THE CONE OF AN ANCIENT NEW ZEALAND TREE INSPIRES THE ACOUSTIC DESIGN FOR THE NEW ZEALAND SUPREME COURT

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1 INTRODUCTION

The New Zealand Supreme Court is the highest court in New Zealand, and in 2006 the NZ Ministry of Justice commenced the design of a new Supreme Court complex in Wellington. The actual Supreme Court room is housed in a visually-floating separate building within that complex. The old NZ High Court building which was constructed in the mid 1850's was restored back to glory and connected to the Supreme Court complex. The building was opened 2010 by HRH Prince William.

ICE Design Australia was engaged to assist the design team with acoustic advice for the Supreme Court room and the public spaces in the old High Court building. Based on good outcomes provided by ICE Design with sound systems in the New Zealand Court of Appeal and the temporary Supreme Court, The Ministry decided to separate the courtroom acoustics from the regular building acoustic work and this allowed us to concentrate on the core-deliverable of high speech clarity and high acoustic comfort in the new Supreme Court room and the restored High Court room which was to be used for Moot Court proceedings and conferences.

This paper discusses the acoustic design features of the new courtroom and the measured performance and mentions some of the issues encountered during the project.

When ICE Design joined the project in 2007, the proposed highly unusual elliptical-dome shape of the new court room had been formally adopted, and the primary goal of our work was to deal with the terrible acoustic echoes and sound concentrations that often occur in domed structures. Given that the courtroom was to be a daily working environment for legal professionals and that speech is the principal communication medium, these echoes and concentrations would have caused grave problems for court proceedings.

In major public spaces where the stakes for good acoustic performance are high (e.g. recital hall) or there exists an inherent design feature with an associated high risk of poor acoustic consequences, the acoustic consultant's fee can be considerable. This is particularly so when virtual and physical scale models must be produced to explore problems, mitigate risks and develop buildable solutions.

As the Ministry had budgeted only a relatively small fee for ICE Design, our approach to the project needed to accommodate that fee whilst still delivering high quality, risk managed outcomes. In this context, constructing a virtual model in software such as Catt, Odeon or Aura was precluded as the significant time needed to develop, run and modify the model could not be justified. We therefore had to find another way to explore the issues.

2 INITIAL APPROACH

The first major piece of work was to identify the potential acoustic problems with proposed room shapes and develop an assessment method that would help the architectural design team to understand the extent of acoustic problems and to adopt a holistic design approach with us.
Figure 1 shows the plan and sectional view of the Supreme courtroom before our engagement. The annotation shows the architectural acoustic issues that needed to be addressed, which are listed in **Table 1**.

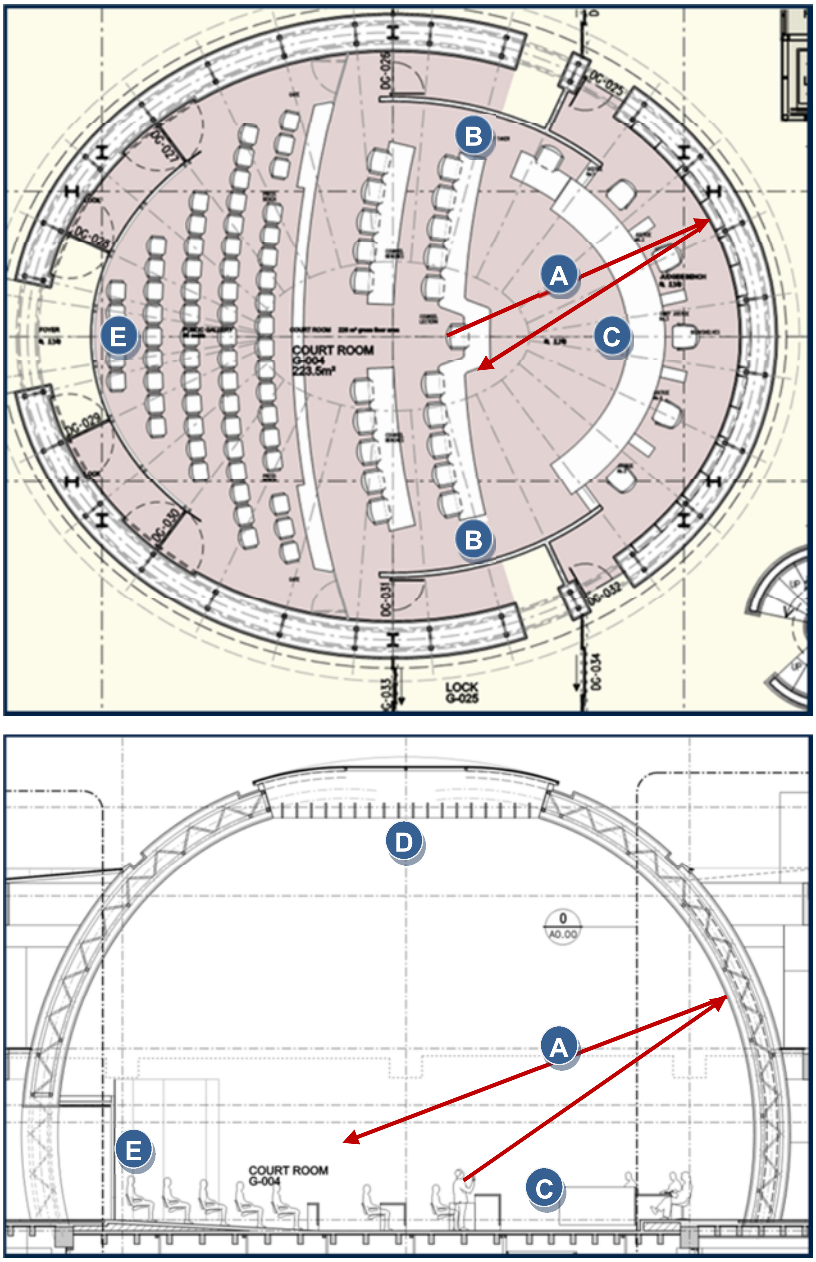

Figure 1 Early plan and sectional views of the proposed Supreme Courtroom showing acoustic issues to be addressed.

Item	Issue
A	Focusing and echoes from walls and ceiling
B	Focusing and echoes from two short curved wall panels
C	Focusing from curved front of judges bench
D	Echoes from skylight blades when in the closed position
E	Focusing and echoes from short back wall panel

Table 1 Acoustic design issues to be addressed, as identified in **Figure 1**.

3 VIRTUAL LASER TRACING

In the early stages of our involvement, it became apparent that the architectural design team was finding it challenging to fully grasp the potential difficulties that the courtroom shapes would impart to speech clarity and acoustic comfort. In response to this, ICE Design developed a simple method to illustrate the focusing and echo problems that would occur in the room.

A lighting software package was modified to "shine" a virtual acoustic laser beam with a slightly conical radiation pattern from specific speaking locations in the room. Google Sketchup was used to rapidly create and subsequently modify a wire frame model of the space for importing into the lighting software. To simulate the relatively omnidirectional nature of natural speech above the talker's head, the orientation of the virtual laser beam was progressively adjusted in pan and azimuth to cover an upward hemispherical range.

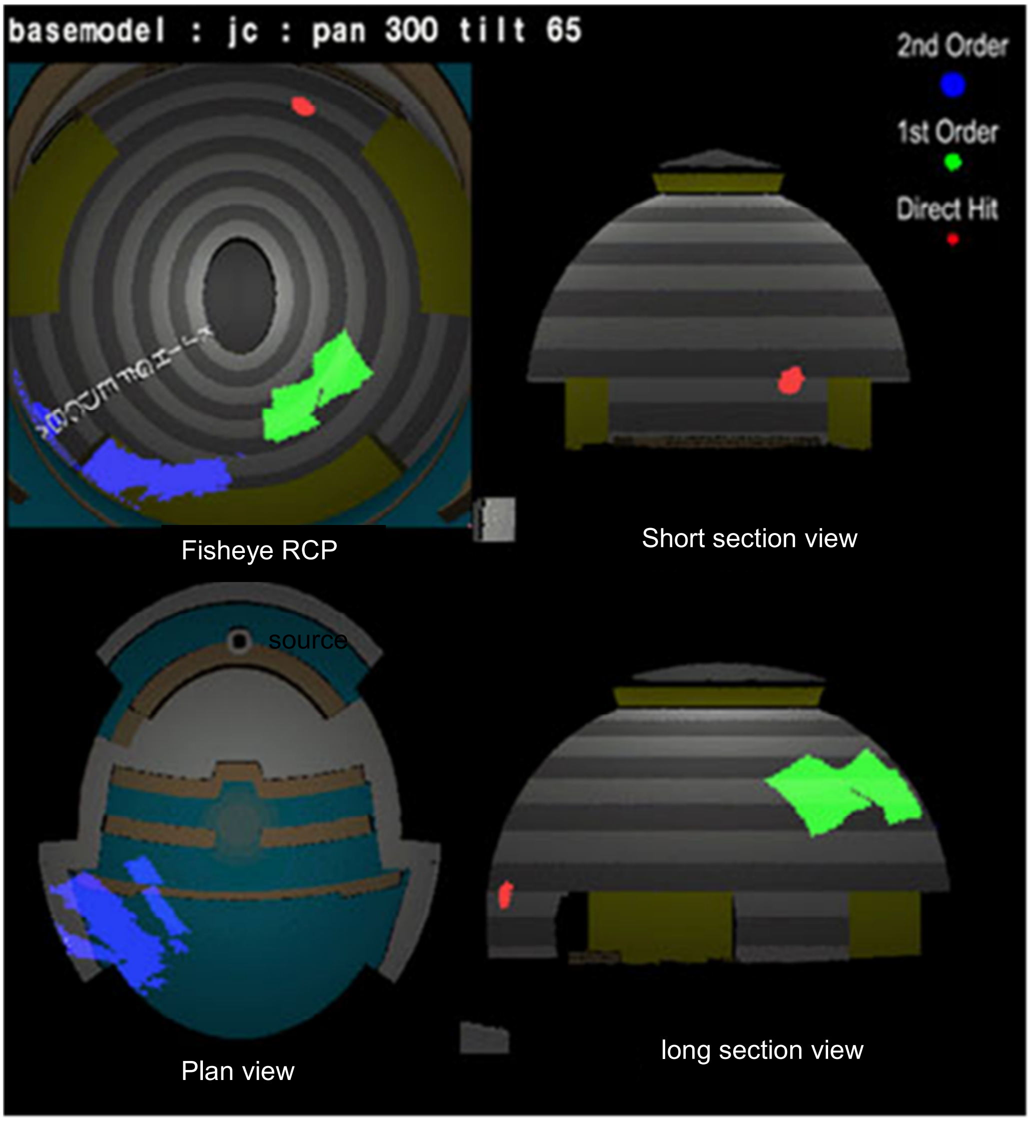

Figure 2 Fish-eye view of the reflected ceiling plan, floor plan and wall elevations for one set of reflection destinations of the virtual laser beam when located at the Chief Justice seat.

Figure 2 shows an example of one set of reflection destinations for a virtual laser beam when aimed in a particular direction into the room from the Chief Justice seat. A fish-eye view of the reflected ceiling plan, floor plan and wall elevations are given to assist understanding the full distribution.

The location of the laser beam impact on the wall/ceiling is shown as a red dot; the destination(s) of the first-order reflection of the slightly expanding beam is shown in green, the destination(s) of the second-order reflection of the expanding beam is shown in blue.

Another example of a set of reflection destinations is given in **Figure 3** with the virtual laser beam located at the Counsel lectern.

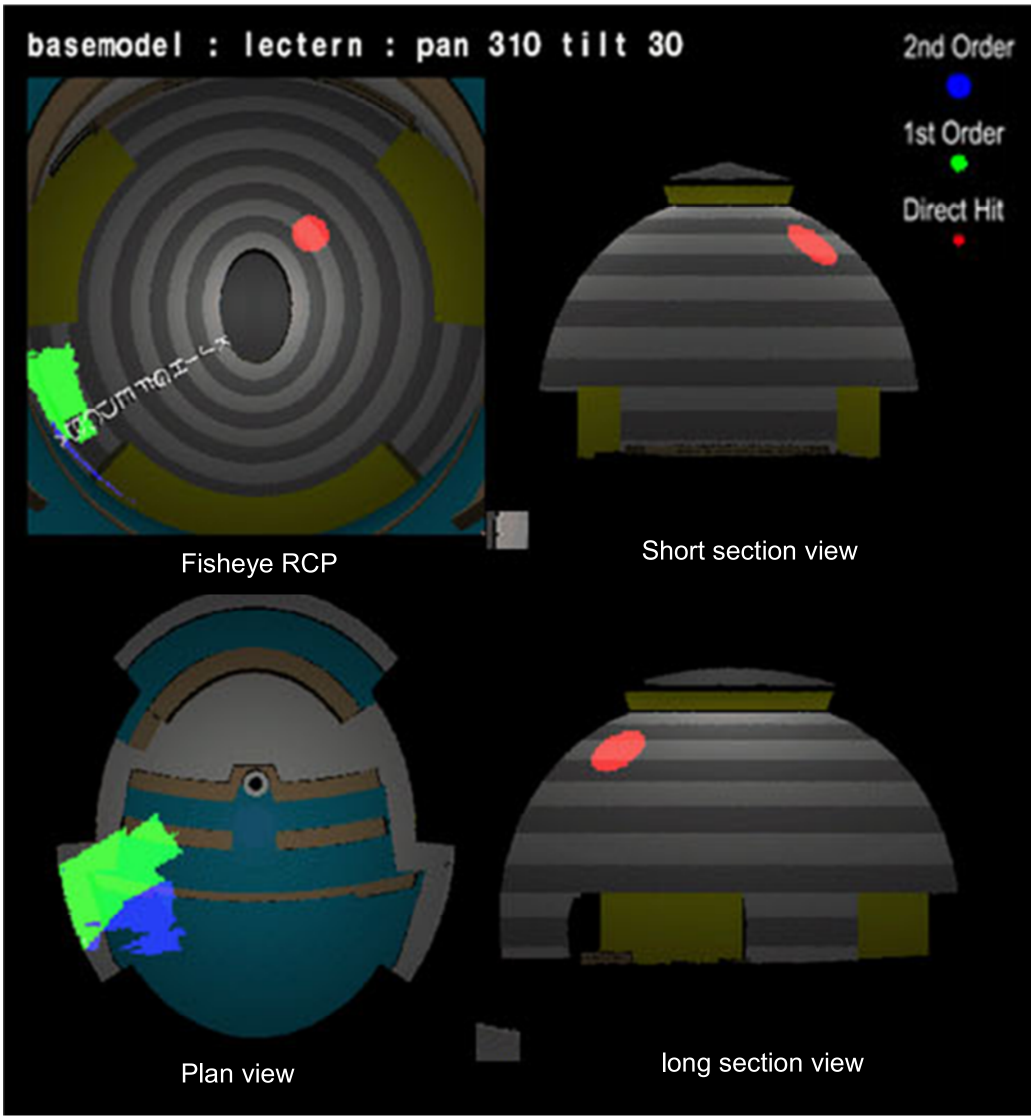

Figure 3 Fish-eye view of the reflected ceiling plan, floor plan and wall elevations for one set of reflection destinations of the virtual laser beam when located at the Counsel lectern.

The model was scripted to run as a batch file so that destinations of the first and second order reflections could be noted for each orientation of the laser beam within the hemispherical envelope,. Importantly, to facilitate an understanding of the destination trends, a real-time browser-based user interface was developed to allow the user to view the changing reflection destinations by simply aiming the virtual laser at the desired area of the ceiling using a computer mouse. . From this work, we were able to determine the locations on the floor at which concentrations of reflections would result.

Figure 4 shows an early sketch of those regions of the ceiling that were observed to be generally responsible for generating primary and secondary concentration areas at listening height above the courtroom floor for a selection of key speaking positions.

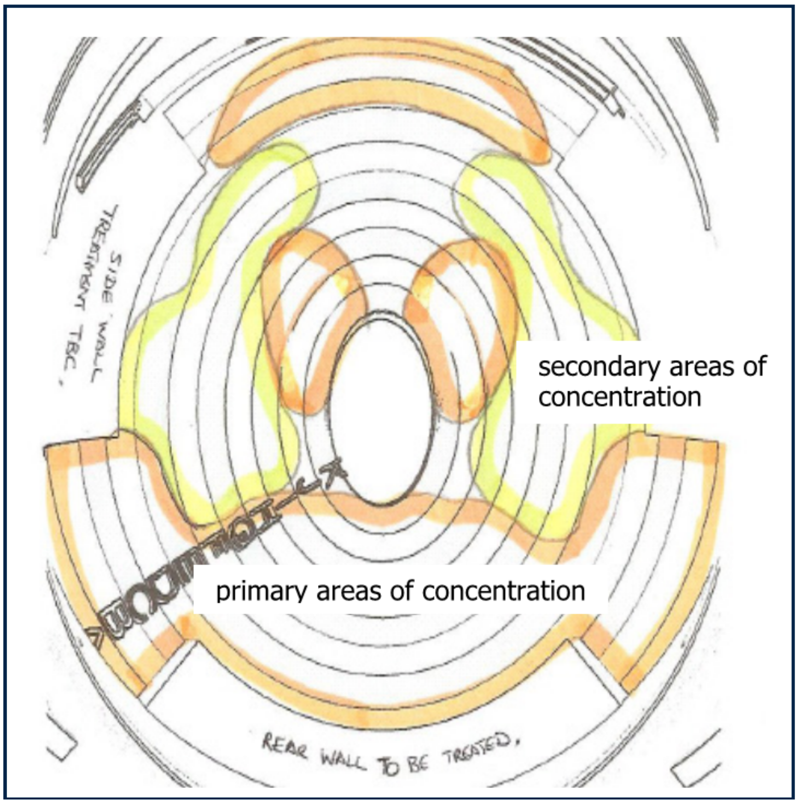

Figure 4 An early sketch showing a fish-eye view of the courtroom reflected ceiling plan and walls highlighting the general regions that were observed to contribute to concentrations of first and second order reflections at listening height

Figure 5 shows two images of the software interface used for detailed analysis to define azimuth and pan angles for incident laser strikes, which in turn result in observed concentrations of first and second reflection arrivals on the listening plane

Using this graphical technique, the architectural and project management team were able to better understand the scale of the problem and the driving principles behind ICE Design's recommendation to develop a solution that would involve extensive and specifically distributed acoustical treatments (absorbing, reflecting and diffusing) to the dome.

4 A SOLUTION

4.1 Modelling

It could be argued that the problems of sound concentration would be eliminated using large amounts of powerful acoustic absorption on the walls and ceiling. However, this approach would render the ambience of the room too dead and destroy any sense of space or grandeur for such an important space. The best solution was diffusion, as this would retain the ambience of the space, whilst dispersing the areas of sound concentration

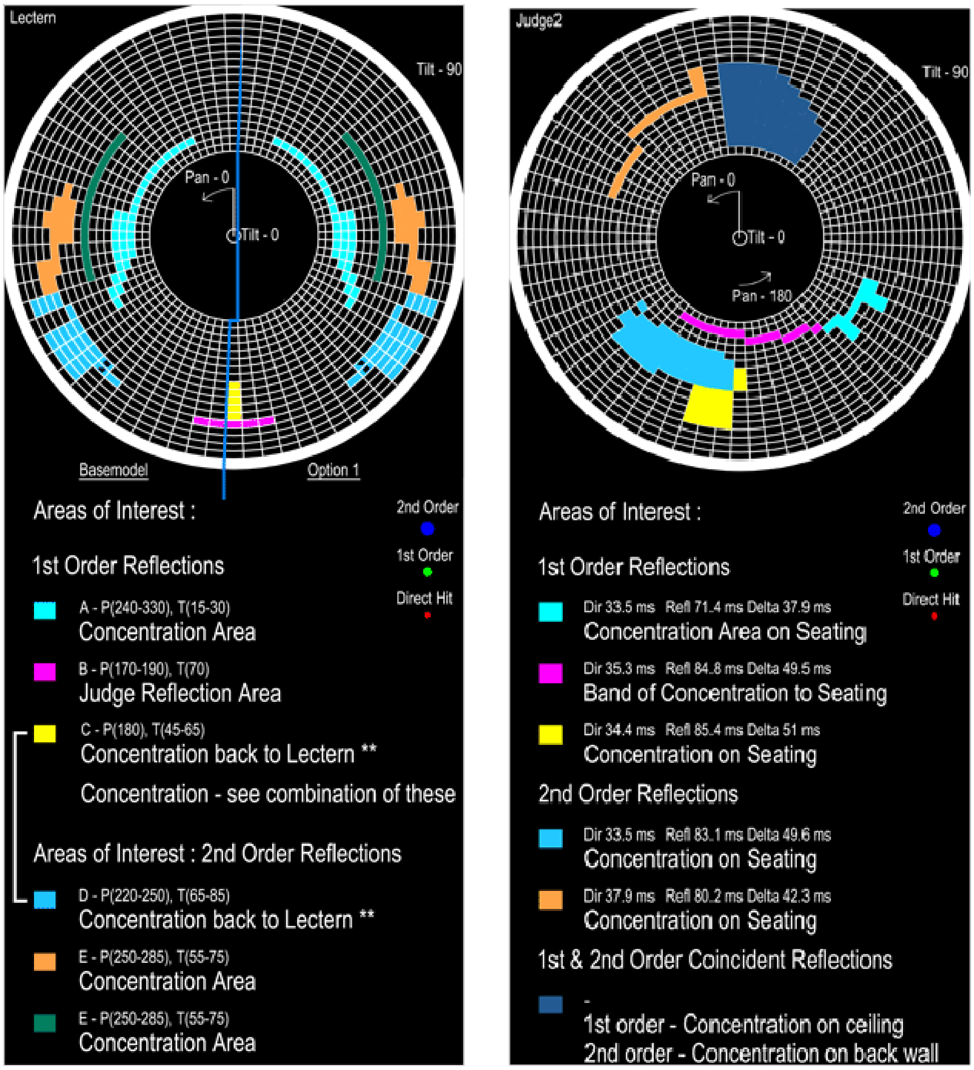

Figure 5 Images of the software interface used for detailed analysis to define azimuth and pan angles for incident laser strikes, which result in observed concentrations of first and second reflection arrivals on the listening plane. The two example scenarios show regions of incident laser strikes that produce listening-plane concentrations for: [left] a speaker standing at the Counsel Lectern position and, [right] a talker sitting at one place to the right of the central Chief Justice position.

5 A SOLUTION

5.1 Modelling

An important feature of our virtual laser model was the ability to rapidly articulate multiple panels in the model. Amongst other configurations, this allowed us to readily apply an offset of 200 mm to a grid of triangulated facets over the entire wall and ceiling area. In situ, a surface articulation of 200 mm would provide diffusion down to 500 Hz with some benefit remaining at lower frequencies.

Figure 6 shows the articulation that was applied to the wall and ceiling surfaces.

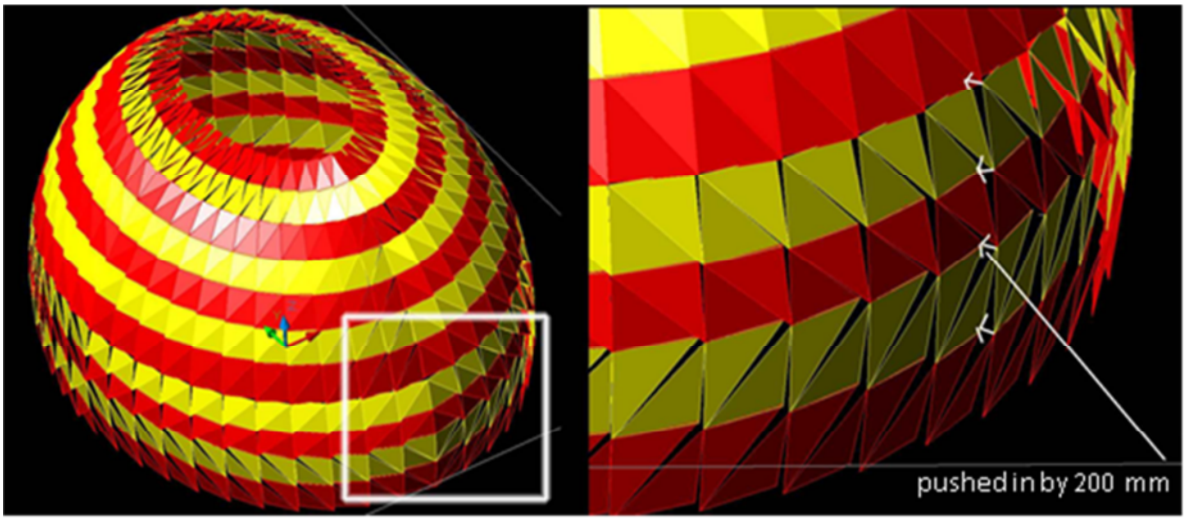

Figure 6 Articulation applied to the surfaces in the laser model

The hemisperical set of laser beams was re-run with the articulated surface in places, resulting in directly comparable reflection concentration outputs such as shown in Figure 7.

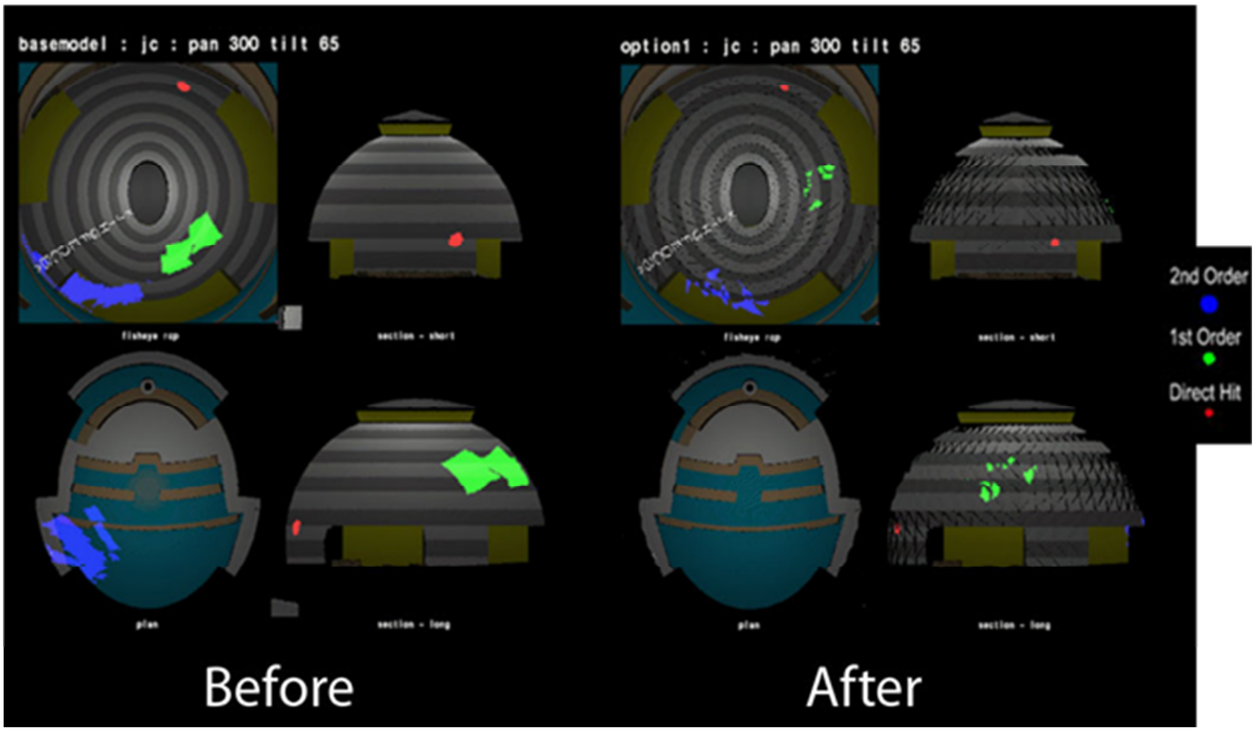

Figure 7 Comparison of the areas of sound concentration with flat panels ("Before") and with articulated panels ("After"). Of particular note is the significant reduction of reflection concentrations incident on the listening plane (or teal coloured area on the floorplan)

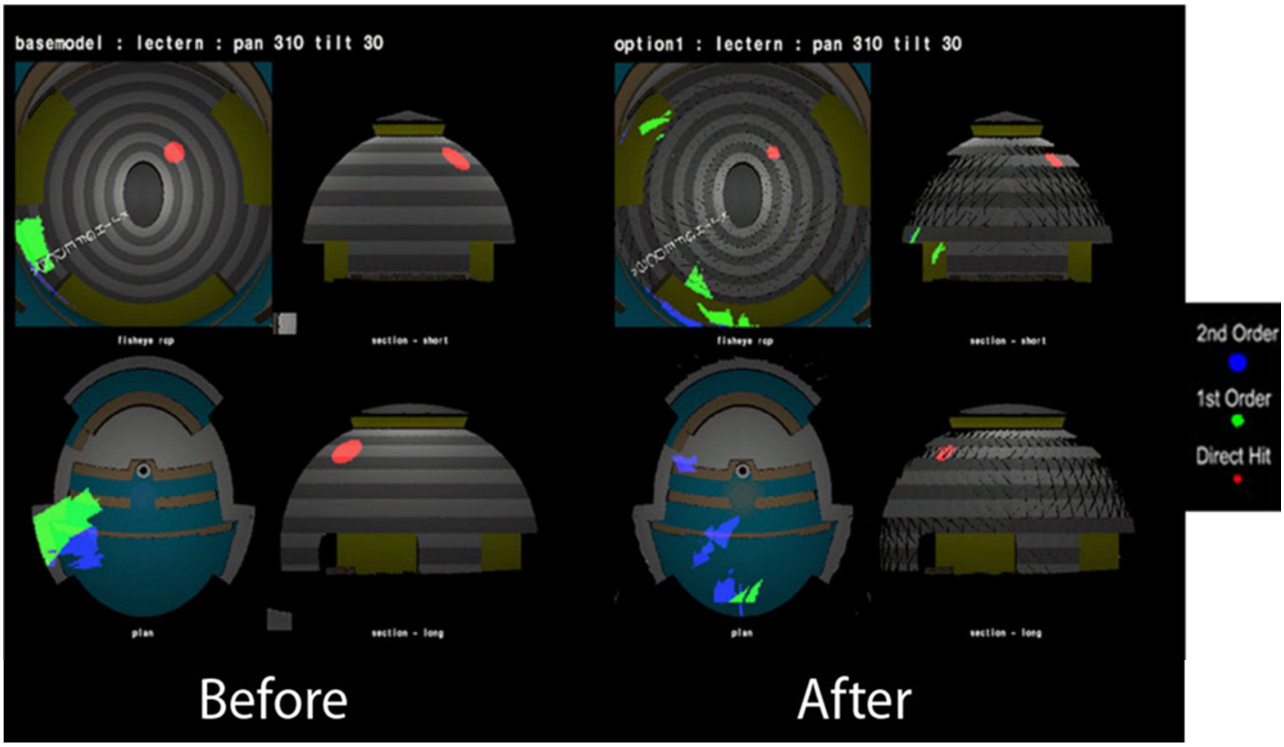

Figure 8 Comparison of the areas of sound concentration with flat panels ("Before") and with articulated panels ("After"). Of particular note is the significant reduction and dispersion (or weakening) of reflection concentrations incident on the listening plane (or teal coloured area on the floorplan)

5.2 Implementing Diffusion

After understanding the problem and our advice to incorporate strong acoustic diffusion, the architects Warren and Mahoney responded with a truly inspired design. They developed an innovative structure for the interior utilising diamond-shaped, angled timber panels that were formed into spiral-wrapped bands, similar to the cone of the ancient native NZ Kauri tree, pictured in Figure 9**Error! Reference source not found.**.

Figure 9 Cone of Kauri tree (from Google Images)

We held a peer review session with colleagues from Acoustic Studio in Sydney, who have significant experience in concert hall design. An important suggestion arising from the review was the importance to the overall ambience of the room of directing and maintaining as much reflected-energy as possible towards the upper part of the ceiling, so that it would continue to reverberate, rather than being reflected towards the floor and seating where it would be absorbed.

Figure 10 shows a simplified reflection pattern for three shapes, illustrating how a dome section does not encourage reverberant reflections of a directional source such as a talker, compared to a rectangular section.

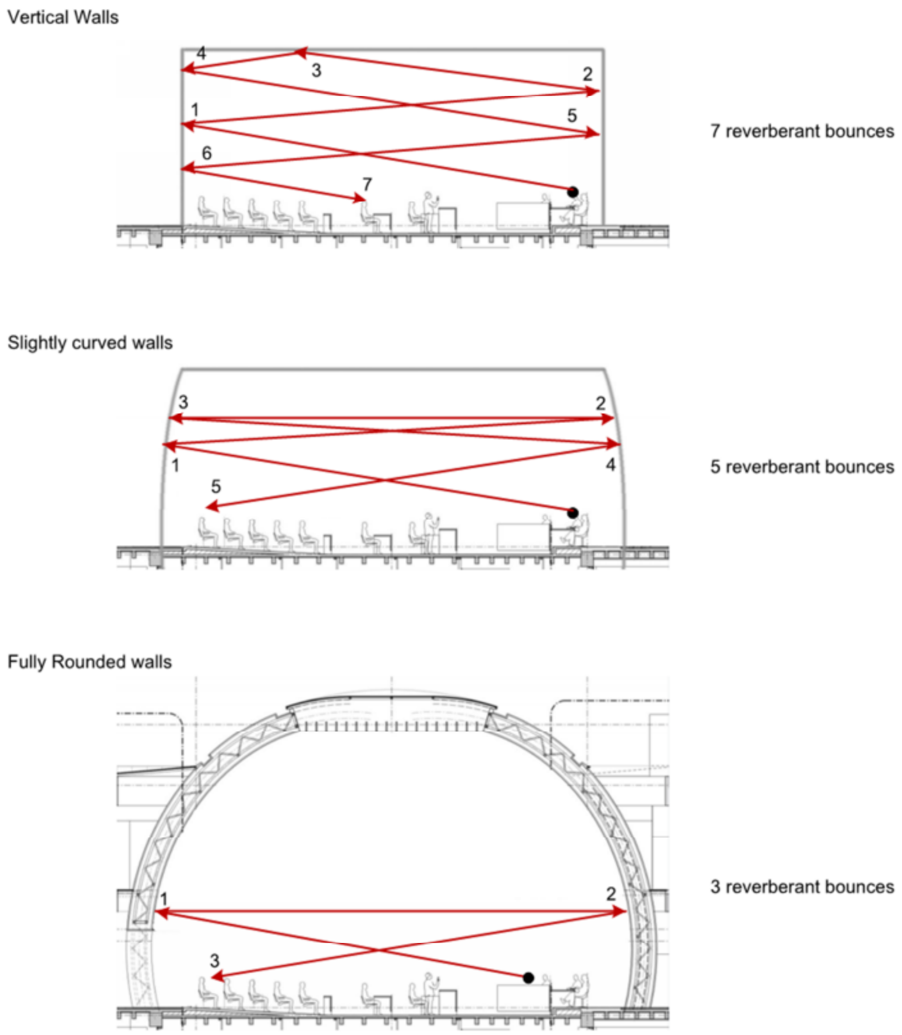

Figure 10 Simplified reflection pattern for three shapes, illustrating how the dome structure does not encourage reverberant reflections of a directional source such as a talker.

ICE Design recommended the maximum possible upward tilt of the panels, subject to architectural and buildability constraints.

The diffusing panels developed by the architects took the form of diamond shaped timber boxes, some with two oppositely inclined faces arranged in an unusual pattern. For these boxes, the upward direction of sound is assisted by the upper inclined face of each box.

Figure 11 shows the arrangement of the diffusing boxes on the walls while Figure 12 shows a close up of view of an area of boxes looking upwards along the wall.

Figure 11 View of the rear of the room showing the arrangement of panels. (Note that the suspended array loudspeakers are visible)

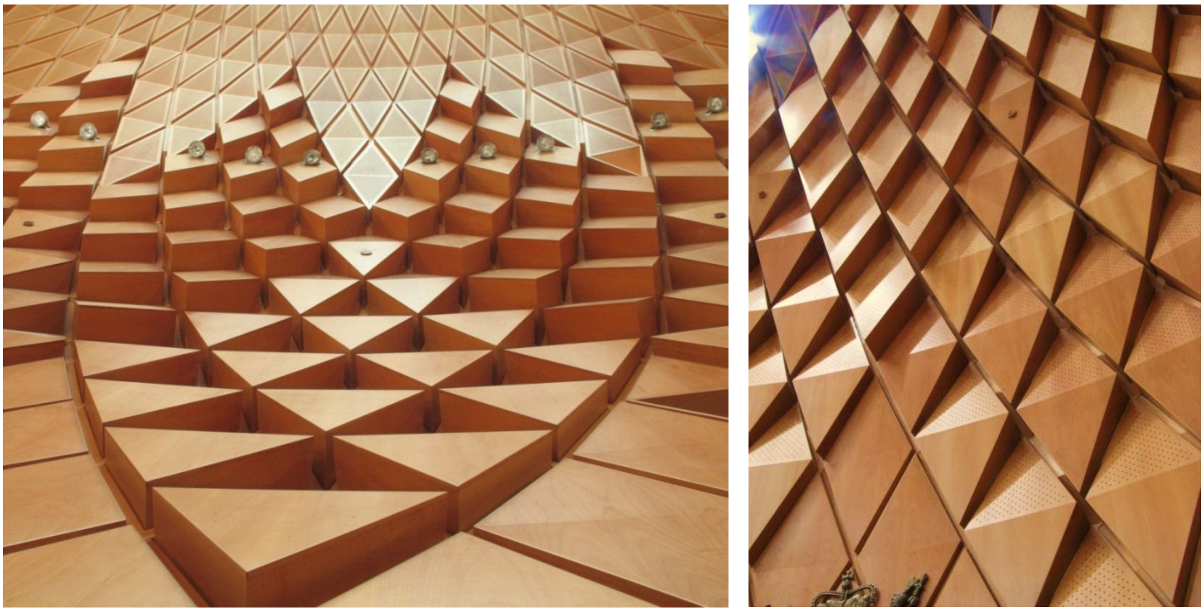

Figure 12 Close up views showing the vertical arrangement of the diffusion boxes.

6 DETAILED DESIGN

6.1 Reverberation Control

Reverberation time calculations showed that some acoustic absorption was necessary to control the reverberation time in the room, and therefore a reverberation control zone was designated above the diffusion band. This absorption needed to have as wide a bandwidth as possible to limit the extent of echoes resulting from the upward radiation of the loudspeakers. Note that there was very little freedom to introduce useful sound diffusion in this region.

Although we would recommended the use of 6 mm thick timber as a perforated cover for absorption, the architects desired to use 9 mm thick timber for this region for aesthetics and structural reasons, and this gave us concern for limited absorption at higher frequencies. To achieve maximum absorption with 9 mm thickness, the perforation ratio was made as high as possible at around 35%, and the holes made as small as possible (3 mm) to minimise distance between the holes. 100 mm thick polyester insulation with flow resistivity of 10,000 Rayls/m was fixed with wire mesh behind the panels. Due to the complex structure that supported the boxes, an air gap ranging between 0 mm and approximately 300 mm was also present which added additional uncertainty.

Figure 13 compares the predicted random incidence absorption characteristics of the adopted 9 mm thick perforated timber system and our preferred system using 6 mm timber thickness. Compared to the 9 mm system, the 6 mm system has appreciably greater absorption at higher frequencies. The method of prediction in described in (1), (2), (3).

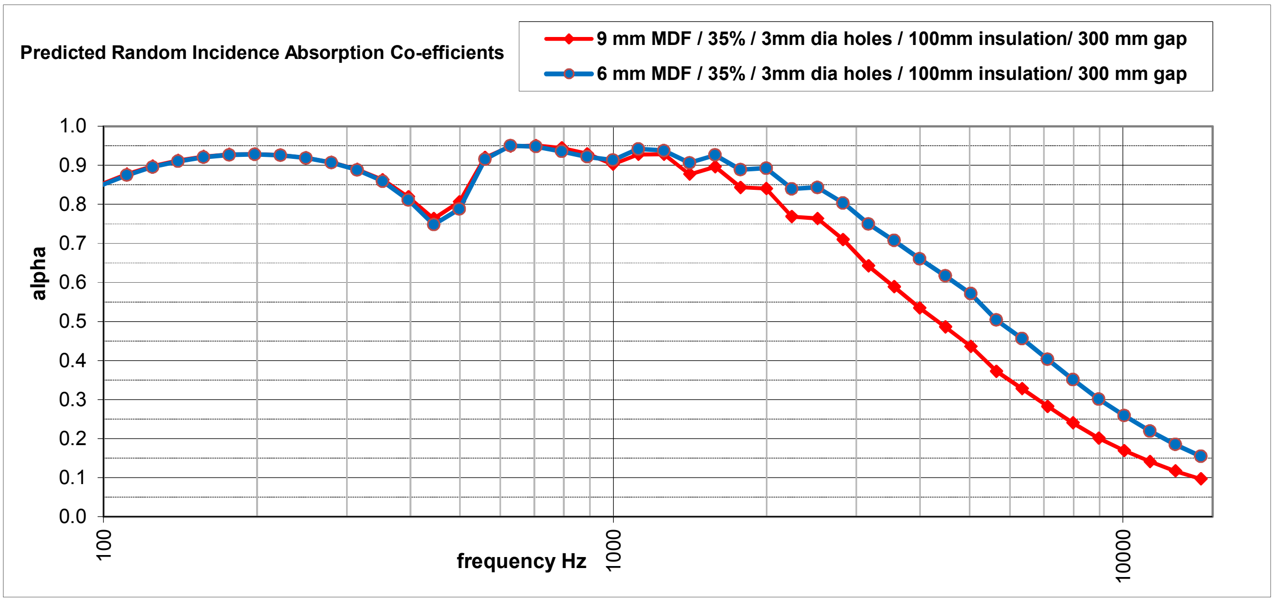

Figure 13 Comparison of predicted random incidence absorption characteristics of 6 mm thick (recommended) and 9 mm thick (as built) perforated timber.

For reasons of robustness and aesthetics, the architects desired the lowest areas in the room to consist of flat un-perforated timber panels. We anticipated that this area would provide some early reflections for unamplified voices, but also some sound concentration at specific areas.

The diffusion panels (intended to diffuse sound down to around 500Hz) were designed to incorporate low frequency absorption to ameliorate any focusing potential below 500Hz and to compensate for the lower absorption properties of the carpeted floor. As the diffusion boxes were open-backed, the air gap to the structure was highly variable. The final design consisted of 9 mm thick board, 5% open area, 6 mm hole-diameter and a variable air-gap up to 300 mm. Figure 14 shows the predicted random incidence absorption characteristics of that system.

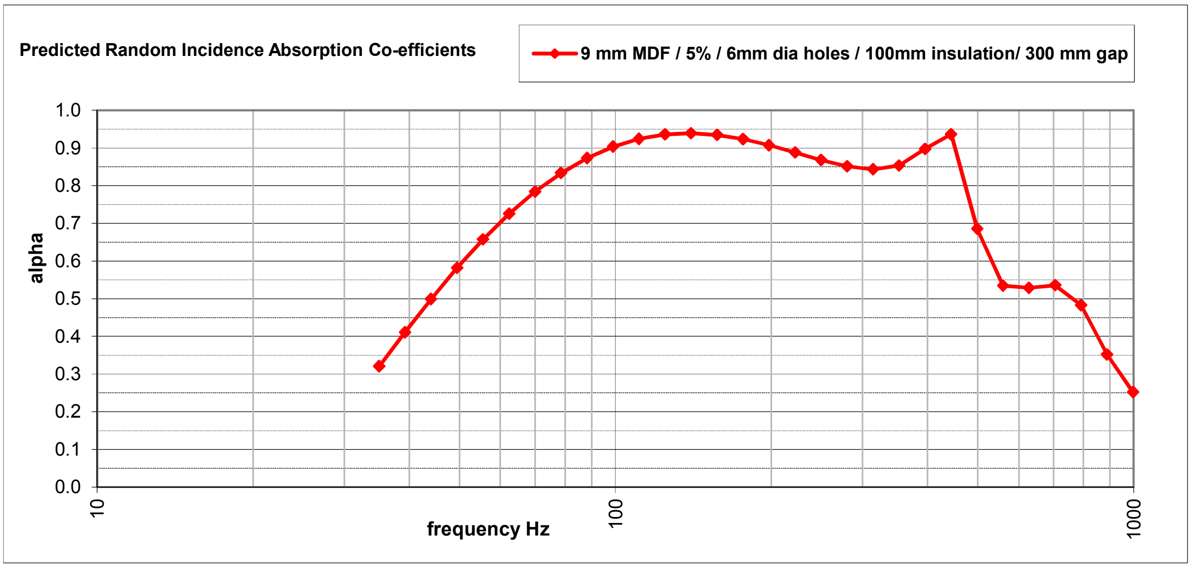

Figure 14 Predicted random incidence absorption characteristics of perforated diffusion boxes.

6.2 Control of Specular Reflections

There were a number of other architectural features in the room that had the potential to cause strong specular reflections and focusing in the room.
These were:

- skylight
- standalone glazed sections of the rear wall (seen in Figure 11)
- standalone sections of the side walls holding entry doors (seen in Figure 11)
- front of judges bench

Skylight

To prevent direct specular reflections of the loudspeaker sound from the flat blades of the skylight in the closed position, a series of angled glass blades was developed in a floral motif as shown in Figure 15.

Rear Wall

The 3.5 m high standalone wall at the rear of the room was originally intended to be curved glass, to facilitate a view through the court to outside. To retain a semi-curved shape for the window whilst preventing focusing, a series of alternately-angled glass panels was used.

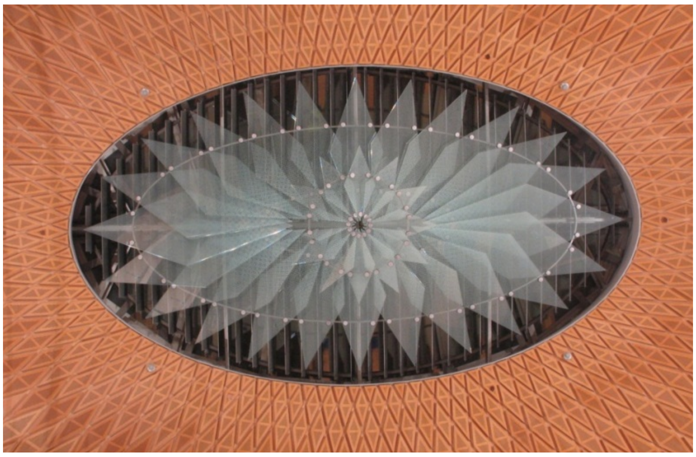

Figure 15. View of glass blades in skylight

For the semi-height wall surrounding the glass, the alternate-angle theme was maintained with an absorptive structure, using high density polyester insulation located behind a relatively open weave wire mesh, of width 8 mm. This type of panel was intended to evoke the traditional Māori Tukuku art form of decorative wall panels.

Side Walls

The side walls were originally intended to be curved timber, but ultimately were implemented as the alternately-angled panels of woven wire mesh, reminiscent of the Maori Tukutuku art-form. 100 mm thick high performance insulation was fixed behind the mesh.

Judges Bench

The judges' bench was curved to follow the shape of the room. To prevent a focusing of a barrister's voice when speaking at the lectern facing the judges, the front face of the bench was angled downwards to generally direct specular reflections into the absorptive carpet.

7 LOUDSPEAKER SYSTEM

The principal activity of court in Australia and New Zealand is information transfer, primarily by live speech. Proceedings in the highest courts in these countries are characterised by lengthy speeches and complex legal arguments that require high speech intelligibility for the listeners.

Aside from the room acoustic environment, there are a number of extraneous factors that impose difficulties for speech intelligibility.

- During lengthy discourse, neither the judges nor counsel are inclined to orate; i.e. they do not raise their voice nor annunciate their words.
- There are significant numbers of listeners behind the lectern, where the off-axis loss at higher speech frequencies is significant, with an attendant loss of subjective intelligibility due to upward masking and background noise.
- There also can be some occupational noise in the room due to attendants, tipstaff and associates and the general public talking quietly and moving about the room

To accommodate the above factors and deliver long-term acoustic comfort for participants, it is necessary to use a sound reinforcement system, regardless of how good the room acoustics are.

Work done previously by the authors has conclusively showed that the lowest equivalent acoustic distances for listeners (equivalent to the highest acoustic gain) and highest speech intelligibility are obtained with an overhead loudspeaker system arranged so that the wavefront of the loudspeakers' direct field impinges at the rear of directional microphones. To achieve the required early-to-late ratio, the loudspeakers need to have a strongly controlled radiation pattern that delivers little sound upwards towards the ceiling at all speech frequencies, and this implies the use of a line-source loudspeaker. .

While acknowledging the need for a sound system, the architects were not in favour of large loudspeakers being suspended from the ceiling. The project moved into a period of angst, during which our recommendations were considered by the Ministry of Justice. Ultimately the Ministry accepted our advice, and the loudspeakers were implemented.

Among the important aspects of the design of the loudspeakers are the following attributes:

- To achieve the required consistency of coverage and frequency response over the wide judges' bench and counsel tables requires two loudspeaker arrays. However, the Chief Justice's seat and counsel lectern would be located exactly equidistant to both arrays, and therefore minor variation in head position would lead to significant variations in frequency response and possibly loss of subjective speech clarity. To prevent this occurrence, a third, central loudspeaker is used which is carefully integrated with the outer two arrays using all pass filters and delay.

- The loudspeakers are a hybrid steered line array, as described in (4). This type of array uses a physically tilted high frequency tweeter array to provide a suitably wide but controlled radiation pattern at high frequencies. Applications of this type of loudspeaker have been described by Leembruggen in (5).
- To achieve vertical control of radiation down to 200 Hz, a 1.2 m long steered array is used.
- Three loudspeaker systems cover the judge and counsel areas, with two loudspeakers covering the public seating gallery at the rear of the court. To minimise visual intrusion, it was deemed essential to physically combine the left, centre and right judge/counsel pairs.
- The mix, delay and equalisation delivered by the judges loudspeaker's needed to be different to that delivered by the counsel loudspeakers, and therefore a means to prevent radiation behind the loudspeakers was required. The system budget did not allow cancellation of this rear radiation by active beam-forming techniques, and therefore acoustic baffles in the form of thick Perspex blades were fitted to the sides of each array.
- To attenuate rear radiation from the public loudspeakers, acoustic baffles were also fitted to these loudspeakers.
- The dimensions of the blades and their spacing were determined by trial and error modelling of diffraction effects using the Leap software.

Figure 16 shows the arrangement of back-to-back hybrid line-array loudspeakers covering judge and counsel areas, while Figure 17 shows one of the single arrays covering the public gallery. The baffles are visible, along with the tweeter arrays at the base of the structure.

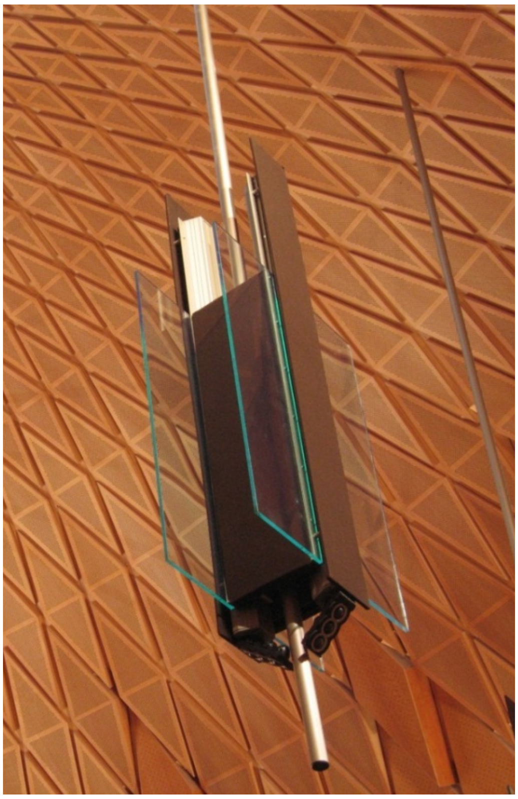

Figure 16 Arrangement of back-to-back hybrid line-array loudspeakers covering judge and counsel areas.

Figure 17 Arrangement of single hybrid array used for public gallery.

8 ACOUSTIC PERFORMANCE

Some specific examples of impulse responses in the room are discussed below.

8.1 Impulse responses

Figure 18 shows the room's impulse response (IR) in the 500 Hz octave band measured at Chief Justice position with a NTI TalkBox loudspeaker simulating a talker at the lectern (and with the sound system turned off). The early arriving energy does not begin to dissipate greatly until 80? ms after the arrival of the direct sound, suggesting that the diffusion in the room is still less than ideal. However, the clarity ratios are still good as seen in **Table 2**.

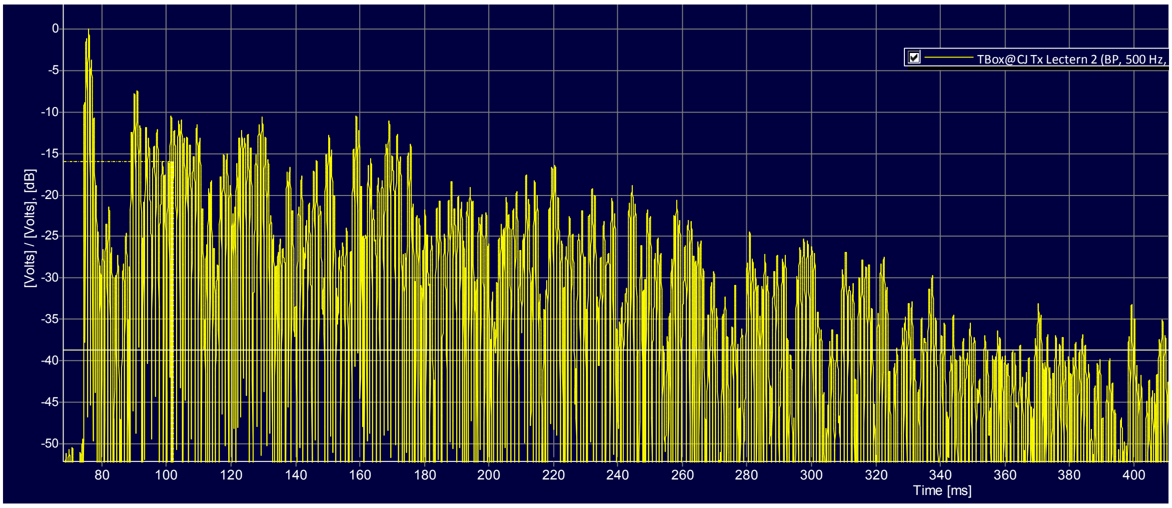

Figure 18 IR in 500 Hz octave band measured at Chief Justice position with Talkbox at lectern

OB centre frequency	125	250	500	1000	2000	4000	8000
C50 (dB)	1.6	2.9	3.4	6.1	7.0	9.1	15.7

Table 2 octave band clarity ratios measured at Chief Justice position with Talkbox at lectern

Examination of the IRs at this position at frequencies above 500 Hz shows that the lingering after the direct sound is substantially reduced, and this is reflected in the higher clarity ratios at these frequencies.

With the sound system operating, the IR shown in Figure 19 shows more rapid decay after the arrival of the direct sound. The arrival times of the three loudspeakers covering the counsel area and the reflections from the table can be seen in the group of arrivals before 45 ms. The source of the arrival at 58 ms is unknown, but it is relatively broadband in nature.

Substantial use of delay and all-pass filters was made to reduce the effect of phase cancellations and reinforcements on the frequency response caused by the inevitable interaction between the spaced loudspeaker arrays. The smearing of the IRs of each loudspeaker at mid frequencies can be seen in Figure 19.

The IR at Judge 2 shown in Figure 20, exhibits substantially faster early-decay than at the lectern. The three arrivals centred at 40 ms are from the three judge loudspeakers, each time-smeared by their all-pass filters.

Figure 21 shows the IRs at the Chief Justice listening position at 500 Hz and 1 kHz with the sound system operating. Rapid decay after the direct field and table reflections is evident.

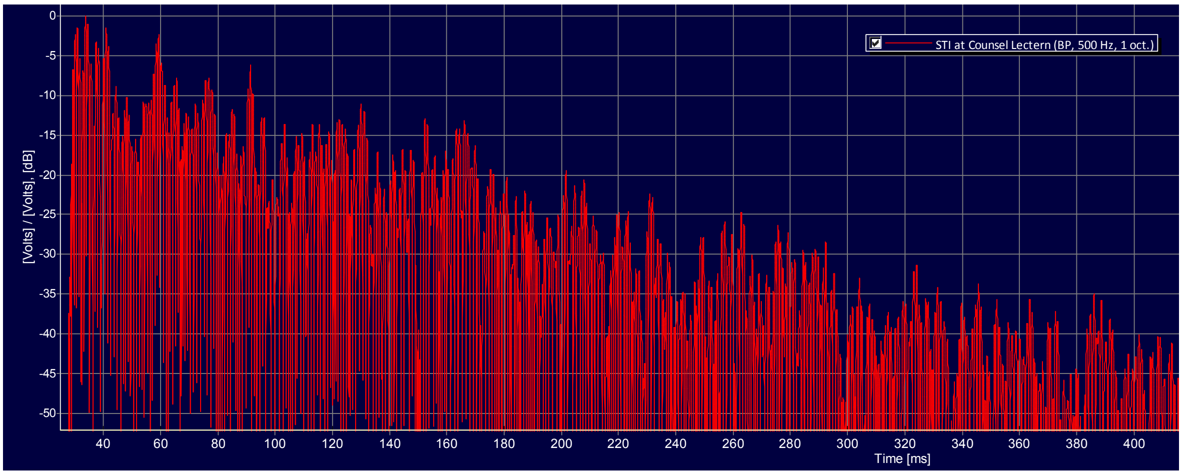

Figure 19 IR in 500 Hz octave band measured at lectern with sound system operating.

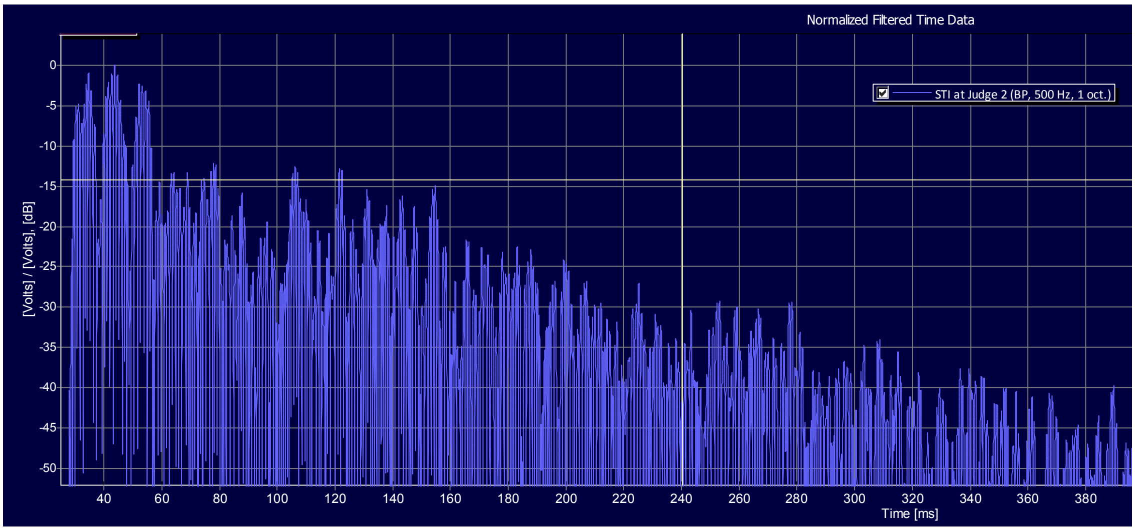

Figure 20 IR in 500 Hz octave band measured at Judge 2 with sound system operating.

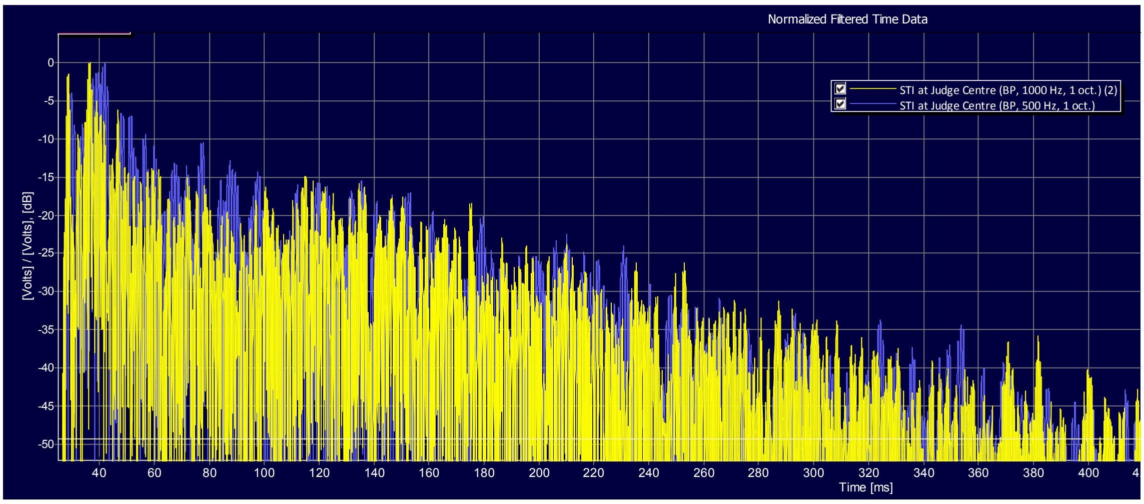

Figure 21 IRs at 500 Hz and 1 kHz measured at Chief Justice with sound system operating

8.2 Reverberation Time

Figure 22 shows the octave band Schroeder decay plots measured at the Chief Justice position (central to the judges' bench) with the source the TalkBox loudspeaker located at the counsel lectern. A minor amount of double-slope behaviour is evident up to 100 ms from the direct sound, but after that time, the slopes are smooth at 500 Hz and above. Even at 125 Hz and 250 Hz, where the diffusion boxes would be less effective, there is still reasonable behavior.

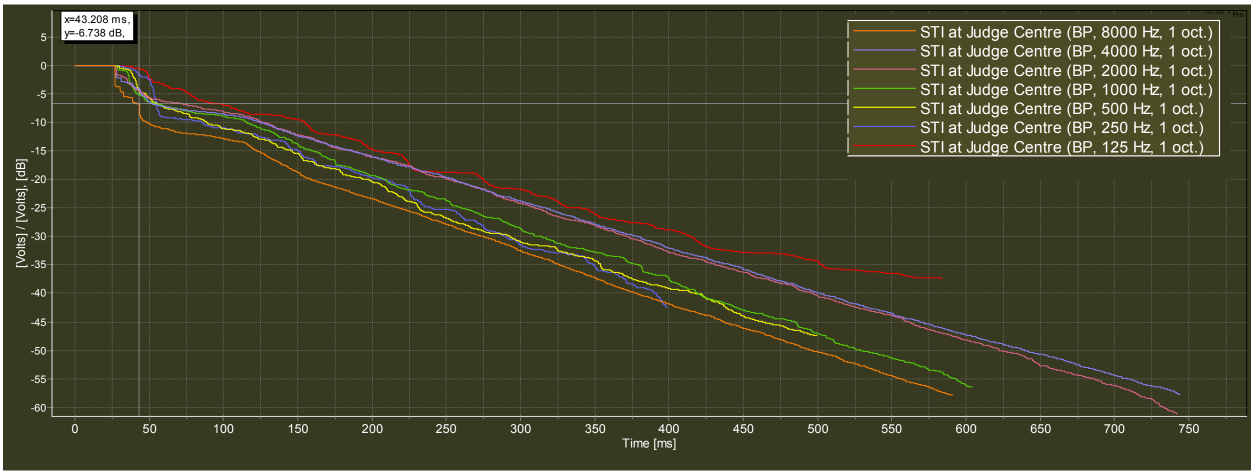

Figure 22 Octave Schroeder decay plots measured at the Chief Justice position with Talkbox loudspeaker as source at counsel lectern.

Figure 23 shows the octave band Schroeder decay plots measured at the counsel lectern position with the sound system as the source. The decays are very consistent, showing that concentration problems have been largely addressed.

The reverberation times were computed from the Schroeder plots over the range -10 dB to -35 dB and are shown in Figure 24. The average of the measured times is compared with the predicted Sabine and Eyring reverberation times. There is remarkable agreement between the Eyring predictions and the measured values. The alpha_bar values are also shown, and given that they are approximately 0.4, the use of the Eyring equation seems valid for alpha_bar values above 0.2.

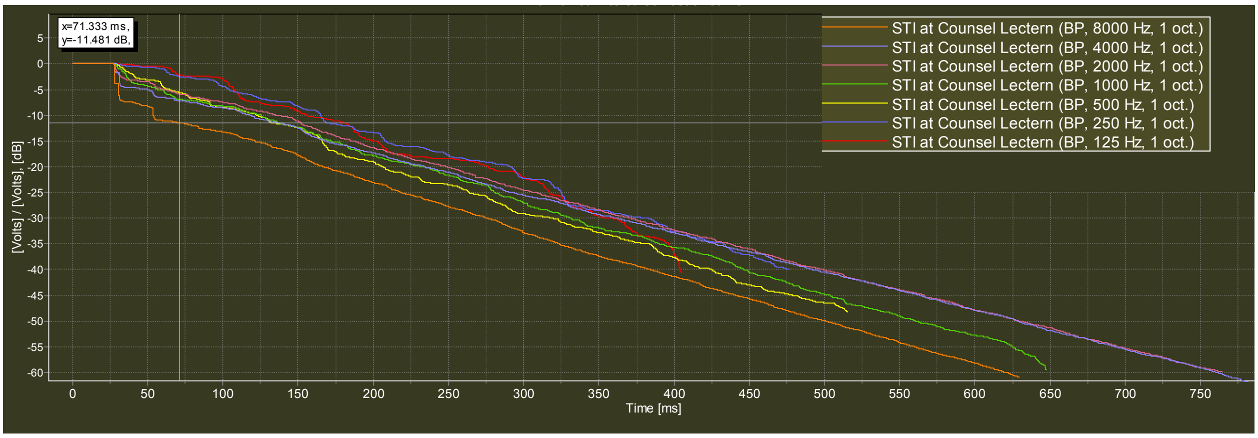

Figure 23 Octave Schroeder decay plots measured at lectern with sound system as source.

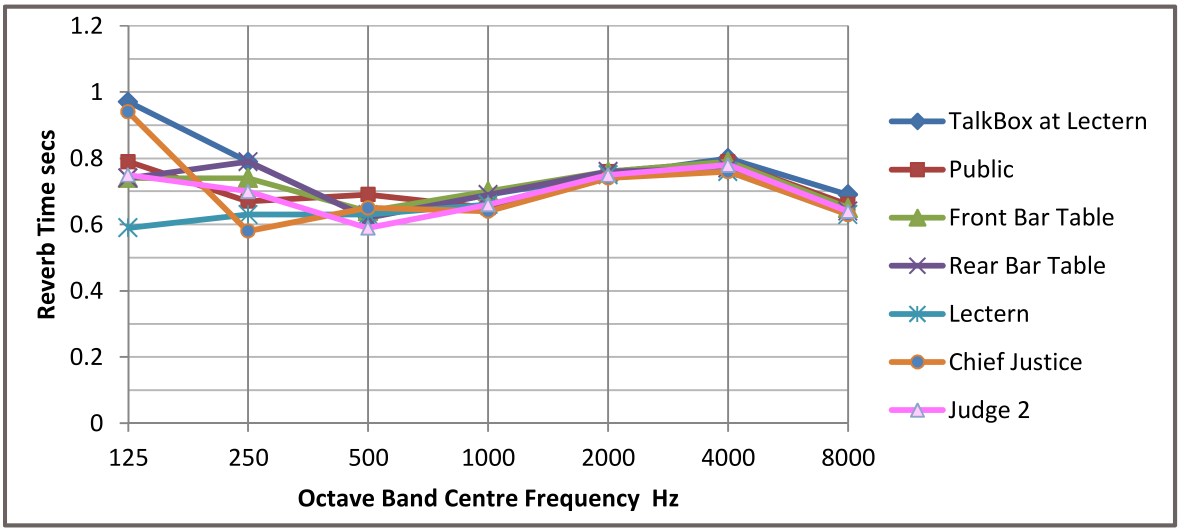

Figure 24 Measured reverberation times at a number of locations in the courtroom.

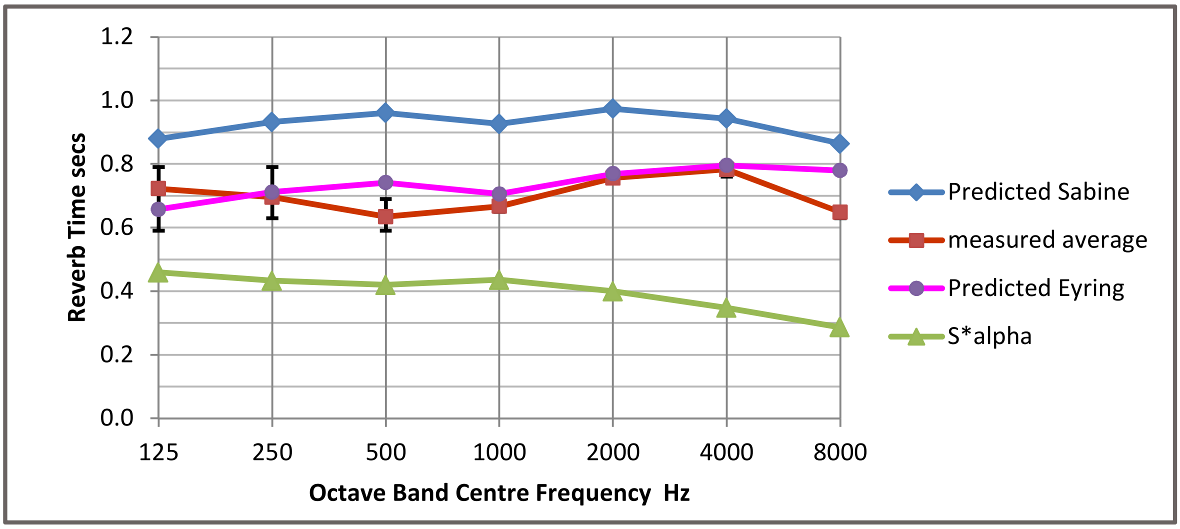

Figure 25 Comparison of measured-average and predicted reverberation times

8.3 Speech Transmission Indices

The STIs were measured using electronic injection of the test signal into the sound system. Limited time precluded measurements with acoustical injection into a microphone using the NTI TalkBox.

In our opinion, under conditions of low background noise, the octave band MTI results are almost as important for subjective speech intelligibility as the overall STI result, as they provide an indication of the intimacy or early-to-late ratio in each frequency range. The weightings applied to the MTI results when computing the STI are biased towards the higher frequencies, and under highly reverberant conditions with low MTI scores at lower frequencies, these weightings can produce an acceptable STI score,. Although the STI may be satisfactory in these situations, significant listener concentration may be required to discern words, which is draining for long periods of speech such as in courtrooms.

Figure 26 compares the STI and MTI values at various locations in the courtroom. The STIs all exceed 0.7, with the MTI results in the frequency bands up to 4 kHz also around 0.7. This is a pleasing result.

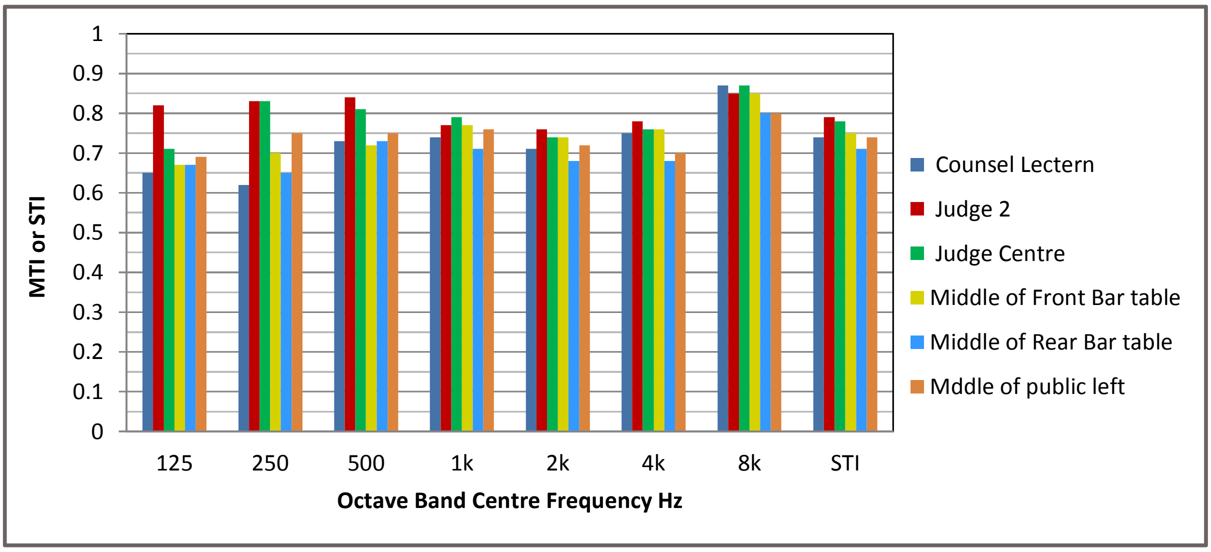

Figure 26 Comparison of STI and MTI values at various positions in the courtroom.

9 DICUSSION AND CONCLUSIONS

The following points are noteable.

- The final result was an excellent example of creative collaboration between architect and acoustician and has met with acclaim.
- The speech of proceedings in the room is intimate, but has a sense of space and grandeur, as would be normally expected in a room of this importance. The sound is extremely natural and the intelligibility is effortless.
- While not perfect, the acoustic results are remarkable in the overall context, given that i) the room shape had been adopted before ICE Design's engagement, ii) we had limited degrees of design freedom with which to rescue the situation and iii) our low fee precluded use of the usual software analysis tools with virtual acoustic models.
- The Supreme Court was recently accorded with New Zealand Architecture award for interior architecture. The citation reads "*An open and dignified foyer space connecting the street to the courtroom serves to signify the transparency of the administration of justice in New Zealand. The interior of the court is an extraordinary room displaying, in its joinery and execution, a high level of refined craftsmanship. In designing the internal surface of the courtroom, the Architects have alluded to the generative role of nature in New Zealand architecture. Radial patterning derived from the cone of the Kauri tree envelops the court, lending warmth and an intriguing complexity:*
- The project tension concerning loudspeakers dissipated, with the architects ultimately seeing the loudspeakers as making a positive contribution to the room.
- As noted by one of the architects' design principals to the authors and then echoed by Paul Malpas at Reproduced Sound 2010, grand spaces necessarily involve constructive tension between design team members. Grand design would not happen otherwise.

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10 ACKNOWLEDGEMENTS

We gratefully acknowledge the assistance of the following companies with this work:

- Architects: Warren and Mahoney   www.warrenandmahoney.com

- Project Manager: The Building Intelligence Group www.thebuildingintelligencegroup.co.nz
- Peer Review: Peter Griffiths and Jason Cameron of Acoustic Studio Pty Ltd.

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