Proceedings of the Institute of Acoustics

UNUSUAL BEAM-STEERED LOUDSPEAKERS OFFER HOLISTIC SOLUTIONS TO ACOUSTIC PROBLEMS IN COURTS AND PARLIAMENTS

Glenn Leembruggen Acoustics Directions Pty Ltd, Sydney, Australia
University of Sydney, Australia

1 INTRODUCTION

Sound reinforcement loudspeakers for courtrooms and parliamentary chambers are subject to challenging issues that apply to few other buildings. As daily working environments, these spaces have a need for high speech intelligibility and aural comfort. In particular, difficult engineering issues to solve are heritage appearance and integration, live room acoustics, diverse coverage areas, restricted loudspeaker locations and talkers with poor-articulation and soft voices, who stand a long way from microphones.

This paper discusses two unusual types of beam-steered loudspeakers that have been designed for a number of prominent courts in Australia/New Zealand and the New South Wales Legislative Assembly in Sydney. In these situations, the use of novel steered line-arrays, and cardio-Bessel arrays have allowed the loudspeakers to fulfil architectural requirements and achieve the required performance for acoustic gain, early-to-late ratio, frequency response source localisation and comfort.

Although the system for the NSW Legislative Assembly employed additional systems to cover the public and press galleries, these systems are not discussed.

2 STEERED ARRAYS FOR COURTS

2.1 Overview

Australian and New Zealand courts often have layouts that are similar to that shown in Figure 1. The judge(s) are located at the front of the room with counsel being located in middle area and the public at the rear. Court officers or associates often sit between the counsel and judges. The areas requiring sound reinforcement are therefore diverse and extensive, and a typical court can require up to 16 microphones without an operator.

In most courts in Australia (and probably the whole world), speech intelligibility and sound quality is quite poor. Court sound systems are usually plagued with the early onset of feedback and poor intelligibility. In most courts, the solution for a low feedback threshold is to simply turn down the level of the sound reinforcement system, but this further degrades intelligibility and aural comfort due to the ambient noise that is always present in courts.

Regrettably, there is a common belief among architects and acoustic consultants that sound reinforcement systems are not required in most courts as the un-amplified voice of participants is sufficiently loud. This is a gross simplification of the complexity of court operational situations. To date our team has not come across any courtroom in which sound reinforcement was not required. Fortunately, court managers and judges are often more aware of the problem. One internationally known judge of the High Court of Australia recently commented that audibility in courts is a major problem that really must be addressed.

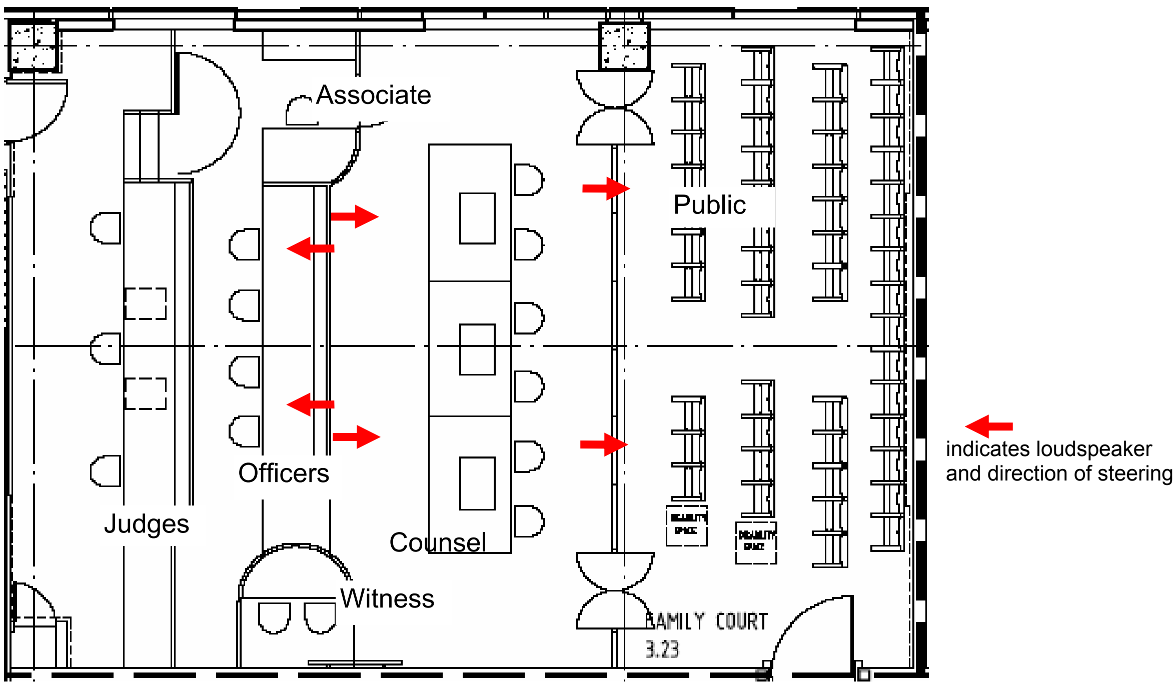

Figure 1 Typical Layout of courtroom and loudspeakers

2.2 Acoustic Gain

The maximum acoustic gain of a sound reinforcement system is the amount of stable amplification that it can provide for a talker who is at a specific distance from a microphone; viz the onset of feedback or ringing is not audible. While a statement of a system's acoustic gain is not readily useful in assessing the amount of amplification, a related parameter Equivalent Acoustic Distance (EAD) is immediately useful. As the provision of suitable acoustic gain seems to be taken for granted by many system designers and specifiers, its discussion is warranted.

A system's EAD is the apparent distance that a listener is from the talker with the sound system operating. The amplification moves the listener from his/her actual position to a distance from the talker equal to the EAD. The EAD is calculated for a specific distance between the talker's mouth and the microphone, and assumes that the system is operating at a gain that is 6 dB below constant regeneration. At this operating gain, the loop gain of the path from microphone to loudspeaker and thence via the air to the microphone is - 6dB.

The sound being fed back to the microphone from the loudspeaker naturally consists of direct sound, reflected sound, and reverberant sound. In most applications, the loudspeakers are relatively close to the microphones and the direct field usually dominates the reflected and reverberant fields. Prediction of the EAD for the direct field only is therefore warranted and is calculated [2] for one open microphone and a 6 dB stability margin as:

$EAD=2D_s.D_{list}/D_{lsp}.\Phi_{mic}.\Phi_{lsp}$ where (1)

D_s is the distance from talker to the microphone

D_{list} is the distance from loudspeaker to the listener

D_{lsp} is the distance from loudspeaker to the microphone

Φ_{mic} is the reduction of the level of sound from the loudspeaker received by the microphone due to the microphone's directional properties

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The listener is assumed to be located on the loudspeakers axis of maximum radiation.

2.3 Performance requirements

Some of the conditions present in courtrooms that impose difficulties on sound reinforcement systems are:

- judges, counsel and witnesses who articulate poorly, or have accents
- judges and witness often speak very softly
- distances between mouth and microphone ranging from 20 mm to 1 m.
- counsel often speak with their head facing down while searching through papers
- noise from HVAC systems is often excessively high; e.g. 40 dB(A)
- high level of noise from activity in the room; e.g. paper shuffling, people entering, leaving and moving through the room, whispering in the public gallery
- poor or inappropriate acoustic environment; e.g. flutter, strong specular reflections and high RTs
- requirement for video-conference links with low bandwidth and poor signal to noise ratios
- architects require loudspeakers to be invisible or mounted close to the ceiling

To achieve satisfactory speech intelligibility and provide aural comfort to the participants under the range of conditions listed above, sound systems must deliver the following performance to all listeners.

- a flat frequency response
- good Early to Late Ratio (ELR) with Speech Transmission Index (STI) of at least 0.6
- subjective localisation to the speech source
- EAD of 1.5 m or less to reproduce soft speech above the ambient noise with the talker standing 0.7 m from the microphone
- the talker should have good foldback to prevent subjective disconnection between his/her internally-heard speech and the late-arriving components of that speech
- aside from foldback, reinforcement is required within a listener group, for example from judge to another judge and from counsel to another counsel.
- no increase in the level of background noise in the room

While frequency response is often viewed as a "motherhood" parameter and is therefore disregarded in importance, its role is vital to subjective intelligibility. At Reproduced Sound 19, Leembruggen and Stacey showed [1] that poor frequency response can greatly degrade subjective intelligibility, regardless of the STI performance. In addition to providing subjective pleasantness of speech, a flat frequency response provides a greater level of subjective intelligibility when the dynamically changing frequency content of speech is delivered in the presence of late-arriving sound and interfering noise with their individual frequency spectra.

2.4 Loudspeaker Solution

The author's novel solution addresses the performance and architectural requirements by using a combination of the loudspeaker performance and the loudspeakers' locations to provide three principal benefits that other systems cannot simultaneously provide:

i. The majority of direct sound arrives at a microphone from its rear, where a hypercardioid microphone has a directional loss exceeding 10 dB. Utilisation of the microphone's loss in this way allows significantly lower (or better) EADs than other types of systems.

ii. The sound arrives at the listener from a frontal direction, enhancing source localisation and comfort.

iii. The loudspeakers are located in the ceiling, minimising visual intrusion into the room.

The solution employs a number of two-way loudspeaker systems mounted in the ceiling. Each system comprises of a beam-steered line-array and a small high-frequency horn and driver. Frequencies up to 2 kHz are handled by the line-array and are steered at angles ranging from 10° to 50° off vertical to cover the target area. Separate loudspeaker chains are used for the judges, counsel and public areas, and the relative levels of the judge and counsel microphones are tailored to each listener area.

Steering of arrays of readily-available high-frequency drivers such as dome tweeters to these angles is extremely difficult due to spatial aliasing caused by the inter-driver spacing. (The smallest inter-driver distance that is readily achievable is 44 mm, and this is too large for steering). A small compression driver and small-format horn is therefore used and this horn is physically tilted at the required angle.

The location of the loudspeakers is setup according to the following criteria:

a) the sound comes to the listener appreciably from the frontal direction
b) the loss due to directional response of the microphone is maximised
c) the consistency of coverage and frequency response over the target area is satisfactory

Figure 1 shows typical locations of the array loudspeakers and their direction of aiming. It is vital that this system has constant directionality with frequency, and therefore the radiation pattern of the steered array must match that of the tilted horn. Figure 2 shows the predicted polar pattern for the array and the measured polar pattern of the horn at 3.15 kHz. Forward-control of the radiation is lost at and above 2 kHz and this directly results from the inter-driver spacing of 85 mm.

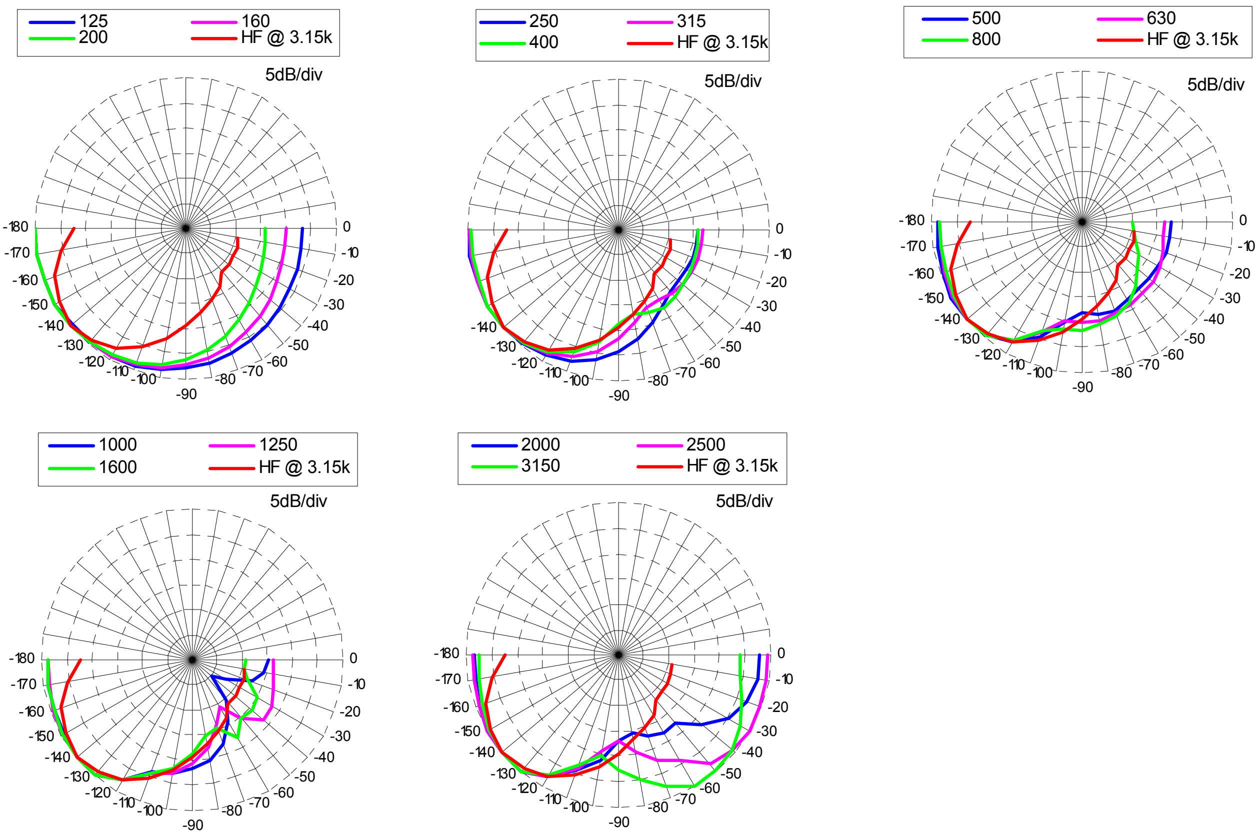


Figure 2 Predicted polar patterns of steered line array at 1/3 octave frequency intervals and associated high frequency horn at 3.15 kHz.

In addition to the principal benefits noted above, this system topology provides the following additional performance benefits:

- The combination of the ceiling mounting and forward beam due to the steering allows a Directivity Index (DI) of approximately 9 at 500Hz to result. This degree of directivity significantly enhances the ELR at mid-range frequencies. Higher DIs are readily achievable with these types of arrays, but are not wanted here as the coverage and frequency response over the listening area would not be consistent.
- As the skirts of the radiation pattern of the counsel loudspeakers extend to the public gallery area, synchronisation between the public and counsel loudspeakers using delay provides a subjective image from the front of the court to the public-gallery listeners.
- Loudspeakers can be located further from listeners, allowing a greater coverage area for a given number of loudspeakers.

The steered-array solution has been implemented in a number of prominent courts, each of them to critical acclaim. Examples are the High Court of Australia in Sydney, the NZ Supreme Court in Wellington, the Northern Territory Supreme Court in Darwin, and the Federal Court in Perth.

Table 1 provides a pertinent comparison of the performance of the steered-array solution with that of a conventional mix-minus system using ceiling loudspeakers, which is often used in courts.

In a mix-minus system, specific ceiling loudspeakers are de-activated whenever microphones near those speakers are active. This de-activation is done automatically under control of the automatic mixer, and is intended to maintain the margin-before-feedback of the system. With loudspeaker de-activation, mix-minus systems produce higher acoustic gain than systems without de-activation.

Attribute	**Steered Array System**	**Mix-Minus Ceiling Speaker System**
Equivalent Acoustic Distance	Excellent. EAD of 1.5 m is achievable with almost no equalisation. NOM (number of open microphones) reduction in gain is not required; allowing a talker to remain at constant level when other mics are activated by local transient noise (eg books).	To achieve the required EAD, all loudspeakers surrounding the microphone must be attenuated, precluding reinforcement within a zone and talker foldback. These systems usually require NOM reduction in gain to remain stable.
Source localisation	Good	Impossible
Consistency of coverage	High frequency horn is more consistent in polar response than almost all ceiling loudspeakers.	Greater number of loudspeakers is required for coverage as the coverage from overhead is provided with a given beamwidth.
Reverberant component of ELR	Reverberant component of the ELR is lower at low/mid frequencies as DIs of arrays are significantly higher than ceiling speakers. Off axis response at high frequencies is better controlled than DML drivers.	Higher reverberant level than the steered arrays as the loudspeaker DIs are lower.
Late-arriving direct sound component of ELR	Low rear radiation from arrays reduces backward spill and increases ELR. e.g. spill from arrays covering the Public area to the Judge area is inaudible.	Spill at mid-range frequencies from rear speakers to the front area is quite audible.

Table 1 Comparison of attributes of steered array and mix-minus ceiling speaker systems

As the arrays steer sound towards the judge and public listening areas which are mostly adjacent to walls, there is potential for reflections from those walls to degrade the ELRs in the courtroom. If the walls are reflective, careful aiming of the array and the high frequency horn is required to direct most of the reflections into the carpeted floor.

2.5 Implementation

Historically, courts have not invested significant sums of money into audio equipment and therefore to be acceptable, the steered-array solution must be relatively inexpensive. As a commercial implementation of the array does not currently exist, it has been assembled from components. As eight-channel amplifiers are commercially available, a maximum of 8 drivers was chosen for the system. Seven channels are used for the low/mid frequency array, and one for the high frequency driver. The array itself is a modified version of an Acoustic Technologies ALA07 line-array with dedicated inter-driver separations. The length of the line-array is 900 mm.

Figure 3 shows a diagram of the preferred implementation of the steered-array system, with the array flush mounted into the ceiling. The small disadvantage of this mounting scheme is that the high frequency horn protrudes below the ceiling for a distance of 100 mm. In situations where architects have been intransigent about the small protrusion of the horn, the array and horn have been mounted in the ceiling void behind mesh grilles. The flush mounting arrangement provides two important benefits; damage to the frequency response from image sources is prevented, and the low frequency response is flat to 100 Hz. In some situations, the arrays have been required to be mounted below the ceiling, and the nulls in the responses from the image source have been quite audible.

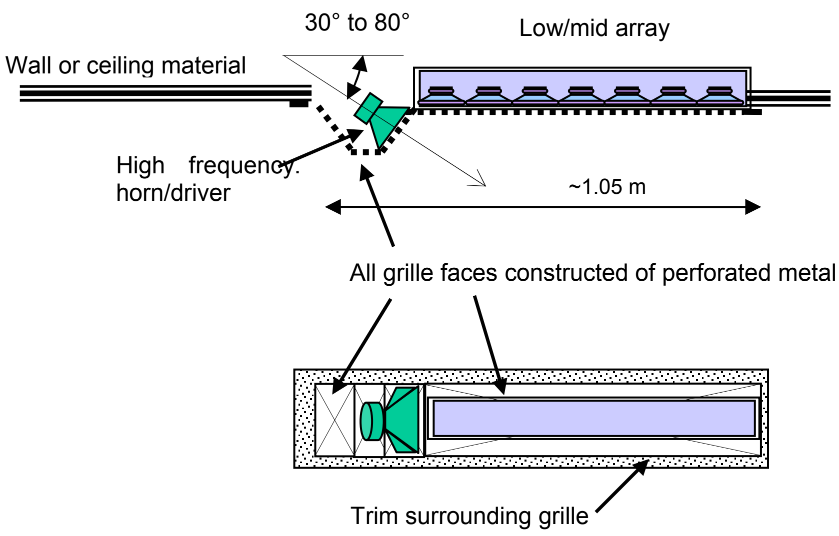


Figure 3 Preferred half-space implementation of array and horn

The steering and radiation pattern are achieved through the physical spacing of the driver units, signal delays, tapering filters, and the group delay of the tapering filters. The signal processing is implemented in a dedicated Biamp Nexia eight-channel processor.

2.5.1 Interaction of Adjacent Arrays

In most court rooms, locating the loudspeakers for the judge and counsel according to the three criteria listed in Section 2.4 requires the judge and counsel arrays to be within 1 m of each other. With this relatively small separation, phase interference between the two arrays damages the polar and frequency responses of both arrays, primarily at frequencies below 1 kHz. When the path length differences to the listener or microphone are small, the damage can be severe as the first null may occur as low or above 400 Hz.

To minimise this damage, a delay of approximately 8 ms is applied to one array. This delay provides some pseudo decorrelation by forcing the spacing of the interference nulls to be narrower than 125 Hz. This pseudo decorrelation effectively smears the damage over a given frequency band and reduces the energy removed by the cancellation. This delay also provides useful synchronisation between the amplified and unamplified voice. Greater delays would provide even greater mitigation of the frequency response damage, but the loss of time-synchronisation between the amplified and unamplified voice becomes audible.

In courts with witness and jury boxes, three arrays are used to cover the forward, back and side directions. In these situations, a delay of 16 ms is applied on the side-aiming speaker would be required to mitigate phase interference effects. However, when this delay of 16 ms is combined with the latency of DSP devices and echo-cancelling algorithms, excessive subjective disconnection between the various sound components occurs.

The solution is to use cascaded 2nd order all-pass filters of suitable Q and centre frequency to provide more delay at low frequencies than at high frequencies. The greater delay at low frequencies is needed to minimise the spacing of the interference nulls where the speaker radiation pattern's overlap. At high frequencies where the ear is much more sensitive to source synchronisation, the path length differences are sufficient to prevent the audibility of the phase interference and the lower delay of the filters prevents this subjective disconnection.

3 CARDIO-BESSEL ARRAYS

3.1 Overview

Parliamentary buildings such as the NSW (State) Legislative Assembly in Sydney often have specific requirements for loudspeakers such as:

- heritage listed building, imposing restrictions on
  - size, shape and form of loudspeakers
  - location and physical attachment methods
- difficult acoustic properties such as long reverberation time and flat hard surfaces
- dynamic range of the speech at lecterns ranging from shouting to soft
- microphones must be effectively open, as there is no operator
- a large amount of noise from Members during sessions such as Question Time.

In the Legislative Assembly situation, loudspeakers could not be mounted on the walls for both heritage and acoustic reasons. In this location they would aim directly towards open microphones, preventing the achievement of suitable EAD, and would excite flutter echoes and modes between the side walls of the chamber. The solution, of course, was to use loudspeakers suspended above the microphones, which forced the majority of reflections into the floor and allowed the microphone polar pattern to provide useful rejection of the loudspeaker sound.

To achieve a satisfactory ELR in the chamber with its live acoustic behaviour and the size of coverage area, listeners needed to be located no further than 4 m from the loudspeakers. This meant that the loudspeakers would be located 3.5 m from the ceiling, and as the ceiling was acoustically reflective, rear radiation from the loudspeakers needed to be minimised if reflections from the ceiling were not to degrade the ELR.

To minimise the rear radiation at all frequencies without a huge baffle or horn requires beam steering over a large frequency range. An alternative is a cardioid-like pattern which would provide consistent coverage over the floor of the Chamber, whilst minimising sound radiated towards the ceiling and the side walls. Figure 4 shows a cardioid pattern superimposed over a view of the chamber. The origin of the polar plot represents the loudspeaker at a height of 5 m above the floor. The cardioid pattern would be produced by a spaced driver-pair with suitable spacing, delay and filtering parameters.

A system of drivers was therefore required for the cardioid system that would deliver a flat frequency response over the 120° wide coverage area up to 2 kHz, from where suitable high frequency devices usually operate. The response needed to also be free of significant phase interference effects, as nulls in the response damage over an octave-wide bandwidth significantly degrade the ELR. These requirements presented a strong challenge, as readily-available loudspeaker drivers or array systems could not produce this performance.

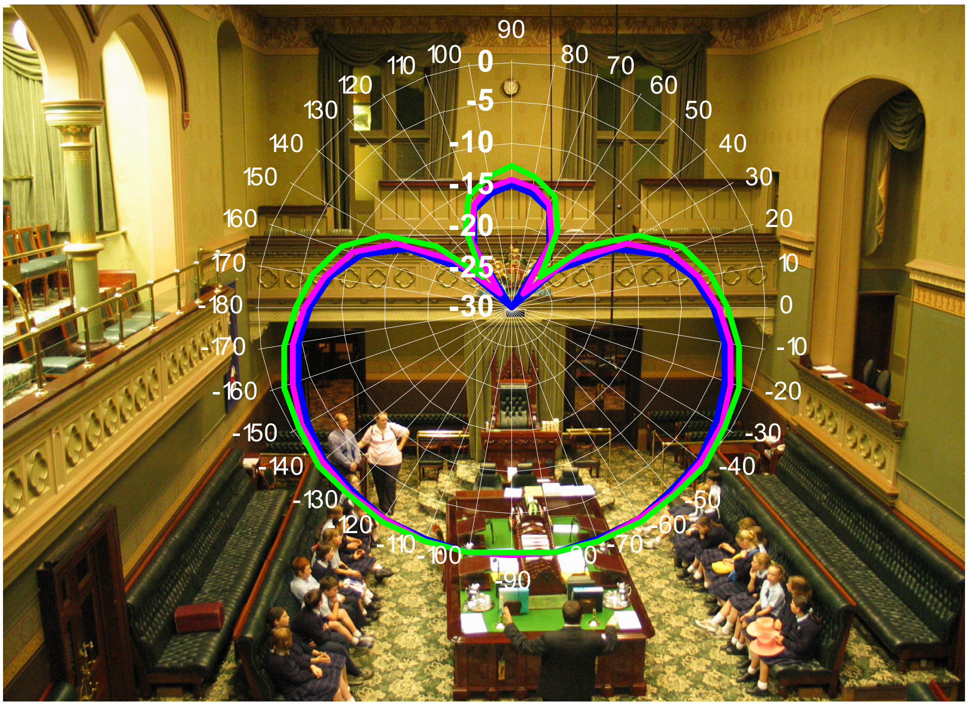


Figure 4 Cross section of chamber and overlay of cardioid pattern

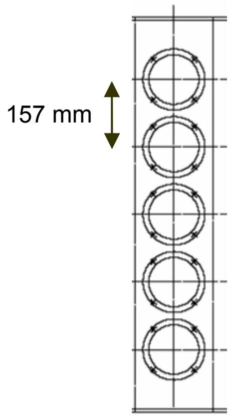
The frequency response requirements suggested the use of a single driver of 200 mm diameter or greater, with a high sensitivity/power rating to provide the required sound pressure level (SPL). But as the response of these drivers at 2 kHz at 60° off-axis is usually between 3 and -6 dB relative to on-axis, they are unsuitable for this application.

Although smaller drivers with diameters of 150 mm or less have the necessary radiation pattern at 2 kHz, a single driver of this size is unable to provide the required SPL requirements under shouting conditions with long term reliability. Arrays of multiple small drivers would meet the sound pressure requirements, but would cause gross irregularities in the coverage above 700 Hz due to spatial aliasing caused by the inter-driver spacing. Although heavy frequency-tapering of such arrays drivers would mitigate the coverage and response irregularities, this would leave only a single driver to reproduce frequencies above 600 Hz, with ramifications of thermal stress from high power levels.

The solution was to use a five-element Bessel array using 150 mm drivers operating up to 2 kHz, with the array parameters shown in Figure 5. Keele [3] gives a comprehensive discussion of Bessel arrays and shows that when the inter-driver separations are greater than 0.25 wavelengths, the ripples in the far-field polar response of the Bessel array are much less than those of simple driver arrays.

The maximum output of this class of Bessel array is equivalent to two drivers. Figure 6 shows the theoretical polar response of the Bessel array in Figure 5 at a distance of 5 m. Although the centre-to-centre driver separation is approximately 1 wavelength at 2 kHz, there are only minor phase interference effects in this frequency range. It is also noteworthy that the polar ripples of the Bessel array decrease as the distance from the array increases.

Figure 7 shows the theoretical frequency response of the Bessel array at various off-axis angles on the long axis at a distance of 5 m from the array centre.



Level	Phase
- 6 dB	0°
0 dB	0°
0 dB	0°
- 6 dB	180°
0 dB	0°

Figure 5 Parameters for five-element Bessel array

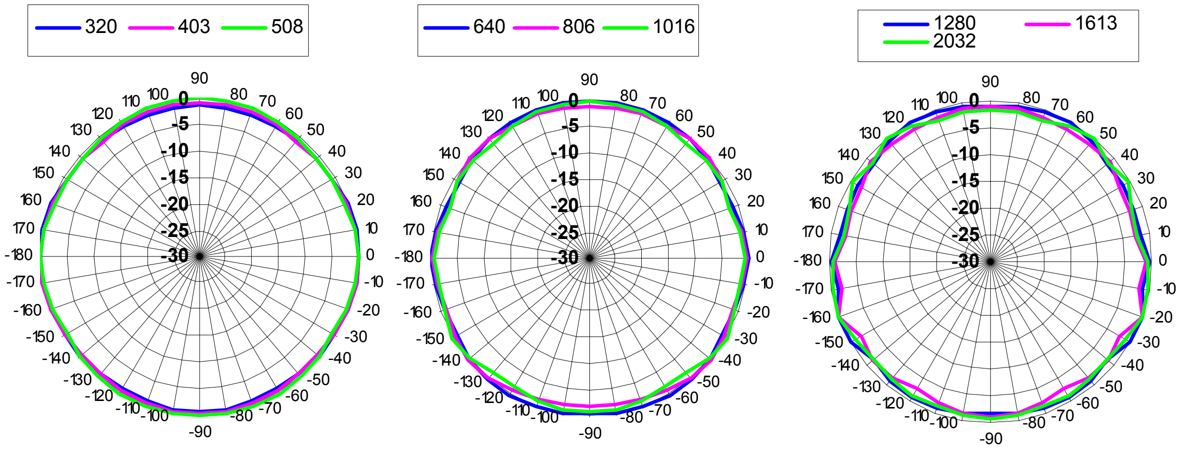


Figure 6 Predicted radiation pattern of five-element Bessel array with inter-driver separation of 157 mm and omni-directional drivers

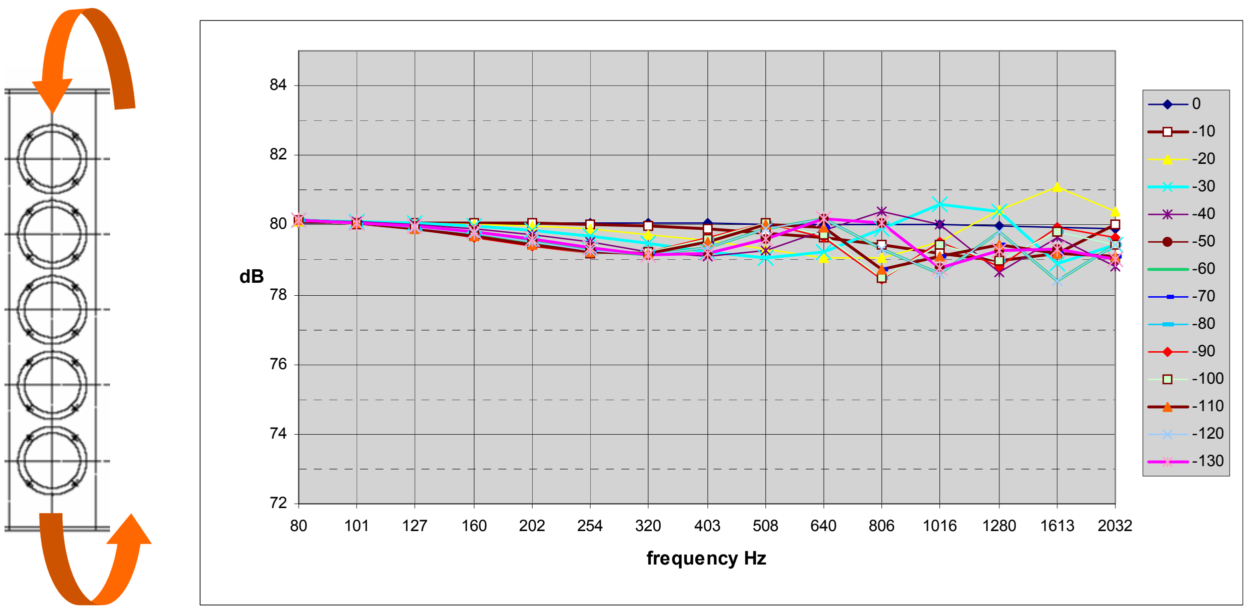


Figure 7 Predicted off-axis frequency responses of five-element Bessel array

For comparison to the five-element Bessel array, Figure 8 shows the theoretical polar pattern of two drivers with same inter-element spacing of 157 mm, while Figure 9 shows the theoretical polar pattern of five drivers with 157 mm centre-to-centre spacing with identical polarity and level. The benefits of polar consistency of the Bessel array are obvious.

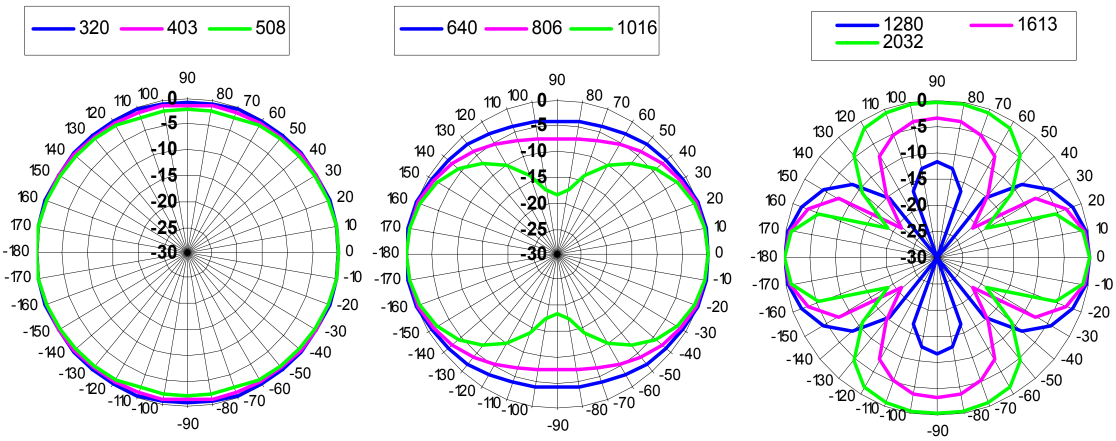


Figure 8 Predicted radiation pattern of two-element array with inter-driver separation of 157 mm

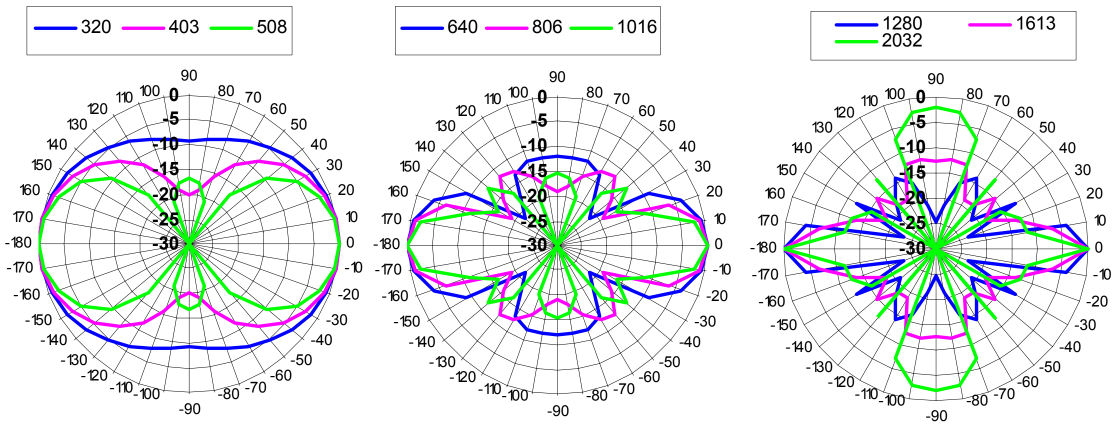


Figure 9 Predicted radiation pattern of five-element line array with inter-driver separation of 157 mm

3.2 Implementation of the Cardio-Bessel Array

Frequencies above 2 kHz would be reproduced by a three-element line array of 26 mm dome tweeters, with an inter driver separation of 40 mm. This array is not discussed here.

A common enclosure can be used for the Bessel array drivers as long as the enclosure is acoustically compliant and the drivers are driven with a low source impedance (less than 0.25 ohms). This common enclosure simplifies design and construction. Although the Bessel array has an unwieldy phase polar pattern, this deficiency is overcome (in preparation for beam-steering) by using identical upper and lower arrays, thereby ensuring equal phase at any point from upper and lower arrays (other than delay due to air-path).

3.2.1 Simple Cardioid System

A classical cardioid radiation pattern can be produced by a spaced-driver pair, with a polarity inversion and a delay applied to the rear driver. Equalisation at a rate of 6dB/octave with decreasing frequency is required to flatten the frequency response. As long as the drivers have sufficient excursion and amplifier and thermal capacity, this system works well up to the frequency at which the inter-driver spacing is approximately 40% of a wavelength. At frequencies with greater acoustic spacing, more energy is steered to the side of the array than in the forward direction. Applying a low-pass filter to the rear driver helps to reduce the sideways spread of energy.

Figure 10 shows the predicted polar pattern of cardioid loudspeaker with inter-driver separation of 190 mm, and a delay of 150 μsecs and 1 kHz 2nd order Butterworth low-pass filter applied to the rear driver. The drivers are assumed to have omni-directional radiation patterns. The polar pattern is usable up to 800 Hz. Once the inter-driver spacing exceeds 40% of a wavelength, the radiation pattern of the drivers when mounted in their enclosures becomes one of the key factors that determine the radiation pattern of the total system.

The major difficulty from a design perspective is the prediction of the frequency response and level of the rear driver in the forward area of the array and vice-versa, as these responses result from the diffraction of sound around the enclosure.

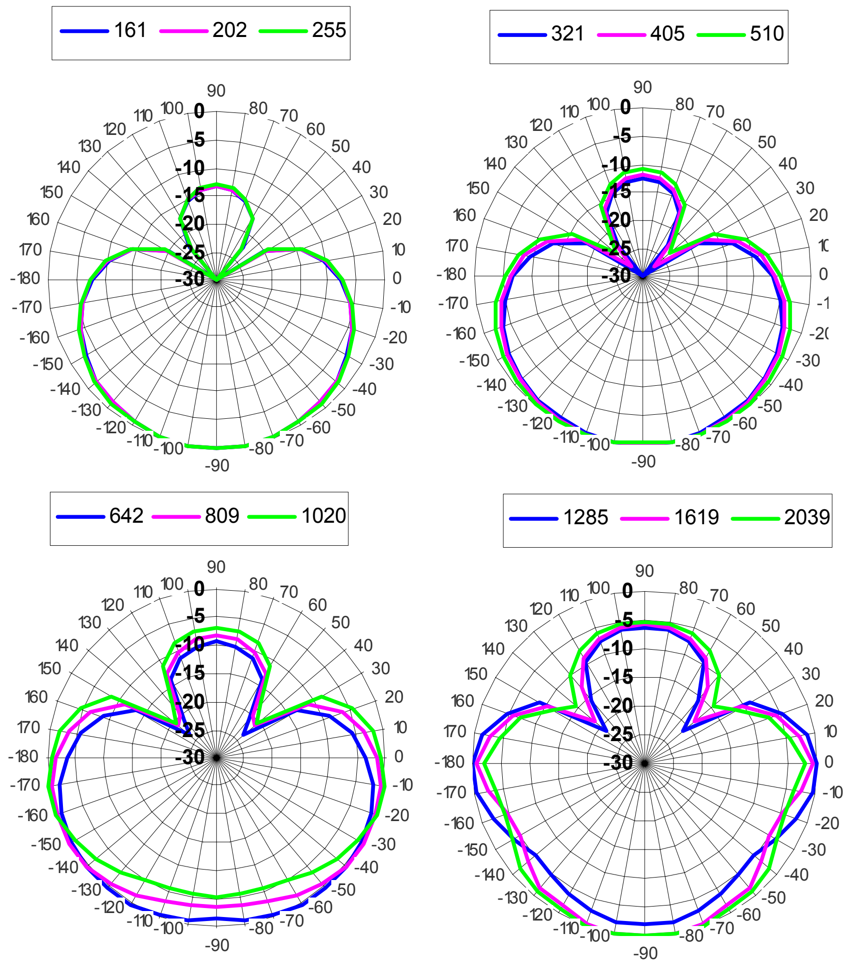


Figure 10 Predicted polar pattern of cardioid loudspeaker with inter-driver spacing of 190 mm and delay of 150 μsecs and 1 kHz 2nd order Butterworth low pass filter applied to the rear driver.

3.2.2 Cardio-Bessel Array

The upper and lower drivers of the simple cardioid system were each replaced by five-element Bessel arrays. As expected, the radiation pattern predicted by our simple cardioid model was unchanged by the substitution of the Bessel array for the omni-directional drivers.

Figure 11 shows sectional, isometric and plan views of the Cardio-Bessel array. Three such arrays were used to cover the Assembly floor, the area occupied by the Members. The brass support structure was designed by the NSW Government Heritage Architects and was used to suspend each array from the ceiling.

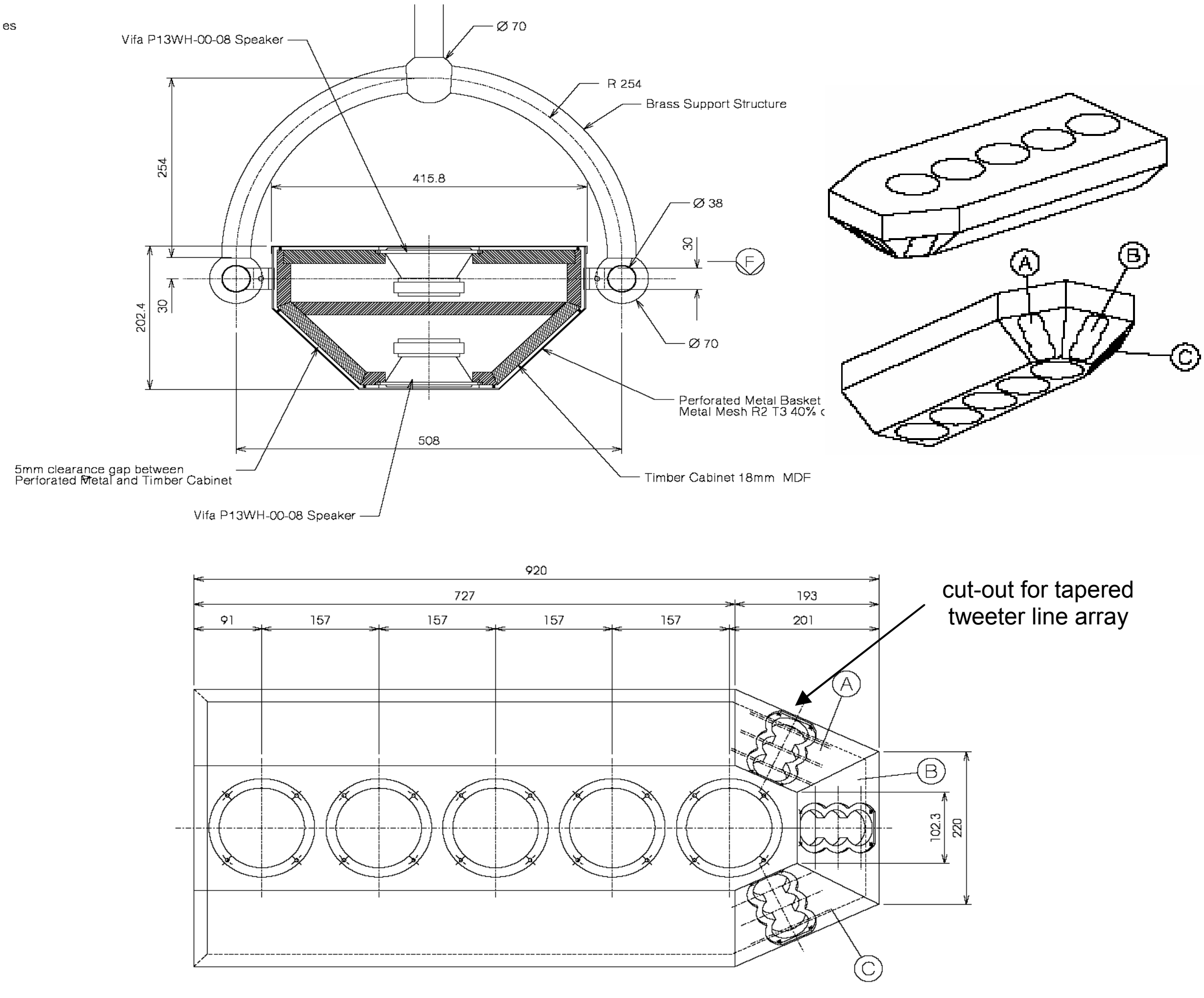


Figure 11 Section, plan and isometric views of Cardio-Bessel array.

For reasons of timing, it was not possible to construct a prototype and the acoustic design proceeded on the basis of our simple model.

3.2.3 Further Development on Site

After the three systems were manufactured and installed, the impulse responses of the upper and lower arrays for all three systems were measured. From the differences in the unwrapped phase of the lower and upper arrays, the effective acoustic inter-array separation was computed at each frequency. Figure 12 shows the measured acoustic separation of the arrays at a point 2.5 m below the enclosure on axis of the innermost driver. The mechanism(s) causing the inter-array separation to vary with frequency below 900 Hz is not understood.

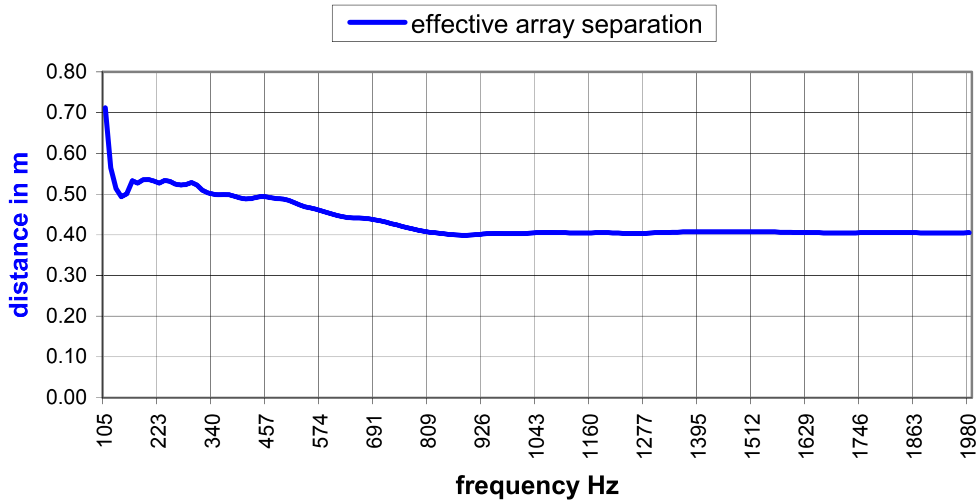


Figure 12 Difference in the equivalent path length difference of the upper and lower Bessel arrays

These array separations were considerably greater than the 0. 20 m enclosure depth and were larger than expected from our previous experience with cardioid systems. Unfortunately, the separations were also too large to produce a classical cardioid/hypercardioid radiation pattern above 300 Hz.

A different approach was therefore used on site to reduce the level of sound radiated towards the reflective ceiling. The complex frequency responses of the upper and lower Bessel arrays were measured with a WinMLS analyser at a number of locations around the enclosure and exported to Acoustic Directions' in-house array prediction software VLADA. Various types of signal processing were applied on a trial and error basis to the upper and lower arrays until a satisfactory reduction of upward-radiated sound and minimal degradation of downward sound was achieved. Figure 13 shows the predicted combined responses achieved with the signal processing of Figure 14.

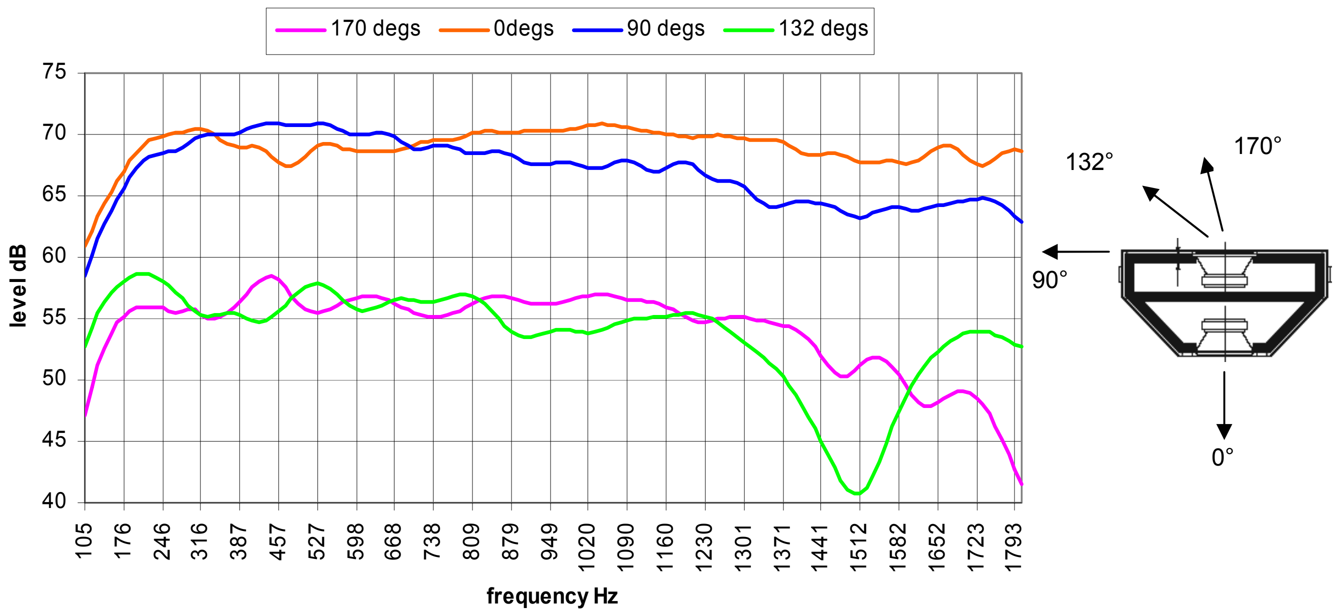


Figure 13 Predicted frequency responses at different angles around the Cardio-Bessel system

The relative difference between the downward (0°) and upward-radiated sound (170° and 132°) is approximately 14dB, which is quite satisfactory. The response at 90° does not exhibit the attenuation of 5 to 6 dB of a true cardioid system. This is a disappointing outcome, as it exacerbated reflections from the side walls and increased the level in one of the public galleries. The local system in that gallery therefore needed to be increased in level to match this additional sideways spill from the Cardio-Bessel system.

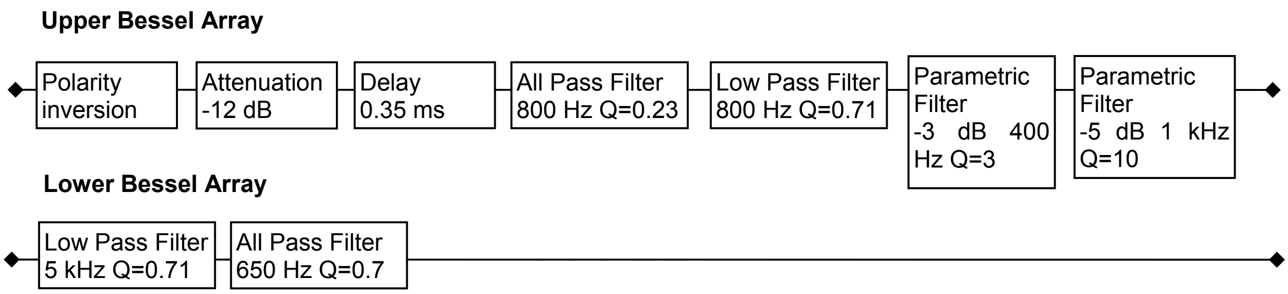


Figure 14 Signal processing used to reduce rear radiation from Cardio-Bessel system

The signal processing for the tweeter arrays was also setup to produce suitable on and off-axis frequency responses using the method of measuring the responses on situ, exporting the data and processing with VLADA software.

3.3 Performance

The signal processing of Figure 14 was implemented and the complete system was re-measured at the same angles. The measured responses were within 1.5 dB of those shown in Figure 13.
With the tweeter arrays and crossovers set up, the sound over the Assembly floor with speech and music replayed from compact disc was remarkably dry and smooth.

Table 2 shows the measured MTIs and STIs at four locations on the Assembly floor. The relatively high MTIs at frequencies below 1 kHz indicate that the subjective sound with speech (where the speech spectrum peaks in the 250Hz and 500 Hz octave bands) will be very comfortable and dry.

	MTIs							
Location	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**STI**
1	0.72	0.74	0.73	0.72	0.72	0.7	0.82	0.74
2	0.73	0.68	0.67	0.69	0.65	0.72	0.79	0.7
3	0.77	0.72	0.68	0.71	0.68	0.74	0.81	0.73
4	0.81	0.69	0.68	0.71	0.72	0.74	0.82	0.74

Table 2 Measured MTIs and STIs at four locations on the Legislative Assembly floor

With the local systems in the Press Gallery and the three public galleries operational, the above STIs on the Assembly floor were reduced by only 0.05. This was a pleasing result, given that the total area of these galleries was equal to that of the Assembly floor.

4 CONCLUSIONS

This paper discusses two unusual beam-steered loudspeakers that provided holistic solutions to acoustic and operational difficulties and constraints in courts in Australia and New Zealand and the NSW State Legislative Assembly in Sydney.

In the court situations, the use of the steered-line array loudspeakers that are flush mounted in the ceiling has yielded significant improvements in acoustic gain, source-localisation and early-to-late ratios that are not available with conventional loudspeaker systems.

In the Legislative Assembly, the Cardio-Bessel array has allowed high early-to-late ratios to be delivered to listeners over a wide coverage area without the damage to frequency response associated with multi-driver arrays.

In all cases, the users of the sound systems have been very positive about the subjective performance of the systems.

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