APPLICATION OF MODERN ROOM ACOUSTICAL TECHNIQUES TO THE DESIGN OF TWO AUDITORIA

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ABSTRACT

Recent advances in the study of room acoustics are formidable. The modern understanding of the behaviour of sound in rooms now allows for much more freedom and confidence in design. The design of two new rooms will be presented. The first is a 3500 seat Assembly Hall of Jehovah's Witnesses to be used primarily for speech. It features a terraced floor plan to provide early reflected sound throughout the audience. The second room is a 300 seat recital hall at Conrad Grebel College in Waterloo, Ontario. In this room, special attention has been given to platform acoustics using the recent findings of Gade and Naylor. Both designs demonstrate the practical application of modern acoustical research.

SOMMAIRE

D'importants progrès ont récemment été réalisés dans le domaine de l'acoustique des salles. Une meilleure compréhension du comportement du son dans les salles permet d'avoir plus de latitude et un meilleur degré de confiance au niveau de la conception. Le design de deux nouvelles salles est présenté. La première est une salle d'assemblée des Témoins de Jéhovah de 3500 sièges utilisée principalement pour des discours et des allocutions. Elle est formée en terrasses de façon à réfléchir promptement le son d'un bout à l'autre de la salle. La deuxième est une salle de récitals de 300 sièges au Collège Conrad Grebel à Waterloo en Ontario. Dans cette salle, une attention spéciale à été donnée à l'acoustique du théâtre, sur la base des récents résultats de recherche de Gade et Naylor. Ces deux modèles démontrent le potential d'application pratique de la recherche moderne en acoustique des salles.

1. INTRODUCTION

Since Haas' seminal study on the effects of early reflected sound on speech intelligibility,[1] nearly forty years ago, a new understanding of the behaviour of sound in theatres and concert halls has emerged. Subsequent studies in the 1950's and 1960's confirmed that the time of arrival of early reflected sound at the listener is critical. For good speech intelligibility, at least half of the acoustic energy must arrive at the listener within 50 ms of the direct sound. Musical clarity is analogous to speech intelligibility except the threshold between useful and detrimental sound is slightly longer at 80 ms.[2]

Work in the late sixties and early seventies established that the spatial aspects of early reflections are also important.[3] It was found that reflected sound arriving at the listener from the sides within 10 to 80 ms of the direct sound promotes a feeling of spatial impression or envelopment.

Multi-dimensional studies of existing concert halls in the 1970's and 1980's[4,5] have brought about a general consensus on the desired subjective and objective attributes of a hall. The subjective qualities are: overall loudness, clarity, reverberance, spatial impression, timbre and intimacy. Most of these attributes are inter-related and there is no single parameter that will, in the absence of the others, guarantee good listening conditions.

2. COMPUTER TECHNIQUES

The findings described above indicate quite clearly that the appreciation of a room's acoustic is determined primarily by the sequence of early reflections arriving at a listener location. In room acoustics design therefore, computer techniques to predict individual reflections are indispensable

Two methods of tracing sound paths in a room are available. The method of images generates a lattice of virtual sources much like a room full of mirrors. The path between a virtual source and the point receiver is the temporal and spatial equivalent of the real reflection path. The other method is often referred to as ray tracing but is perhaps more accurately described as particle tracing. A single source is used to radiate "particles" of sound which reflect about the room until they are intercepted by a receiver volume or until their energy has decayed to an insignificant level.

Both methods have their advantages and disadvantages and some recent algorithms have combined the two.[6] The method of images cannot account for diffusion or diffraction and execution times increase exponentially with the complexity of the room and the number of reflections. Vorlander estimates that to generate the first 400 ms of decay in a typical 15,000 m^3 concert hall, modelled with thirty surfaces, the execution time on a AT compatible personal computer will be in the range of 10,000 years.[6] Because the method of images employs a point receiver it can produce extremely accurate spatial resolution, accurate enough to generate binaural computer simulations of sound fields in a room before it is built. For this same reason, it is also a useful predictor of stage acoustics parameters, some of which are measured as close as 0.5 m from the source.

Particle tracing can model acoustic diffusion and for complex rooms its execution time is much shorter than the method of images. It also lends itself well to multiple receivers, which can be used to create maps of the acoustical conditions in the seating area of the room.

Both methods produce reasonably accurate representations of the important early reflected sound. For later sound, e.g. the reverberant decay beyond 200 ms, the precision is less accurate. Legrand & Sornette point out that two rays, starting out with an apparently insignificant difference in direction (10^{-14} radians), can propagate at right angles to each other after only 20 reflections.[7] It is apparent therefore that the reverberant field is, like many other natural phenomena, chaotic. Just as Lorenz has established that the prediction of weather beyond a few days is intrinsically inaccurate[8], it would appear that algorithms such as the method of images and particle tracing are not and perhaps cannot be accurate beyond the first few reflections.

Hodgson's studies seem to support this thesis[9]. He has found significant differences between conventional computer predictions of sound fields and the actual measurements. He demonstrated that particle tracing predictions correspond better with measurements if the calculations implement a compensation corresponding to random Lambertian diffusion. Diffusion is inherently chaotic so it would appear that his findings confirm what we are beginning to understand as the chaotic nature of (late) reverberant sound.

The computer software we have developed to predict reflection sequences in a room is called TRACES. Two algorithms are implemented: the method of images, based on Borish[10] and particle tracing based on Krokstad et al.[11] The two algorithms are independent, no attempt is made to blend early reflections from the method of images with the late reflections generated by particle tracing. Data is entered using a three dimensional (3D) graphics interface. Results can be viewed as sound energy impulse responses, either as function of time or angle of incidence. 3D "wire diagram" representations of the room show the path of sound rays as they reflect about the room. It is also possible to view the range of reflections cast by a given reflector. This module of the program, again using 3D graphics, is extremely useful especially in the early design phase of a project.

TRACES is still in development and has not as yet been calibrated. For this reason, it is used only for comparative studies of various design alternatives.

3. 3500 SEAT ASSEMBLY HALL

The 3500 seat Assembly Hall for Jehovah's Witnesses in Norval, Ontario will replace the existing hall for 1812. Like the present hall, it will be used primarily for speech with the aid of electro-acoustic reinforcement. The hall has been specifically designed to optimise listening conditions, using a central loudspeaker cluster located above the stage and appropriate early reflected sound. To do this and still accommodate the design requirement of 3500 seats, with at least 2300 on the ground floor, it was decided to use a terraced floor plan based, loosely, on rooms such as Berliner Philharmonie, the 2500 seat concert/congress hall in Las Palmas, Canary Islands[12] and the Sapporo Cultural Centre in Sapporo, Japan.[13] The design has been greeted with excitement by the both the architect and the owner because, in addition to solving the obvious acoustic problems, it opens up new architectural

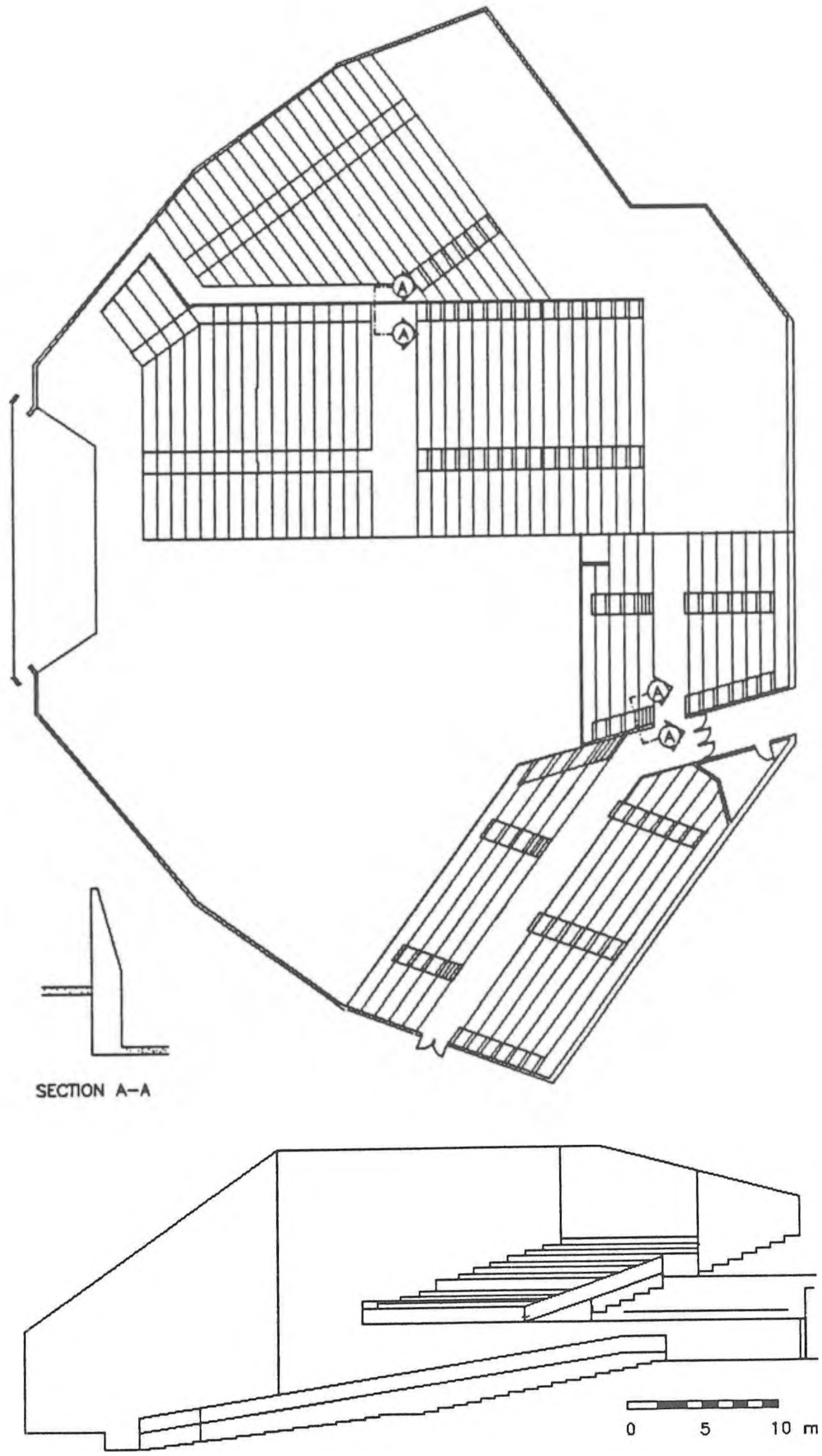

Figure 1 Plan and Centre Line Section of the Jehovah's Witnesses Assembly Hall in Norval, Ontario.

possibilities giving a large scale room a better sense of intimacy. The new hall will accommodate almost twice as many people as the existing room yet no one will be seated any further from the stage.

A plan and section of the room are shown in Figure 1. The central portion of the ground floor seating area is approximately 1 m below the two side areas. The same is true in the balcony. The wall separating the central and side portions is 2 m high, the top half of which is inclined upwards at a 1 in 6 slope. The orientation of this sloped wall is based on the loudspeaker location, approximately 7 m above the front of the stage. Using a sloped surface provides (loudspeaker) reflections throughout the central seating area whilst maintaining a low dividing wall. The reduced height of the wall translates into a lower overall building height.

The critical elements of the acoustic design are the dividing walls and the ceiling, both of which provide the requisite early reflections for good speech intelligibility. The sloped dividing walls provide first and sometimes second order reflections to listeners, both within 50 ms of the direct sound.

The ceiling was designed in the light of recent findings by Barron and Lee[14] and Bradley.[15] These studies of existing halls found that rooms with diffusing or backscattering elements in the ceiling consistently demonstrated lower Total Sound Levels and shorter Reverberation Times near the back. For this reason the ceiling is simple, without ornamentation or major openings for lighting or ventilation.

4. PLATFORM ACOUSTICS

It has long been accepted that the acoustical requirements of listeners and performers are not the same. Research in the past decade has begun to establish relationships between the subjective judgements of musicians and the measurable objective acoustic properties on an orchestra stage. Work by Marshall et. al.,[16] Meyer[17] and most notably by Gade[18] and Naylor[19] has extended our understanding significantly beyond the previous common sense observations.

Meyer has studied the masked thresholds of audibility for instrumental musicians. He found that for reciprocal hearing, "reflections falling vertically from above may be more prominent in the acoustic perspective of most instrumental players than wall reflections or sound reach

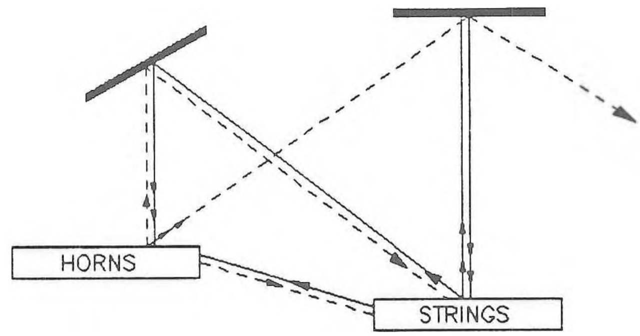

Figure 2 Schematic stage ceiling proposed by Meyer. The solid lines indicate the intensity of sound radiation and the open lines demonstrate the aural sensitivity to indirect sound.

ing the player diagonally from above".[17] He proposed a ceiling design, shown in Figure 2, that takes advantage of the directional characteristics of the musicians' hearing and the radiation patterns of the instruments they are playing.

Early reflections also influence the perception of the performer's own instrument or voice. Gade has established that the threshold of perception for a single reflection by a musician playing an instrument is much higher than the amplitude of the reflection off a plane surface, assuming normal spherical attenuation[19,20]. This is illustrated in Figure 3. In other words, a single reflection cannot, on its own, contribute to a soloist's acoustic impression of his performance. Therefore, to ensure adequate Support for a soloist, a stage enclosure must provide a series of early reflections, one or two will not suffice. The term subjective term "Support" has been defined by Gade as "the property which makes the musician feel that he can hear himself and that it is not necessary to force the instrument to develop the tone"[20]. He proposed the following parameter to quantify Support:[21]

$$ST2 = 10\log\frac{\int_{20}^{200} p^2(t)dt}{\int_{0}^{20} p^2(t)dt}$$

He found that on stages were ST1 was less than the thresholds of perception described in Figure 3, the halls were found to be lacking in Support.

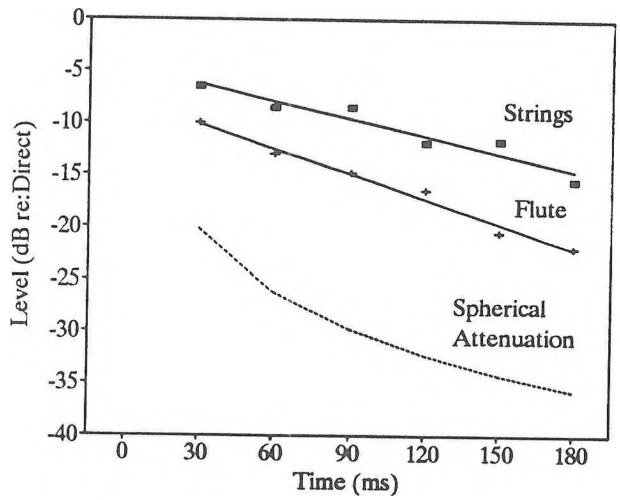

Figure 3 Threshold of perception of a single reflection for soloist, after Gade. The thresholds for strings (violins and celli) and flutes are significantly above the level of a single reflection, shown with the broken line.

Naylor expanded on the musical and acoustical influences on ensemble[19,22]. He found that the Modulation Transfer Function (MTF), previously used by Houtgast and Steeneken to model speech intelligibility,[23] was also a good model for what he called Hearing of Other.

The MTF treats the propagation of sound in a room much like an Amplitude Modulated (AM) radio signal. The sound is characterized by two components, a carrier signal in the audio frequency range and modulating signal that shapes the envelope of the carrier signal. The carrier represents the musical note, for example A-440 Hz, and the modulation signal corresponds to the rhythm at which it is played, typically between .5 and 5 Hz. At higher frequencies, between 5 and 20 Hz, the modulation signal contains information about dynamic transients (i.e attack and release). Figure 4 shows a music/acoustic interpretation of the information content of a modulation signal. The MTF is a ratio between the input and output modulation depth which indicates how much the signal modulation has been degraded by the transmission path and noise. The MTF ranges from 0 to 1, the latter indicating perfect transmission.

Naylor found that in the presence of noise only, there was a linear relation between the MTF and musicians' judgement of Hearing of Other. When reverberation was added the relation became non-linear, quite similar to the speech intelligibility curves developed by Houtgast and Steeneken.

As in previous studies, Naylor found that a balance must

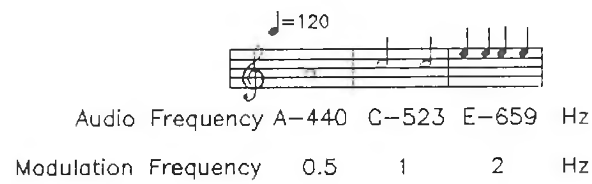

Figure 4 A music/acoustic representation of the information content in a modulation signal.

be struck between Hearing of Self and Hearing of Other. He points out that the simple doctrine of "more energy returned to the orchestra is better" is "clearly not tenable".[19]

5. 300 SEAT RECITAL HALL

The new recital hall for Conrad Grebel College at the University of Waterloo, Ontario will seat 300 in a volume of approximately 2700 m^3. The room is based on a classic shoe box shape, although the side walls are in fact non-parallel, forming a slight reverse fan. This was done to avoid flutter echo or the tonal colouration which precedes flutter echo. Because the room will be used as teaching

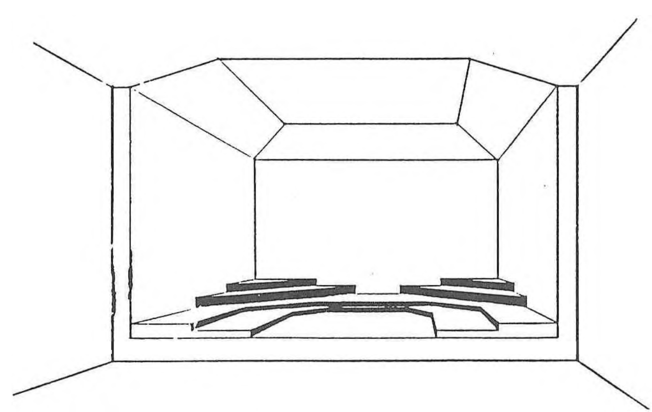

Figure 5 Perspective drawing of the proposed stage for the recital hall at Conrad Grebel College, University of Waterloo, Ontario.

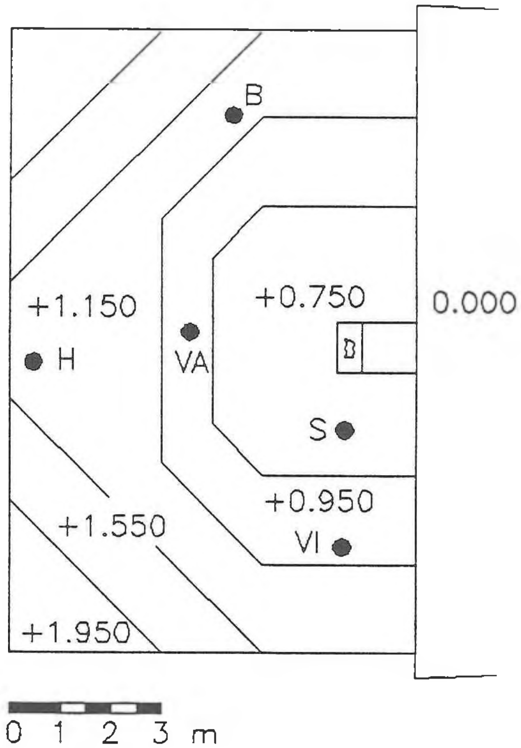

Figure 6 Source and receiver for locations of the analysis of the Conrad Grebel Recital Hall stage (Plan).

facility, special attention was given to the performing conditions on stage.

Using the method of images module of TRACES, we have analyzed four stage configurations, implementing some of the parameters described by Gade and Naylor. The first configuration has a flat floor and a nominally flat ceiling 8.25 m high. The second has a tiered floor with the same ceiling as the first. The third stage, shown in Figure 5 has a tiered floor and a shaped ceiling, 8.25 m high. The ceiling design is based on Meyer's proposal, cognizant of Gade's observations on reflection thresholds (Figures 2 and 3 respectively). The forth configuration is similar to the third except the ceiling is lower, at 6.25 m. Calculations were performed for 5 locations on the stage, as shown in Figure 6. The positions correspond roughly to: Violins (VI), Bass (B), Violas (VA), Horns (H) and Soloist or First Violin (S).

Figure 7 compares the change in MTF when the shaped ceiling is lowered from 8.5 m to 6.5 m (i.e. the third and fourth configurations). MTFs are seen to improve above 1.6 Hz when the shaped ceiling is lowered. Roughly speaking, the improvement is proportional to the distance, i.e. the positions furthest from the violinist see a greater improvement. At the closest position, the change is minimal, less than 0.1. Although MTF difference limens have not as yet been established, Naylor has advised that a change in MTF of 0.1, such as that shown in Figure 7, is "likely to lie around the limit of what is noticeable".[24] One would expect therefore that the violinists' Hearing of Other would improve for some sections on the stage when the ceiling is lowered from 8.5 to 6.5 m. The improvement will be most significant for the furthest section (Bass) and will not be noticeable for the closest section (Soloist).

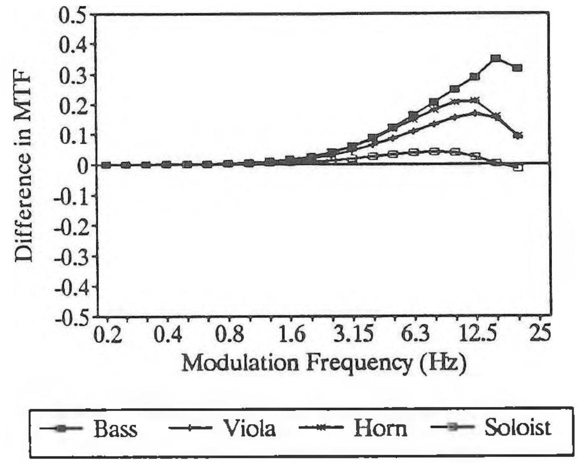

Figure 7 Change in the MTF re: location VI comparing a stage with a 8.5 m high shaped ceiling to one with a similar ceiling 6.5 m high.

Although the MTF model would suggest that the lower ceiling is better, experience with existing halls suggests otherwise. The accepted wisdom is that stage reflectors work best at heights of 8 to 10 m. Why then the discrepancy? The answer lies in the fundamental dilemma of stage acoustics design - the conflicting needs of a performer to hear both himself and his associates and the listeners' desire to hear the music as a whole, embellished with reverberation.

Although MTFs and ST1 increase as the ceiling is lowered, a balance must be struck between the two. That is, Hearing of Other must not be sacrificed for Hearing of Self or vice versa. To date, a method of quantifying that balance does not exist. Furthermore, as the ceiling is lowered, Early Decay Times will decrease. This will result in a reduced sense of reverberance. In a recent survey of existing auditoria,[25] we found that, where the orchestra had the option of adjusting the height of the stage reflector,(at the Centre in the Square, Kitchener, Ontario) it was set at 11 m. That is, above what is thought to be the optimum height. When the reflector was lowered from 11 m to 8.5 m, both the MTFs and the ST1 ratios improved. The Early Decay Times however decreased significantly, from approximately 2.2 to 1.7 seconds. It would appear that the conductor, given the choice of reflector height, decided in favour of the listener.

Now that we have decided on the reflector height, let us consider the effect of the shaped ceiling versus the nominally flat ceiling. Predicted ST1 values showed little or no change between the two ceilings. Using predicted MTFs, there were some quantifiable differences between the two ceilings but the difference was in the range of ±0.1 or less. As we pointed out before, Naylor's experience is that performers will probably not notice a change in MTF of this magnitude.

This is not to say that the shaped ceiling is without merit. The TRACES study of early reflections revealed that the horn section receives more overhead reflections from the violin section with the shaped ceiling than it does with the flat one. This, according to Meyer, suggests increased audibility of the string section in the horn section.

The successful ceiling design therefore was the third configuration, i.e. a shaped ceiling 8.5 m above a tiered stage as shown in Figure 5.

6. CONCLUSIONS

Some of the many new developments in rooms acoustics have been reviewed. The advances in audience and platform acoustics as well as computer techniques are formidable. Perhaps the most significant of these developments is the realization that reverberant sound is a chaotic phenomenon.

The acoustic design of two halls has been described. The two rooms presented different acoustical challenges. The Jehovah's Witnesses Assembly Hall in Norval, Ontario will be a very large room, used primarily for speech. The recital hall at Conrad Grebel College, Waterloo Ontario will be used for music with an emphasis on teaching. The method of images/particle tracing software, TRACES, was used to analyze various room configurations in an attempt to optimise the acoustic design.

For the Assembly Hall, the design uses a terraced layout to provide reflected sound to all the listeners within 50 ms. The Conrad Grebel recital hall design is based on a classic "shoe box" configuration. Special attention was given to the acoustical conditions on the stage using some of the recent findings of Gade, Naylor and Meyer.

Because room acoustics research cannot always provide foolproof recommendations, the design of both rooms was based, as much as possible on existing successful halls. This was particularly true for the stage design of the Conrad Grebel recital hall.

ACKNOWLEDGEMENTS

I would like to thank Drs. Murray Hodgson and John Bradley who helped with the ceiling design of the Jehovah's Witnesses Assembly Hall. Ms. Rose Tardao provided the perspective drawing of the Conrad Grebel Recital Hall stage. Much of what is shown here was developed without financial remuneration, costs that were inevitably borne by my family. I would like to thank my wife Jacqueline Hayden for her infinite patience.

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