Concepts and applications of directivity controlled loudspeaker arrays

G. de Vries and G. van Beuningen, Duran Audio BV.

AXYS®
is a registered trademark
of
DURAN
AUDIO
Koxkampseweg 10
P.O. box 2050
5300 CB Zaltbommel
the Netherlands
Phone: 31 418 515583
Fax: 31 418 518077

CONTENTS

1. Introduction

Over the last few years there has been a noticeable increase in the interest in the application of array technology for obtaining improved overall transducer directivity. Theoretical aspects regarding the optimization of transducer positioning and transfer functions of filters and delays, can be found in [2], [3], [5] and [6]. This report focuses on the directivity behavior of controlled loudspeaker line-arrays as schematically shown in fig 1.

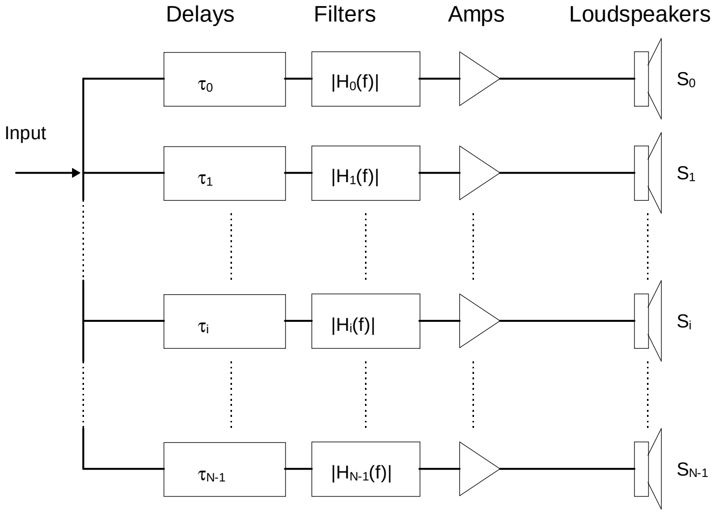

Fig 1 Block schematic view of controlled loudspeaker array.

In order to predict the speech intelligibility as ALcons or STI values, it is necessary to have accurate loudspeaker directivity data, expressed as directivity ratio (Q) or Directivity Index ($DI = 10 \cdot {}^{10}\log(Q)$, in dB). Measuring directivity data of large sound columns is difficult and time consuming because the Q will only be nearly independent of the measuring distance (d), if the column is measured in the far field (d >> L, and L representing the effective column length). In chapter 2 this dependence of the Directivity Index and related direct sound pressure level is examined.
To clarify this effect on speech intelligibility, chapter 4 compares predicted speech intelligibility values based on simulated column directivity data with in situ measurements.

Simulations are used to examine the directivity behavior of loudspeaker columns. The simulation model accounts for directional effects of real-life transducers with cone-shaped diaphragms, mutual acoustical coupling between transducers, baffle diffraction effects and any set of required complex filter transfer functions (including delays). In chapter 5 directivity measurements are compared with results obtained from the simulation model.

2. Loudspeaker array directivity

First we assume the listening plane to be situated on an axis of the lowest loudspeaker in the column ($y_c = y_{li}$). Fig 2 explains the simulation setup, the azimuth (or elevation) angle of the main lobe will be set to 0 deg. Positive azimuth angles refer to an upward pointing main lobe.

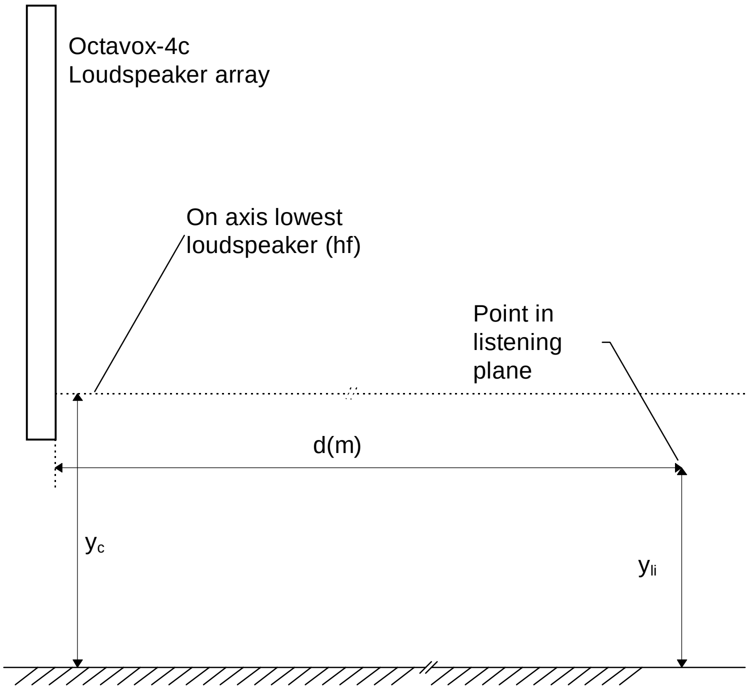

Fig 2 General simulation set-up (side view).
High frequency part located at lower array side.

The Octavox-4c is a 16 channel (17 element) asymmetrical log spaced loudspeaker array with a focusing delay design (the focus point is located at d = 50 m).The column is designed as a 9λ array which means that the effective array length is 9 times the wavelength (controlled by digital filters for each individual loudspeaker, except channel 16 which drives two loudspeakers). Of course this cannot be met at frequencies below approx. 800 Hz (limited by the physical array length of 3.7 m) and frequencies above 4 kHz (limited and determined by transducer's physical dimensions). An approximation for the vertical opening angle of an nλ array is given by 72/n deg [3]. So we expect the vertical opening angle in the far field to be around 8 deg. for the frequency band of 800 Hz to 4 kHz.

Fig 3 shows the dependency of the vertical opening angle on frequency for a position in the near field (10 m) and the far field (50 m). It is obvious that the vertical opening angle widens if the listening position is located in the near field of the array. Another effect which influences the differences in near field and far field directivity behavior is the shift in apparent azimuth angle of the main lobe. This effect is caused by the upward shift in acoustic origin for lower frequencies (because more speakers are active) which is of course more noticeable in the near field region. Fig 4 shows this effect for a frequency of 500 Hz. The lower the frequency, the more the main lobe will shift upward.

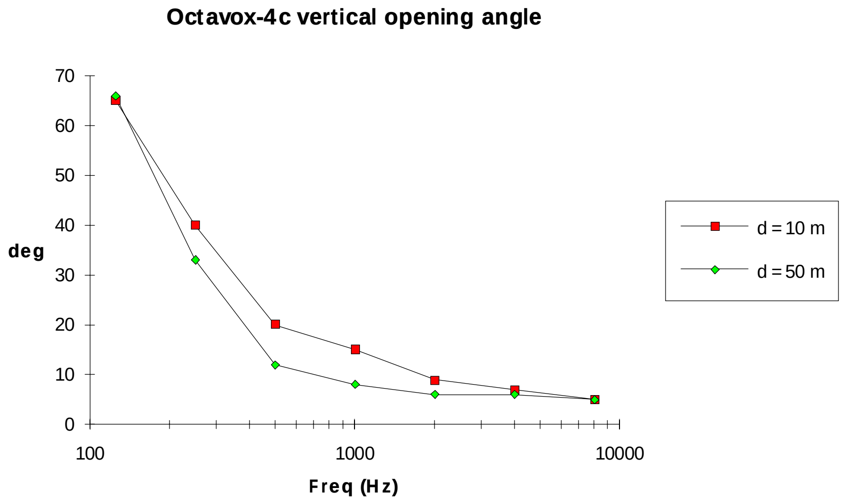

Fig 3 Simulated vertical opening angle (-6 dB) as a function of frequency for two distances.

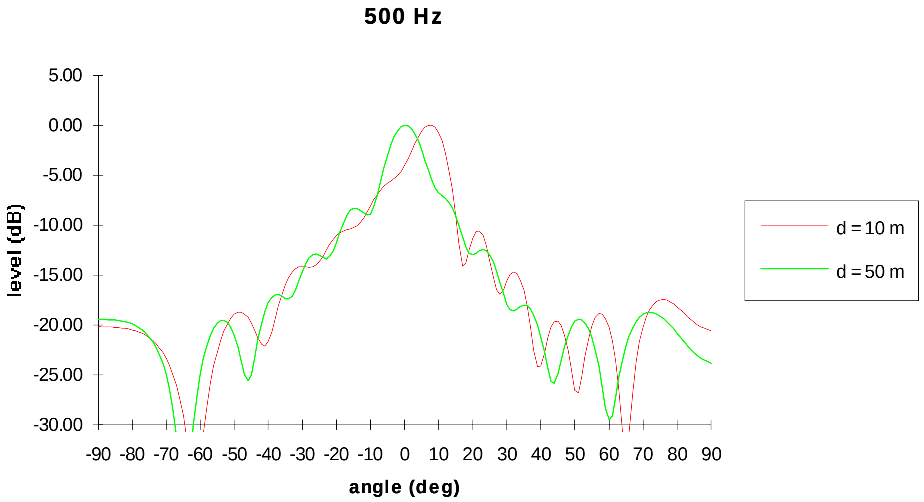

Fig 4 Simulated vertical polar data for 500 Hz at two distances (maximum scaled to 0 dB).

In fig 5 simulation results are shown for the Directivity Index (DI) as a function of distance to the Octavox-4c loudspeaker column for the octave bands of 125 Hz to 8 kHz. As can be derived from this figure the DI stabilizes if the distance is larger than approx. 30 m, which is considered large compared to an effective column length of 3.7 m. Fig 6 shows the simulated DI as a function of frequency for three different distances. This figure shows a tendency of higher DI for distances in the far field.
The DI in general increases with frequency because:

- Physical array length becomes too small for low frequencies. As a result vertical coverage control is lost for frequencies below approx. 800 Hz.
- Although the far field vertical opening angle is nearly constant for frequencies larger as approx. 1 kHz, the horizontal opening angle narrows with increasing frequency (normal cone-type transducer behavior). This behavior might be improved (i.e. mounting a baffle with a slit in front of the cone).

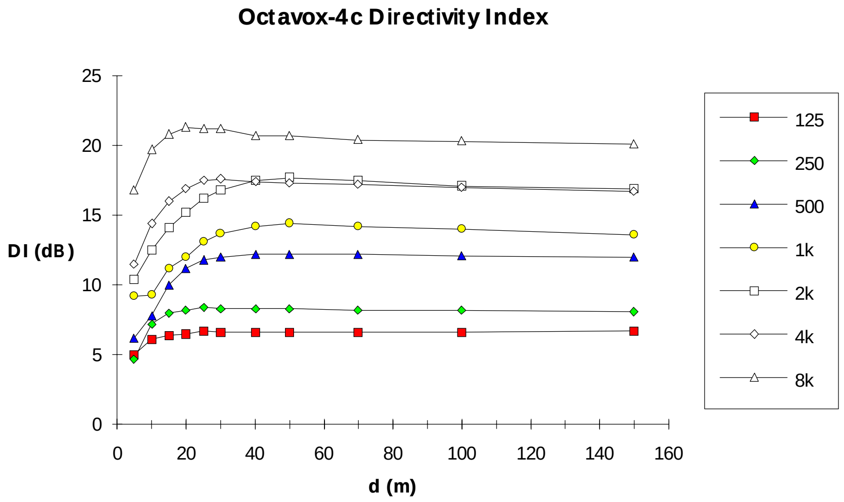

Fig 5 Simulated Directivity Index of Octavox-4c as a function of distance.
No reflecting boundaries (free field). On axis lowest loudspeaker (high frequency).

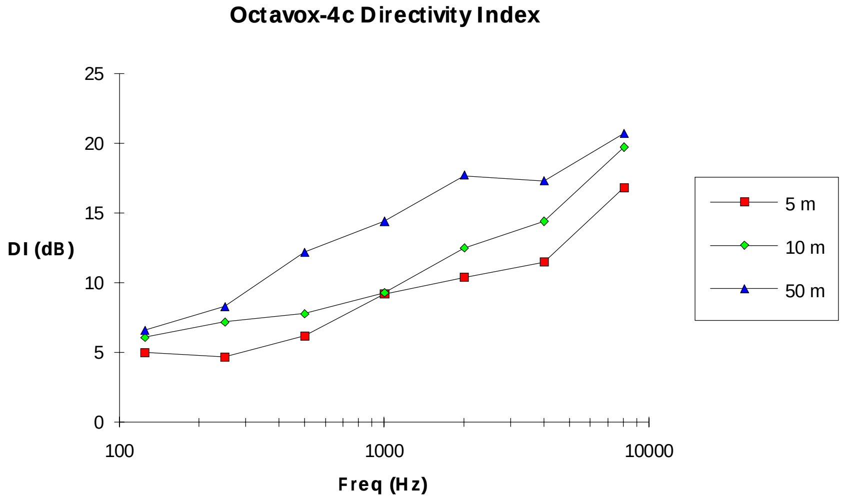

Fig 6 Simulated Directivity Index of Octavox-4c as a function of frequency.
Distance 5, 10 and 50 m from column (on axis lowest loudspeaker).

From this analysis it becomes clear that in general, one cannot accurately predict STI or ALcons values with room simulation programs which do not take into account the dependency of DI on distance in the near field region of the loudspeaker array.

3. Direct sound spectra

In fig 7 the simulated free-field direct SPL is shown for one Octavox-4c column. Mounting height (y_c = on axis lowest speaker) minus listening height (y_{li}) is set to 0.7 m, azimuth angle of main lobe = -4 deg (pointing downwards). The high-pass shelving EQ which normally corrects for the frequency dependent loudspeaker density and number of active loudspeakers has been omitted during the simulations.

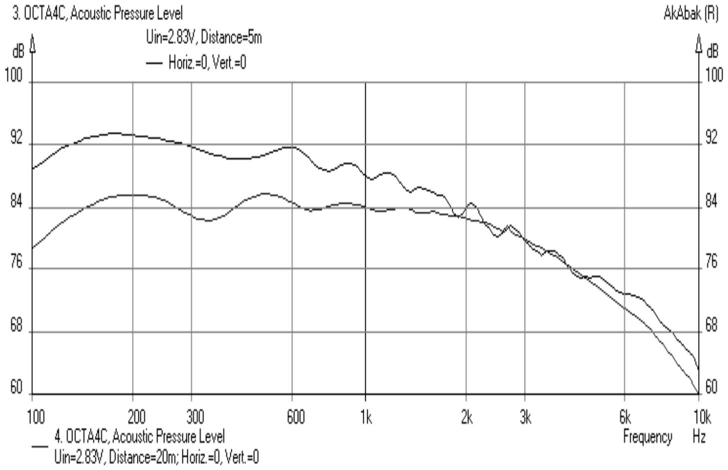

Fig 7 Simulations of direct SPL as a function of frequency for d = 5 (upper curve) and 20 m.

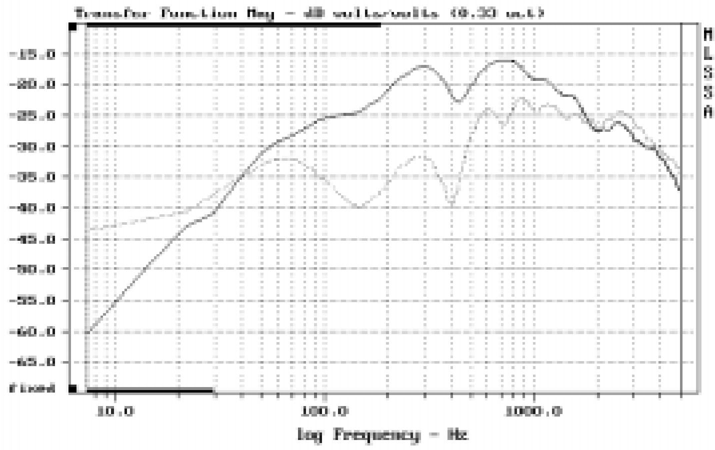

Fig 8 Comparison of direct sound spectra at d = approx. 23 m (dashed) and d = approx. 4 m.
Two Octavox-4c active (notches are caused by arrival time differences).
Adaptive (speaker) half-hamming window (10 ms H.F. part, FFTsize = 2048 pt, Fs = 15 kHz).

Simulations and measurements both show the same tendency: nearly distance independent direct SPL for the higher frequency bands caused by the strong increase of DI_{eff} as d increases from 5 to 20 m. DI_{eff} is defined as the Directivity Index at a position in the listening plane, DI_{eff} is equal to DI if y_c = y_{li} in fig 2.

Fig 9 shows the results of distance dependent direct SPL measurements of a large (32 element) loudspeaker column (with y_c = 2.25 m, refer to fig 2). The direct SPL is averaged in the 1 kHz octave band and shown for two different measuring heights (y_{li}).

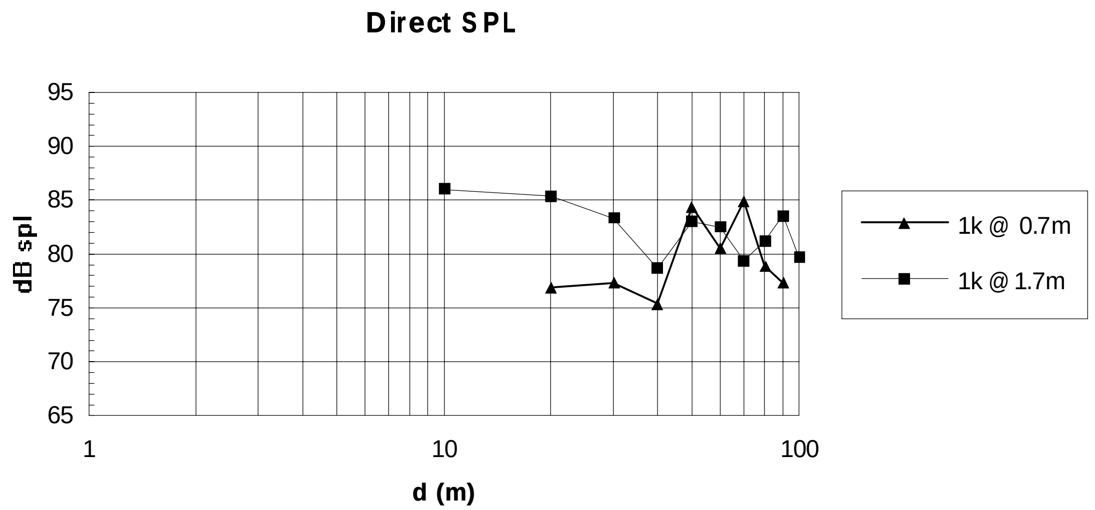

Fig 9 Measured direct SPL in 1 kHz octave band for a large column as a function of distance.

4. Speech intelligibility

Speech intelligibility simulations based on statistical acoustics are compared to STI values calculated from measured impulse responses for two different rooms.

Example 1.

Peutz’ formula (see for example [1] or [2]) was used to predict noiseless ALcons values for the following situation.

V : 20000 m^3
Ma : 1
N : 2
$Q_{eff}(d,f)$: Calculated from $DI_{eff}(d,f)$ shown in table 1
RT60(f) : As in table 2

d(m)	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
5	2.8	3.4	3.7	4.2	-0.6	-1.8
10	5.6	6.3	6.5	10.1	9.5	7.8
15	6.3	7.9	9.4	11.7	13.4	14.7
20	6.4	8.3	11.3	13.6	15.7	17.3
25	6.4	8.4	12.1	14.7	15.3	17.1

Table 1 Simulated effective DI values (dB) as a function of distance for octave bands of 125 - 4 kHz.
Listening plane located at 1.2 m below axis lowest loudspeaker.
Azimuth angle = -4 deg, column placed perpendicular to listening plane.

125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
4.8	5.5	5.1	4.7	3.7	2.5

Table 2 Averaged RT60 in seconds measured with MLSSA system.

Table 3 shows the distances D_L after which the calculated ALcons will not increase any further ($D_L = 3.16 \cdot D_C$, with D_C is critical distance). ALcons will be 9·RT60 for distances > D_L.

d(m)	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
5	16.0	16.1	17.3	19.1	12.4	13.1
10	22.2	22.4	23.8	37.6	39.5	39.5
15	24.0	27.0	33.3	45.2	61.9	87.5
20	24.3	28.2	41.4	56.2	80.7	118.1
25	24.3	28.6	45.4	63.8	77.1	115.4

Table 3 D_L (m) values calculated from tables 1 and 2.

From table 3 it is clear that all measuring distances are smaller than D_L (except at 25 m in 125 Hz band). Given this and the assumption that statistical acoustics are valid, Peutz' equation to predict ALcons might be used.

Data for the 8 kHz band was omitted because no measured data was available (MLSSA's bandwidth was restricted to 6 kHz during the measurements).

Fig 10 shows the predicted and measured octave Modulation Transmission Index (MTI) values.

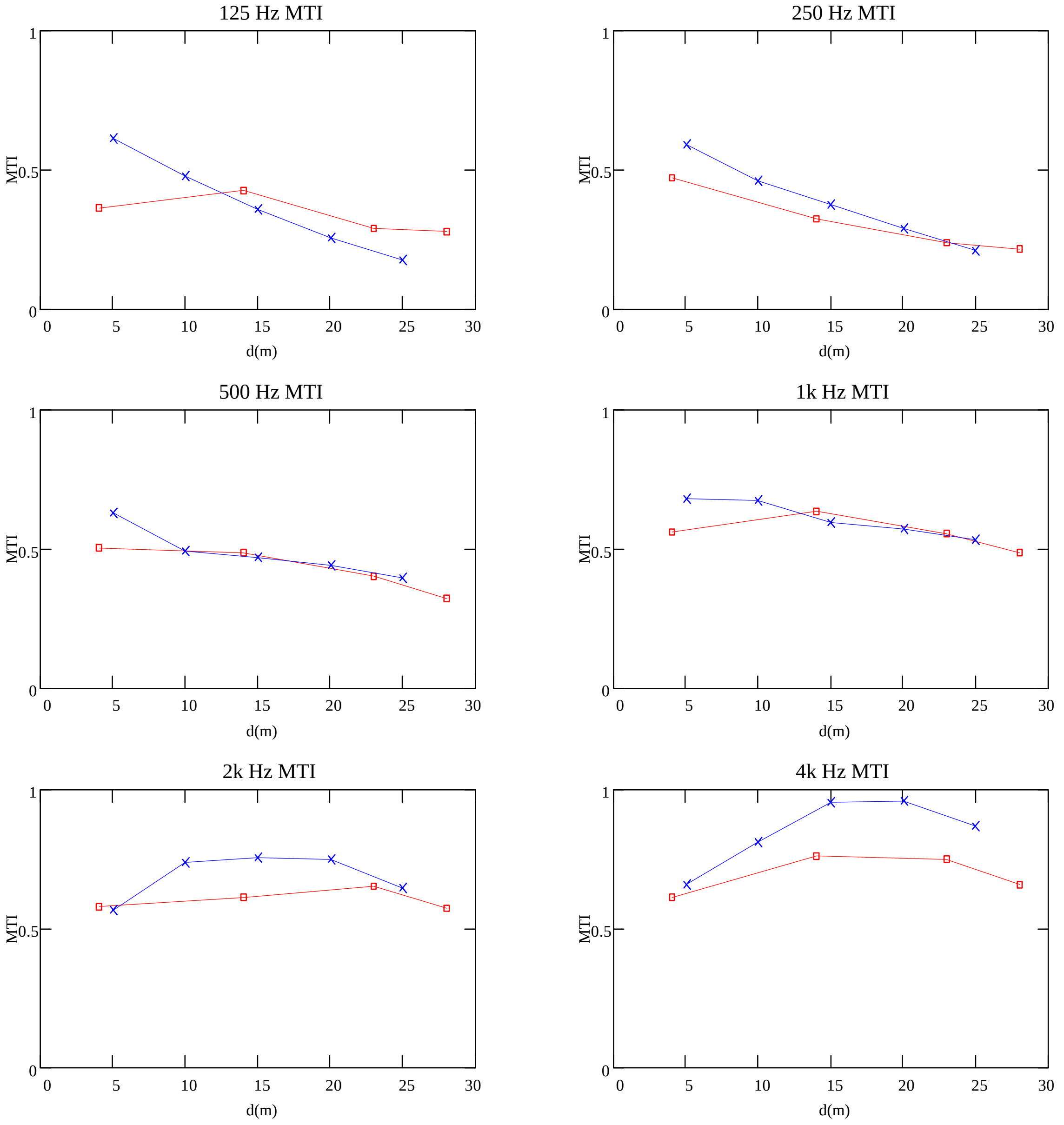

Fig 10   Simulated (x) and measured ( ) MTI values for octave bands of 125 to 4 kHz.

The MTI values for the lower octave bands decrease much faster with increasing distance compared to the MTI of the higher bands. This could be expected from the behavior of the effective Directivity Index as listed in table 1.

Fig 11 shows the simulated and measured STI. The octave MTI values are combined to the STI value by means of the modified weighting factors (by French and Stienberg) to allow easy comparison between MLSSA's calculated STI and simulated STI. MLSSA will represent an erroneous STI value with normal weighting factors if no 8 kHz MTI data is available.

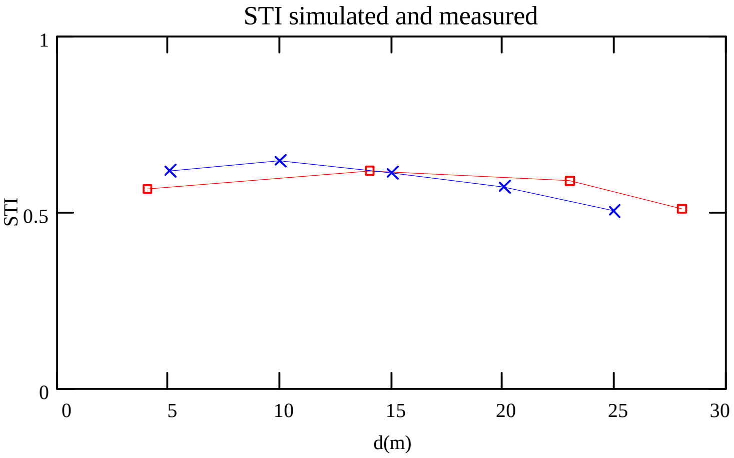

Fig 11 Simulated (x) and measured ( ) STI values, modified weighting factors.

Example 2.

Fig 12 shows the floor plan of the hall with indicated measurement positions (numbers 1 to 17) and 3 Octavox-4c loudspeaker columns mounted against the back wall at a height of 2.6 m (on axis lowest speaker) from the floor.

Room parameters are:

V : 24000 m^3
Ma : Adapted for all absorbing material mounted at the ceiling (Ma around 0.78)
N : 3
RT60(f) : As in table 4

125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
3.6	2.6	2.3	2.1	1.8	1.6

Table 4 Averaged RT60 in seconds measured with MLSSA system.

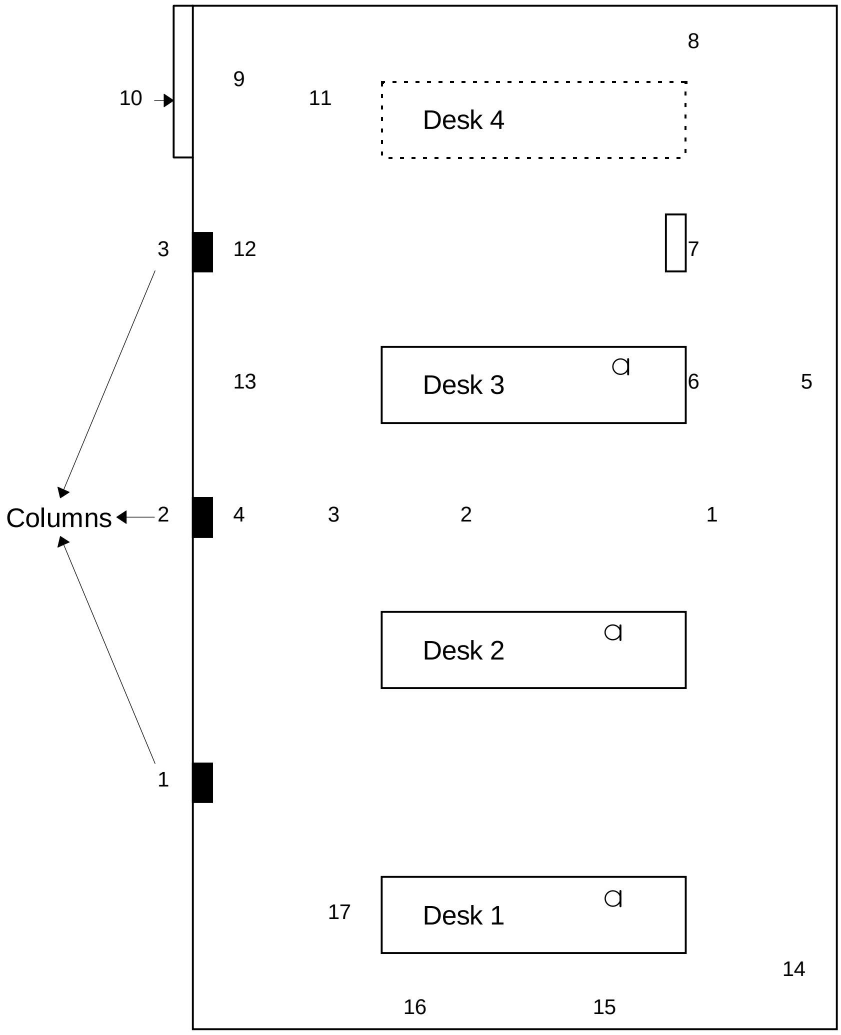

Fig 12 Hall floor plan (not to scale).

The elevation beam-angle (azimuth) was set to -5 deg. (down). With a vertical opening angle of 8 deg. the area covered by the main lobe just reaches to the back wall (at 1.7 m listening height). During the measurements all Octavox-4c columns were active. The measurement microphone was placed on a stand at ear height (approx. 1.7 m).

The speech intelligibility figures (expressed in ALcons, computed from the modulation indices for the octave bands of 125 Hz to 4 kHz) are shown in table 5.

Position	ALcons (%)	Description
1	5.0	On axis column 2, distance. = 25.6 m
2	5.8	On axis column 2, distance = 12.5 m
3	7.5	On axis column 2, distance = 6.0 m
4	4.6	On axis column 2, distance = 2.5 m
5	3.9	Behind desk 3, near back wall, distance = 34 m
6	9.1	Behind desk 3, close to desk, distance = 27.2 m
7	5.9	Behind board, distance = 27.2 m
8	7.6	Near side wall, distance = 27.2 m
9	11.1	Near side wall, distance = 2.5 m
10	15.6	Behind mounting wall (niche)
11	10.9	Near desk 4, distance = 4.8 m
12	5.2	On axis column 3, distance = 2.5 m
13	4.5	In between column 2 and 3, distance = 2.5 m
14	12.2	Behind desk 1, distance = 34 m
15	13.2	Near desk 1, 2.4 m from side wall, distance = 25.2 m
16	7.6	Near desk 1, 2.4 m from side wall, distance = 11.6 m
17	9.5	Near desk 1, distance = 4.4 m

Table 5 Measured modified ALcons for 17 positions.
Distance refers to distance from microphone to column mounting wall.

Fig 13 shows measured and simulated STI values at position 1 - 4.

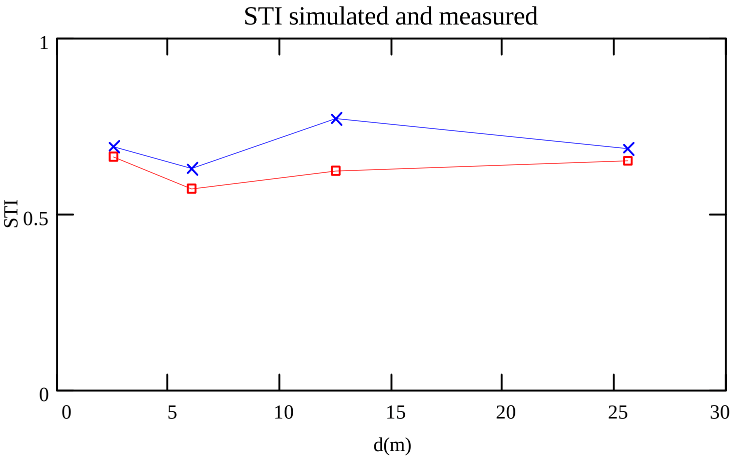

Fig 13 Simulated (x) and measured ( ) STI values, modified weighting factors.

Remarks:

- Average ALcons value is around 4 - 6% at positions where a direct line of sight on at least one of the columns exists. Even the positions which are located very close to the wall to which the columns are mounted show good ALcons values (except at locations very close to one of the side walls).
- If this direct line of sight is disturbed, for example at positions 6, 14, 15 and 16 by the monitors present above desk 1 to 3, the measured ALcons value is increased but still is under 15% (which is generally considered as being sufficient).

5. Directivity simulations versus measurements

Horizontal and vertical polar data of a small loudspeaker were measured and simulated to examine the correlation between measurements and simulations. The loudspeaker was mounted in an enclosure representing a part of the Octavox-4c array (fig 14).

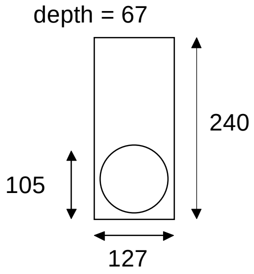

Fig 14 Loudspeaker array element front view, dimensions in mm.

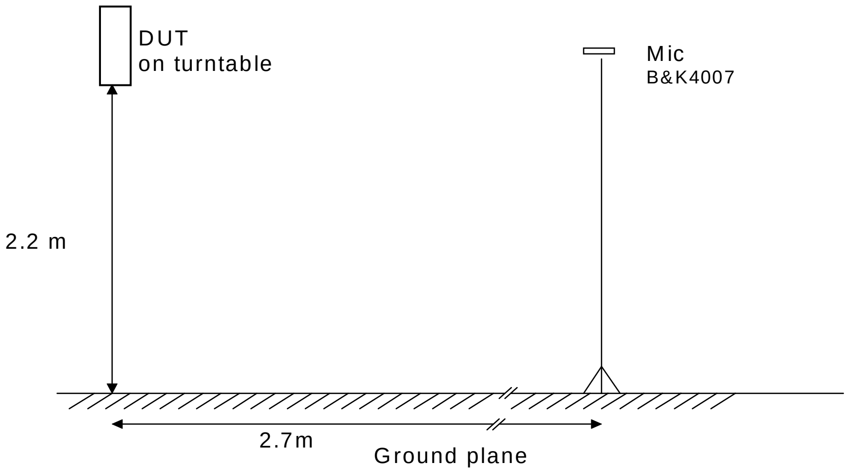

Fig 15 Measurement setup.

Full 360 deg horizontal and vertical complex polar measurements were made with the TEF20 system with an angular resolution of 5 deg. To eliminate the ground reflection the time window is set to 7 ms (frequency resolution = 143 Hz).

0 deg horizontal and vertical : on axis.
+x deg horizontal : equivalent to rotating measuring mic. +x deg to the right.
+x deg vertical : equivalent to rotating measuring mic +x deg to the top.

Simulated and measured horizontal polar response curves are plotted in fig 17. The simulations are only shown for single frequencies 1, 2, 4 and 8 kHz(no octave averaging) and angles between -90 and +90 deg. The simulation program in general somewhat underestimates the attenuation for larger angles. Simulations are accurate up to +/- 50 deg. Notice that the measured values in the 125 Hz band are not accurate due to the fact that the time window is only 7 ms.

The measured polar data of the single speaker was imported into EASE, the elliptical modeling routine was used to fill the directivity matrix and calculate the DI for the different octave bands. This 'measured' DI is compared to the simulated DI (fig 16).

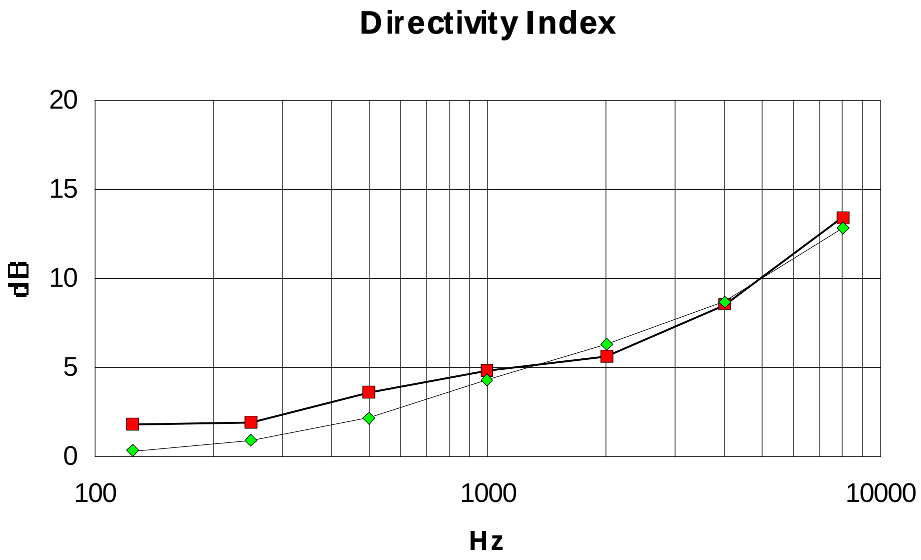

Fig 16 Simulated (◊) and 'measured' ( ) Directivity Index of small array element (one speaker).

In fig 18 the vertical polar response of the Octavox-4c column is compared to the simulations. The simulations are at single frequencies, the measurements 1/3 octave averaged.

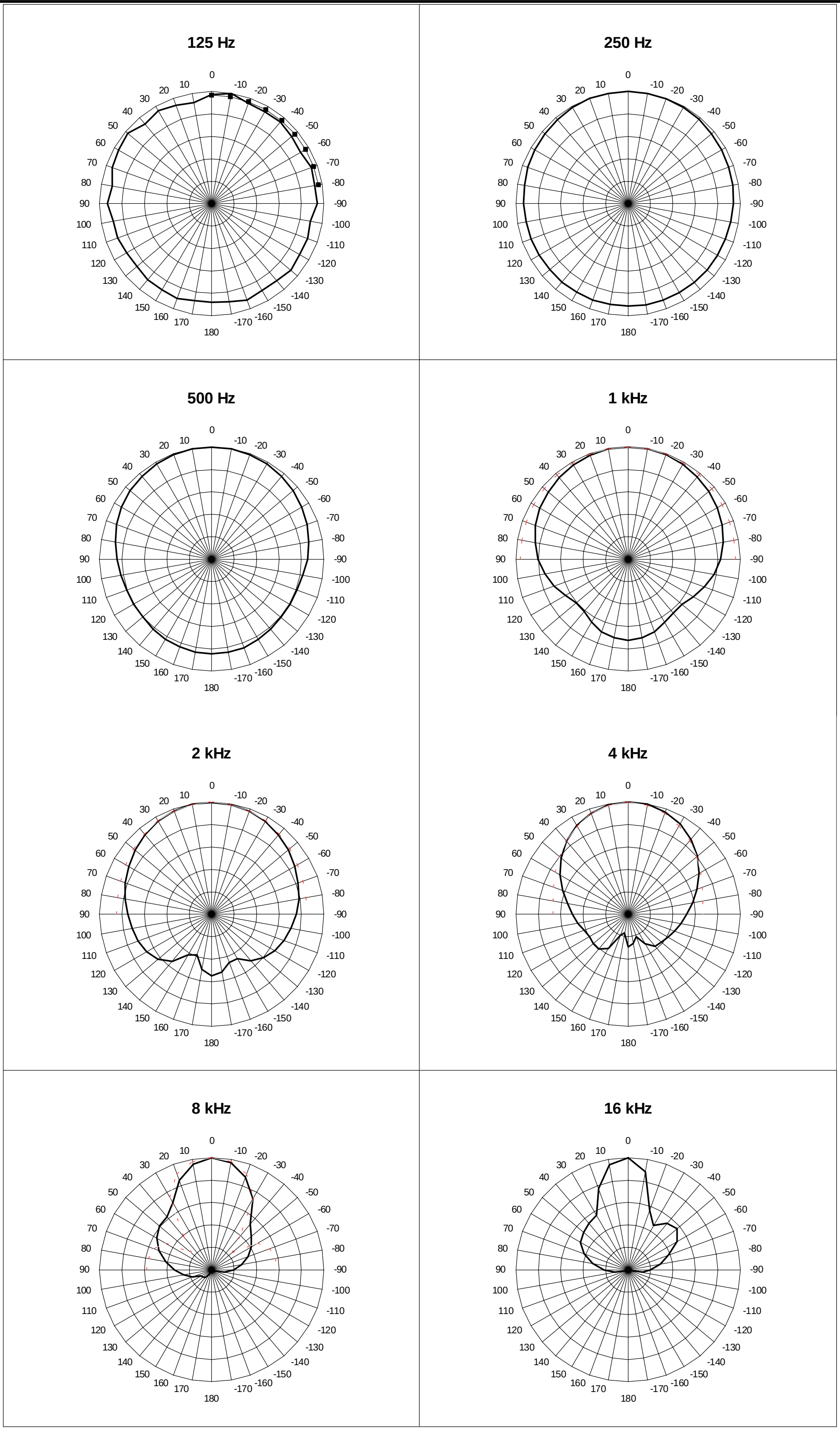

Fig 17 Measured (1/1 Oct. averaged) and simulated horizontal polar plots, 6 dB/div.

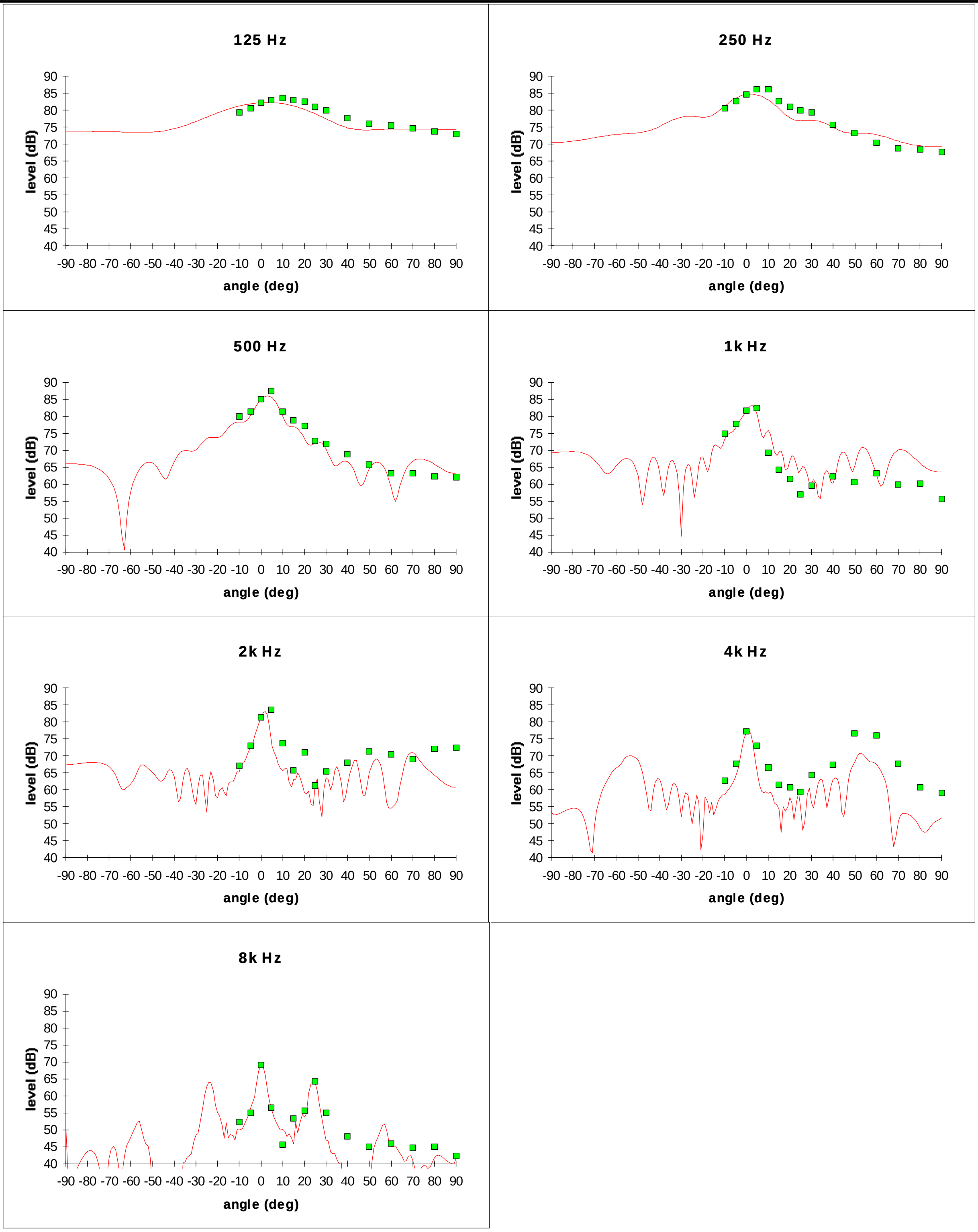

Fig 18 Vertical polar data of simulations (line) and measurements ( ) of Octavox-4c at d = 20 m. Measurements are 1/3 Oct. averaged, simulations single frequency.

6. Conclusion.

- A simulation model has been built and tested which seems quite capable of predicting the directivity characteristics of loudspeaker arrays.
- The Directivity Index is dependent upon the distance in the near field region of the array, and care must be taken when using room acoustical modeling software which generally assumes fixed DI values.
- More realizations (also two-dimensional array solutions) are currently under evaluation to draw conclusions on a more statistically solid basis regarding the correlation between simulations and measurements.

Literature

[1] Sound System Engineering, chapter 10.
D. and C. Davis.
Howard W. Sams & Co., 1987.

[2] Design and implementation of a sound column with exceptional properties.
J. van der Werff, Peutz and Associes BV.
96th AES convention Amsterdam, AES preprint 3835, 1994.

[3] Wave front optimization of loudspeaker arrays.
G. de Vries, Thesis Hogeschool Eindhoven, 1993.

[4] A digital control unit for loudspeaker arrays
G. de Vries and G. van Beuningen, Duran Audio BV.
96th AES convention Amsterdam, AES preprint 3836, 1994.

[5] Design of a constant directivity microphone array.
M. van der Wal, Thesis Delft University of Technology, June 1995.

[6] Design of logarithmically spaced constant-directivity transducer arrays.
M. van der Wal, E.W. Start, D. de Vries
JAES June 1996.

Measurements

We herewith would like to thank Mr. Johan de Sousa Mestre of Akustikon, Göteborg, Sweden for giving permission to use actual MLSSA data measured in the ‘Skara Domkyrk”.