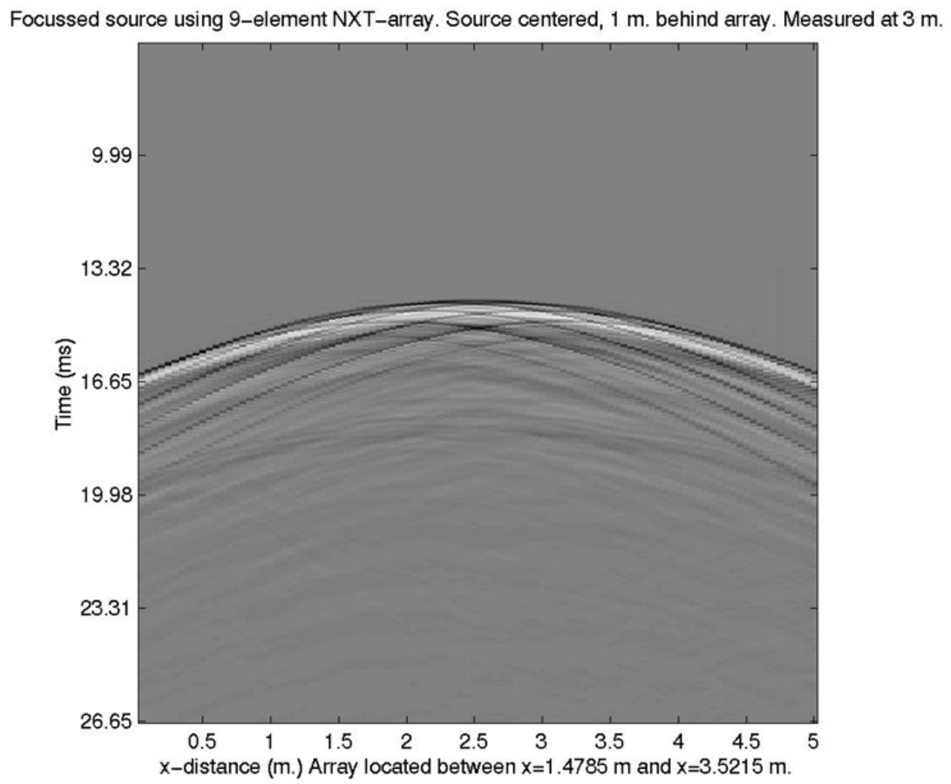

Figure 7: Multi-trace impulse response of 9 DML-panels, reproducing source behind the array with WFS.

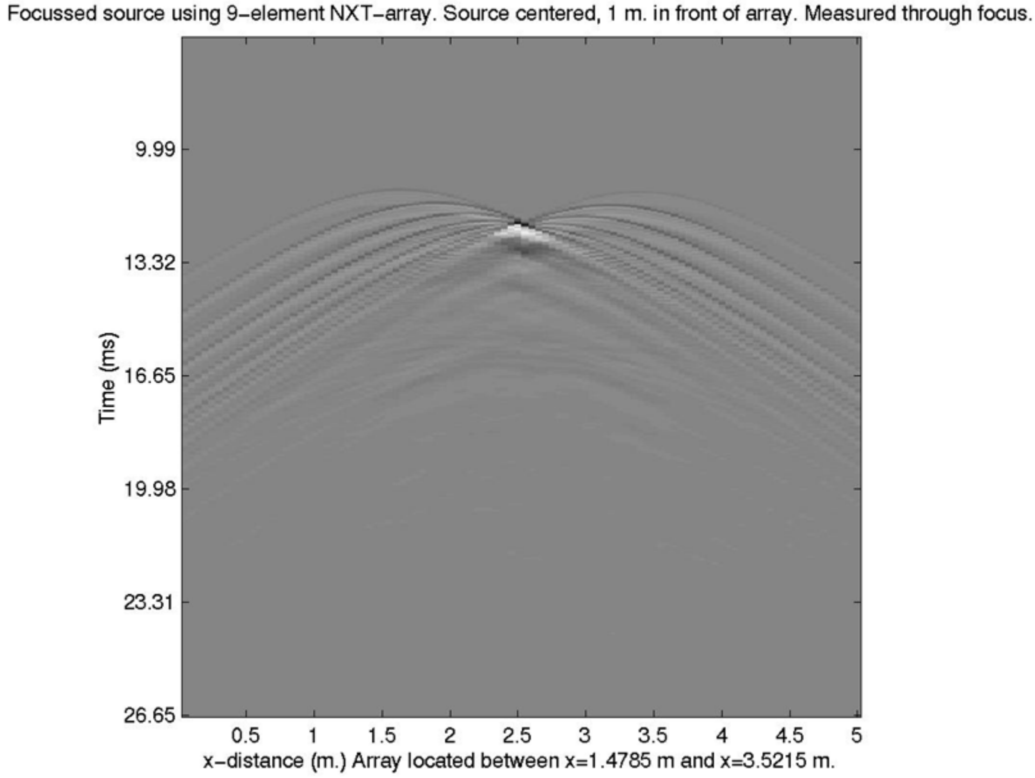

Figure 8: Multi-trace impulse response of 9 DML-panels, reproducing a focussed source in front of the array with WFS.