inter.noise 2000
The 29th International Congress and Exhibition on Noise Control Engineering
27-30 August 2000, Nice, FRANCE

I-INCE Classification: 7.2

MICROPHONE T-ARRAY TECHNOLOGY FOR MOVING NOISE SOURCE MEASUREMENTS

T.C. Van Den Dool, M.M. Boone

TNO Institute of Applied Physics, P.O. Box 155, 2600 AD, Delft, Netherlands

Tel.: +31 15 2692457 / Fax: +31 15 2692111 / Email: dendool@tpd.tno.nl

Keywords:
ARRAY, BEAMFORMING, SIDE-LOBE, TRAIN

ABSTRACT
A disadvantage of single omnidirectional microphone measurements is that they do not discriminate between noise sources. Arrays of microphones can be used for that purpose. However, careful consideration of the array configuration and signal processing is necessary to avoid aberations. We will present a two-dimensional sparse array with swept focus processing that is both efficient and accurate. Measurements carried out on trains and other moving sources confirm the simulated performance.

1 - INTRODUCTION
In industrial and transportation applications it is often needed to identify the contribution of several noise sources to the total noise level. Both the individual source locations and their strength should be found. Single, omni-directional microphone measurements do not discriminate between noise sources. Arrays of microphones can be used for that purpose. However, careful consideration of the array configuration and signal processing is necessary to avoid aberrations. We will present a two-dimensional sparse array with swept focus processing and show theoretically and by experiment that it is both efficient and accurate.

2 - CONVENTIONAL ARRAY PROCESSING (BEAMFORMING)
A two-dimensional array is needed for locating the position of sources in two dimensions. Ideally such an array consists of a plane filled with microphones e.g. like in Fig. 1. For each frequency of interest, standard (time-domain) beamforming can be applied, which can efficiently be evaluated using Fast Fourier Transforms in the spatial domain. Fig. 2 shows the result for a 31×27 full planar array and two noise sources, one at 0 degrees, the other 10 dB weaker at 45 degrees in one direction. A Hamming shading function was applied to enhance the image.
Although the resulting image is good, with -44 dB side-lobe levels, the excessive number of microphone (868) prevents practical use. In most measurements therefor, other array configurations, with less microphones are used. The cross-array of Fig. 3 is a common example, e.g. see Hamet et al. [1]. In most cases the same beamforming as for the full array is applied which leads to high side-lobe levels of −5 dB as shown in Fig. 5. These high side-lobe levels are caused by the deformed shading function, in this case a cross, which is forced by the form of the array.

3 - CO-ARRAY PROCESSING
Using the concept of co-arrays [2], [3] can enhance the cross-array images. The co-array consists of all differential distances in the array. Fig. 4 shows the co-array of a cross. The flat part can be used to construct a full array by selecting the corresponding microphones and using their cross-correlation to construct a full matrix of cross-spectra.
Notwithstanding the power character of the cross-correlation matrix, all entries have the same mutual phase relationship as in the full microphone array. Therefore standard beamforming can be applied. Fig. 6 shows that the result has the same quality as the full microphone array with beamforming. The only difference is compression of the dB-scale by a factor of two, due to the power property of the cross-spectrum. The side-lobe levels now are −22 dB.

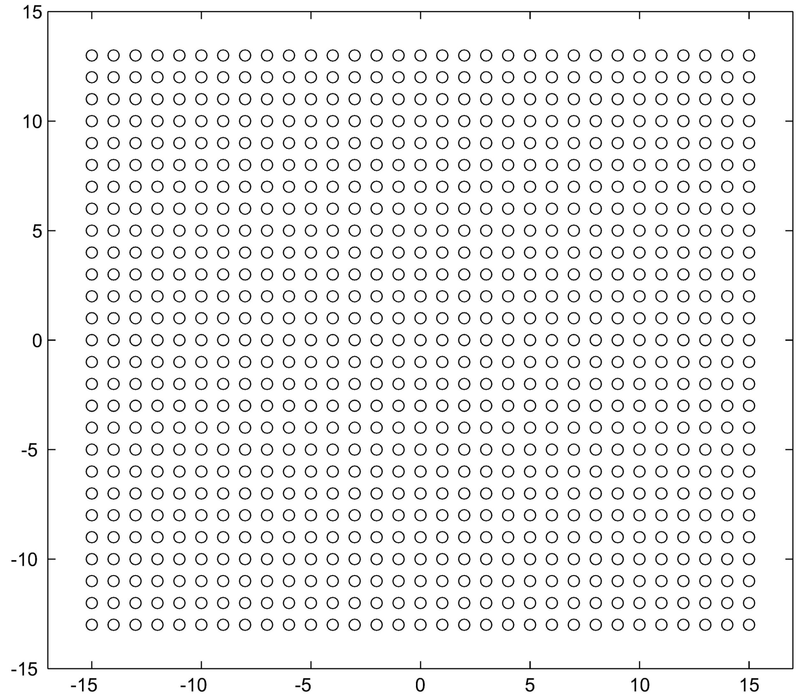

Figure 1: Planar full array.

4 - T-ARRAY PROCESSING

Note that the co-array of the cross in Fig. 4 has double entries for the flat part, which was used for the beamforming. So every differential distance still occurs twice. This redundancy can be exploited to reduce the number of microphones even further. We found [4] that the T-array in Fig. 7 exactly canceled the redundancy. The image after beamforming remains the same as for the cross-array (fig. 6).
Due to the nature of the cross-correlation matrix and the applied processing, individual noise source levels can be interpreted very neatly. In the cross-correlation matrix, exactly one entry (the central one) contains a real-valued auto-spectrum. After beamforming the integrated beampattern equals this auto-spectrum. So the beampattern can be considered as a decomposition of the spectrum on the central microphone. All other microphones are just used for the decomposition. The immission level of one of the contributing sources is found by integrating the corresponding lobe in the beamforming image.
It seems that T-arrays only have advantages compared to full arrays:

- Less microphones.
- The same image quality.
- Proper noise source levels.

But a couple of notes should be made:

- The side-lobe levels are higher, as noted above, although very much lower than with conventional beamforming and very useful in practical situations.
- More variance / less suppression of random (e.g. wind) noise because of less averaging. Apart from wind-tunnel tests this does not seem to be a major effect in practice.
- Time-domain beamformed signals cannot be retrieved. In most noise control applications this is no limitation.
- Tonal, correlated (mirror) sources will disturb the cross-spectral matrix, leading to false positions and levels and/or ghost sources. Fortunately such sources do not often occur in practical situations. For broadband correlated sources only the resolution and side-lobe levels are influenced a bit.

The T-array is an example of a sparse array, as contrasted to full arrays. We have not yet found a more efficient, scalable, sparse, two-dimensional array with a full cross-correlation matrix. For one-dimensional

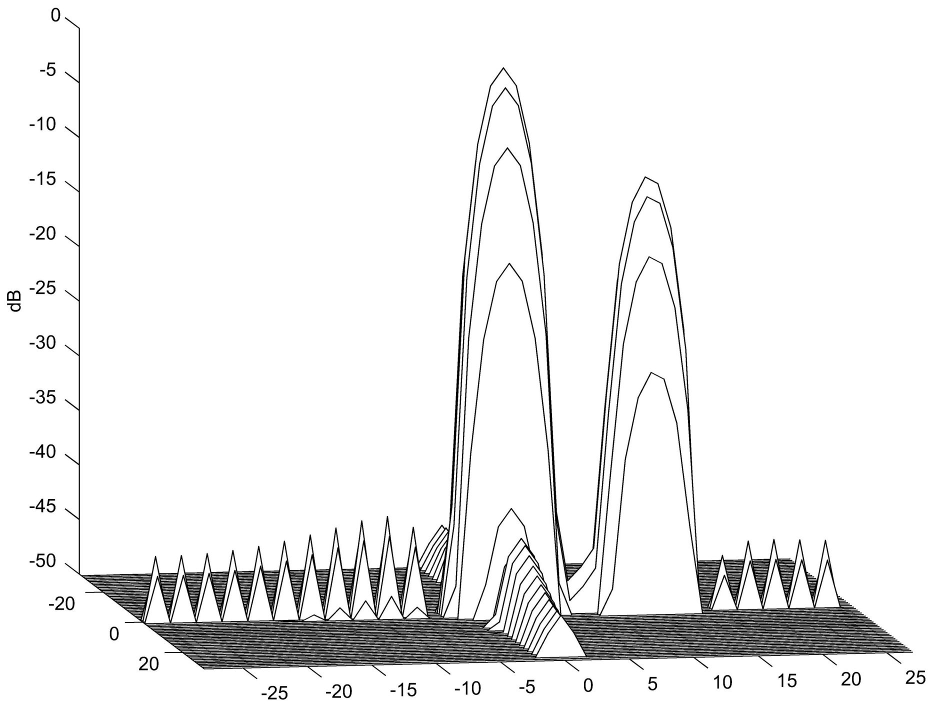

Figure 2: Full array with conventional beamforming.

(line) arrays, more optimal sparsing schemes do exist, as was shown by Boone [5]. Apart form the T-array, also one of those sparse linear array designs is in use for industrial applications at the TNO Institute of Applied Physics.

5 - SWEPT FOCUS

The cross-correlation method assumes that the signals impinging on the antenna are a superposition of plane waves coming from the direction of the various sources. For sources closer to the array than approximately 5 times the width of the array, focussing is needed. We implemented time-domain focussing as a pre-processing step, transforming spherical waves into plane waves, suited for the cross-correlation method. Focussing is carried out at a single, central point for the complete image, multi-point focus is needed only at source distances shorter than approximately the width of the antenna.

Most of the processing is carried out in the frequency domain, using time-blocks to carry out FFT's. When the velocity of the sources is high, the distance traveled by the sources within a single time block can become larger than the spatial resolution of the antenna. In that case source tracking, or swept focus if combined with focussing, will enhance image quality. An additional advantage of source tracking is that it removes the Doppler shift, at least for sources around the point of focus.

Source tracking helps if the source speed $V > 2{\cdot}d{\cdot}c/D{\cdot}f{\cdot}T$, where d is the distance between antenna and source(s), c is the speed of sound, D is the size of the antenna and T is the time block duration. For the measurement example given below: distance d=2 m, c=340 m/s, antenna size D=3.2 m, f_{max}=2.8 kHz, time step T=45 ms. This results in source tracking being profitable for source velocities higher than 12 km/h which was true for our train passages. The source tracking was implemented in the time-domain, together with the focussing.

6 - MEASUREMENTS

The T-array measurement system was applied to passages of a cargo train (Fig. 9). The train was composed of a locomotive on both ends, four hoppers, eight container carriers of which four were fitted with wheel shrouds, and two coaches (Fig. 10). The purpose of the measurements was to show the effectiveness of the shrouds for screening wheel noise.

The T-array was positioned at 2 meter distance from the nearby track and had a size of 31 microphones horizontal and 14 vertical, making a total of 44 microphones and a cross-correlation matrix size of 31×27. The spacing of the microphones was 10 cm making the maximum spatial aliasing free angle 45 degrees in the 2 kHz octave band. The T-array cross-correlation matrix size is 3 m × 2.6 m giving a resolution

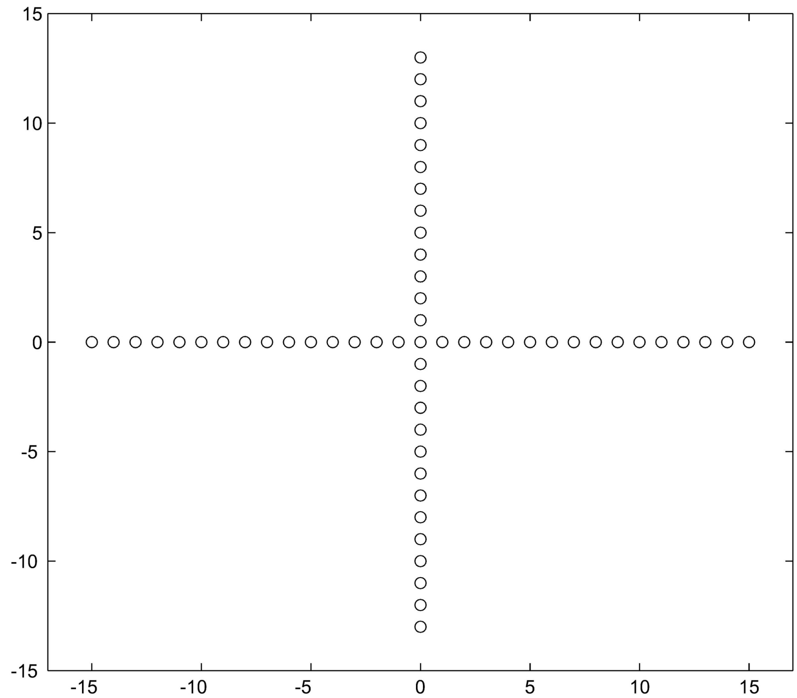

Figure 3: Cross array.

of approximately 4 degrees or 15 cm at 2 m distance in the 2 kHz octave band, 30 cm @ 1 kHz, 60 cm @ 500 Hz.

An optical trigger was used to synchronize the wheel passages with the noise measurements. Three octave bands were analyzed: 500 Hz, 1 kHz, and 2 kHz spanning a frequency range of 353 Hz to 2825 Hz.

Fig. 10 shows the 2 kHz octave result for one of the passages at 77.5 km/h. Note that the color range spans 20 dB from dark blue to dark red. Still lower levels are indicated as white. The gray part above 2.5 meter is beyond the 45 degrees spatial aliasing range of the antenna. No sources are visible on the super-structure, showing that the super-structure contribution to the total noise level is negligible and that the antenna side-lobe level is sufficiently low to be able to draw this conclusion. The highest side-lobe levels occur near and in between the wheels and are in the order of −15 dB.

Clearly each wheel can be identified separately and the wheel and rail radiation dominates the noise. On average it is even apparent that the wheel circumference is the main noise source. The effect of shrouds on the four container carriers, from 150 to 220 meters, is also very clear, as at those positions only the rail appears to radiate noise. The noise reduction created by the shrouds was quantified at approximately −6 dB.

These measurements showed the effectiveness of the T-array system. Even if a single wagon or a single boogie had been fitted with wheel shrouds, the effect of the shrouds would have been clearly quantifiable.

7 - CONCLUSION

An optimized signal processing method was presented for imaging of uncorrelated moving noise sources with a T-shaped microphone array. The method is based on processing of the spatial cross-correlation function of the wave field and swept focussing. The method results in images with low side-lobes and high resolution using a small number of microphones. Measured results on train passages confirm the theoretically predicted higher performance (better than −15 side-lobe levels) compared to standard beamforming (−10 dB at best).

ACKNOWLEDGEMENTS

Implementation and first measurements with the T-array system have been carried out within the METARAIL 4th framework EC program for which the final report was published in December 1999.

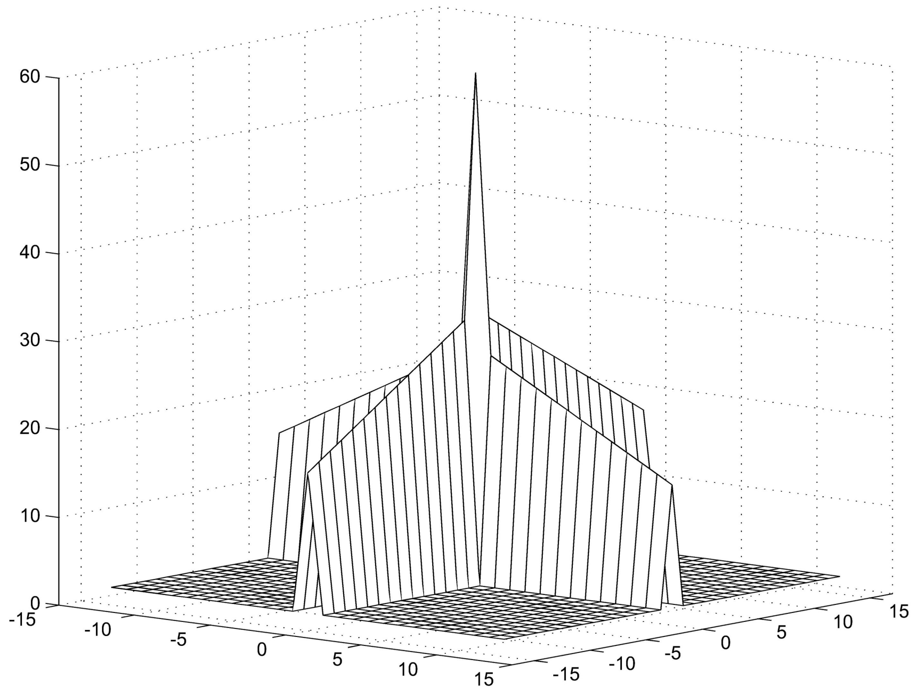

Figure 4: Co-array of cross-array.

REFERENCES

1. **Jean-François Hamet et al.**, Deufrako-1: microphone array techniques used to locate acoustic sources on ICE, TGV-A and Transrapid 07, In *Internoise 94*, pp. 187-192, 1994

2. **Percy F. Wang et al.**, 2-D sensor array configurations and its use in noise source visualization, In *Internoise 95*, pp. 1183-1186, 1995

3. **Georges Elias**, Source localization with a two-dimensional focused array: optimal signal processing for a cross-shaped array, In *Internoise 95*, pp. 1175-1178, 1995

4. **Boone, M.M. et al.**, Two-dimensional noise source imaging with a T-shaped microphone cross-array, *submitted to JASA*, 1999

5. **Boone, M.M.**, On the optimization of antenna beamforming for directional acoustic measurements, In *Internoise 88*, pp. 191-194, 1988

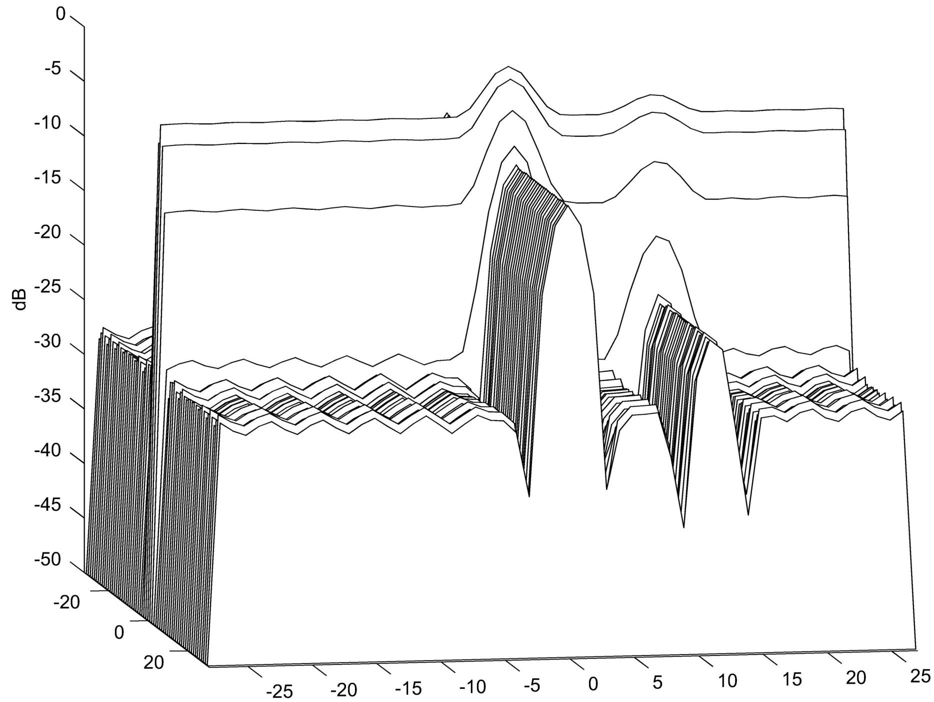

Figure 5: Cross-array with conventional beamforming.

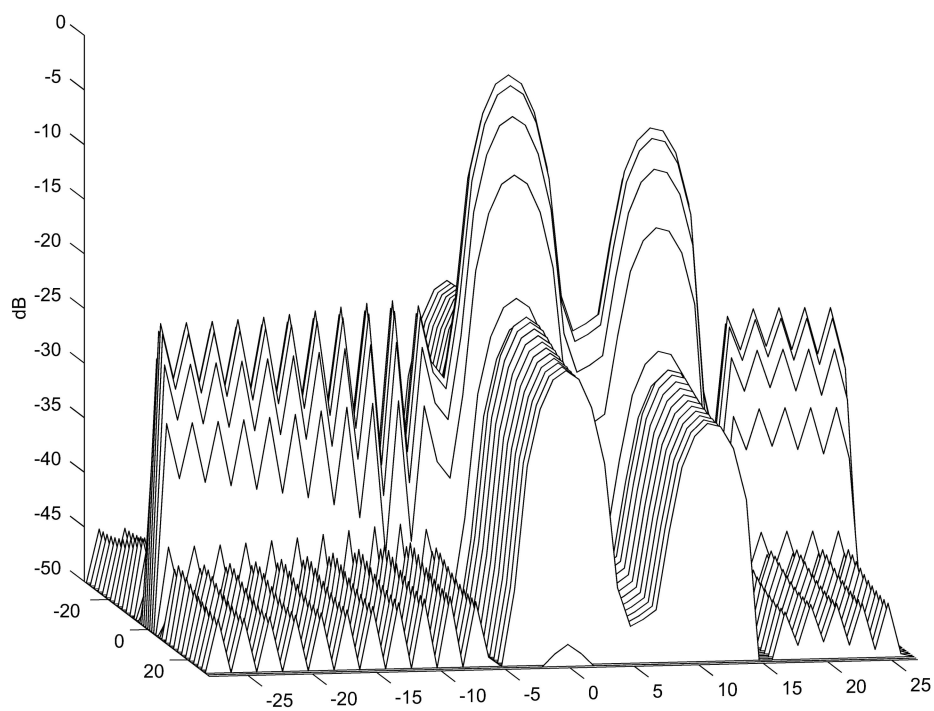

Figure 6: Cross-array with co-array processing.

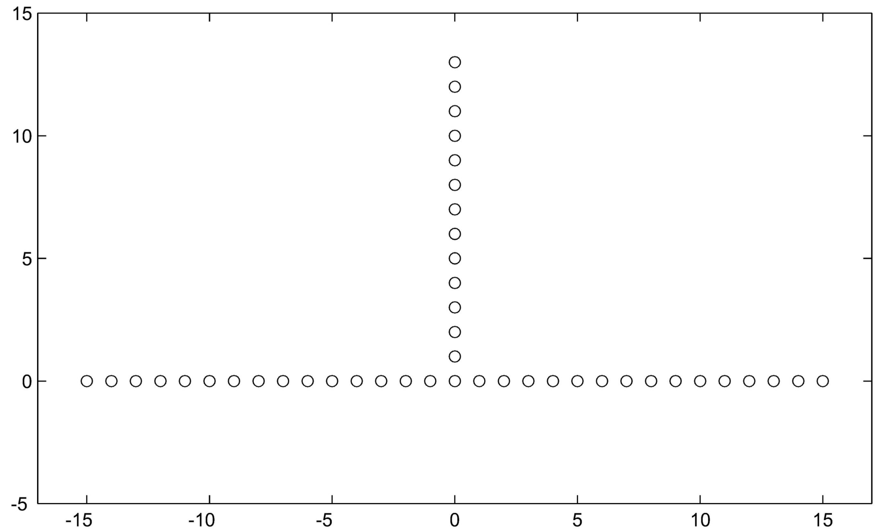

Figure 7: T-array.

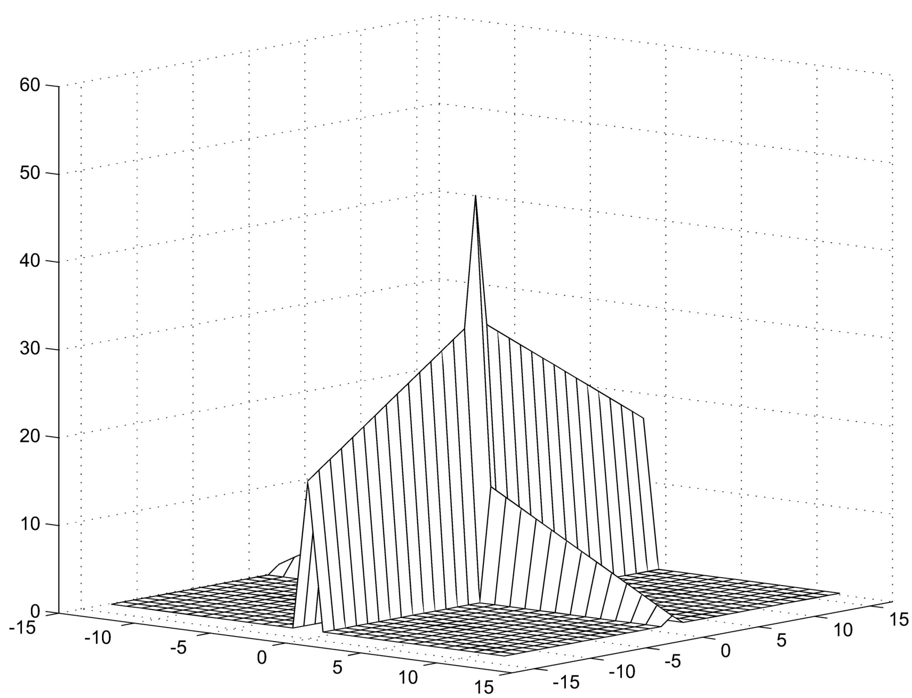

Figure 8: Co-array of T-array.

Figure 9: T-array measurement set-up.

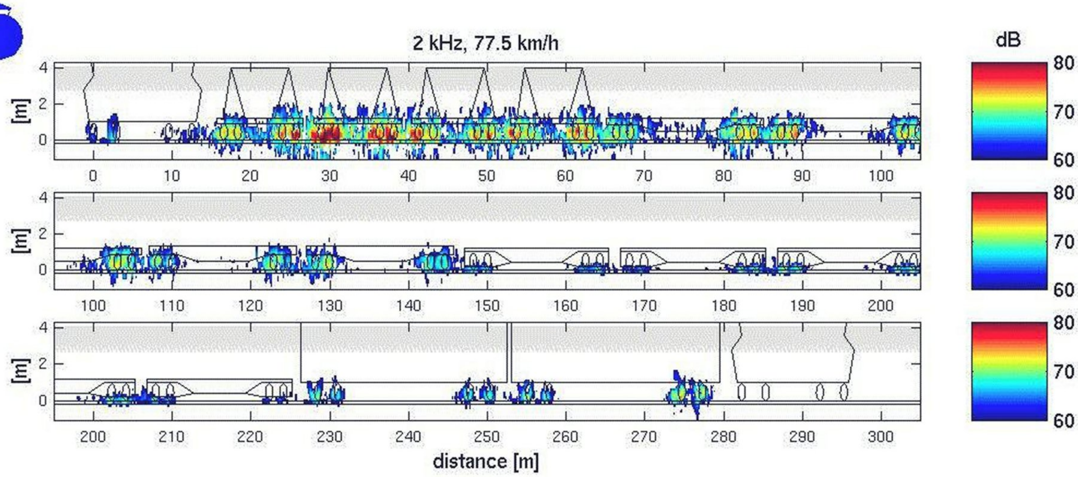

Figure 10: Measurement result with T-array.