HYBRID LINE ARRAYS - A VIABLE ALTERNATIVE

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1 INTRODUCTION

In this paper we investigate a hyrbid combination of a high frequency horn and a steered end-fire array loudspeaker. After a brief review of established line array methods we describe the hybrid line array and the advantages of this combination. We then explain how numerical optimisation can be applied to the hybrid array to determine the elemental transfer functions that can optimise the system to meet user requirements. The performance of this system is analysed and its limitations discussed. Finally we suggest some areas where more investigation is required.

2 ESTABLISHED METHODS OF RADIATION CONTROL

2.1 Horns

Aside from relying on the size of a direct radiator, horns offer the simplest of all methods to control radiation pattern. Constant or differential-dispersion horns are commonplace, well understood and can be produced relatively cheaply. However, when the mouth size is small compared to the radiated wavelength, the device behaves more like a simple source, thus losing the ability to control its radiation pattern. With increasing frequency, the horn becomes acoustically larger and enters the region of effective pattern control. At the highest frequencies, increasingly smaller regions concentrated at the throat have most influence on the output.

In practice, to reproduce high SPL over the audio spectrum with consistent pattern control at all frequencies, four or sometimes more horns are required. The major problem with such an arrangement is more often size rather than cost; it is frequently architecturally unacceptable to install very large horns even though it may offer the best technical performance.

2.2 'Broadside' Aperture Type Arrays

Arrays of acoustic sources that are closely spaced relative to the upper wavelength of operation can produce a highly controllable radiation aperture. A variety of useful designs have appeared over the years, many well before the current period of readily available components including fixed passive designs[1,2] and actively steered examples[3,4,5]. To achieve a radiation pattern that is free of unwanted artefacts generally imposes constraints on the spacing[6] of the transducers and therefore, the size of the transducers limits the available SPL. Some interesting schemes to mitigate these artefacts have been found[7], yet for high SPL or full-range reproduction, such systems are often inadequate.

Linear arrays of direct-radiator elements in narrow cabinets are commonly used and produce a wide and non-consistent horizontal polar pattern that is directly related to each element’s polar pattern.
When the beam is steered, it will be steered similarly at all radial positions around the array, which is ideal when all audience positions are within a particular radius from the array. In circumstances where some coverage positions are significantly more distant from the source than others, there will inevitably be potentially undesirable output on other surfaces. Providing elemental horizontal constant directionality by acoustic means or using a 2D aperture would prevent such output but no known examples are available.

2.3 "Articulated" Line Arrays

This class of linear array is comprised of drive elements that are relatively widely spaced compared to the wavelength of frequencies in the upper region of their pass-bands. This spacing allows higher powered drivers to be employed so that high SPLs can be achieved. At lower frequencies, the array could be considered an aperture type array.

Vertical coverage control is principally governed by the physical shape of the array, which is adjustable. The technique scales well and many increasingly smaller versions have been introduced. Optimising such arrays for particular venues has been studied [8,9] and can result in excellent performance.

Although articulated arrays cannot be steered in the traditional sense, recent work[10] indicates that numerical optimisation of independent elemental transfer functions can offer very desirable performance gains and an extra degree of control. However, since the array typically needs to be curved it still occupies an appreciable amount of space which can be problematic in some circumstances.

3 HYBRID METHODS

3.1 The Principle

The idea of combining a mechanically adjustable high frequency horn with a low/mid steered array was introduced and implemented some years ago by one of the authors[11] ,fixed combinations of steered and purely acoustic high frequency devices have been considered before[12,13].

The technique not only solves many of the problems associated with the established methods described earlier, it is also a scalable and cost-effective engineering solution. The high frequencies can be reproduced at high SPL using a single amplifier/DSP channel with proper control of both horizontal and vertical coverage. Low and mid frequency output is generated with a level of pattern control that would require a truly enormous horn to match that of the high-frequency horn, output also tracks the HF horn orientation using only a modest number of active channels. When installed, the system can be made practically invisible.

There are two hybrid-array configurations that have some degree of overlap between them. The first is the combination of the horn with an array that is primarily an end-fire array; the second combines the horn with an array that is primarily broadside. When using a normal constant-directivity horn, the end-fire configuration is the natural choice since both components can be made to have similar radiation characteristics. If a more constant SPL with distance is desired in situations where some parts of the audience are much closer than others. then a differential dispersion horn with a broadside array configuration is likely to be more suitable. In this paper we concentrate on the original idea of a constant directivity horn and a primarily end-fire low/mid array.

3.2 Performance Benefits

1) The principal benefits of the hybrid line-array are:
    a) Delivery of a flat frequency response to all listeners. The authors believe that a consistent frequency response across the audience area is much more important for fidelity, clarity and enjoyment than a constant overall level.
    b) Minimisation of vertical radiation towards high reflective ceilings.
    c) Loudspeakers can be mounted vertically or horizontally, whichever results in lower visual impact.

2) Implementation
   a) The vertical directivity of the high frequency horn can be used to provide some compensation of distance loss if reflections from rear wall are not problematic.
   b) If all listeners are in the far field of the array, beam steering and frequency tapering techniques can be employed to match the polars of the array with those of the high-frequency horn. This ensures consistent frequency response with position
   c) The partial end-fire nature of the array creates a pattern that minimises irradiation of the ceiling, with minimisation of the upward radiation being a key part of its design.
   d) Compared to broadside arrays, the semi-end fire approach narrows the horizontal pattern somewhat, partially matching the horn's pattern and increasing the directivity of the array.

3.3 Performance Limitations

1) When paired with simple constant directivity horns, optimum compensation of distance loss usually results in too much sound striking the wall behind the audience, with resultant audible reflections.
2) There is no direct parametric control over the horizontal pattern of the low/mid array.
3) The simultaneous need for small inter-element spacings relative to wavelengths in the upper pass-band of the array and high SPLs often means that multi-range arrays are required.

3.4 Examples of field use

Fig 1**Error! Reference source not found.** shows a hybrid array used in the debating chamber of the New Zealand Parliament. To obtain i) the required output SPL, ii) strong control of radiation pattern both above the array and iii) to match the high frequency horns, it was necessary to employ three array sections. Fig 2 shows a hybrid for the Australian Parliament employing a horn and LF array and Fig 3 shows a two way hybrid for the High Court in Hamilton New Zealand.

In all these instances, three requirements had to be addressed:

1) Consistent frequency response over listening area
2) Minimal irradiation of ceiling (for vertical systems) or area that is opposite the direction of steering **Error! Reference source not found.**
3) Horizontal or vertical mounting with minimal visual bulk

3.4 Recent Developments

End-fire arrays for public address are not new concepts[14], however, only recently have they been studied in greater depth. In one study[15], a constant beam-width end-fire array was designed for the decade range 20Hz to 200Hz using a numerical optimisation technique after the author considered a particular analytical approach was impractical to implement. A simple point source model was employed which could not account for element interactions, however, in a later work[16], a BEM model was created for an array covering the decade range 100Hz to 1000Hz which gave significant improvement to the agreement between measured and predicted output. Elemental filters were determined by finding the best value of the stability factor for the “optimal beam-former” given a target array gain and directivity index.

3.5 A New Design Approach

In this paper we concentrate on the audience area to be covered and those areas to be avoided rather than far-field polar output since the usual assumptions cannot be made when audience regions are close to the array.

The room chosen, shown in Fig 4, is 20m long by 12m wide and 2.5m high. The intended region of coverage starts at 2.5m in front of the Hybrid which is mounted on or in the ceiling 5m away from the front wall of the space. The amount of sound radiating towards the region behind the array and the rear and side walls is to be minimised. The Hybrid itself, Fig 5, is formed from a special, uniquely driven constant directivity horn aimed 23 degrees down and 16 Martin Audio Omniline enclosures extending behind the horn with the HF devices in the Omniline disconnected. Axial 1m sensitivities referenced to a 2.83V input are 112dB for the HF horn and 87.5 dB for each LF element.

Using this arrangement, we expect the upper limiting frequency of array control to be 1500 Hz and this frequency is thus the target crossover point. The array elements have a 70 Hz -3dB point, and ideally we would extend pattern control down to that frequency to make this a 2 way full-range system.

4 ACOUSTIC MODEL

Without careful modification[8,17], point source models are too inaccurate for simulation of array loudspeakers at low and medium frequency . For speed of development, all direct field output was calculated using BEM at 1/36th octave resolution from 50Hz to 16000Hz. The pressure incident on all surfaces of the room was determined for each source in isolation at 4000 points evenly distributed throughout the room. After some 20 hours of computation, all results including the HF horn were stored for post-processing in MATLAB.

Fig 6 displays the output of the HF section of the hybrid on the room surfaces; immediately we recognise a pattern control that is impressively consistent with frequency with very good rear rejection well below the horn’s pass-band.

5 NUMERICAL OPTIMISATION

The problem of determining the elemental transfer functions that give a desired sound-field has been studied in the context of touring loudspeaker arrays[10]. We will now apply similar techniques to find the elemental transfer functions of the Hybrid array that match the output of the horn in the audience area and reduce unwanted irradiation of non-audience surfaces.

Fig 7 shows the output of the LF array without signal processing, and as expected there is an intensely loud area directly beneath the array, which diminishes in both extent and level as frequency increases. The unprocessed output therefore represents a poor starting point for the optimisation process. A better starting point is shown in Fig 8, in which the main lobe has been steered using simple delay techniques in roughly the same direction as the horn orientation. Of course, as it stands, this array is still unusable over the full desired frequency range. If global equalisation was used to correct the balance, the array’s output at higher frequencies would have unacceptable levels of radiation beneath the array with the pattern being quite different from that of the horn at crossover.

A objective function with two components was formulated; the first component gives a measure of ‘leakage’ by comparing the outputs of the array on audience and non-audience areas. The second component is an absolute ‘target’ obtained from the output of the HF horn at the crossover point just in the audience area. By altering the balance between these two objectives, it should be possible to achieve a reasonable pattern match to the HF horn whilst reducing the output on non-audience areas.

The optimisation progresses one frequency at time and at each step determines the magnitude and phase components that minimise the objective function. Both magnitude and phase are constrained in absolute terms and dynamically by limiting the gradient (with frequency) of the resultant transfer function. Imposing these restrictions on the answer has been shown to produce results that are ‘sensible’ and reasonably straightforward to implement in appropriate hardware. Importantly, we make no restriction on how the transfer function changes between elements.

The results were obtained with absolute gain limited to 12dB and phase constrained to one period. Fig 9 displays the optimised output of the low/mid array for a particular combination of the objective component weights that favoured the reduction in irradiation of non-audience areas over matching the pattern to the HF horn. The reduction of irradiation of these areas is quite dramatic; the difference in level between the audience area and that behind and below the speaker is typically more than 40dB. Above 1000 Hz the array pattern starts to develop a forked shape which is apparent in the starting point, below this however, the pattern is consistent and reasonably well matched to the HF horn. It is worth noting that usable frequency range of the system extends an octave lower than previously seen in the literature which is usually limited to a decade range.

Where pattern-matching to the HF horn is considered more important than avoiding output on non audience surfaces, a different balance between the two components can be struck. Fig 10 displays the output of such a compromise, immediately apparent is an increase in ‘leakage’ particularly at the upper and lower extremes of frequency. However, the pattern is significantly more uniform with frequency.

An alternative way to view the outputs of the two solutions is by looking at the output on a single vertical section through the main horizontal area. Fig 11 and Fig 12 show the output on a central line from underneath the array to the rear wall at full frequency resolution. From these plots it is clear which of the two solutions will offer the flattest frequency response in the audience area and is best matched to the HF Horn pattern. We should note though that it would be possible to improve the minimum leakage solution with some global EQ to improve the overall balance.

6 DISCUSSION

6.1 Efficiency

If all N elements of the LF array were positioned exactly at the origin then we would expect a 20*log10(N), increase in level with radiation characteristics similar to point source. This arrangement, although practically impossible, is useful since is gives the theoretical maximum sensitivity of such a system. We would expect a similar maximum sensitivity from a pure end-fire array although we would need to account for additional distance losses when close to the array. Fig 13 shows the expected levels on the centreline of the room for both these cases, note that the extra distance is accounted for in the purely end-fire array and has effectively shifted the source origin back with a very slight change in shape.

Also plotted on the same axes are the output from the HF horn at 1500 Hz and the output of the LF array at 1000 Hz for the solution which favoured pattern matching over non-audience rejection. The LF array is 2-3dB less that the ‘perfect’ end-fire arrangement and 1-2 dB less than the HF horn output. Examination of only the output on the centreline gives a slightly distorted view at high frequencies since the LF pattern produces minima on axis here and the optimisation considers the entire audience area.

The question we now need to answer is how much this performance has cost in terms of additional gain. We know that no more than 12dB of gain can be applied since this was a fixed constraint of the optimisation, but in reality much less gain was needed. Fig 14 shows the magnitude and phase plots vs frequency for the solution that favoured pattern matching excluding the phase associated with the simple beam-steering delays. Interestingly, the magnitude plot is mostly green indicating that very little additional gain was needed, the exception being above 1000 Hz on the rear half of the array where 6-8dB was required and up to 12 dB on the first box at very low frequencies (not present in the other solution).

Although somewhat imprecise by looking at the magnitude plot, it would seem that a maximum gain of around 3dB below 1000Hz and 8dB above 1000Hz is required. When combined with the difference to the theoretical maximum cases mentioned above, the numerically-optimised array is 6 dB less sensitive below 1000Hz. than the 'perfect' but unusable end-fire array.

6.2 Coverage Performance

It is apparent we cannot meet our objective of a 1500Hz crossover point with this LF array. The upper frequency limit was based on a one-half wavelength criterion and it would seem that a one-third wavelength criterion would have been a better choice. Shifting the performance up in frequency slightly is merely a case of reducing the elemental spacing a little which, until a fast model is available, would have taken 20 hours to do. Since the performance is still good down below 50Hz with the current array we can have confidence that a smaller spacing will allow us to maintain good performance down to 75Hz; the lower bandwidth of the array.

The particular room we chose had quite a low ceiling and required the Hybrid to be placed reasonably close to the audience. We chose to aim the constant directivity horn to reduce reflections from the back wall and in doing so made no attempt to compensate for distance loss. It would be interesting to see the results with the horn aimed differently or with a different type variable dispersion horn. Similarly, we need to investigate the performance using this technique when the audience is more equally distant from the Hybrid.

6.3 Implementation

Acoustically there is nothing particularly difficult to implement, however, the filters do present some issues. Whilst we can implement these transfer functions with long FIR filters without the associated latency penalty using in-house development hardware, there are currently no commercially available professional quality platforms that can do this. We also think it is possible to get quite close to the desired functions using IIR filters, however, more work need to be done in that area.

7 CONCLUSION

Numerical optimisation of a Hybrid line array that is carefully guided can produce good results with a balance that is user defined between flat frequency responses over the audience area and minimising irradiation on non audience areas.

The arrangement studied is viable in terms of pattern control, frequency range, usable efficiency, and cost, however a slightly reduced spacing is required to meet the target crossover point.

Translation to the faster CPDS[17] acoustic model is required to enable a wider exploration of the usefulness of numerical optimisation in different venues and with coverage different coverage requirements.

8 ACKNOWLEDGEMENTS

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Figure 1 Hybrid system in New Zealand Parliament using three steered line-arrays

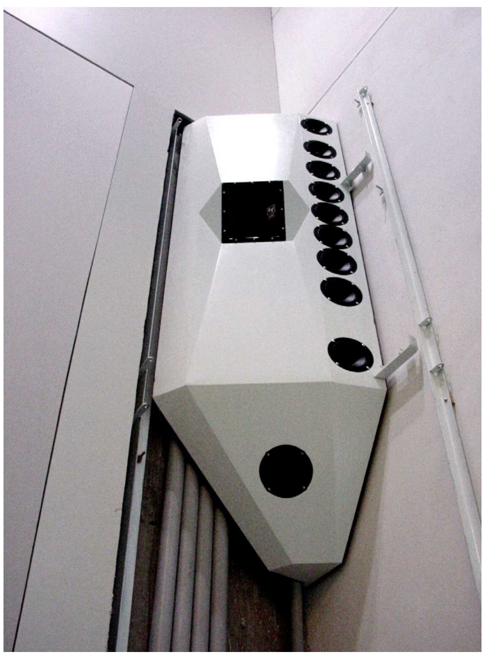

Figure 2 Hybrid array in gallery of Australian Parliament House (cover is removed)

Figure 3 Hybrid array in High Court Hamilton New Zealand. Note the use of Plexiglas baffles to control radiation behind the loudspeaker

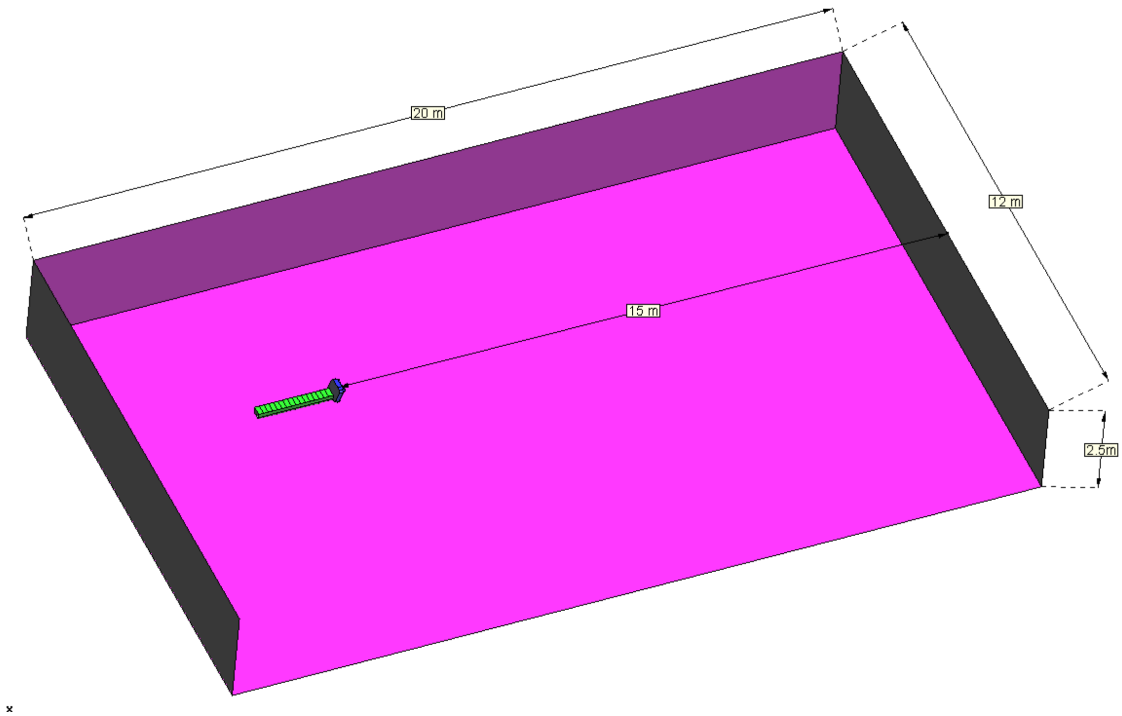

Figure 4 Geometric details of room used for analysis

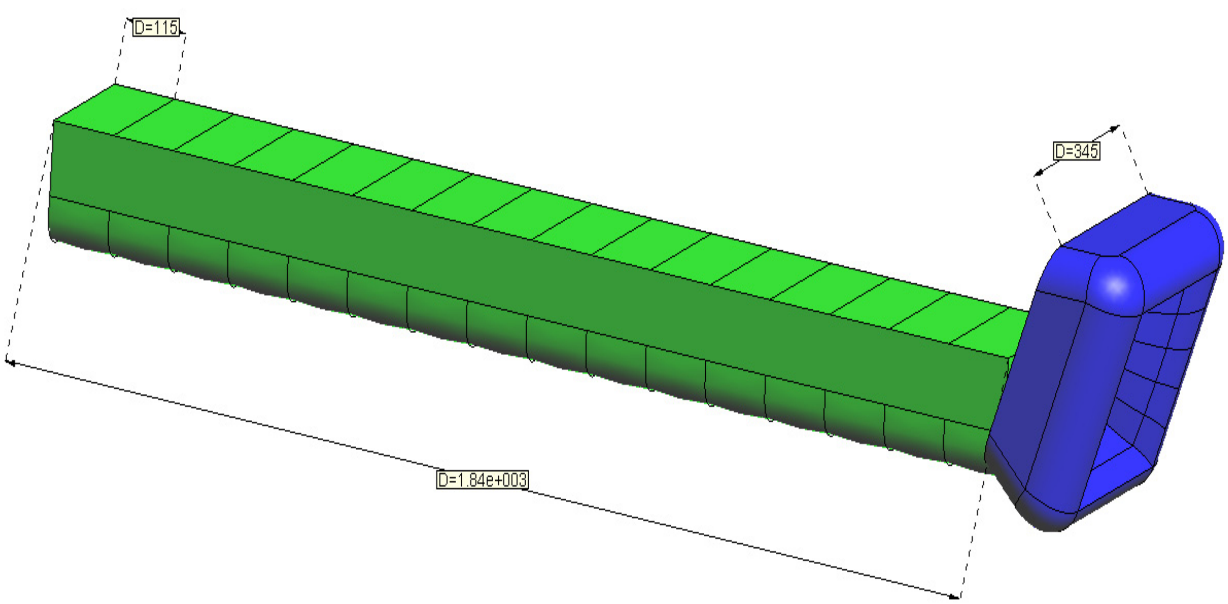

Figure 5 Hybrid end-fire array

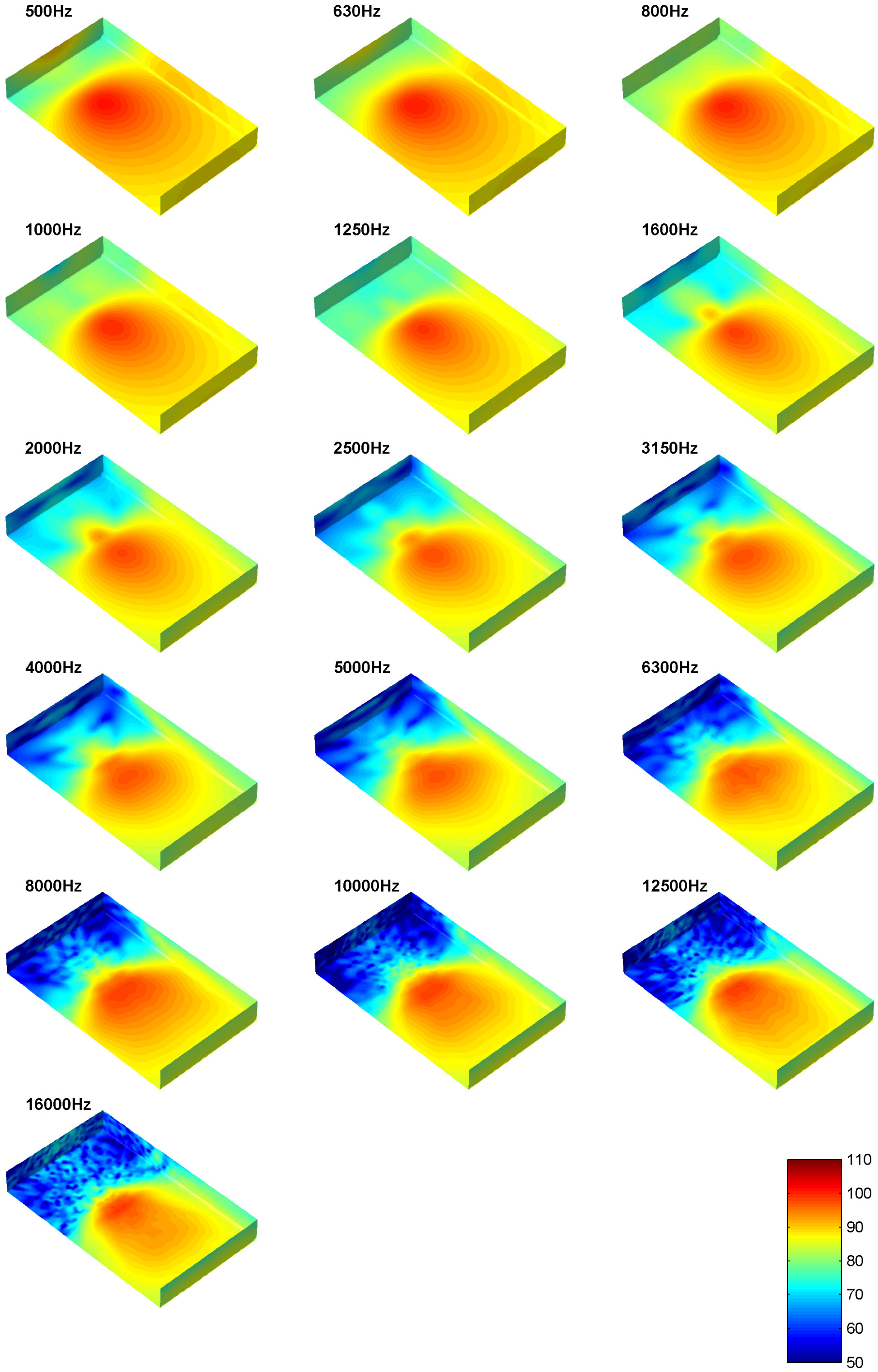

Figure 6 Predicted room coverage of HF component of hybrid system

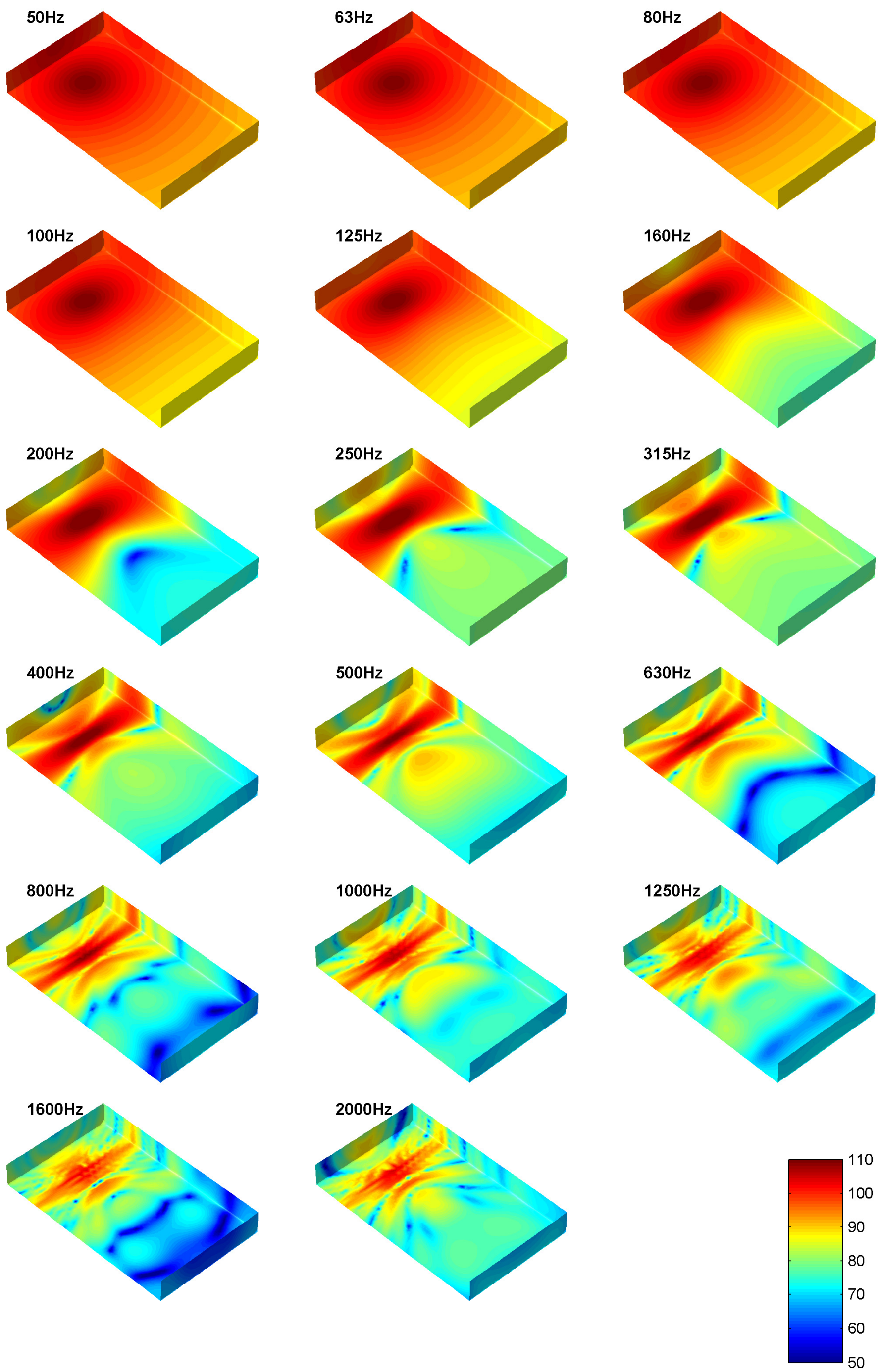

Fig 7 Output of the Hybrid LF array without signal processing

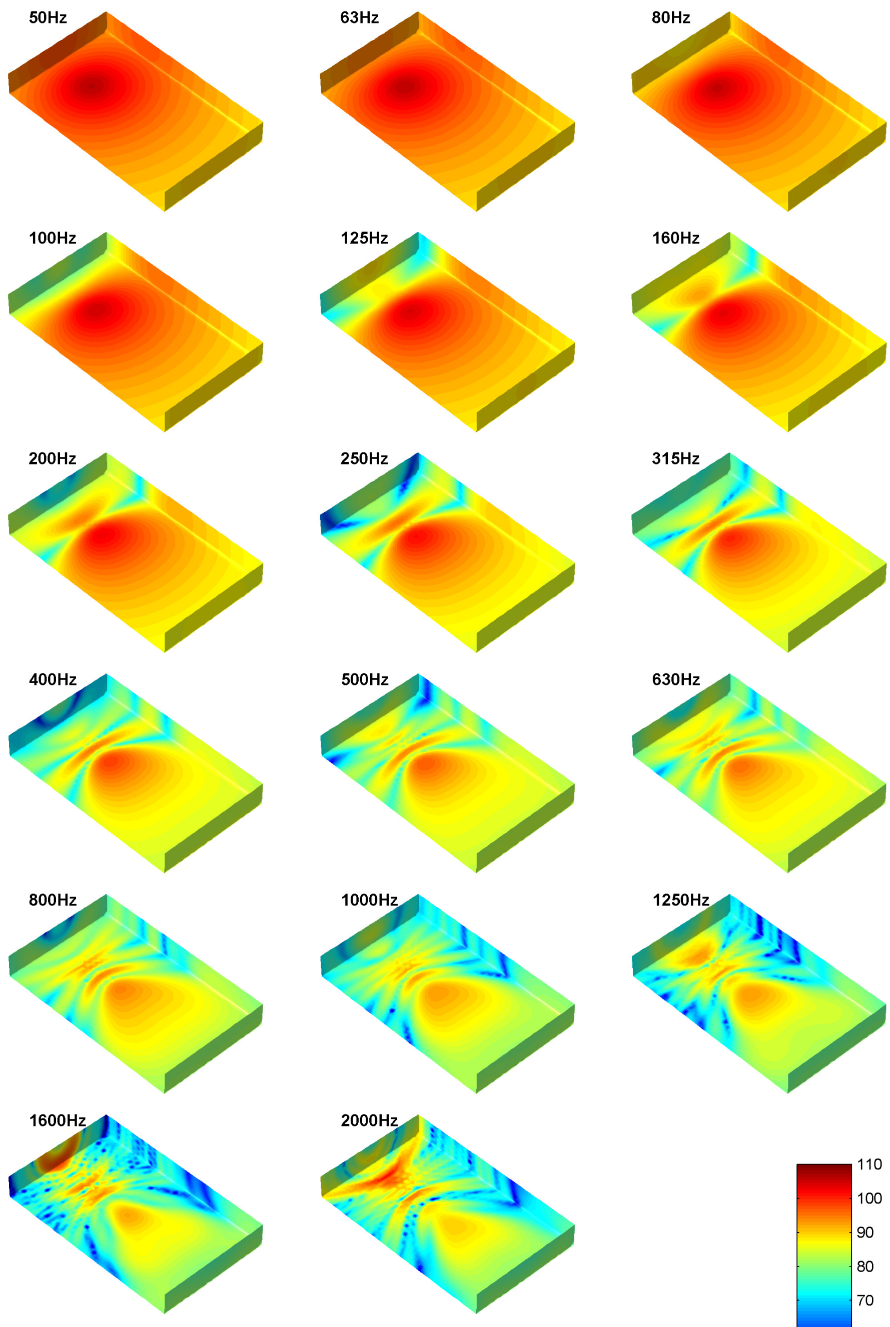

Fig 8 Output of the Hybrid LF array with simple beam-steering using delays.

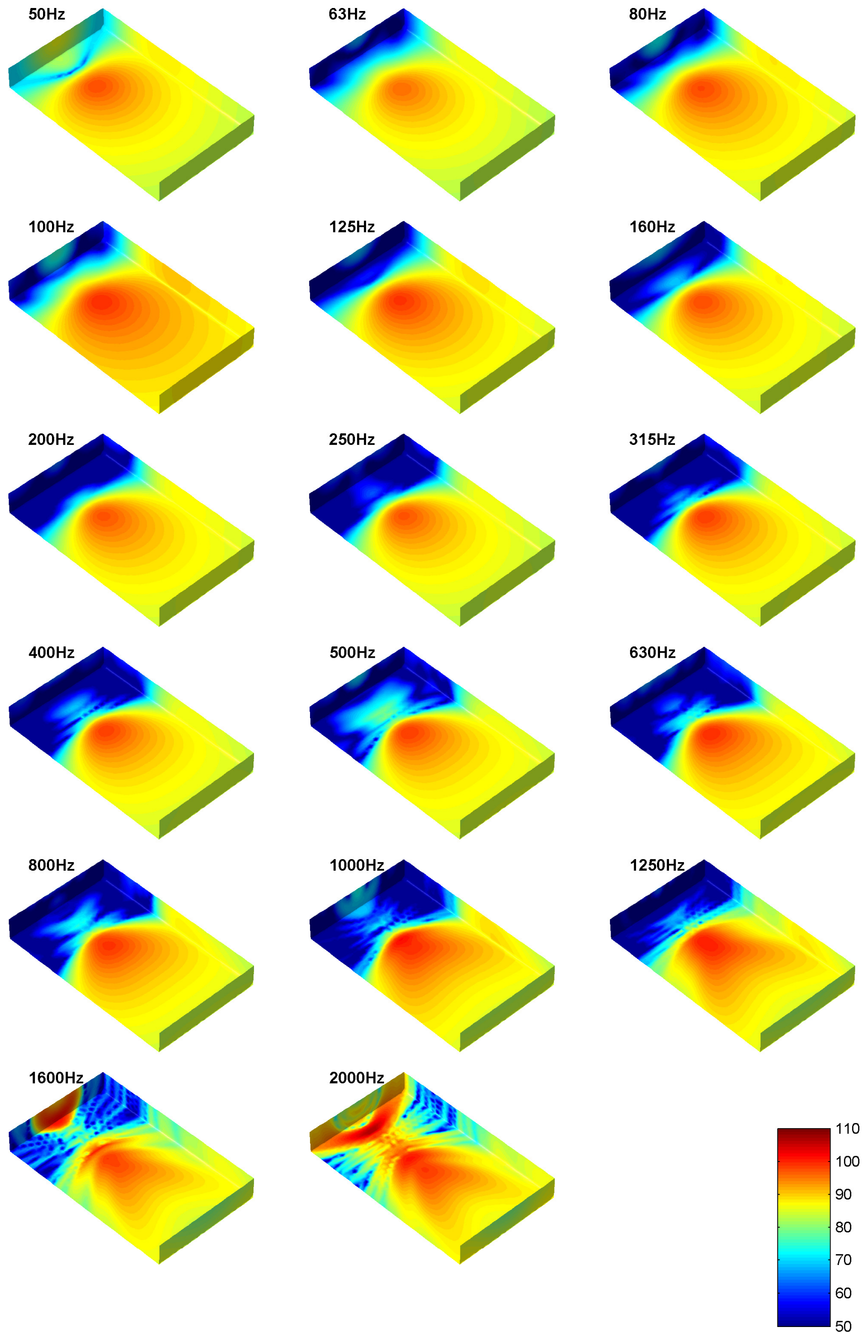

Fig 9 Optimised output of the low/mid array with objective component weights favouring reduction in irradiation of non-audience areas over matching the pattern to the HF horn

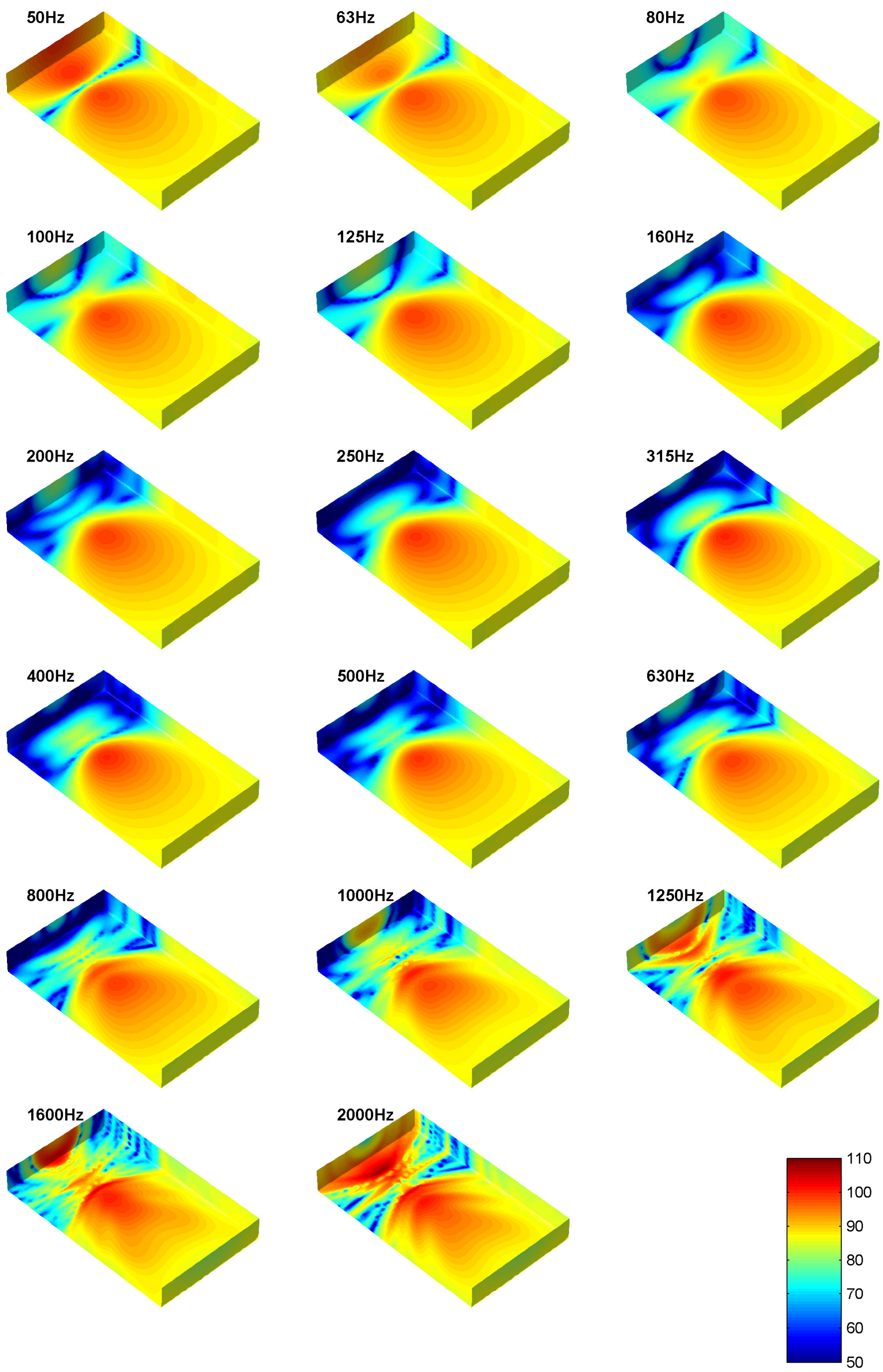

Fig 10 Optimised output of the low/mid array with objective component weights favouring pattern matching to the HF horn over irradiation of output non audience surfaces.

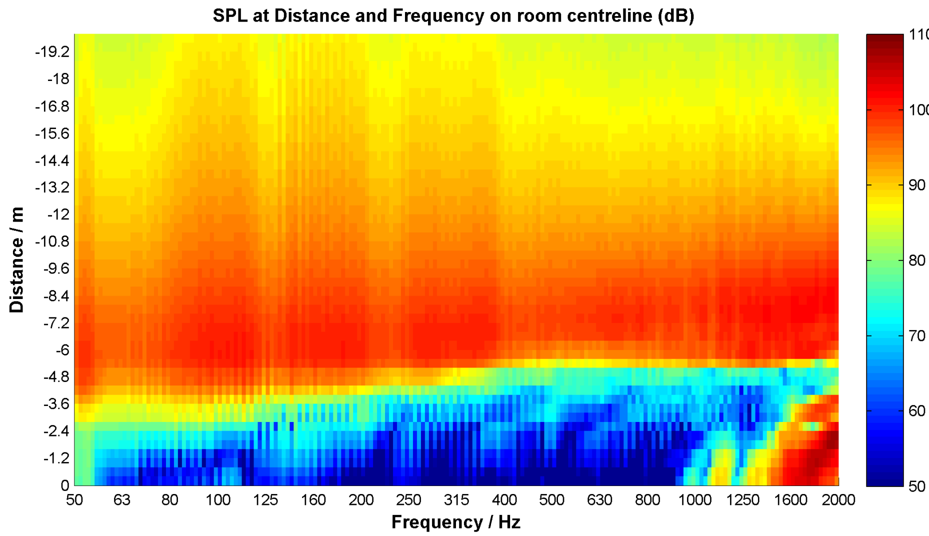

Fig 11 SPL vs distance of the low/mid array along centreline of room with objective component weights favouring reduction in irradiation of non-audience areas. NB increasing negative distance is away from the loudspeaker.

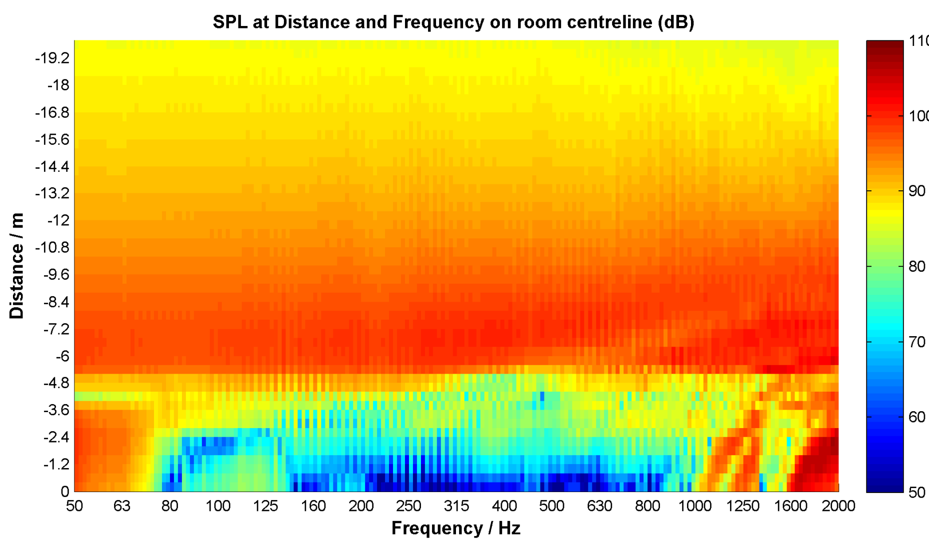

Fig 12 SPL vs distance of the low/mid array along centreline of room with objective component weights favouring pattern matching to the HF horn. NB increasing negative distance is away from the loudspeaker.

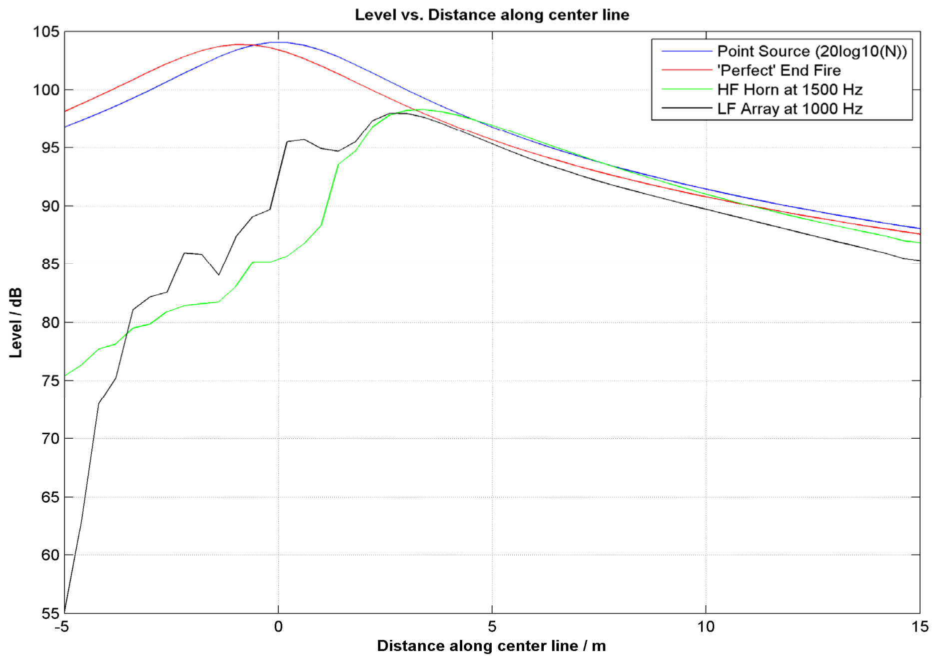

Fig 13. Predicted levels on centreline of room for point source and end-fire arrays compared with outputs of LF array and HF horn of solution favouring pattern matching over non-audience rejection.

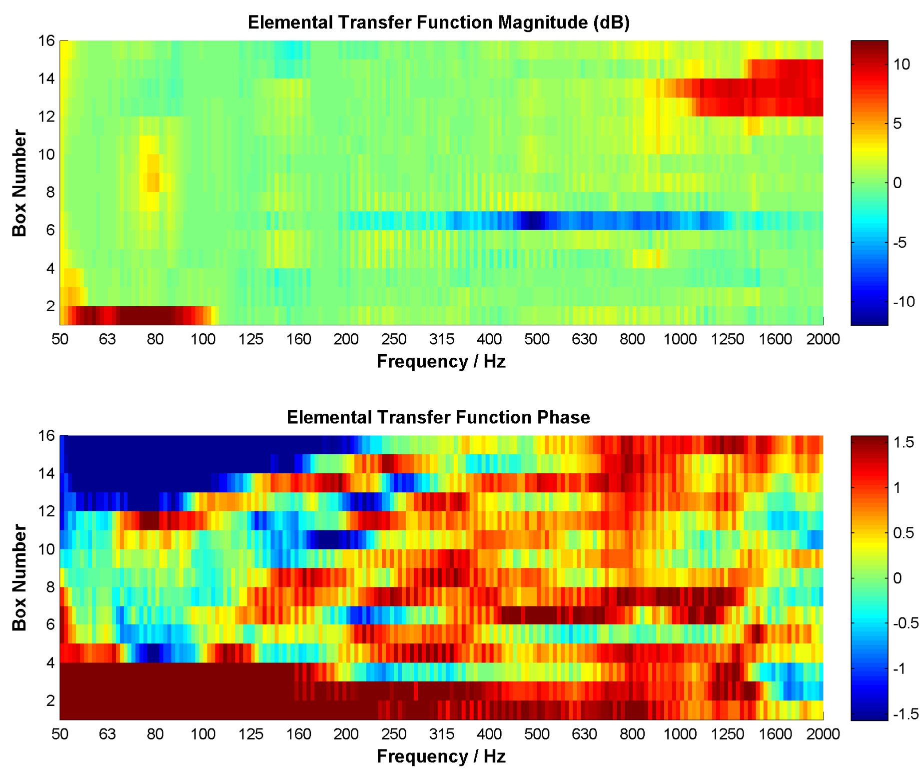

Fig 14 Magnitude and phase vs frequency plots of filters driving each array element for solution favouring pattern matching. NB Phase plot excludes the phase associated with the simple beam-steering delays.