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DGRC arrays : A synthesis of geometric and electronic loudspeaker arrays

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ABSTRACT

Loudspeaker arrays offer an efficient way of achieving both uniform SPL coverage and high sound clarity over a large audience area. Two types of arrays have been proposed over the last 15 years : geometrically steered J shape arrays, mainly for high power sound reinforcement ; and electronically steered vertical arrays, mainly for speech diffusion in public spaces. This paper introduces the "Digital and Geometric Radiation Control" (DGRC) principle, which combines the advantages of geometrical arrays and electronic arrays : array is vertical so that it can be mounted on a wall ; it is controlled with great flexibility using its DSP ; and the power is evenly distributed upon loudspeakers.

1. INTRODUCTION

The idea of using several loudspeakers acting in a coherent way has arisen long time ago, and first column loudspeakers appeared soon after 2nd world war. Right from these early days, it was well understood that the structure of the radiated sound field (or "directivity") could be controlled using an array of loudspeakers. Study of speech perception in a reverberant environment has enlighten the importance of a high direct-to-reverberant ratio : direct sound has a positive role upon speech intelligibility, whereas reverberation tends to impair it. It was then clear that column loudspeakers are an efficient way of increasing speech intelligibility in reverberant environments such as churches.

In 1992, Christian Heil introduced his special wave guide, which he named VDOSC, that transforms the radiation of a loudspeaker into the radiation of an isophase rectangular slit, thus yielding the concept of the "line source" [1]. In application of the Huygens principle, assembling several of these VDOSC sources along the shape of the desired wave front lead to the first "line array", a concept which was soon adopted by many other manufacturers. These line arrays (at least the good ones) allow remarkable control of directivity up to high frequencies, thus yielding uniform SPL coverage and high sound clarity over the audience area. In the following, we shall refer to these arrays as "geometrically steered array", or more simply "geometric arrays", as the directivity is controlled by the geometrical positions and orientations of the individual sources.

More recently, Van der Wal *et al* worked on a vertical array of loudspeakers driven via DSP processing [2]. In these arrays, the wave front generation is no longer controlled by the source positions, but by the filtering performed in the DSP. In the following, we shall refer to these arrays as "electronically steered arrays", or "electronic arrays".

These pioneering works were followed by many others, giving rise to the concepts of Wave Field Synthesis [3] and Wave Front Sculpture [4].

This paper introduces a new type of array, which could be named "hybrid array" as it can be seen as a synthesis of geometric and electronic arrays. This new array is based on a principle we have named "Digital and Geometric Radiation Control" (DGRC), which is based both on the positioning and orientation of the loudspeakers, and on the corresponding DSP filtering (patent pending).

Second section of this paper will discuss the main features, advantages and disadvantages of geometric and electronic arrays. In section 3, we shall explain the DGRC principle, discuss its advantages and limitations, and present results from modeling and experiments.

2. ELECTRONIC AND GEOMETRIC ARRAYS

2.1. Geometric arrays

It is rather easy to calculate the shape of the wave front which provides uniform SPL coverage (in free field) over a given axis. The local radius of curvature r of the wave front should essentially increase with the focus distance d, as explained on figure 1.

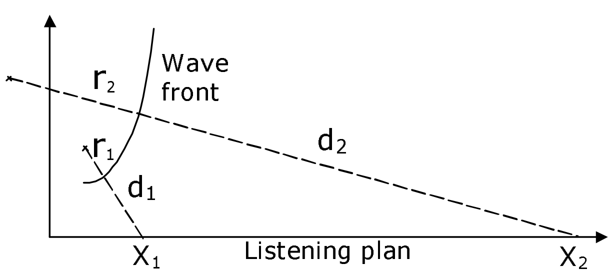

Figure 1 : Illustration of the wave front sculpture in a vertical plane.

In situations where the audience is on a plane (usually horizontal or slightly tilted), the desired wave front has approximately a J shape in the median vertical plane (in fact, when the plane is long and the initial radius of curvature at the bottom of the wave front is chosen small, the top part of the J is slightly leaned to the right). Of course acoustics is not optics, and the SPL obtained will depend on frequency, or more precisely on the ratio (wavelength / length of the array). At a given frequency, the distance range of the array (defined below) is essentially proportional to the array length. The directivity is symmetrical about the vertical median plane, and a rectilinear horn in the horizontal plane is generally used at high frequencies.

It is interesting to note how even a small error on the wave front shape results in a rather large errors on the SPL obtained (see figure 2). As a consequence, it is important that geometric arrays are installed using a sophisticated mechanical system, which secures the loudspeaker positions and orientations with great precision. One of the main disadvantages of geometric arrays is that there is very little control on the directivity once it has been installed. Also, because of their J shape, they can't be flush mounted on a wall.

On the other hand, use of line sources in arrays ("line arrays") enable accurate radiation control up to very high frequencies. Secondary lobes are efficiently reduced, thus optimizing the direct-to-reverberant ratio, and reducing frequency response variations over the audience. In addition, all loudspeakers are driven with the same power, thus optimizing the maximum SPL output.

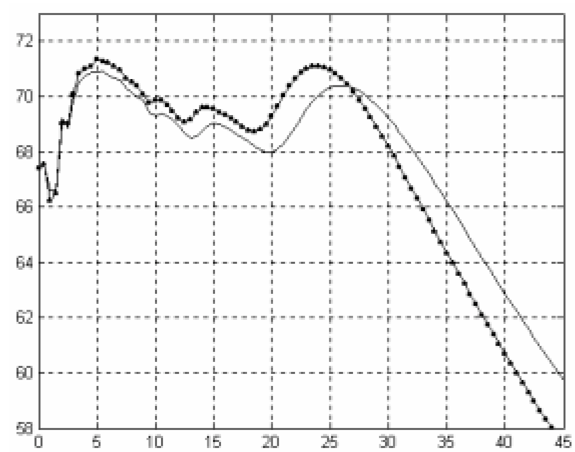

Figure 2 : Perturbation of line array geometry.
Line array is 2.4 m high ; its bottom is 1.0 m above the listening plan. Figure plots dBSPL on the listening plan vs distance from the array (m) in the 4kHz octave.
Solid curve : loudspeakers at their nominal position.
Dotted curve : top of the array tilted forward by 2 cm.
Simulation data.

2.2. Electronic arrays

Electronic arrays generally use direct radiation loudspeakers placed on a vertical line. As a result, directivity at low frequencies tends to be symmetrical about the vertical axis of the loudspeakers. Directivity is generally controlled by gains, delays, and FIR filters performed by DSPs on all loudspeaker channels. Radiation is no longer restrained to the shape of the wave front, but also to its local amplitude.

Electronic arrays can't use line sources because there would be a strong discontinuity between the radiation of the top of a source and the bottom of the next source. In addition, their depth would be quite large as wave guides used in line sources are rather long.

As a consequence, electronic arrays use direct radiating loudspeakers. Hence the wave front shape is spatially sampled, as opposed to the line source in which the radiation is (ideally) continuous. This results in secondary lobes at frequencies greater than c/d, where c is the sound velocity and d is the sampling interval. These lobes generate reverberated energy, and irregularities in the frequency response over the audience area.

For example, a sampling interval of 43 mm is required if one wants to avoid lobes below 8 kHz, which yields 58 loudspeakers for a 2.5 m long array, each having its own filtering and amplification. This setup is rather costly, and most manufacturers use a sampling interval of approximately 100 mm. In 1996, Van der Wal *et al* [1] proposed a principle in which loudspeakers are placed according to a Lin/Log scheme : in the bottom part of the array, loudspeakers are side-by-side (regular interval), and then distances between loudspeakers increases gradually as moving towards the top of the array. The effective height of the column is then controlled with low-pass filters which are essentially keeping the ratio (effective height / wavelength) constant, so that directivity is (ideally) no longer depending on frequency. With this principle the number of loudspeaker-processing channels is reduced, but the power is unevenly distributed on loudspeakers, thus impairing the maximum SPL output.

Later on, van Beunningen and Start [5] presented their DDS method for optimizing directivity using a LMS approach to compute FIR coefficients.

Reducing the number of loudspeakers implies using bigger loudspeakers, so that they can supply the desired maximum SPL. But then, because of their larger moving mass, it is hard with these loudspeakers to obtain a clean restitution at high frequencies. This lead several manufacturers to develop arrays using 2 way coaxial loudspeakers, or even to have two distinct arrays, one for the low and mid frequencies, one for high frequencies.

3. DGRC ARRAYS

3.1. Principle

The DGRC principle is presented on figure 3. The idea is simply to chop the desired wave front shape into sections and move them back on a vertical line, much like what is done in the Fresnel lenses used in optics. Then the DSP basically just has to perform the delays corresponding to propagation over distance d_i between the sections. The saw-tooth profile is characteristic of the DRGC array principle. Let us see that in more details, referring to figure 3.

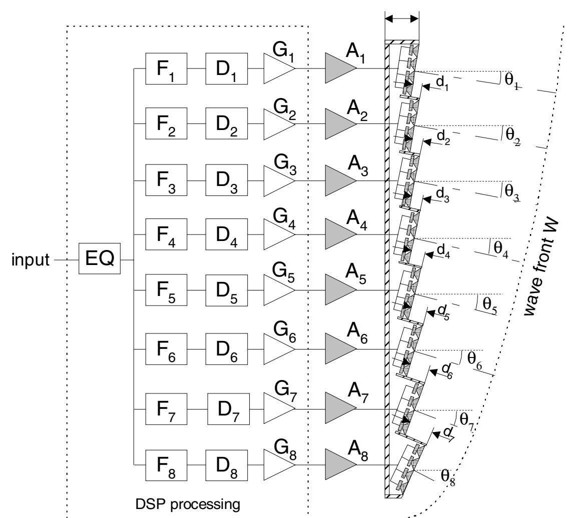

Figure 3 : The DGRC principle
EQ : Equalizer – F_i : Filters – D_i : Delays – G_i : Gains – A_i : power Amplifiers

An array of N « electroacoustic sources » is associated to delays D_i, filters F_i, gains G_i, and power amplifiers A_i. (on figure 3 there are 8 electroacoustic sources consisting of groups of 4 loudspeakers). Delays D are set to values corresponding to propagation along distances d_i :

$$D_n = \frac{1}{c} \cdot \sum_{i=1}^{n-1} d_i \quad \text{for } n \geq 2,$$

c being the sound velocity (m/s) ; and $D_1=0$.

Thus the wave front W generated by the array is that in dashed line. This choice for delays D results in almost no diffraction on the edges between steps, as will be shown below.

Positioning and orientation of the sources is set such that the wave front W corresponds to the nominal coverage desired for the array. Note that the altitude of the column relative to the listening plan is a key parameter in the column design and/or settings. The SPL coverage can be varied either by slightly varying the delays D_i, and/or by acting on gains G_i. Filters F_i are linear phase FIR used to compensate propagation absorption : they boost the high frequencies according to the focus distance of each channel, so that at a given frequency their gain increases as the index of the channel decreases. Equalizer EQ is used to equalize the frequency response of the whole system.

"Electroacoustic sources" can be either direct radiating loudspeakers, or groups of loudspeakers, or loudspeakers loaded with wave guides such as line sources.

An experiment has been made in order to verify that diffraction at angles of the saw-tooth shape doesn't pose problem : we have measured the polar directivity of a vertical array consisting of 8 three inches loudspeakers side-by-side (figure 4), and compared it to the polar directivity measured using an elementary DGRC array consisting of 2 groups of 4 loudspeakers shifted by 36 mm (figure 5). Polar directivities of both arrays are very similar, even at high frequencies, with a typical standard deviations between the two cases of 1.4 dB, thus validating the DGRC principle.

The number of loudspeakers per channel of a DGRC array is not necessarily identical for all channels. As loudspeaker tilting angles θ_i are increasing as i increases (see figure 3), smaller number of loudspeakers for the bottom channels yields minimum depth of the column ("b" on figure 3). An example is given on figure 6.

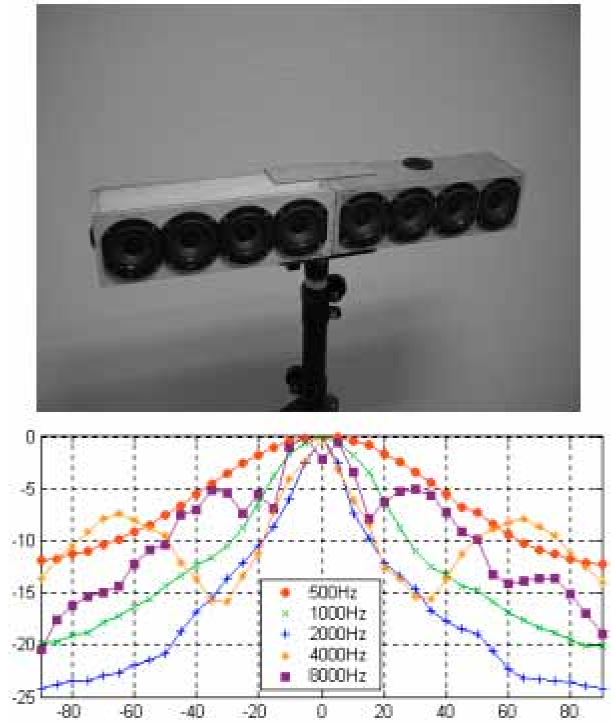

Figure 4 : Directivity of a horizontal linear array of 8 three inches loudspeakers side-by-side.
Top : loudspeaker layout.
Bottom : Directivity (dB vs deg) per octave band measured at 1.5 m in the horizontal plane.

In the frequency range where directivity control is important, loudspeakers are generally mass-controlled (i.e. well above the resonance frequency). Thus, it is not necessary to partition the column volume for each loudspeaker, and they may all share the same rear acoustic load.

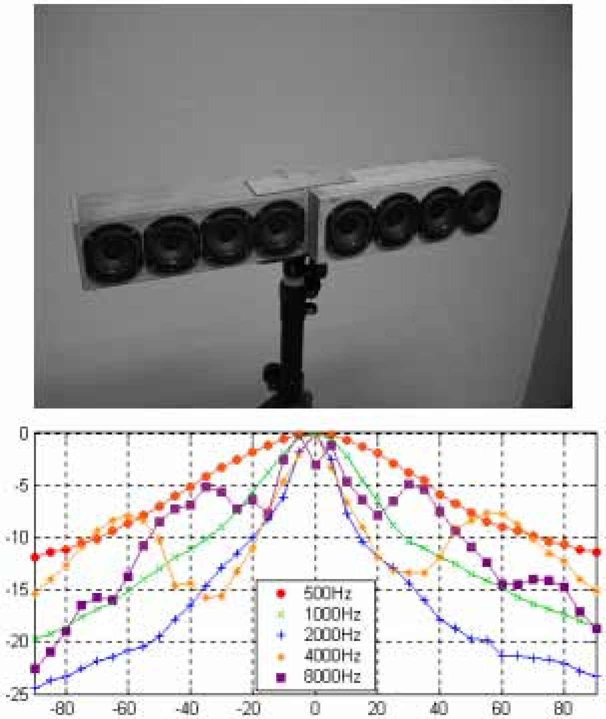

Figure 5 : Directivity of a horizontal DGRC array consisting of 2 sub-arrays of 4 three inches loudspeakers shifted by 36 mm. Signal applied to the right sub-array has been delayed by 104 µs.
Top : loudspeaker layout.
Bottom : Directivity (dB vs deg) per octave band measured at 1.5 m in the horizontal plane.

3.2. Advantages and limitations

Main advantages of the DGRC principle are :

- The number of electronic channel (DSP and amps) is dramatically reduced. For example, column model SA250P, which is 2.5 m high and 124x150 mm in section, only needs 6 channels (see below). The consequence is of course a reduced cost

- The number of channel doesn't depend on the number of loudspeakers. Consequently, a large number of small wide-band loudspeakers may be used, thus obtaining a clean restitution at high frequencies, and reduced secondary lobes.

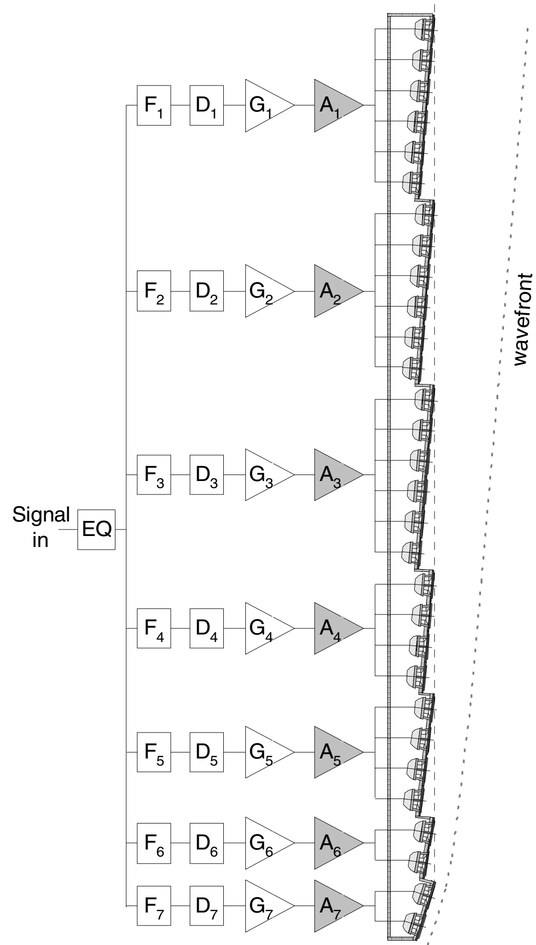

Figure 6 : DGRC array with variable number of loudspeakers per channel.
EQ : Equalizer – F_i : Filters – D_i : Delays – G_i : Gains – A_i : power Amplifiers

- Power is evenly distributed on loudspeakers, so that their individual responses matches better. Moreover, they can be all used up to their maximum power, thus maximizing the SPL output

- The principle is applicable to line sources, so that it can be used for high power sound reinforcement systems, in which case it simplifies the mechanical hanging system, and gives more tuning possibilities.

Limitation of the DGRC principle :

- Having a limited number of DSP channel, there is less flexibility on directivity control with a DGRC array than there would be with one DSP channel per loudspeaker. For example, it is not possible with a DGRC array to generate several lobes. However, DGRC arrays are essentially designed for the usual situation where the column is vertical and the audience is on a single plane (usually horizontal).

3.3. Results

Grouping channels 6 and 7 of the DGRC array of figure 6 into one single channel leads to the layout of model SA250P shown on figure 7, a 2.5 m high column using 30 three-inches loudspeakers and 6 channels DSP and amplification.

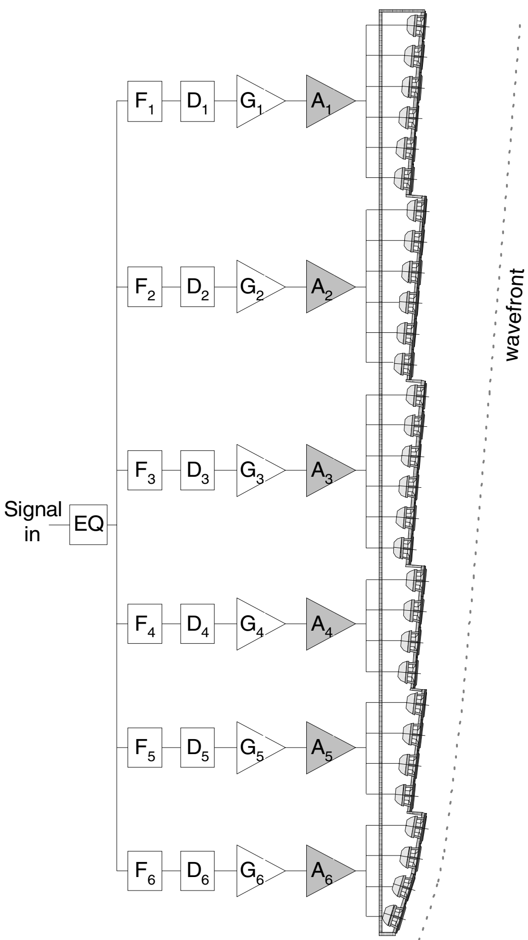

Figure 7 : Same as figure 6, except channels 6 and 7 have been merged into one single channel.

Figure 8 shows the measured and predicted SPL versus distance in octave bands for model SA250P. Curves have been normalized to the 10 m distance value, and shifted by 5 dB steps for better readability. The bottom of the column is 2.5 m from the floor. Microphone is 1.5 m from the floor, in front of the column. DSP parameters are “nominal”, i.e. their default values. Predicted value were obtained using measured directivity data for all loudspeakers.

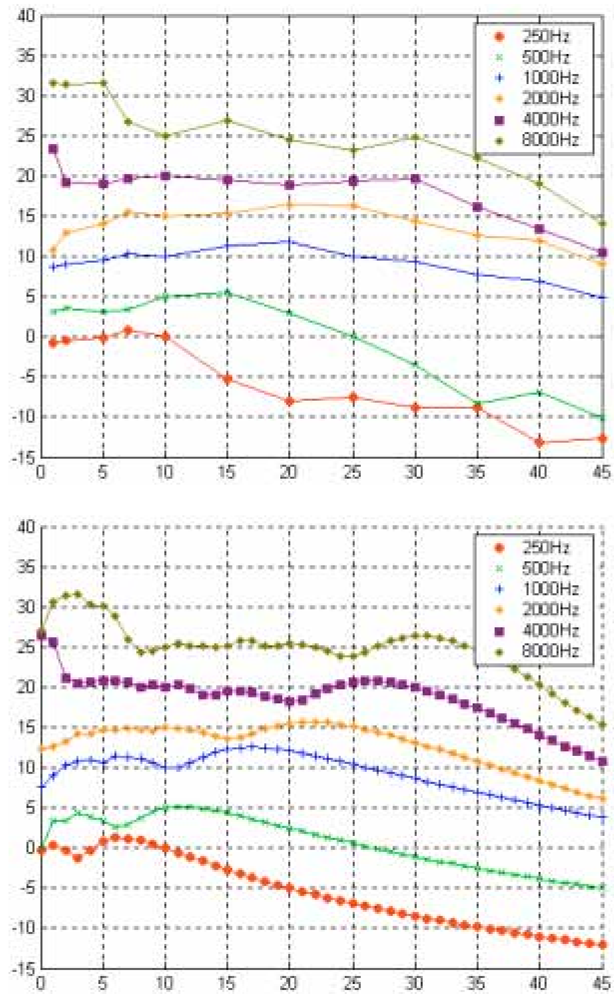

Figure 8 : SPL (dB) per octave vs distance (m) measured with a 2.5m DGRC column. Bottom of the column is 2.5 m from the floor. Microphone is 1.5 m from the floor, in front of the column. Floor is reflecting. Curves have been normalized to their value at 10 m, and shifted for more readability.
Top : Measured - Bottom : Predicted.

It can be seen that modeling and experiment are in very good agreement, with a standard deviation between measured and simulated values of approximately 1.2 dB, except for the 500Hz octave where the std is 2.4 dB. Main sources of discrepancies are : i) the fact that simulations do not take into account the reflection of the direct sound on the floor ; ii) the room where measurements were made was somewhat encumbered, so that there was some diffraction on surrounding objects.

If we define the range of the column as the distance interval in which the sound level fits in a +/-3dB interval, we get [1:26] m at 500 Hz, [1:43] m at 1kHz, [1:42] m at 2kHz, and [2:38] m at 4kHz. Of course, the SPL vs distance curves may be modified very simply by altering the DSP parameters. For example, setting the gains of the upper channels to zero shortens the range, which can be useful in case where only a small audience area has to be covered.

Figure 9 shows the SPL versus horizontal angle for the same setup. As expected, the –6dB opening angle decreases as frequency increases, but remains greater than 140° up to the 4kHz octave.

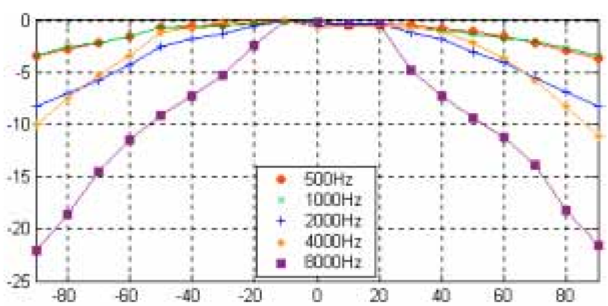

Figure 9 : SPL (dB) per octave vs horizontal angle (deg) measured with column SA250P. Bottom of the column is 2.5 m from the floor. Floor is reflecting. Curves have been normalized to their value at 0°.

Figure 10 shows the dependence of the SPL per octave upon the height of the microphone (in cm). One can see that typical variation is +/-2dB between 90 cm and 160 cm : a tall listener standing up will hear nearly the same sound as a small listener sitting down.

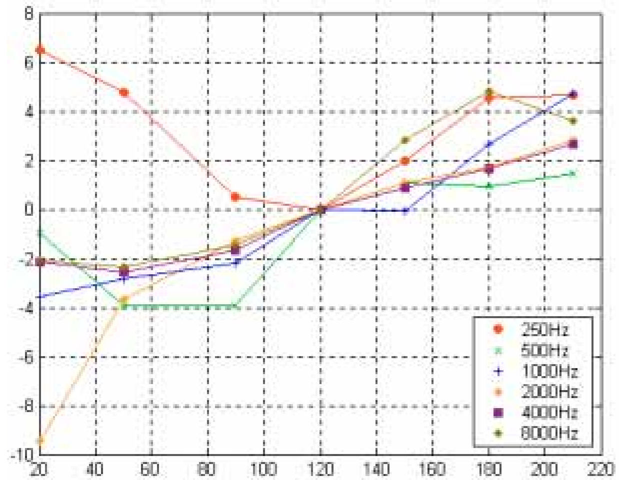

Figure 10 : SPL (dB) per octave vs microphone height (cm) measured with column SA250P. Bottom of the column is 2.5 m from the floor. Floor is reflecting. Curves have been normalized to their value at 120 cm.

4. CONCLUSION

In this paper, we have introduced the DGRC principle for loudspeaker arrays. The DGRC principle can be seen as the synthesis of geometric and electronic arrays. We have seen that DGRC arrays offer a number of advantages, of which that of a reduced number of DSP and amplification channels, and an even distribution of power upon loudspeakers.

We have seen that a 2.5 m tall column provides a range of more than 30 m (+/-3dB 500-4kHz), and a wide horizontal opening angle. Measured and predicted data are very similar.

DGRC arrays are a highly efficient and cost-effective way for public address in large and reverberant spaces such as worship spaces, railway stations, airport terminals, shopping malls…

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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