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**ROOM ACOUSTICS:
An investigation into the Computer
Simulation of Room Acoustics, with
special reference to Jameson Hall**

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Terms of Reference

This thesis was commissioned by Mr A W D Jongens on 1 February 1999. Mr Jongens requested that the thesis be a research investigation into the computer simulation of room acoustics.

Mr Jongens specific instructions were:

- Investigate physical room acoustics
- Analyse the acoustics of an existing room, for example the Jameson Hall
- Perform research on existing methods of computer simulation of room acoustics
- Write a computer program to simulate room acoustics, using the knowledge gained from research
- Compare simulated room acoustic results with the measured results for the same hall.
- To submit the thesis by 29 September 2000.

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Statement of Work Done

The work contained in this thesis was all performed by the author, Gareth Priede. Where assistance has been given or research made it is referenced. General assistance was also given by Mr Jongens, my supervisor for this thesis.

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Synopsis

This thesis consists of essentially two parts. The first deals with the theory and measurement of room acoustics while the second examines the room acoustic prediction methods.

1.1. Synopsis: Theory and Measurement of Room Acoustics

The most important tool of the acoustician in the analysis the acoustics of a room or building is the impulse response, measured with a gun-shot and a microphone. From the curve of the graph of the impulse response curve reverberation time can be derived, which relates to the human subjective sensation of reverberance. Other qualities can also be obtained, although reverberation is the most essential.

The Jameson Hall was used as a measurement example, and average reverberation times of about 4s were measured in the empty hall. Also some localisation of the sound field was observed, for example in the left and right alcoves and directly underneath the dome.

1.2. Synopsis: Room Acoustics Prediction Methods

Room acoustic prediction consists of the theory behind simulation methods and a discussion of the results created by the simulation program developed for this thesis, called RoWena.

1.2.1. Theory of Simulation Methods

The nature of a physical sound field in a room was described and it was determined that an exact mathematical description of the sound field is not possible. This is because the number of modes in a realistically complex room is too great. The role of a 'diffuse sound field' in describing this complexity is explained, and diffusion will be seen to be an important criterion in predicting a room's acoustics.

The use of geometrical acoustics, which simplifies the nature of sound waves into discrete rays that travel along straight lines and reflect from walls like billiard balls, is used instead.

Limitations in ray tracing, such as the finite number of rays that can be simulated, induce the usage of a modified algorithm called secondary sources. In this technique less rays are used but a better approximation of the impulse response curve is obtained. However the requirement that the hall has a diffuse sound field is now critical because of the assumptions in the model.

Early reflections, which are useful again for reverberance and also for many other important room acoustical quantities, can be found using mirror imaging. This process searches for geometrically exact ray paths, but is limited in the number of consecutive surfaces per ray path it can calculate. This makes it useful for early reflections only.

An additional technique that simulates the effect of scattering from a surface is widely agreed to improve the accuracy of the simulation results. Although this technique has no strong basis in reality, it was found by independent researchers to be important in obtaining accurate simulation results.

Because of the predominance of curved surfaces in the Jameson Hall, independent research was carried out on the simulation of curved surfaces. Of most importance is a method for finding early exact ray paths, previously found by mirror imaging, using a search method.

1.2.2. Results of Room Acoustic Simulation on Jameson Hall

A computer program was developed by the author that included all the simulation methods discussed. It was tested on a computer model of the Jameson Hall. The results were compared with the measured results obtained in the first section. Unfortunately, although some favourable comparisons were found, in general the results could not be said to be reliable in predicting the acoustics of the hall.

However other predictions, such as the direction of arrival of specific reflections and the exact reflecting nature of the domed ceiling of the hall, were good.

1.3. Conclusion and Recommendations

While some successful room acoustic prediction programs have been developed, the program developed for this thesis requires some more work. However the basic principles are sound and some useful information can be obtained.

Some new work on curved surfaces has been made, specifically in determining early ray paths. However more research into the effects of curved surfaces on the sound field needs to be conducted, in particular the energy of rays reflected by curved surfaces. The simulation model takes no account of the nature of spreading or concentrating a ray when reflected from a curved surface, a fact which requires research and implementation.

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2. INTRODUCTION

The environment in which people listen to music, speeches or in fact any sound, plays a large part in determining the quality of the sound that is actually heard. For example an orchestra playing an open-air concert in a park will sound different to an otherwise identical performance in a restaurant.

Determining what effect the influence of a room on the sound has, as perceived by people, is a complicated problem. As humans we are able to make judgments on whether a sound is pleasing or not, but this does not necessarily aid in finding out why, nor in distinguishing which aspect of the sound was pleasing.

Until the beginning of the 20th century there were few qualities about the acoustics of concert halls that could be compared. Halls and buildings were simply built with aesthetic or practical ideals and the acoustics were left to fend for itself. Interestingly many of these halls have better acoustics than halls that are built today using acoustic principles.

However the pursuit of scientific absolutism has led to much research on acoustics and now a significant knowledge base has been created. So much so that it is now nearly possible to accurately reproduce the acoustics of a hall entirely on a computer.

The objectives of this report are:

1. To describe the qualities relating objective and subjective room acoustics.
2. To describe the objective acoustics of the Jameson Hall.
3. To describe the existing computer simulation methods for simulating objective room acoustics.
4. To describe the results of the computer simulation program written for this thesis.

The thesis begins by describing how objective room acoustics is measured and its relation to subjective acoustics, i.e. as perceived by humans. This is followed by a description of the acoustics of the Jameson Hall as measured using the described techniques.

The next section of the thesis begins by explaining the nature of sound in a room, leading onto a description of the means of simulating this. The techniques of ray tracing, secondary sources, mirror imaging and scattering are explained in that order. This is followed by a section dealing entirely with the simulation of curved surfaces. Lastly the Jameson Hall is simulated using the techniques explained and the results compared to the measured results. Finally conclusions and recommendations are drawn on the various parts of the thesis.

3. INTRODUCTION TO ROOM ACOUSTICS

A sound heard in a room, such as a concert hall or lecture theatre, differs vastly from the same sound as heard in the open. This is because the walls of the room, and any other objects contained in the room, reflect the sound, and the reflected sound often passes the listener many many times. The listener therefore hears not just the sound from the loudspeaker (or other sound source) but also subsequent repeated reflections from different directions (Figure 1).

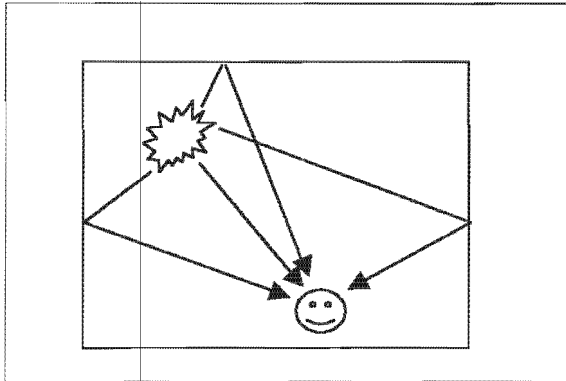


Figure 1: Reflections in a Room Arriving at a Listener

If these reflections occur quickly enough after one another, as is usually the case, then they are not heard as different sounds, but rather the human brain amalgamates them into a single sound. The original sound is perceived differently because of this, and the effects of these differences on the listener are what is meant by the 'acoustics' of a room.

In order to measure the acoustics of a hall, it is not sufficient to record a piece of music or speech played in the hall and analyse it. There are too many variable quantities in such a procedure, such as the type or speed of the music/speech.

Instead the *transfer function* of the room is found, which quantitatively determines the way in which a room modifies the original sound.

The transfer function is ideally the response of the room to an infinitely short impulsive sound. In practice a gun-shot is usually used, or a computer synthesised sound. A microphone is situated at a position in the hall where the impulse response is to be measured, and all the sound detected by the microphone is recorded. A typical impulse response graph is shown in Figure 2.

¹ The most commonly used computer technique is called an MLS response, which stands for Maximum Length Sequence

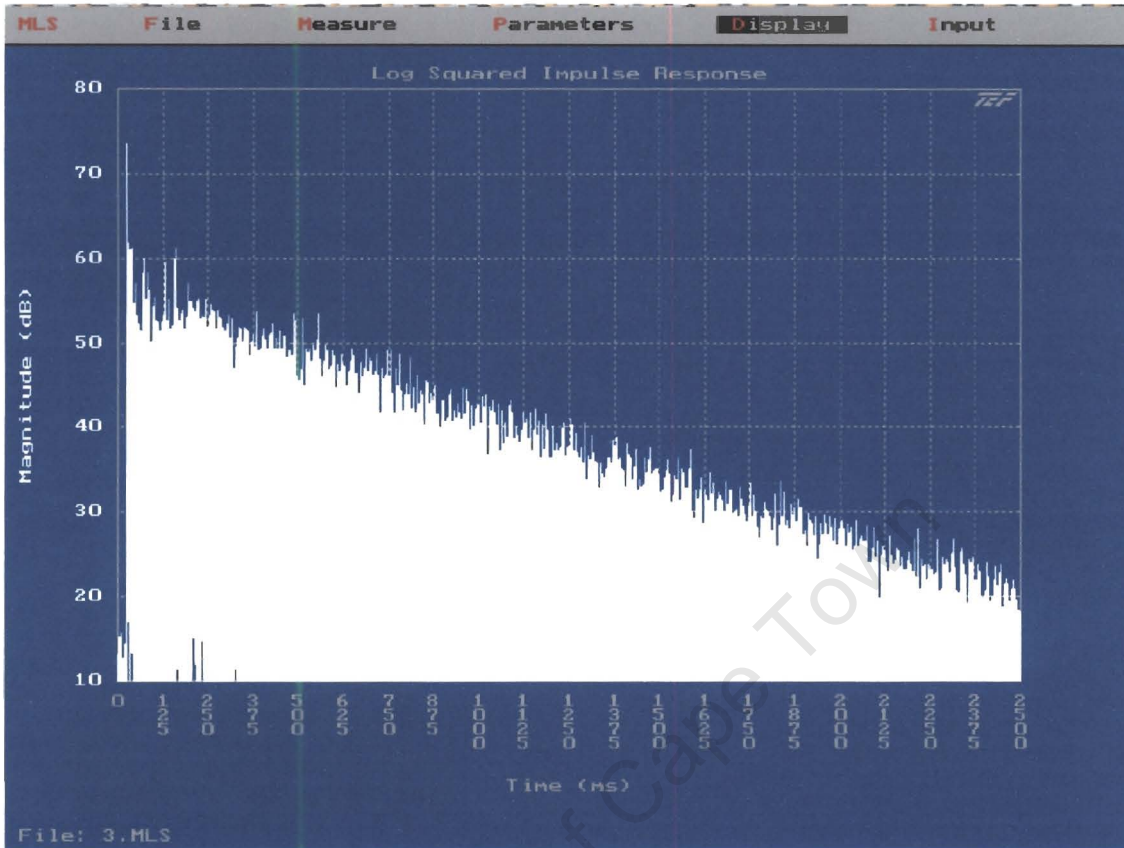


Figure 2: Example of an Impulse Response Graph

The x-axis of the impulse response graph is time in milliseconds, and the y-axis is the sound intensity in decibels. At the far left of the graph, at an intensity of 74dB, is the first sound to reach the microphone, after a travel time of 25ms from the source. The intensity of this sound is the highest because it has not been reflected, and therefore absorbed, by any surfaces. This is called the direct sound and in a measurement on a hill with no nearby reflecting surfaces this would be the only mark on the impulse response graph. (see 7.2.6 for an explanation of the absorption of sound by surfaces).

Shortly after this are some reflections with an intensity of about 60dB. These have reflected at least once but the propagated distance of each is only slightly longer than the direct sound since they have arrived very soon after it. These reflections are individually discernable.

As time progresses the sound reflects off more and more surfaces, consequently decreasing in intensity through repeated reflections with the room surfaces and through spherical spreading of the sound. It is clear from Figure 2 that there are a great many reflections arriving at the measurement point. This causes the distinctive decay of the envelope impulse response graph. It shall be seen later that the envelope of the graph is an important characteristic of the hall's acoustics.

Eventually the sound decays away to inaudibility. In the graph shown in Figure 2 there are still audible reflections after 2½ seconds.

Some information, such as the phase of the recorded sound, is not shown on the impulse response graph, which is very important for some purposes. Nevertheless most important acoustical attributes can be determined from the impulse response graph. Some of these are discussed in the next section.

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4. SUBJECTIVE AND OBJECTIVE QUALITIES OF HALLS

Having now introduced the physical mechanisms of room acoustics, it is possible to take a step back and examine what a human listener experiences upon hearing sounds in a hall. By taking surveys of audiences attending concerts and other events, and by controlled listening tests in special environments, acousticians have isolated distinct characteristics of music and speech that can be separately measured.

Unfortunately it is difficult to obtain precise results because of the variable nature of human impressions. The surveys have questions such as "Rate your experience of the Warmth of the sound from 1 to 10". The use of the word 'warmth' allows interpretation by the respondent, which introduces uncertainty into such surveys. Even worse, the same person might answer the same question differently on different days.

A more controlled method involves playing many similar sound samples that differ in one quality only. The subject then records his/her impression of the sound. Ideally in this way the precise effect of particular qualities of the sound could be determined. In practice however the subject becomes tired and confused after listening to many almost similar samples.

In spite of these difficulties, some accepted qualities have been determined. This section contains a survey of the more common qualities. More detailed descriptions of these and other qualities can be found in books by Barron (1993) and Beranek (1996) as given in the bibliography.

4.1. Reverberance and Reverberation

W C Sabine was one of the first pioneers of acoustics as a science. In about 1910 he investigated many properties of concert hall music, and specifically determined the importance of the reverberance of a hall¹.

Reverberance, which is a subjective effect, is quantified by the objective measurement called reverberation.

4.1.1. Reverberance

Reverberance is a subjective effect caused by a sound reflecting off the walls of a building and being heard by a listener many times over. Since the walls of the hall partially absorb the sound, eventually the reflections are too weak to be audible. The time for this to occur determines the reverberance of the hall.

A commonly used example of extreme reverberance is a tiled bathroom. Tiles do not absorb sound well and so bathrooms are often very reverberant. At the other extreme a luxurious room with a thick padded carpet is likely to have little reverberance, since the carpet will absorb much of the sound.

The experiment of talking in a bathroom demonstrates that a long reverberance makes speech intelligibility difficult. This is because each syllable is still audible while the next syllable is being spoken and it is difficult to distinguish between them. It is therefore necessary to wait for the reflections from the first sound to die away before speaking the second. Because of this there is a maximum acceptable reverberance that a hall can have if it is to be used for speech or talking. In music the distinction between notes is often not as critical as those between words and a slightly higher reverberance is tolerated.

On the other hand a reverberance that is too low is also not desirable. The subjective effect of reverberance is pleasing, as long as it does not interfere with the detail of the sounds. A balance must be sought for, a balance that partly depends on the type of sound the hall is used for.

4.1.2. Reverberation and RT60

4.1.2.1. History and Measurement Technique for RT60

When W C Sabine investigated reverberance he used organ pipes to produce a sound. Then he turned the pipe off and measured the time for the sound to decay to inaudibility using a watch.

This is not a very scientific and exact method, and so he proposed that reverberation time be defined as the time a sound took to decay by 60dB below the initial level of the sound. The 60dB limit corresponds to a sound a million times weaker than the initial sound, and is termed RT60, which is "Reverberation Time 60dB".

RT60 was subsequently measured using a gun shot as the initial sound, but with the advent of computers this has now been largely replaced by an MLS (Maximum Length Sequence) measurement. An MLS measurement uses computer generated pseudo-random noise that is continuously played through a loudspeaker while the sound at a particular position is recorded. The computer then removes the noise and interpolates the reverberation time.

Also, since a very loud source is required to obtain a sound 60dB above the background noise level in the hall, more commonly a 30dB decay time is used and multiplied by two. This decay time is measured from 5dB to 35dB below the direct sound. The 5dB specification ensures that only the reverberant reflections are included in the calculation.

4.1.2.2. Early Decay Time (EDT)

It was later determined that specifically the *early* reflections after the direct sound are important indicators of reverberance. This is because the reverberance of initial sounds masks successive sounds until it (the initial reverberation) decays sufficiently to be inaudible. The listener therefore judges reverberance based on the short interval between notes/words².

Early Decay Time (EDT) is a measurement of this reverberation. It is measured as the decay time from the direct sound to 10dB below the intensity of direct sound, multiplied by 6.

Even so the importance of the RT60 measurement cannot be ignored, since even if the EDT is short, an overly long late reverberance will still detract from the performance/speech.

4.1.2.3. Recommended Values for RT60 and EDT

Through the surveys and experimental techniques described in the introduction, some recommended values for RT60 and EDT have been accepted. Different situations, including the volume of the hall, and different musical styles call for different times and no single value is best for all situations.

Values measured when the hall is occupied or empty may be significantly different, since people absorb a large amount of sound. Some halls have fully upholstered chairs that absorb the same amount of sound as a person, which minimises this difference. The values given below are for fully occupied halls.

Speech is best heard with an RT60 of about 1.2s while choir music is best heard with an RT60 time of about 1.6s to 1.8s. Musical styles are further divided into categories based on the different eras of classical music.

Baroque music is one of the earliest well documented styles, roughly dated from 1600-1750. Bach and Vivaldi are perhaps the best-known composers from this era. Most music was played in small groups, often including the harpsichord and violins. An RT60 time under 1.5s is recommended for this style of music because of the large amount of detail in the music and relatively short time between notes. Classical music (1750-1820, e.g. Mozart) suits an RT60 of between 1.6s to 1.8s. Romantic music (1800-1900, e.g. Liszt) and Organ music sounds best when the RT60 time is between 1.9s and 2.1s.³ Recommended EDT values are usually similar or slightly higher than the RT60 values.^{4 5 6 7 8}

A hall must compromise to a single reverberation time, unless the absorption in the hall can be adjusted for each performance. Note also that a difference of about 0.1s to 0.2s in the reverberation time is significant.

4.1.2.4. Recommended Frequencies for Measurement of RT60 and EDT

The frequency content of the sound has not been discussed before this point. However it has important subjective effects on the listener's experience of the sound. It is possible to filter out any particular frequency range from the impulse response graph using a computer. Because of the nature of human hearing the frequency ranges are usually centered at 125Hz, 250Hz, 500Hz, 1kHz, 2kHz, 4kHz and 8kHz. The doubling of frequency at each range is called an octave.

The reverberation time at different frequencies may be very different. At high frequencies, above about 4kHz, the air in the hall absorbs a large proportion of the sound and so the reverberation at these frequencies will usually be lower than at lower frequencies⁹.

It has been established that RT60 relates the best to subjective reverberance filtered at the 500Hz octave (called RT60(500Hz)) while EDT should be measured for the whole pass band¹⁰, which is the unfiltered response.

When considering other characteristics, such as Warmth and Liveness, other frequencies may be more important (see 4.5).

4.1.2.5. Sabine and Eyring Reverberation Time Formula

As an alternative to measuring the reverberation in a hall, the Sabine Reverberation time formula can be used. This is a formula, devised experimentally by W C Sabine, to determine the reverberation of a hall based only on the volume of the hall and the area and absorption coefficients of each surface¹¹. It is very useful primarily for estimating the differences in difference wall materials.

The Sabine formula is $T = 0.161 \cdot \frac{V}{S\alpha + 4mV}$, where V is the volume of the hall in m^3 , S is the total surface area of the hall, α is the average absorption coefficient of the wall materials in the hall (see 7.2.6), and m is the air absorption coefficient for the frequency to be estimated.¹²

This formula can only be used where the sound field is known to be diffuse, which means that the sound is essentially uniform throughout the hall (see 7.4.3). Also the absorption of the surface materials must be similar throughout the hall.

Where the surface materials differ significantly a more accurate reverberation time formula, called the Eyring reverberation time, should be used. This is $T = -0.161 \cdot \frac{V}{S \ln(1 - \bar{\alpha}) - 4mV}$, where

$\bar{\alpha} = \frac{1}{S} \sum S_i \alpha_i$. In this formula the absorption and size of each surface are incorporated into the result.

4.2. Clarity and C80

Reverberance was used as the sole judgment of a hall's acoustics for a long time. Eventually it was discovered that even amongst halls with similar reverberation times, the quality of the music was still different. More quantities were therefore sought to further characterise and identify these differences. One of the more useful and commonly used is Clarity, and corresponding clarity factor C80¹³.

4.2.1. Explanation of Clarity

Clarity refers to how much discrete sounds stand apart from each other¹⁴. It is therefore a descriptor of the listener's ability to discern different notes or music events. It is partly based on the skill of the musicians (in the case of music) and partly on the acoustics of the hall.

Clarity is closely related to reverberance. A long reverberation will usually indicate a low clarity, and visa versa.¹⁵

As with reverberance, clarity should not be too low or too high. If clarity is too high music will sound tinny and harsh. For speech a large clarity is usually desirable.

4.2.2. Measurement of Clarity

The subjective sensation of clarity is determined by the number and strength of the reflections arriving very soon (within 80ms) after the direct sound reaching the listener^{16 17}. If many (strong) reflections arrive within this time, relative to the number of reflections arriving after this time, then clarity will be good, and visa versa.

Several measurements of the ratio of early to late reflections have been proposed by different researchers, each purporting to measure clarity more accurately. Even so many conflicting results have been obtained when relating these measurements to subjective clarity¹⁸.

4.2.2.1. C80 and C50

The C80 is the ratio of sound energy arriving within 80ms after the direct sound over the sound energy after 80ms. This is shown in the following formula, where $p(t)$ is the instantaneous pressure of the measured impulse response:

$$c_{80} = 10 \log \frac{\int_{.08}^0 p^2(t) dt}{\int_{.08}^{\infty} p^2(t) dt} dB$$

Optimum C80 values for music (hall occupied) should lie between -4dB (low clarity) and +4dB (high clarity).^{19 20 21}

C50 is same as to C80 but is measured to 50ms rather than 80ms. C50 is a better descriptor of speech, whilst C80 describes musical clarity.

4.2.2.2. Definition/Deutlichkeit (D)

Deutlichkeit is similar to C50 in that it is an early to late ratio measurement up to 50ms. However the denominator of the equation is an integral over the whole impulse response measurement, rather than from 50ms²².

$$D = \frac{\int_0^{.05} p^2(t) dt}{\int_0^{\infty} p^2(t) dt} \cdot 100\%$$

Definition is expressed as a percentage rather than as a decibel value as for C50. Recommended values for Definition are between 15% (low clarity) and 59% (high clarity)²³.

4.2.2.3. Center Time (t_s)

Center Time is again a ratio, but instead of being a ratio between early and late time, it is a time-weighted ratio over the whole impulse response^{24 25}. The formula is

$$t_s = \frac{\int_0^{\infty} t \cdot [p(t)]^2 dt}{\int_0^{\infty} [p(t)]^2 dt} \text{ and is measured in seconds.}$$

Center Time (also called Center-of-Gravity Time and Schwerpunktzeit) appears to relate well to speech intelligibility²⁶.

A maximum time of 140ms is the limit of minimal acceptable clarity, with lower values indicating increasing clarity^{27 28}.

4.3. Intimacy and Initial Time Delay Gap

Intimacy is related to the listener's sense of size of the hall. An intimate hall is one where the listener feels that the hall is small and that he/she is close to the sound source. This is a desirable quality for a hall. A hall with little intimacy causes the listener to feel removed from the performance or event, and interest and involvement is therefore decreased.

Intimacy is related to the time taken for the first reflection of the sound to reach the listener¹. For example in Figure 3, the path length of the direct sound is 5m, while the path length of the first reflection is $2 * \sqrt{10^2 + 2.5^2} = 20.6m$.

¹ The first can also be considered the first loudest. See Ando for this explanation.

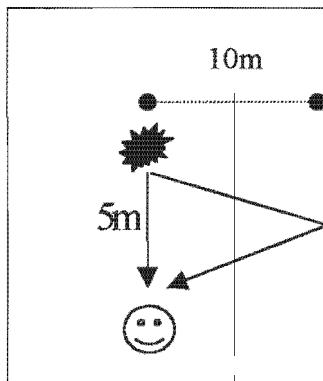


Figure 3: Example of an ITDG Calculation

If the speed of sound is 344m/s , then the arrival time of the first reflection is $0.060\text{ms} - 0.014\text{ms} \approx 46\text{ms}$ after the direct sound. This time is the Initial Time Delay Gap (ITDG). The listener subconsciously uses this time gap to judge the size of the hall.²⁹

In a smaller room the ITDG would be shorter, and therefore perceived intimacy would be greater³⁰. Also, for a listening position further back in the same room, even though the first reflection's path length would be longer, the difference between this time and the direct time would be shorter than for a closer position. For this reason special reflectors are often used to direct early reflections from the stage to the front of the hall. In this way it is possible to trick the listener into thinking a large hall is actually smaller.

The ITDG should be between 8ms and 30ms ^{31 32 33}. Intimacy is also related to visual cues that cannot be accurately measured. If the hall appears small, yet in actual fact the ITDG is large, the listener might still regard the hall as intimate³⁴.

4.4. Spaciousness (Envelopment and Apparent Source Width)

Spaciousness is the sensation by the listener that the sound arrives from all directions around him/her. This means that even though the sound is originating from a particular place (on the stage) and this place is easily identifiable by the listener, a proportion of the sound is heard to come from other parts of the hall. This quality is linked to Intimacy in that it is determined by the early reflections, but in this case not their time of arrival but rather their direction of arrival. Spaciousness causes the listener to feel enveloped by the music, which is a pleasurable effect.

In order to explain how the sensation of spaciousness occurs, note that humans have two ears, each on different sides of the head. Sound reaching one ear first, say the right ear, takes a little bit longer to reach the other ear (Figure 4). From this slight time delay it is possible to localise the direction of a sound.

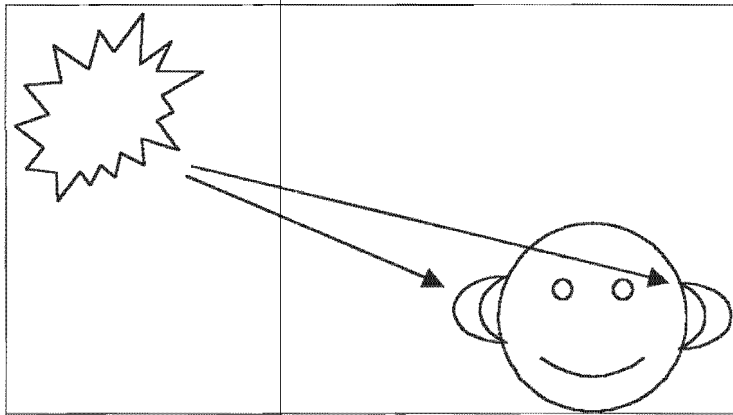


Figure 4: Spatial Location of Sound by a Listener

Since human ears are on the sides of the head, sound or its reflections that travel on this plane, as opposed to from the top or rear, are more effective at providing a sense of spaciousness. Thus (subjective) spaciousness can be determined by measuring the proportion of sound energy that arrives from the sides versus the total sound energy.

4.4.1. Lateral Fraction (LF)

Lateral Fraction is measured using a figure-of-eight microphone. Such a microphone possesses maximum directivity in opposing directions along a line.

Lateral Fraction (sometimes called Lateral Efficiency) is a measure of the ratio of sound energy measured using a figure-of-eight microphone over that measured by an omni-directional microphone.

The formula is

$$LF = \frac{\int_{0.005}^{0.08} p_8^2(t) dt}{\int_0^{0.08} p^2(t) dt}, \text{ where } p_8 \text{ is the measurement made with the figure-of-eight microphone.}$$

(The 5ms time in the lower limit of the numerator integral is to ensure that the direct sound does not form part of this integral.)

Increasing LF values indicate greater spaciousness, with 0.46 considered optimum. 0.18 is considered the lower limit for a typical concert hall³⁵.

LF is usually measured up to 80ms. Reflections arriving after this time were initially considered not to have any effect on spaciousness. Later studies have shown that LF is more accurate when measured up to infinity (or the end of the measured impulse response)³⁶. The reason for this is that late lateral reflections diminish the effect of early lateral reflections, so in halls where late lateral reflections are large, the relevance of LE, measured up to 80ms, is lessened.

Unfortunately few examples of such measurements exist in the written material.

4.4.2. Inter-Aural Cross Correlation (IACC)

In an attempt to provide a better correlation to perceived spaciousness, a different measure was introduced, called the Inter-Aural Cross Correlation (IACC). Much initial work on this measurement was made by Ando.³⁷

IACC is measured in a more direct manner than LF. A dummy head, similar to a human head, is placed in a position where a typical listener's head would be. A twin microphone head set is placed on the dummy's ears, similar to a walkman headset, and two separate impulse response graphs recorded, one for each ear. The two impulse response measurements are then used in the following formula:

$$IACC(\tau) = \frac{\int_{t_1}^{t_2} p_L(t) p_R(t + \tau) dt}{\sqrt{\int_{t_1}^{t_2} p_L^2(t) dt \int_{t_1}^{t_2} p_R^2(t) dt}}, \text{ where } p_L \text{ is the left signal and } p_R \text{ is the right signal}^{38}. \tau \text{ is}$$

varied from -1ms to $+1\text{ms}$ and the maximum value taken. This accounts for the maximum time delay in a signal traveling from one side of the head to the other, and choosing the maximum IACC value over τ measures the maximum similarity of all waves reaching the dummy head.

The maximum possible IACC value is 1, which indicates no lateral reflections. The minimum value is zero.

The limits t_1 and t_2 of the integrals can be varied to measure different aspects of spaciousness. For $t_1=0\text{ms}$ and $t_2=80\text{ms}$, called $IACC_{E(\text{early})}$, it best correlates to Apparent Source Width, which is the perception of size of the stage or other sound source. Thus a low $IACC_E$ indicates that the listener will feel that the stage is very wide.³⁹

For $t_1=80\text{ms}$ and $t_2=1000\text{ms}$, called $IACC_{L(\text{late})}$, it best correlates to envelopment. In both cases values between 0.3 and 0.6 indicate good spaciousness.

4.5. Warmth/Bass and Brilliance/Treble

Warmth and Brilliance are related to the frequency content of the sound. Warmth relates to bass (low frequency, below 500Hz) sound and Brilliance to treble (high frequency, above 2kHz) sound. Both are desirable to a certain degree.

It is difficult to define either of these two terms precisely, and similarly to provide good measurements of them. Many proposals for the measurement of warmth have been proposed, for example the ratio of low frequency reverberation time to mid frequency reverberation time⁴⁰. An alternative result can be obtained by using the intensity of low frequency sound during the first 50ms after the direct sound, though this still does not provide a good correlation to subjective impressions^{41 42}.

At high frequencies air absorption becomes prominent. Therefore the reverberation time of high frequency sound is usually lower than lower frequencies. Brilliance may therefore be related to the ratio of the loudness of high frequency sound after 80ms, once air absorption has had a significant effect, to the loudness at 1kHz.

Perhaps the most useful measurement is to ensure that the reverberation time of the various frequencies conform to the graph in Figure 5.^{43 44} (See also ⁴⁵)

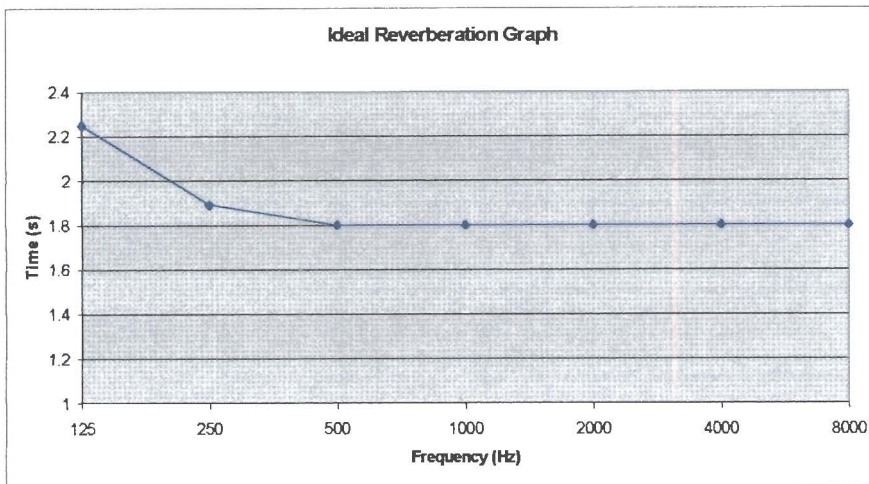


Figure 5: An Ideal RT60 Time versus Frequency Graph

This graph is for a reverberation time (RT60) of 1.8s, and should be moved up or down for other RT60 values. All RT60 times are the same except below 500Hz, where the bass reverberation is increased. Also the reverberation time above 4kHz does not decrease (due to air absorption) which causes the perception of brilliance⁴⁶.

In order to obtain such a graph in a hall, it is necessary to choose the hall's surface materials such that they absorb very little low frequency and high frequency sound. The exact absorption coefficients have to be worked out carefully.

4.6. Speech Transmission Index (STI) and %Alcons

With specific regard to speech, the measurement called the Speech Transmission Index (STI) is an evaluation of how well the amplitude modulation patterns of speech are preserved. Modulation patterns determine the intelligibility of speech and this may be impaired by excessive reverberation, noise and other effects.⁴⁷ STI ranges from 0 to 1, where 1 is excellent and <0.45 is poor.

Similarly %Alcons stands for Percentage Articulation Loss of Consonants. Here 0% indicates perfect clarity, and 15% is the maximum allowable loss⁴⁸.

4.7. Echoes

An echo is a detrimental effect that is present in some poorly designed halls⁴⁹. Normally the reflections in a hall arrive in such quick succession that they are not individually identifiable and they form a single cohesive sound. If however a particular reflection is much louder than the other reflections arriving at that time, then it will be heard by the listener as a unique sound.

Echoes detract significantly from a musical performance, since they break the cohesiveness of the piece and depending on the direction from which the echo arrives may also confuse the listener about the direction of the sound source.

Echoes can be caused by a reflective focusing surface located some distance away from the listener. Sound reaching such a surface will arrive at the listener some time after the direct sound, yet because it has undergone only one reflection will be relatively stronger than the other reflections which have undergone multiple reflections from the closer surfaces (Figure 6). The listener will thus hear the reflection as an echo.

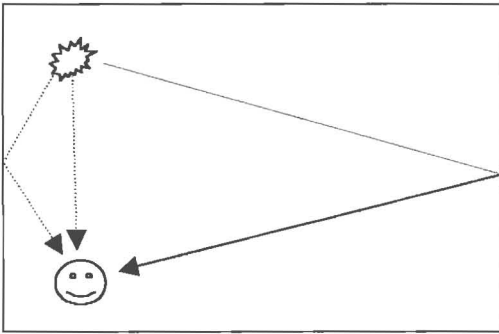


Figure 6: An example of an echo

To identify echoes it is necessary to visually inspect the impulse response curve for reflections that are have a substantially greater intensity than the surrounding reflections. As an example consider the measured impulse response graph in Figure 7.

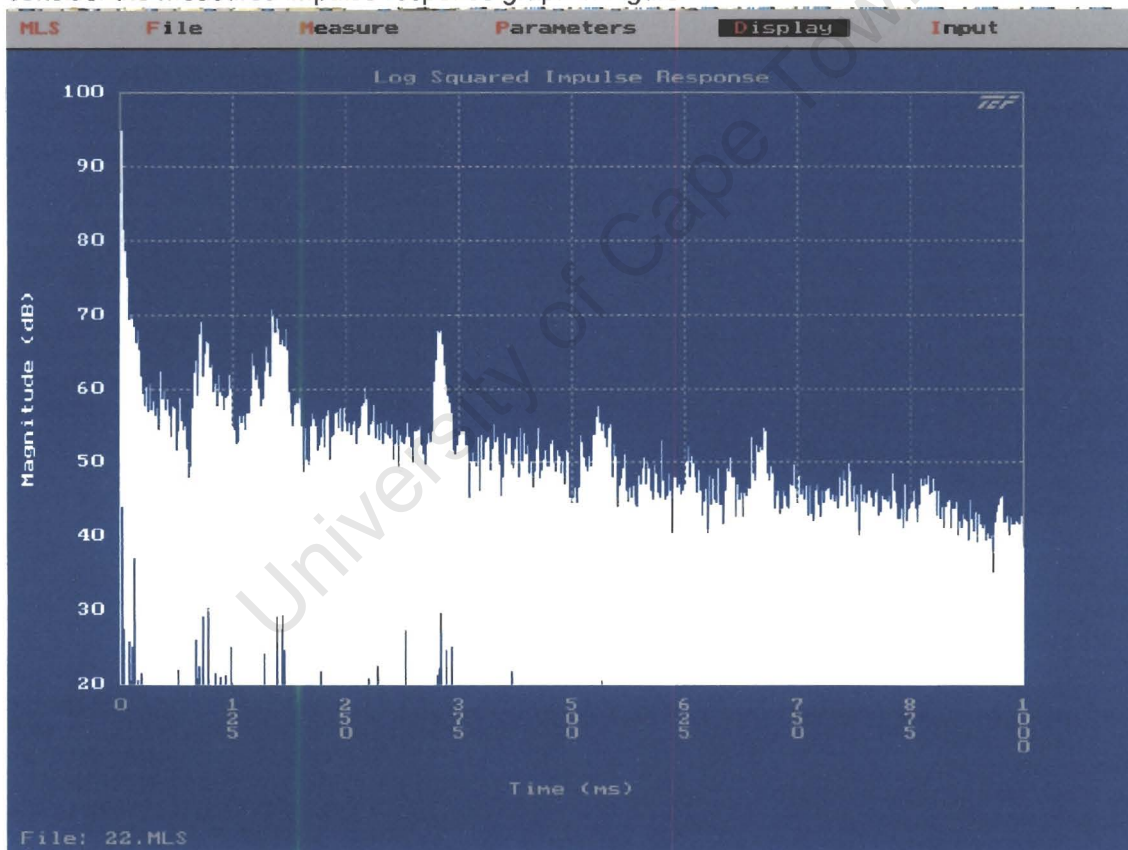


Figure 7: A Measured Impulse Response Graph showing Echoes

This measurement was taken directly beneath the dome in the Jameson Hall, with speaker and microphone beneath the dome. The dome causes a focusing effect, so that a large amount of sound energy is directed beneath it. This sound reflects to the floor and back to the dome, where it is again focused to the center of the dome (see 16.8 for a detailed explanation of the effect of the dome).

In Figure 7 a number of large reflections can be seen at 100ms, 175ms and 370ms, amongst others. Each of these reflections can be heard as an echo if one stands beneath the dome and claps.

The audibility of echoes is subjective. Sometimes an echo will disturb one person and not another.⁵⁰

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5. THE ACOUSTICS OF JAMESON HALL

The Jameson Hall is the historically central building on the University of Cape Town campus. It is used primarily for speeches and also as an exam venue. It has been repeatedly criticised for its poor acoustics, specifically low speech intelligibility. A sound system was installed to correct this problem but without proper consultation and with little improvement. In 1999 the University issued a tender for renovations to the hall to improve the acoustics but has since cancelled the project due to limited fundsⁱ.

The Jameson Hall is the basis for the evaluation of the simulation techniques explained in the computer simulation section, and so acoustical measurements were made in the hall. This section presents some of these measurements.

It does not attempt to provide a complete acoustical evaluation of the hall since this falls outside the scope of the thesis. Rather the results and possible causes are given.

Broadly speaking there are two parts to the presentation, the first covering general aspects of the acoustics throughout the hall, followed by more specific treatment of the various sections of the hall.

5.1. Introduction to Measurement Presentation Style

Many of the measurement results are displayed in a 3D graph that was created using the SigmaPlot software package. An example of such a graph is shown in Figure 8.

ⁱ Conversations with Mr. AWD Jongens, Head of Acoustical Department, UCT

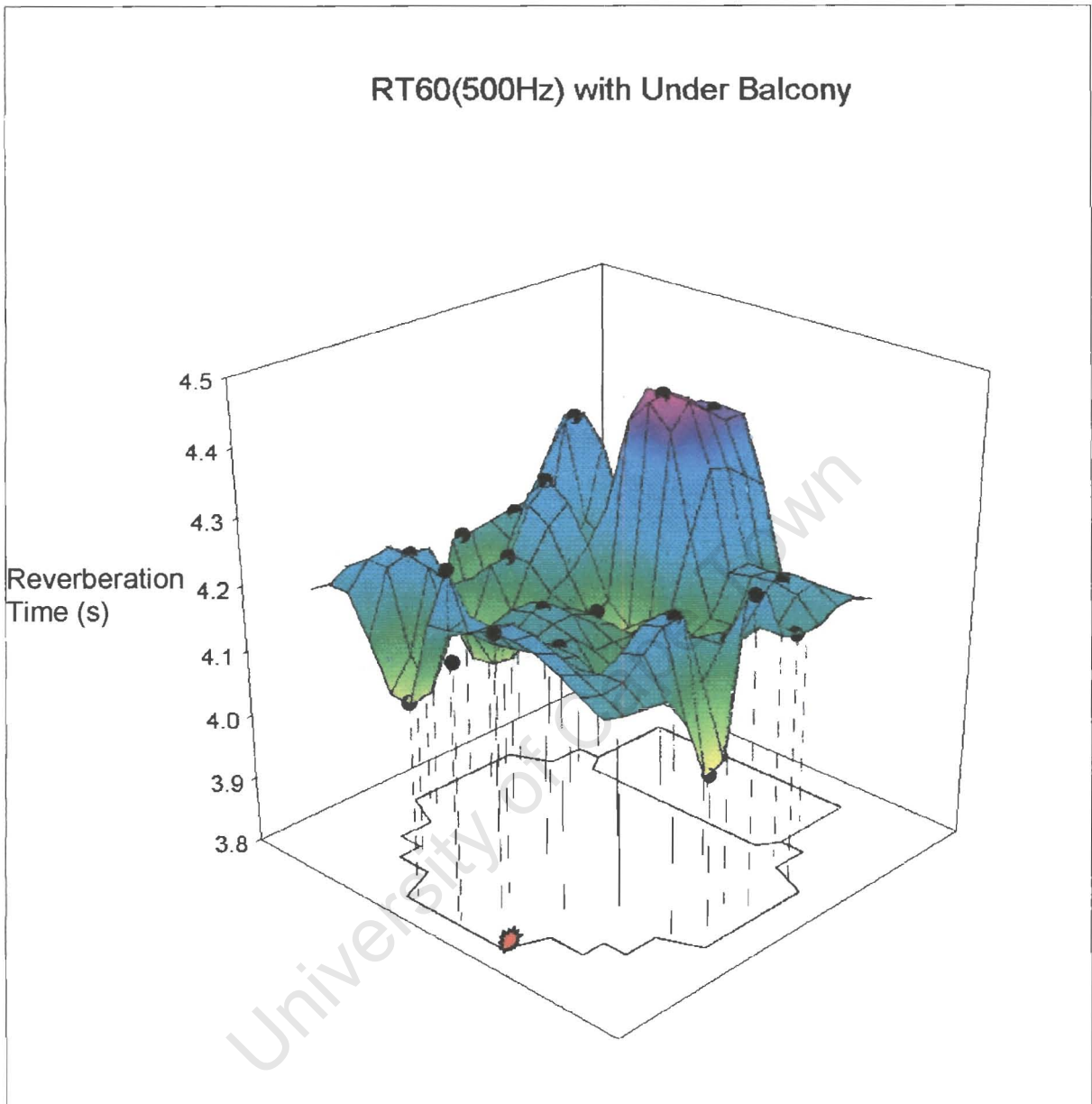


Figure 8: An example of a 3D Measurement Presentation

This graph shows the values on the Z-axis at the left hand side, ranging in this case from 3.8 to 4.5. The graph data has been interpolated from a number of discrete measurements to the continuous graph seen by the SigmaPlot software program. Also shown on the graph are the actual data values, indicated by black dots, with projection lines to the XY plane. It is apparent that the interpolated and physical data match up.

On the XY plane is a representation of the Jameson hall, which is shown in plan view in Figure 9.

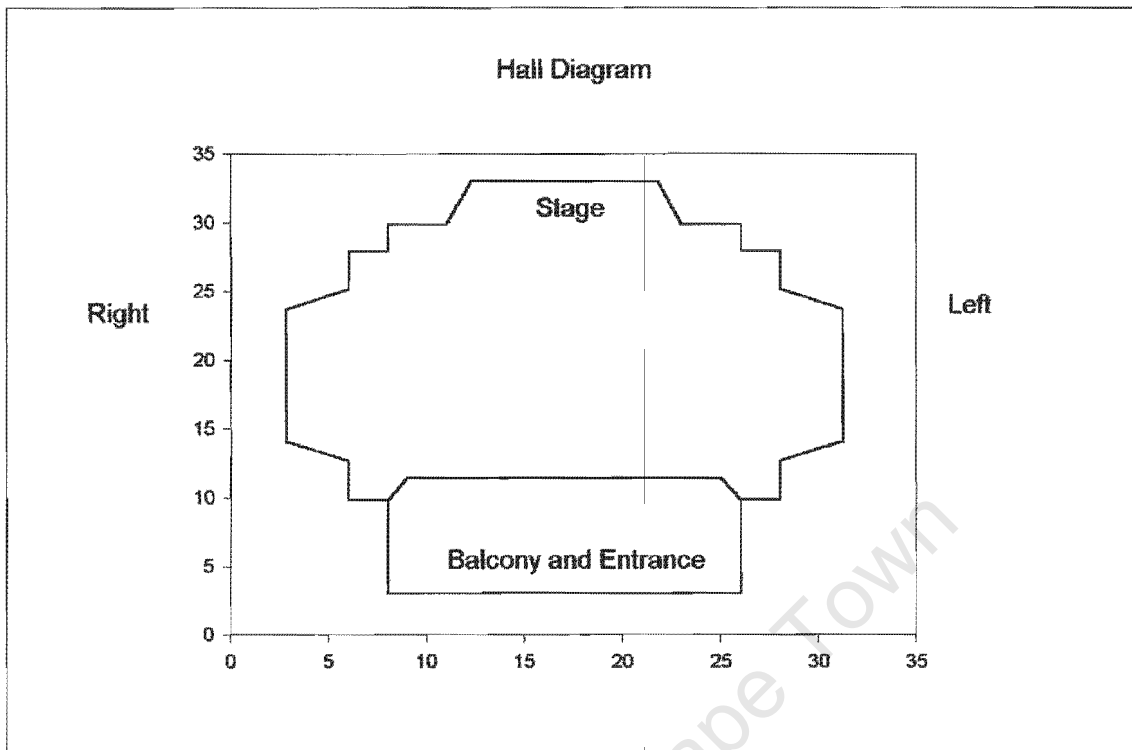


Figure 9: Simplified Plan View of the Jameson Hall

The stage is at the top of the diagram and the balcony at the bottom. The side projections are the seating alcoves. When referring to the hall it is customary to refer to left and right as seen from the stage, as indicated in the diagram. The X and Y-axes are the coordinates of the measurement positions, relative to an origin at the left hand side corner of the foyer. The red spark in Figure 8 is the position of the sound source.

Note that the SigmaPlot 3D graph extrapolates measurements that lie outside the measuring area, i.e. in the corners of the graph. These measurements should be ignored.

From this combined graph it is possible to see the trends of the various acoustical parameters measured in the hall. For example in Figure 8 the values in the middle of the hall in front of the balcony are higher than those closer to the stage.

5.2. Measurements in the Jameson Hall

Measurements were made using the TEF system, for which specific details are given in Appendix E. Briefly the TEF system includes a sound analysing device with associated software. The system automates the process of recording impulse response measurements and calculating values such as RT60 and EDT."

Two different sets of measurements were considered. The larger set was performed by the author, while a previous smaller set was performed by Leroy Kahn for his undergraduate thesis as referenced in the bibliography.

However on completing the simulated measurements it was decided that only the larger set would be presented here, since no new relevant information is provided by Leroy Kahn's measurements.

Two different sets of measurements were considered. The larger set was with the sound source placed to one corner of the stage. This is a position directly beneath one of the speakers used as a sound reinforcement system.

All measurements were made with the hall empty.

5.2.1. Measurement Positions: Source Position

The sound source for the measurements performed by the author, which are presented here, was placed at the right side of the stage. This was done initially to judge the effect of the Jameson Hall speaker system, which consists of speakers placed at the sides of the stage. (The Jameson Hall amplification system was not used at any time during this thesis.) Since the tender for the improvement of the acoustics of the hall was withdrawn the source position has become irrelevant since no attempt to qualify the acoustics of the hall has been made.

5.2.2. Measurement Positions: Microphone Positions

A number of microphone positions, also called receiver positions, were used in the measurements of the Jameson Hall. To show the measurement positions the hall diagram in Figure 10 is used, which was created using the RoWena room acoustics prediction software that will be discussed thoroughly in the simulation section of this thesis.

In Figure 10 the stage is at the left of the diagram and the balcony is at the right. The star in the middle is the dome and the appendages on the top and bottom are the seating alcoves. The top of Figure 10 is *left* and the bottom is *right*. These directions relate to the directions given in 5.1.

The zigzag lines shown on the drawing represent curved surfaces and are the arches found in the hall.

The red cross shows the speaker position for these measurements.

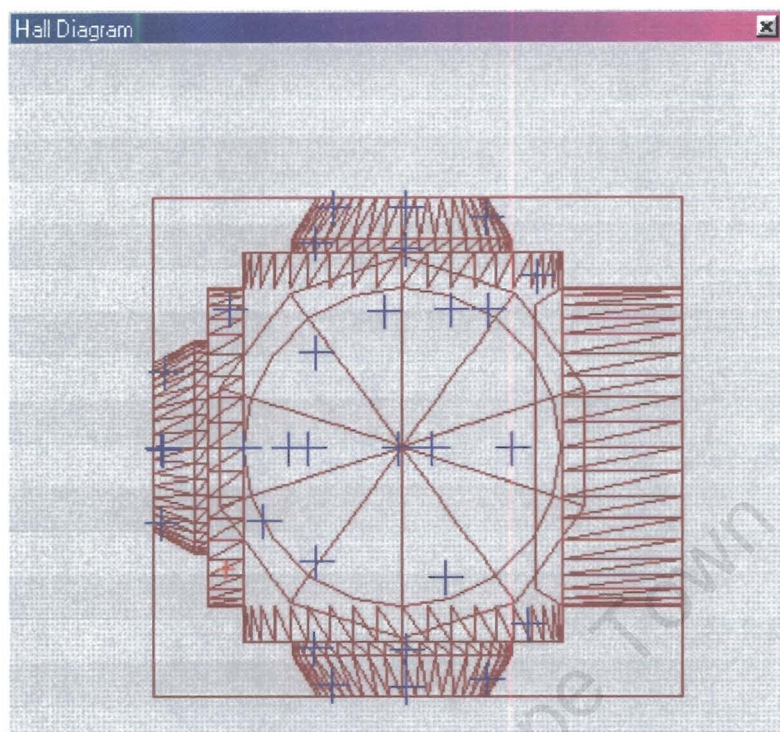


Figure 10: Measurement Positions in the Main Hall Area

Figure 10 shows only the measurement positions in the main part of the hall. Measurements in the balcony and below the balcony in the entrance hall are shown separately in Figure 11 and Figure 12 respectively.

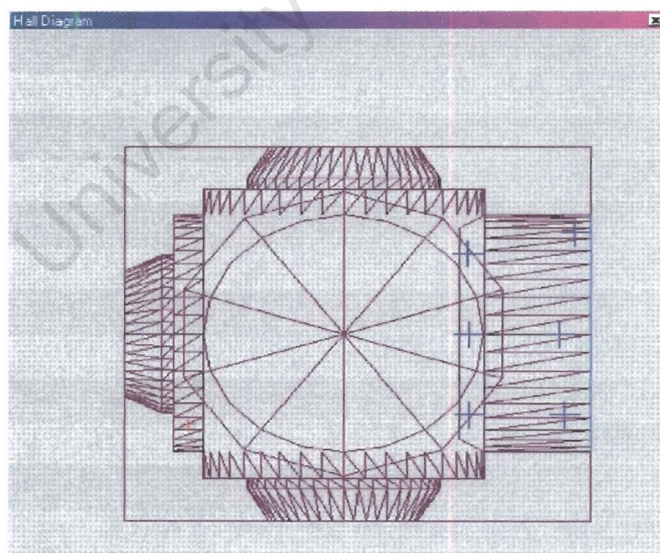


Figure 11: Measurement Positions on the Balcony

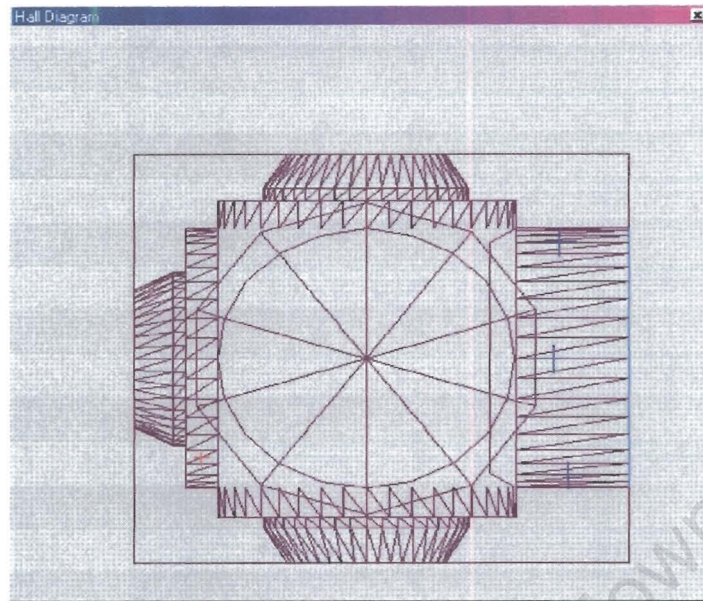


Figure 12: Measurement Positions under the Balcony

In the measurements in the later sections measurement results from receiver positions taken in the balcony are titled 'Balcony' while those from underneath the balcony in the entrance area are titled 'Under Balcony'.

The microphone for all these measurements was 1.3 meters above the surface the measurement was taken on.

5.3. RT60(500Hz) and EDT(Pass) Measurements

The measurements of RT60(500Hz) and EDT(Pass band) are the primary means of predicting reverberance, which is the most common initial indication of the acoustical quality of the hall (see 4.1).

5.3.1. Average Reverberation Measurements

Table 1 shows the maximum, minimum and average values for these two measurements as taken throughout the hall with the source as in Figure 12.

Table 1: Global Reverberation Times

	RT60(500Hz)	EDT(Pass)
Max	4.45s	4.28s
Min	4.05s	3.78s
Average	4.21s	4.00s

The minimum and maximum values range by about 0.4s, which is a significant variation. (see 4.1.2.3). Also the EDT values are about 0.2s less than the RT60 values, as opposed to being 0.2s higher as is common (see again 4.1.2.3).

5.3.2. Specific Measurements for RT60(500Hz)

Figure 13 and Figure 14 both show a 3D plot of RT60(500Hz). Figure 13 shows values for the balcony while Figure 14 shows figures for below the balcony. In other respects they are the same, except for being at slightly different viewing angles.

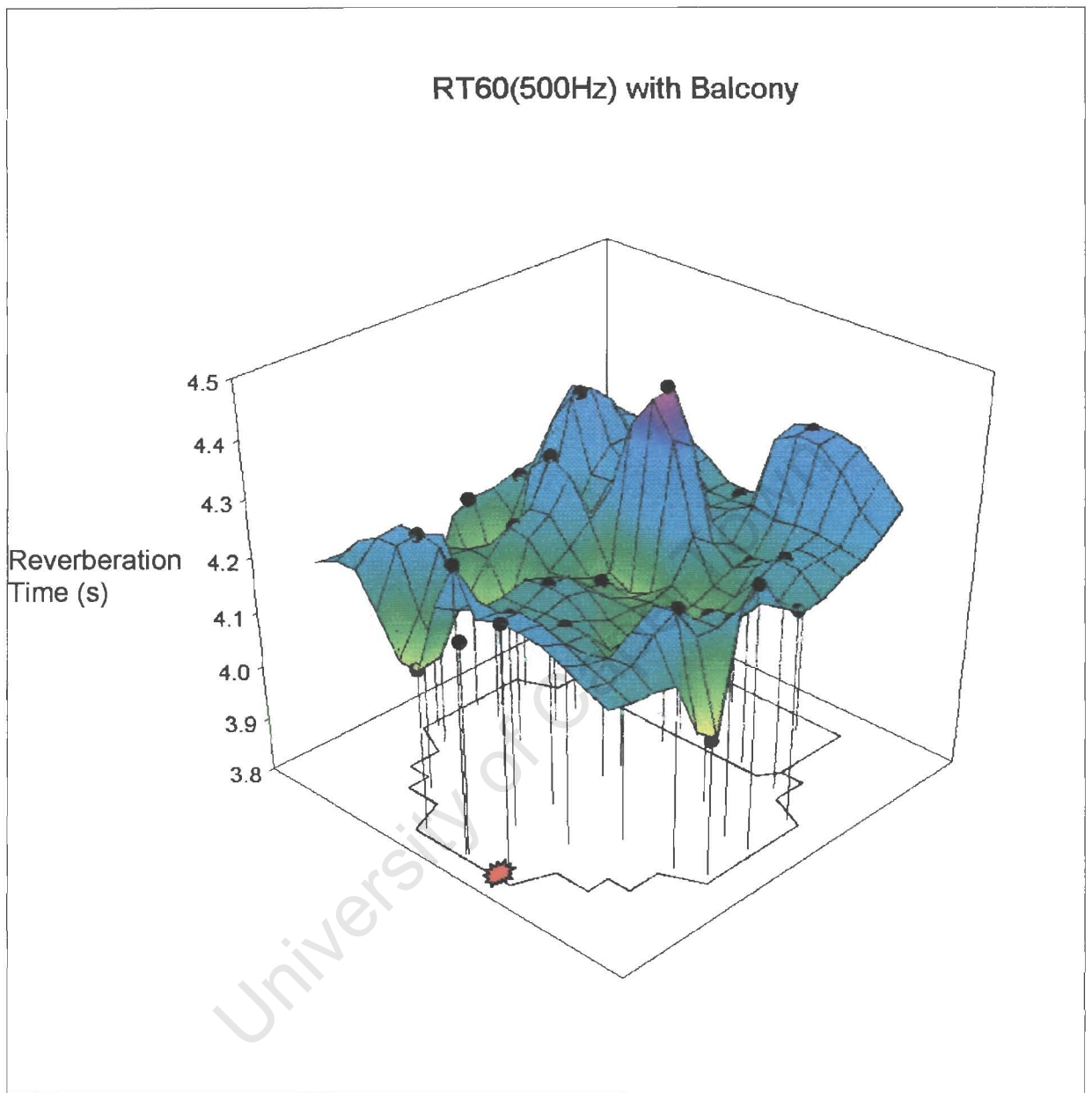


Figure 13: RT60 Measurements (with the Balcony)

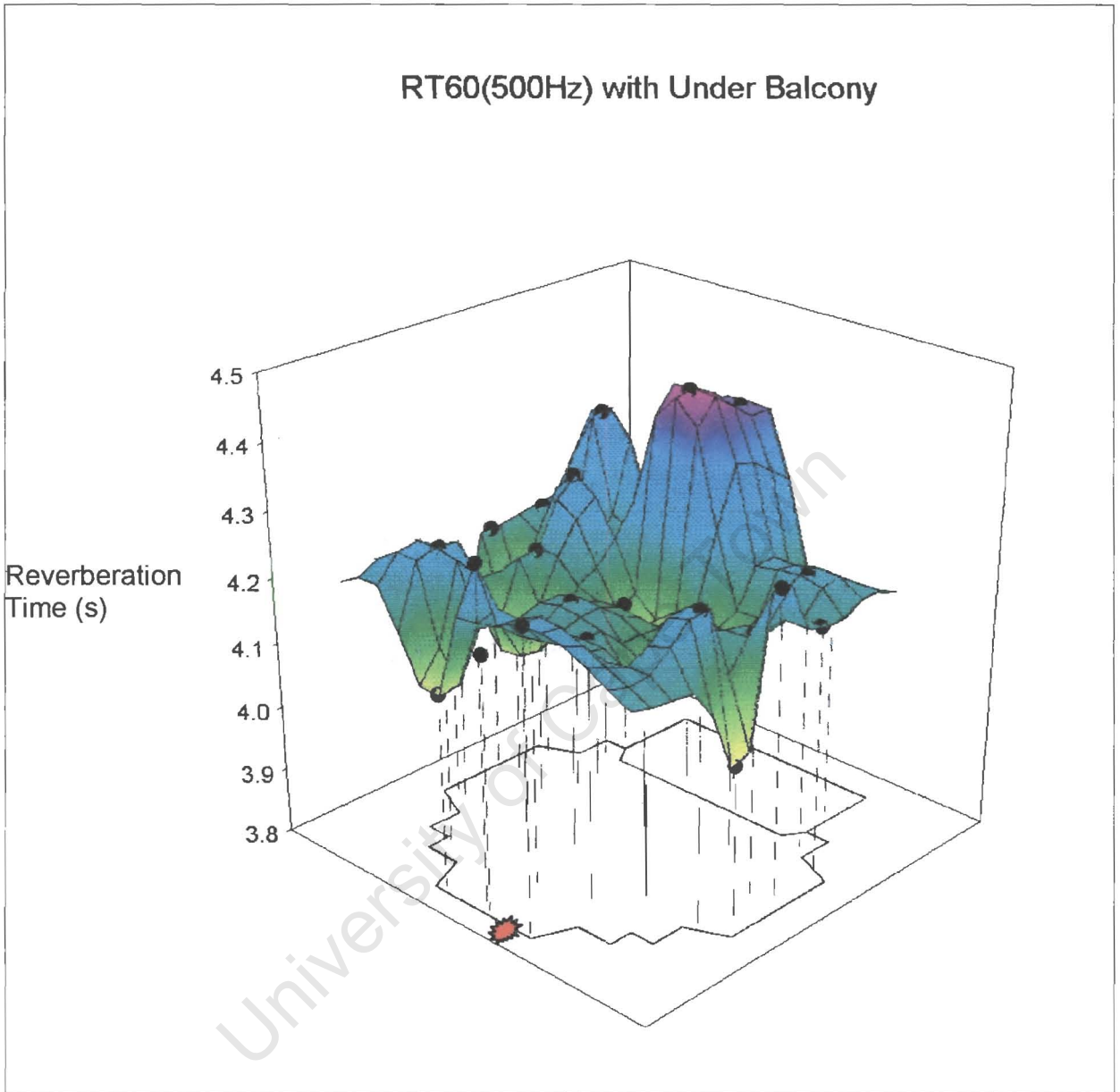


Figure 14: RT60 Measurements (with the area below the balcony)

The variation in reverberation between most parts of the hall is not large ($\approx 0.2s$). However towards the rear of the hall in the entrance area the reverberation reaches its maximum. The reverberation in the balcony is comparatively low. The alcoves to the left and right have lowest reverberation times.

5.3.3. Specific Measurements for EDT(Pass Band)

Early Decay Time (EDT) measured the reverberation that occurs shortly after the direct sound. This means that the variation in early reflections is reflected by these measurements.

As in the previous section (Section 5.3.2) Figure 15 and Figure 16 are two similar measurements for EDT, with Figure 15 showing balcony measurements and Figure 16 showing measurements below the balcony.

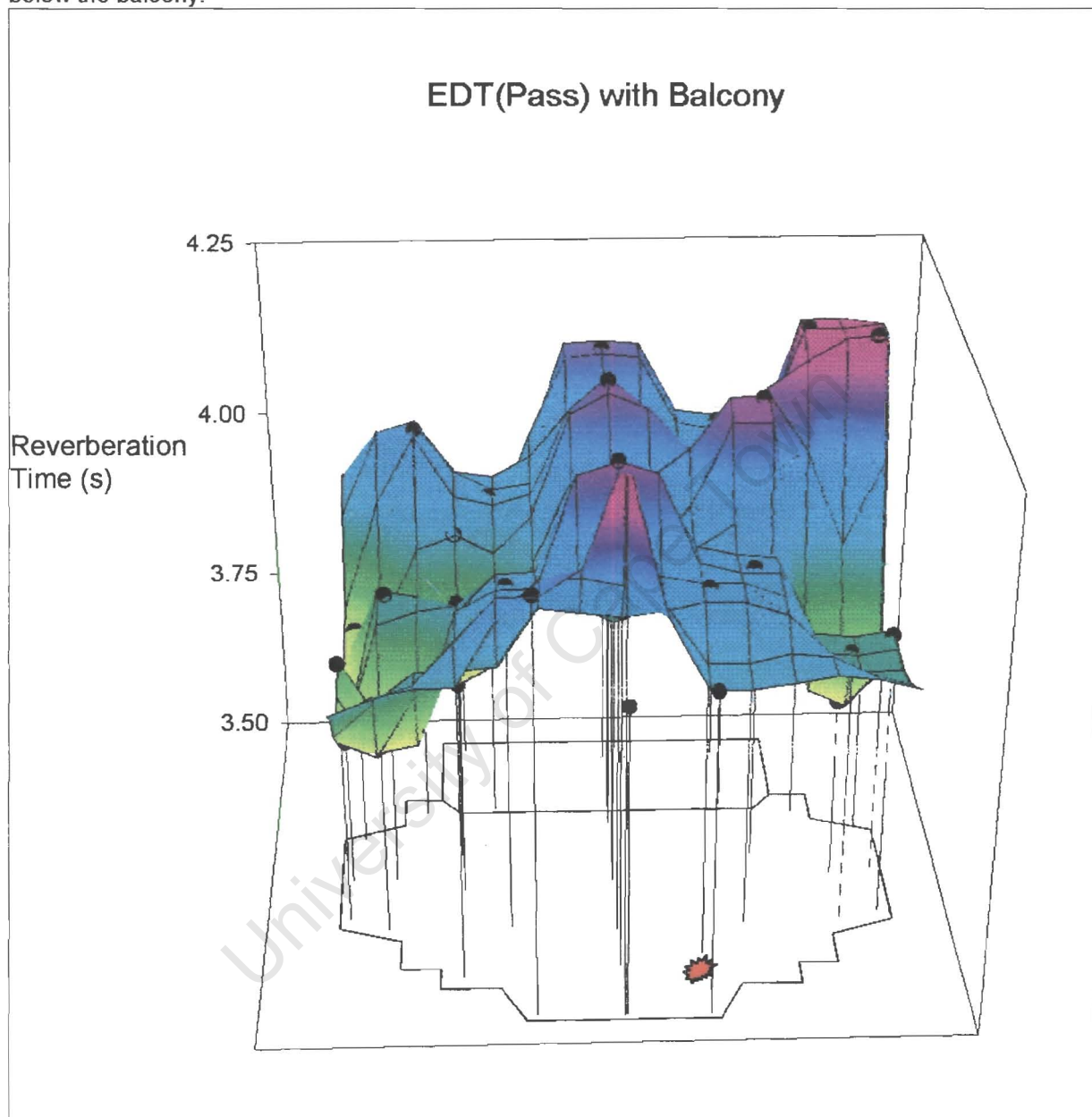


Figure 15: EDT Measurements (with the Balcony)

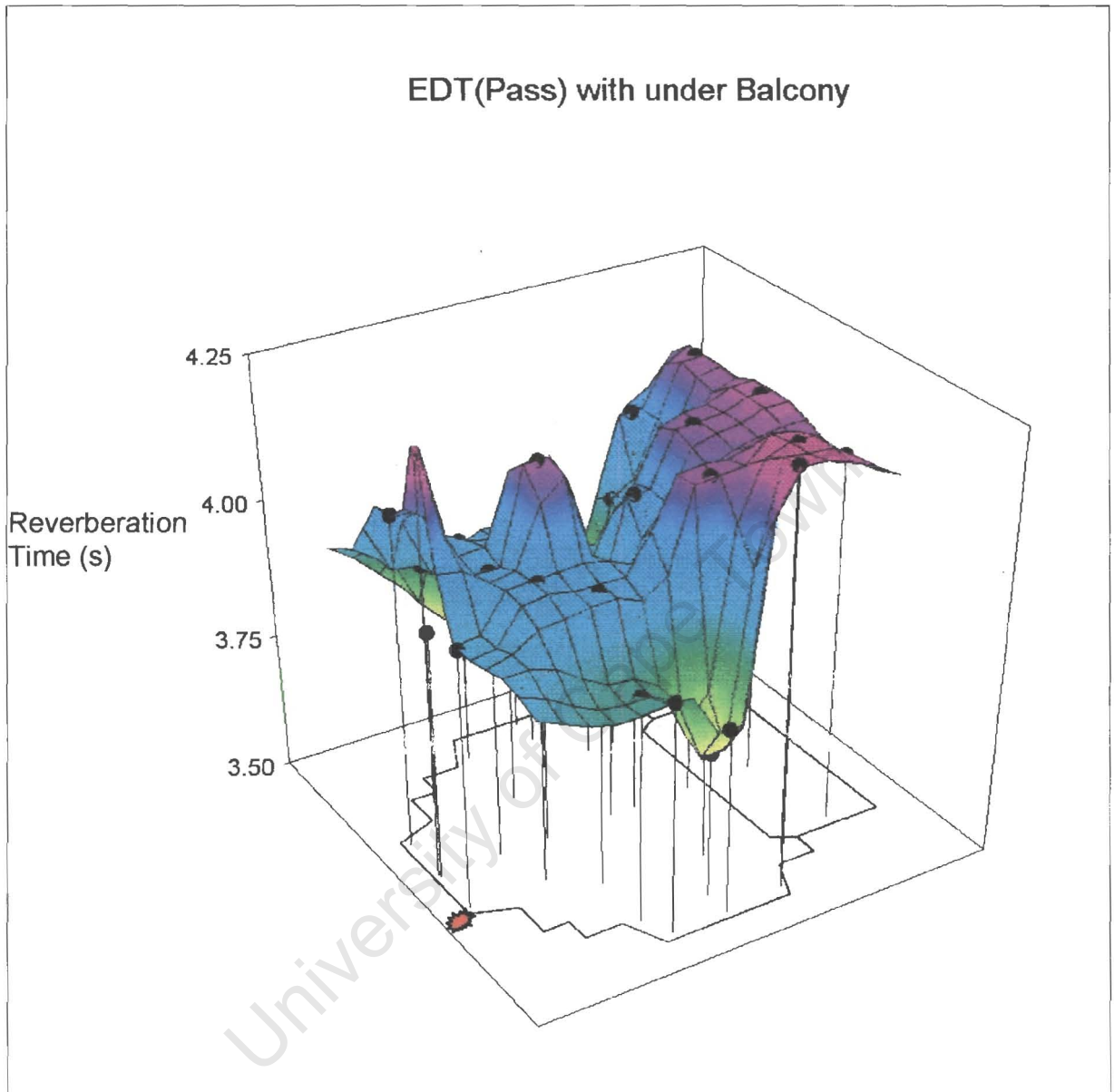


Figure 16: EDT Measurements (with the area below the balcony)

Again the rear of the hall has a longer reverberation. A second peak, that of the measurement directly under the center of the dome, has also occurred.

The alcoves have the lowest EDT values, indicating that these areas lack early reflections. In general the central parts of the hall have higher EDT values than the sides.

5.4. STI Measurements

STI, or Speech Transmission Index was discussed earlier in 4.6. This is a number from 0 to 1, where 1 is excellent and <0.45 is poor.

Both these measurements are performed automatically by the TEF SoundLab software.

5.4.1. Average Speech Intelligibility Measurements

Best, worst and average values are shown in Table 2.

Table 2: Global STI and %Alcons Measurements

	STI	%Alcons
Best	0.59 (Fair)	7.03 (Fair)
Worst	0.31 (Poor)	31.05 (Bad)
Average	0.41 (Poor)	19.6 (Bad)

The results are as expected, since the high reverberance will decrease speech intelligibility. Again these results are for measurements taken with the hall empty so do not relate to speech intelligibility when an audience is present.

5.4.2. Specific Speech Intelligibility Measurements

Figure 17 and Figure 18 show graphs of STI measurements in the hall. Figure 17 includes measurements of the balcony and Figure 18 includes measurements under the balcony. Note that they are shown at different angles for an improved overall perspective.

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STI with Balcony
(Higher=Better Intelligibility)

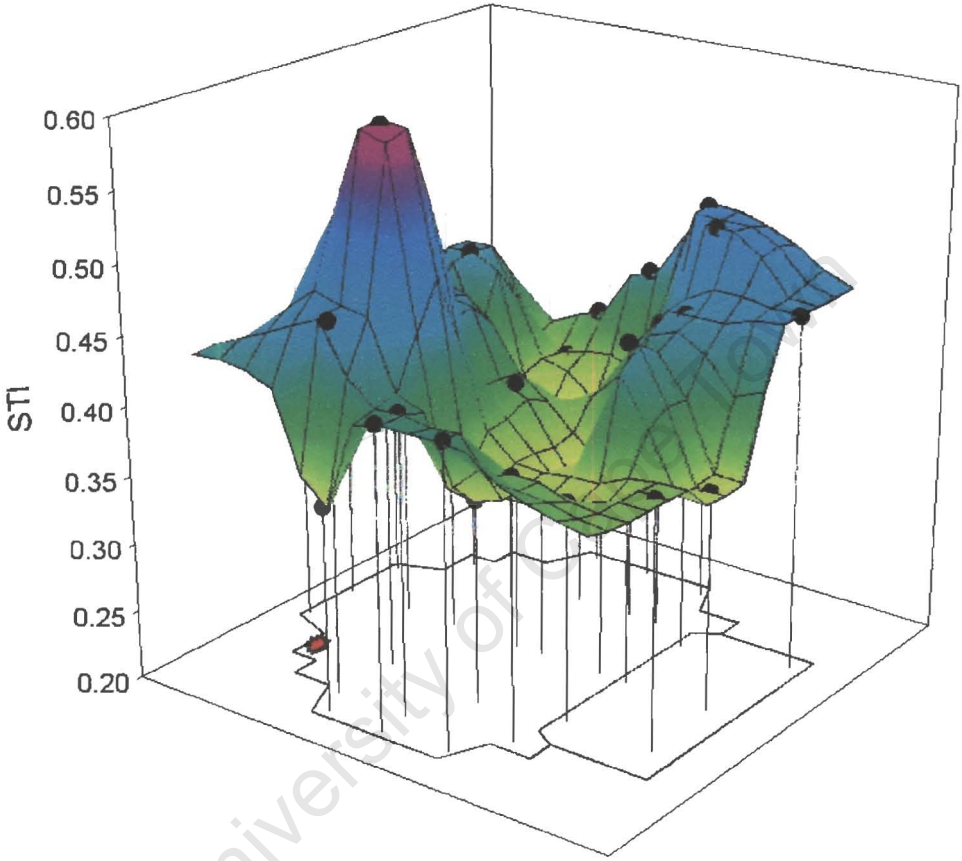


Figure 17: STI Measurements (with the Balcony)

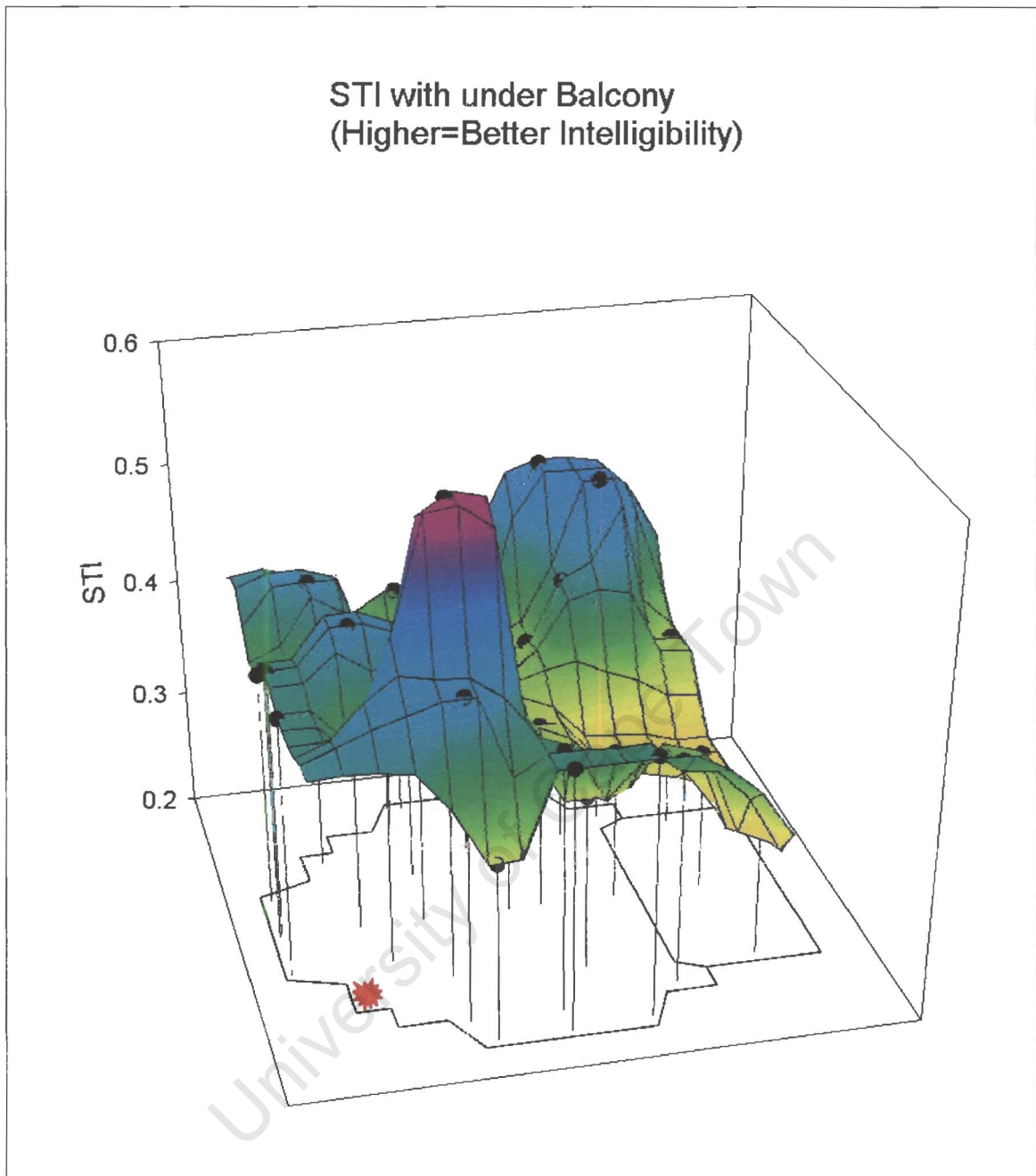


Figure 18: STI Measurements (with the Entrance Area)

The graphs show that speech intelligibility is generally consistent. Under the balcony, where the reverberation was highest, the speech intelligibility is lowest.

A very dominant peak can be seen at a point just in front of the speaker on the hall floor. Here the speech intelligibility is fair.

Figure 19 (with balcony) and Figure 20 (under balcony) show 3D graphs for %Alcons. Again two different views are shown.

**%Alcons with Balcony
(Lower=More Intelligibility)**

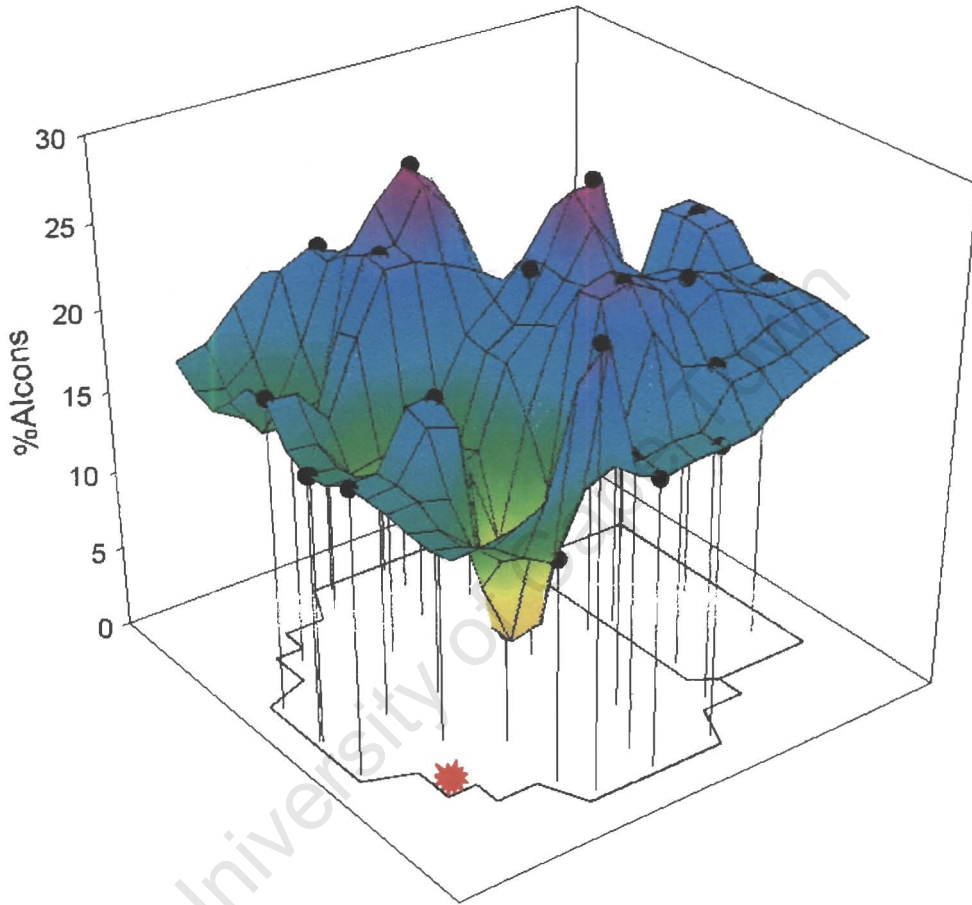


Figure 19: %Alcons Measurements (with the Balcony)

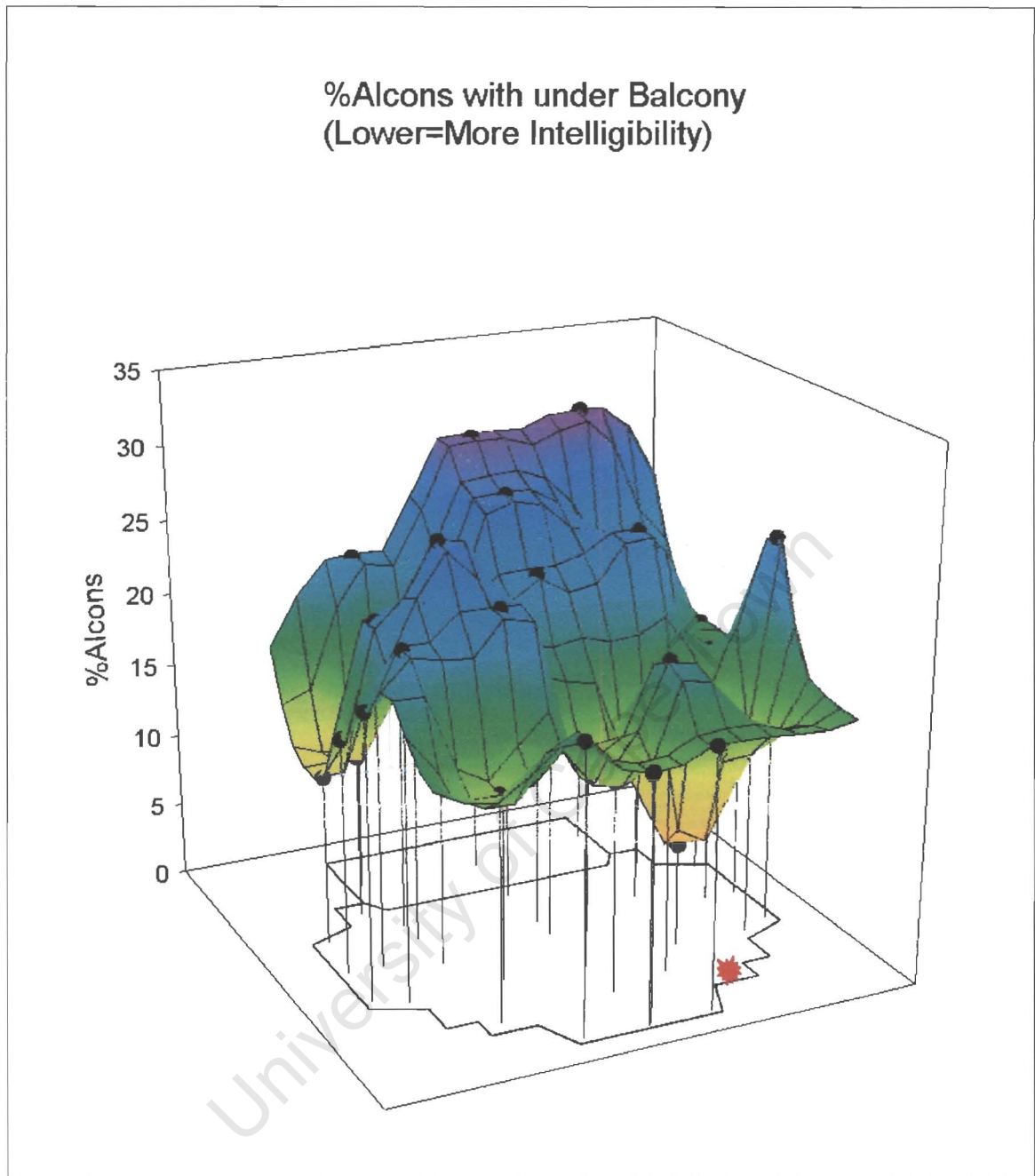


Figure 20: %Alcons Measurements (with the Entrance Area)

There is more variation in the %Alcons graphs, with a large decrease in speech intelligibility under the balcony.

5.5. Clarity Measurements

Four clarity measurements exist, C50, C80, Deutlichkeit (D) and Center Time (Ts), as discussed previously (see 4.2).

5.5.1. Average Clarity Measurements

Table 3 shows the maximum, minimum and average values for these measurements.

Table 3: Global C50, C80, D and Ts Measurements

	C50	C80	D (%)	Ts (s)
Best (most clear)	2.5	3.1	64.0	15.8
Worst (least clear)	-9.7	-7.4	9.3	327.7
Average	-5.7	-3.7	22.1	192.4

-4dB is generally considered the minimum of acceptable clarity for C50 and C80. From the table it is clear that clarity is low in most parts of the hall, although the best value is acceptable. (Again these are for an empty hall.)

5.5.2. Specific Clarity Measurements

Figure 21 (with balcony measurements) and Figure 22 (with measurements under the balcony) show the C50 measurements throughout the hall.

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C50 with Balcony
(Higher=More Clear)

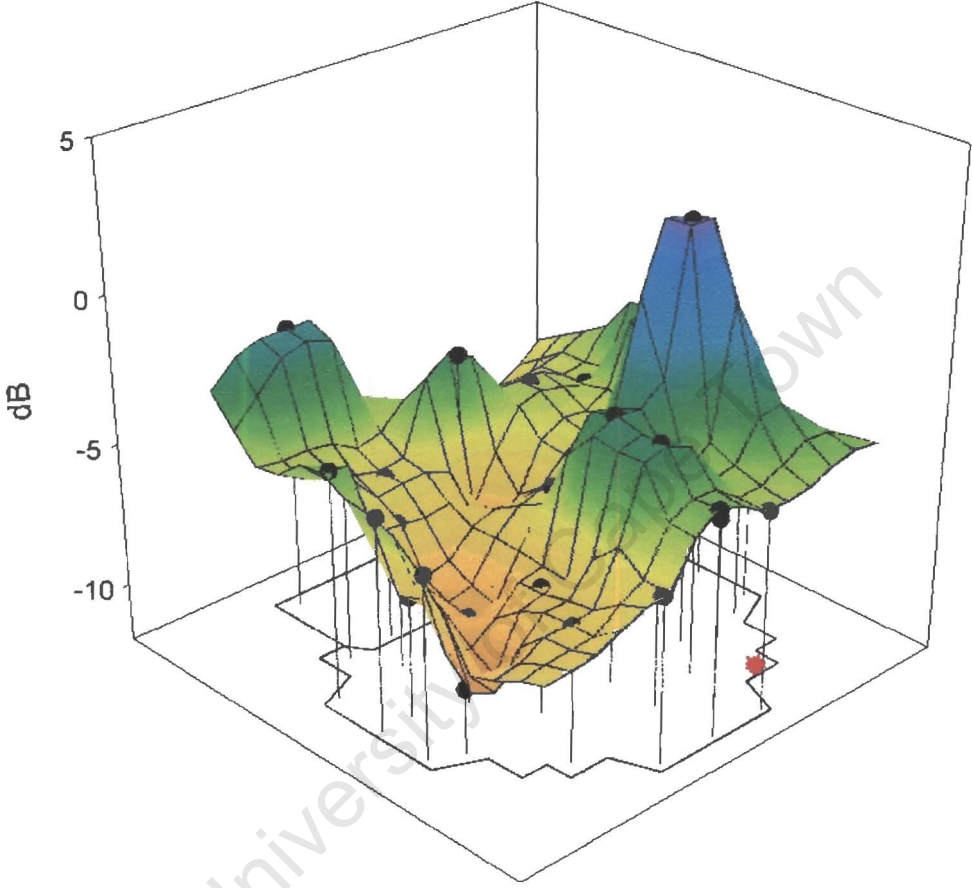


Figure 21: C50 Measurements (with the Balcony)

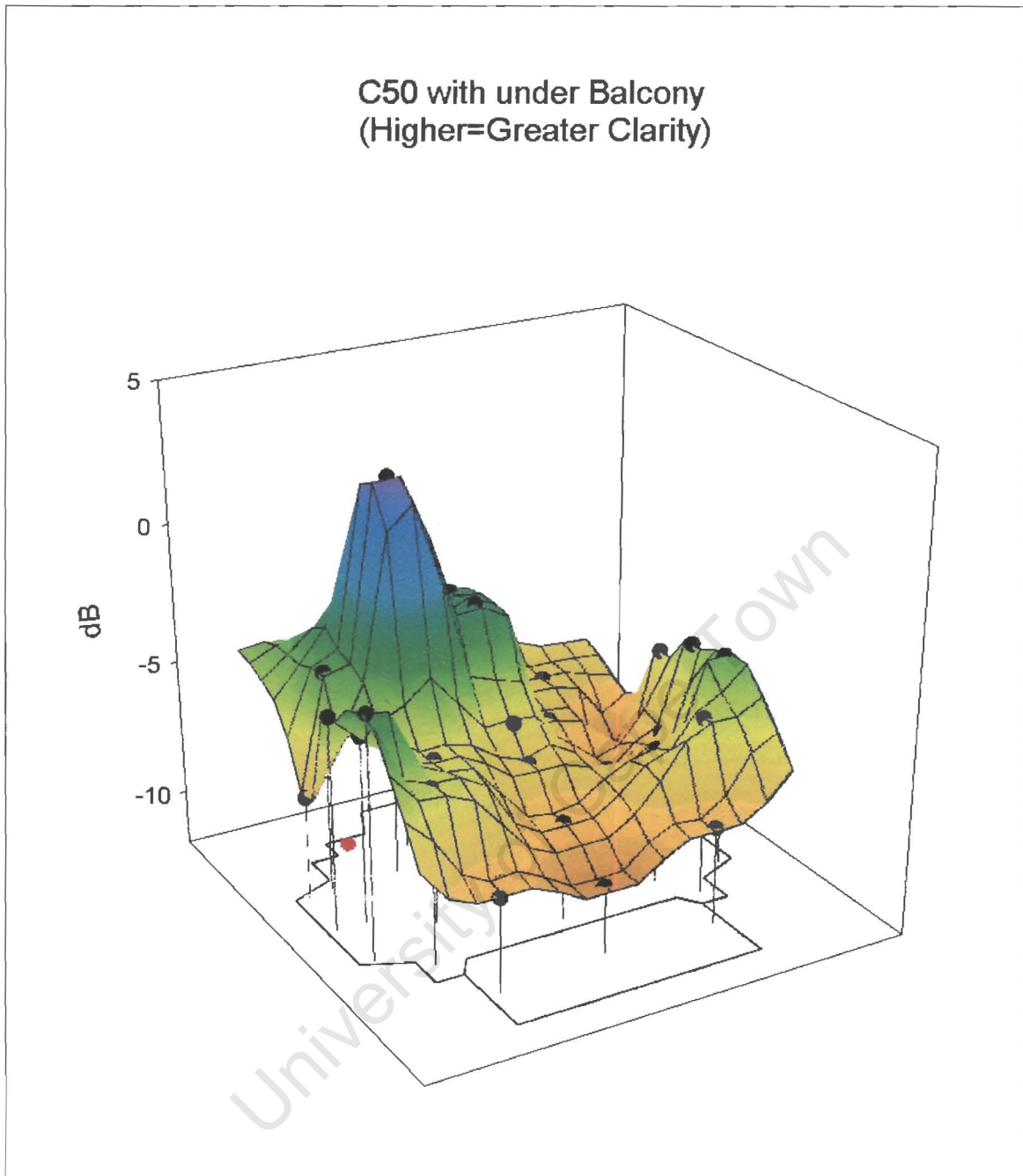


Figure 22: C50 Measurements (with the Entrance Area)

As in the STI and %Alcons measurements, a very clear area is found in front of the speaker on the hall floor. The opposite side of the stage has a correspondingly very low C50.

5.6. Discussion of Measurement Results

In the graphs which have been presented above a few distinct areas have been isolated.

5.6.1. Under the Balcony

RT60 times and EDT times are both relatively high under the balcony. Similarly STI and %Alcons indicate poor speech intelligibility and C50 (clarity) is low. This demonstrates the expected relationship between an exceptionally high reverberation and a low clarity and speech intelligibility, as was explained in 4.1.1.

Because there are reflecting surfaces close to the receiver positions under the balcony, these being the walls and underside of the balcony, reflections arrive at these positions soon after the direct sound. This increases the measured reverberation times, especially the EDT as evidenced in figure 16.

This will occur even in the early time but is offset by the many reflections also arriving later. Therefore the C50 ratio remains low.

Note that this trend still exists just in front of the balcony. The cause is the same, as demonstrated for example in Figure 13 where there is a sudden change in values above the balcony.

5.6.2. Above the Balcony

Above the balcony by contrast the acoustics are similar to the rest of the hall. RT60 and EDT times are lower than below the balcony. Speech intelligibility ratings are similarly slightly higher.

5.6.3. In Front of the Stage

The STI, %Alcons and C50 all show a particular hotspot in front of the stage where speech intelligibility and clarity are proportionally high. Since RT60 and EDT are not similarly exceptional this indicates a large amount of early reflections arriving to this point. An obvious source for these reflections is the walls surrounding the source point, such as folds on the *right* side of the source point.

If the simulation discussion is pre-empted temporarily then it is possible to show the path of the sound as it reflects from these surfaces. (In 16.7 a complete discussion is given of how these reflection paths are obtained.) In Figure 23 possible reflection paths (called ray paths) for the early reflections to a receiver point close to the one under discussion are shown.

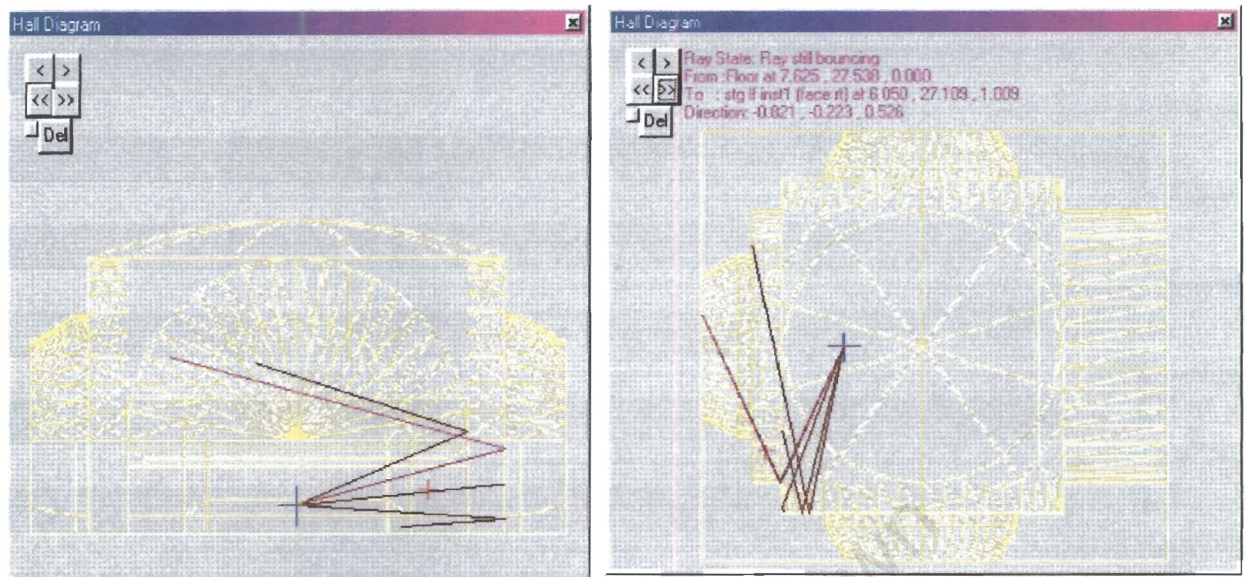


Figure 23: Ray Paths from a Receiver near the Stage

The blue cross is the measurement point and the red cross is the source point. Because of the nature of the ray tracing process required to draw these graphs the ray paths, shown as dark line, appear to come from the receiver. The direction of the ray paths was obtained from directional measurements in the Jameson Hall. These were performed using the TEF system and give the direction of arrival of individual reflections.

The receiver point of interest is slightly closer to the *right* of the stage than shown in Figure 23 but the reflection paths would be similar. It can therefore be seen that the sound can reflect from the surfaces close to the source on the *right* of the stage and thereby provide many early reflections to the receiver as expected.

5.6.4. Left and Right Alcoves

The alcoves at the sides of the hall have generally lower EDT values, though normal RT60 times. They also have lower speech intelligibility and clarity ratings. This indicates a lack of early reflections arriving to this area, which being early do not affect the RT60 values but do decrease the C50 ratios and similarly the STI and %Alcon measurements.

5.6.5. General Comments on Acoustical Areas in Jameson Hall

The importance of early reflections in determining the different acoustical areas has been demonstrated. In the main area of the hall, which is shaped roughly as a cube, reflecting surfaces are necessarily far from most positions in the hall. Also the presence of curved surfaces that do not distribute sound evenly through the hall.

The sound field in the hall is not diffuse, meaning that listeners in different parts of the hall will experience different sound qualities. This, as will be seen later in the computer simulation section, is an important limitation in simulating room acoustics.

5.7. Frequency Response Measurements

The average values for RT60 at octave frequencies from 125Hz to 4kHz is shown in Figure 24.

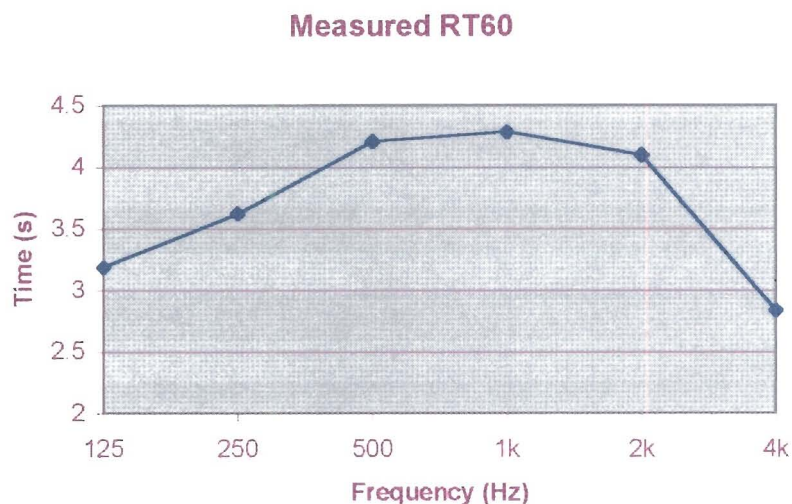


Figure 24: Measured RT60 times versus Frequency

Low and high frequency reverberation is shorter than mid-frequency. At low frequencies this is explained by the many wood surfaces in the hall, a material which typically absorbs low frequency sound. At high frequencies air absorption predominates, which decreases the reverberation times at these frequencies (see 4.5).

To modify the frequency response curve of the hall it would be necessary to decrease low and high frequency sound absorption, or to increase mid-frequency absorption. The absorptive effect of an audience, which decreases the overall reverberation times, would influence this choice.

5.8. Conclusions on Physical Room Acoustics

Relationships can be found between objective (measurable) and subjective (perceived) qualities of sounds as heard in rooms. The relationships are well documented although research is continuously being done to improve the understanding of these relationships.

The Jameson Hall, the acoustics of which were measured, has an exceptionally high reverberation time and similarly low clarity when empty. Also, possibly due to the curved surfaces in the hall, the sound field is not diffuse. This means that different parts of the hall experience a different sound quality because of the nature in which the hall reflects the sound.

In some parts of the hall, particularly near the front of the stage when the sound source is at the *right* of the stage, have a significantly higher clarity and speech intelligibility. Also the smaller area underneath the balcony causes this space to have noticeably different acoustics.

PART 2

Room Acoustic Computer Simulation

6. INTRODUCTION TO COMPUTER SIMULATION CONCEPTS AND AIMS

Part 1 explained the principles of room acoustics, and also described an analysis of a typical room (Jameson Hall). There are however many cases where it is not possible nor desirable to have a physical hall to examine. For example where a modification to the hall is proposed. In order to determine what effect the modification will have on the hall's acoustics it would be necessary to perform the modification, which may be expensive and time consuming. Obviously this is impractical. Of even more importance is predicting the acoustics of a hall that has yet to be built.

One way of predicting the acoustics of a building is to make a scale model. There are many difficulties in this procedure but it can be done and be useful⁵². However a simpler approach is to use a computer program that could simulate the acoustics of the hall, and that of any changes to the hall. This holds the advantage that predictions can be made relatively quickly and with more flexibility.

There are at present a number of such simulation programs, each with varying degrees of accuracy. Two of the best known are called ODEON⁵³ and CATT-Acoustic⁵⁴.

This section presents the history of computer simulation programs. A new program has also been written by the author for this thesis in order to test the capabilities of the methods, and it will be referred to frequently. The final part of this section is a computer-assisted examination of the acoustics of Jameson Hall.

7. PHYSICAL ROOM ACOUSTICS

Before explaining the simulation techniques it is necessary to begin with the fundamentals of room acoustics on a physical level. The information in this section may be found in any acoustics textbook, for example 'Fundamentals of Acoustics'.⁵⁵

7.1. Sound in General

Any complex sound, such as that produced by a violin or even a car engine, can be broken down into a certain number of simple sine waves. Each of these sine waves has its own frequency and amplitude, and the exact combination of the component sine waves characterises the sound. Typically the relative amplitudes of the component sine waves also change with time. For example the decay of a piano note that is heard when the note is held down is due to a general decrease in amplitude of the component sine waves over time. Since each wave decreases at a different rate the sound of the piano note also changes as it decays.

7.2. Sound Waves in One Dimension

Sound waves produced by a source radiate in all directions away from the source, like ripples in a pond, albeit in three dimensions. It is possible to restrict and thereby simplify this motion to one dimension by confining the sound to a long tube. If the tube is correctly constructed (see 7.2.2), the sound will only travel along the length of the tube.

7.2.1. Sound Wave in an Open Tube

If the tube is infinitely long in one direction and a sound source is placed at the other, and the source produces a sound of a single frequency, then a measurement of the sound pressure at a particular point will produce a graph similar to that shown in Figure 25. (The units of the graph are irrelevant and may be ignored.)

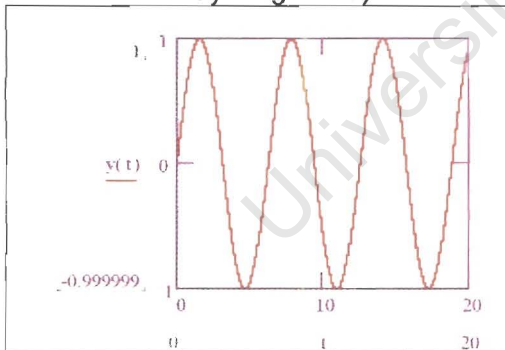


Figure 25: Sound Pressure in an Open Tube

Figure 25 shows the typical sinusoidal shape of a single frequency sound wave.

The formula for the pressure of such a wave is $p(x,t) = p_0 e^{i(\omega t - kx)}$. ω is the frequency of the sound in rad/s and k is a constant indicating the phase of the wave. (The exact values of the wave shown are unimportant for this example.) The sign separating the two parts of the exponent indicate the wave direction. If it is positive the wave is traveling in the negative x direction and visa versa.

A useful measure of the 'strength' of the sound wave is called intensity and is defined as the average sound energy flowing per second across an imaginary surface orientated perpendicular

to the wave direction.⁵⁶ The formula for intensity is $I = \overline{pv} = \frac{p_{rms}^2}{\rho_0 c}$, where p is the instantaneous pressure of the wave and v is the velocity of the wave. The bars indicate the time average of the quantity.

The ratio $\frac{P}{v}$ is called the characteristic impedance of the medium and is equal to $\rho_0 c$, where c is the speed of sound in the medium and ρ_0 is the static value of the gas density. $\rho_0 c$ is a constant for all frequencies for a medium under particular conditions.

Intensity is usually written as a decibel figure, obtained from $I_{db} = 10 \log(I/I_{ref})$, where I_{ref} is usually 10^{-12}W/m^2 .

7.2.2. Tube Construction

In order for the sound wave to travel only in the x -axis the diameter of the tube must be much smaller than the wavelength of the sound. A wave traveling only in one direction is called a plane wave, since any plane perpendicular to the direction of travel has a constant phase.⁵⁷

7.2.3. Sound Wave in a Closed Tube

If the tube is now closed and a continuous sound produced, the sound wave produced by the source will reflect from the opposite close side of the tube and interfere with the forward traveling wave. Figure 26 shows such a case, where the reflected wave (y_2 , in blue) has a different phase to the incident wave (y , in red). The incident wave is that produced by the sound source. The measured wave is now the sum of the pressures of the incident and reflected wave and is shown as y_{sum} (in green).

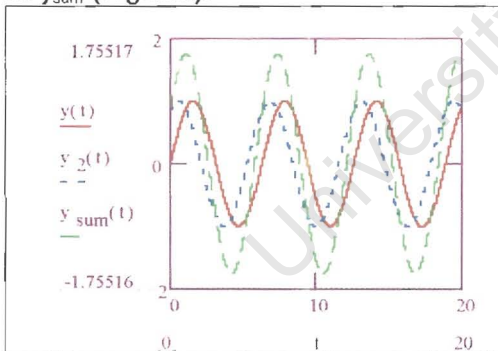


Figure 26: Standing Wave Pressure in a Closed Tube

The combined wave (y_{sum}) is called a standing wave. Different phase relationships will produce different standing waves, with different amplitudes and phase. For example if the reflected and incident waves have opposite phases then they will cancel out and no sound will be measured.

7.2.4. Resonance in a Closed Tube

If the phase of the incident and reflected wave match exactly then a standing wave with very large amplitude will result. This is called a resonant condition. Standing waves, where they occur, dominate the sound field even if the sound source produces other sine waves. The study of standing waves is thus very important.

If the tube is closed at both ends and neither end influences the phase of the wave, then resonance will occur whenever the length of the tube (l) is an integer multiple of half a wavelength, i.e. $l = \frac{n\lambda}{2}$, $n=1,2,3\dots$ ⁵⁸.

In such cases the pressure of the standing wave will be a maximum at the ends of the tube.

If the tube is closed at both ends (still with a sound source at one end), and each end may introduce a phase change to the wave, then the wave will reflect from both ends in a particular manner along the length of the tube. There will always be some lengths of the tube (length l) which cause the phase of the waves be equal and therefore to cause maximum amplitude of the standing wave and therefore resonance. This condition of 'Round Trip with Matched Phase'⁵⁹

occurs for frequencies with $f_n = \frac{c}{2l} \left(n + \frac{\gamma_{(f_n)}}{2\pi} \right)$, where $\gamma_{(f_n)}$ is the total phase change

introduced by the two reflecting surfaces, and n is any positive integer.

7.2.5. Impedance of the Reflecting Surface

A phase change in the reflected wave as referred to in 7.2.4 may occur because of the properties of the reflecting surface. The properties of a surface are described by its impedance, which is a complex number Z . Z describes the phase relationship between the incident and reflected wave, and also the absorption of the sound energy by the surface.

In the previous examples the reflecting surface was tacitly assumed to reflect the wave without loss of energy. In all real cases however some energy is lost to the reflecting surface (see 7.2.6), and the reflected wave has a lower energy than the incident wave.

If the sound source is switched off and the sound is allowed to reflect off both ends of the tube then the energy density in the tube will decrease with each reflection with the ends of the tube. A graph of this decay rate will be an inverse exponential graph, as shown in Figure 27.

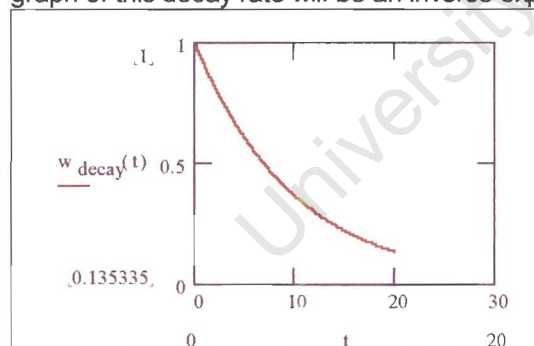


Figure 27: Decay Curve of a Standing Wave

A similar decay can be seen in an impulse response graph and it is for the same reason. For example see Figure 2 where the y-axis is a log scale and so an exponential decay is seen as a straight decay.

7.2.6. Sound Absorption by a Surface

Any surface absorbs a proportion of the sound energy incident on it. This occurs because the sound is converted into heat through friction between the air molecules and the surface material and also by movement of the surface caused by the pressure of the sound wave.

The proportion of the incident sound energy absorbed by the surface is called the absorption coefficient and is represented by α_n , where the subscript n (for normal) indicates it is for sound arriving perpendicular to the surface. α varies between 1 for a completely absorbing surface and 0 for a completely reflecting surface.

Every surface material has a particular absorption coefficient for different frequencies, with most materials typically absorbing more sound at higher frequencies.

$$\alpha \text{ is related to the surface impedance } Z \text{ by } \alpha = \frac{4 \operatorname{Re} \left(\frac{Z}{\rho_0 c} \right)}{\left(\frac{Z}{\rho_0 c} \right)^2 + 2 \operatorname{Re} \left(\frac{Z}{\rho_0 c} \right) + 1}.$$

$\frac{Z}{\rho_0 c}$ is called the specific acoustic impedance of the material.

7.3. Sound Waves in a Rectangular Room

The sound tube describes a simple case of sound propagation. The same principles as were derived for a sound tube in one dimension can be extended to 3 dimensions. In order to retain simplicity a rectangular room with dimensions l_x , l_y and l_z is described. Also all the walls of the room are hard so that no phase change occurs.

7.3.1. Standing Waves in a Rectangular Room

Standing waves in a rectangular room are similar to those in the sound tube described in section 7.2. However since there are now 3 dimensions many more standing waves can exist. These waves can also involve combinations of axes and need not lie parallel to a particular axis. Such standing waves are called modes.

7.3.2. Modes in a Rectangular Room

It was seen in section 7.2.4 that for certain lengths of the sound tube, resonant conditions would occur. Similar resonant conditions can occur in the rectangular room and each of these resonant standing waves is called a 'normal mode of vibration'⁶⁰. The frequency for which a mode exists in the room is called a normal frequency.

Again as in the sound tube, normal modes occur when $l = \frac{n\lambda}{2}$, or $f_n = \frac{nc}{2l}$ using $\lambda = \frac{c}{f}$. The distance l in this case is the length of the standing wave.

If the component lengths in each axis direction (l_x, l_y, l_z) are used instead then the normal

frequencies are $f_n = \frac{c}{2} \sqrt{\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2}$. (n_x, n_y, n_z) can each be an independent positive integer, including 0.

Each frequency f_n found by this formula corresponds to a frequency that will produce a resonant standing wave in the rectangular room.

Larger numbers for (n_x, n_y, n_z) produce higher normal frequencies. Since there are also more combinations of large numbers than low numbers there will be more modes for a high frequency range than for a low one. Therefore the modal impulse response will be simpler for low frequencies.

7.3.3. Example of a Normal Mode in a Rectangular Room

The standing wave consists of plane waves that travel around the room in a pattern dependent on the frequency of the wave. The path length of the wave must be necessarily such that phase matching occurs at the end of every loop of the standing wave.

To illustrate the normal modes of the room a single particular room mode is described. If (n_x, n_y, n_z)=(1,1,0), then the z-axis can be ignored and the standing wave is produced in the x- and y-axes.

Figure 28 shows the direction of travel of the wave fronts making up the standing wave.

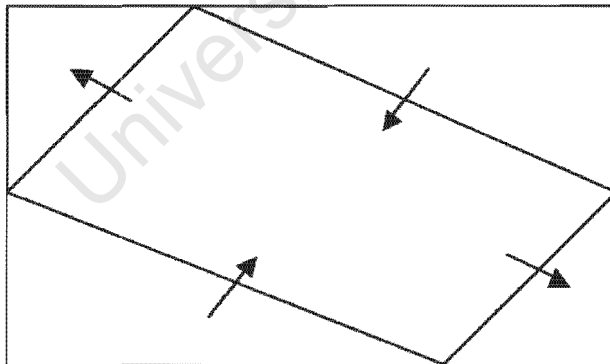


Figure 28: Movement of a Standing Wave in a Rectangular Room

A contour map of the pressure of the standing wave seen from above is shown in Figure 29.⁶¹

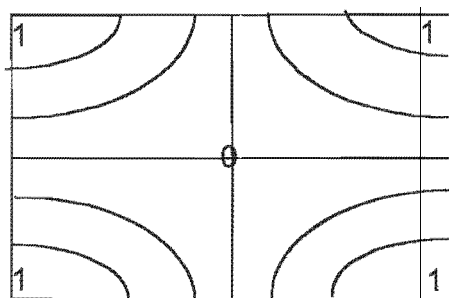


Figure 29: Contour Map of the Pressure of a Standing Wave in a Rectangular Room

The maximum pressure of the wave occurs at the corners with a pressure node at the center of the room. The numbers indicate relative sound pressure.

Since there is zero pressure in the center of the room, this mode cannot be excited by a sound source placed at that position. Conversely if the sound source is placed in the corner of the room the mode will be excited to the fullest.

Not all standing waves have a node at the center of the room, but all modes have a pressure maximum in the corners of the room. Therefore a sound source placed in any corner of a room can potentially excite all the modes of the room.

7.3.4. Decay of the Normal Modes in a Rectangular Room

If the walls of the rectangular room are partly absorbent, then the modes will be weakened by reflection from the walls. Therefore if the sound source is turned off, the modes will decay at a rate proportional to the absorbency of the walls and also by the number of reflections of the standing wave each second.

A standing wave that on average undergoes one reflection every millisecond will decay slower than a wave that reflects twice every millisecond, if the walls have the same absorbency. For example if the room has one particularly long dimension l_y , then the standing wave with $(n_x, n_y, n_z) = (0, 1, 0)$ will decay slower than the standing wave $(1, 0, 0)$.

The complete formula for the pressure of a particular mode is $p_n = \psi_n e^{-j\omega_n t} e^{-kt}$. The first term is the maximum pressure of the wave and is dependent on the measurement position. The second term describes the oscillation of the wave, where ω_n is the frequency of the oscillation in rad/s. The last term describes the decay of the wave where k is the decay constant of the wave and depends on the path of the standing wave.

If $\alpha' = (-\ln(1 - \alpha))$ then the decay constant for a particular mode is

$$k = \frac{c}{4} \left[\frac{\cos \vartheta_x (\alpha_{x0}' + \alpha_{xl}')}{l_x} + \frac{\cos \vartheta_y (\alpha_{y0}' + \alpha_{yl}')}{l_y} + \frac{\cos \vartheta_z (\alpha_{z0}' + \alpha_{zl}')}{l_z} \right]^{62}. \vartheta \text{ refers to the angle}$$

of incidence of the standing wave on each surface of the room for each axis and can be obtained

$$\text{from } \frac{n_x \pi}{l_x} = k \cos \vartheta_x \text{ (similarly for y and z) and } k^2 = \pi^2 \left[\left(\frac{n_x}{l_x} \right)^2 + \left(\frac{n_y}{l_y} \right)^2 + \left(\frac{n_z}{l_z} \right)^2 \right].$$

7.3.5. Multiple Modes in a Rectangular Room

If the sound source does not produce a single frequency sound, but rather a large band of frequencies, and it is placed in the corner of the room, then all the room modes in the frequency range of the sound source will be excited. These excited modes will dominate the sound in the room because of their excessive resonant sound pressure.

Figure 30 shows a graph of the instantaneous pressure of two modes with different frequencies and different decay rates at a position in an arbitrary room.

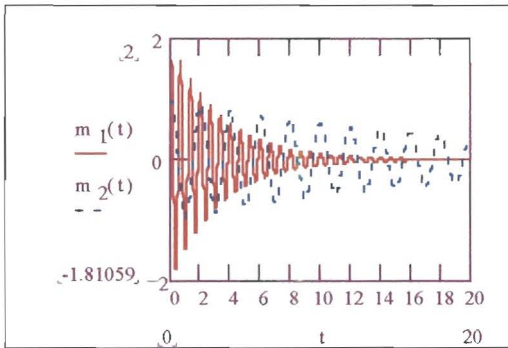


Figure 30: Two modes with different decay times

The mode indicated in red has a faster decay rate and a larger initial intensity than the mode in blue. The difference in frequency is for visual distinction only and has no direct bearing on the decay rate.

If the instantaneous pressure of these two modes is added together as shown in Figure 31 then it can be seen that at first the decay rate is a combination of the two modes but after the first mode has decayed significantly the second mode's decay rate dominates.

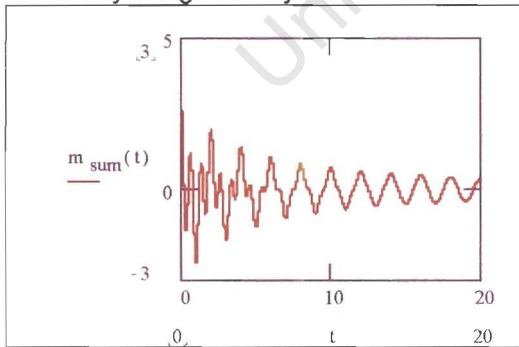


Figure 31: Interference between two modes with different decay times

In a complete example with all the excited modes in the room a more complicated graph will emerge. Each mode will have a slightly different frequency and decay rate and the resultant graph will be equal to the measured impulse response graph for a similar room.

7.3.6. Sound Field in a Rectangular Room

All the excited modes in the room at a particular time make up the sound field in the room. If an impulse response measurement is taken at a particular point in the room, and the corresponding room mode calculations are made using the formulae given in 7.3.4, similar transfer functions should be obtained.

Cremer⁶³ notes however that it is very important that the room be completely sealed and that no objects are in the room. Any deviation from these requirements will result in a poor correlation between the measured and calculated graphs. In the situation that was available for the measurements for this thesis such stringent requirements could not be attained. Therefore a good correlation is not expected with the measured impulse response graph.

The room that was measured is the reverberation room on the University of Cape Town campus. It is rectangular with dimensions $l_x=7.371\text{m}$, $l_y=5.715\text{m}$ and $l_z=4.405\text{m}$. The absorption of all the walls is $\alpha_n = 0.01$. Diffusers are suspended from the ceiling which are designed to break up standing waves at high frequencies but are not effective below 125Hz.

Ideally the room should be completely sealed. However, air conditioning vents in the ceiling (approx 0.5mx0.5m) and various smaller ventilation holes along the walls prevented this.

A measured impulse response graph was taken in the room, band limited to 125Hz. Also all modes up to 125Hz were calculated by the room acoustics simulation program RoWena.

The correspondence between the calculated and measured impulse response graphs was poor, although some similarities were found. Figure 32 shows small portions of the two graphs (0ms to 250ms) with the same scale. The measured graph is above and the simulated graph below.

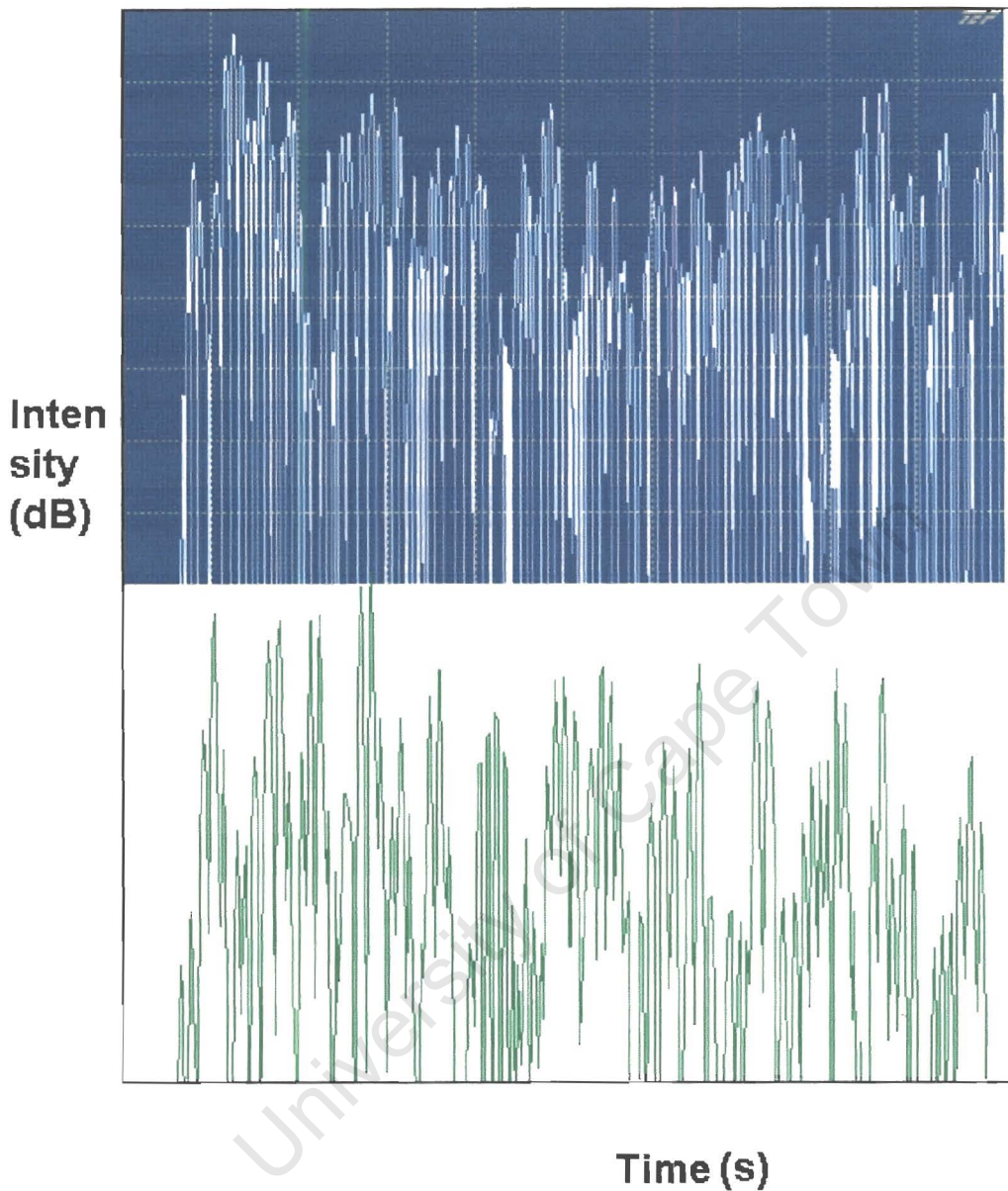


Figure 32: Comparison between measured and calculated impulse response graphs in a simple rectangular room.

It is clear that the two graphs are significantly different. Although it is possible with some imagination to see similarities, these in no way give confidence in the calculated modal response curve as a useful prediction model.

The discrepancies are assumed to come primarily from irregularities in the measurement room, these being chiefly air conditioning gaps, general lack of sealing, and the presence of a large speaker used as the sound source. If all these could be remedied, and some independent verification of the RoWena calculation model could be made, then a better correlation should be obtained as explained by Cremer⁶⁴.

7.3.7. Conclusions Regarding the Mathematical Simulation of a Simple Room

It is clear from 7.3.6 that even in a simple room it is difficult to obtain a good calculated impulse response curve. An improved correlation could be obtained with more controlled and accurate measurements, but this makes an already unrealistic situation all the less useful.

7.4. Sound in a Large Irregular Shaped Room

Rooms that typically require room acoustic analysis, such as the Jameson Hall, are very complicated and are at present impossible to describe mathematically. This section approaches the differences between simple rooms and complicated realistic rooms, as a prelude to introducing a more realistic method of simulating room acoustics.

7.4.1. Structure of an Irregular Room

A perfectly irregular room differs from a regular room in that surfaces are not aligned parallel or perpendicular to each other. Thus modes of the type described by the equations in 7.3 are not possible. Also the surfaces of the room introduce phase changes to the sound reflected from them and even scatter the sound in various directions.

In such a room it is not possible to mathematically describe the sound field since the geometry becomes too complex. There are however approximations and statistical methods which can partly categorise the sound field.

7.4.2. Modes in an Irregular Room

Just as in a regular rectangular room, modes occur in an irregular room. However there are so many of them and they involve nearly all angles of incidence with the walls that a sound source that produces a sound with even a small frequency range in an irregular room excites many many modes which travel in all directions.⁶⁵

If the room is not completely irregular, if for example there are two large parallel facing walls, then a strong standing wave may be set up between them which will stand out above the sound field of the room. This, or a similar condition, is often the case in real rooms but it is a departure from the irregularity that is discussed here.

7.4.3. Diffuse Sound Field

An important effect of the irregularity of the room is that a diffuse sound field is created. A diffuse sound field is defined as a sound field that has "isotropy of propagation directions and incoherence of the wave components".⁶⁶ 'Isotropy of propagation' means that the sound measured at any point in the room arrives from all directions equally. Incoherence of wave components means that the phase of the all the sound waves reaching a point are randomly related and therefore their specific inter-relationship is unimportant and can be treated statistically. The effective rms pressure is therefore a simple energy addition of all the wave components, ignoring the phase.^{67, 68} Therefore in a perfectly diffuse sound field it is not necessary to consider the phase of the individual sound waves, nor their direction, to quantify the sound field. Individual modes and standing waves become insignificant.

The diffusivity of the sound field makes statistical methods of analysis more important and relevant than wave theory, since the effects of wavelength and frequency interference are less

important. Even where the room is not completely irregular the assumption of a diffuse sound field is often more accurate than not⁶⁹.

7.4.4. Diffuse Reflections

One cause of a diffuse sound field, apart from general irregularity in the room geometry, is scattering surfaces. These are surfaces that reflect sound in many directions in a more or less diffuse manner.⁷⁰ The term 'diffuse' and 'diffuseness' has come to refer to any part of the sound field that involves diffusely reflecting surfaces.⁷¹ Scattered or diffuse reflections break up the directionality of the sound waves and aid in creating a diffuse sound field.

A scattering surface typically has irregularities that reflect the sound in many directions. The irregularities must be of the same order of size as the wavelength of the sound that must be scattered. Low frequency sounds therefore require large irregularities and visa versa.⁷²

A completely diffusive reflection means that the direction of the sound reflection does not depend on the direction of the incident sound at all.⁷³ Such reflections are described by Lambert's Law (see 13.1).

7.4.5. Scattering Due to Different Surface Impedances

When the impedance between two surfaces is different, then the sound that reflects from a point close (relative to the wavelength) to the boundary between the two impedances is affected in a complicated manner that is not described by either of the surface's impedances individually⁷⁴.

Because the exact nature of the reflection is very complicated it is often assumed in prediction models that such complications do not occur, and that the surfaces are all 'locally reacting', which means that the reflecting surface is the only surface that has any effect on the sound wave, regardless of the wavelength and the proximity of other surfaces.

7.4.6. Conclusions Regarding Simulation of Complex Rooms

Where the simple rectangular room was just possible to describe completely in mathematical terms, a realistic irregular room is impossible. The calculations would become excessively unwieldy, and also the number of unknowns, such as phase effects of surfaces, becomes prohibitive of an accurate calculation.

Another simpler means is needed to obtain reasonable results. This is the topic for the next section.

8. INTRODUCTION TO ROOM ACOUSTIC COMPUTER SIMULATIONS

Having established that it is nearly impossible, and certainly impractical, to completely describe the acoustics of a room, it is necessary to determine to what extent the acoustics can and must be known.

In this regard note that all room acoustic quantities discussed in section 4 were determined from the impulse response of the room. Therefore a good simulation program would produce an impulse response with enough information to obtain these quantities. It shall be seen that a number of different techniques will be required to obtain this accuracy.

Since reverberation is considered the most useful and widely used room acoustic quantity, it is the benchmark by which simulation programs are initially judged. This will therefore be the primary focus in the discussion that follows.

8.1. Room Model

In order for the computer to simulate a room, the room must first be modeled inside the computer. This is done by approximating the room as a number of surfaces that together represent the room's bounding surfaces and any objects in the room. Because halls generally consist of a great many surfaces, some simplification is usually needed. A typical computer room model will consist of about 100 to 200 surfaces. The more surfaces that are used the longer the simulation will take, which may or may not improve the accuracy of the results.

Surfaces in the simulation model are usually required to be planar, that is flat and containing a single normal over the whole surface. Thus curved surfaces must be usually be represented by a number of smaller planar surfaces each at a slightly different angle. This requirement is historical rather than necessary since it is only slightly more difficult to program a curved surface than a planar surface. However all the research in simulation models has concentrated on planar surfaces. The simulation program written for this thesis allows the use of curved surfaces, since they are an important part of the Jameson Hall around which this thesis is based (see 5).

8.2. Approximation of a Sound Wave

As has been established, a simpler description of a sound wave is required. In 7.4.3 it was stated that if a sound field is diffuse then the phase (and direction) of the sound is unimportant. If this is so then the phase (and also frequency) of the simulated sound wave can be ignored. Since the sound in many halls and rooms is diffuse, or nearly diffuse, this is deemed a practical approximation (see 7.4.3), and is termed geometrical acoustics.

On the other hand it is possible, and has been attempted, to create a simulation program that includes phase. However the computer processing power and time required is much greater than for the simpler geometrical methods and the time span of the impulse response curve is limited. Also the method as a whole is limited since the complex impedances for most surfaces, which are required by a phase simulation model, are usually unknown. At present the overwhelming majority of room acoustic simulation programs use geometrical methods, though in the future, with more powerful computers and better knowledge of room surface properties, this balance may change. Phase simulation models are not discussed further in this thesis.

9. GEOMETRICAL ACOUSTICS / RAYS

Geometrical acoustics refers to an approach to acoustics where sound waves are assumed to be entities with no phase and therefore are unable influence each other in any way. These simplified sound waves are called rays. A formal definition of ray is a "line everywhere perpendicular to the surfaces of constant phase of a sound wave."⁷⁵

Instead of spreading like sound waves as they travel away from a source or reflection point, rays travel in straight lines. Figure 33 shows different instants of a sound wave (the circles) and some corresponding sound rays, where each ray represents an infinitely small piece of the sound wave. Ideally therefore an infinite number of rays are needed to approximate the shape of the complete sound wave, which of course is impossible.

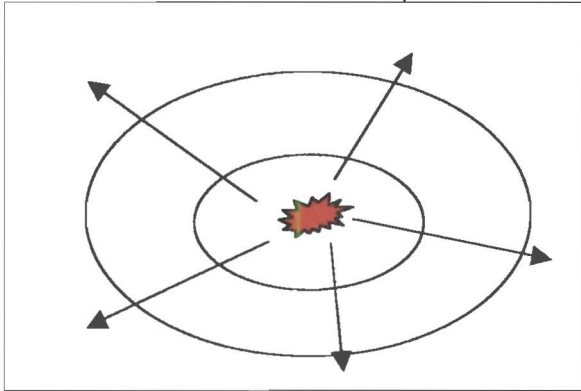


Figure 33: Illustration of Rays in a Sound Field

Ideally rays reflect from surfaces according to Lenz's law. This law states that the angle of reflection equals the angle of incidence, as in Figure 34.

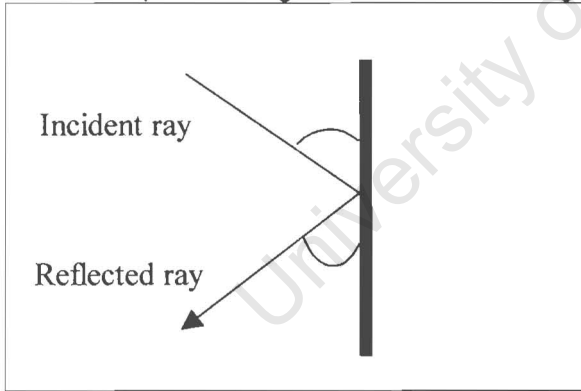


Figure 34: Lenz's Law of Specular Reflection

However irregularities in the surface of an order comparable to the wavelength of the incident sound, as is usually the case in reality, mean that this perfectly specular reflection rarely occurs.

It is not only the size of the irregularities of the surface that are important. If the entire surface is small compared to the wavelength of the sound incident on it, then the sound will diffract around the surface. Geometrical acoustics has no means of simulating this complicated process, and so diffraction cannot be simulated.

9.1. Frequencies of Relevance for Geometrical Acoustics

Geometrical acoustics strictly only applies when the reflecting surface size is large compared to the wavelength of the sound. At 500Hz, which is the middle of the range of useful room acoustic frequencies, the wavelength of sound is 68cm. This is neither large nor small compared to typical room surfaces. Above this frequency, for example at 2kHz ($\lambda=17\text{cm}$), the wavelength may be considered small compared to the room surfaces. Below, for example at 125Hz where $\lambda=2.5\text{m}$, the wavelength is typically large compared to the room surfaces⁷⁶.

In spite of these requirements geometrical acoustics is used regardless of the shape and size of the hall.

9.2. Simulating using Ray Tracing

The use of rays in simulating acoustics is called ray tracing. This term, along with much of the theory, was borrowed from optics. More information on ray tracing may be found in any good optics textbook.

In ray tracing a large number of rays are used to represent a sound wave produced by a source. These rays are produced one by one and allowed to travel around the computer room model. At each surface in the model they reflect according to Lenz's law and consequently change direction. Each time they pass a measurement point their strength and time of arrival is recorded on a graph. This process is shown in Figure 35 that shows a few rays, one of which will reach the measurement point (also called the receiver).

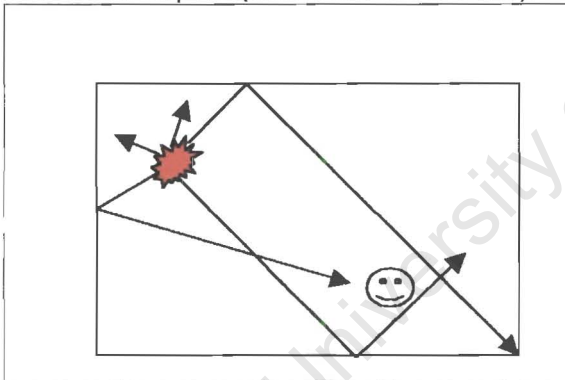


Figure 35: Multiple Rays in the presence of a Receiver

The strength of the ray which is recorded by the receiver is dependent on the number of reflections of the ray from the surfaces in the room model, on absorption by the air which is dependent on the distance traveled, and spreading, which is also dependent on the distance traveled. Each of these calculations is a simple one. (see Appendix A).

The resultant simulated impulse response graph looks similar to that shown in Figure 36.

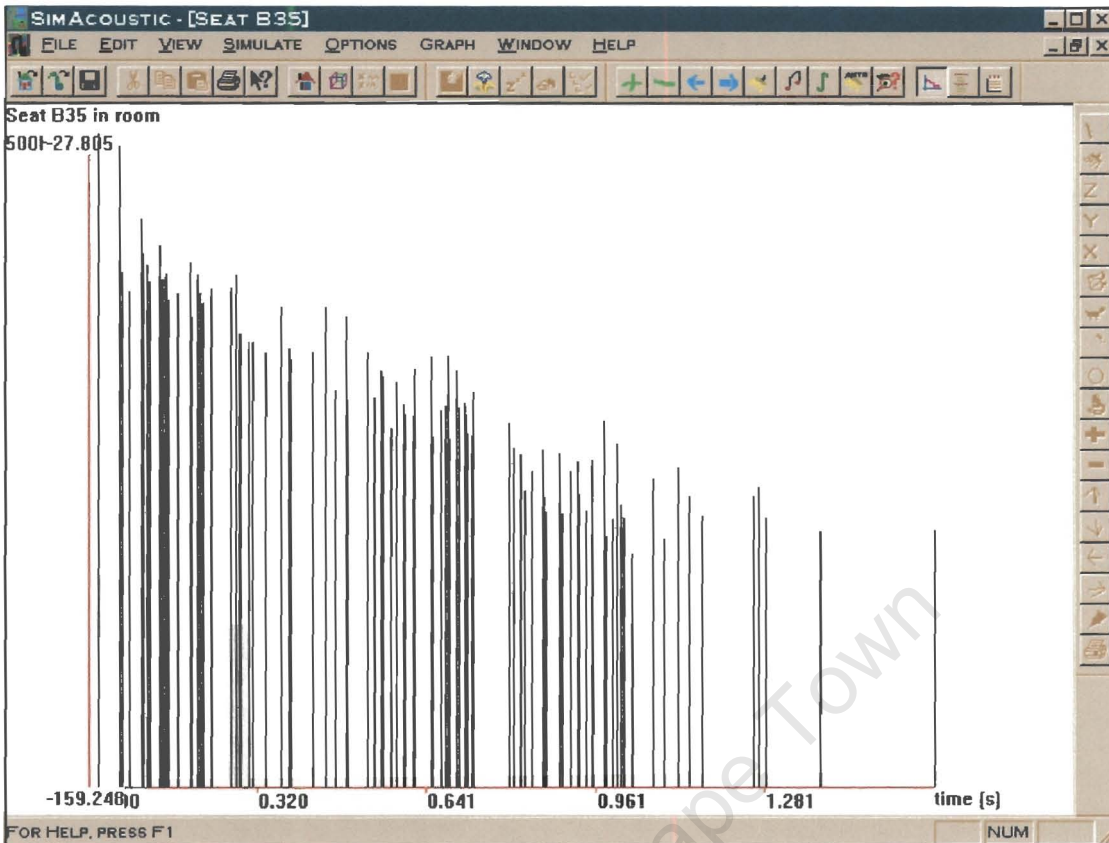


Figure 36: Example of a Simulated Impulse Response Graph

If this graph is compared to one of the earlier measured impulse response graphs, it is clear that a significantly smaller number of reflections have been recorded in the simulation graph. However the distinctive decay slope is visible and reverberation times can be obtained from it. The accuracy of the objective quantities obtained from such a simple simulation method is usually poor and some modifications must be made to improve the accuracy.

The interested reader may wish to refer to appendix D for a proof of the mathematical equivalence of ray tracing to the Sabine Formula.

9.3. Mixing Time/Diffusion

Much reference has been made to the importance of a diffuse sound field in the simulation methods (see 7.4.3). Another way of looking at diffusion is to use the concept of mixing time, which was developed from the mathematical theory of ray tracing. This theory is called billiard theory, named after the game.

In billiard theory, mixing time is defined as the time after which two rays with initially similar paths are seen to be independent and uncorrelated.⁷⁷ As shown in Figure 37, two rays with similar initial directions will follow similar paths. However these paths will slowly diverge as they hit different surfaces due to their slight difference in trajectory. This difference will increase until such time as they are uncorrelated. The time for this to occur is called the mixing time.

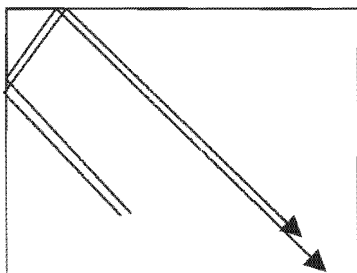


Figure 37: Two initially similar rays

After mixing time the initial direction of any ray is unimportant, since even a slight variation in initial direction will result in a large difference in resulting direction and position. Therefore the sound field at any part of the room (after mixing time) could be simulated by any particular ray. Thus a diffuse sound field is analogous to a ray-traced field after mixing time, as far as the directional and temporal aspects are concerned.

9.4. Number of Rays Required to Simulate a Sound Field

Besides the directional and temporal aspects of ray tracing in a diffuse sound field, the intensity of received rays is also important. If insufficient rays are detected by the receiver (measurement point) then the energy at the receiver will be too low, and *visa versa*.

In practice the receiver never receives too many rays, since the finite number of rays simulated is always less than the total energy of a sound wave. On the other hand, because of this, the total energy detected is usually too low.

It is possible to mathematically calculate the expected energy, and that obtained through the ray-tracing model. This is explained in the following sections.

9.4.1. Theory of Mirror Image Rooms

When a ray reflects from a surface, rather than reflecting the *ray*, the *room* can be reflected, with the reflecting surface as the mirror. Figure 38 shows an example where a ray has reflected off a surface. The mirror room is shown in dotted lines, except for the shared surface. Using the concept of the mirror room, the ray appears as a straight line from the real room into the mirror room.

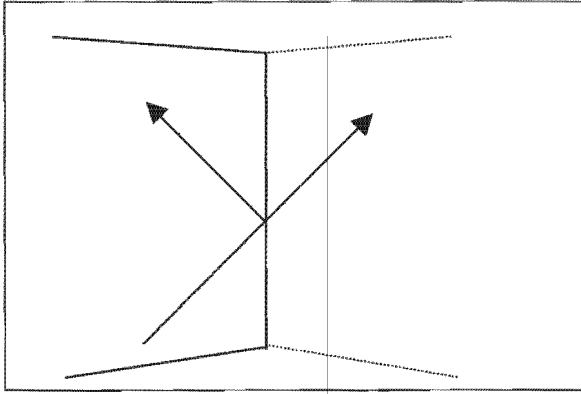


Figure 38: A Single Mirrored Room with Associated Ray Path

If the ray is to be continued and reflected again, then the mirror room must itself be reflected through whichever surface the ray intersects. In this way a sequence of mirror rooms is created, one for each reflection, with a single straight ray passing through each (see also 12.3).

The concept of mirror image rooms is therefore simply another way of looking at the flight of a ray. Its usefulness comes in because it makes it possible to speak of the number of reflections occurring in a radius r around the ray starting point. The circle described by the radius r extends into the mirror rooms and so the number of reflections in r is the number of mirror rooms in that circle.

9.4.2. Number of Rays Required to Hit Each Surface in the Room

If the number of rays simulated is N , then in a radius r as explained in 9.4.1 the smallest surface which could be guaranteed to be reflected a ray is $\Omega = \frac{4\pi r^2}{N} = \frac{4\pi c^2 t^2}{N}$, which is the number of image sources divided by the number of simulated rays⁷⁸.

If the area of the smallest surface is A_{min} , and the smallest surface in the room is 1.3m^2 (e.g. the balcony front in the Jameson Hall) then at 1s $N=1$ million rays are required to be sure of hitting the surface.

9.4.3. Number of Reflections per Second in a Room

More importantly it is possible to calculate the expected number of reflections occurring in a room. This can then be compared to the number of simulated reflections calculated in 9.4.4.

The number of reflections occurring between a time t and time $t+dt$ is the number of mirror rooms within a spherical shell of inner radius ct and outer radius $c(t+dt)$. The shell volume is

$$V_{shell} = \frac{4}{3}\pi(ct + cdt)^3 - \frac{4}{3}\pi(ct)^3. \text{ If } dt \text{ is made very small compared to } t \text{ then this simplifies to}$$

$$V_{shell} = 4\pi c^3 t^2 dt.$$

If the volume of the room is V , then the volume of the room (and also of any mirror room) is contained within the shell volume V_{shell}/V times. This ratio is the number of mirror rooms per time t , and since each mirror room corresponds to a single reflection, it is also the number of reflections per time t .

Therefore the temporal density of expected reflections is $\frac{dN}{dt} = \frac{4\pi c^3 t^2}{V}$, where dN/dt is the rate of arrival of reflections at time t .⁷⁹

9.4.4. Number of Ray Traced Reflections

The rate of occurrence of reflections is $I_m = \frac{cN}{l}$, where N is the number of rays simulated and c is the speed of sound. l is the mean free path length of a single ray, which is calculated as $\bar{l} = \frac{4V}{S}$. This is the average distance the ray may travel in a perfectly diffuse sound field before reflecting from a surface⁸⁰

Ideally l_m and $\frac{dN}{dt}$ should be equal, but this rarely occurs. For the Jameson hall, with a volume of 6830m^3 , the temporal density of expected reflections after one second is 74000 reflections per second. The mean free path length of a ray in the hall is 33.58m and so the number of rays required to obtain the desired temporal density is 7200 rays. This is a reasonable number of rays for a simulation model.

At 2s, 29 thousand rays are required. At 3s, 65 thousand rays are required. At 4s, 116 thousand rays. The number of required rays increases in this exponential manner. However impulse response calculations of longer than 4s are required very rarely, the Jameson hall when empty being a pertinent exception.

In cases where the required number of rays is not correct, one could multiply the intensity of each received ray by the ratio of $\frac{dN}{dt} / I_m$ in order to correct their energies. This would ensure that the total energy content of the simulated impulse response would be correct. Naturally this does not improve the temporal accuracy of the simulation.

Also for this to be valid it is important that enough image sources are produced in the simulation model that the ray paths are mixing, i.e. that the simulated sound field is diffuse. This assumption is valid only when sufficient rays are produced, which as has already been stated is usually a very large number of rays. More on this may be found in 11.

10. IMPLEMENTATION OF A BASIC RAY TRACING SIMULATION METHOD

This section explains in simple terms how a single ray is simulated⁸¹. A more detailed explanation can be found in Appendix A.

10.1. Description of a Ray

A ray is a line composed of multiple segments. The first segment of the ray starts at the simulated sound source point. It is given a specific direction such that the directions of all the rays simulated form a sphere around the source point.

The simulation program then determines which surface in the room model the ray segment would intersect. The intersection point, called the puncture point, is thus the end point of this segment, and also the start point of the second segment of the ray. The second segment has a new direction which is calculated by Lenz's law (reflected angle=incident angle) as described in section 62.

10.2. Strength of a Ray

The simulated source has a certain intensity that is arbitrarily set to 1 W/m^2 (intensity). Each of the many rays is also given this initial intensity. It would appear from this that the total intensity of the source is thus the number of rays times the initial source intensity, which would be incorrect. However because spreading is included in the final ray strength calculation the energy is corrected.

10.2.1. Spreading Strength of a Ray

If the ray is detected by a receiver, then the received strength of the ray is calculated as

$I_{\text{received}} = \frac{I_{\text{ray}}}{4\pi l^2}$, where l is the distance that the ray has traveled to the receiver, including reflections⁸². In this way spherical spreading by the source is taken into account.

10.2.2. Absorption Strength of a Ray

Each surface from which the ray reflects has a certain absorption associated with it. This absorption is expressed as an absorption coefficient that is identical to the normal absorption coefficient attributable to real surface materials (see 7.2.6). The strength of a ray after reflecting from a surface is thus $I_{\text{reflected}} = I_{\text{incident}} \cdot (1 - \alpha)$.

Since the absorption coefficient is usually different for each octave frequency a separate intensity for the ray is stored for all the octave frequencies that will be simulated. This is the only correction for wavelength that is incorporated into the basic ray-tracing model.

10.2.3. Detection by Receiver

After each reflection the simulation program determines whether the ray will intersect a receiver. If it does then the ray strength and time of arrival is recorded on the respective receiver's

simulated impulse response. The time of arrival of the ray is calculated as the length of the ray from the source point to the receiver point divided by the speed of sound.

It is quickly obvious that if the receiver were merely a point specification in the simulation model then very few, if any, rays would be detected by the receiver. Therefore the receiver is commonly modeled as a sphere of a certain size, usually about 1m radius (see Figure 39). This ensures that a reasonable proportion of the rays will intercept the receiver, although errors as described in 10.3.2 will occur.

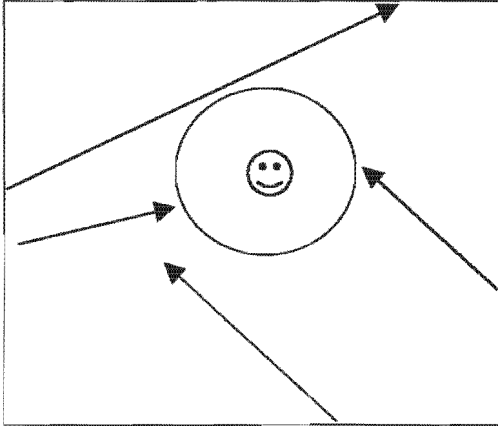


Figure 39: Receiver with surrounding sphere

An example of the resultant simulated impulse response graph has already been shown in Figure 36.

10.3.Errors in the Ray Tracing Simulation Model

Apart from the errors inherent in the geometrical simulation model, errors also arise because of limitations in the ray tracing procedure. These stem from the finite number of rays allowed, and the enlarged size of the receiver when modeled as a sphere.

10.3.1. Errors due to the Finite number of rays simulated

A sound wave does not leave gaps as it propagates through the room. However the myriads of sound rays used in the simulation model can never completely represent the physical sound wave. This means gaps exist in the simulated sound field which can cause the simulated impulse response curve to have too little energy. A potential situation illustrating this is shown in Figure 40.

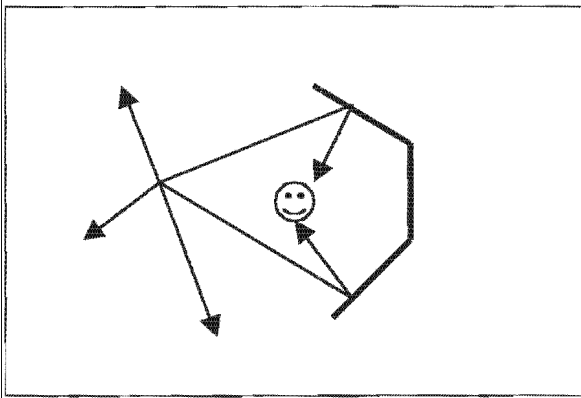


Figure 40: Three reflecting surfaces, one of which is not seen by a ray

In this case the receiver (shown as a smiley face) does not receive sound reflected by the middle surface because not enough rays were present.

This sort of error is very hard to correct since it is caused by a fundamental limitation of the ray tracing process, namely that an infinite number of rays cannot be simulated. If the number of rays is increased the likelihood of this error occurring will diminish, but the simulation time will increase as discussed in 9.4.2.

10.3.2. Errors caused by the enlarged receiver size

The second primary error is due to the receiver sphere size. This enlarged receiver size may cause too many rays to intercept the receiver, resulting in an excess of sound energy reaching the receiver. Also the receiver itself could be hidden behind an object, yet the sphere surrounding it could be visible to the rest of the room. In both these cases the receiver will detect some invalid sound rays.

11. IMPROVED SIMULATION OF LATE TIME: SECONDARY SOURCES

It was determined in section 9.4 that an extremely large number of rays are required for a thorough simulation of a sound field. Unfortunately the time taken to simulate these large numbers of rays is sometimes unreasonable, especially for complicated room models. Also the results of such simulations rely very much on the exact number of rays simulated, with lower number often resulting in insufficient energy in the simulated impulse response (see 16.3.6).

Reference was also made to the ratio of expected temporal density to that obtained through ray tracing which could be used to increase the intensity of detected rays to an acceptable amount. However the number of received rays decreases with longer ray paths, and therefore not enough rays may be generated to validate this technique.

A technique called Secondary Sources can be used to overcome these obstacles. The idea and description that follows comes from a research article concerning the ODEON simulation model⁸³.

11.1. Overview of the Secondary Sources Technique

'Secondary Sources' is a term given to a method devised to maintain the correct amount of late time energy in the simulated impulse response, based on the expected reverberation time formula, without losing the usefulness of the ray tracing process.

Simply the number of detected rays is increased at least a hundred fold, and the energies of these rays adjusted according to theoretical expectations. Thus sufficient reflections can be produced using only a fraction of the number of rays used in the basic ray-tracing model.

11.2. Ray Detection in the Secondary Source Model

In the basic ray tracing process, rays are detected if they happen to pass within the receiver sphere. In the secondary source model, every ray at every reflection is detected by the receiver. So instead of waiting for a ray to intersect a receiver sphere, each ray is detected after every reflection. This is shown in Figure 41.

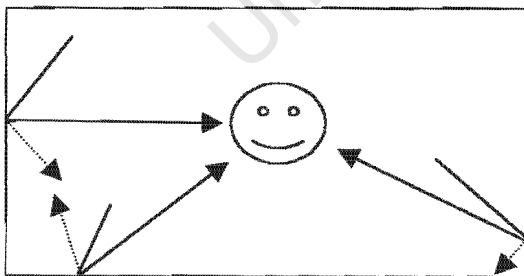


Figure 41: Secondary Source directivity of rays towards a receiver

In Figure 41 even though the rays' specular direction does not lead towards the receiver (the dotted arrows show the specular reflection path), for the purposes of the secondary source model they are directed towards it. (After being detected by the receiver, this last part of the ray is ignored and the usual specular reflection of the ray occurs.)

A very large number of reflections are detected by the receiver in this way, which is useful in that using only a small number of rays a very dense simulated impulse response graph can be produced. The energy of simulated impulse response curve will however be too high and must be corrected.

11.3. Validity of Ray Detection in the Secondary Source Method

Most of the detected rays will be invalid, in that it would not be possible for a geometrical path to be constructed from the receiver to the source reflected through the surfaces of the ray. Such ray paths are called 'hidden'. Detecting hidden paths, although seemingly incorrect, is in fact legitimate when considered in the light of mixing (see 9.3).

After mixing time the position and direction of any ray is unrelated to its initial direction. This means, as was explained, that any particular position in the hall could statistically be arrived at by any initial ray direction. Therefore whether a ray path is specularly valid or not is unimportant.

11.4. Correction of Rays' Energies in the Secondary Source Model

As was discussed in 9.4 it is possible to calculate the theoretically predicted number of reflections that will occur in a room. The ratio of this number to the number of reflections produced by the secondary source model gives the proportion by which each ray in the secondary source model must be adjusted.

The ratio is $\frac{I_r(t)}{I_m} = \frac{4\pi c^2 t^2 \tilde{I}}{NV}$, where the symbols are as described in section 9.4. This formula is

dependent on the number of rays simulated (N) and the volume (V and \tilde{I}).

It is important that enough rays are detected that the importance of any single ray is negligible, i.e. that the sound field is diffuse. Also this model, more so than the basic ray tracing method, is not accurate for coupled and non-diffuse sound fields.

11.5. Effectiveness of Secondary Sources in Simulating Non-Diffuse Sound Fields

The entire basis of ray tracing and secondary sources is on a diffuse sound field. This requires a sufficient number of detected rays such they become statistically unimportant individually.

However in the case of rooms with different spaces, such as coupled areas below a balcony, it may be feasible to use the geometrical nature of the ray tracing process to relax the diffuse requirement slightly.

If instead of allowing each secondary source ray to be detected by the receiver, the requirement is made that a direct line of sight must exist between the last reflection point and the receiver. Thus objects such as balconies and stage fronts could block sound to some areas of the room⁸⁴.

This defeats the acceptance of absence of directionality in the simulation, but may produce results that demonstrate coupled trends in reality. No research has been performed to directly quantify this modification to the secondary source technique.

11.6. Deficiencies of the Secondary Source Technique

The secondary source technique properly calculates the energy ascribed to any ray, and enforces the diffuse sound field requirement. However it is often very useful to inspect the impulse response curve for non-diffuse anomalies, such as echoes. For these the direction of the sound path is important since they are caused by specific surface reflections or focusing by curved surfaces.

An impulse response curve simulated by the secondary source technique will not show echoes and the like, since every simulated ray is detected by all receivers. The basic ray tracing model, where receivers are modeled as spheres, are more likely to show echoes on the simulated impulse response graph, since particular ray paths are more important in this model, although the echoes may be missed completely anyway.

This deficiency is particularly important in the early time, where such characteristics as the Early Decay Time, initial time delay gap (ITDG) and LE_{early} (see 4) can only be determined by accurate knowledge of the direction and arrival time of reflections.

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12. IMPROVED SIMULATION OF EARLY REFLECTIONS

A typical measured impulse response consists of a direct sound and closely following reflections. This can be seen in the impulse response graph in Figure 2.

That simulating these early reflections is important is given by a round robin test hosted by M Vorländer in which only those simulation programs that specifically found exact early reflections provided consistent accurate predictions of many parameters⁸⁵.

Basic ray tracing, because of the enlarged receiver size, cannot find exact ray paths (see 10.3). More so with the secondary source technique, where all reflections reach all receivers (see 11.6).

A separate process is required to determine accurately the ray paths of early reflections.

12.1. Basis of Early Reflection Path Finding Methods

The exact path of a ray depends on the direction of its reflections from the surfaces it intercepts. If purely specular reflections are assumed, as is the case for this section, then it is possible to determine mathematically the ray path from a source point, reflected from a particular sequence of surfaces, and then to a receiver point, if such a path exists. If the reflections are not specular but scattered then such a method cannot be used.

The commonly used method for determining such paths is called Mirror Imaging. Some of the basics concerning image sources have been explained in 9.4.1, and is elaborated on here. Mirror imaging is a mathematical process that was designed for planar surfaces, and will be presented first. A more complete description may be found in Appendix B. An alternative method suitable for curved surfaces is described in 15.5.

12.2. Invocation of the Early Reflection Path Finding Methods

It is important to examine every possible ray path in the early time in order that a good simulation of all the early reflections be obtained. In this regard it is possible to exhaustively inspect all surface combinations up to a given order, but this is time consuming and wasteful, especially since the vast majority of surface combinations do not provide valid ray paths between source and receiver⁸⁶.

A better method is to use the normal ray tracing process and then examine each ray at each reflection to determine whether a valid ray path to the receiver could be obtained through that ray's sequence of surfaces. In this way a large proportion of the total potential ray paths are eliminated, leaving only those with a high potential success.

Therefore at every reflection of a ray the "exact ray path" finding method is invoked. If a valid ray path is found between source and receiver then its energy is assigned to the relevant simulated impulse response.

After a certain time, equivalent to a certain length of ray, the default simulation method is invoked, which is either basic ray tracing method or secondary sources. This changeover time should ideally be equivalent to the mixing/diffuse time. However because geometric methods do not find accurate ray paths after more than a few reflections, as can be seen in 16.7, the changeover is usually set to 2 or 3 reflections.

12.3. Mirror Imaging

Mirror Imaging is the technique commonly used in room acoustic simulation programs to mathematically deduce the exact reflection path from source to receiver.

12.3.1. Description of the Mirror Imaging Algorithm

The algorithm discussed here is as described by Lee&Lee⁸⁷. A detailed description of the algorithm may be found in Appendix C.

The algorithm uses the source point, the sequence of surfaces in the reflection path, and the receiver point. Each of the reflection surfaces is dealt with in turn as follows.

First the mirror image of the source point (S) through the selected surface is found. This point (S'), as shown in Figure 42, is the point where a straight line drawn from the point through the surface, at the reflection point, would lie on top of the reflected line.

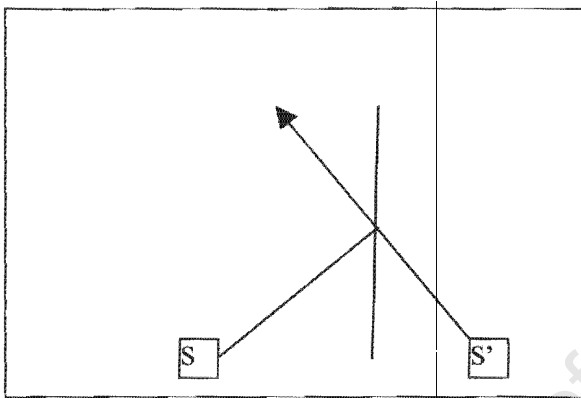


Figure 42: A single mirrored source point

The original room surfaces are now mathematically transformed into the image source's (S') coordinate frame, as in Figure 43.

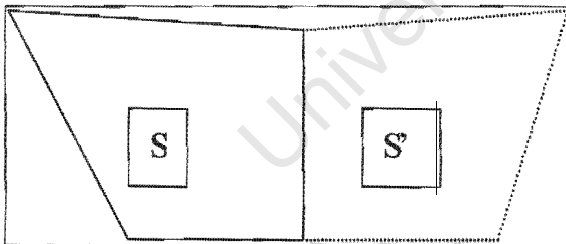


Figure 43: A single mirrored source room

In Figure 43 the room on the right is the mirror image of the room on the left, mirrored through the reflecting surface.

Now the process begins again, using the image room as the basis for further images. Figure 44 shows a three surface reflection with corresponding image rooms.

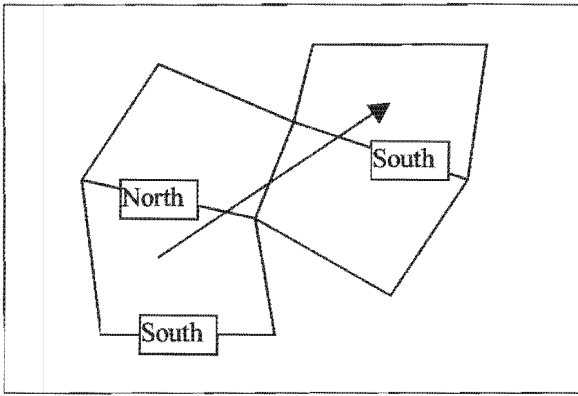


Figure 44: Multiply mirrored source rooms with associated ray path

In Figure 44 a source point in the bottom left room is reflected through its North surface. An image room is then created (North of the original room), which is a mirror image of the original room. Then, from this image room, there is a further reflection through the East surface, and similarly again through the South surface (note: the original room was turned upside down in the first reflection, so the two South surfaces are the same surface in the original room.)

The end point of the ray is the multiply mirrored source position. Note that the line joining the original receiver to the mirrored source is a straight line and remains within the surface boundaries of each image room. It will always be straight by the nature of the process, but if it strays outside the boundaries of a particular image room, the ray path will be invalid.

The intersection points of the ray with each image surface represent reflection and puncture points in the original room, and when transformed from image to original will give the correct ray path through that sequence of surfaces.

12.3.2. Limitations of the Mirror Imaging Method

The mirror imaging algorithm is far more complex than the basic ray tracing process, and so takes longer to compute. However, this is in fact not as large a problem as it used to be now that computers are reasonably fast.

A more important limitation as regards the Jameson Hall is that the algorithm only works for planar surfaces. The mirror imaging algorithm uses the surface normal in its calculations, which is assumed to be constant over the whole surface. Curved surfaces however have a normal that varies across the surface and therefore mirror imaging in the form described cannot be used. A more complete description of this limitation is given in 15.5 as well as an alternative method.

13. IMPROVED SIMULATION OF SCATTERING/DIFFUSION OF SOUND

Thus far the ray tracing process has involved only specular reflections. The secondary source technique allows non-specular reflections for reflections directed towards the receiver, but all reflections from surface to surface are specular.

Research has found that ray tracing models that do not incorporate scattering from surfaces (non-specular reflections) over-predict the energy content of the simulated impulse response curve⁸⁸. This research has not included the use of secondary sources and is concerned with the basic ray-tracing model only.

13.1. Scattering from Surfaces Perfectly Diffusive Surfaces

As was explained in 9.1, surfaces reflect sound specularly only when they are smooth and large compared to the wavelength of sound. This is not always the case in real rooms, and some surfaces are specially designed to scatter sound⁸⁹.

The manner in which the reflected sound is scattered depends on the shape of the irregularities on the surface and also on the incident angle of the sound with the surface (see 7.4.4). As such it can rarely be accurately predicted except for special cases.

However there is a rule, called Lambert's Law⁹⁰, which approximately gives the distribution of reflected sound from a completely diffusive surface, i.e. a surface that scatters sound equally in all directions. Such surfaces are common at light frequencies, although at sound frequencies less so.

For perfectly scattering surfaces, Lambert's Law may be used to predict how much light will be reflected to any position in front of the surface. Figure 45 shows such a case, where a particular direction θ is shown.

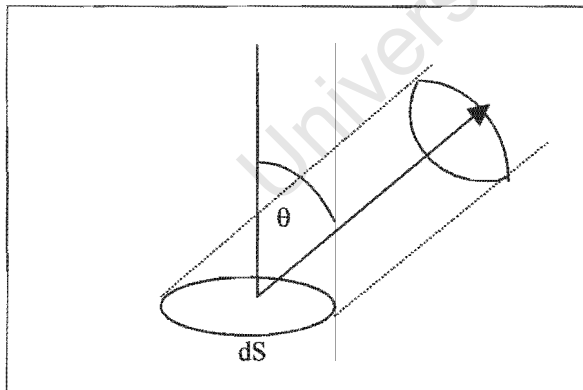


Figure 45: Lambert's Law Illustrated

A small area dS on the surface is illuminated by sound such that it has I_0 energy to illuminate the entire hemisphere bordering on the surface. At any receiving point the amount of energy received is equal to $I_0 dS \cos \theta$, which is proportional to the projected area of dS . Thus receiving points perpendicular to the surface receive most of the energy while receiving points with a large θ receive least. (see for e.g. Longhurst⁹¹).

This rule also applies for sound incident on the area, and so if B_0 is the incident energy on the surface at angle θ , the reflected energy will be $B_0 dS \cos \theta \cos \theta$.

Although it is called Lambert's Law, it is more accurately called a rule since although it describes such surfaces well it is experimental rather than derived.

13.2. Simulating Scattering in the Ray Tracing Model

A scattering surface breaks up the incident sound into a number of non-specular directions. It is not possible to simulate each of these directions since the number of rays required would be excessively large and exponentially increasing with each reflection.

It is however possible to simulate any single scattered direction. This involves simply modifying the reflection direction by some amount dependent on the scattering properties of the surface. The intensity of the reflected direction is then determined by Lambert's Law.

Using this method the complete effect of the scattering surface is not accounted for and thus scattering as a whole is not well simulated.

13.2.1. Choosing the Scattered Reflection Direction

As described in 13.1 a perfectly scattering surface scatters sound in all directions. Therefore the simulated scattered direction can be found simply by choosing two random numbers representing the azimuth and elevation of the reflected ray. The strength of the ray would then be calculated by Lambert's Law.

However, since most sound is reflected in a direction perpendicular to the surface (from Lambert's Law), and considering the limited number of rays which are likely to strike the surface within the same time period, it is more practical to choose a reflection direction with probability based on Lambert's Law and leave the strength of the ray unadjusted.

13.2.2. Simulating Partially-Scattering Surfaces: The Diffusion Coefficient

At the wavelength of sound most surfaces do not scatter sound perfectly. Many surfaces are relatively smooth, and in fact few surfaces, including specifically constructed diffusive surfaces, scatter sound completely⁹².

In order to quantify the degree of scattering attributable to a surface, a diffusion coefficient is used. This coefficient is not a physically measurable quantity and its use is restricted to room acoustics computer simulations. Also the exact choice of value for any particular surface depends on the scattering model used, of which there are a number.

However in general the diffusion coefficient varies between 0, for a completely smooth surface with no scattering, and 1 for a surface that scatters according to Lambert's Law. Since surfaces may scatter sound by different amounts depending on the wavelength of the incident sound, a diffusion coefficient for each frequency of interest is attributed to the surface.

Note that the diffusion coefficient does not describe the exact nature of the scattering from the surface, only the degree amount of scattering. Its choice is based primarily on trial and error testing within a specific scattering model.

13.2.3. Simulating Partially-Scattering Surfaces: Implementation

The simulation model for a completely scattering surface was described in 13.2. The use of the diffusion coefficient allows the possibility of simulating partially scattering surfaces. A number of models are described by Rindel^{93,94}. Only one model will be described here, and is perhaps the simplest.

A random number is generated between 0 and 1. If this number is lower than the diffusion coefficient then the ray is reflected in a completely diffuse manner, otherwise it is reflected specularly. In this way surfaces that a large diffusion coefficient will produce many diffuse reflections, and visa versa.

Simulation programs using this model have been implemented many times and the resulting predicted acoustical parameters show a good correlation with expected results.⁹⁵

13.2.4. Applicability of Scattered Reflections in the Early Time

The use of finding exact reflection paths in the early time (see 12) is compromised by the scattering model, since exact paths are not relevant for scattering surfaces. Insufficient research into scattering has been performed for it to be more useful than mirror imaging at finding early ray paths.

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14. COMPARISON OF SIMULATION MODEL WITH THE ODEON ROOM ACOUSTIC SIMULATION PROGRAM

The ODEON room acoustic simulation program is reputed to be an accurate predictor of most room acoustical quantities⁹⁶. For this reason it has been chosen as a benchmark of the accuracy of the simulation model created for this thesis, and described above.

Only a demo version of the program was available, which is limited by the particular rooms that can be simulated.

14.1. Room Model

The room model that was simulated is shown in Figure 46 (from RoWena) and also in Figure 47 (from ODEON).

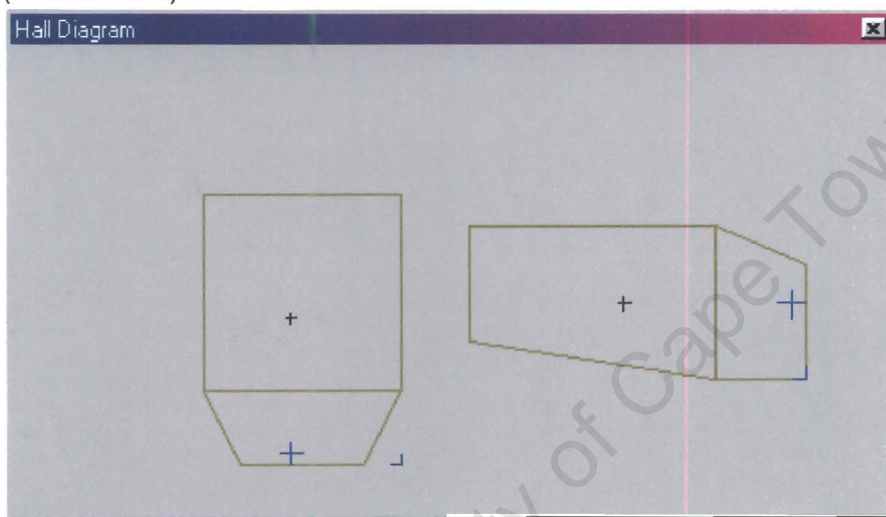


Figure 46: Top and Left views of the sample auditorium by RoWena

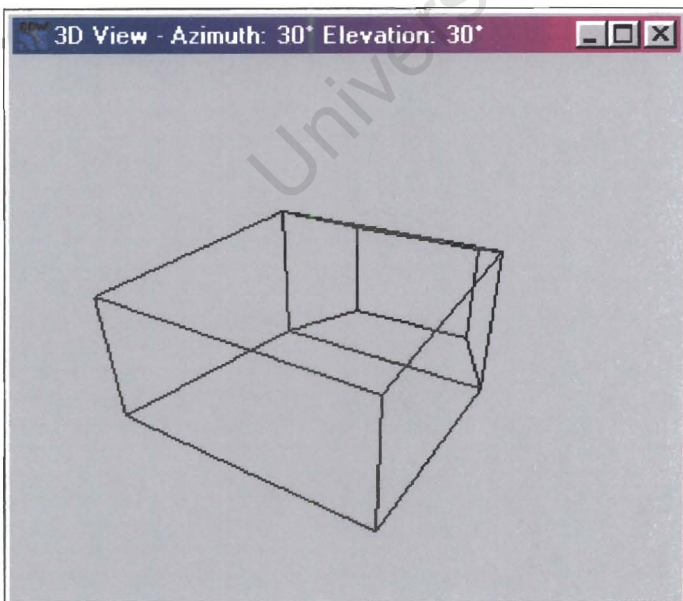


Figure 47: Isometric view of the sample auditorium by ODEON

The room is essentially a simplified auditorium with raked seating and an angled ceiling above the stage.

14.2. Surface Materials

The choice of surface materials was essentially arbitrary, since the room model is not based on a real life building. The chosen surface materials and associated absorption coefficients are shown in Table 4.

Table 4: Absorption Coefficients of surfaces in the sample room

	<i>Material</i>	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Floors	Wood (Joists)	0.15	0.11	0.1	0.07	0.06	0.07
Walls	Wood (Facing)	0.25	0.15	0.1	0.09	0.08	0.07
Ceilings	Concrete	0.01	0.01	0.01	0.02	0.02	0.02

14.3. Simulation Results

The exact workings of the ODEON program are unknown, and many of the settings cannot be adjusted. For example the simulation is always performed using secondary sources. However effects such as diffusion and edge diffraction were turned off.

Two simulations were made using the RoWena program, one with ray tracing (30000 rays) and the second with secondary sources (500 rays).

The RT60 reverberation times for all the simulations, including the calculated Eyring reverberation times, are shown in Figure 48. 'Ray Traced' and 'Secondary Source' are as simulated by RoWena.

Comparison between ODEON and RoWena Simulated Reverberation Results

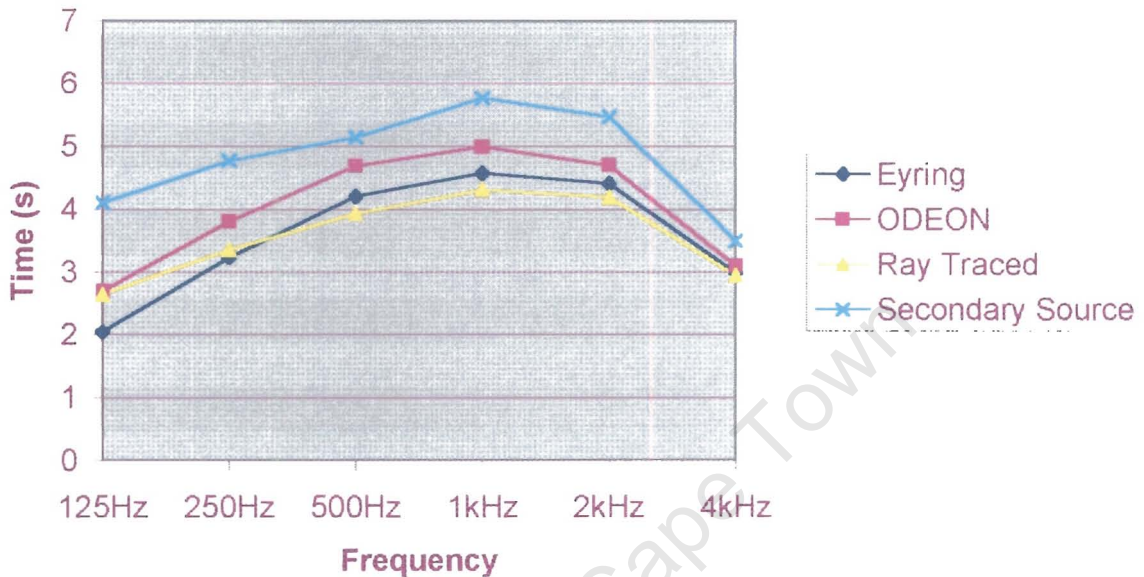


Figure 48: Simulated Results in the Sample Auditorium

The ODEON and RoWena ray traced results are within 0.5s of the calculated Eyring reverberation times, except at 125Hz. The secondary source times simulated by RoWena are at least 1.5s longer than the Eyring results.

For the Eyring calculated reverberation times to be appropriate the sound field must be diffuse. Because of the irregularities of the room geometry this is likely. Therefore it appears that the RoWena results are poor indicators of reverberation times.

The secondary source results are particularly poor, the cause of which is either the theory of the secondary sources, which is unlikely considering the ODEON program uses the same theory (presumably) or an error in the RoWena program. The program has been carefully examined but this remains a possibility.

An ODEON simulation performed with the options 'diffusion' and 'edge diffraction' on gave similar results (within 0.1s) to those with these options disabled. Since the author is not an experienced user of the ODEON program it is possible that it may be possible to produce more accurate results.

15. ISSUES CONCERNING CURVED SURFACES IN ROOM ACOUSTIC SIMULATION PROGRAMS

The restriction by most (possibly all) room acoustic simulation programs that all surfaces be planar is prohibitive. This section compares two approaches to treating curved surfaces, and then deals with some problems relating to the approach taken by this thesis.

Where unreferenced the work in this section is that of the author.

15.1. Issues Relating to the Handling of Curved Surfaces

Simulation programs at present treat curved surfaces by means of an approximation. This section explains the implications of this approximation.

15.1.1. Subdivision of a Curved Surface in Segments

All research conducted by this author indicates that curved surfaces are modeled in room acoustic simulation programs by breaking them up into a number of planar surfaces. For example ODEON version 3.1 has a command that automatically breaks cylindrical surfaces into a user-selected number of planar surfaces.⁹⁷ Thus a cylinder for example would become 20 smaller rectangular surfaces, each inclined so that together they approximate the shape of the cylinder. ODEON further recommends that planar surfaces are angled a maximum of 10°-30° apart, though no reason is given.

For any surface other than the supported shapes however, the user must manually determine how to break up the surface, and also how many planar surfaces to use. In the case of the Jameson Hall, which contains more than 20 curved surfaces, such a process is daunting.

As an example, the domed ceiling of the Jameson Hall (see also 16.8.1.1) was modeled using planar sections angled at 30° to each other. This was done with 24 separate surfaces, arranged in two rings of 12 surfaces each. The top, left and isometric view of the dome modeled in this manner is shown in Figure 49.

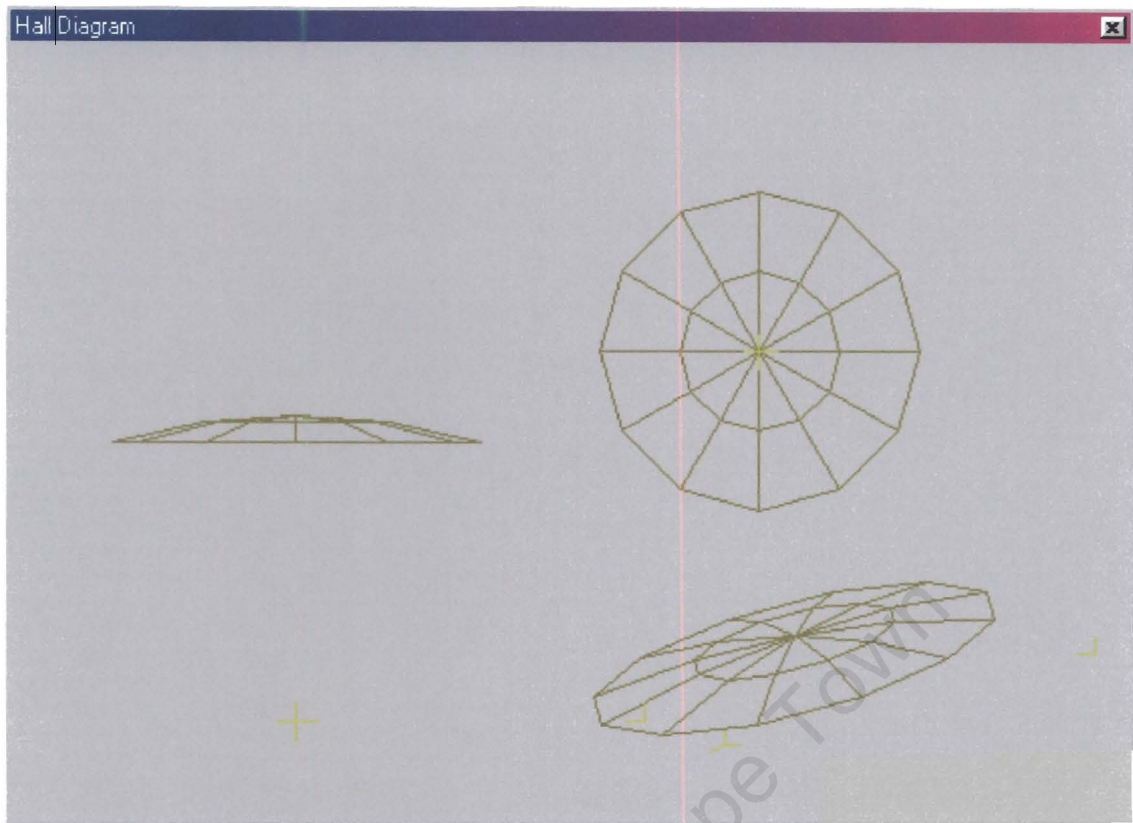


Figure 49: Division of a dome into planar segments

If a similar number of planar surfaces were required for the other curved surfaces in the Jameson Hall, which is probable, then this process would entail modeling more than another 400 surfaces for the entire Jameson Hall. This is costly, in terms of both user time and simulation time.

15.1.2. Boundary between two Segmented Curved Surfaces

The manner in which the curved surfaces bound with each other is also important. As an example Figure 50 shows two arbitrarily curved surfaces.

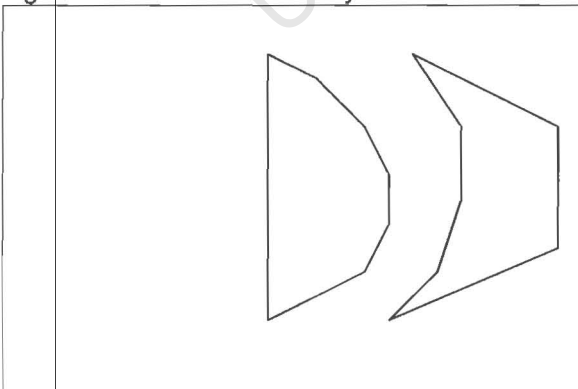


Figure 50: Aligned Curved Surfaces shown pulled apart

Although the surface shapes as a whole are uncommon, aligned curved sections are common, especially in the Jameson Hall. If the two surfaces were intended to bound on each other then the number of segments making up each surface would have to be the same, or there would be gaps at the join. If the surfaces shown in Figure 50 are also curved in 3 dimensional space, for example as sections of a sphere, then the complexity and correspondingly the time spend by the user on just modeling these two surfaces would be large.

15.2. Direct Treatment of Curved Surfaces

For the reasons given in 15.1 it is better for the simulation program to handle curved surfaces directly, without segmenting the surface. This also simplifies user input of the surface. In the RoWena simulation program the user can choose the desired surface shape from a list, as shown in Figure 51.

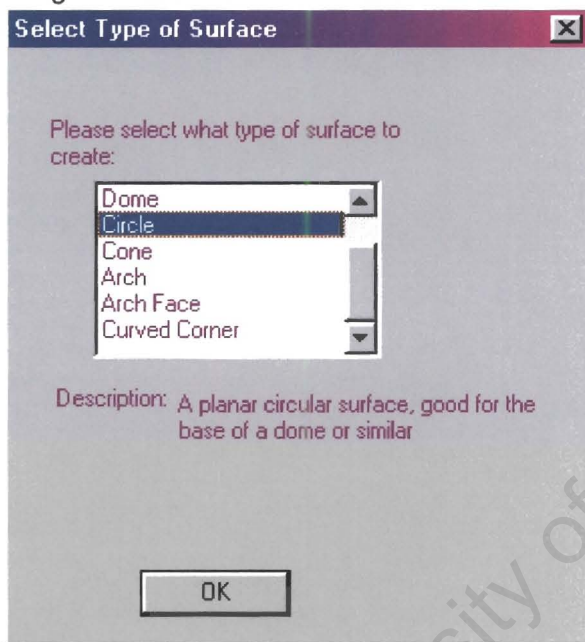


Figure 51: Surface Type Selection box (from RoWena)

A number of curved surface types are included, such as 'Cone', 'Arch' and 'Dome' and there is no limit on the number of surface types that could be included in the list with comparative ease on the part of the programmer.

As an example of the user input of a curved shape's specifications, Figure 52 shows the window for editing a dome surface and Figure 53 shows a front, left and isometric view of the dome surface as specified.

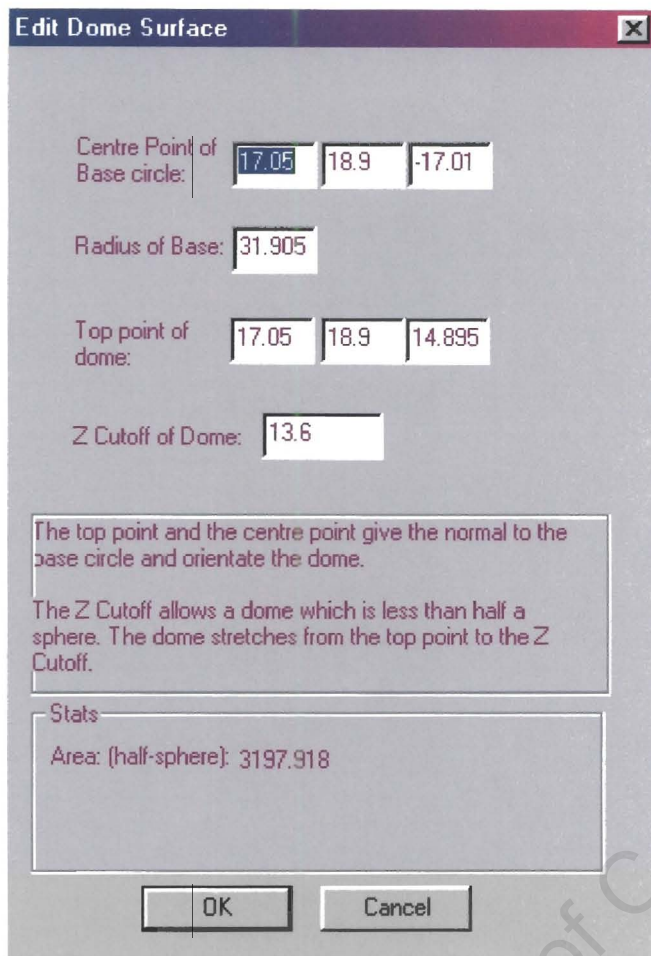


Figure 52: Dome parameter editing box (from RoWena)

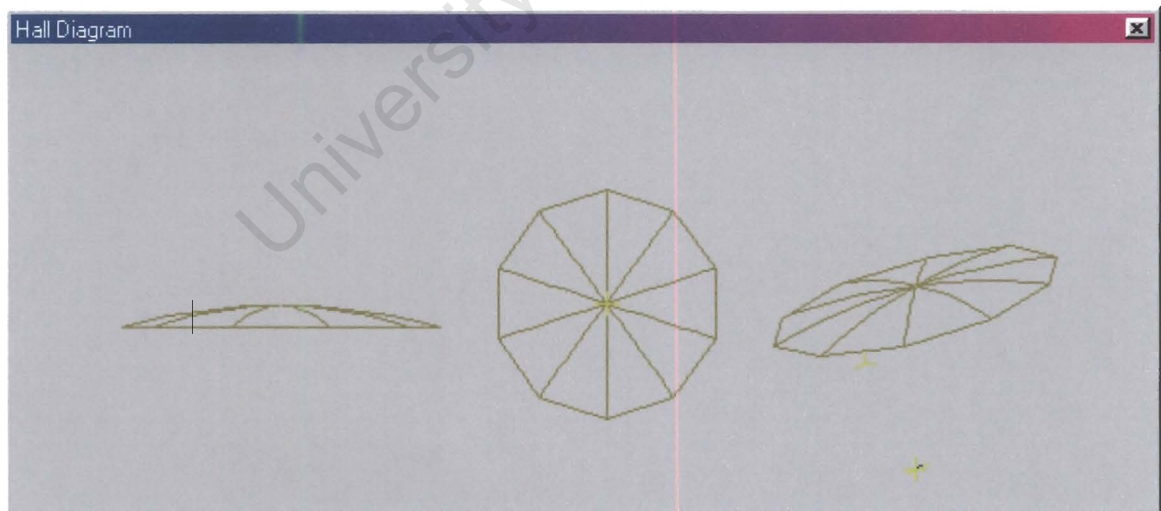


Figure 53: Dome as drawn by RoWena

Note that the diagram in Figure 53 is for visual purposes only and does not represent in anyway the manner in which the dome is simulated. This is in contrast to Figure 49 where the dome is shown as a collection of smaller surfaces.

15.3. Comparison between Direct and Segmented Modeling of Curved Surfaces

To compare the results of simulations using both segmented curved surfaces (see 15.1) and proper curved surfaces (see 15.2), simulations of the Jameson Hall dome with both methods were performed. (See also 16.8.1.4 for a description of the reflecting nature of the dome). The other surfaces in the hall were omitted for clarity. The segmented example shown in Figure 49 was used, which consists of 24 segments.

Figure 54 shows a large number of ray paths reflected from the dome. On the left is the dome simulated directly and on the right using the segmented method. The source point is directly underneath the dome at half the focal length. Note again that the dome is not a hemi-sphere but only a small section of a hemi-sphere.

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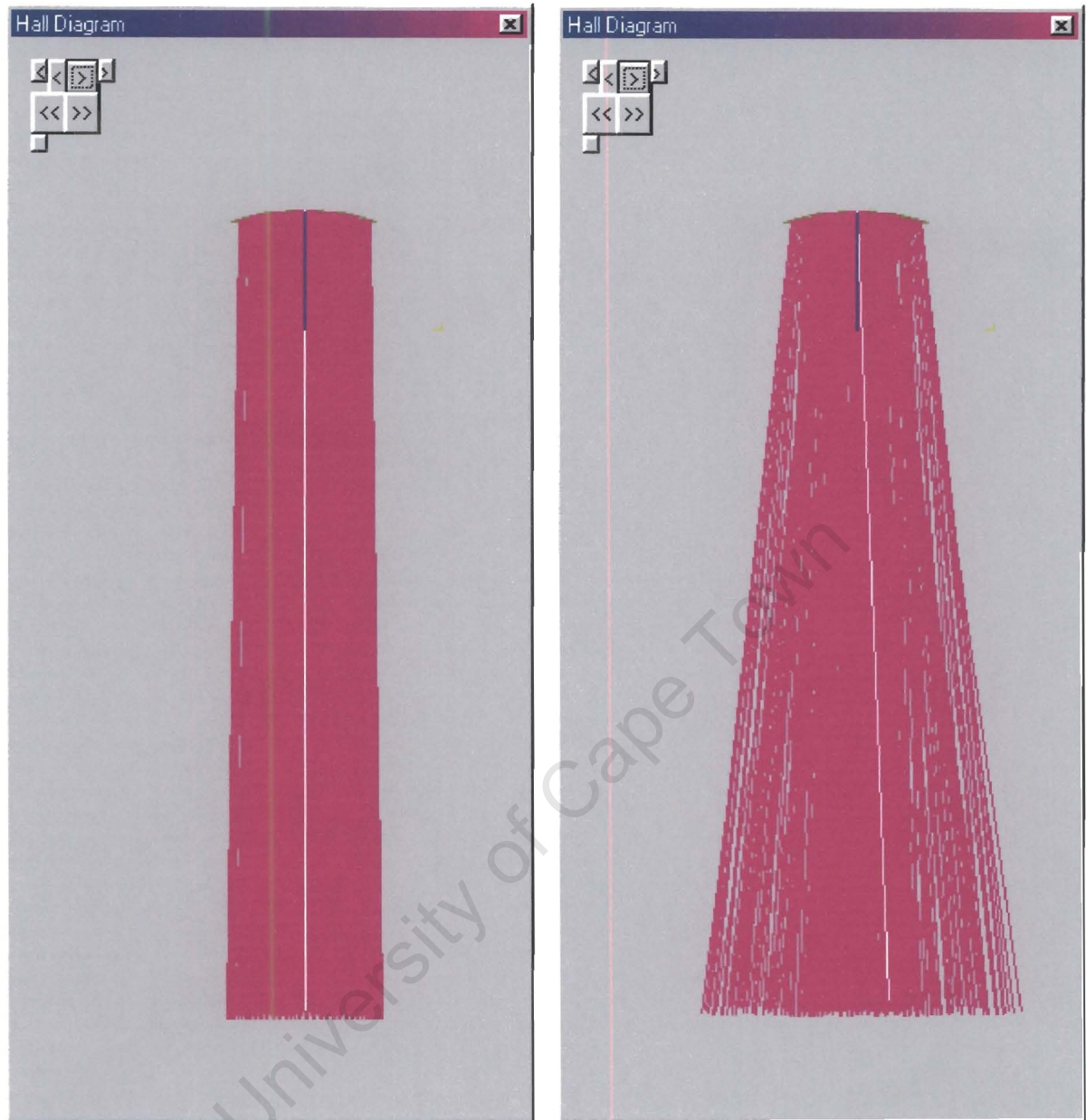


Figure 54: Ray Paths produced by Curved Surface Simulation (left) and Planar Surface Segmentation (right)

It is clear from the diagrams that the segmented surface causes the reflected sound to spread out more than the direct simulation. This occurs because the normal to the dome surface at the ends is the same as the normal closer to the center, since they are both described by the same planar surface. In the correct simulation the normal to the surface changes with respect to the exact point of reflections on the dome and so the reflected angle is correct at all points.

With the dome segmented into more planar surfaces, specifically three rings of 12 pieces each, forming a total of 36 surfaces, as shown in Figure 55, the distribution of the reflections from the surface is as shown in Figure 56.

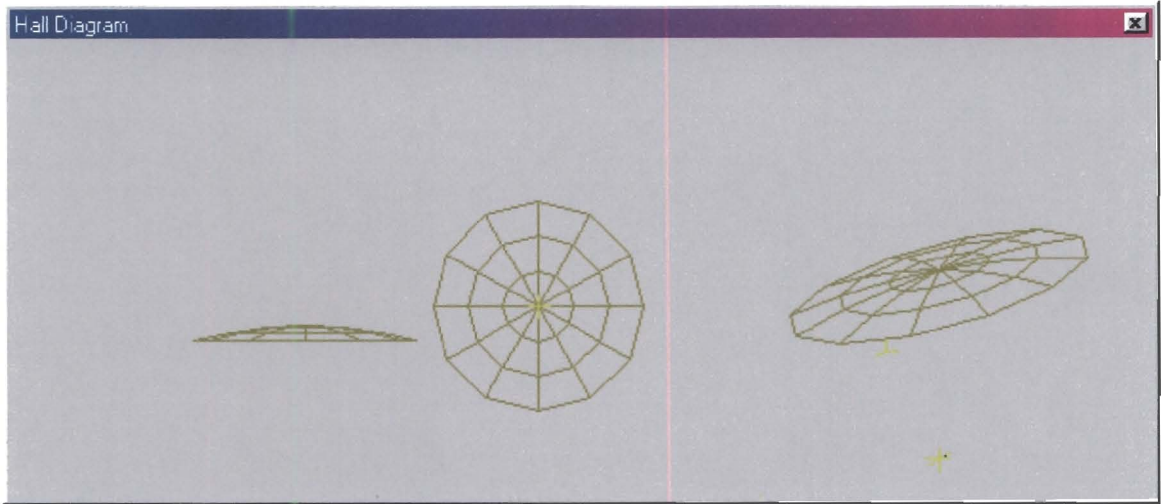


Figure 55: Dome segmented into many Planar Segments

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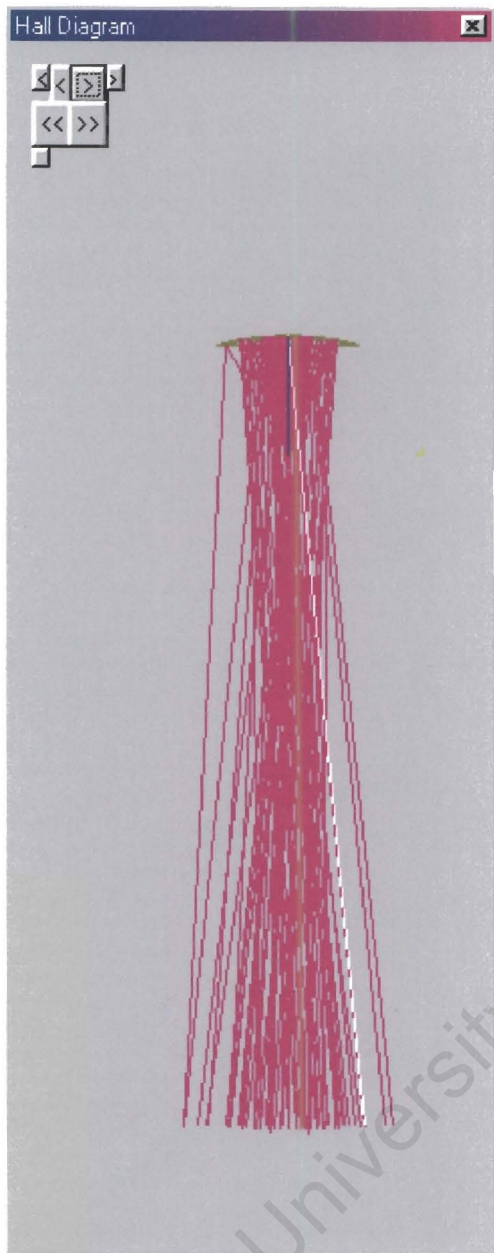


Figure 56: Reflection pattern from multi-segmented dome

This reflection pattern is significantly different to that obtained with fewer planar segments (Figure 49), indicating the critical nature of the choice of the number of segments in creating an accurate reflection pattern.

Also the simulation time increased by about 50 times because of the large number of surfaces making up the dome (36 segments). If such a large segmentation were used for the other surfaces in the Jameson Hall the simulation time would become prohibitive under current computer power.

An example of where the lack of focusing caused by the segmentation method of simulation would be important is given in 122 where a particular arched surface is examined. Although the results of that section are not perfect and evidently more research is required, using segmented surfaces means that it would be impossible to find exact ray paths to specific measurement

points. For example in Figure 57 the full focusing effect of the arch is not simulated because the planar segments are necessarily angled incorrectly.

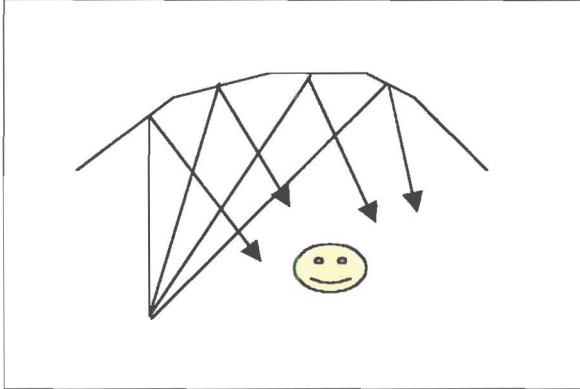


Figure 57: Illustration of reflection pattern from segmented arch

15.4. Programming Procedure for Including Curved Surfaces in the Room Model

Any well-defined curved surface can be described mathematically, and can therefore be incorporated into the simulation program. To reiterate what was explained in detail in 10 the flow chart in Figure 58 shows a simplification of the process.

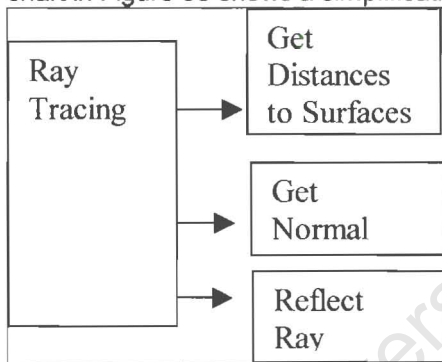


Figure 58: Flowchart of ray tracing process

The ray tracing procedure requires the distance to each surface. The normals to some of the surfaces are then required which is used to finally reflect the ray. For planar surfaces the normal remains the same over the whole surface. For curved surfaces however this is not the case. Therefore a different piece of programming code must be executed for each type of surface.

15.4.1. Obtaining the Distance to Surface

Just as for planar surfaces, the distance to any surface is calculated by substituting the formula for a line, which describes the ray segment of interest, into the formula for the surface.

As an example the workings for obtaining the distance from a point in a specified direction to a dome are given:

$$\text{Line : } P = S + tD$$

$$\text{Sphere : } (P_x - C_x)^2 + (P_y - C_y)^2 + (P_z - C_z)^2 = R^2$$

$$\text{Subst : } P_x = S_x + tD_x, P_y = S_y + tD_y, P_z = S_z + tD_z$$

$$\Rightarrow (S_x + D_x t - C_x)^2 + (S_y + D_y t - C_y)^2 + (S_z + D_z t - C_z)^2 - R^2 = 0$$

$$\Rightarrow t^2(D_x^2 + D_y^2 + D_z^2) + t(2S_x D_x + 2S_y D_y + 2S_z D_z - 2D_x C_x - 2D_y C_y - 2D_z C_z)$$

$$+ (S_x^2 + S_y^2 + S_z^2 - 2S_x C_x - 2S_y C_y - 2S_z C_z + C_x^2 + C_y^2 + C_z^2 - R^2) = 0$$

Using $t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$ the solution follows easily.

This gives two possible points. (Invalid answers are missed lines and are treated as such). Since the dome is further restricted by limiting reflections to the inside of the dome only (a reasonable assumption) the point one furthest from the line start point is taken.

The limits of the surface must also be inspected to ensure that the line intersects within the surface boundaries. For example for a dome surface the program must determine if the point is indeed in the dome or in the greater sphere which does not exist. Since the dome is oriented upwards (assumed), this is merely a matter of checking if the z value of the point is larger or equal to the center point z value of the dome, as shown in Figure 59.

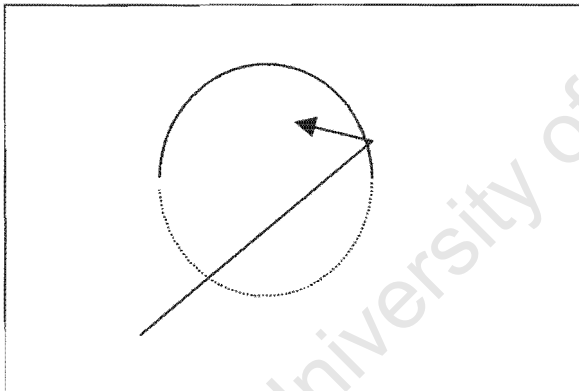


Figure 59: Dome/Ray Path intersection validity

If the z-value is replaced with a smaller cutoff-z value, then the size of the dome can be reduced to any smaller section of the sphere.

15.4.2. Obtaining the Angle of Reflection/Normal to Surface

The angle of reflection from the surface is calculated in the same way as for planar surfaces, namely that the angle between the incident ray and the normal to the surface, and the angle between the reflected ray and the normal to the surface, are the same.

For curved surfaces it is necessary to calculate the normal to the surface at the point of intersection. For most curved surfaces this is determined by calculating the angle between the intersection point and the focal point of the surface. (Each curved surface may have only one

focal point. Surfaces with more than one focal point must be broken up into a number of different surfaces.)

Again, using the dome as an example, this entails finding the intersection of a line with the normal to the dome at the reflection point. The normal is given by [PuncturePoint-CentreOfDome]. Then

Plane : $N = \text{Normal}, P = \text{PuncturePoint}$

$$\Rightarrow N_x(x - P_x) + N_y(y - P_y) + N_z(z - P_z) = 0$$

Line : $S = \text{Start}$

$$x_0 = S_x + tN_x, y_0 = S_y + tN_y, z_0 = S_z + tN_z$$

$$\text{Subst} : N_x(S_x + tN_x - P_x) + N_y(S_y + tN_y - P_y) + N_z(S_z + tN_z - P_z) = 0$$

$$\Rightarrow t(N_x^2 + N_y^2 + N_z^2) = N_x(P_x - S_x) + N_y(P_y - S_y) + N_z(P_z - S_z)$$

t is now the distance to the normal plane. From this the reflection angle can be obtained as for a planar surface.

15.4.3. Adding More Surfaces to the Simulation Program

These two functions are called by the ray tracing part of the program for whichever surface is under inspection, whether it is planar or curved. Thus it is possible, though not yet implemented, for the user to create his/her own list of curved surfaces, specified by means of appropriate formulae that can be remembered by the program. Even compound surfaces, such as stairs, could be implemented, with relatively little programming expense (see also 15.6.6).

However the treatment of such surfaces raises other problems that are described below.

15.5. Early Time Exact Ray Paths

Mirror imaging is usually used to find exact ray paths in the early time (see 12.3), but as was explained it is not suitable for finding ray paths involving curved surfaces. This section gives a detailed explanation for the unsuitability of mirror imaging and also a working alternative.

15.5.1. Description of Transformation Matrices for Planar Surfaces

Mirror Imaging, as described by Lee & Lee⁹⁸, entails using transformation matrices to find the reflection of a point through a surface. For example in Figure 60 a planar surface is shown end on.

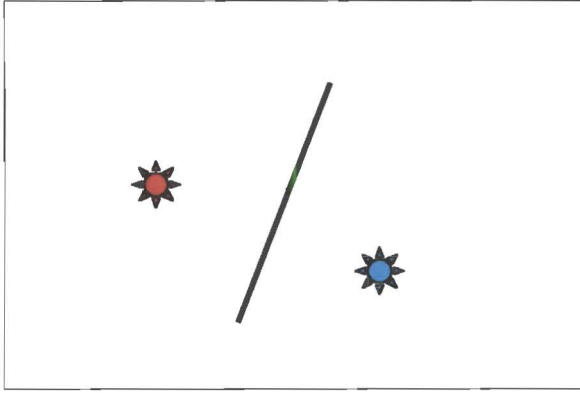


Figure 60: A vector point mirrored through a surface

The blue star, which represents a vector point, is the mirror image reflection of the red star. Note that they are equidistant from the surface and also that a straight line connecting the two stars is perpendicular to the surface. To find the mirror image of a point P through the i th surface the transformation matrix S_i is used. If P' is the mirror image point then $P' = P * S_i$.

S_i is a constant 4x4 matrix particular to the i th surface. It is constructed from the variables d , θ and ϕ which describe the normal to the surface in spherical coordinates. Since the normal to a planar surface is constant over the entire surface it can thus be calculated before the simulation begins, which reduces the simulation time.

15.5.2. Description of Transformation Matrices for Curved Surfaces

The normal to a curved surface is not constant over the entire surface, and therefore the reflected point depends on the point of reflection on the surface. An example is shown in Figure 61, where the red star represents the original point. The pink star is the mirror image of the red star through the normal shown by the pink line, and similarly the blue star is the mirror image reflected through the blue normal.

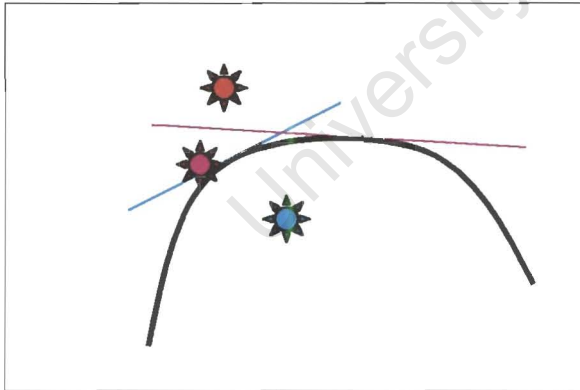


Figure 61: A vector point mirrored in two ways through a curved surface

(That the pink star does not lie on the opposite side of the surface to the original red star is unimportant.) If a ray from the red star is assumed to reflect from the intersection point between the pink normal line and the surface, then a straight line drawn from the pink star through that intersection point lies on the reflected ray, as shown in Figure 62.

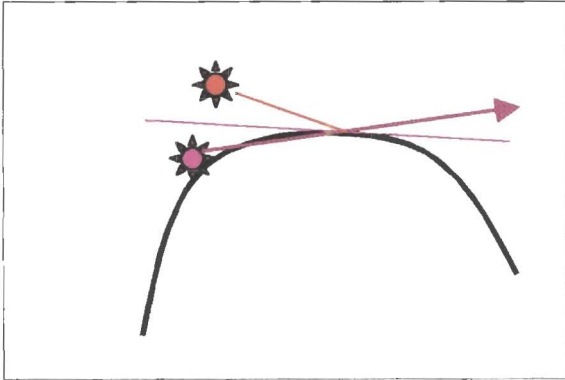


Figure 62: The reflection path of a vector point as mirrored through a curved surface

Because the normal to the curved surface is not constant the transformation matrix is not constant. Rather the variables d , θ and ϕ are given by functions dependent on the shape of the surface and the reflection point. Since the reflection point is not known at the beginning of the mirror image process these functions will contain variables that must be solved for.

15.5.3. Mirror Imaging for Curved Surfaces

The complete mirror imaging algorithm requires multiplication of the transformation matrices for all the surfaces involved in the ray path, which is usually about 2 or 3 surfaces. Thus for curved surfaces the different transformation matrices, involving formulae for the variables d , θ and ϕ , would have to be multiplied together and simplified.

While this is a relatively simple task on paper, programming a computer to do this is a large task. Also since the result would depend on the exact sequence of transformation matrices to be multiplied together the calculation would have to be done at simulation time, which would lengthen the process accordingly.

The expense in terms of complication and computation time provided an inspiration to find an alternative method to finding early time exact ray paths.

15.5.4. Introduction to the Search Method for Finding Early Ray Paths

Rather than calculate the exact ray path using mathematical means, a search method tests a number of possible ray paths and chooses the most suitable. This process is repeated refined until a ray path meeting the various requirements is found.

Initially this entails producing a large number of rays in random directions. Each of these rays is followed for the required number of reflections. If the ray fails to hit the correct surfaces in sequence then it is aborted, otherwise it is given an accuracy rating based on how close it passed to the receiver.

The rays with the best accuracy rating are used as the basis for a new set of rays, and the procedure is repeated until the accuracy of the best ray falls below a certain threshold. Note that an exact ray path is not found, although any desired accuracy can be obtained.

15.5.5. Description of the Search Method

Ultimately the ray path that is found must travel from the source point to the receiving point and reflect off particular surfaces along the way. For simplicity consider a simple room as shown in Figure 63.

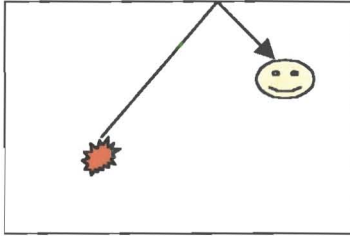


Figure 63: A single reflection in a simple room

The example room is in the shape of a rectangular box, with the z-axis ignored. For now curved surfaces are also ignored. Shown on the diagram is a ray path consisting of a single reflection. As described earlier the search algorithm finds this ray path by producing a number of pseudo-random rays that better and better approximate the desired ray path.

15.5.6. Definition of Accuracy for the Search Algorithm

In order for the search algorithm to 'home in' on the correct ray path, some definition of accuracy for every ray must be given. This accuracy is defined as the distance the ray path comes to the receiver point after reflecting from all the required surfaces. If any required surface is missed then the ray's accuracy is undefined. The search algorithm therefore attempts to maximise the accuracy of the ray, which entails minimising the distance to the receiver.

In Figure 64 three potential ray paths are shown.

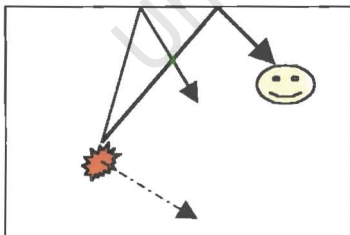


Figure 64: Multiple reflections showing the different accuracy of each

The ray path shown with a thick line has the best accuracy, since it comes closest to the receiver. The ray path with the thin line has a lower accuracy, while the dotted ray path is invalid since it will not reflect off the desired surface.

15.5.7. Generating each Group of Rays

Each group of rays is generated pseudo-randomly, the exact nature of which is determined by the search algorithm itself. The only requirement is that at least one, and preferably more than one, ray must reflect from the desired surface sequence.

The first group of rays is usually determined completely at random. However to ensure at least partial success one of the rays is given a direction towards any random point on the first surface to be hit. Thus each group has at least one ray that will hit the first surface.

If the desired ray path involves more than one surface then after reflecting from the first surface it is very possible that no ray will hit the second surface. This occurs particularly when the surfaces are relatively small, or the distances between them are large. This means that the majority, and possibly all, of the rays will have an invalid accuracy.

This is a very important problem, since the chances of success become almost zero. Some method is required to assist the search algorithm 'home in' on the correct surface sequence.

15.5.8. Assisting the Search Algorithm to 'Home In' on the Correct Surface Sequence

Up until this point each ray path inspected by the search algorithm has been assumed to be a valid and complete ray path, determined by the normal ray tracing procedure. This includes the restriction that the ray path has reflected from within the boundaries of each surface it reflects from.

If this requirement is relaxed then ray paths that reflect from outside the surface boundaries could be allowed. For example in Figure 65 the first surface in the required ray path is shown extended (to infinity) by dotted lines.

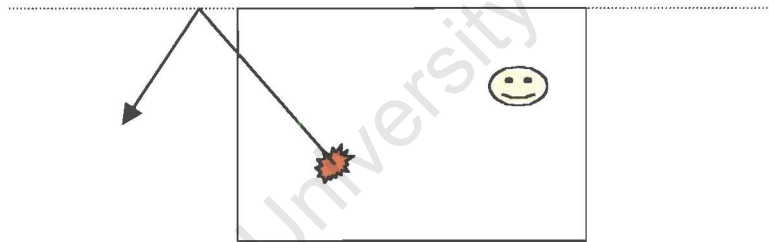


Figure 65: Reflection from an extended surface

Ray tracing usually treats surfaces like this in the initial simulation stages and only later validates the ray according to the surface boundaries, and so no large changes to the program is required. The benefit occurs because the chance of a ray hitting the required surface is increased enormously.

Also shown in Figure 65 is a typical ray path that has reflected from outside the surface boundaries. This ray path, although invalid, can be used to give an accuracy rating which the search algorithm can use to home in on the receiver. Such a technique is especially useful when considering multiple reflection ray paths, since the surfaces become infinitely big and therefore the chances of at least one ray hitting the surface are greatly increased.

The final ray path must be inspected to ensure that it does hit within the boundaries of the surfaces.

15.5.9. Finding Curved Surfaces

Allowing a ray to reflect from outside the physical boundaries of a surface generally works only for planar surfaces, since curved surfaces usually close in on themselves. For example a dome forms a sphere when extended beyond its boundaries. Thus even though the chances of a ray hitting the surface is increased, it may be still too small for the search algorithm to find.

In these cases any point on the surface is chosen, preferably near the center of the surface. This point is then used for the distance calculation, rather than the receiver point, and the ray is aborted immediately at that stage. If the search algorithm now attempts to minimise the accuracy then eventually the ray will hit the surface properly.

Since the search method has no implicit knowledge about the geometry of the hall it is important that a distinction is made between this type of accuracy value and a valid accuracy. This is discussed in the next section.

15.5.10. Penalty for Missing a Surface

To ensure that the invalid ray paths are selected against, meaning that valid ray paths are preferred over invalid ray paths, a penalty is assigned to the accuracy of any invalid ray. The penalty is given as a large distance, say 2000 meters, times the number of missed surfaces. The exact amount is unimportant, as long as it is larger than the maximum valid distance that a ray could come to a receiver, which is sure to be less than 2000 meters in most rooms.

To illustrate the process consider the following example: If the second surface of a sequence of three was missed, then the penalty incurred by that ray path would be $2 \times 2000\text{m} = 4000\text{m}$ (because of two missed surfaces). This would be added to the amount by which the ray paths came close to the arbitrary point on the missed surface. If none of the rays reflected properly from the second surface then all the accuracies for that ray path group would be in excess of 4000m. Let the group of ray paths consist of 3 rays, which is an unrealistically low number. Further let their accuracies in this example be 4003m, 4010m and 4011m. The search algorithm would choose the first ray path, with 4003m, as the basis for the next group, since it probably came closest to the required ray path.

If the ray accuracies in the new group are 2010m, 4001m and 4002m then it is clear that the first ray has reflected correctly from the second surface but missed the third surface. Now the next group of ray will be based on a ray that hit two surfaces correctly. In this manner eventually a ray is chosen which hits all the surfaces correctly. Then further the ray path that comes within a certain distance to the receiver point will be accepted as valid.

If the penalty system is also imposed on planar surfaces then it becomes unnecessary to check that the complete ray path does in fact reflect within the physical boundaries of the surfaces.

Once a ray is found which misses no surfaces, the distance value will decrease very sharply, since no penalty is incurred. The search algorithm will therefore home in very quickly on such a ray path, which improves the success rate of the algorithm.

15.5.11. Choice of Search Algorithm

A large number of search algorithms of the desired form are available, each suited to a particular application. The choice is largely determined by the complexity of the search space. In this case

the Nelder-Mead Simplex Downhill Search algorithm was used. A description of the algorithm is out of place in this thesis, and details can be found for example in an article by M. H. Wright⁹⁹.

Other search algorithms include Newton's method, unsuitable because of the many local maxima and minima in the search space. Genetic algorithms were considered too powerful and correspondingly too slow for this application¹.

In practice all ray paths found using the mirror image algorithm were also found by the simplex search algorithm. Unfortunately the simulation time is about 600 times longer than for the mirror image algorithm, because of the large number of rays that must be produced, though this is less of a problem with fast computers.

15.5.12. Advantages of the Search Algorithm over Mirror Imaging

Apart from the obvious advantage that mirror imaging cannot be used with curved surfaces, there is another very useful potential advantage. Because the search algorithm uses essentially the same ray tracing process as the rest of the program, any future advances that are made to the ray tracing process are automatically passed on to the search algorithm detection process.

For example if in the future an exact description of scattering from surfaces were devised which could be incorporated into the ray tracing process, this would automatically affect the early rays. This is unlike the mirror imaging algorithm that always assumes specular reflections. However the search algorithm can not be used where random components are included in the ray paths.

15.5.13. Disadvantages of the Search Algorithm

Apart from the very long simulation time, two other disadvantages present themselves. Firstly the search algorithm will not find an exact ray path to the receiver. However any arbitrary maximum distance can be defined as the limit for the search, which may for example be the size of a human ear.

The second disadvantage is that the process is non-deterministic and partly random, so that it is not possible to be sure that a ray path that could not be found by the search algorithm does not in fact exist. In practice, due to the inclusion of infinite surfaces and penalties, the vast majority of ray paths are found.

15.6. Multiple Reflection Removal

In many implementations of the ray tracing process, rays with duplicate ray paths are removed. This is necessary because the receiver point is modeled as a sphere of a certain diameter, usually one meter. Such a receiver detects more rays than a point source, which is important in the late time where the limited number of rays simulated causes many valid ray paths to be missed, and these multiple rays must be removed. Even in the early time where this is not a problem, multiple ray paths found by whatever means (mirror imaging or a search algorithm) must be removed (see also 10.3.2).

In a room with only planar surfaces this is justified, since only one ray path with a unique surface sequence is geometrically possible between source and receiver point. With curved surfaces however this is not true. A dome for example can reflect sound to its focal point from anywhere on the dome, and all such ray paths must be considered (Figure 66).

¹ Thank you to Prof. Green at UCT for his help in this matter.

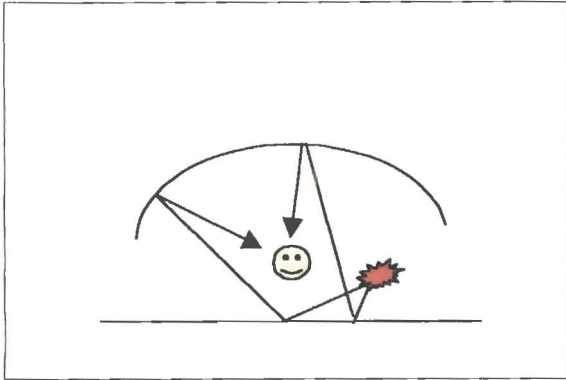


Figure 66: Multiple Reflections to the focusing point of a dome

It is important therefore to determine the proper way to discard multiple reflections.

15.6.1. Approximating Curved Surfaces by Smaller Planar Surfaces

If the curved surface is divided into a number of planar surfaces, as is usually the case in such programs, and assuming that multiple reflections are removed in the usual way, then the number of multiple reflections allowed from the approximated curved surface would equal the number of planar surfaces making up the surface (Figure 67).

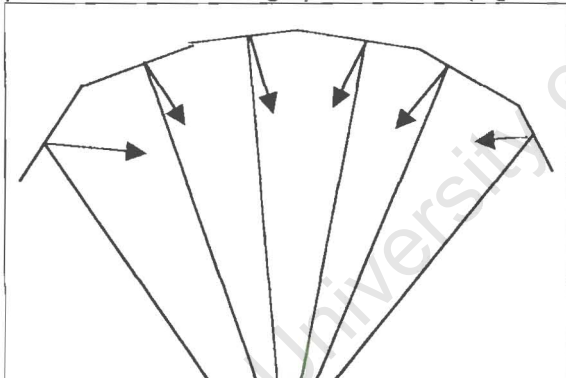


Figure 67: Multiple reflections from a segmented dome

The number of these planar surfaces thus dictates how much energy the curved surface is allowed to focus. Using only one planar surface would create no focusing, whereas using an infinite number of planar surfaces would create a very high energy at the focus point of the curved surface. Thus the choice of planar division of the surface has an important relation to the focusing effect of the surface. Such a distinction is not important where the curved surfaces are modeled directly.

15.6.2. Multiple Reflections Dependent on the size of the Curved Surface

All ray paths, early or late, are initially found by the basic ray tracing technique, in which rays evenly spread out over the source point are propagated. Because of the even spreading of the rays, small surfaces will be involved in proportionally fewer ray paths than large surfaces. Thus even if multiple reflections (where curved surfaces are involved) are not discarded, the number of

these will still be relative to the size of the surface. Thus all else being the same, multiple reflections involving curved surfaces need not be removed.

15.6.3. Multiple Reflections involving Curved Surfaces in the Early Time

Consider a room with only two large surfaces, one arbitrarily curved and the other planar (Figure 68). The receiver is positioned at a focal point of the curved surface, which has a number of focal points. The initial ray tracing process will find a surface sequence involving these two surfaces a large number of times, since many ray paths exist between the two surfaces, as shown in Figure 68.

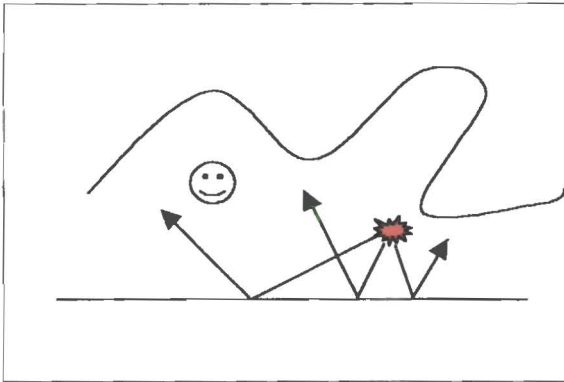


Figure 68: A curved surface with many focal points

In the early time the search algorithm will attempt to find ray paths that reach the receiver point, using the ray traced possible surface sequences. However, because only a small portion of the curved surface will produce reflections directed towards the receiver (due to its many focal points) most of the reflection paths found by the search algorithm will be very similar, concentrated on the small portion of the curved surface which focuses towards the receiver point. The receiver would therefore receive a large amount of energy from the curved surface, which is incorrect.

To solve this problem the curved surface should be divided into smaller curved surfaces, each with only one focal point. In fact most curved surfaces found in buildings, including the Jameson Hall, have only one focal point. In this case the solution is to allow multiple reflections where curved surfaces are involved, and remove multiple reflections where only planar surfaces are involved.

Since all curved surfaces involving multiple focal points can be divided into a number of simple curved surfaces each having a single focal point, this solution is adequate for any situation.

15.6.4. Multiple Reflections involving Curved Surfaces in the Late Time

There are two primary approaches in common use to rays in the late time. They are either simulated using the normal ray tracing process (see 10), or the technique of secondary sources (see 11) is used.

15.6.4.1. Multiple Reflections in the Basic Ray Tracing Model

The discussion in 15.6.3 applies, namely that curved surfaces should have only one focal point, and that multiple reflection paths involving curved surfaces be allowed. Multiple reflection paths involving only planar surfaces should be removed.

15.6.4.2. Multiple reflections in the Secondary Source Model

In secondary source theory all rays are detected after each reflection whether they would hit the receiver or not, and the late energy is subsequently corrected based on the expected number of rays reaching the receiver.

In this case multiple reflections should be allowed from all surfaces, planar or curved. This is because the energy of each ray is based on the approximate calculated norm for the room, based on its size and surface area. Focusing effects and the ray paths themselves are irrelevant.

15.6.5. Influence of Curved Surfaces on the Diffusivity of the Sound Field

The diffusivity of the sound field of the room is an important criterion for most simulation models as has been repeatedly explained in this thesis. Concave curved surfaces however disrupt the homogeneity of the sound field because of focusing effects.

Therefore, even though it is possible to simulate concave curved surfaces from a technical point of view, many simulation models will be disrupted in a negative way. Convex surfaces on the other hand aid in diffusivity and should improve simulation results.

15.6.6. Size of Surface and Diffusion

A surface such as a dome reflects differently depending on the frequency of the sound reaching it. A low frequency sound with a wavelength larger than the diameter of the mouth of the dome will reflect as though the dome were a flat surface, whereas a high frequency sound would reflect as described earlier.

Such a distinction could not be made in a program where small planar surfaces are used to approximate a curved surface, since the individual surfaces have no intrinsic knowledge of each other, and it would probably be a difficult task to implement. However where the curved surfaces are simulated directly it would be a fairly simple matter. This has not however been included in the simulation program.

As a by-product of the manner in which curved surfaces must be implemented, composite surfaces such as stairs could be included in the simulation model. Again the nature of a reflection from such a composite surface could be made to depend on the frequency of the sound incident on it, a task that is not easily possible where the surface is modeled as a series of discrete surfaces.

16. SIMULATION OF THE ACOUSTICS OF JAMESON HALL

The acoustics of the Jameson Hall have been discussed in section 5. Here some simulated results created by the RoWena simulation program are presented.

16.1. The Jameson Hall Room Model

The first step to simulating the Jameson Hall is to obtain the dimensions of the surfaces in the room. This was done by Leroy Kahn for his undergraduate thesis as referenced in the bibliography. Then the handling of the many different types of curved surfaces then had to specifically programmed into RoWena. Figure 69 shows a number of views as displayed by RoWena.

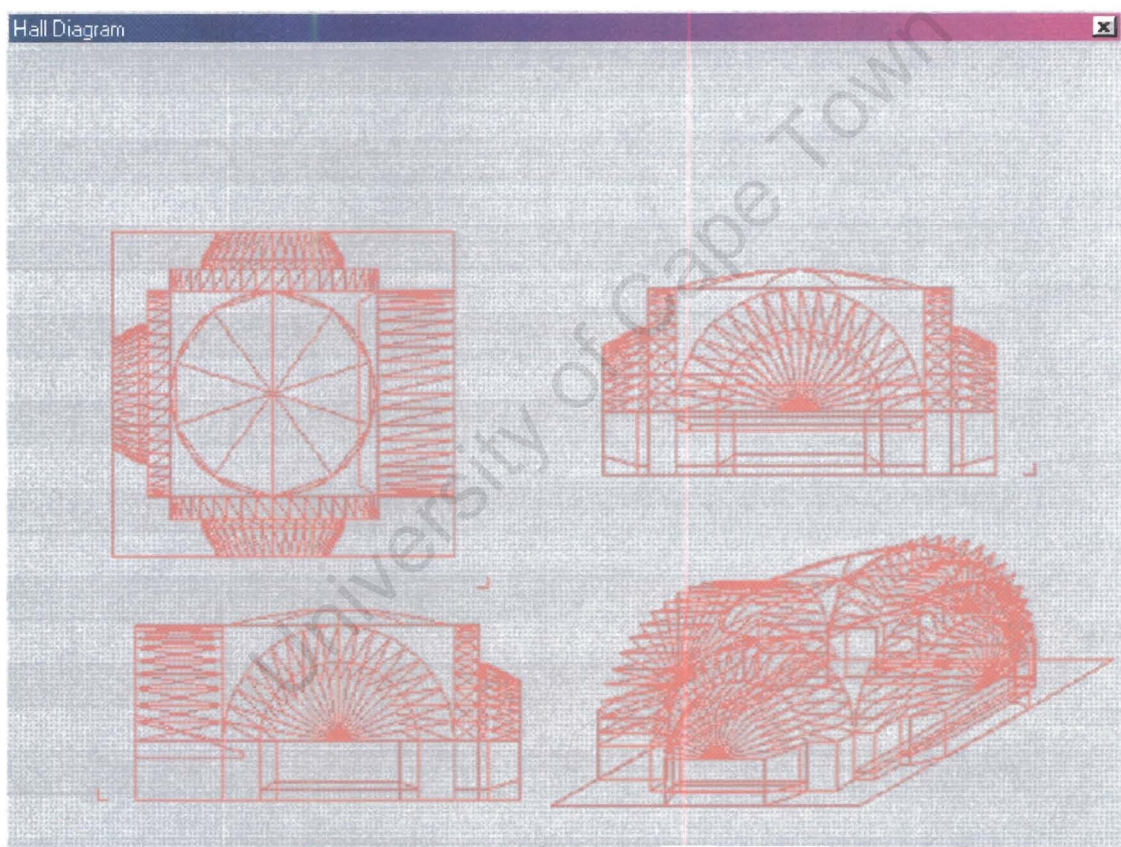


Figure 69: Top, Front, Left and Isometric views of the Jameson Hall (by RoWena)

16.2. Determining the Absorption Coefficients of the Hall Surfaces

It is important to select the correct absorption coefficients for the surface materials of the hall. In order to determine the absorption coefficients of the hall surfaces, a table of known surface materials and their absorption coefficients was used.

Because many variables affect the absorption of the surfaces, for example their exact construction, the Eyring reverberation formula was used to ensure that the estimated reverberation time in the hall matched the measured times. However the sound field in the Jameson Hall is not diffuse, as demonstrated by the RT60 measurements presented in 5.3, which renders the use of Eyring's formula invalid. Even so there is no alternative method to verify the choice of surface absorption coefficients.

16.2.1. Surface Materials

Visual inspection indicates that there are 5 different surface materialsⁱ:

Floors: The floor of the hall, of the stage, and of the balcony is made of wood planks, probably on joists.

Walls: The walls of the hall up to 4.6m from the ground level, and the front, sides, rear and underneath of the balcony are constructed from sheets of thin wood above an air gap of unknown depth, probably less than 3cm.

Ceiling: The ceiling of the hall is constructed from plaster formed on wire mesh.

Chairs: The fixed chairs in the left and right alcoves are fully upholstered.

Glass: Three large hemi-spherical windows are found in the left and right alcoves and on the rear wall of the stage.

The estimated absorption coefficients for each of these materials are shown in Table 5.

Table 5: Estimated Absorption Coefficients of Wall materials in the Jameson Hall

	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Floors	0.15	0.11	0.1	0.07	0.06	0.07
Walls	0.15	0.25	0.12	0.08	0.08	0.08
Ceiling	0.2	0.15	0.1	0.05	0.05	0.05
Chairs	0.12	0.28	0.28	0.3	0.32	0.37
Glass	0.04	0.04	0.03	0.03	0.02	0.02

16.2.2. Jameson Coupled Space

Two separate spaces are distinguishable in the Jameson Hall, the main hall space and the entrance space under the balcony.

The ratio $k = \frac{\text{Coupling Area}}{\text{Coupling Area} + \text{Small Room Absorptive Area}}$, which varies between 0 and 1,

is called the coupling factor¹⁰⁰. For the Jameson Hall this value is $k=0.126$. Since this value is much less than 1 the coupling area may be considered as an open window and the absorption of the smaller space otherwise ignored. Therefore, based on this assumption, the entrance space is ignored and an imaginary surface directly under the edge of the balcony, with absorption $\alpha=1$, is used. This surface covers the rectangular area stretching from the bottom of the balcony front edge to the floor, and for the entire width of the balcony.

The recommendation of this reference was however over-ruled by Mr. Jongensⁱⁱ who stated that the hall should be treated as a single acoustical space. Initial results using both assumptions are given below, but subsequent tests used the assumption of a single acoustical space.

ⁱ Thank you to Mr. Jongens for assistance in this regard.

ⁱⁱ Mr. Jongens, Thesis Supervisor, Head of Acoustics Department, University of Cape Town

16.2.3. Total Areas of Different Materials

The surface areas of the different surface materials are given in Table 6. The surface called “coupling” is added, as described in 16.2.2. The areas of the surfaces in the entrance area are given at the end of the list.

Table 6: Areas of primary surface materials

Material Name	Area (m ²)
Floors	623
Walls	571
Ceiling	809
Chairs	72
Glass	107
Coupling	60
Entrance Walls	293
Entrance Floor	122.4

When the “entrance walls” and “entrance floor” surfaces are included in the calculation, the “coupling surface” is excluded.

16.2.4. Volume of the Hall

The volume of the hall without the entrance area is approximately 6830m³. The smaller entrance space's volume is 490m³.

16.2.5. Results of Eyring Reverberation Time

Including air absorption, the Eyring reverberation times are shown in Figure 37. Also shown are the measured results from 5.7.

Estimated and Measured (Speaker in Corner) Reverberation Times in Jameson Hall

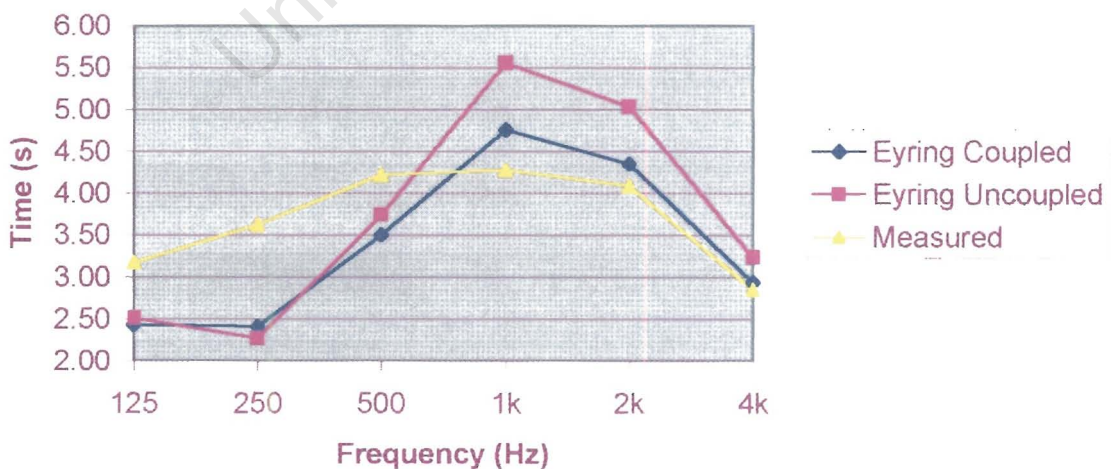


Figure 70: Eyring Estimated RT times versus frequency

From the graphs it is apparent that the estimated reverberation times do not match the measured values, being too low in the low frequencies and too high at mid frequencies. At high frequencies the effect of air absorption dominates, which causes the estimated and measured values to be similar.

The coupled and uncoupled results are similar except at mid-frequencies. Following Mr. Jongens' recommendations the hall was treated as a single acoustical space for the rest of this section.

16.2.6. Adjusted Absorption Coefficients

The reverberation times are very sensitive to changes in the absorption coefficients of the materials. And since the absorption coefficients can vary due to for example the type of wood used or the particular construction style of the walls, it is acceptable to 'tweak' the absorption coefficients in an attempt to obtain a good match with the measured results. Naturally it is not possible to determine which material's coefficients should be tweaked so the outcome may not be strictly valid. Unfortunately there is no other method for determining the exact absorption coefficients apart from testing samples of the material, which was impractical.

Table 7 shows the original and adjusted values. The columns containing adjusted values have a star in the column names.

Table 7: Original and Adjusted absorption coefficients for Jameson Hall surface materials

	125	125*	250	250*	500	500*	1k	1k*	2k	2k*	4k	4k*
Floor	0.15	0.12	0.11	0.1	0.1	0.09	0.07	0.09	0.06	0.08	0.07	0.08
Ceiling	0.2	0.2	0.15	0.15	0.1	0.08	0.05	0.06	0.05	0.058	0.05	0.057
Walls	0.15	0.1	0.25	0.11	0.12	0.13	0.08	0.135	0.08	0.13	0.08	0.13

As can be seen from the table, the values have not been adjusted by a large amount, except in the low frequencies where large compensation was required.

Using these values an exact match with the measured values was obtained, as shown in Figure 71.

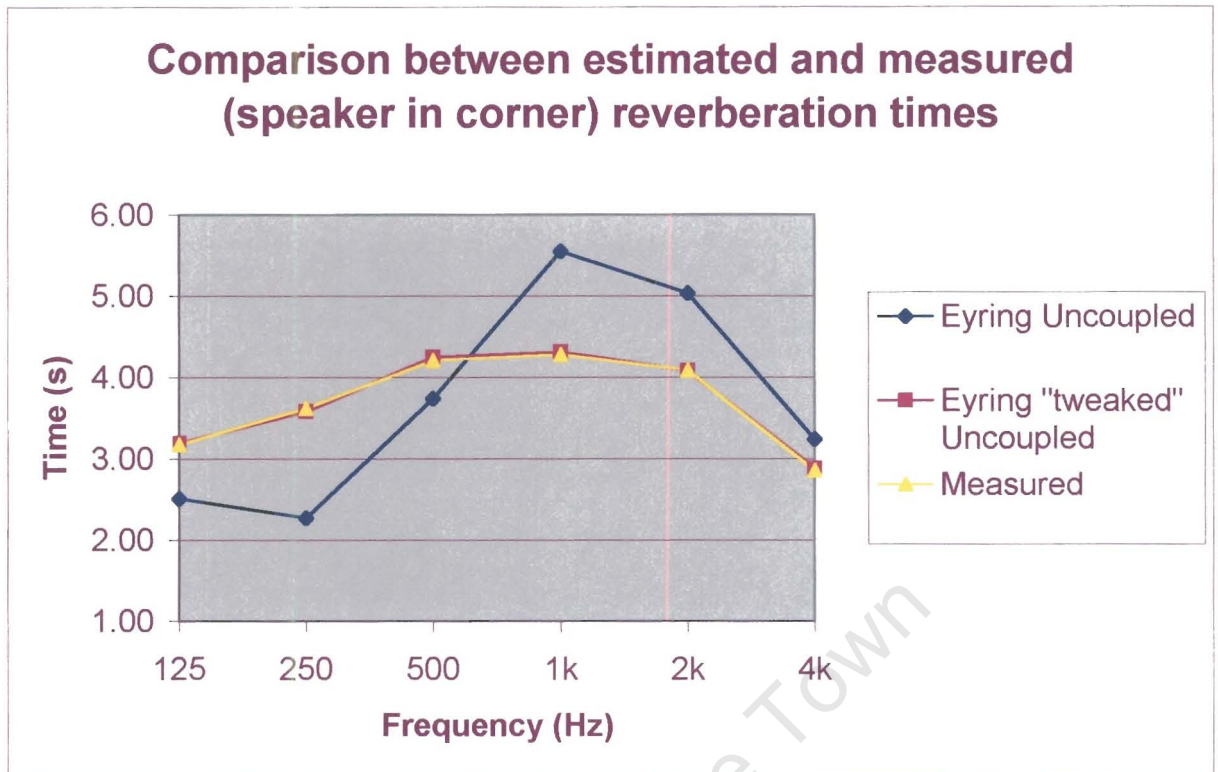


Figure 71: RT times versus frequency for adjusted absorption coefficients

These tweaked absorption coefficients were used in the simulations that follow.

16.3. Basic Ray Tracing Results of Simulation

Initial simulations were performed using the basic ray tracing method described in 10.

16.3.1. Visual Inspection of Ray Traced Impulse Response Graphs

As an example of the accuracy obtained with the ray tracing simulation method graphs of both the measured and simulated impulse responses at a position close to the left alcove (Figure 72) were performed. Figure 73 shows the measured impulse response graph at this position and Figure 74 shows the simulated impulse response graph.

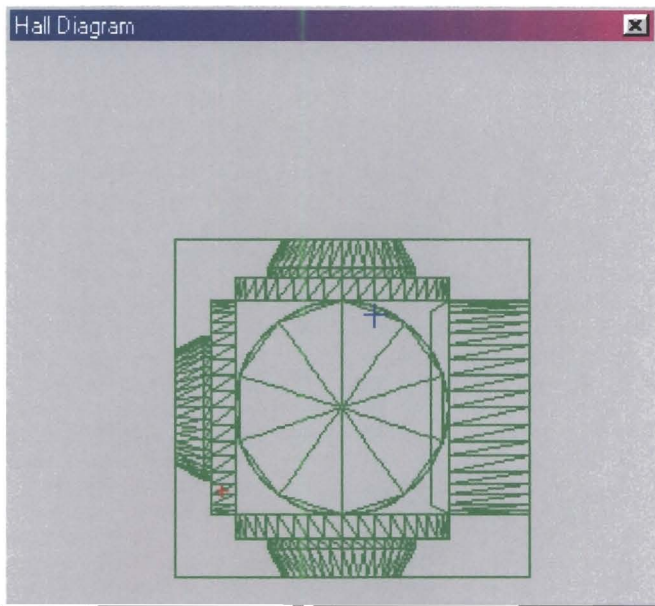


Figure 72: Measurement Position for Impulse Response Comparison (position #10)

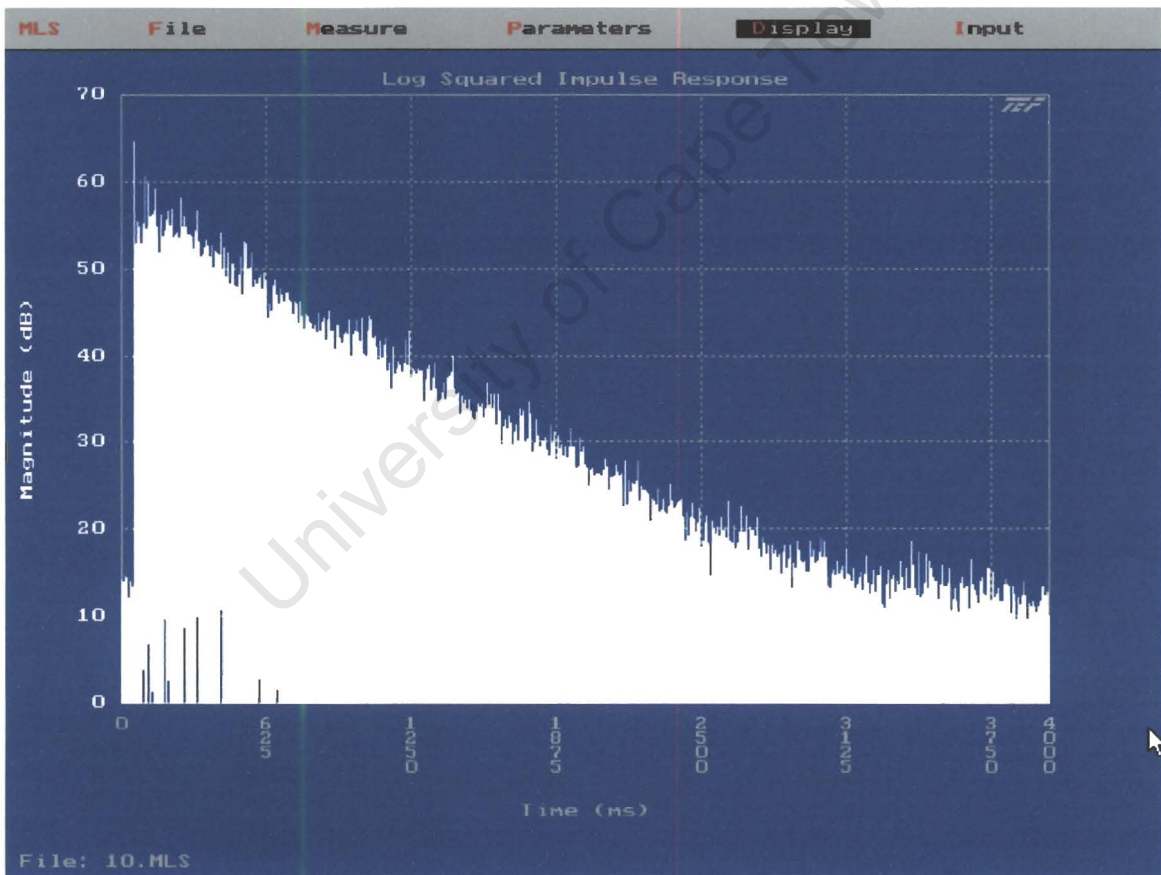


Figure 73: Measured Impulse Response Graph (position #10)

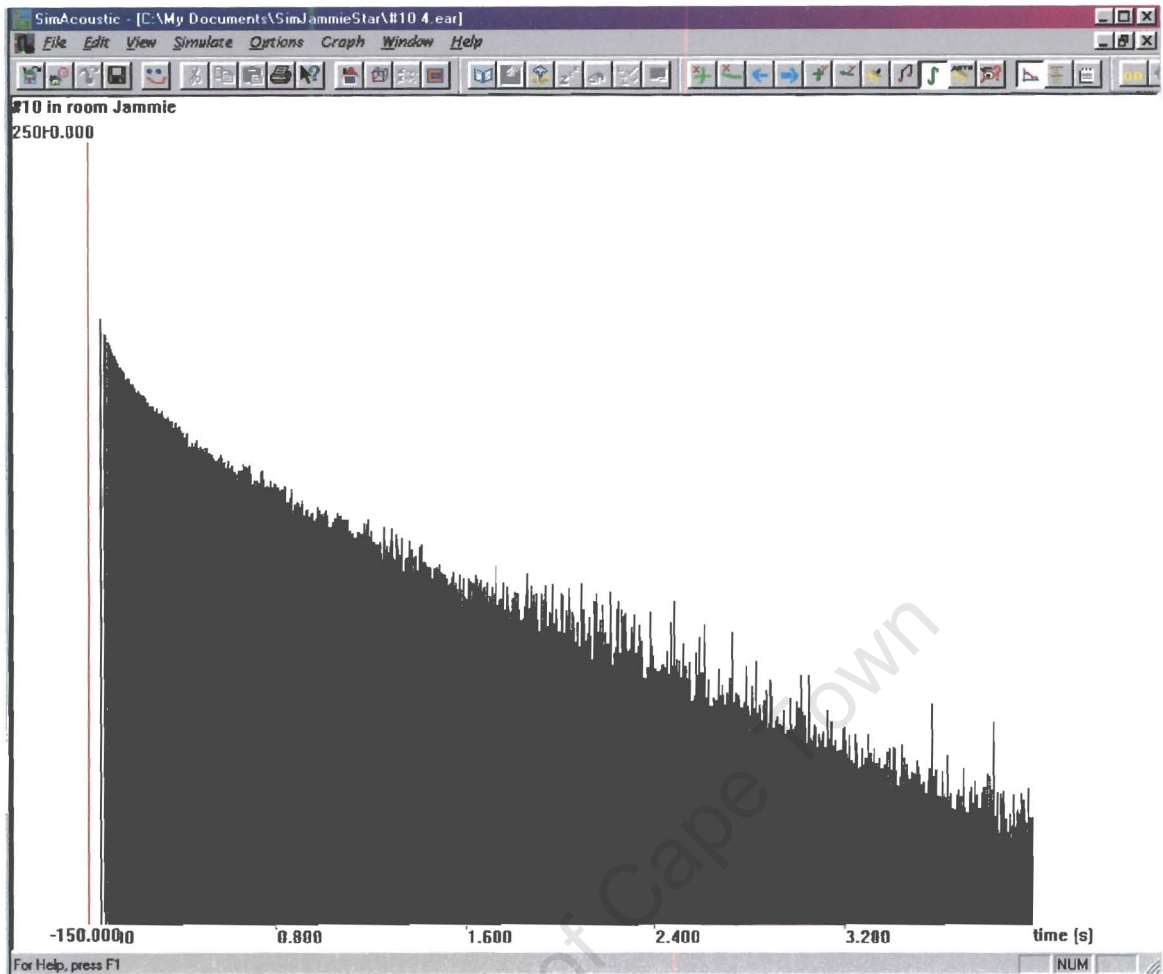


Figure 74: Simulated Impulse Response Graph (position #10)

Early time exact reflections were not simulated so the early time is different, there being no prominent reflections as seen in the measured graph.

Apart from this in the measured graph the sound decays from 55dB to 15dB in 3.125s, which is an average decay rate of 12.8dB/s. In the simulated graph a decay from -37dB to -116dB in 3.126s that is an average decay rate of 25.27dB/s. Thus the simulated decay rate is about twice the measured decay rate. Therefore some error in the calculation of the reflection strength is evident, namely that the energy of each reflection is too low.

16.3.2. Examination of Errors in the Ray Tracing Algorithm

It has been noted that the energy content of the reflections is too low (see 16.3.1). This may be due to a number of reasons.

The error may be an incorrect choice in the absorption coefficients in the hall. As was explained in 16.2 it is difficult to determine these accurately and perhaps they were estimated at too high a value. If this were the source of the error then changes to the absorption of the hall should produce proportional changes to the measured reverberation time. This was not tested.

Alternatively the energy error may be due to errors in the understanding of the simulation calculations. Changing the spreading ratio from $1/4\pi$ to $1/\pi$ caused an increase of 0.5s in the reverberation time, which is significant. More research generally may be needed to understand the nature of a sound field in a non-diffuse sound field.

Another possibility is the energy lost to spreading of rays, which would still be present in the physical wave. Simulation using secondary sources (16.4) implicitly addresses this error.

Lastly a bug (programming error) in the program may be the problem. To solve this it is necessary to carefully scrutinise the program, examining each step. This was done by both examining a print out of the relevant part of the program and also by examining each line of the program as it was being executed. It appeared in both cases that the program performed as intended.

In conclusion the cause of the error in the energy of the simulated reflections was not determined, although there are a number of possibilities.

16.3.3. Simulated RT60 Frequency Measurements

A simulation using the simple ray tracing method as described in 10 was performed. Measurement positions as described in 5.2.2 were simulated.

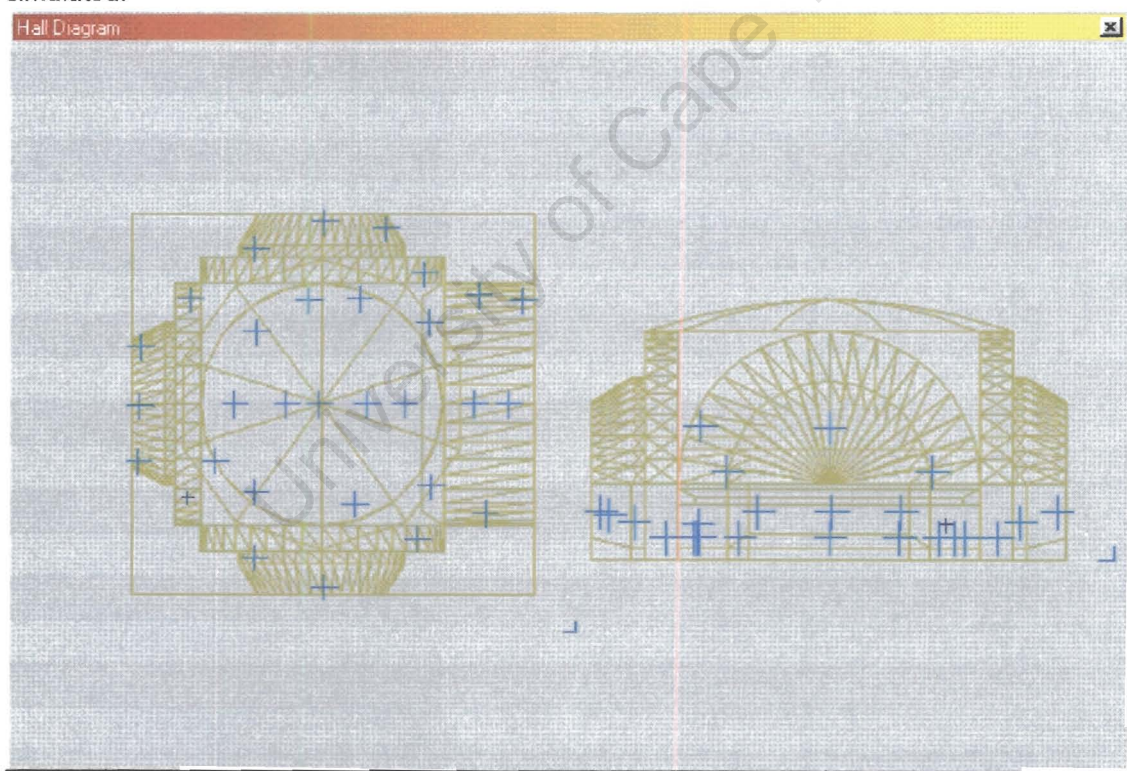


Figure 75: Measurement positions for the Simulation

30000 rays were used, which is less than the 117000 rays theoretically required to find all image sources up to 4s, but as can be seen from Figure 76, which shows the simulated graph for a position near the front of the stage along the center line, this number was sufficient to produce a dense impulse response graph.

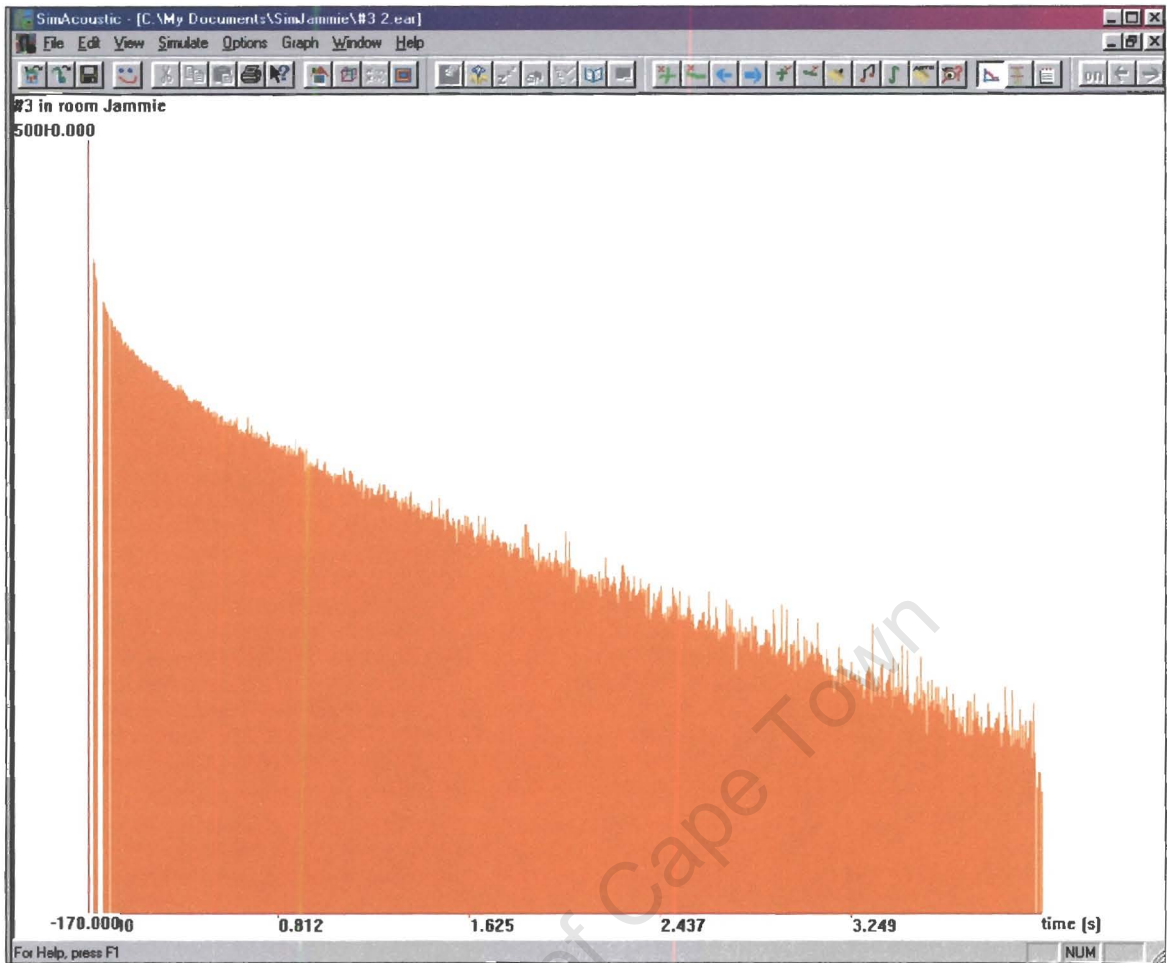


Figure 76: Example of a Simulated Impulse Response Curve in the Jameson Hall

The graph shows the characteristic decay slope of a typical impulse response graph. Figure 77 shows graphs of the simulated and measured reverberation times.

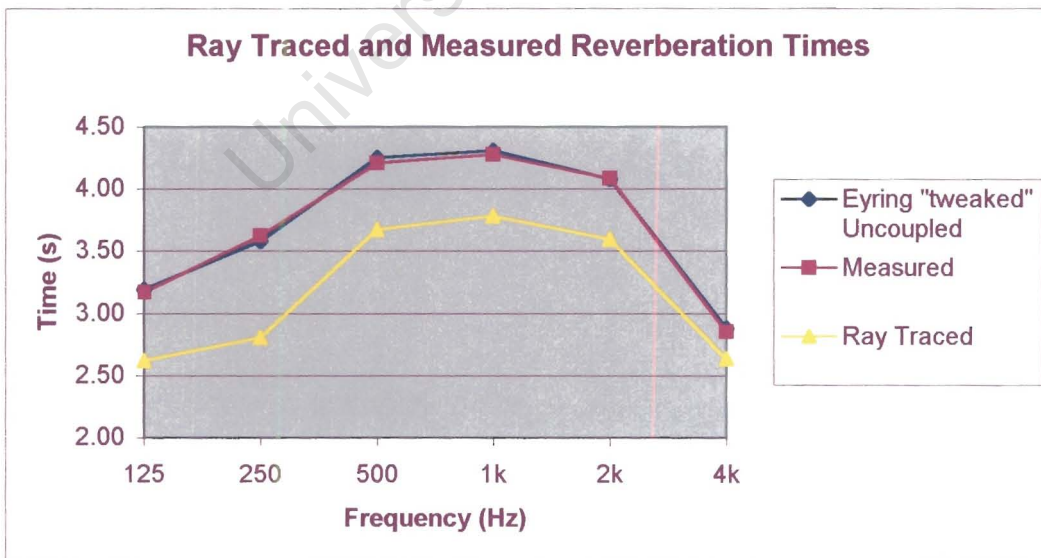


Figure 77: Ray Traced RT60 Times

The ray traced values are again consistently 1 second lower than the Eyring values, except at high frequencies where air absorption predominates over surface absorption and the value become similar.

Note that the shape of the graphs are all similar, consisting of similar low and high frequency RT60 times with mid-frequency times about 1s higher. This suggests the simulation has performed correctly, but has underestimated the times consistently. Remembering that in the ODEON comparison test (see 14) the RoWena RT60 times were about 0.5s below the expected results and 1s below the ODEON results. This is consistent with the results obtained here. It appears therefore that the RoWena ray traced results suffer from a lack of energy content.

It is also possible that the use of Eyring's reverberation formula to estimate the absorption coefficients is at error. However given that the coefficients have already been adjusted away from the expected values based solely on experienced inspection of the surface materials this is unlikely to be a significant error.

16.3.4. Complete Simulated RT60 Results

Figure 78 shows a 3D mesh graph of the simulated results, in the manner as explained in 5.1. This can be compared with Figure 79 which is for the measured results, as was presented earlier (see 5.3.2). Note that the scales for the two graphs are different, an unavoidable necessity considering the large difference in results.

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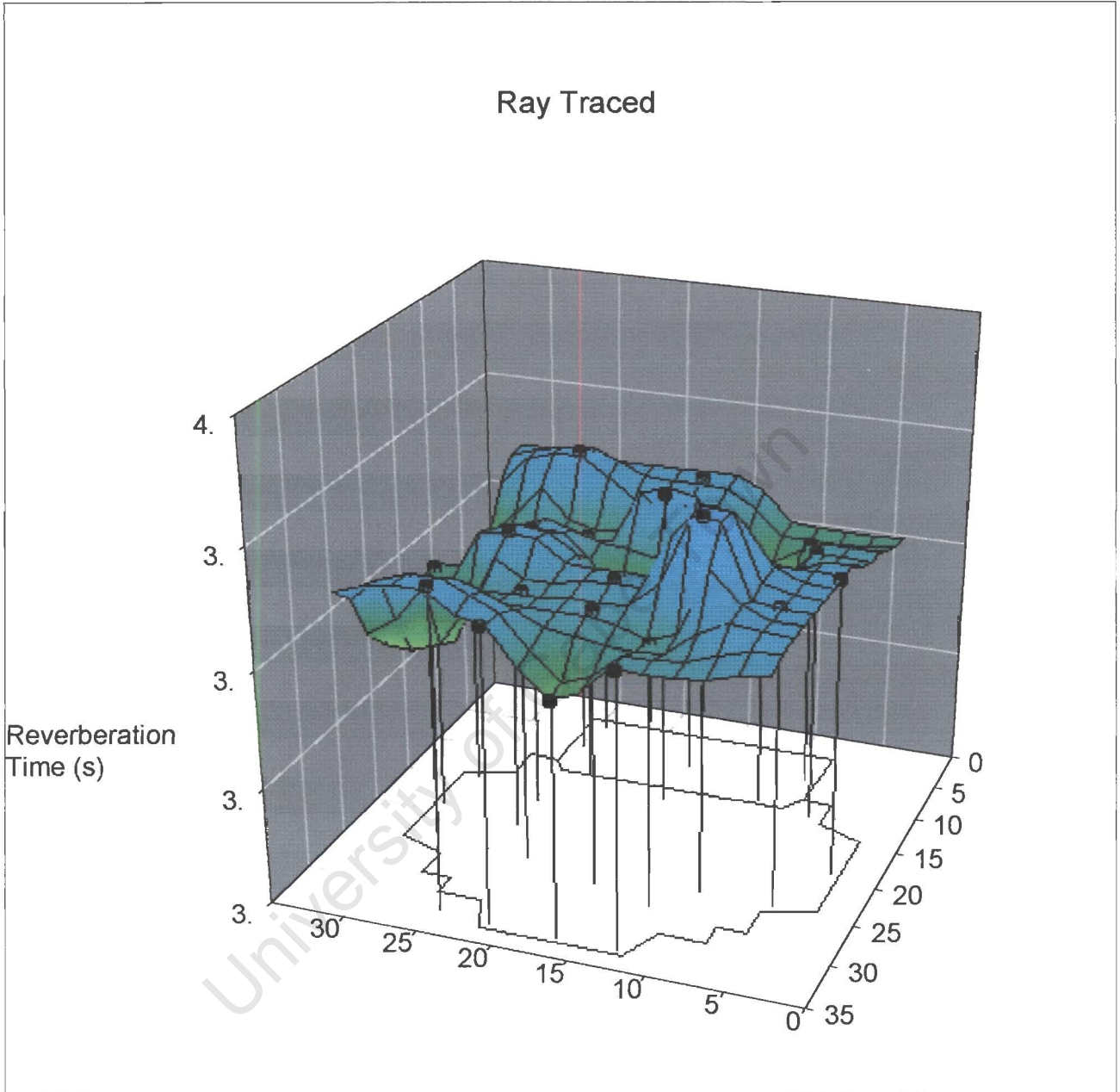


Figure 78: 3D Representation of Ray Traced Simulation RT60 Times

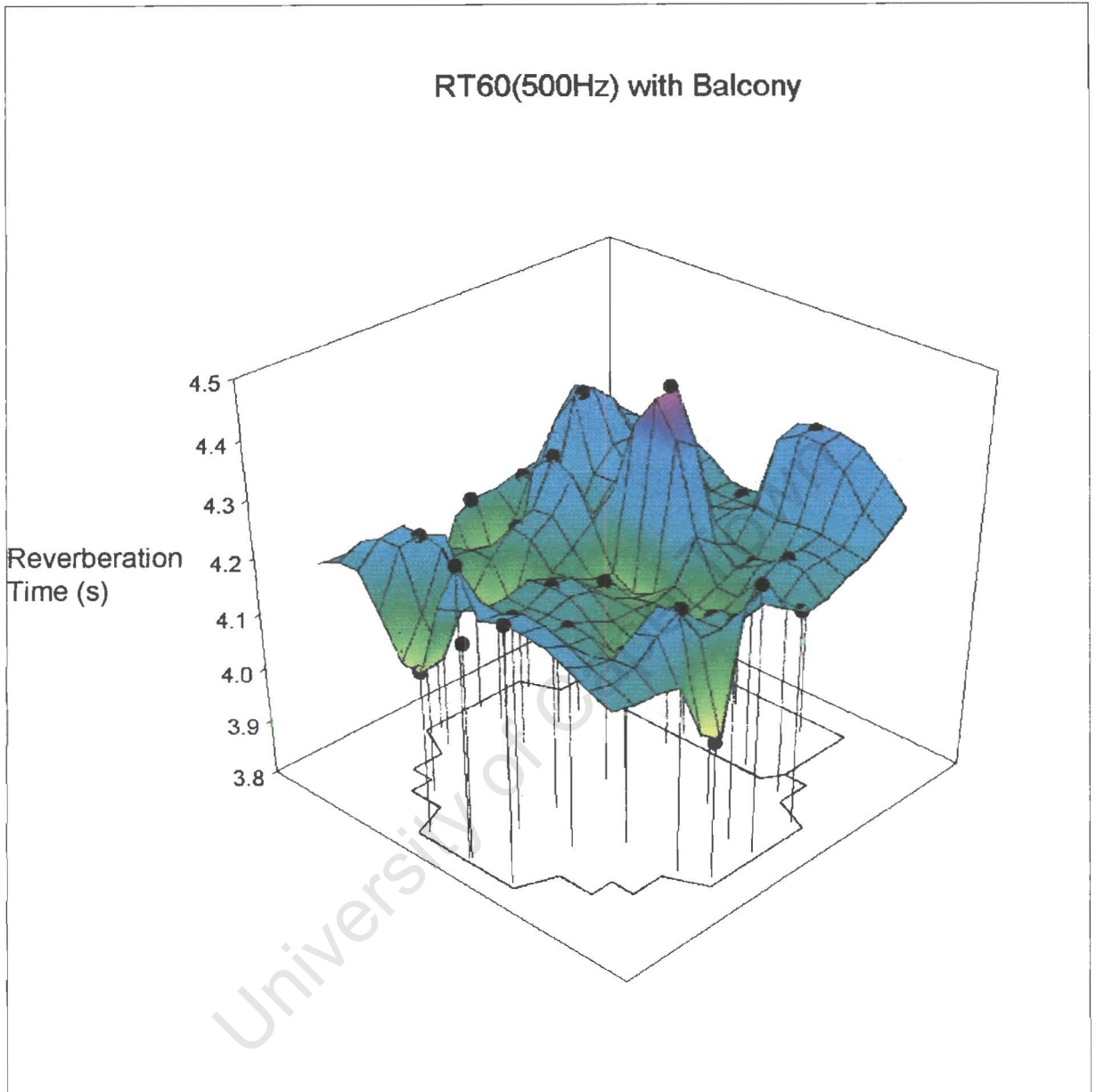


Figure 79: Measured RT60 Times

From inspection of the two graphs it is possible to make the following comparisons:

- The simulation graph has less variation in the RT60 values than the measured graph. This is partly due to the expectation of the simulation program of a diffuse sound field, where the reverberation times should be similar throughout the whole room.
- Aside from that, the prominent hump near the center of the hall to the *right* is present in both graphs. This shows that the effects of focusing from curved surfaces is at least partly approximated.
- Also both graphs show lower values in the *left alcove*.
- Both graphs show larger values for the *right* of the balcony.
- However the simulated graph does not show the lower values in the *right alcove* or the raised values in the *left balcony*.

16.3.5. Other Simulated Results

RoWena is able to calculate EDT, C50, C80, Center Time and Definition. However these values are not calculated accurately. This is for the same reason as the poor RT60 results, namely that the energy content of the simulated impulse response is incorrect. For this reason results for these qualities are not given here.

STI and %Alcons cannot be simulated using RoWena yet. Although the code would be relatively easy to implement it was thought that the existing errors in the program should be corrected first.

16.3.6. Influence of the Number of Rays on the Simulation Results

The dependency on the basic ray tracing technique on the number of rays used has already been described (see 9.4). This section provides a demonstration of the effect of changing the number of rays in the simulation.

Simulations were made for a smaller set of measurement positions, as shown in Figure 80.

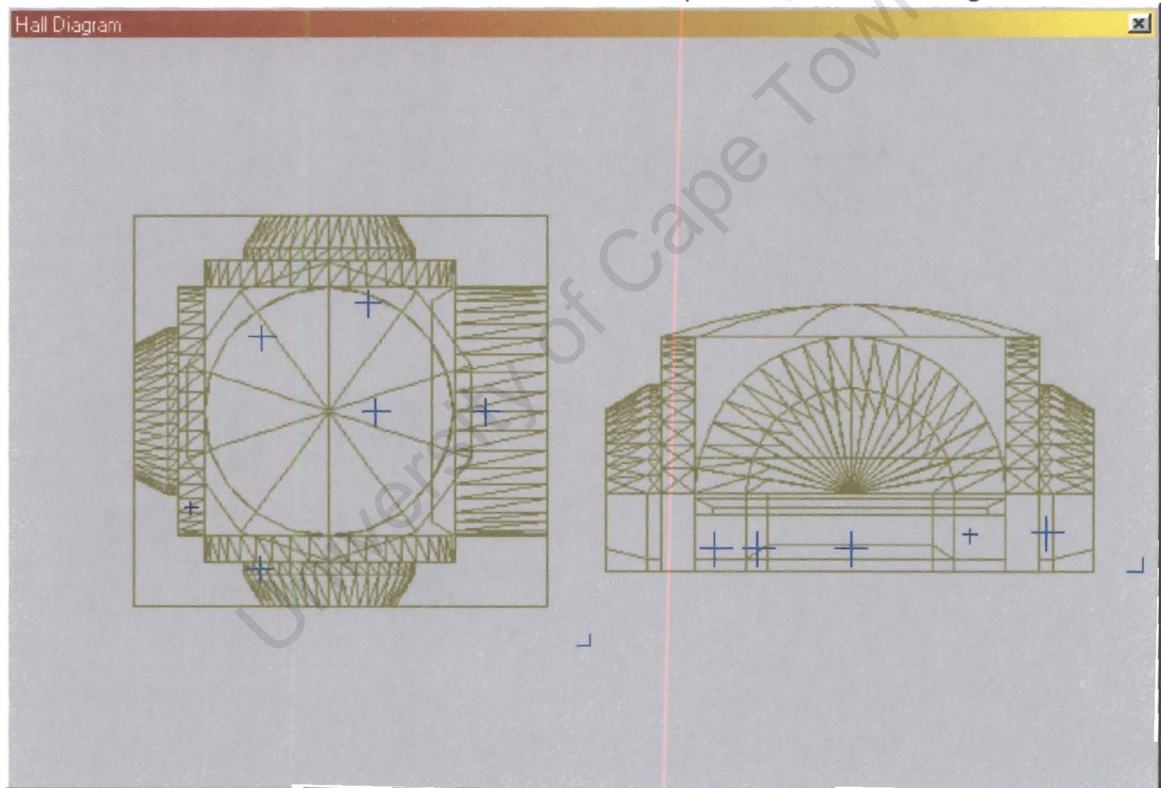


Figure 80: Positions of smaller receiver set

Ray traced simulations were carried out with 1000 rays, 30 000 rays and 100 000 rays. Graphs of the average results of these simulations, along with the measured values, are shown in Figure 81.

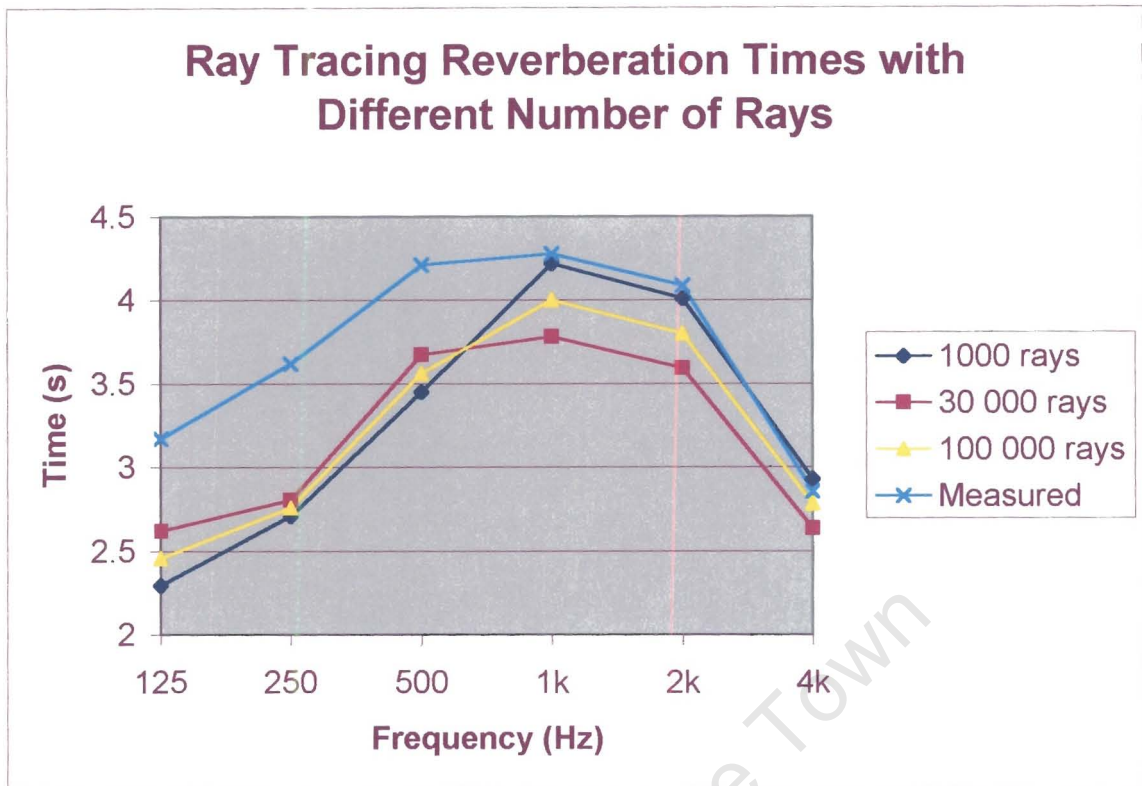


Figure 81: Ray Traced RT60 times versus frequency with different number of rays

The simulated graphs are all similar, except at mid-frequencies. Interestingly the results with 1000 rays and 100 000 rays are closer to the measured values than with 30 000 rays. This shows the reliance on the number of simulated rays, with a larger number not necessarily indicating better accuracy.

16.3.7. Influence on the Multiple Reflection Removal Technique

As explained in 15.6, the matter of multiple reflection removal has not been an important issue in other simulation programs, because of the lack of curved surfaces. It was decided that for this simulation program only planar surface reflection should be removed, which is the case for all the results presented thus far.

To illustrate the effect of removing multiple reflection paths involving planar surfaces only, simulations with the different removal types were performed. Figure 82 shows graphs for simulations using 30 000 rays removing all multiple reflections and removing no multiple reflections.

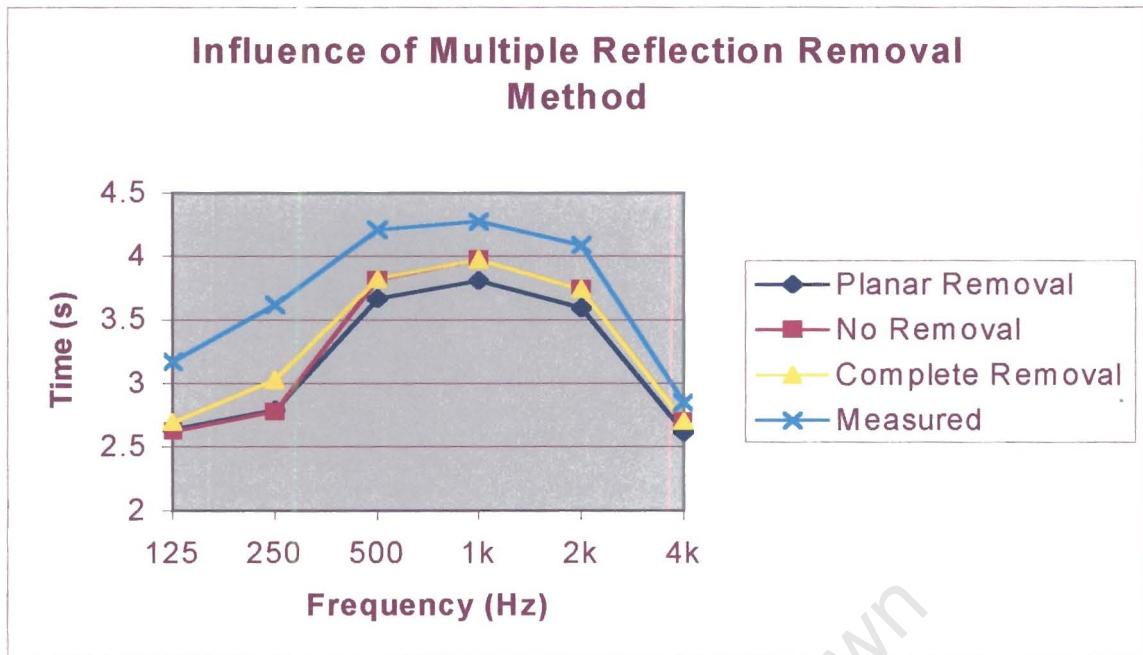


Figure 82: Ray Traced RT60 times versus frequency with different multiple reflection removal techniques

Small differences in the results can be seen from the graphs. These are large enough to be important, but because of the general inaccuracy of the results it is unclear which method is more accurate.

16.4. Simulation Using Secondary Source Technique

The secondary source method adjusts the energy of the received rays according to the theoretical energy that is expected to be received (see 11). Therefore considerably fewer rays are used for the simulation. However the requirement of a diffuse sound field is important, which as has been seen (see 5.3.2) is not the case in the Jameson Hall.

16.4.1. Secondary Source Reverberation

Figure 83 shows graphs of RT60, simulated using the secondary source method. Varying numbers of rays were used; 200 rays, 500 rays and 1000 rays. Also shown are the measured values and the basic ray traced values.

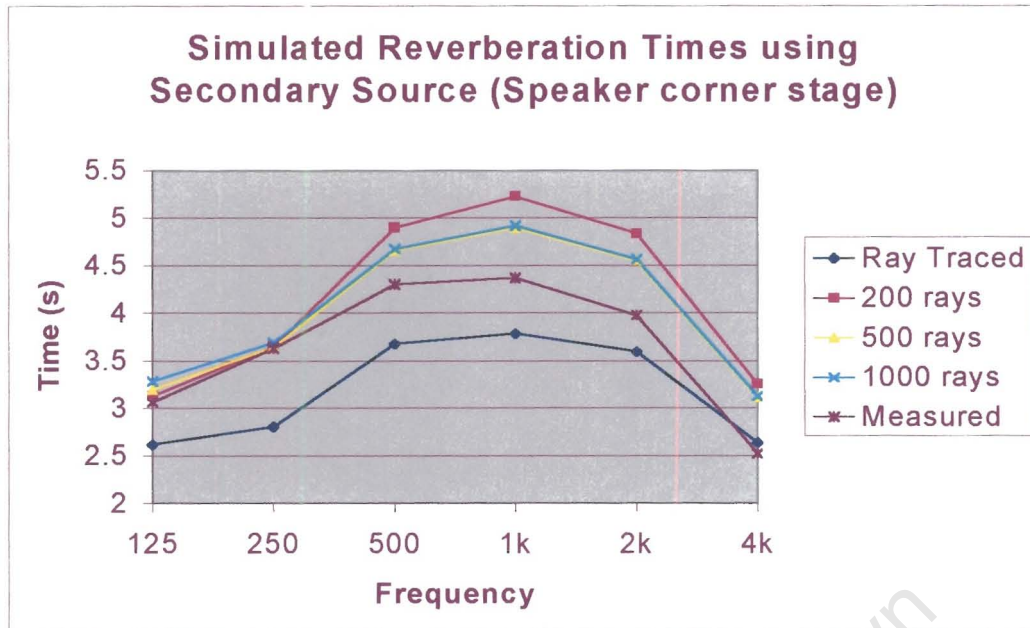


Figure 83: Secondary Source RT60 times versus frequency with different number of rays

The secondary source values correlate better to the measured results at low frequencies than the ray traced values. At higher frequencies however the discrepancy is large.

Using 200 rays produced the least favourable values, but the difference between 500 rays and 1000 rays was negligible.

16.4.2. Secondary Source Visibility Checking Method

In 11.5 a potential method for simulating the effect of blocking surfaces was described. A suitable surface in the Jameson Hall is the balcony. Two simulations were performed with measurement positions as shown in Figure 84.

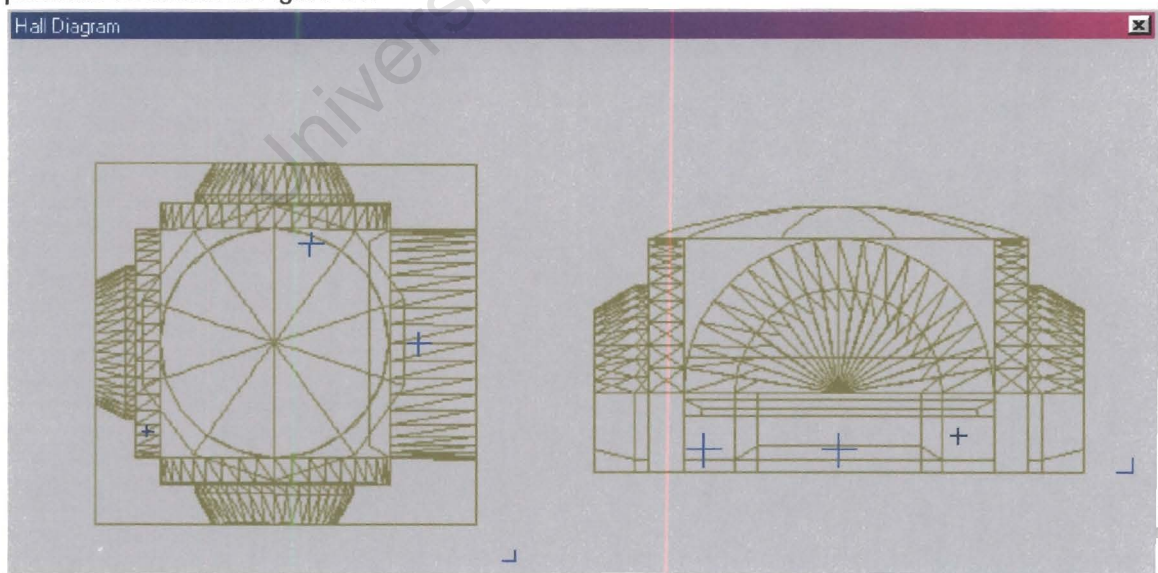


Figure 84: Receiver positions for visibility checking simulation

One of the positions is in an open area of the hall floor, and the second is under the balcony.

The two simulations were performed with and without the visibility checking algorithm active. Figure 85 shows the four simulated graphs; 2 for each measurement position. The sound source was at the corner of the stage.

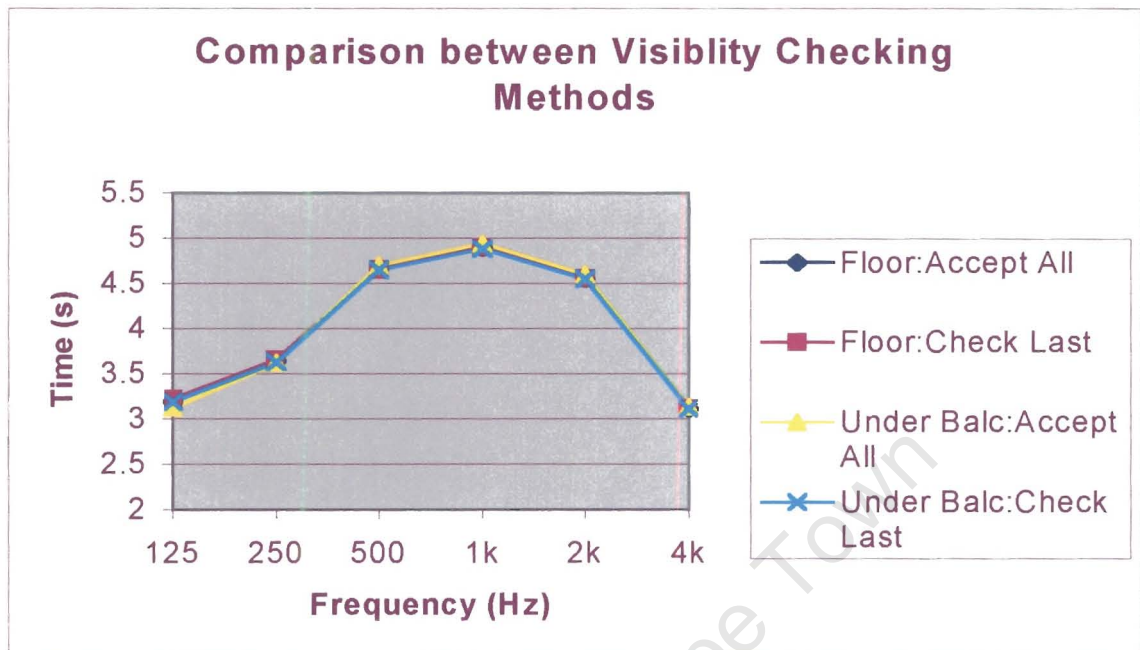


Figure 85: Secondary Source simulation RT60 times versus frequency with different visibility checking methods

The graphs show an insignificant difference between the results using the two visibility checking methods.

16.5. Early Time/Mirror Imaging

Section 12 discussed the importance of finding exact early time reflection paths, while 15.5 discussed the method used for curved surfaces. This section demonstrates the accuracy of these methods.

Figure 86 shows the first 500ms of a measured impulse response graph, taken at a position close to the stage on the center line of the hall. Figure 87 shows the corresponding ray traced graph using 38000 rays.

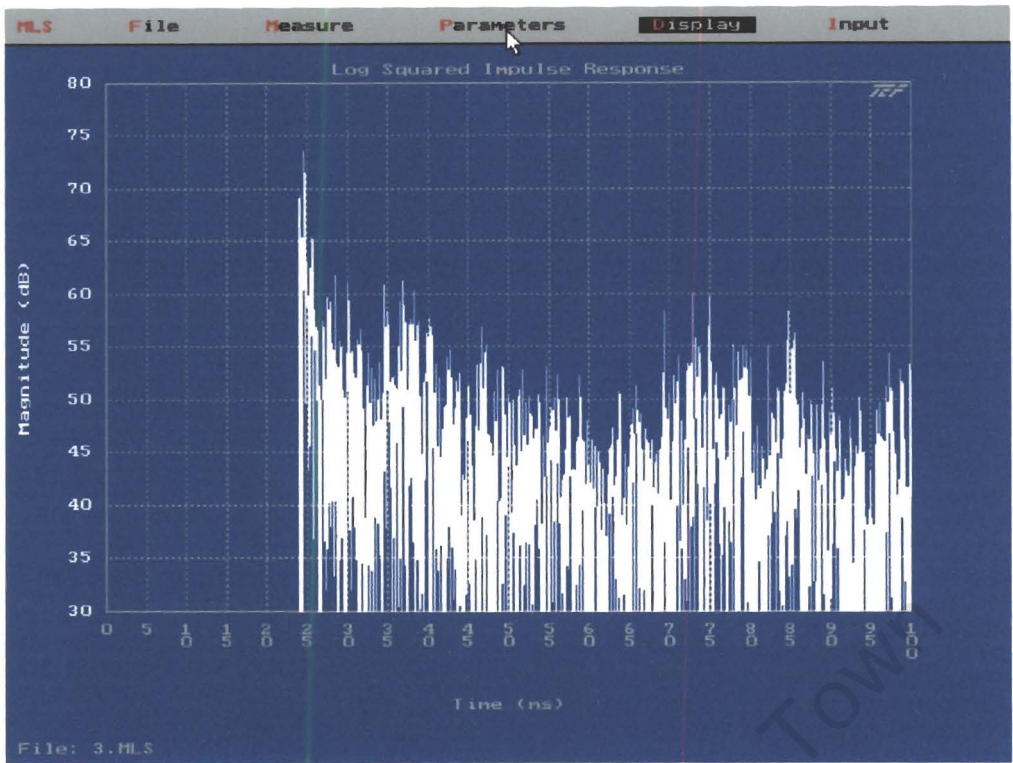


Figure 86: Early portion of measured impulse response graph

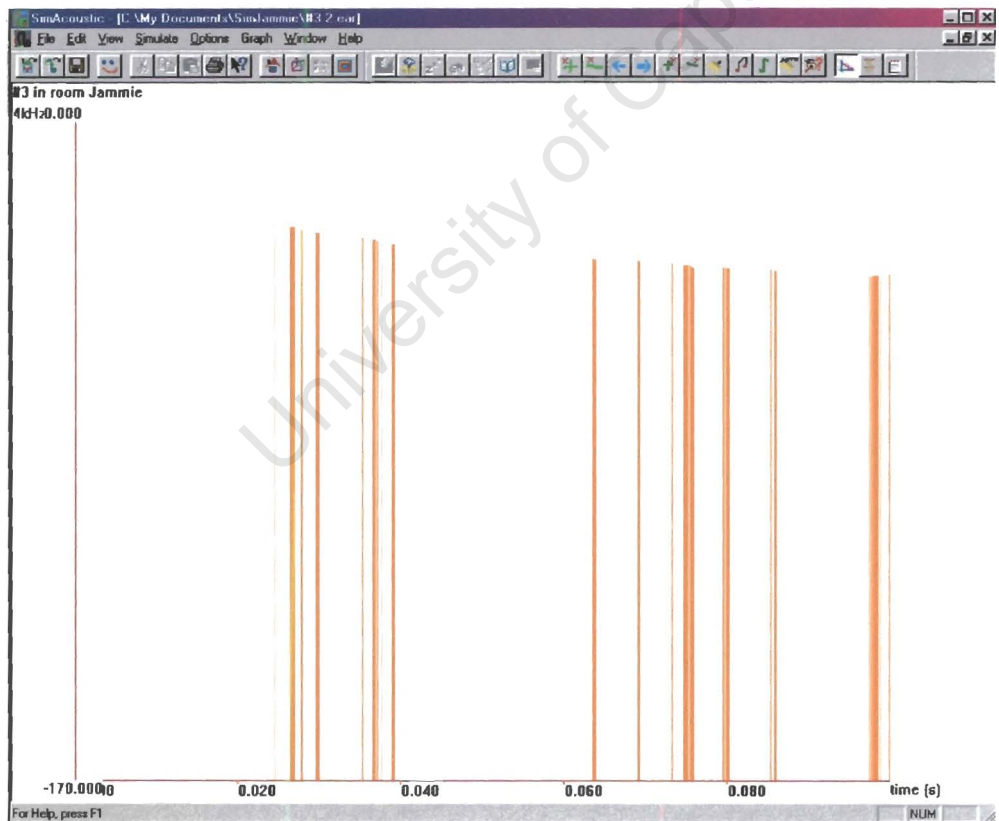


Figure 87: Ray traced early reflections

As expected very few early reflections were found with the basic ray tracing method. Using the simplex search algorithm to find early reflections results in the graph shown in Figure 88, for only 10000 rays.

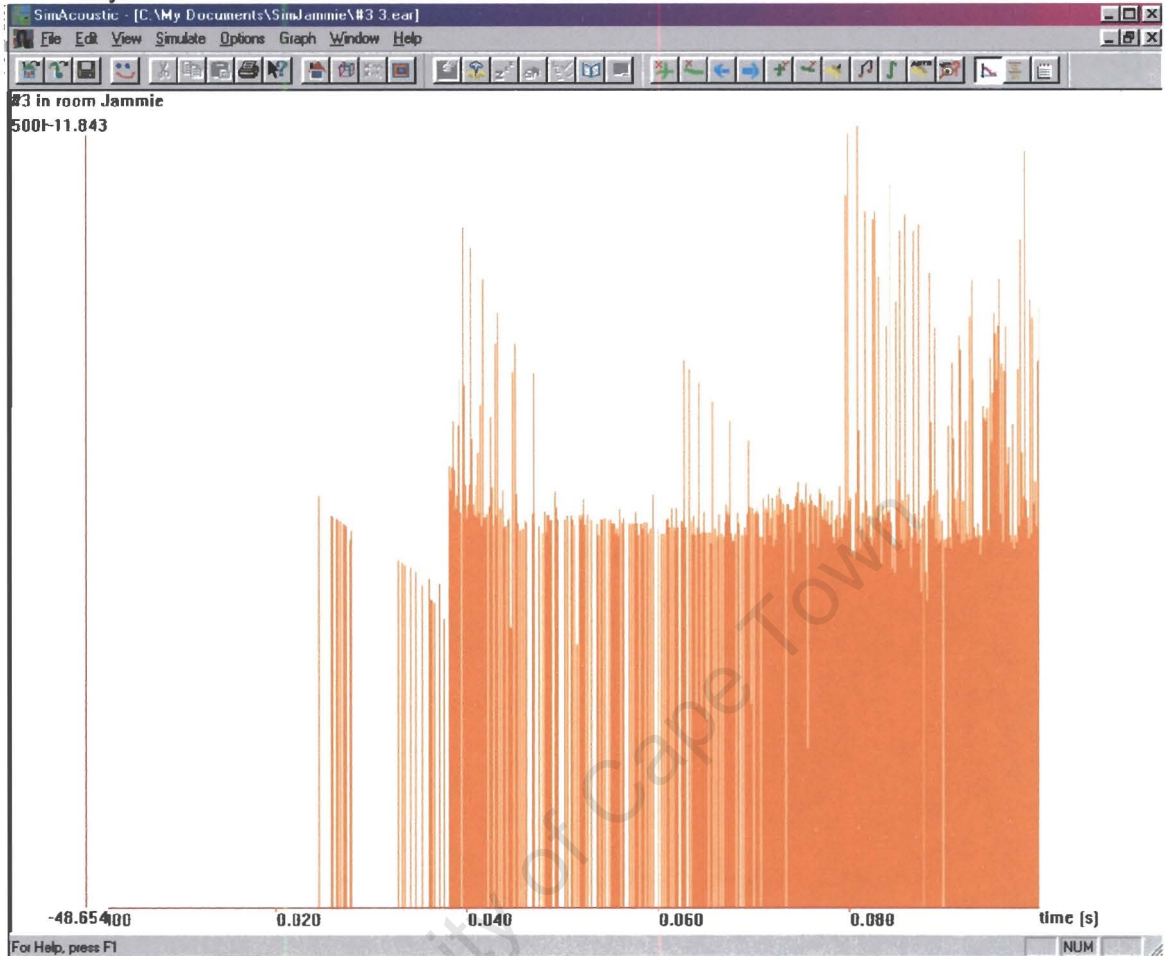


Figure 88: Early Reflections Found with Simplex Search

Many reflections are found with this method. The large difference in intensity between some of the reflections is due to the correspondingly shorter path length of these reflections. Because this simulation represents the early time the sound field is not diffuse and so phase relationships should be taken into account. If this were done then the differences would not be as great. Rather the general curve of the graph would be seen to be raised and lowered as relevant.

(Also, of interest, without the extended surface and penalty additions described in 15.5.8 and 15.5.10 less than 5 reflections are found by the search algorithm. This demonstrates the importance of these techniques. All ray paths shown in Figure 88 are specularly relevant.)

A composite of the graphs in Figure 86 and Figure 88 are shown in Figure 89.

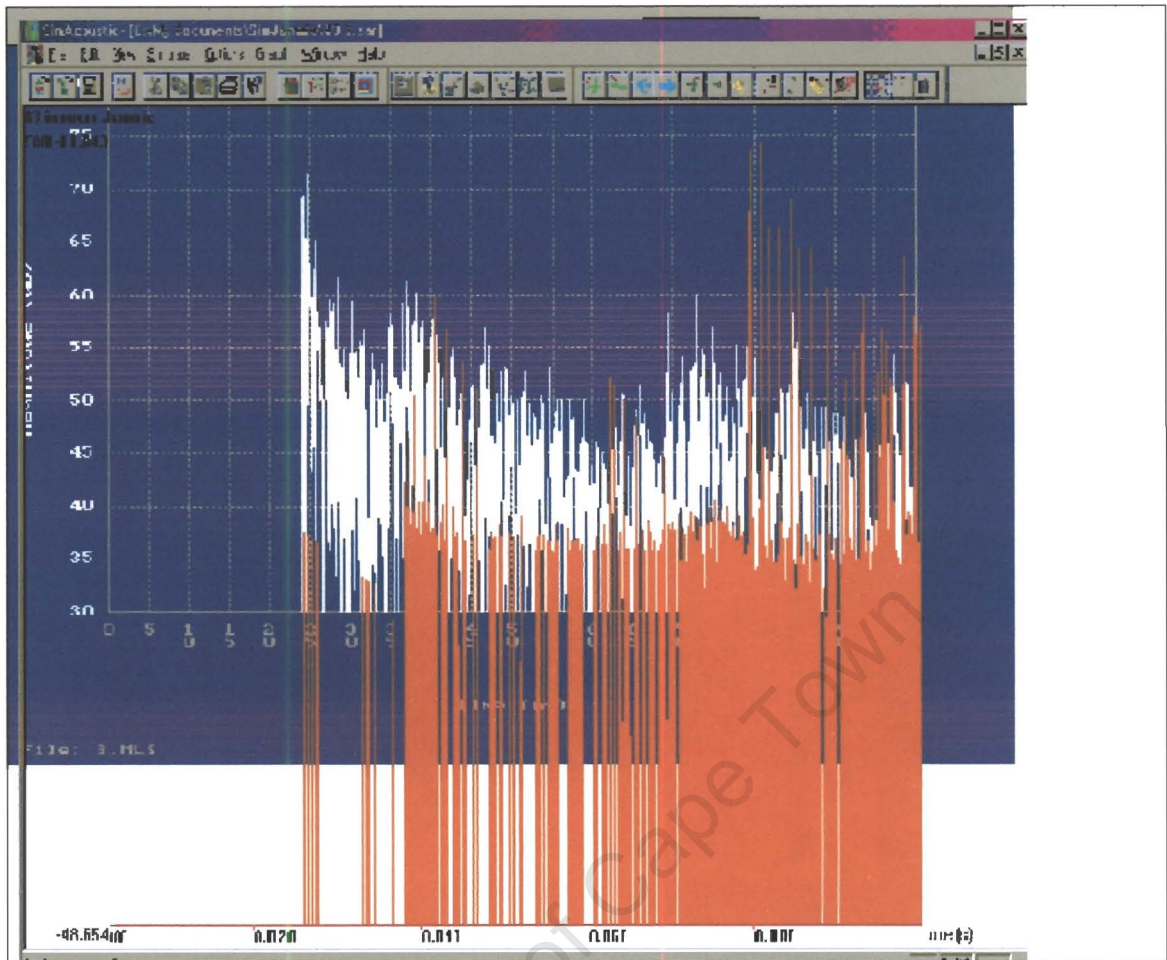


Figure 89: Combined graph of Measured and Simplex Search early time reflections

From this figure it can be seen that the dense areas of the simulated graph match up well with the measured graph. The reason that the shape of the simulated graph is not the same as the measured graph is because of the assumption of uncorrelated phases (see 7.4.3).

Also it is clear that while the measured graph has continuous reflections there are gaps in the simulated graph. These may be due to scattered sound in the early time.

(The simulation time for this graph was 8 minutes. An equivalent time period, simulated using the ray tracing procedure, would take only 30s, also using 10000 rays.)

16.6. Simulation of Scattering

Although RoWena is capable of simulating scattering in the manner described in 13 such a simulation was not performed. This is because in light of the poor RT60 results no useful information would be gleaned.

16.7. Using Ray Tracing to Identify Problem Surfaces

Part of investigating the acoustics of a hall is determining which surfaces, if any, are the causes for acoustical anomalies. For example determining which surface(s) are causing an echo. The

SoundLab program, which was used to take measurements of the Jameson Hall, can produce a graph called a PET (Polar Energy Time) graph (see Appendix D). This graph shows the direction of arrival of all reflections.

Figure 90 shows a PET graph for a position close to the stage in the middle of the hall, with the speaker at the front corner of the stage.

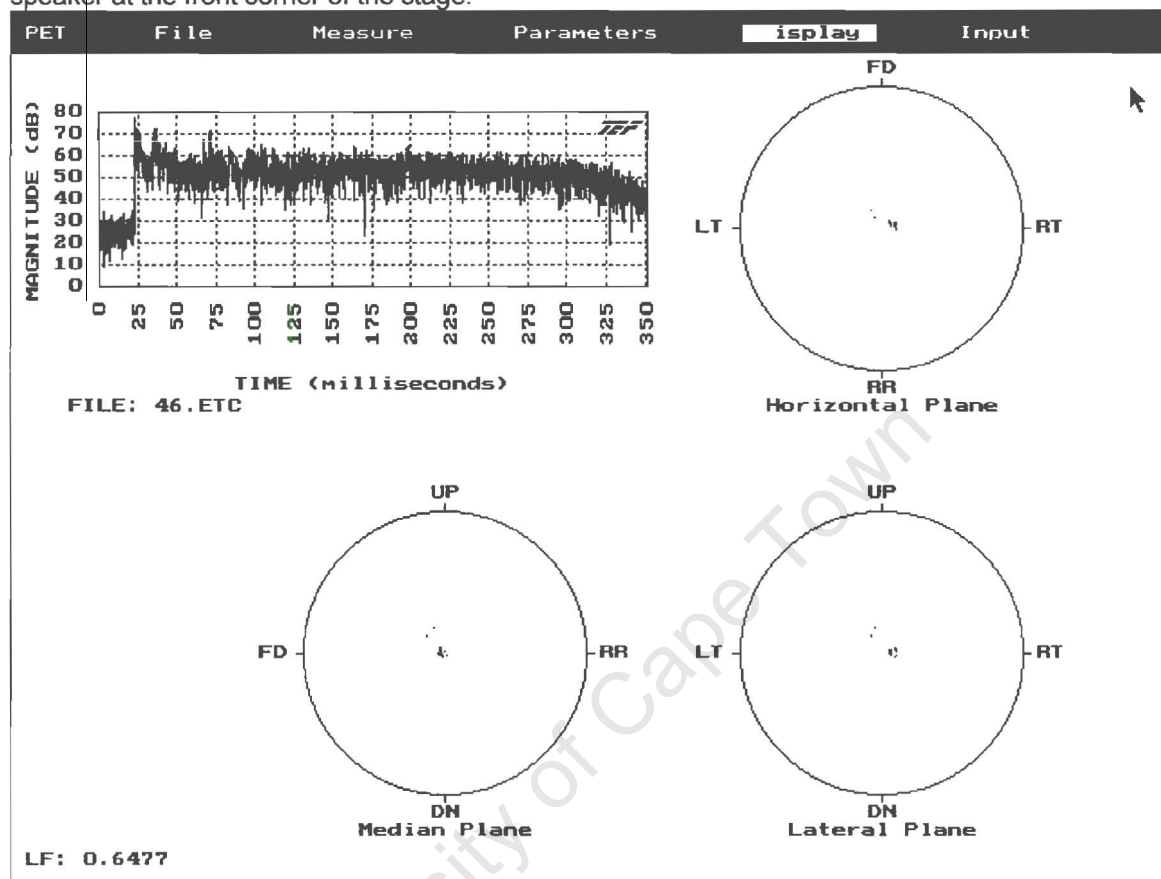


Figure 90: PET Graph for a position close to the stage

The graph at the top left of the figure is the impulse response graph. The three circles show different sections through the receiver point, with selected reflections shown as dots. Only a few of the strongest reflections have been shown in this graph. The azimuth and elevation of any reflection can then be obtained from this graph.

Because of the difficulty of mentally visualising 3D ray paths in a complex room it is still difficult to locate the exact surface from which the reflection last reflected. However using the RoWena program it is possible to produce the ray path and visually identify the relevant surfaces.

Figure 91 shows a number of ray paths for reflections arriving at 35ms, derived from the PET measurement shown in Figure 90.

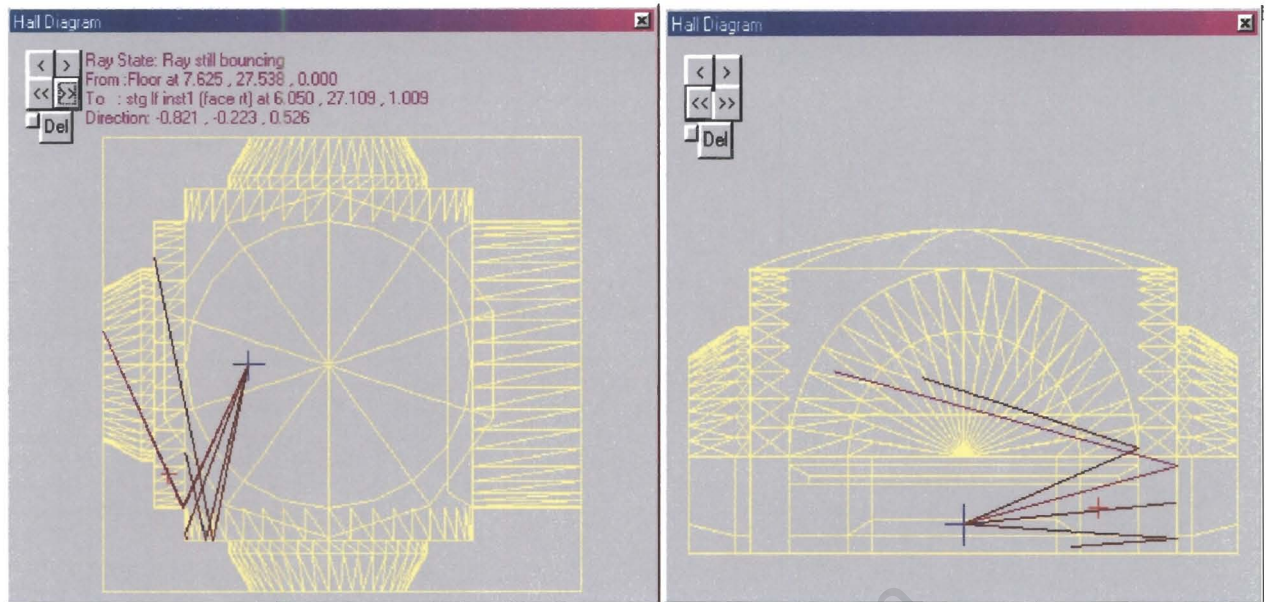


Figure 91: Early Ray Paths for a Receiver close to the stage

The receiver point is marked by the blue cross and the source point by the red cross. Ideally these ray paths should pass through the source point after a certain number of reflections. It can be seen from the figure that the ray paths come close to the source point, though do not pass directly through it. Such errors arise from errors in the basic assumption of geometrical acoustics (see 9), and also possibly unknown errors in the nature of reflections from curved surfaces.

However the ray paths are accurate enough to provide a visual indication that the reflections arriving at this time are reflected by the walls directly to the right of the source. It is thus possible to identify surfaces that may be causing strong reflections.

As another example, the PET graph shown in Figure 92 indicates a number of very strong reflections arriving between 25ms and 40ms after the direct sound.

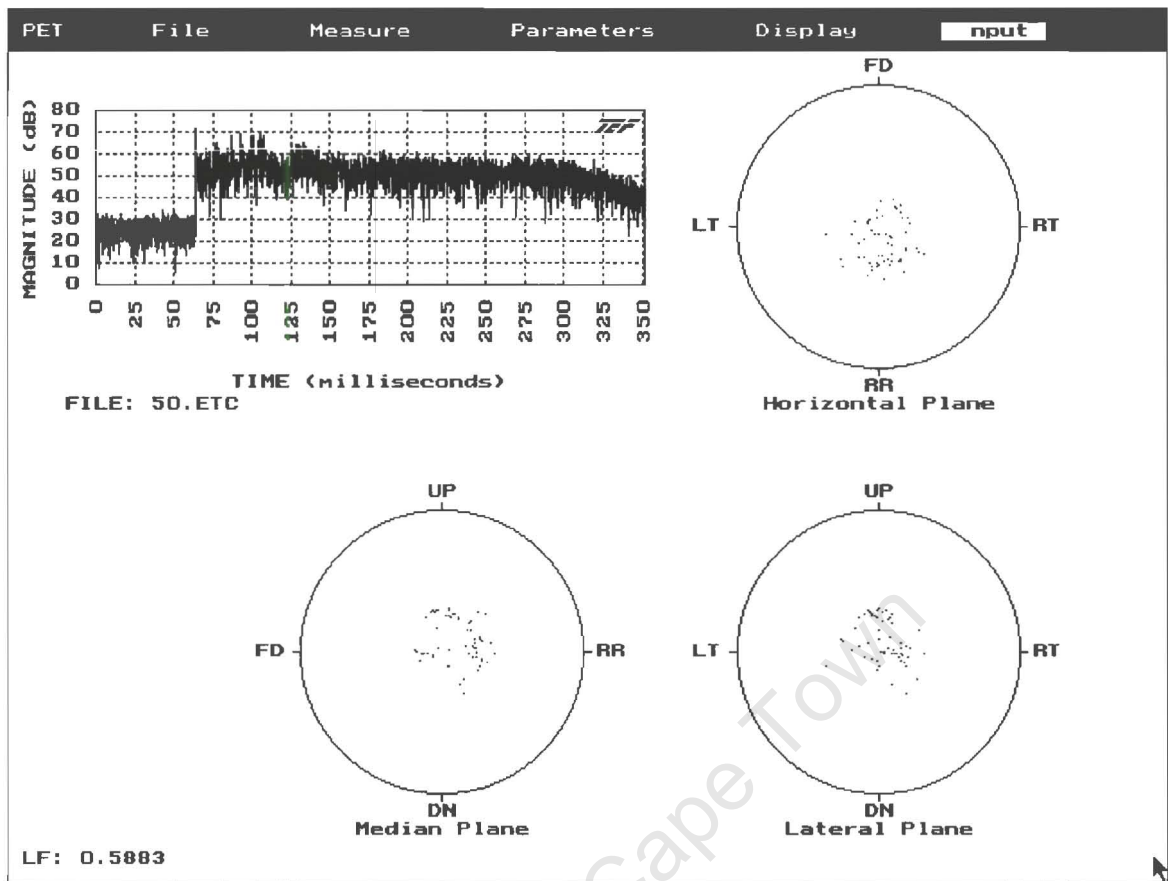


Figure 92: PET Graph for a receiver in the left alcove

To establish which surfaces are causing these reflections the method described is used. Figure 93 shows ray paths for reflections arriving at 104ms to 107ms (absolute time).

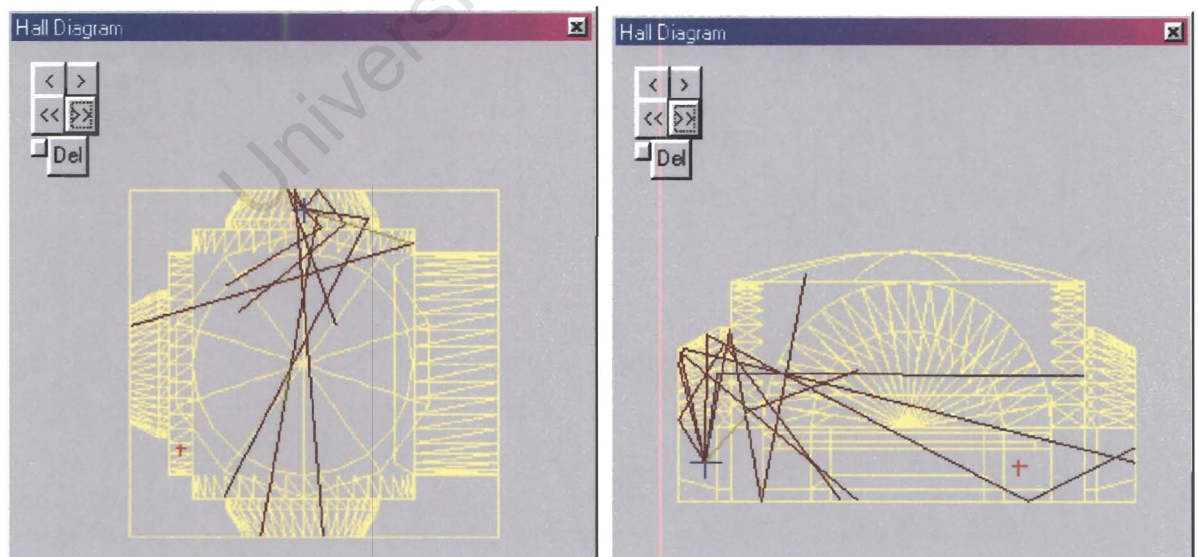


Figure 93: Early Ray Paths for a receiver in the left alcove

Although the diagrams appear slightly messy, with a little patience it is possible to see that all the reflections are focused to the measurement point (in the left alcove) by the conical arch above the alcove.

Note that the ray paths involve more than one reflection and that they do not pass close to the source point. Again this is due to inaccuracies in the assumption of geometrical acoustics and the absence of scattering methods.

In spite of this, the first part of each ray path traveling away from the receiver would be completely accurate, since it is derived directly from the PET measurements. Therefore an acoustical consultant can be confident that these reflections are caused by the focusing effect of the conical arch. This also gives an indication of the inaccuracy of ray paths in real rooms.

16.8. Analysis of the Dome

As an extension of the discussion in 16.7 it is possible to more closely analyse the effect of a particular surface. As an example the domed surface in the Jameson Hall has been used, since it is a prominent architectural feature.

16.8.1.1. Architectural Structure of the Dome

The perpendicular distance from the center of the dome to the floor is 15.4629m, and the lowest point is at 13.6m. The dome consists of three separate radii. The largest, which describes the top part of the dome is 32.472m. (about twice the distance to the floor). The shorter radius is 11.7943m, while a short joining section has a radius of 1.2993m.

The focal point of the main part of the dome is (almost) exactly twice the distance from the top of the dome to the floor. This relationship seems unlikely to be coincidence although no reason is known to the author.

16.8.1.2. Effect on Acoustics: Beneath the Dome

If the dome's focusing point were on the floor, an extreme concentration of sound energy would be expected directly beneath the dome by any source at that point. In the Jameson hall however the focal point of the dome is not at the floor. Cremer¹⁰¹ shows that sound produced at a point on the Jameson floor, directly under the dome, will concentrate at the geometrically opposite side of the extended sphere created by the dome, which for the Jameson Hall lies beneath the floor.

In order to examine the effects of such a situation, a simple computer model was constructed, using the RoWena room acoustics simulation program. To isolate the features prevalent to the dome the room model that was used consisted just two surfaces: a domed surface and a planar floor surface beneath it (see Figure 95). The radius of the dome was varied to investigate different situations, but the maximum extension of the dome was set at 15.5m above the floor, as in the Jameson Hall.

16.8.1.3. Focal Point of the Dome on the Floor

If the highest point of the dome is made 15.46m above the floor (as in the real hall), and the focal point is at the floor (radius=15.46m), and also the source and receiving point are placed at the focal point, then the path length of the shortest ray is 31m, which is the distance from the floor to the dome and back again. Multiples of this path length are also expected and thus reflections with a period of 90ms should appear on an impulse response graph. This is concurred by the simulation. (Figure 94).

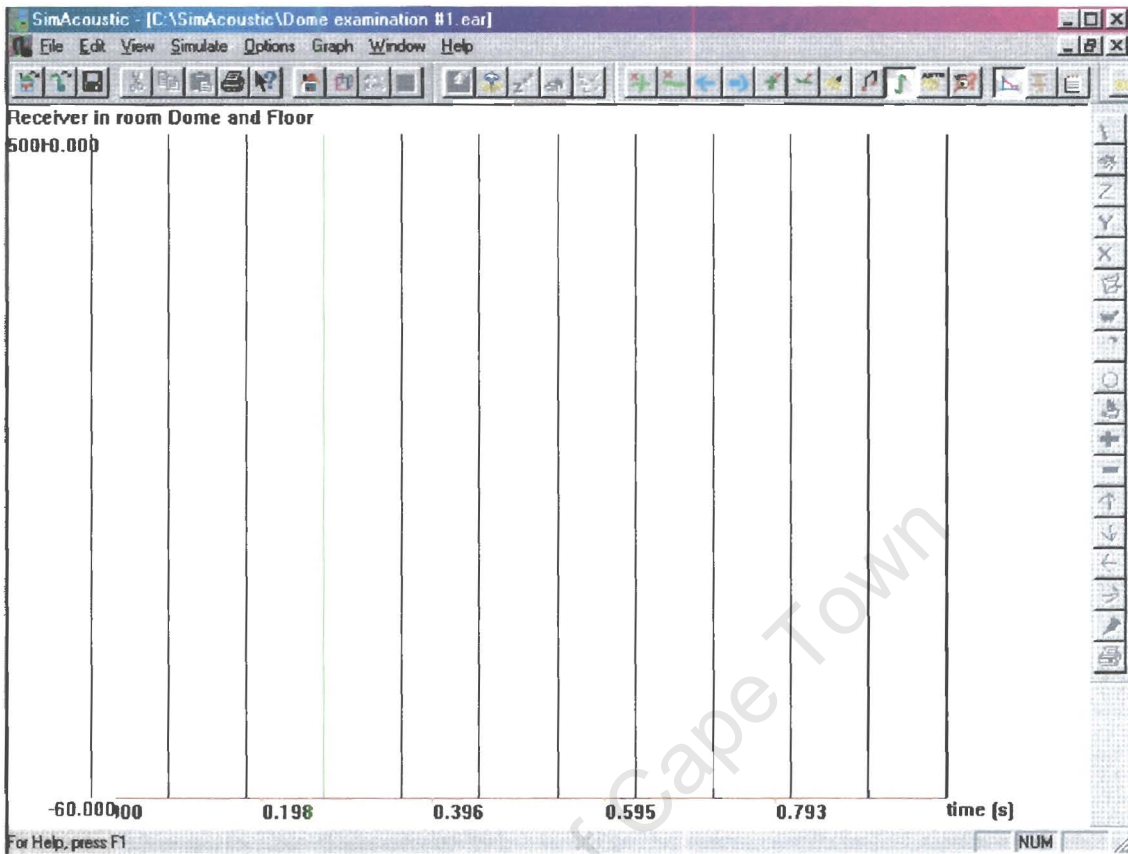


Figure 94: Periodic pattern of reflections from a dome

The graph shows reflections, indicated by the vertical lines, arriving every 90ms. Since no other surfaces exist in this simple room model no other reflections are detected. Also no absorption was assigned to the surfaces nor was the spreading of sound included in the simulation. Therefore no decay curve is visible.

Each reflection shown in Figure 94 is actually a multitude of reflections arriving nearly simultaneously from different parts of the dome. Figure 95 shows a much enlarged portion of the (apparently single) reflection at 90ms in Figure 94, which shows the many individual reflections.

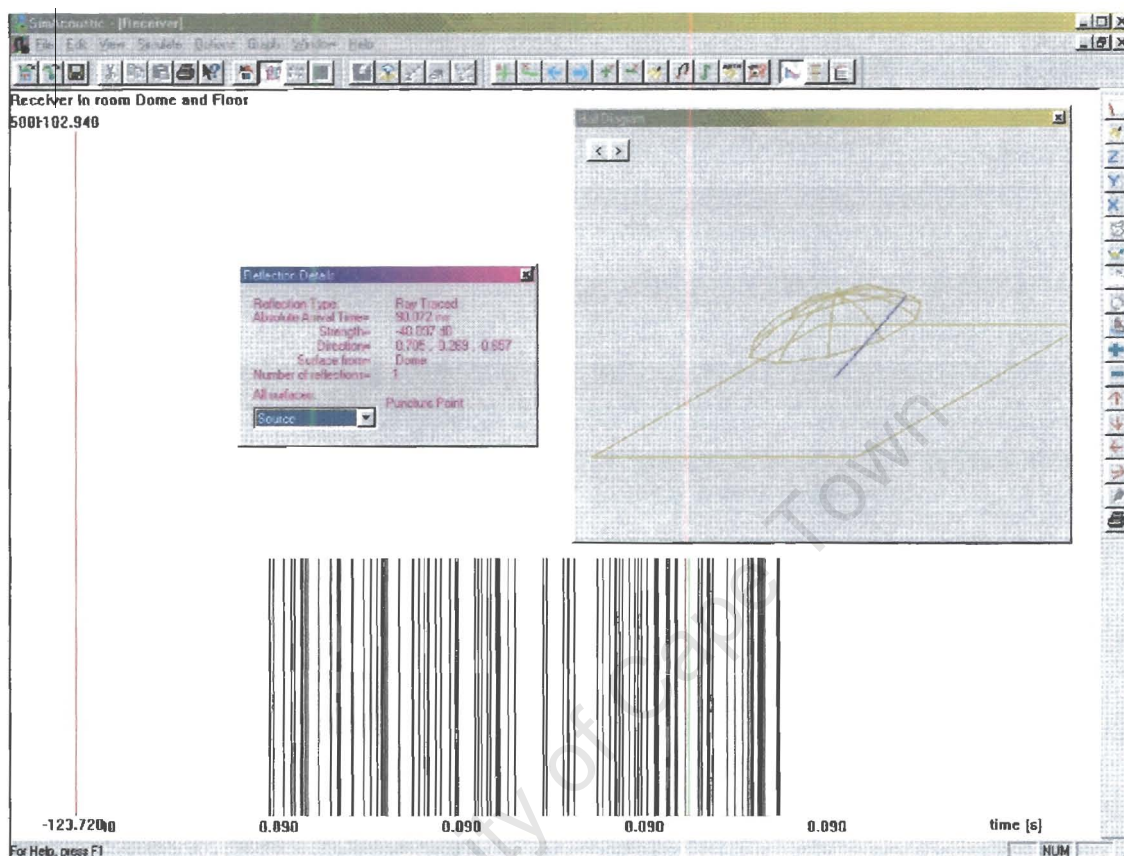


Figure 95: Many reflections arriving almost simultaneously from a dome

A typical ray path is shown on the inset 'hall diagram' picture. All the ray paths look similar; that is a straight path to the edge of the dome and back again.

The ray path shown in Figure 95 may be traversed many times; once for the first echo, twice for the second echo and so on.

16.8.1.4. Focal Point of the Dome beneath the Floor

If instead the focal point is made 17m below the floor, which is the situation in Jameson Hall, then the sound will not be reflected back to the source point unless reflected from the very top point of the dome.

Cremer¹⁰² explains that in the case of a sphere the sound would approximately concentrate in a large area at the geometrically opposite side of the extended sphere. In the case of the Jameson Hall dome, which is only a small section of a sphere, the focusing will not be as visible. The dome will actually reflect most rays directly downwards.

This is shown in Figure 96, which was simulated by the RoWena program.

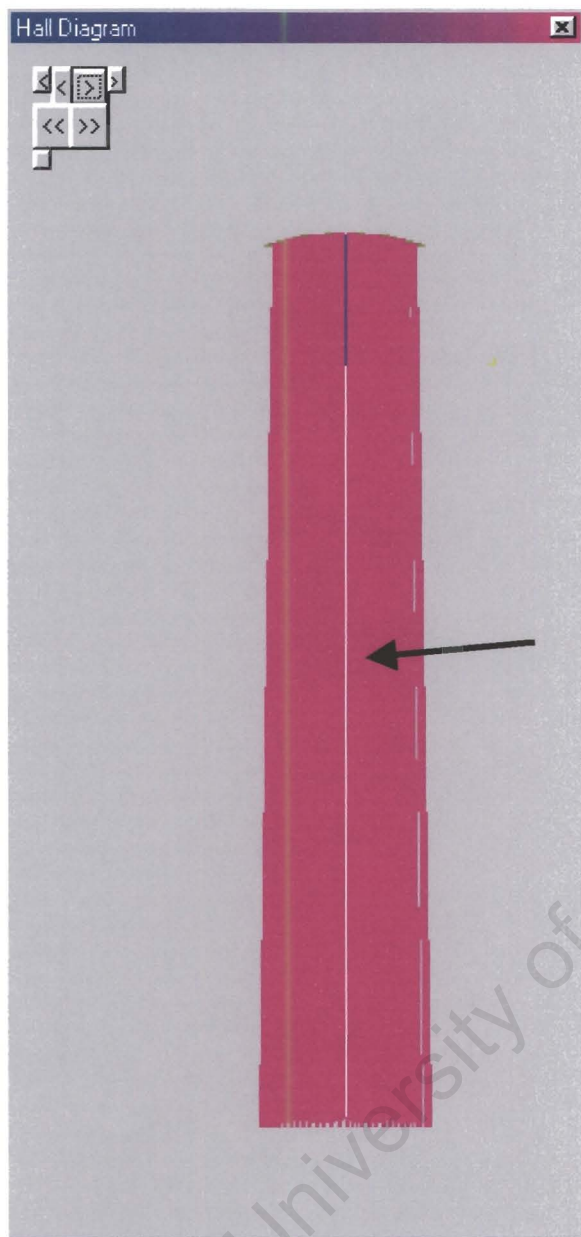


Figure 96: Multiple Ray Paths from a dome (from RoWena)

The many pink lines are the ray paths that have reflected from the dome. One particular ray path is shown in white, as indicated by the arrow. The ray has traveled upwards from the source point, reflected from the dome, and then traveled downwards.

If a floor is included, 17m below the top point of the dome, then sound rays will be reflected by the floor and travel back to the dome, and then to the receiver. Thus every 180ms (path length= $4 \times 15.46\text{m}$) after the direct sound a reflection will be detected, as opposed to every 90ms as before.

However there will still be reflections arriving every 90ms because the top of the dome will reflect sound straight down to the source. These reflections will be weaker than those every 180ms because a smaller area of the dome produces these reflections. Also the path length of the 180ms periodic reflections is actually longer than 180ms, so on the simulation graph the two type of echoes will appear further and further apart.

The simulated graph of this room setup (not shown) is superficially identical to that shown in Figure 94. However closer inspection of a particular reflection, as shown in Figure 97, reveals two distinct groups of reflections. The first group represents ray paths traveling directly up to the dome's top point and down again. The second group, for which a typical ray path is shown in the inset 'hall diagram', represents reflections of the type discussed above. Inspection of the graph shows that such a situation with two groups of reflections occurs as expected every 180ms, but not at other times.

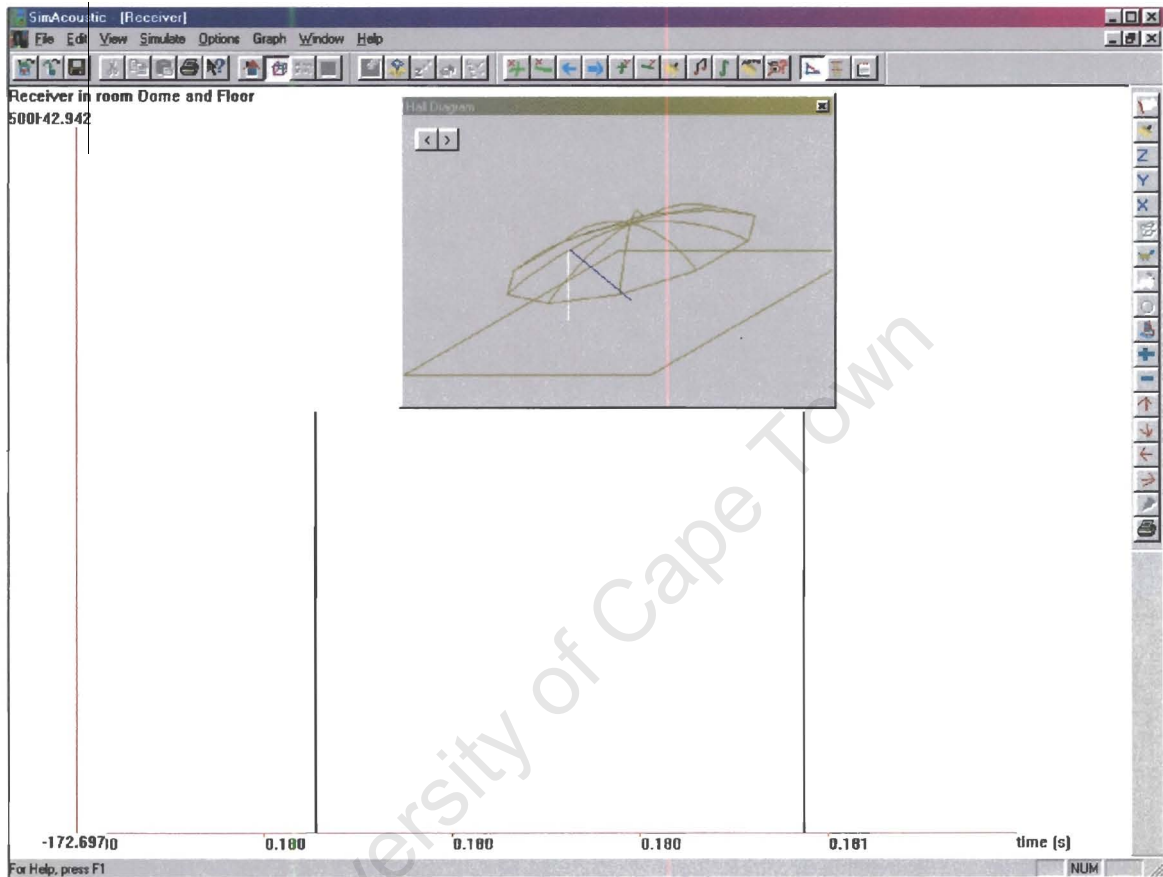


Figure 97: Delayed reflection arrival of reflections from the top of the dome and from the side

The ray path in the inset Hall diagram figure shows a ray path that has reflected nearly vertically until the floor, then returned along a similar path and back to the receiver.

16.8.1.5. Simulation of Echoes from the Dome

To inspect the effect of the dome in producing echoes when the source and receiver are directly beneath the dome, a simulation with the complete model of the Jamison Hall, with the source and receiver point as described, was performed. The simulated impulse response graph is shown in Figure 98.

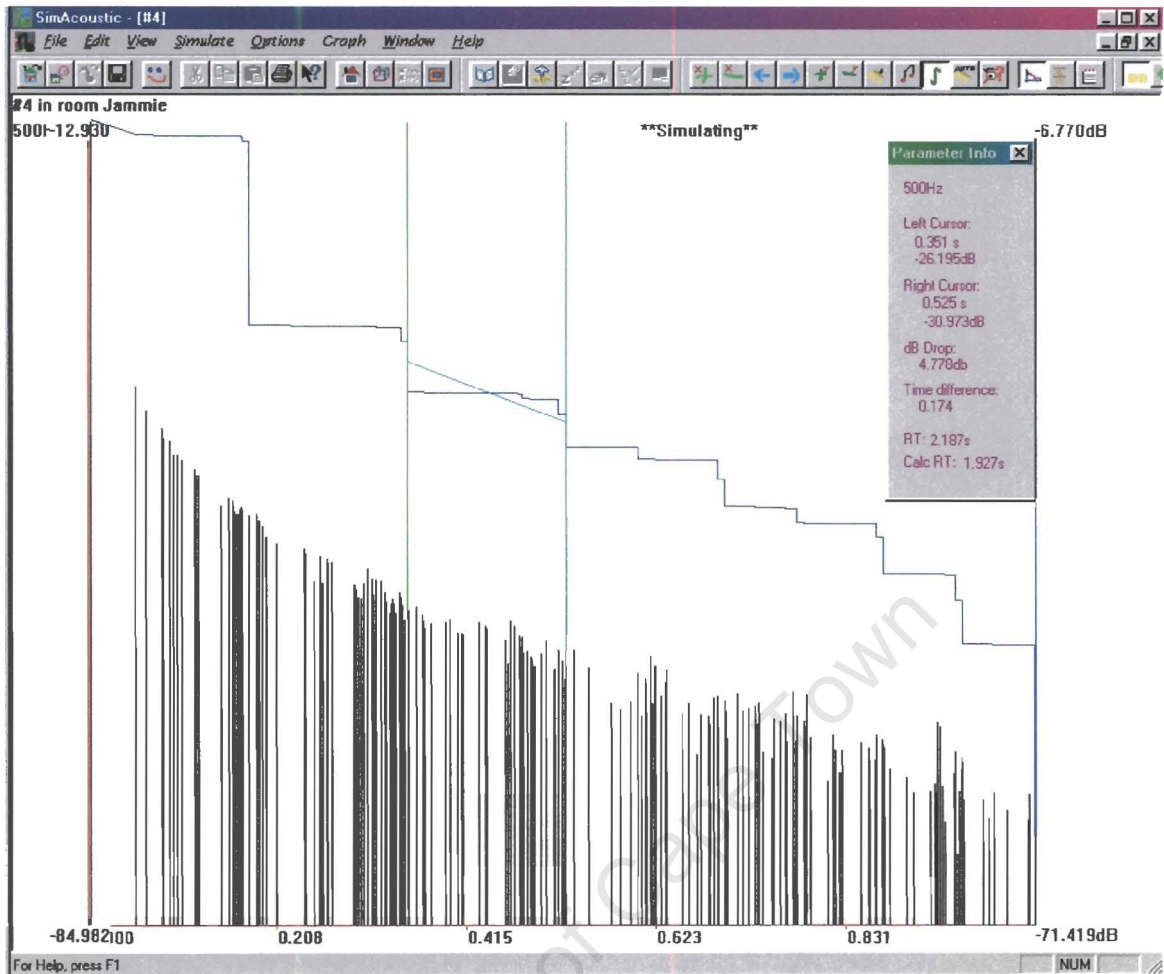


Figure 98: Identification of simulated echoes in the Jameson Hall

Prominent echoes are not visible in the simulated impulse response curve. This is because constructive interference, caused by the similar path lengths of the sound, which is not accounted for in the simulation program (see 7.4.3). However the blue backwards integration curve (see Appendix E), also shown in the figure, shows discrete steps at intervals of 174ms. (The interval may be confirmed by inspecting the small inset box where the time difference between the two vertical markers is shown as 'Time difference: 0.174s'.) The steps in the integration curve are due to a large concentration of reflections at these points. Thus the simulation does show the effects of focusing expected by the dome.

Note that after 620ms the shorter path length of the echoes, and consequently the increased intensity, is evident as the echoes become slightly prominent above the other weaker echoes.

16.8.1.5.1. Measurements with Speaker and Microphone Beneath the Dome

To verify what the theory and simulation results have shown, some measurements with both the speaker and microphone under the dome were taken. Figure 99 shows the measured impulse response graph up to 1 second.

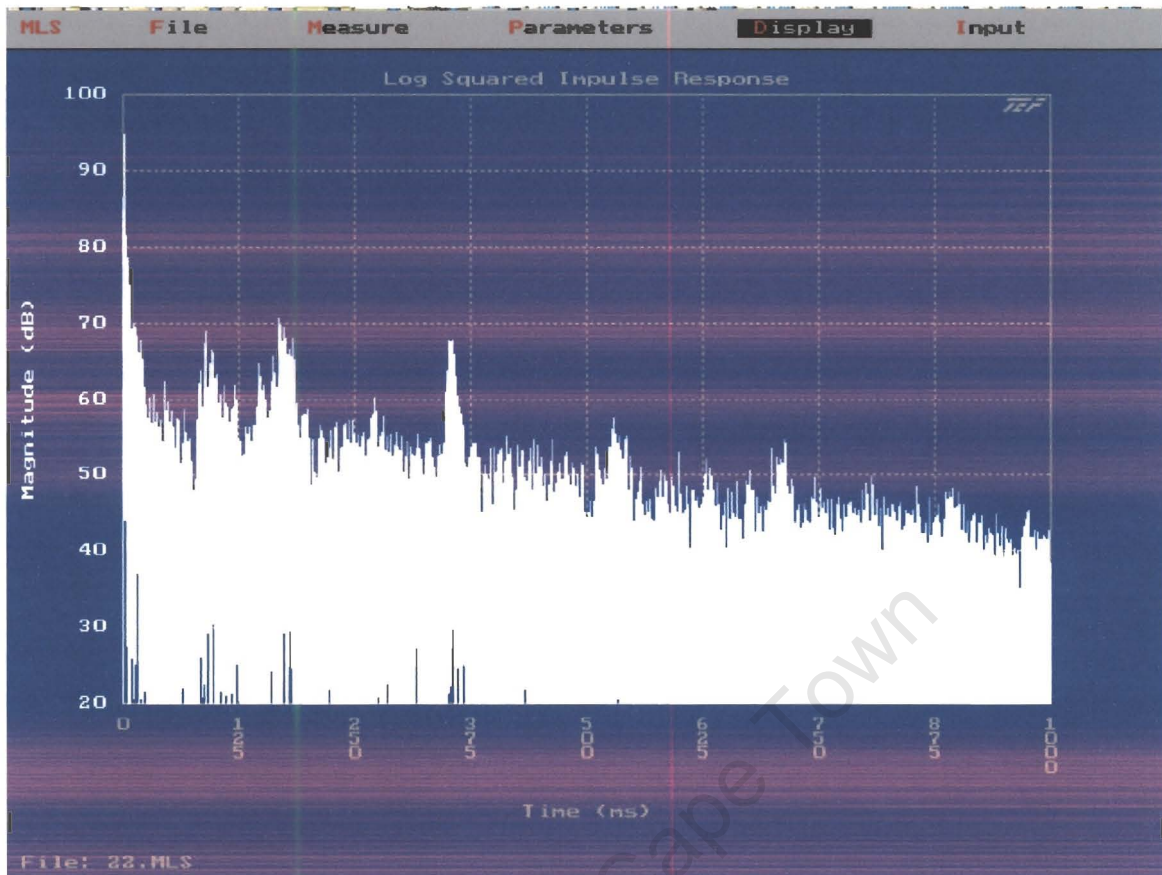


Figure 99: Identification of measured echoes in the Jameson Hall

Periodic groups of reflections are clearly visible. It is possible to identify periodic groups of reflections. The relative time and strength of the strongest reflection of each echo group is tabulated in Table 8.

	<i>Time (ms)</i>	<i>Distance (m)</i>	<i>Strength (dB)</i>	<i>Spacing (ms)</i>
1	89.188	30.716	-25.7	NA
2	167.917	57.831	-24	78.729
3	269.583	92.844	-34.5	101.666
4	353.063	121.595	-27.2	83.48
5	528.938	182.166	-37.1	175.875
6	711.0	244.868	-39.9	182.1

Table 8: Time of arrival of measured echoes in the Jameson Hall

The time delay of the first echo is 89ms, which is very close to the predicted 90ms for echoes coming directly from the top of the dome.

The second groups of strong reflections arrive between 164ms and 200ms, which includes the 180ms expected repeat echo time. This reflection group is stronger than the first, confirming the assumption of strong reflections every 180ms.

The remaining echoes appear every 180ms. Weaker reflections can be discerned with a 90ms period, again as predicted. The measurements therefore confirm what was expected.

17. CONCLUSIONS

Having presented a large part of the field of room acoustical analysis and prediction there are a number of conclusions that can be made.

17.1. Conclusions Regarding Physical Room Acoustics

(Text as in 5.8)

Relationships can be found between objective (measurable) and subjective (perceived) qualities of sounds as heard in rooms. The relationships are well documented although research is continuously being done to improve the understanding of these relationships.

The Jameson Hall, the acoustics of which were measured, has an exceptionally high reverberation time and similarly low clarity when empty. Also, possibly due to the curved surfaces in the hall, the sound field is not diffuse. This means that different parts of the hall experience a different sound quality because of the nature in which the hall reflects the sound.

In some parts of the hall, particularly near the front of the stage when the sound source is at the *right* of the stage, have a significantly higher clarity and speech intelligibility. Also the smaller area underneath the balcony causes this space to have noticeably different acoustics.

17.2. Conclusions Regarding Computer Simulation Models of Room Acoustics

The limitation of geometrical acoustics, on which the principle of ray tracing is based, is not too restrictive, in spite of it being a physically incorrect model. This is especially true if the techniques of mirror imaging, secondary source and scattering are included in the model.

However simulation programs to date have not addressed the issue of curved surfaces adequately. This thesis has approached some of the issues involved with curved surfaces and solved some of them. However the theoretical nature of reflections from curved surfaces, and especially how they influence the diffuse nature of the sound field in the room, have not been researched. Such research might also aid the acoustician in understanding the nature of sound and simulations for completely planar halls.

17.3. Conclusions Regarding RoWena and the simulation of the Jameson Hall

RoWena is a new program, having been written specifically for this thesis. Although its usefulness in many areas of room acoustics prediction has been demonstrated unfortunately it appears that the accuracy of the program in predicting general room acoustic qualities is not good yet. Although it is based on the simulation principles of programs that provide accurate room acoustic measurements (such as ODEON and CATT-Acoustic), RoWena cannot be regarded as a reliable prediction tool yet. The reasons for this may be an inaccuracy in calculating the energy of individual reflections as they are detected, which may be a bug in the program or a vital oversight.

As regards the simulation of the Jameson Hall, the fact that the sound field is very complex due to the curved surfaces prevalent in the hall, brings the basis of the simulation models into doubt. However the ability of RoWena to correctly predict the reflective nature of these curved surfaces was shown and therefore it seems possible that even the Jameson Hall may be amenable to prediction in the near future.

18. RECOMMENDATIONS

The focus of this thesis was on the simulation techniques that are in use at this time. That RoWena was not able to produce accurate room acoustic measurements is therefore due to errors in the program, especially as regards its energy calculations. These errors need to be addressed.

More research is needed into the nature of curved surfaces, especially as regards their effect on diffuse sound fields. If need be a more accurate simulation model needs to be devised which can cope better with non-diffuse sound fields. Also the focusing or spreading of individual rays upon hitting a curved surfaces should be examined and implemented if necessary into the simulation model.

Scattering, which was introduced but not simulated because of the poor initial results, needs more research, especially into the exact nature of scattering and how it can be simulated accurately. This may be especially useful in the early time where the assumption of specular reflections is unfounded.

The possibility of simulating large complex surfaces by combining them into a single surface with many reflecting properties (see 15.6.6) is an interesting possibility and should be investigated.

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APPENDIX A: Ray Tracing Algorithm

Elements of a Single Ray

A ray is essentially a series of line segments, joined head to tail. The first line segment starts at the source point of the sound wave, and ends at the first surface reflected from. The next line segment then starts at the reflection point, and ends at the next surface reflected from, and so on. Each line segment that forms part of a ray thus consists of a starting point, which is initially the sound source point, and a direction. The ray as a whole also contains an intensity, which is decreased following each reflection with a surface.

The term 'ray' refers to both the ray as a whole, which is a combination of all the line parts of the ray, and also to the last line segment of the ray. Thus if the ray is described as hitting a surface, this means that the last line segment will intercept the surface.

At any point along its path the ray may intercept a measurement point. In such a case the simulated impulse response graph for that measurement point is registered as having received a reflection.

A Single Line Segment Formula

Each ray consists of a number of line segments, each of which is modelled by the simple formula for a line: $P=S+tD$; where S is the starting point for the line segment, t is the length of the line segment, and D is the normalised direction of the line segment.

At the beginning of a ray simulation, only the starting point and the direction of the line segment are known. It is the task of the simulation program to determine which surface the line segment will intercept and subsequently to calculate the distance of the line segment.

Intensity of a Ray

Each ray has a certain intensity. Exactly what this intensity represents depends on the specific simulation model. In the simple case it is the same as the source intensity, however that is defined by the model. When the ray is intercepted by a measurement point and added to the respective impulse response graph the intensity is corrected.

The intensity W/m^2 of the ray is diminished by the reflection coefficient of any surfaces it reflects off, where the reflection coefficient of a surface is simply $1-\alpha$, where α is the absorption coefficient of the surface. Thus if the intensity of the ray is initially $10W/m^2$ and it reflects off a surface with $\alpha=0.4$, then the ray intensity following the reflection will be $4W/m^2$.

The intensity of the ray may be converted to a decibal figure using any reference value. If a reference value equal to the starting intensity of the ray is used, then the simulated impulse response graph will have a maximum value at 0dB, which would be a ray which has undergone no reflections and no spreading.

Simulation of a Single Ray

Each of the many rays making up a simulated sound wave are simulated one by one to completion. They are placed in the simulated impulse response curve each time they pass the measurement position, according to their time of travel from the source point. Thus the impulse response curve is not created sequentially from 0s to the maximum simulated time of the simulation, but rather over its whole length.

The steps involved in simulating a single ray are:

- Generating a new ray.
- Determining if the ray will pass a measurement/receiver position
- Determining which surface the ray will hit next
- Reflecting the ray off the surface.

These steps are discussed fully below.

Ray Generation

In order to provide a fully omni-directional source, the rays to simulate are evenly spread around the source point. Thus each new ray is positioned so that the total rays will cover an imaginary sphere around the source.

Ray/Receiver Collision Detection

Although the receivers are defined in the model as existing at a specific point, the receivers are actually modelled as spheres in order that the chances of a ray intercepting a receiver are increased. This is necessary because the finite number of rays simulated means that there will always be gaps in the simulated sound field where receivers could be missed.

To determine interception with a receiver, a new point is found by multiplying the line segment direction (D) with the distance from the receiver point to the line segment starting point (S). If the magnitude of the distance between this point and the receiver source is less than the size of the receiver sphere, the ray is considered to have collided with the receiver. This is demonstrated in Figure 1.

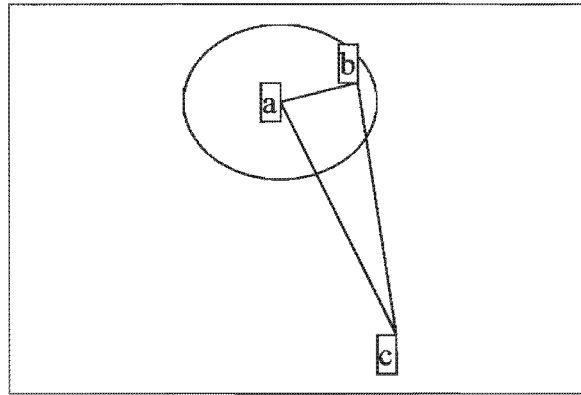


Figure 1: Receiver/Ray collision detection mechanism

In Figure 1, 'c' is the source point of the ray, 'a' is the center of the receiver sphere, and 'b' is the new point. Line a,c is the same length as line b,c. If line a,b is less than the radius of the sphere, the ray is determined to have collided with the receiver.

This method does not provide accurate distances to the perimeter of the receiver sphere. However it does give the closest passing distance of the ray to the exact measurement position.

The simulation allows the use of multiple receivers and they are all checked sequentially in this manner.

If a receiver is intercepted, a reflection is drawn in the impulse response graph for that receiver. The reflection has an arrival time value equal to the distance of the total ray path divided by the speed of sound. The intensity of the reflection is equal to the intensity of the ray with spherical spreading taken into account.

Ray/Surface Collision Detection

A means must be made to determine which surface each ray will meet next on its path, and where on the surface it will hit. Because the simulation program has no intuitive means of knowing which surface will be hit, each surface in the hall model must be examined. Consequently this is the slowest part of the simulation.

There are two parts to this procedure: finding the distance to all the surfaces, and then checking them for validity.

FINDING THE DISTANCE TO EACH SURFACE

The distance to each surface is determined as extensively described by Vörländer¹. The formula assumes that each surface is a continuous plane stretching to infinity in every direction. Therefore it is possible that the distance as found here may actually refer to a part of the surface that does not exist.

This calculation provides an initial indication of surfaces which cannot be hit by the ray, being parallel to the ray, or in the opposite direction to the ray. In these cases, the calculation terminates immediately and the surface is marked as invalid. This speeds up the process slightly.

CHECKING THE SURFACES FOR VALIDITY

At this stage a distance has been found to each surface. However, some surfaces may be hidden by others, or the ray may hit the surface outside the surface's boundaries. Therefore a thorough validity check must be made to ensure that the surface will be intercepted by the ray.

The surfaces are checked in order of shortest distance, to ensure the surface to be checked is not obscured by another, until a valid surface is found. The procedure is then ended.

The checking is done as follows: First the collision point of the ray with the surface is calculated, based on the distance to the surface as obtained earlier. This is a relatively quick calculation.

This collision point (called the puncture point) must now be checked to ascertain whether it lies within the boundaries of the surface (up until now the surface was considered to be a continuous infinite plane). The method used entails creating an imaginary line and extending it from the puncture point to infinity in any direction (in this case the x-axis). The number of crossings with the edges of the surface are counted, and if odd, indicate that the point lies inside the surface. This technique is shown in Figure 2.

¹ M Vörländer, 'Simulation of the Transient and steady-state sound propagation in rooms using a new combined ray-tracing/image-source algorithm', *Journal of the Acoustical Society of America*, **86** No.1 (1989), p172-178

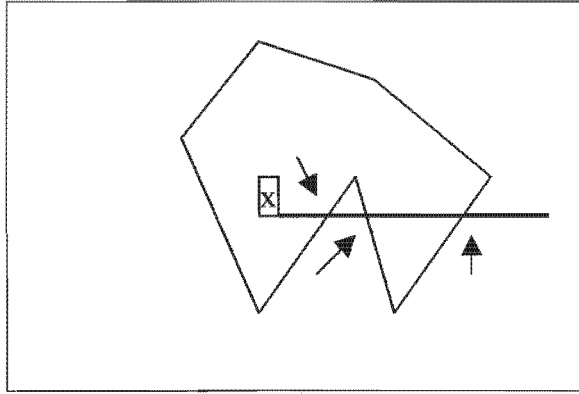


Figure 2: Number of crossings of a line with the edges of a surface

The 'x' indicates the puncture point. The arrows show the crossing points of the ray with the edges of the surface. In this case there are three crossings and this confirms that the point is within the surface boundaries.

The method is common in computer graphics and the algorithm was obtained specifically from *Computational Geometry in C*.² This method has been found to be 20 times faster than the more commonly used method of finding the cross product of the normals at the vertices of the surface³, as prescribed by Vörländer⁴ and used in most simulation programs to date.

It is possible to follow the same procedure in the three dimensions necessary for the simulation, but in an effort to reduce computation time, the calculation is reduced to three dimensions. This is done by discarding the dimension in which the surface changes the least, i.e. examining only the two axis planes (X,Y or Z) which are most parallel to the surface⁵. The choice of which axis to discard is made when the surfaces were created, so no extra computation is necessary. This does not entail any loss of information, since all that is affected is a small change in orientation.

² O'Rourke, J. *Computational Geometry in C*., 1994, p235

³ O'Rourke, J. *Computational Geometry in C*., 1994, p237

⁴ M Vorländer, 'Simulation of the Transient and steady-state sound propagation in rooms using a new combined ray-tracing/image-source algorithm', (1989), p172-178

⁵ G Naylor, 'ODEON-Another Hybrid Room Acoustical Model', *Applied Acoustics*, 38(1993), p131-143

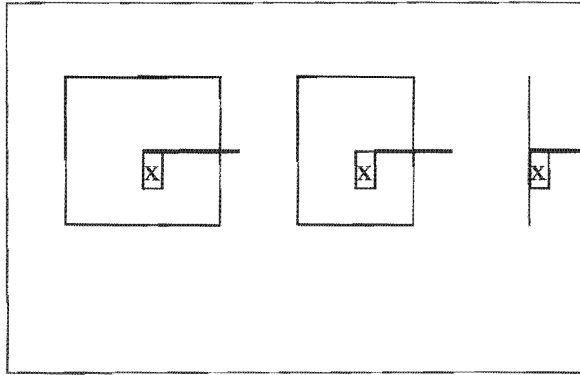


Figure 3: Validity of the 2-D approximation of a 3-D surface

Figure 3 shows a 3D surface initially viewed square on. In this case it is clear that the point is within the surface. The following diagram shows the surface rotated, by bringing the right-hand side closer. The point is still within the surface. Only when the surface is completely perpendicular to the viewing angle does the calculation fail, and at this point, another axis would have been discarded and therefore a different viewing angle/direction of the infinite crossing line would be chosen.

Determining the Reflection Direction of the Ray

At this stage the surface to reflect off, the distance to the surface, and the point of reflection, are known. The direction of reflection is determined by projecting the source point of the ray through the puncture point, perpendicular to the normal of the surface.

The new direction is then the normalized vector of the puncture point minus the projected (image) point. The new source point (which is the puncture point of the surface), and direction are now used to continue the ray model.

Calculating the Strength of the Ray

Each surface has a reflection coefficient for each octave frequency from 125Hz to 8kHz. The ray similarly has an intensity parameter for each octave frequency, which is initially 1. At each collision the octave strength of the ray is multiplied by the reflection coefficient of the surface to find the new strength of the ray. This strength figure is analogous to a dB value, and needs only to be converted to dB by:

$$10 \log \left(\frac{\text{Ray_Strength_at_Octave}}{1} \right)$$

Determining the Termination of a Ray

At each reflection of the ray, the ray is checked to see whether it should be terminated or continued. The terms of termination made in this simulation are the strength of the ray and the length of the ray.

TERMINATION DEPENDANT ON THE STRENGTH OF THE RAY

The strength of the ray in each octave band is compared to a user-selected strength threshold. If any octave strength is greater than the threshold the ray is continued, otherwise it is ended.

TERMINATION DEPENDANT ON THE LENGTH OF THE RAY

In order to provide a maximum length to the simulated impulse response graph, a maximum time length can be set, after which the ray is terminated.

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Appendix B: Mirror Imaging Algorithm

The principle parts of the mirror imaging process are to find the image point for a particular room and source point. Then to transform the room into its image coordinates. These two steps are repeated as many times as desired. Once a ray path from mirrored source to original receiver has been determined, it is backwards transformed to obtain the original ray path.

TO FIND THE MIRROR IMAGE SOURCE POINT

In the Lee&Lee algorithm⁶, which is described here, all the points are found in one step without recursion. A transformation matrix, which represents a mirror transformation, is found (before simulation) for each surface, i.e. any vector multiplied by this transformation matrix will produce a vector mirrored through that surface.

These matrices can be multiplied together to produce a matrix which represents successive reflections through a sequence of surfaces, eg if [Ts] is the transformation matrix for the South surface, and similarly [Tn] and [Te], then the transformation matrix for the final source point in the third mirror room is represented by $[Ts][Te][Tn]=[Tn,e,s]$.

Thus the mirror source point reflected through this sequence of surfaces can be found by $S^*T[n,e,s]=S'''$.

FIND EACH PUNCTURE/REFLECTION POINT.

Each intersection of the line joining the mirrored source point (S''') and the original receiver point (R) represents a reflection point in the ray path, albeit in mirror coordinates. To obtain the reflection points in the original coordinates, it is necessary to undo the coordinate transformation, using the surface transformation matrices again. (the transformation matrix is equal to its inverse so undoing is equivalent to doing).

Thus point 1, corresponding to the reflection/puncture point just before the receiver (i.e. in the North surface in the original room) can be found by simply equating the North surface equation with the S'''->R line.

Then both S''' and R are transformed through the transformation matrix of surface North and the new ray is equated with East to obtain the next reflection point.

The both are transformed again through the transformation matrix of surface East and the new ray is equated with South to obtain the last reflection point.

⁶ H Lee & B Lee, 'An Efficient Algorithm for the Image Model Technique', *Applied Acoustics*, 24(1988), p87-115

Appendix C: Validity of the Ray Tracing Method

Ray Tracing was derived partly on the basis of a diffuse sound field. Similarly the Sabine reverberation formula also requires a diffuse sound field. In this section the two methods will be shown to be equivalent. The explanation is mathematical, but not difficult, and is perhaps worth following since it explains how the energy in the rays is calculated, although it can be skipped without loss of continuity. Most of the derivation that follows comes from Kuttruff⁷, albeit arranged differently.

A Single Ray's Energy

Let a single ray have an initial energy of E_r . At each reflection the energy falls by $(1-\alpha)$, where α is the absorbant coefficient of the surface material, assuming all reflecting surfaces have the same material. If this is not the case then let α be the average absorption coefficient of all the surfaces in the hall.

If the rays undergoes k reflections, then the energy of the ray will be $E_r(1-\alpha)^k$. If n is the number of reflections undergone by the ray each second, then this formula become $E_r(1-\alpha)^{nt}$.

Introducing air absorption (e^{-mct}) gives

$$E_r(e^{-mct} + (1-\alpha)^{nt})$$
$$\Rightarrow E_r e^{(-mct + nt \ln(1-\alpha))}$$

Average Number of Reflections per Second

n is more usefully replaced by the *average* number of reflections per second of any ray. To obtain this result an arbitrary rectangular room with dimensions L_x , L_y and L_z is considered.

In Figure 4 this room is shown with solid lines. If the walls are assumed to be mirrors then the room would be seen reflected through each wall, as shown by the dotted rooms. In such a diagram a ray may be drawn as a straight line through the reflected rooms rather than changing its direction at each reflection.

If the room is reflected a number of times through all its bounding surfaces, as in Figure 4, then it is clear that a particular ray angled at θ_x to the x-axis undergoes n_x crossings with surfaces perpendicular to the x-axis, where

$$n_x(\theta_x) = \left| \frac{c}{L_x} \cos \theta_x \right|$$

⁷ H. Kuttruff, *Room Acoustics 3rd Ed.*, England: Elsevier Applied Science, 1991, p92-94

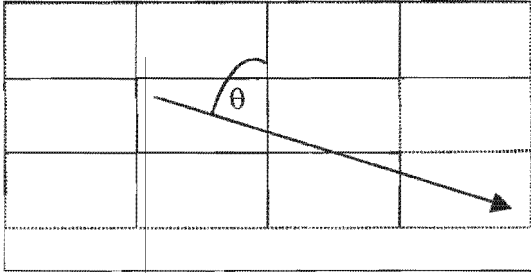


Figure 4

$|\cos\theta_x|$ averaged over all possible directions, where the x-axis is polar, yields

$$\frac{1}{4\pi} \times 2\pi \times 2 \int_0^{2\pi} \cos\theta_x \sin\theta_x d\theta_x = \frac{1}{2}$$

and therefore the average of n_x over all directions is $c/2L_x$.

Other axes follow similarly and the average total number of wall reflections per second is $\bar{n} = \frac{cS}{4V}$, where S is the total area of all walls in the original room. This result relies on the average of all possible directions on the wall surfaces, which is thus either an average for many rays propagating in all directions, or a single ray encountering many scattering surfaces. In other words it requires that the sound field be diffuse.

Although this result was derived specifically for a rectangular room, it applies equally to arbitrary shaped rooms.

Substituting \bar{n} into the previous ray formula gives

$$E(t) = E_r e^{\left(-mct + \frac{cS}{4V} \ln(1-\alpha)t\right)}$$

$$\Rightarrow E_r e^{\left(-ct \frac{4mV - S \ln(1-\alpha)}{4V}\right)}$$

Equivalence to Eyring Reverberation Time Formula

The Eyring reverberation time is the time for the average energy in the hall to drop to one millionth of the original energy. This occurs when the second term in the formula above equals 10^{-6} . Thus:

$$10^{-6} = e^{\left(-ct \frac{4mV - S \ln(1-\alpha)}{4V}\right)}$$

$$\Rightarrow -6 \ln 10 = -ct \frac{4mV - S \ln(1-\alpha)}{4V}$$

$$\Rightarrow t = \frac{1}{c} \cdot \frac{24V \ln 10}{4mV - S \ln(1-\alpha)}$$

$$T = 0.16 \frac{V}{4mV - S \ln(1 - \alpha)}, \text{ which is Eyring's reverberation formula}$$

This shows that the geometrical model produces the same result as the Eyring reverberation formula, provided the sound field in the late time is diffuse.

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Appendix D: Jameson Hall Model

The model of the Jameson Hall, as determined by Leroy Kahn for his undergraduate thesis (see bibliography) was used in the simulation for this thesis. This appendix contains a printout, produced by RoWena, of the room model coordinates for each surface.

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Coordinates of room: Jammie (Page 1)
 Name: Alcove lf (front)
 Coordinates: Surface Type: Planar□
 Edge#0:from 6.050 , 12.700 , 0.000 to 6.050 , 25.100 , 0.000□
 Edge#1:from 6.050 , 25.100 , 0.000 to 6.050 , 25.100 , 0.800□
 Edge#2:from 6.050 , 25.100 , 0.800 to 6.050 , 12.700 , 0.800□
 Edge#3:from 6.050 , 12.700 , 0.800 to 6.050 , 12.700 , 0.000□

Mat : Jammie Walls*
 Area: 9.920

Name: Alcove lf seats (top back)
 Coordinates: Surface Type: Planar□
 Edge#0:from 5.250 , 12.700 , 0.800 to 2.850 , 14.100 , 1.400□
 Edge#1:from 2.850 , 14.100 , 1.400 to 2.850 , 23.700 , 1.400□
 Edge#2:from 2.850 , 23.700 , 1.400 to 5.250 , 25.100 , 0.800□
 Edge#3:from 5.250 , 25.100 , 0.800 to 5.250 , 12.700 , 0.800□

Mat : Jammie Chairs
 Area: 27.212

Name: Alcove lf seats (top front)
 Coordinates: Surface Type: Planar□
 Edge#0:from 6.050 , 12.700 , 0.800 to 5.250 , 12.700 , 0.800□
 Edge#1:from 5.250 , 12.700 , 0.800 to 5.250 , 25.100 , 0.800□
 Edge#2:from 5.250 , 25.100 , 0.800 to 6.050 , 25.100 , 0.800□
 Edge#3:from 6.050 , 25.100 , 0.800 to 6.050 , 12.700 , 0.800□

Mat : Jammie Chairs
 Area: 9.920

Name: Alcove rt (front)
 Coordinates: Surface Type: Planar□
 Edge#0:from 28.050 , 25.100 , 0.800 to 28.050 , 12.700 , 0.800□
 Edge#1:from 28.050 , 12.700 , 0.800 to 28.050 , 12.700 , 0.000□
 Edge#2:from 28.050 , 12.700 , 0.000 to 28.050 , 25.100 , 0.000□
 Edge#3:from 28.050 , 25.100 , 0.000 to 28.050 , 25.100 , 0.800□

Mat : Jammie Walls*
 Area: 9.920

Name: Alcove rt (top back)
 Coordinates: Surface Type: Planar□
 Edge#0:from 28.850 , 25.100 , 0.800 to 31.250 , 23.700 , 1.400□
 Edge#1:from 31.250 , 23.700 , 1.400 to 31.250 , 14.100 , 1.400□
 Edge#2:from 31.250 , 14.100 , 1.400 to 28.850 , 12.700 , 0.800□
 Edge#3:from 28.850 , 12.700 , 0.800 to 28.850 , 25.100 , 0.800□

Mat : Jammie Chairs
 Area: 27.212

Name: Alcove rt (top front)
 Coordinates: Surface Type: Planar□
 Edge#0:from 28.050 , 25.100 , 0.800 to 28.850 , 25.100 , 0.800□
 Edge#1:from 28.850 , 25.100 , 0.800 to 28.850 , 12.700 , 0.800□
 Edge#2:from 28.850 , 12.700 , 0.800 to 28.050 , 12.700 , 0.800□
 Edge#3:from 28.050 , 12.700 , 0.800 to 28.050 , 25.100 , 0.800□

Mat : Jammie Chairs
 Area: 9.920

Coordinates of room: Jammie (Page 2)
 Name: Alcove rt (top front)
 Coordinates: Surface Type: Planar□
 Edge#0:from 28.050 , 25.100 , 0.800 to 28.850 , 25.100 , 0.800□
 Edge#1:from 28.850 , 25.100 , 0.800 to 28.850 , 12.700 , 0.800□
 Edge#2:from 28.850 , 12.700 , 0.800 to 28.050 , 12.700 , 0.800□
 Edge#3:from 28.050 , 12.700 , 0.800 to 28.050 , 25.100 , 0.800□

Mat : Jammie Chairs
 Area: 9.920

Name: Balc Rear wall
 Coordinates: Surface Type: Arch Face□
 Centre Point=17.050 , 3.000 , 4.600□
 InnerRadius=0.000□
 OuterRadius=9.000□
 Normal=0.000 , 1.000 , 0.000□

Mat : Jammie Walls*
 Area: 127.235

Name: Balcony arch
 Coordinates: Surface Type: Arch□
 CentrePoint 1=17.050 , 9.800 , 4.600□
 CentrePoint 2=17.050 , 3.000 , 4.600□
 Radius=9.000□
 Normal=0.000 , 1.000 , 0.000□

Mat : Jammie Ceiling*
 Area: 192.265

Name: Corner Front Left
 Coordinates: Surface Type: Curved Corner□
 XY: Centre=17.050 , 18.900 , 13.600 Radius=9.000□
 XZ: Centre=17.050 , 9.800 , 4.600 Radius=9.000□
 YZ: Centre=26.050 , 18.900 , 4.600 Radius=9.000□

Mat : Jammie Ceiling*
 Area: 63.617

Name: Corner Front Rt
 Coordinates: Surface Type: Curved Corner□
 XY: Centre=17.050 , 18.900 , 13.600 Radius=9.000□
 XZ: Centre=17.050 , 9.800 , 4.600 Radius=9.000□
 YZ: Centre=8.050 , 18.900 , 4.600 Radius=9.000□

Mat : Jammie Ceiling*
 Area: 63.617

Name: Corner back rt
 Coordinates: Surface Type: Curved Corner□
 XY: Centre=17.050 , 18.900 , 13.600 Radius=9.000□
 XZ: Centre=17.050 , 27.900 , 4.600 Radius=9.000□
 YZ: Centre=8.050 , 18.900 , 4.600 Radius=9.000□

Mat : Jammie Ceiling*
 Area: 63.617

Coordinates of room: Jammie (Page 3)
 Name: Corner bk left
 Coordinates: Surface Type: Curved Corner□
 XY: Centre=17.050 , 18.900 , 13.600 Radius=9.000□
 XZ: Centre=17.050 , 27.900 , 4.600 Radius=9.000□
 YZ: Centre=26.050 , 18.900 , 4.600 Radius=9.000□

Mat : Jammie Ceiling*
 Area: 63.617

Name: Ent Rt Inst1 (face lf)
 Coordinates: Surface Type: Planar□
 Edge#0:from 28.350 , 9.800 , 0.000 to 28.050 , 12.700 , 0.000□
 Edge#1:from 28.350 , 12.700 , 0.000 to 28.050 , 12.700 , 4.600□
 Edge#2:from 28.050 , 12.700 , 4.600 to 28.050 , 9.800 , 4.600□
 Edge#3:from 28.050 , 9.800 , 4.600 to 28.050 , 9.800 , 0.000□

Mat : Jammie Walls*
 Area: 13.340

Name: Ent Rt Inst1 (face stg)
 Coordinates: Surface Type: Planar□
 Edge#0:from 26.050 , 9.800 , 0.000 to 28.050 , 9.800 , 0.000□
 Edge#1:from 28.050 , 9.800 , 0.000 to 28.050 , 9.800 , 4.600□
 Edge#2:from 28.050 , 9.800 , 4.600 to 26.050 , 9.800 , 4.600□
 Edge#3:from 26.050 , 9.800 , 4.600 to 26.050 , 9.800 , 0.000□

Mat : Jammie Walls*
 Area: 9.200

Name: Ent Rt Inst2 (face stg)
 Coordinates: Surface Type: Planar□
 Edge#0:from 28.050 , 12.700 , 0.000 to 28.850 , 12.700 , 0.000□
 Edge#1:from 28.850 , 12.700 , 0.000 to 28.850 , 12.700 , 4.600□
 Edge#2:from 28.850 , 12.700 , 4.600 to 28.050 , 12.700 , 4.600□
 Edge#3:from 28.050 , 12.700 , 4.600 to 28.050 , 12.700 , 0.000□

Mat : Jammie Walls*
 Area: 3.550

Name: Ent Rt Wall
 Coordinates: Surface Type: Planar□
 Edge#0:from 26.050 , 3.000 , 0.000 to 26.050 , 9.800 , 0.000□
 Edge#1:from 26.050 , 9.800 , 0.000 to 26.050 , 9.800 , 4.600□
 Edge#2:from 26.050 , 9.800 , 4.600 to 26.050 , 3.000 , 4.600□
 Edge#3:from 26.050 , 3.000 , 4.600 to 26.050 , 3.000 , 0.000□

Mat : Jammie Walls*
 Area: 31.280

Name: Ent Wall
 Coordinates: Surface Type: Planar□
 Edge#0:from 8.050 , 3.000 , 0.000 to 26.050 , 3.000 , 0.000□
 Edge#1:from 26.050 , 3.000 , 0.000 to 26.050 , 3.000 , 4.600□
 Edge#2:from 26.050 , 3.000 , 4.600 to 8.050 , 3.000 , 4.600□
 Edge#3:from 8.050 , 3.000 , 4.600 to 8.050 , 3.000 , 0.000□

Mat : Jammie Walls*
 Area: 82.800

Coordinates of room: Jammie (Page 4)
 Name: Ent Wall
 Coordinates: Surface Type: Planar□
 Edge#0:from 8.050 , 3.000 , 0.000 to 26.050 , 3.000 , 0.000□
 Edge#1:from 26.050 , 3.000 , 0.000 to 26.050 , 3.000 , 4.600□
 Edge#2:from 26.050 , 3.000 , 4.600 to 8.050 , 3.000 , 4.600□
 Edge#3:from 8.050 , 3.000 , 4.600 to 8.050 , 3.000 , 0.000□

Mat : Jammie Walls*
 Area: 82.800

Name: Ent lf inst1 (face rt)
 Coordinates: Surface Type: Planar□
 Edge#0:from 6.050 , 12.700 , 0.000 to 6.050 , 9.800 , 0.000□
 Edge#1:from 6.050 , 9.800 , 0.000 to 6.050 , 9.800 , 4.600□
 Edge#2:from 6.050 , 9.800 , 4.600 to 6.050 , 12.700 , 4.600□
 Edge#3:from 6.050 , 12.700 , 4.600 to 6.050 , 12.700 , 0.000□

Mat : Jammie Walls*
 Area: 13.340

Name: Ent lf inst1 (face stg)
 Coordinates: Surface Type: Planar□
 Edge#0:from 6.050 , 9.800 , 0.000 to 6.050 , 9.800 , 0.000□
 Edge#1:from 6.050 , 9.800 , 0.000 to 6.050 , 9.800 , 4.600□
 Edge#2:from 6.050 , 9.800 , 4.600 to 6.050 , 9.800 , 4.600□
 Edge#3:from 6.050 , 9.800 , 4.600 to 6.050 , 9.800 , 0.000□

Mat : Jammie Walls*
 Area: 9.200

Name: Ent lf inst2 (face stg)
 Coordinates: Surface Type: Planar□
 Edge#0:from 5.250 , 12.700 , 0.000 to 6.050 , 12.700 , 0.000□
 Edge#1:from 6.050 , 12.700 , 0.000 to 6.050 , 12.700 , 4.600□
 Edge#2:from 6.050 , 12.700 , 4.600 to 5.250 , 12.700 , 4.600□
 Edge#3:from 5.250 , 12.700 , 4.600 to 5.250 , 12.700 , 0.000□

Mat : Jammie Walls*
 Area: 3.680

Name: Ent lf inst2* face stg
 Coordinates: Surface Type: Planar□
 Edge#0:from 5.250 , 12.700 , 0.000 to 2.850 , 14.100 , 0.000□
 Edge#1:from 2.850 , 14.100 , 0.000 to 2.850 , 14.100 , 4.600□
 Edge#2:from 2.850 , 14.100 , 4.600 to 5.250 , 12.700 , 4.600□
 Edge#3:from 5.250 , 12.700 , 4.600 to 5.250 , 12.700 , 0.000□

Mat : Jammie Walls*
 Area: 12.781

Name: Ent lf wall
 Coordinates: Surface Type: Planar□
 Edge#0:from 8.050 , 9.800 , 0.000 to 8.050 , 3.000 , 0.000□
 Edge#1:from 8.050 , 3.000 , 0.000 to 8.050 , 3.000 , 4.600□
 Edge#2:from 8.050 , 3.000 , 4.600 to 8.050 , 9.800 , 4.600□
 Edge#3:from 8.050 , 9.800 , 4.600 to 8.050 , 9.800 , 0.000□

Mat : Jammie Walls*
 Area: 31.280

Coordinates of room: Jammie (Page 9)
Name: balc rt front
Coordinates: Surface Type: Planar
Edge#0:from 25.050, 11.400, 3.325 to 25.050, 11.400, 3.710
Edge#1:from 25.050, 11.400, 3.710 to 26.050, 9.800, 4.240
Edge#2:from 26.050, 9.800, 4.240 to 26.050, 9.800, 3.325
Edge#3:from 26.050, 9.800, 3.325 to 25.050, 11.400, 3.325

Mat : Jammie Walls*
Area: 1.226

Name: balc top back
Coordinates: Surface Type: Planar
Edge#0:from 8.050, 9.800, 4.240 to 8.050, 3.000, 6.625
Edge#1:from 8.050, 3.000, 6.625 to 26.050, 3.000, 6.625
Edge#2:from 26.050, 3.000, 6.625 to 26.050, 9.800, 4.240
Edge#3:from 26.050, 9.800, 4.240 to 8.050, 9.800, 4.240

Mat : Jammie Floor*
Area: 129.710

Name: balc top front
Coordinates: Surface Type: Planar
Edge#0:from 9.050, 11.400, 3.710 to 9.050, 9.800, 4.240
Edge#1:from 9.050, 9.800, 4.240 to 26.050, 9.800, 4.240
Edge#2:from 26.050, 9.800, 4.240 to 25.050, 11.400, 3.710
Edge#3:from 25.050, 11.400, 3.710 to 9.050, 11.400, 3.710

Mat : Jammie Floor*
Area: 28.653

Name: cone lt 1
Coordinates: Surface Name: Cone
Centre Point 1=2.850, 18.900, 4.600
Radius 1=4.800
Centre Point 2=5.250, 18.900, 4.600
Radius 2=6.200
Normal=1.000, 0.000, 0.000

Mat : Jammie Ceiling*
Area: 5.278

Name: cone rt 1
Coordinates: Surface Name: Cone
Centre Point 1=31.250, 18.900, 4.600
Radius 1=4.800
Centre Point 2=28.850, 18.900, 4.600
Radius 2=6.200
Normal=1.000, 0.000, 0.000

Mat : Jammie Ceiling*
Area: 5.278

Name: dome
Coordinates: Surface Type: Dome
Centre Point=17.050, 18.900, -17.010
Radius=31.905
Top Point=17.050, 18.900, 14.895
Height=31.905
Z Cutoff=13.600

Coordinates of room: Jammie (Page 10)
Name: dome
Coordinates: Surface Type: Dome
Centre Point=17.050, 18.900, -17.010
Radius=31.905
Top Point=17.050, 18.900, 14.895
Height=31.905
Z Cutoff=13.600
Normal=0.000, 0.000, 1.000

Mat : Jammie Ceiling*
Area: 3197.918

Name: dome hole
Coordinates: Surface Type: Circle
Centre Point=17.050, 18.900, 13.600
Radius=9.000
Normal=0.000, 0.000, 1.000

Mat : Jammie Ceiling*
Area: 127.235

Name: stg arc 4
Coordinates: Surface Type: Arch
Centre Point 1=17.050, 29.850, 4.600
Centre Point 2=17.050, 27.900, 4.600
Radius=9.000
Normal=0.000, 1.000, 0.000

Mat : Jammie Ceiling*
Area: 55.135

Name: stg arc face 3
Coordinates: Surface Type: Arch Face
Centre Point=17.050, 29.850, 4.600
InnerRadius=6.000
OuterRadius=9.000
Normal=0.000, 1.000, 0.000

Mat : Jammie Ceiling*
Area: 70.686

Name: stg arch 2
Coordinates: Surface Type: Arch
Centre Point 1=17.050, 30.630, 4.600
Centre Point 2=17.050, 29.850, 4.600
Radius=6.000
Normal=0.000, 1.000, 0.000

Mat : Jammie Ceiling*
Area: 14.703

Name: stg bck
Coordinates: Surface Type: Planar
Edge#0:from 21.800, 33.000, 0.000 to 12.300, 33.000, 0.000
Edge#1:from 12.300, 33.000, 0.000 to 12.300, 33.000, 4.600
Edge#2:from 12.300, 33.000, 4.600 to 21.800, 33.000, 4.600
Edge#3:from 21.800, 33.000, 4.600 to 21.800, 33.000, 0.000

Mat : Jammie Walls*
Area: 13.800

Coordinates of room: Jammie (Page 11)
Name: stg bck
Coordinates: Surface Type: Planar
Edge#0:from 21.800, 33.000, 0.000 to 12.300, 33.000, 0.000
Edge#1:from 12.300, 33.000, 0.000 to 12.300, 33.000, 4.600
Edge#2:from 12.300, 33.000, 4.600 to 21.800, 33.000, 4.600
Edge#3:from 21.800, 33.000, 4.600 to 21.800, 33.000, 0.000

Mat : Jammie Walls*
Area: 43.700

Name: stg cone 1
Coordinates: Surface Name: Cone
Centre Point 1=17.050, 33.000, 4.600
Radius 1=4.750
Centre Point 2=17.050, 30.630, 4.600
Radius 2=6.000
Normal=0.000, 1.000, 0.000

Mat : Jammie Ceiling*
Area: 4.653

Name: stg lf blk (face ent)
Coordinates: Surface Type: Planar
Edge#0:from 6.050, 27.900, 0.000 to 6.050, 27.900, 0.000
Edge#1:from 6.050, 27.900, 0.000 to 6.050, 27.900, 4.600
Edge#2:from 6.050, 27.900, 4.600 to 8.050, 27.900, 4.600
Edge#3:from 8.050, 27.900, 4.600 to 8.050, 27.900, 0.000

Mat : Jammie Walls*
Area: 9.200

Name: stg lf blk (face rt)
Coordinates: Surface Type: Planar
Edge#0:from 8.050, 29.850, 0.000 to 8.050, 27.900, 0.000
Edge#1:from 8.050, 27.900, 0.000 to 8.050, 27.900, 4.600
Edge#2:from 8.050, 27.900, 4.600 to 8.050, 29.850, 4.600
Edge#3:from 8.050, 29.850, 4.600 to 8.050, 29.850, 0.000

Mat : Jammie Walls*
Area: 8.970

Name: stg lf extension
Coordinates: Surface Type: Planar
Edge#0:from 11.050, 30.630, 0.000 to 11.050, 29.850, 0.000
Edge#1:from 11.050, 29.850, 0.000 to 11.050, 29.850, 4.600
Edge#2:from 11.050, 29.850, 4.600 to 11.050, 30.630, 4.600
Edge#3:from 11.050, 30.630, 4.600 to 11.050, 30.630, 0.000

Mat : Jammie Walls*
Area: 3.588

Name: stg lf inst1 (face ent)
Coordinates: Surface Type: Planar
Edge#0:from 11.050, 29.850, 0.000 to 8.050, 29.850, 0.000
Edge#1:from 8.050, 29.850, 0.000 to 8.050, 29.850, 4.600
Edge#2:from 8.050, 29.850, 4.600 to 11.050, 29.850, 4.600
Edge#3:from 11.050, 29.850, 4.600 to 11.050, 29.850, 0.000

Mat : Jammie Walls*
Area: 9.200

Coordinates of room: Jammie (Page 12)
Name: stg lf inst1 (face ent)
Coordinates: Surface Type: Planar
Edge#0:from 11.050, 29.850, 0.000 to 8.050, 29.850, 0.000
Edge#1:from 8.050, 29.850, 0.000 to 8.050, 29.850, 4.600
Edge#2:from 8.050, 29.850, 4.600 to 11.050, 29.850, 4.600
Edge#3:from 11.050, 29.850, 4.600 to 11.050, 29.850, 0.000

Mat : Jammie Walls*
Area: 13.800

Name: stg lf inst1 (face rt)
Coordinates: Surface Type: Planar
Edge#0:from 6.050, 27.900, 0.000 to 6.050, 25.100, 0.000
Edge#1:from 6.050, 25.100, 0.000 to 6.050, 25.100, 4.600
Edge#2:from 6.050, 25.100, 4.600 to 6.050, 27.900, 4.600
Edge#3:from 6.050, 27.900, 4.600 to 6.050, 27.900, 0.000

Mat : Jammie Walls*
Area: 12.880

Name: stg lf inst2 (face ent)
Coordinates: Surface Type: Planar
Edge#0:from 6.050, 25.100, 0.000 to 5.250, 25.100, 0.000
Edge#1:from 5.250, 25.100, 0.000 to 5.250, 25.100, 4.600
Edge#2:from 5.250, 25.100, 4.600 to 6.050, 25.100, 4.600
Edge#3:from 6.050, 25.100, 4.600 to 6.050, 25.100, 0.000

Mat : Jammie Walls*
Area: 3.680

Name: stg lf inst2* (face ent)
Coordinates: Surface Type: Planar
Edge#0:from 5.250, 25.100, 0.000 to 5.250, 25.100, 4.600
Edge#1:from 5.250, 25.100, 4.600 to 2.850, 23.700, 4.600
Edge#2:from 2.850, 23.700, 4.600 to 2.850, 23.700, 0.000
Edge#3:from 2.850, 23.700, 0.000 to 5.250, 25.100, 0.000

Mat : Jammie Walls*
Area: 12.781

Name: stg lf wall
Coordinates: Surface Type: Planar
Edge#0:from 12.300, 33.000, 0.000 to 11.050, 30.630, 0.000
Edge#1:from 11.050, 30.630, 0.000 to 11.050, 30.630, 4.600
Edge#2:from 11.050, 30.630, 4.600 to 12.300, 33.000, 4.600
Edge#3:from 12.300, 33.000, 4.600 to 12.300, 33.000, 0.000

Mat : Jammie Walls*
Area: 12.325

Name: stg rt blk (face ent)
Coordinates: Surface Type: Planar
Edge#0:from 28.050, 27.900, 0.000 to 26.050, 27.900, 0.000
Edge#1:from 26.050, 27.900, 0.000 to 26.050, 27.900, 4.600
Edge#2:from 26.050, 27.900, 4.600 to 28.050, 27.900, 4.600
Edge#3:from 28.050, 27.900, 4.600 to 28.050, 27.900, 0.000

Mat : Jammie Walls*
Area: 9.200

Appendix E: TEF Measuring System (MLS and PET)

The measurements in the Jameson Hall were performed using the TEF acoustic measurement system. The full details of the system are:

TEF System 20 Analyzer.

Techron TEF Products

Crown International Inc.

1718 W. Mishawaka Road

Elkhart, IN 46517-4095

© 1995

Measurements were taken according to the details given in the user manual accompanying this system. Briefly this consists of:

- Plugging the microphone (on tripod) into the input of the TEF analyser.
- Plugging the speaker amplifier into the output of the TEF analyser
- Plugging the speaker into the speaker amplifier. The speaker consisted of a single large speaker and a spherical constructed speaker to provide omni-directional sound at high frequencies.
- Plugging a computer running the SoundLab software provided with the TEF analyser into the Tef analyser.

All graphs of measured impulse response measurements, and also the STI and %Alcons measurements were created by the SoundLab software.

Appendix F: Backwards Integration of Impulse Response Graphs

To obtain RT60 and EDT values it is necessary to backwards integrate the impulse response graph. Much research has been performed on this technique, for which some references are given in the bibliography.

Before backwards integration, forwards integration was used. This unfortunately was sensitive to discontinuities in the impulse response which often occur in the early time. Backwards integration starts at the relatively smooth part of the graph and allows repeatable measurements of reverberation parameters.

Backwards integration entails simply adding the intensity of the measured sound with limits starting from the end of the graph and ending at the start. No averaging is applied.

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Appendix G: Calculating C80, C50, Center Time and Definition

To calculate the clarity values of C80, C50, Center Time and Definition a MathCAD worksheet was used. To do this the measured impulse response was saved in an ASCII format, which can be understood by MathCAD. Even though the absolute values of the SoundLab format saved file are not completely understood, C80 etc. refer to relative values so it is still possible to use the values saved by SoundLab.

A printout of the worksheet follows.

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TO CALCULATE IACC and OBJECTIVE SUPPORT and CLARITY

Notes on IACC:

The variable t (Tor) is not included in the calculation due to time constraints. However, t should be kept at zero and this is normally the case, so it is a reasonable approximation. Including it would allow a measure of mislocalisation of the source to be measured. If there is an obvious mislocalisation of the source, this value will be incorrect.

NB: You need to associate the MLS ASCII code filename with MLSA, and the two ear MLS ASCII signals, left and right, with IACCL and IACCR. If you don't want to calculate IACC don't associate their filenames

ENDTIME is the time when the impulse response has entered the noise level. Effectively the time when the impulse response graph has ended. The choice of this value is not critical to the results.

All time values are in milliseconds

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ENTER THE TIME OF THE DIRECT SIGNAL HERE (in ms):

DIRECTTIME := 13.417

LEFT SIGNAL (or MLS signal)

DIRECTTIMEB := 0

RIGHT SIGNAL (only necessary for IACC tests)

ENDTIME := 3500

End time of MLS signal

(Loading left and right signals)

MLS := READPRN(MLSA)

IA1 := READPRN(IACCL)

IA2 := READPRN(IACCR)

File not found

File not found

File not found

MLS =

MAXBITLENGTH := $\frac{MLS_{10}}{10}$

MAXBITLENGTH =

MAXTIMELENGTH := $\frac{MLS_{10}}{MLS_{11}} \cdot 1000$

MAXTIMELENGTH =

DIRECTTIMEOFFSET := floor $\left(\frac{DIRECTTIME \cdot MAXBITLENGTH}{MAXTIMELENGTH} \right)$

TIME PERBIT := $\frac{MAXTIMELENGTH}{MAXBITLENGTH}$

BIT PERTIME := $\frac{MAXBITLENGTH}{MAXTIMELENGTH}$

BIT PERTIME =

HEAD := 36 + DIRECTTIMEOFFSET (Header of file+direct time)

MAXBITLENGTH := MAXBITLENGTH - DIRECTTIMEOFFSET

TOR := DIRECTTIME - DIRECTTIMEB

TOR = 13.417

MAXBITLENGTH := MAXBITLENGTH - BIT PERTIME $\cdot (MAXTIMELENGTH - ENDTIME)$

BROAD = floor $(50 \cdot BIT PERTIME)$

EARLY := floor $(80 \cdot BIT PERTIME)$

EARLY =

MAXBITLENGTH =

$N_E = \lfloor \frac{HEAD}{MAXBITLENGTH} \rfloor + 1 \dots \lfloor \frac{EARLY + HEAD}{MAXBITLENGTH} \rfloor$

$N_E = \lfloor \frac{HEAD}{MAXBITLENGTH} \rfloor + 1 \dots \lfloor \frac{EARLY + HEAD}{MAXBITLENGTH} \rfloor$

$N_V = \lfloor \frac{HEAD}{MAXBITLENGTH} \rfloor + 1 \dots \lfloor \frac{MAXBITLENGTH + HEAD}{MAXBITLENGTH} \rfloor$

$N_L = \lfloor \frac{EARLY + HEAD}{MAXBITLENGTH} \rfloor + 1 \dots \lfloor \frac{MAXBITLENGTH + HEAD}{MAXBITLENGTH} \rfloor$

CALCULATE IACC(E)

$$ACNUM_E := \sum_{N_E} [IA1_{N_E} \cdot (IA2_{N_E})]$$

$$ACNUM_L =$$

$$ACDEN_E := \sqrt{\left[\sum_{N_E} (IA1_{N_E})^2 \right] \cdot \sum_{N_E} (IA2_{N_E})^2}$$

$$ACDEN_L =$$

must be range

$$ACC_E := \frac{ACNUM_E}{ACDEN_E}$$

$$ACC_L =$$

CALCULATE IACC(L)

$$ACNUM_L := \sum_{N_L} [IA1_{N_L} \cdot (IA2_{N_L})]$$

$$ACNUM_L =$$

$$ACDEN_L := \sqrt{\left[\sum_{N_L} (IA1_{N_L})^2 \right] \cdot \sum_{N_L} (IA2_{N_L})^2}$$

$$ACDEN_L =$$

must be range

$$ACC_L := \frac{ACNUM_L}{ACDEN_L}$$

$$ACC_L =$$

CALCULATE ENVELOPMENT IACC

$$ACNUM_V := \sum_{N_V} [IA1_{N_V} \cdot (IA2_{N_V})]$$

$$ACNUM_V =$$

$$ACDEN_V := \sqrt{\left[\sum_{N_V} (IA1_{N_V})^2 \right] \cdot \sum_{N_V} (IA2_{N_V})^2}$$

$$ACDEN_V =$$

must be range

$$ACC_V := \frac{ACNUM_V}{ACDEN_V}$$

CALCULATING OBJECTIVE SUPPORT

$$R_{TWENTY} := \text{floor}(20 \cdot \text{BIT_PER_TIME})$$

$$R_{TEN} := \text{floor}(10 \cdot \text{BIT_PER_TIME})$$

$$R_{HUNDRED} := \text{floor}(100 \cdot \text{BIT_PER_TIME})$$

$$N_{TOP} := R_{TWENTY} + \text{HEAD}, R_{TWENTY} + \text{HEAD} + 1, \dots, R_{HUNDRED} + \text{HEAD}$$

$$N_{BOTTOM} := \text{HEAD}, \text{HEAD} + 1, \dots, R_{TEN} + \text{HEAD} + 1$$

$$ST := 10 \cdot \log \left[\frac{\sum_{N_{TOP}} (MLS_{N_{TOP}})^2}{\sum_{N_{BOTTOM}} (MLS_{N_{BOTTOM}})^2} \right]$$

must be range

CALCULATING CLARITY

(need at least 3000ms of sample time)

$$R_{C80} := \text{floor}(80 \cdot \text{BIT_PER_TIME})$$

$$N_{C80} := 1 + \text{HEAD}, 2 + \text{HEAD}, \dots, R_{C80} + \text{HEAD}$$

$$N_{3000} := R_{C80} + \text{HEAD}, R_{C80} + \text{HEAD} + 1, \dots, \text{MAX_BIT_LENGTH} + \text{HEAD}$$

$$C_{80} := 10 \cdot \log \left[\frac{\sum_{N_{C80}} (MLS_{N_{C80}})^2}{\sum_{N_{3000}} (MLS_{N_{3000}})^2} \right]$$

must be range

$$C_{80} =$$

CALCULATING C50

$$R_{c50} := \text{floor}(50 \cdot \text{BIT_PER_TIME})$$

$$N_{C50} := 1 + \text{HEAD}, 2 + \text{HEAD}, \dots, R_{c50} + \text{HEAD}$$

$$N_{3001} := R_{c50} + \text{HEAD}, R_{c50} + \text{HEAD} + 1.. \text{MAXBITLENGTH} + \text{HEAD}$$

$$C_{50} := 10 \cdot \log \left[\frac{\sum_{N_{c50}} (\text{MLS}_{N_{c50}})^2}{\sum_{N_{3001}} (\text{MLS}_{N_{3001}})^2} \right]$$

must be range

$$C_{50} =$$

Center-Time

$$N_t := \text{HEAD}, \text{HEAD} + 1.. \text{MAXBITLENGTH} + \text{HEAD}$$

$$\text{TIME_PER_BIT} =$$

$$t_s := \frac{\sum_{N_t} \text{TIME_PER_BIT} \cdot (N_t - \text{HEAD}) \cdot (\text{MLS}_{N_t})^2}{\sum_{N_t} (\text{MLS}_{N_t})^2}$$

$$t_s =$$

must be range
Definition

$$\text{BROAD} := \text{floor}(50 \cdot \text{BIT_PER_TIME})$$

$$\text{BROAD} =$$

$$\text{HEAD} =$$

$$N_D := \text{HEAD}, \text{HEAD} + 1.. \text{BROAD} + \text{HEAD}$$

$$N_{\text{INFINITY}} := \text{HEAD}, \text{HEAD} + 1.. \text{MAXBITLENGTH} + \text{HEAD}$$

$$D_1 := \left[\sum_{N_{\text{INFINITY}}} (\text{MLS}_{N_{\text{INFINITY}}})^2 \right]$$

$$D_1 =$$

must be range

$$D_2 := \left[\sum_{N_D} (\text{MLS}_{N_D})^2 \right]$$

$$D_2 =$$

must be range

$$D := \frac{D_2}{D_1} \cdot 100$$

$$D =$$

$ACC_V =$

BROADENING OF THE SOURCE

$ACC_L =$

ENVELOPMENT

$ACC_E =$

BROADENING OF THE SOURCE

(THE CLOSER TO ZERO THE BETTER)

Good value is 0.35 to 0.6

$ST =$

OBJECTIVE SUPPORT (dB)

(-12dB TO -14dB TYPICAL)

(-17dB STILL POSSIBLY OK)

$C_{80} =$

CLARITY

(about -2dB to +2dB)

$C_{50} =$

CLARITY 50ms

$D =$

Definition (%) TYPICAL 15%-59%

$t_s =$

Center Time (Max 140ms) Lower is clearer

Appendix H: Jameson Hall Complete Results

The results of the measurements and simulations taken for this thesis are included in the Excel sheet on the CD which accompanies this thesis.

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User's Guide to RoWena



This section provides a brief introduction to the working of the room acoustic prediction program written for this thesis, called RoWena. Since the program is even now under continuous development this guide is not complete. Also there may still be bugs in the program, these being functions that cause the program to stop working or to do unforeseen operations. This aside, the program works correctly and it is possible to obtain all the results that were described in the main body of the thesis.

The term 'user' refers to the person that is using the program. Menu options are specified by for example *File|Save*, which means select *File* from the menu and then *Save* from the resultant drop down menu. Icons are the buttons that appear at the top of the screen just below the menu. It is assumed further that the user is familiar with the workings and terminology of the Windows operating system.

It is advised that the reader study the first part of this document that described room acoustic simulation programs in detail.

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1. Outline of User Interface with RoWena

There are four main areas where the user will spend the majority of time. These are

- **Hall Sheet**, where the model of the hall to be simulated is contained,
- **Simulation Parameters**, where the operation of the simulation itself is specified,
- **Graphs**, where the results of the simulation are given, and the
- **Hall Diagram**, where visual indication of the model is given.

The order of operation of a simulation from start to end is as follows:

1. **Create or Load a Hall Model**
2. Specify **Receiver(s)** and **Source**
3. Select the **Simulation Parameters**
4. **Begin Simulation**
5. Obtain **Results** from the **Graphs**
6. (Optional) Inspect **Ray Paths** on the Hall Diagram

Each of these steps will be discussed in turn below. They are intended to be read in order, as this will guide the user through the steps necessary to creating and simulation a new hall model.

1.1. Create or Load a Hall Model

The hall model to be simulated must be inserted into the program, either by creating a new model or by loading an existing model.

1.1.1. Load an Existing Hall Model

If a hall model has already been created and saved to disk, it can be loaded in one of two ways. If it was recently created it can be loaded by selecting *File|Recent Halls*. A sub menu will appear which contains the most recently loaded or saved halls.

Alternatively the *File|Open Room* function can be selected. An explorer style box will appear from which the file can be loaded.

1.1.2. Create a New Hall Model

To create a new hall model, first the Hall Settings box must be opened. To do this select *View|Hall Settings*. The box shown in Figure 1 will appear.

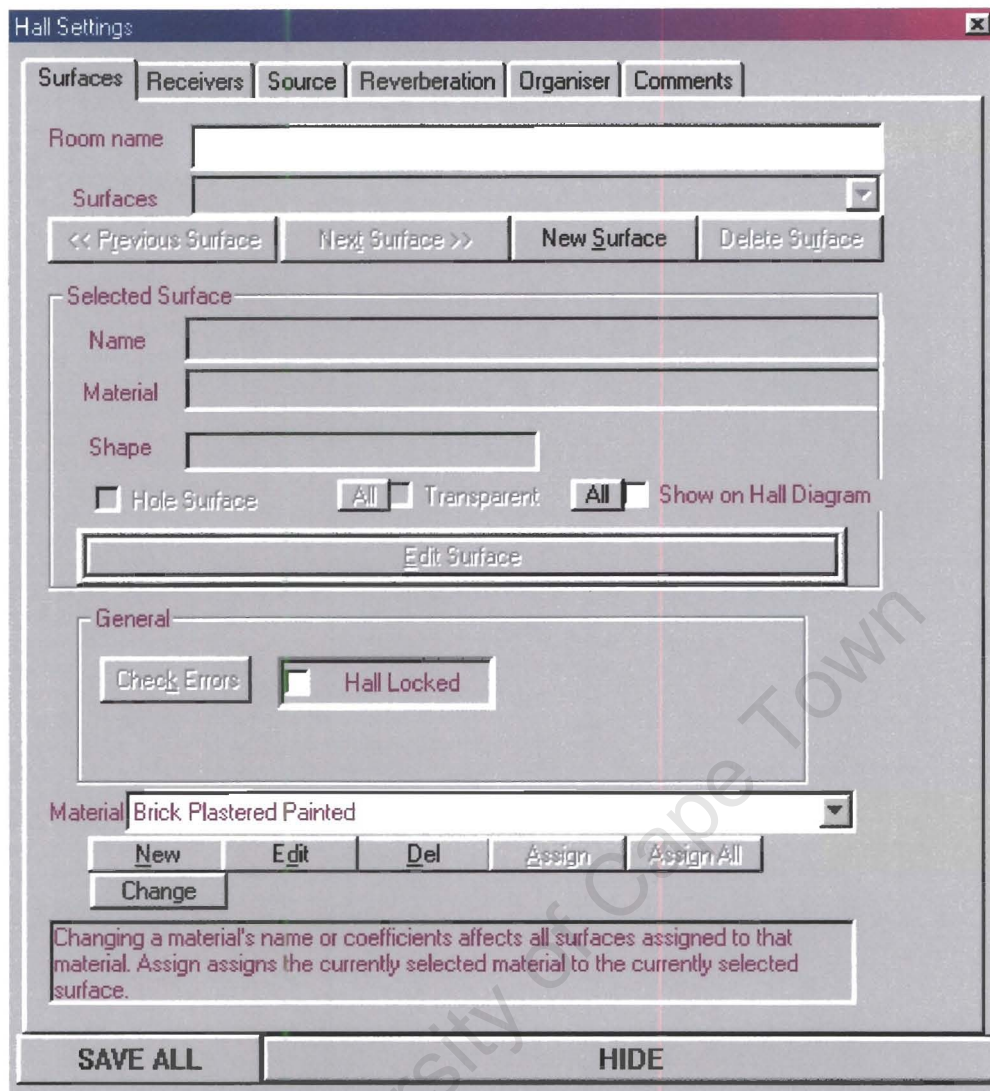


Figure 1: Hall Settings Box: Surfaces Page

At the moment no room model exists so many of the functions of this box are disabled. Note that while this box is visible other parts of the program can still be accessed. To make this box disappear press the *Hide* button or select *View|Hall Settings* again.

1.1.3. Save the Room Model

Next the *Hide* button at the bottom of the *Hall Sheet* box is a button called *Save All*. Pressing this button allows the user to save the hall model and also all open unsaved graphs. When the button is pressed an explorer box will appear allowing the user to select a name to save the room under.

Once the room has been saved at least once then instead a smaller box will appear asking the user for confirmation of the name to save under. An example is shown in Figure 2.

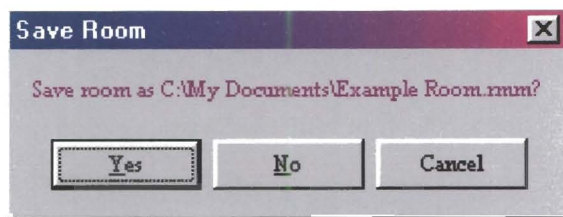


Figure 2: Save Room Confirmation Box

Pressing *Yes* will save the room under the same filename. Pressing *No* will allow the user to specify a different file name. *Cancel* aborts the save process.

Graphs are each saved under different names that are automatically selected by the program.

Because the program is in a developmental stage it may occur that the program will crash during the save operation. If this occurs all new information, including unsaved graphs, will be lost. Also the hall model file will be damaged and cannot be loaded again. To provide some security in this eventuality a copy of the hall model file is made before saving begins. It is saved to the same directory as the original file and given the name of the original hall's filename plus the word 'SafetyCopy'. If the program crashes during a save operation then this file can be loaded. If the save operation completes successfully then this file is automatically deleted.

1.1.4. Create a New Surface

The following describes the steps required to create a new surface.

1.1.4.1. Select a Surface Type

To create a new surface press the *New Surface* button. The box shown in Figure 3 will appear.

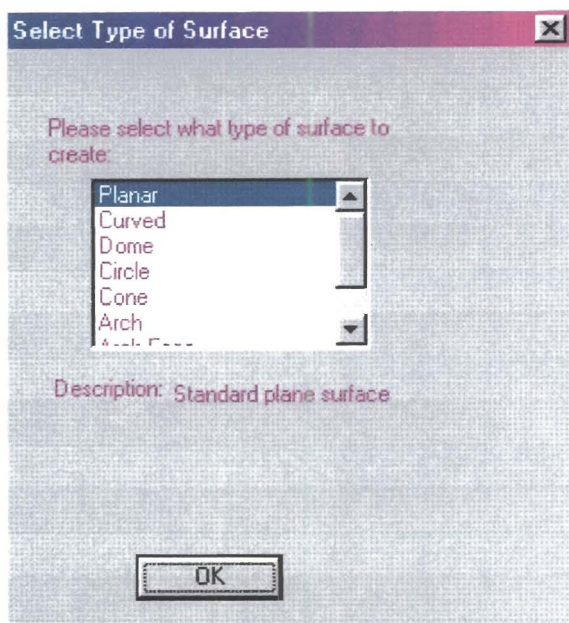


Figure 3: New Surface Type selection box

This box contains a list of the supported surface types. The most commonly used surface type will be *Planar* that is at the top of the list. Choose the desired surface type and press OK.

This surface has now been created and added to the room model. However no coordinates or dimension have been specified yet. The user will also notice that many of the functions that were previously disabled are now enabled.

1.1.4.2. Enter the Surface Name

In the *Name* field of the surfaces page of the hall settings box, as shown in Figure 1, the user can type a name describing the surface. As with all such items in the program the name can be any length and contain any characters. The name will be remembered automatically as it is typed in.

1.1.4.3. Specify the Surface Coordinates

The dimensions or coordinates of the surface must now be entered. To do this press the *Edit Surface* button. Depending on the type of surface which is currently selected a different editing box will appear.

1.1.4.3.1. Planar Surface Edit Box

If the surface is of type planar then the box as shown in Figure 4 will appear.

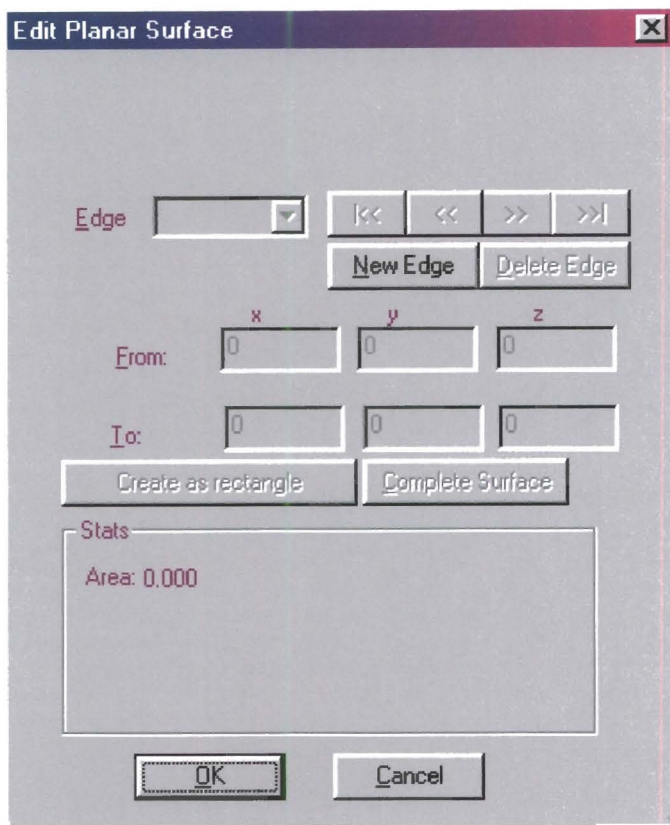


Figure 4: Planar Surface Edit box

A planar surface consists of a number of line segments, called **edges**, which must form a continuous loop. Since the surface currently contains no edges most of the functions of this box are disabled.

1.1.4.3.1.1. Creating Edges

Press the *New Edge* button. Immediately all the functions become enabled. A new edge has been created from (0,0,0) to (0,0,0). Type the start and end points of the any edge of the surface.

Now press the *New Edge* button again. A new edge will be created. This time however the *From* field of the box has already been filled in with the *To* point of the previous edge. In this way the program anticipates that the edge of this surface will be entered in a sequential order from head to tail. However this requirement is not obligatory and the edges can be entered in any order. Type in the *To* point of this next edge.

Continue in this manner until all the edges have been entered. If the edges have been entered sequentially then *To* point of the last edge must join up with the *From* point of the first edge. To ensure that this is so press the *Complete Surface* button when the last edge has been created with the *New Edge* button. The program will automatically set the *To* point as the *From* point of the first edge.

Press the OK button to close this box. This surface can be re-edited at any time by selecting the surface from the *surfaces* page and pressing the *edit surface* button as before.

1.1.4.3.1.2. Viewing and Editing Edges

To view precisely entered edges use the arrow buttons at the top of the box. The << button select the previous edge, the |<< button selects the first edge, and similarly for the >> and >>| buttons. The edge list box allows selection of any of the edge quickly.

1.1.4.3.1.3. Creating Rectangular Surfaces

If the surface to be created is a rectangular surface, which is common, then it can be created in a simpler manner. First ensure that the surface does not contain any edges. This can be done by pressing the *Delete Edge* button until all edges are deleted. Now press the *New Edge* button. In the *From* field enter any corner of the surface. In the *To* field enter the diagonally opposite corner of the box. Now press the *Create as Rectangle* button. A rectangular surface will automatically be created.

This function will only work if surface is perpendicular to on primary axis, i.e. one of the coordinates of the *To* and *From* points will be the same. Otherwise this specification of the surface is ambiguous.

1.1.4.3.2. Dome Surface Edit Box

If the selected surface type was a dome surface then the box as shown in Figure 5 will appear.

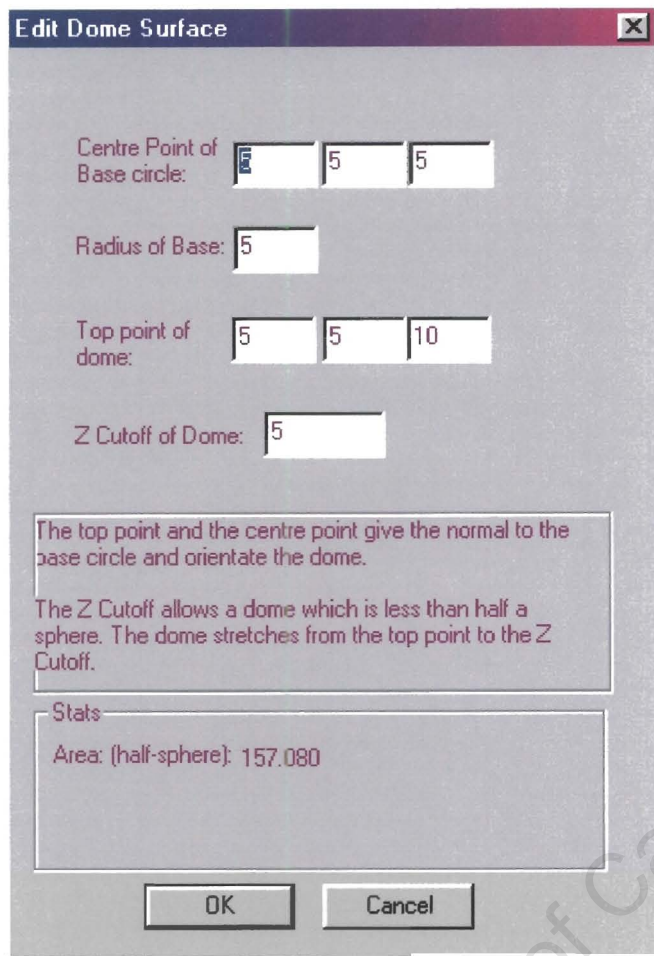


Figure 5: Dome Edit Box

A simple dome shape has already been specified which will almost certainly need to be changed by the user. The dome is required to be upright, i.e. the mouth of the dome points directly down. This requirement will be lifted in later versions of the program.

The fields that must be entered are:

- **Center Point of Base Circle;** this is the center point of the sphere of which the dome is a section
- **Radius of Base;** this is the radius of the sphere.
- **Top Point of Dome;** because the orientation of the dome is fixed this field is superfluous. However it must be filled in correctly. It will simply be the center point of the sphere with the z-coordinate increased by the radius, as correctly shown in Figure 5.
- **Z Cutoff of Dome;** this specifies the minimum z-coordinate value of the dome. This field therefore specifies how far down the (imaginary) large sphere the dome extends. A value close to the *top point of dome* z-coordinate will mean that the dome is a small sliver. This value may not be less than the z-coordinate of *center point of base circle*.

Press OK to accept this information. Note that the surface area calculation shown at the bottom of the edit box has not been fully implemented yet and should therefore be ignored.

1.1.4.3.3. Circle Surface Edit Box

If the surface was a *circle* type then the box shown in Figure 6 will appear.

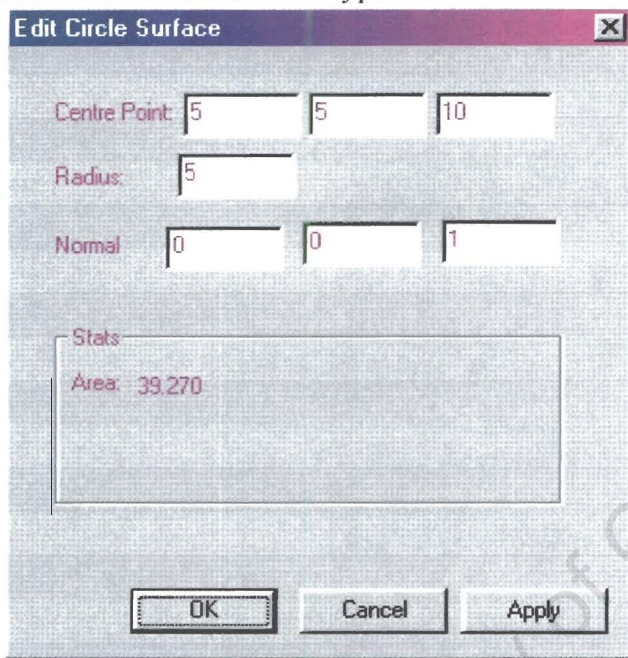


Figure 6: Circle Edit Box

A circle surface is a flat disc-like surface. It is specified by a center point, a radius and a normal. Both the center point and the radius are self-explanatory. The normal specifies the orientation of the surface. However in this development version of RoWena it is required to be orientated downwards. Therefore do not change the value of the *normal* field. Press OK to accept this surface's coordinates.

1.1.4.3.4. Cone Surface Edit Box

If the surface is a cone surface, then the box shown in Figure 7 will appear.

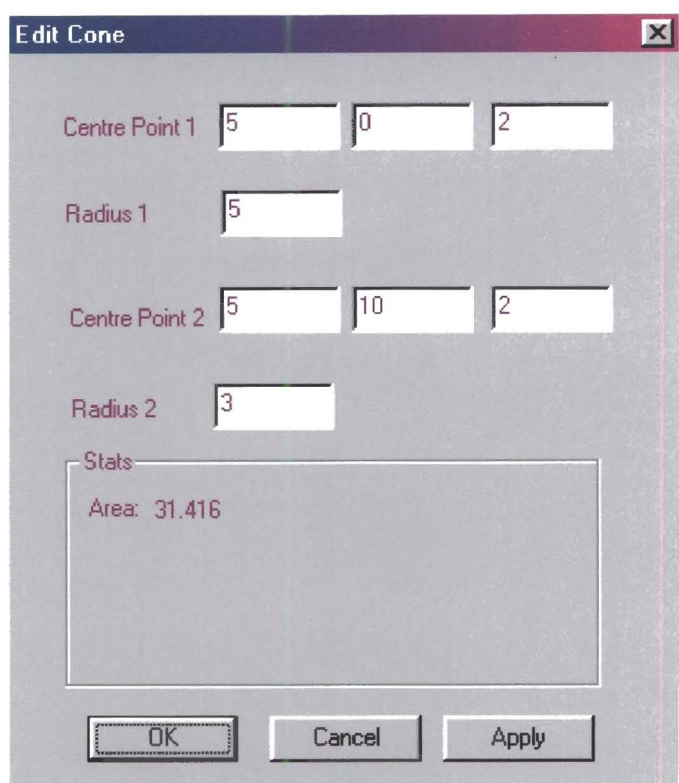


Figure 7: Cone Edit Box

The shape of a cone surface may be mentally visualised as a tunnel that gets narrower and lower at one end. It is specified by the two semi-circles at either end, given by their center points and radii. In this development version of the program the surface is required to be orientated parallel to either the x- or the y-axis. Also the surface exists only as the top half of the specified cone.

1.1.4.3.5. Arch Surface Edit Box

If the surface is a arch type surface, then the edit box as shown in Figure 8 will appear.

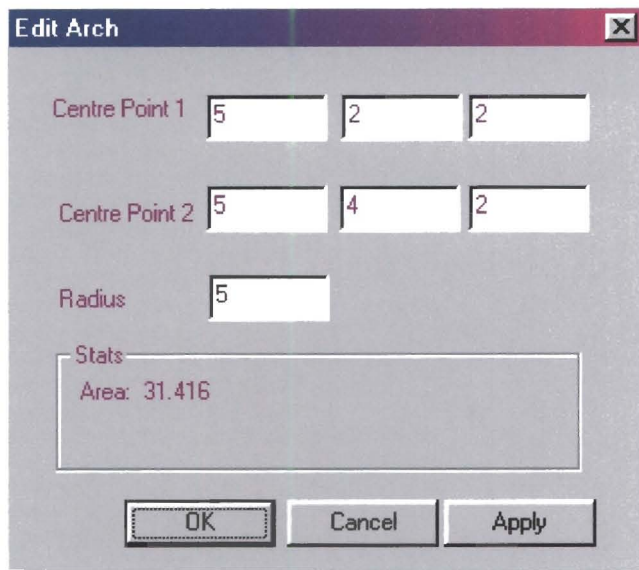


Figure 8: Arch Edi Box

An arch surface is similar in all respects to a cone surface (see 14) except that the radii of the two ends of the surface are the same. Thus this same surface could be specified by using the *cone* surface type and making the two radii the same. However the simulation is speeded up slightly if the *arch* surface type is used where applicable. The restrictions as described for the *cone* surface apply also to the *arch* surface.

1.1.4.3.6. Arch Face Edit Box

If the surface to be edited is and *arch face* type surface, then the box as shown in Figure 9 will be shown.

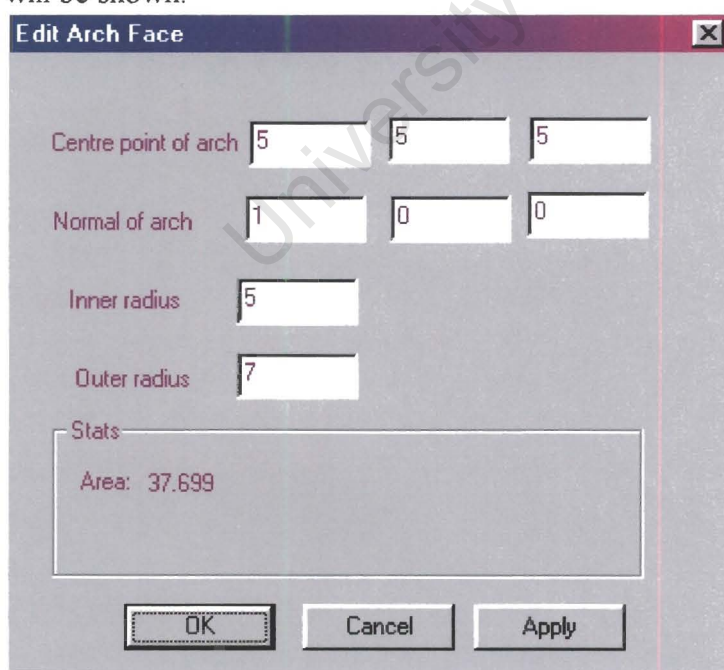


Figure 9: Arch Face Edit Box

An *arch face* surface is a section of a flat doughnut. It is specified by the center point of the doughnut and the inner and outer radius of the doughnut. It is required to be orientated parallel to either the x- or the y-axis, which is specified by entering (1,0,0) or (0,1,0) for the *normal of arch* field for the x- and y-axes respectively. The arch face is the top half of the doughnut. Such restrictions will be lifted in later versions of the program.

1.1.4.3.7. Curved Corner Edit Box

If the surface is a *curved corner* type surface, then the box as shown in Figure 10 will be appear.

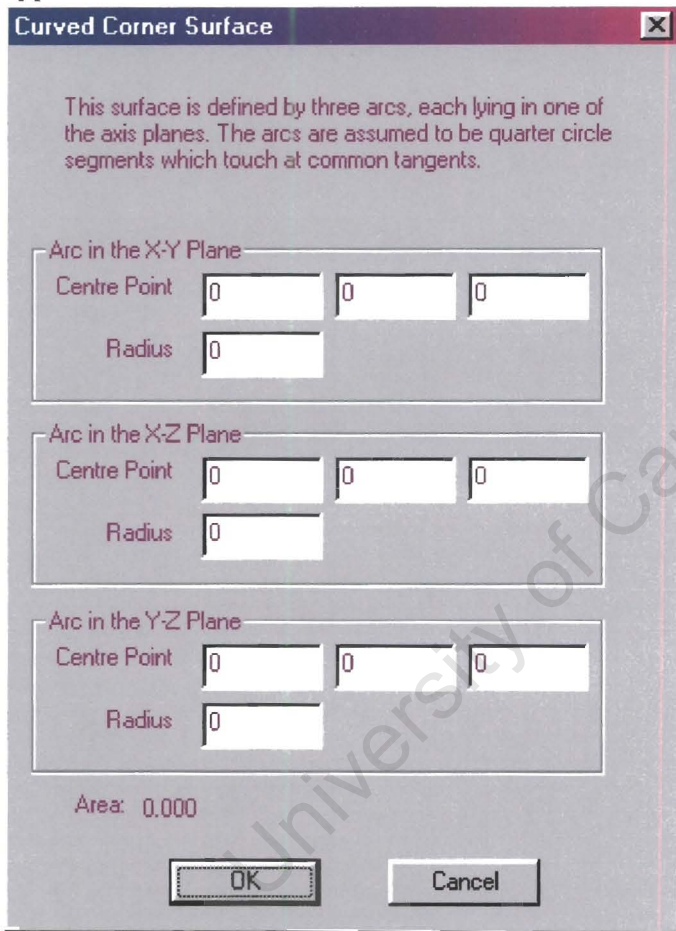


Figure 10: Curved Corner Edit Box

A *curved corner* surface is not a common surface type. It is found in the Jameson Hall, which is the reason for its inclusion in the program. The surface is a triangular section through a dome. Its three sides are defined by arcs, parallel to each primary axis, which intersect at their tangents. Each arc is specified by a center point and a radius. From this information the program will calculate the coordinates of the larger sphere and the orientation of the surface.

The automatically calculated *area* value is an approximation.

1.1.5. Selecting Surfaces

Once a number of surfaces have been created, the user can select from them using the buttons near the top of the *Surfaces* page, called *Previous Surface* and *Next Surface*. These two buttons select surfaces in the order in which they were created. To select a surface from an alphabetical list use the surface list box that is shown directly above these buttons.

1.1.6. Transparent and Hole surfaces

All surface types may be either transparent, holes, or neither. Most surfaces in the hall model will be neither.

A **transparent surface** is a surface that is invisible to the simulation. This is useful for temporarily removing surfaces from the room model.

A **hole surface** is a surface that is used to create complex shapes in the room model. It may be imagined as a magic portal in the shape of the surface. Its operation is best described by an example.

Imagine a room shape that consists in part of a flat ceiling with a dome in the middle. The ceiling would be specified as a *planar* surface type and the dome naturally by the *dome* surface type. However because the ceiling is continuous it will cover the mouth of the dome. Here it is necessary to place a *circle* surface, specified as a *hole* surface on the ceiling surface of the same radius as the mouth of the dome. The *circle hole* surface will allow sound rays to pass through the roof surface and into the dome.

Any surface may be a hole surface. Also the hole surface need not lie entirely on another surface, as was the case in the example above.

1.1.7. Shows Surface on Hall Diagram

Each surface may be individually specified as to whether it is shown on the hall diagram or not. This is to enable the user to remove surfaces that may clutter the hall diagram. It has no effect on the simulation whatsoever. If the *Show on Hall Diagram* check box has a tick then the surface will be shown on the hall diagram otherwise not.

The small *All* button next to this check box can be used to make all surfaces invisible. Pressing it once will make all surfaces invisible. Pressing it again will make all surfaces visible. This button operates in the same manner as the *All* button next to the *transparent* check box described in 1.1.6.

1.1.8. Surface Material Types

Each surface must have a material type assigned to it. The list of available material types is shown at the bottom of the *Surfaces* page of the *Hall Settings* box (see Figure 1). To assign a material select a material type so that it is showing in the materials window. Then press the *assign* button. The user will observe that directly beneath the name of the current surface the material type will be shown.

1.1.8.1. New Material Button

To create a new material type, press the *New* button. The window shown in Figure 11 will appear.

	Absorption	Diffusion
125Hz	0	0
250Hz	0	0
500Hz	0	0
1kHz	0	0
2kHz	0	0
4kHz	0	0
8kHz	0	0

Figure 11: New Material Box

Here the name of the material as well as its absorption and diffusion coefficients can be specified. When the OK button is pressed this new material will be added to the materials list.

1.1.8.2. Edit an existing Material

To edit the properties of an existing material select the material and press the *Edit* button. The window shown in Figure 11 will appear, which is the same window as shown for the *add material* function.

Note importantly that all surfaces with this material type will be updated with the new material properties. This means that if the material name is changed from for example 'glass' to 'stained glass' all surfaces with the material type 'glass' will now have the material 'stained glass'. This applies for the absorption and diffusion coefficients as well.

1.1.8.3. Delete a Material

To delete a material select the material and press the *Del* button.

1.1.8.4. Assign a Material

To assign the selected material to the selected surface press the *Assign* button. The material will be assigned immediately. To assign the same material to all surfaces in the room model press the *Assign All* button.

1.1.8.5. To Change Multiple Surface Material Types

To change all surfaces with a particular material type to another material type press the *Change* button. The box as shown in Figure 12 will appear.

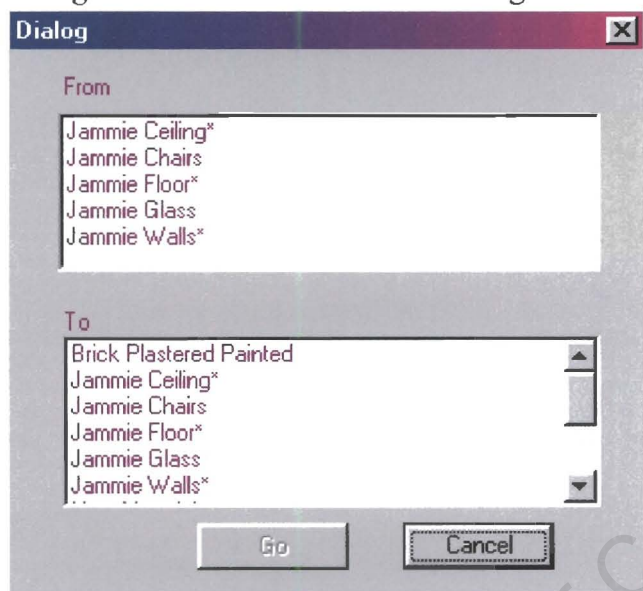


Figure 12: Change Material Box

The top window of this box shows a list of all the materials that are currently assigned to surfaces in the room model. The bottom window shows all the materials in the program. To change all surfaces with a particular material type to another material type select the existing material type in the top window and the new material type in the bottom window. Then press the *Go* button, which will become automatically enabled.

1.1.9. Check Errors in the Room Model

On the *Surfaces* page in the *Hall Settings* box there is a button called *Check Errors*. Pressing this button causes the room model to be checked to find errors. The errors that are checked are:

- Each planar surface is examined to ensure it has only one normal.
- Each planar surface is examined to ensure that the edges form a complete surface when joined head to tail.
- Each planar surface is examined to ensure that it contains at least three edges.
- Curved surface are checked to ensure that they are correct as per their surface type.

If a particular surface is incorrect it will be automatically selected. The checking procedure stops after the first incorrect surface. Therefore once the error has been

corrected the *Check Errors* button should be pressed again to ensure that no other errors are found.

1.1.10. Locking the Hall

In the middle of the *Surfaces* page in the *Hall Settings* box there is a tick box called *Hall Locked*. If this option is ticked then many of the options on this page become disabled. This option is ticked automatically after a simulation to ensure that the hall model is not modified since modifying the hall model would mean that the previous simulation results may not be valid for the hall model.

The hall may be locked and unlocked by the user by clicking on the tick box. No error will occur, but it is up to the user to ensure that the integrity of the simulation results is maintained.

1.2. Specify Receiver Positions

The second page of the *Hall Sheet* box is called *Receivers*. This page is shown in Figure 13.

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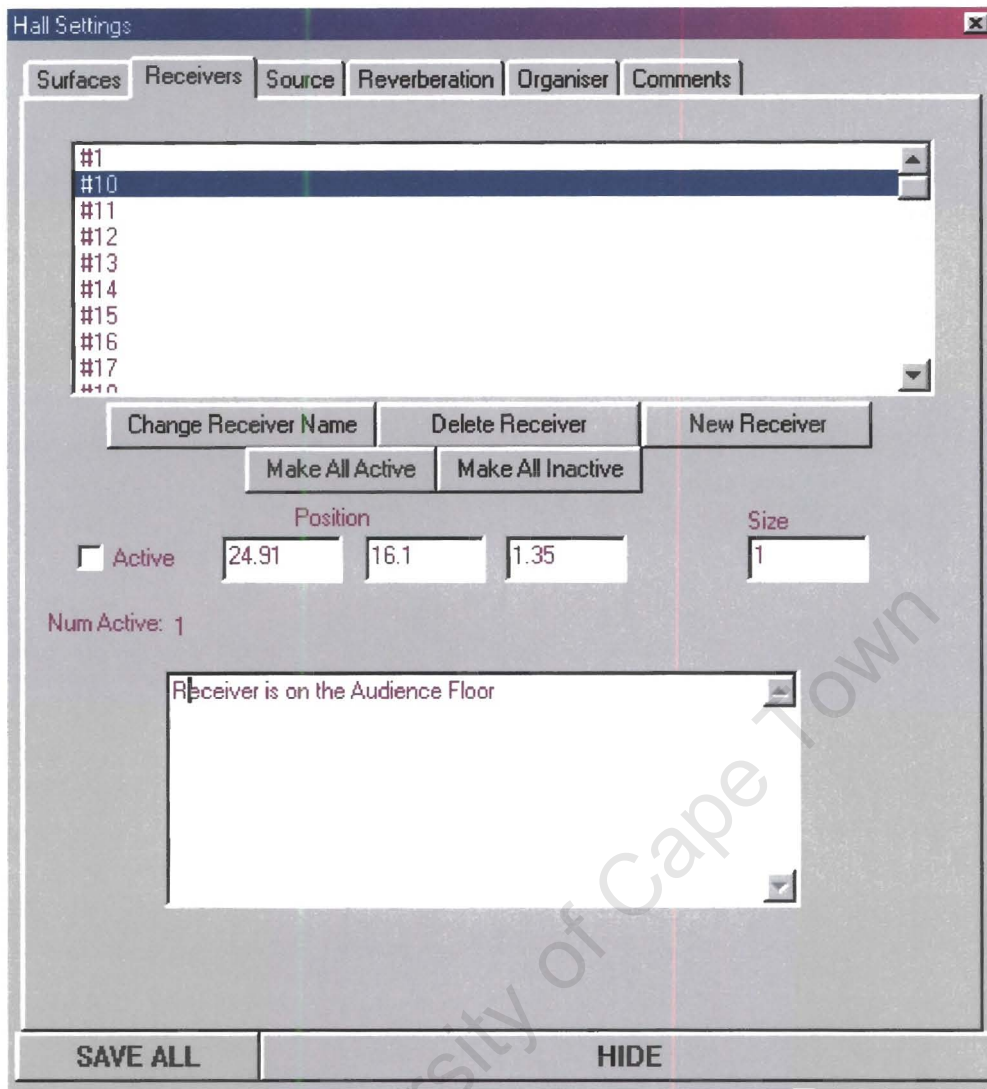


Figure 13: Hall Settings Box: Receiver Page

The large window at the top of the box contains a list of all the receivers that have already been created. Selecting a receiver causes its position, size and active state to be shown in the relevant fields further down the box.

1.2.1. Create a New Receiver

To create a new receiver press the *New Receiver* button. The box shown in Figure 14 will appear.

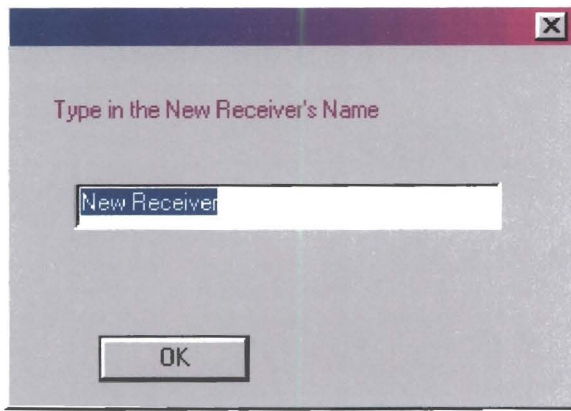


Figure 14: New Receiver box

Type the name of the receiver and select OK. The receiver will be added to the receiver list windows in the receiver page. The position, size and active state of the receiver can now be specified. Pressing the *Change Receiver Name* button allows the user to change the name of an existing receiver. Also the *Delete Receiver* button allows the user to delete the currently selected receiver.

1.2.2. Position and Size of a Receiver

The position of the receiver is the three dimensional position of the receiver relative to the room model. The size of the receiver is the radius of the sphere that surrounds the receiver point. It is used only for the basic ray tracing type simulation and ignored for secondary source type simulations.

1.2.3. Active State of a Receiver

If a receiver is active, as indicated by the tick box called *Active* then it will be included in a subsequent simulation. If it is not active then the receiver will be ignored.

1.2.4. Comments on the Receiver

At the bottom of the receiver page is a window where any desired comment on the receiver can be typed. In the example given in Figure 13 the comment reads 'Receiver is on the Audience Floor'.

1.3. Specify Source Position

The source position is the position of the sound source in the simulation. The source page is the third page of the *Hall Settings* box and is shown in Figure 15.

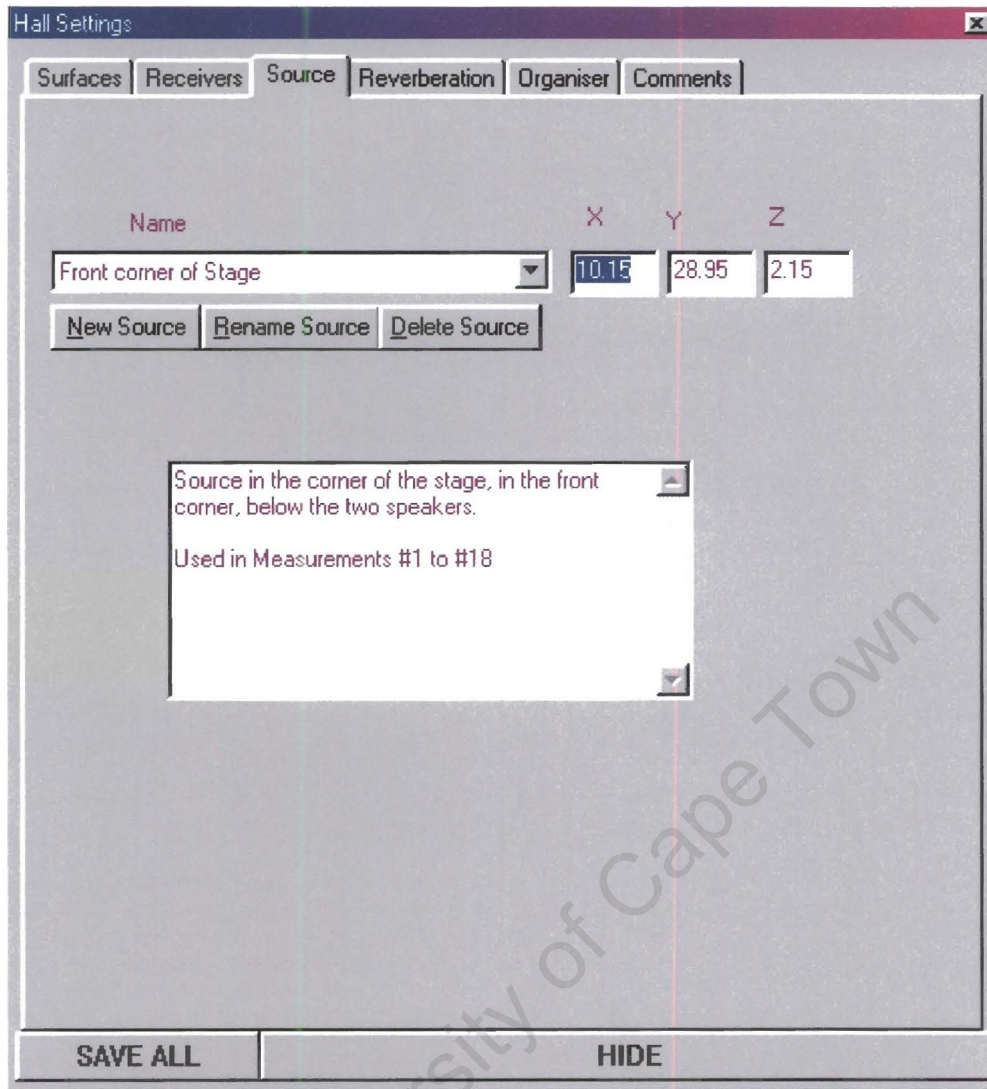


Figure 15: Hall Settings Box: Source Page

Only one source may be active at any time, which in the example in Figure 15 is called 'Front corner of Stage'. The source is specified by a position shown to the right of the source name.

1.3.1. Creating a New Source

Press the *New Source* button to create a new source. The box shown in Figure 16 will appear.

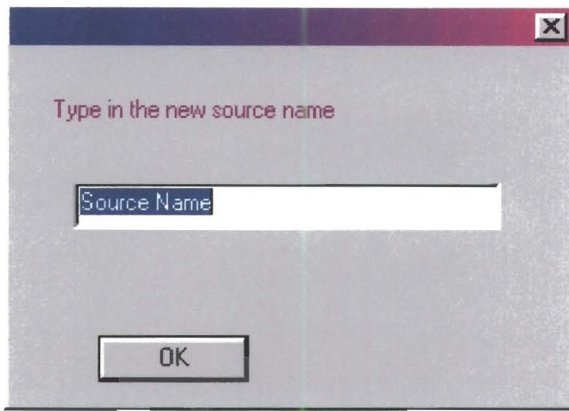


Figure 16: New Source Name Box

The user may type in a name for this source and then press OK. The source will be added to the source list. Other operation such as *Rename Source* and *Delete Source* operate on the currently selected source and are self-explanatory.

1.3.2. Active Source

Only one source may be active at a time. To select which source is active select the source from the drop down list which contains all the sources in the room model. The source name that is visible is the active source.

1.3.3. Comments on the Source

At the bottom of the source page is a window where any desired comment on the source can be typed. In the example given in Figure 15 the comment begins 'Source in the corner of the stage...'.
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1.4. Reverberation Page

The fourth page of the *Hall Settings* box is called the *Reverberation* page and is shown in Figure 17.

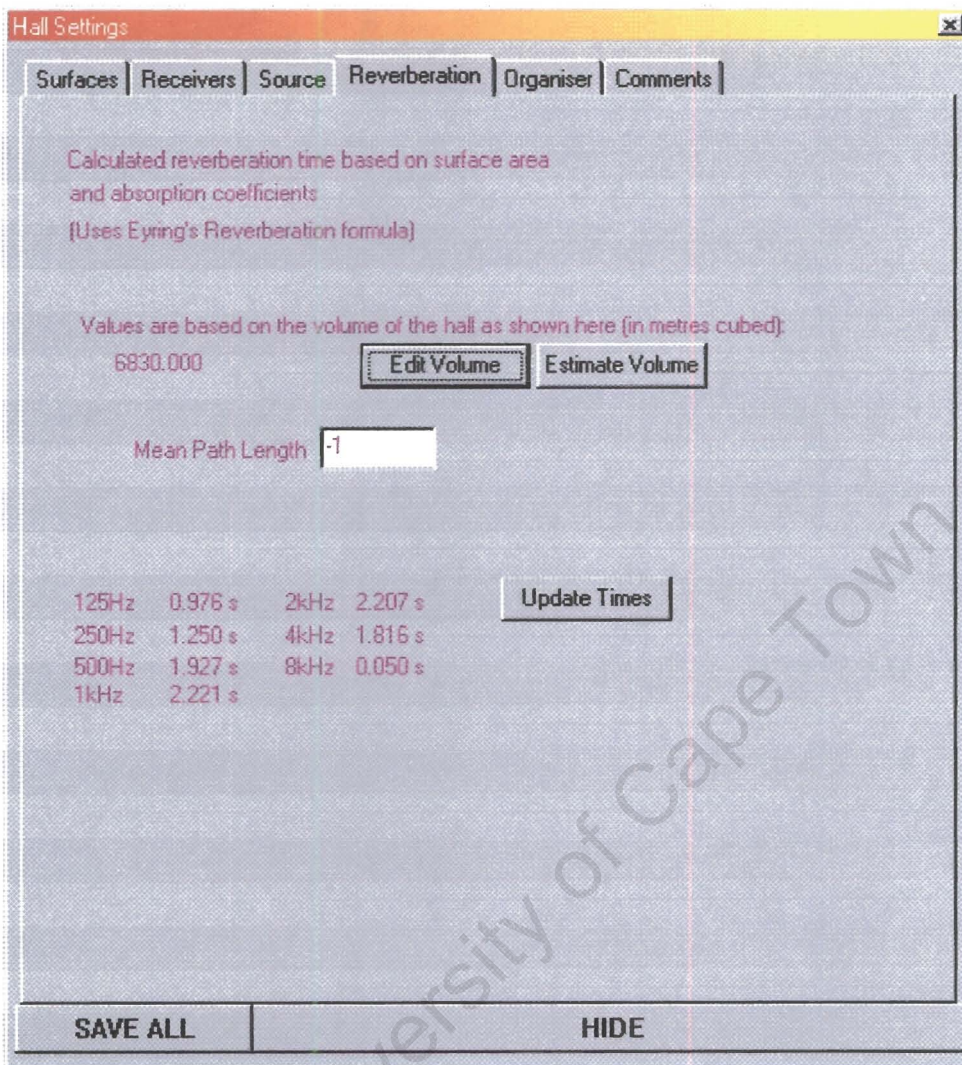


Figure 17: Hall Settings Box: Reverberation Page

The description of this page will be brief because parts of it are still under development. The purpose of this page is to obtain Eyring calculated reverberation times for the hall model. The reverberation times are calculated from the volume of the hall and from the surface materials as specified in the *surfaces* page.

1.4.1. Specify the Volume of the Hall

The volume of the hall may be entered manually by pressing the *Edit Volume* button. Alternatively the program can attempt to calculate the volume. To do this press the *Estimate Volume* button. In the new box that appears press the *Begin Estimate* button. If the estimate was successful and the *Ray Traced Volume* value seems correct press the *Select Ray Traced Volume* button.

1.4.2. Mean Path Length

Unless the user is informed as to the value of the mean path length of the hall this value should be ignored. The program will maintain this value as necessary.

1.4.3. Update Reverberation Times

If some part of the hall model has been modified then pressing the *Update Times* button will recalculate the reverberation times shown on this page.

1.5. The Organiser Page

The fifth page of the *Hall Sheet* page is called the *Organiser* page and is shown in Figure 18. For a new hall the large central window will be empty.

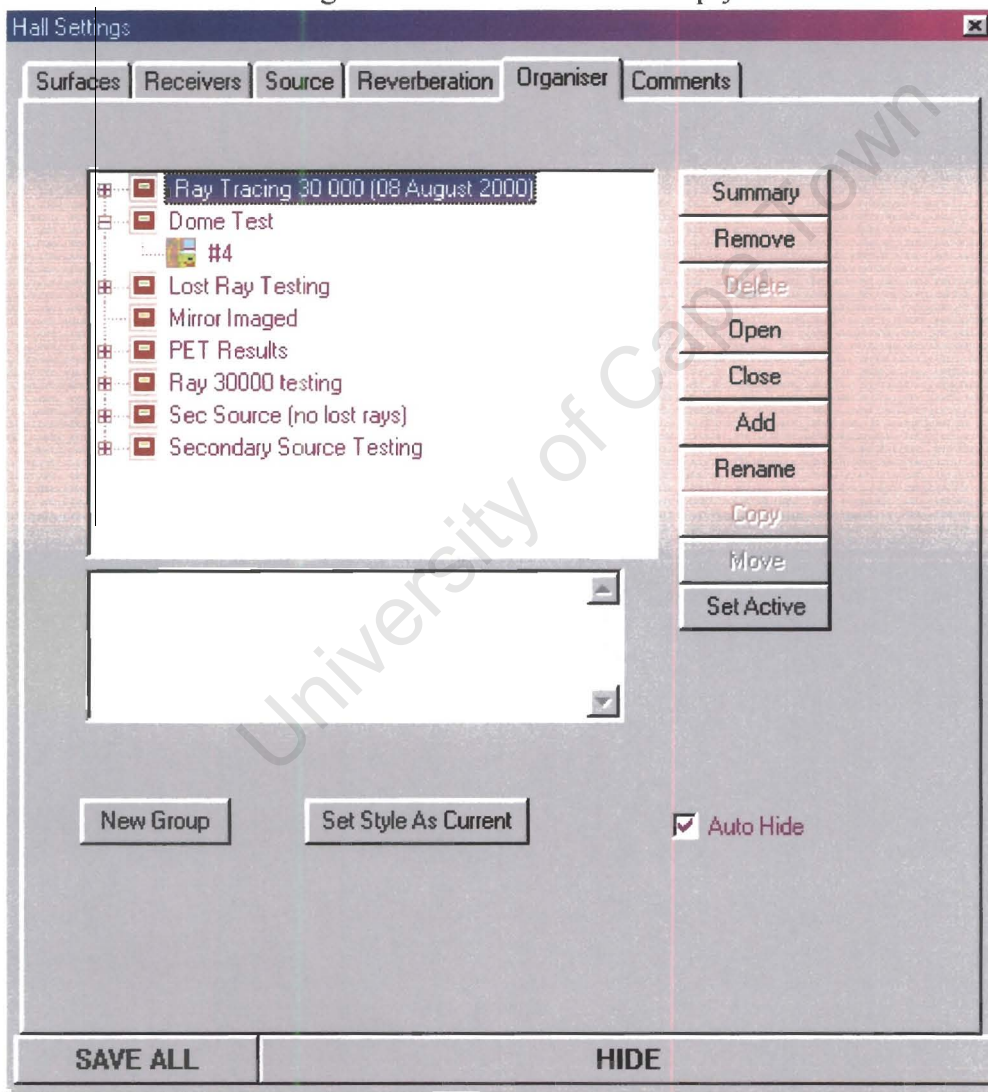


Figure 18: Hall Settings Box: Organiser Page

The description of this page is properly only useful after at least one simulation has been performed. Therefore the user should skip this section and return later. It is included here since it forms a logical part of the description of the *hall settings* box.

The organiser page is where all the simulation results are stored. It is useful for quickly accessing previous simulation results and for organising them in an easily manageable order.

1.5.1. Hierarchy of Organiser Groups

The main central window of the organiser page shows a list of simulation groups. In the example shown in Figure 18 the second group name is called 'Dome Test'. Each group is a collection of simulated graphs (see 4) or ray paths (see 5.3.2). The 'Dome Test' group in Figure 18 contains the graph called '#4'. Groups may contain any number of graphs or ray paths.

1.5.2. Summary of a Group

The *summary* button shows a summary of the selected group or group item. This feature is limited in functionality in this version of RoWena.

1.5.3. Removing an Item

Pressing the *remove* button allows an item to be removed from the list. If the item is a group name then the user is asked to decide whether the sub items of the group are deleted from disc or just removed. If the item is a graph or a ray path then the item is just removed from the organiser list but not from the disk.

1.5.4. Delete an Item

Deleting an item is similar to removing an item but the graph or ray path is permanently deleted from the disc and cannot be recovered.

1.5.5. Open an Item

If the *Open* button is pressed then the currently selected item is loaded into the program. Double clicking on a graph or ray path in the organiser list performs the same operation. If the item is a group then all the sub items of that group are opened.

1.5.6. Close an Item

The *close* button is not operational.

1.5.7. Add an Item

Pressing the *Add* item button allows the user to add a graph or ray path to the organiser page. A box appears from which the user may select the items (graphs or ray paths) to be added. The items will be added to the organiser group which was selected when the *add* button was pressed. For this reason the *add* button is disabled when anything other than a

group name is selected. Please also read 10.1 which describes a potential problem with this command.

1.5.8. Rename an Item

Group names and ray path names can be renamed by pressing the *rename* button. Graphs cannot be renamed.

1.5.9. Copy an Item

An item can be copied from one group to another group by pressing the *copy* button. To do this select the item (graph or ray path) then press the *copy* button. Many of the existing buttons will disappear and a new button will appear called *Select*. Select the group to copy to and press the *Select* button. Even though the item now exists in two different groups only one copy exists on disc.

1.5.10. Move an Item

Moving an item is identical to copying an item as described in 29, except that the *move* button is pressed rather than the *copy* item.

1.5.11. Set Active Receivers

As a quick method of selecting a group of receiver the *Set Active* button can be pressed. This button causes all the receivers relating to the graphs of the selected group to be made active, as described in 23. This operation assumes that the receiver names of the graphs in the group have not been changed.

1.5.12. Creating a New Group

To create a new group press the *New Group* button. A box will appear in which the user can specify a name for the new group. By default the program will choose the current date and time for the new group.

The new group that is created will contain all the information concerning the simulation parameters, as discussed in 2. This enables the user to recall the simulation parameters relevant to the group at a later stage.

When the OK button is pressed an option is given to create a SimWizard style. Select No. Another box will appear for which only OK can be selected. Press OK and the new group will be created.

1.5.13. Set Style as Current

As described in 29 each group is associated with a particular set of simulation parameters. If the user wishes to examine the simulation parameters for a group the *Set Style as Current* button can be pressed. This causes the current simulation parameters to be set to the simulation parameters associated with the currently selected group. When the button is pressed a box will appear as shown in Figure 19.

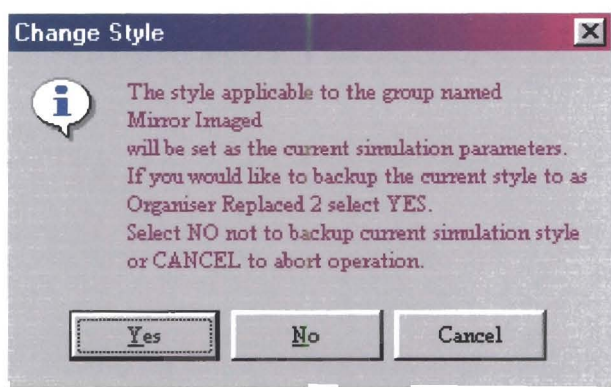


Figure 19: Set Simulation Style Confirmation Box

Press No at this page, or Cancel if the *Set Style as Current* button was pressed in error.

1.5.14. Comments for a Group

The user may type comments on the selected group in the smaller window below the group window. Comments may only be given for group names, and not for graphs and ray paths.

1.5.15. Auto Hide Organiser Page

This option should remain ticked.


1.6. Comments on the Room Model

The last page on the *Hall Sheet* box is the *comments* page. This page consists of a single large window where the user may type any comments on the hall.

2. Setting the Simulation Parameters

Once the hall model has been created, and before the simulation is begun, the parameters defining the operation of the simulation must be selected. There are two ways in which this may be done. The first, longest and most comprehensive is to directly select each simulation parameter. The second, shortest and most user friendly is to select all the simulation parameters in one go. Both these methods are discussed in this section.

2.1. Selecting Simulation Parameters using the SimWizard box

Pressing the  button, which shows a rabbit in a hat, causes the SimWizard box to appear, as shown in Figure 20.

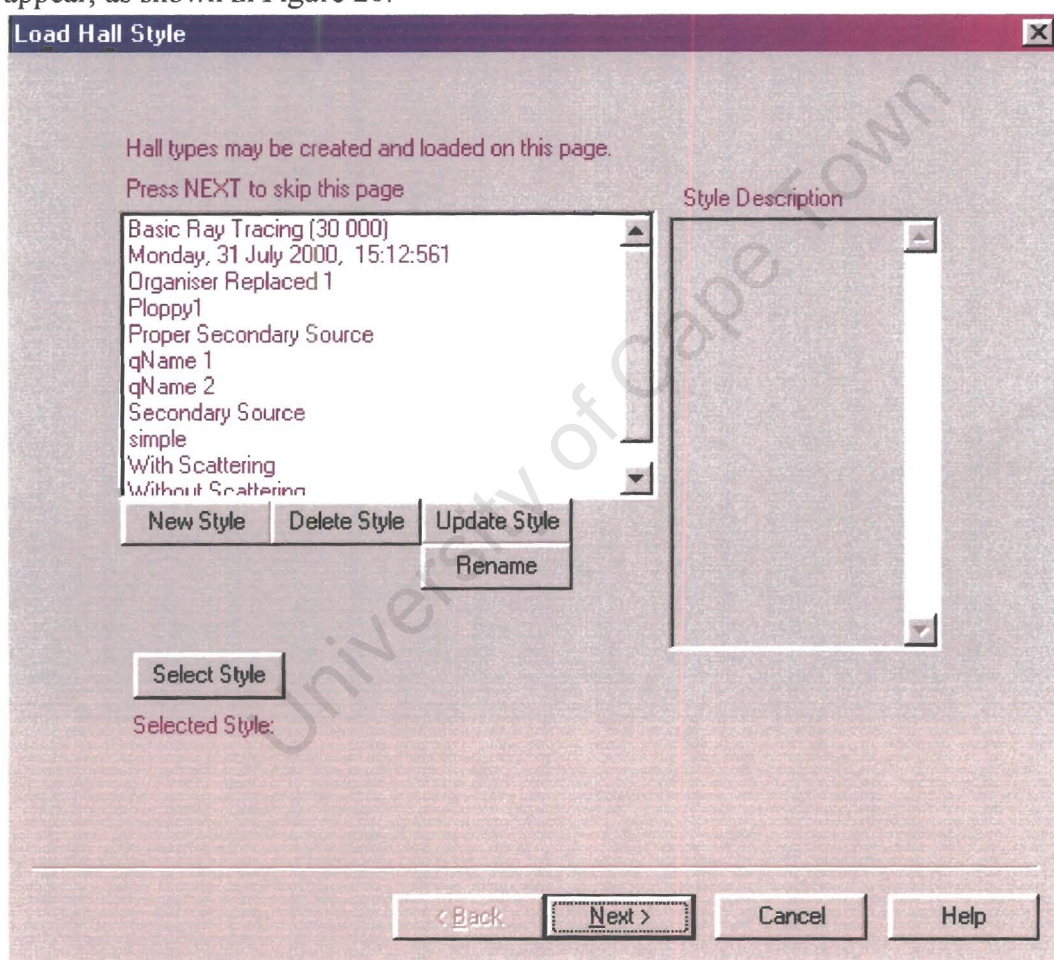


Figure 20: SimWizard Box

This page contains a window where a number of user specified simulation styles are given. To select all the simulation parameters in one go select the desired simulation style and press the *Select Style* button. The simulation parameters of the program will be immediately changed. The *Next* button at the bottom of the box will change to a *Finish* button. Press this to leave the SimWizard box. Do not press the *Next* button at any time.

2.1.1. Add a Simulation Style

To add simulation styles to the list press the *New Style* button. A box will appear in which the name for the new style can be entered. Once this is done and the *Ok* button is pressed a new simulation style with that name will be created. The simulation parameters associated with the new style will be those that were currently selected, as fully described in 2.2.

Therefore the correct procedure for adding a new simulation style is to first select the simulation parameters as desired from the simulation parameters box. Then open the SimWizard box and create a new style.

2.1.2. Update a Simulation Style

If the user wishes to change the simulation parameters associated with a particular simulation style name, then the following steps should be performed:

- Select the desired simulation parameters from the Simulation Parameters box (see 2.2).
- Open the SimWizard box and select the style to be updated.
- Press the *Update Style* button.

2.1.3. Delete and Rename a Style

To delete or rename an existing style select the style and press the *delete* or *rename* style button respectively.

2.1.4. Comments on a Style

The long window to the right of the style list window provides space for the user to type comments about a style. The sequence of steps for adding or changing a comment is as follows:

- Select the style who's comment is to be changed
- Press the *select style* button.
- Add or change the comment.
- Press the *Update Style* button.

2.1.5. The Next Page

If the *Next* button is pressed a different page will appear. This page is still under construction and should be ignored. If this occurs press the *Cancel* button to leave the SimWizard box.

2.2. Selecting Simulation Parameters Manually

All the simulation parameters governing the operation of the simulation can be changed manually by the user. To access this page select *Options|Simulation Options* from the menu. The simulation parameters box consists of a number of pages, each of which is discussed below.

2.2.1. Air Simulation Parameters

The *Air* page of the simulation parameters box is shown in Figure 21

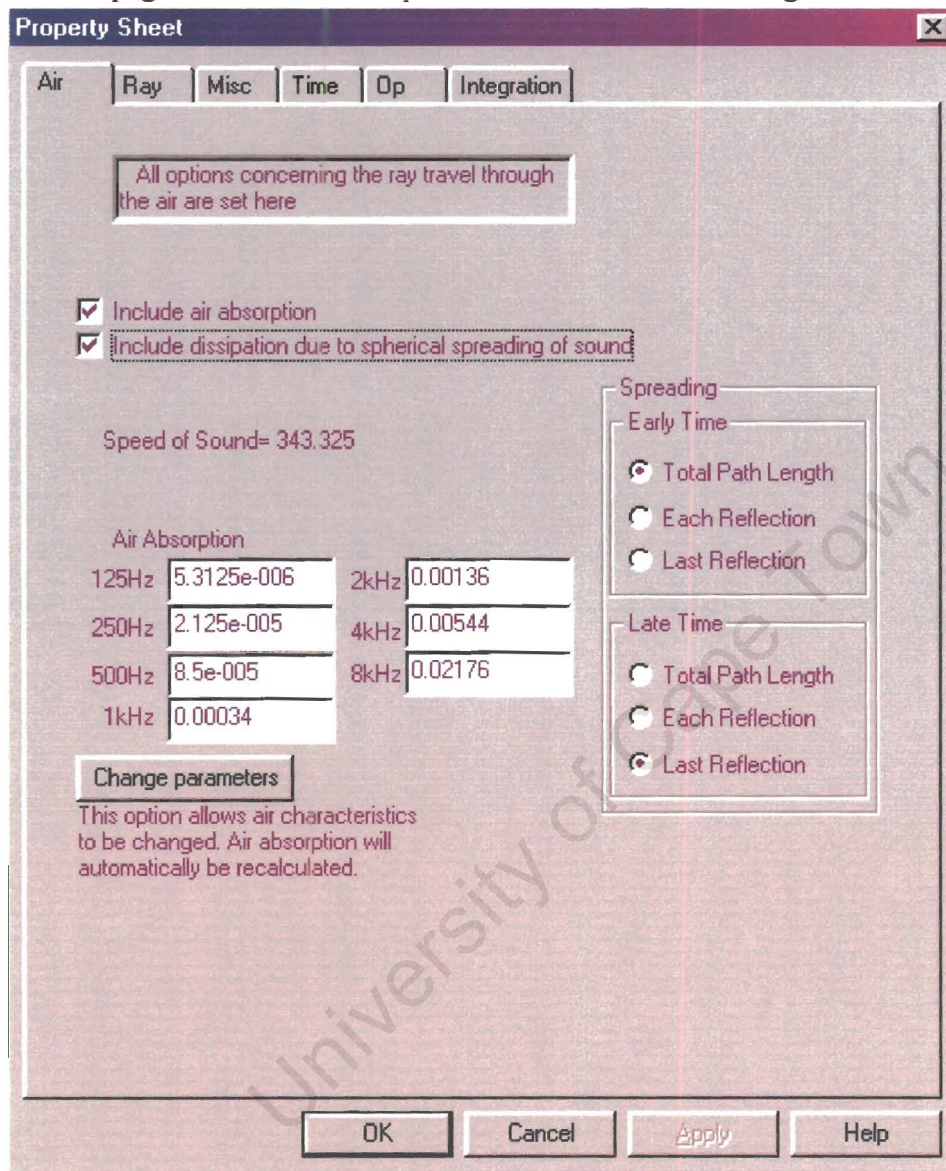


Figure 21: Simulation Parameters Box: Air Page

This page contains information concerning the medium of propagation of the sound. Most of this information should remain unchanged.

- The *include air absorption* check box should be ticked
- The *include dissipation* check box should be ticked
- *Spreading Early Time* should be *Total Path Length* always
- *Spreading Late Time* should be *Last Reflection* for Secondary Source simulations and *Total Path Length* for Ray Traced simulations.

- *Air Absorption* is automatically calculated by the program. The values can either be changed by hand or the *Change Parameters* button can be pressed. This allows the humidity and the temperature of the air to be altered, based on which the air absorption coefficients and the speed of sound will be recalculated.

2.2.2. Ray Simulation Parameters

The ray simulation parameters page is shown in Figure 22.

Property Sheet

Air Ray Misc Time Op Integration

Maximum number of rays: 200 This number is approximate since in some situations fewer rays will be simulated.

Kill ray after 200 reflections.

Kill ray when it is weaker than -60 dB

Kill ray when it is longer than 1 seconds

Ray distribution method Random Evenly Distributed

Drop 0 %rays after 0.5 seconds.

The remaining ray's energy will decrease proportionally. This speeds up the simulation without losing accuracy.

OK Cancel Apply Help

Figure 22: Simulation Parameters Box: Ray Page

This page contains information concerning individual rays in the simulation. The fields that can be changed are:

- *Number of Rays*: Should be about 500 for secondary source simulations and about 30000 for ray-traced simulations. The actual number of rays to be simulated may

be less than this value if the *ray distribution method* options is set to *evenly distributed*.

- *Kill Ray after x Reflections*: If this option is ticked then each ray will be terminated after x reflections. This should usually be set to some large value.
- *Kill Ray when weaker than x decibels*: If this option is ticked then each ray will be terminated when its strength is less than x decibels below the source intensity level. This should usually be set to -60dB .
- *Kill Ray when it is longer than x seconds*: If this option is ticked then each ray will be terminated when its travel time is longer than x seconds. This provides an upper limit to the simulated impulse response time. At least one of the above three options must be ticked.
- *Ray Distribution Method*: This should be *Evenly Distributed*. This ensures that rays are generated in an even manner about the source.
- *Drop x % rays after y seconds*: This should be 0% for all simulations except secondary source simulations, where $x=90$ and $y=0.5$ are suitable values. Even for secondary source simulations $x=0$ is a suitable value.

2.2.3. Miscellaneous Simulation Parameters

A screen shot of the miscellaneous simulation parameters page is shown in Figure 23.

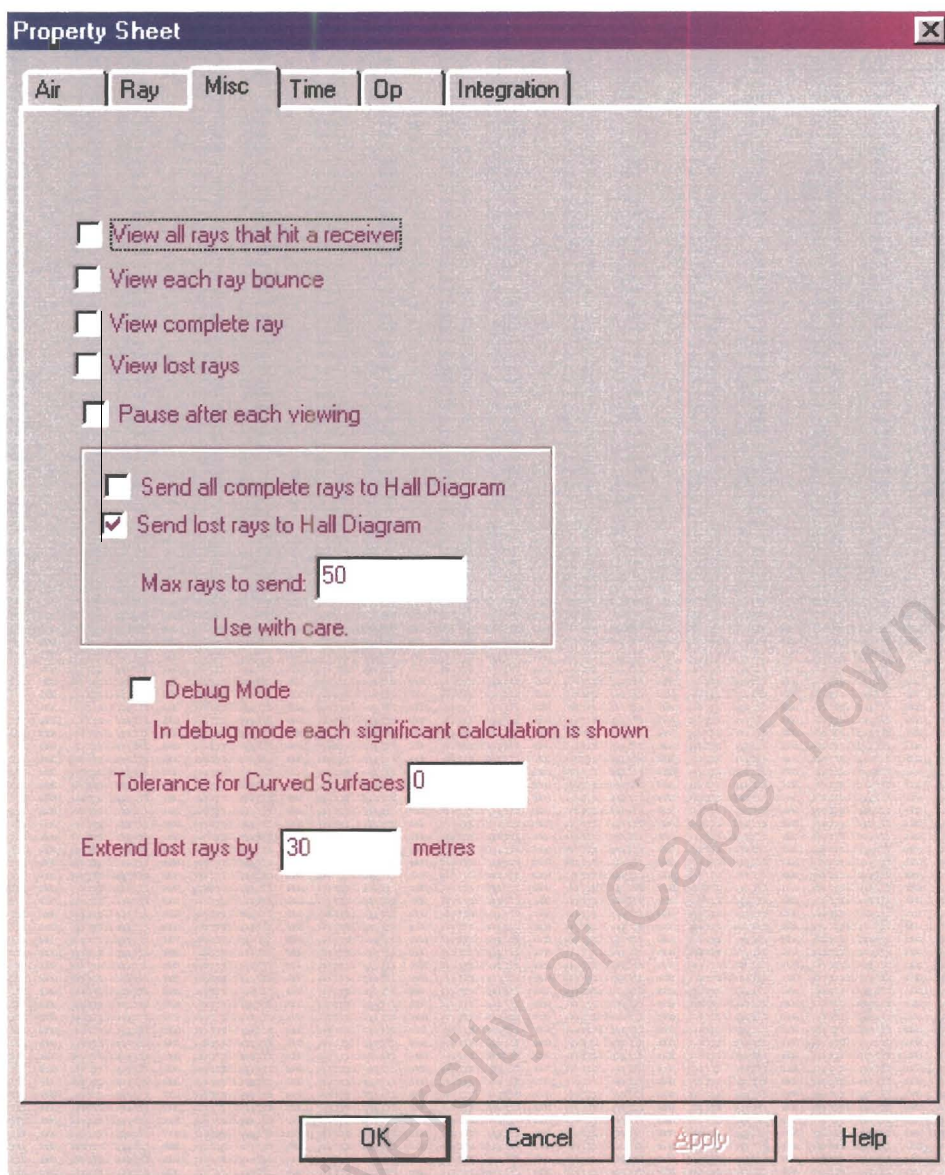


Figure 23: Simulation Parameters Box: Miscellaneous Page

This page contains options that are not vital to the simulation process itself but may aid in examining simulation results.

The options are:

- *View all rays that hit a receiver*: If ticked then, during the simulation, the ray path of any rays that hit a receiver are drawn on the hall diagram. Each successive ray replaces the previous ray.
- *View each ray bounce*: Similar to above except at every bounce the ray is sent to the hall diagram.
- *View complete ray*: Similar to above except every ray that is completed is sent to the hall diagram.
- *View lost rays*: Similar to above except those rays which are lost are sent to the hall diagram. Lost rays are rays that have left the hall diagram. This occurs

because of gaps in the hall diagram or because the source point is outside the hall diagram. Lost rays are always detrimental to the simulation results unless the user has special circumstances that are to be examined.

- *Pause after Viewing*: This option affects all the previous *view* options. After each ray which is sent to the hall diagram the simulation will pause and wait for the user to continue the simulation.
- *Send all Complete Rays to Hall Diagram*: This option operates similarly to the previous *view complete ray* option except that the rays are stored in the hall diagram in a group and can be viewed after the simulation is complete. (see also 5.3).
- *Send Lost rays to Hall Diagram*: This option operates like *Send all complete rays to Hall Diagram* except only lost rays are sent to the hall diagram.
- *Max Rays to Send*: This option effects both the above *Send...* options. Only x number of rays will be remembered by the hall diagram. This is useful for example where a large number of rays are lost but only a smaller number are to be retained for inspection. This number can be any positive value.
- *Debug Mode*: This option allows the user to inspect the progress of the simulation in fine detail. In very few cases will the user desire this option to be active and it should generally be left unchecked.
- *Tolerance for Curved Surface*: In some circumstances where a large number of curved surfaces are used in the room model, floating point number rounding off errors may occur. The simulation program will handle these automatically in an appropriate manner. This value should be set at 0.1 or lower at all times. If a large number of rays are still lost this value can be increased. Do not increase this value above 0.
- *Extend Lost rays by x meters*: Lost rays are rays that have passed outside the room model. Their length is therefore infinite or rather indeterminate. When and if they are sent to the hall diagram the length of final (indeterminate) segment will be set at x meters. 30 meters is a typically useful value.

2.2.4. Time Simulation Parameters

The time simulation parameters page, as shown in Figure 24, governs the relationship and division between early and late time.

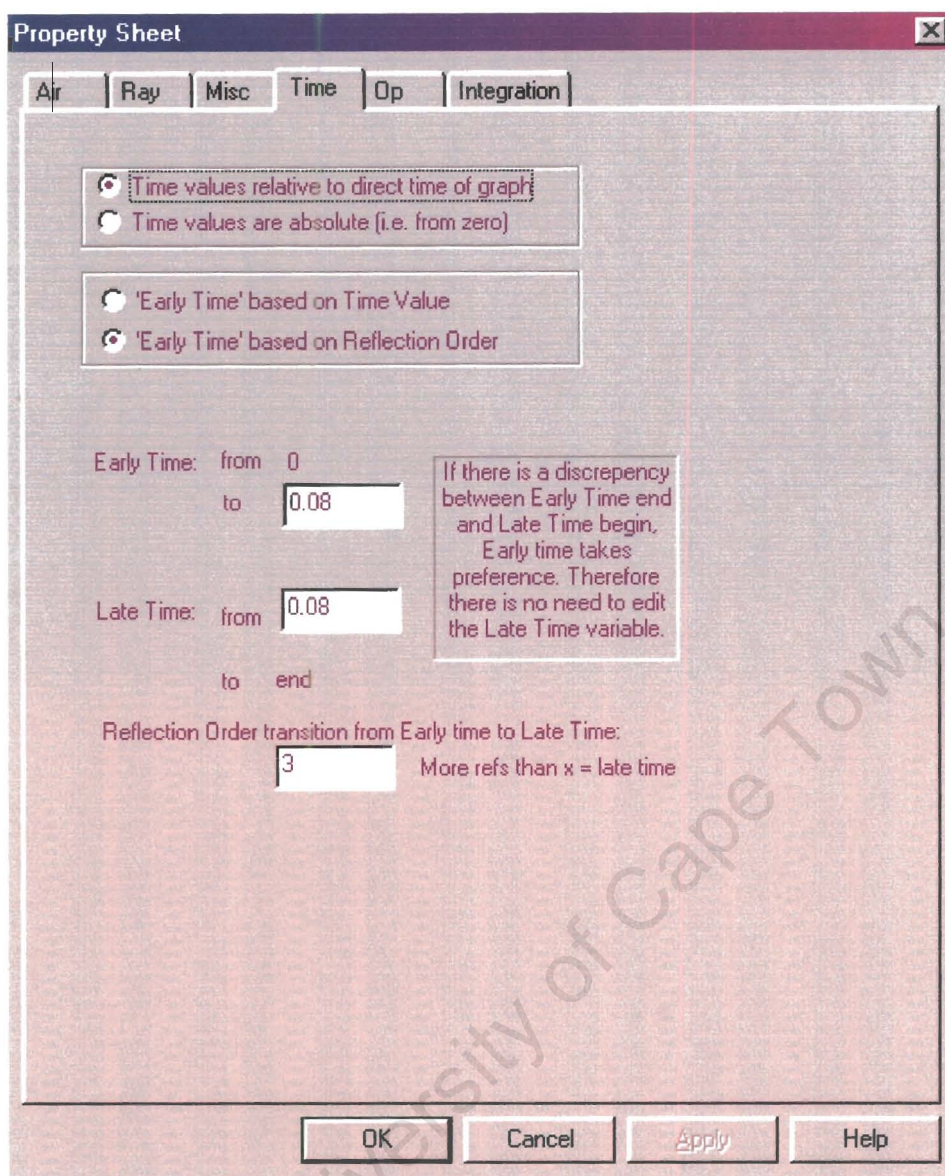


Figure 24: Simulation Parameters Box: Time Page

The division may be defined as a time interval, usually 80ms after the direct sound, or as a number of reflections.

- *Time values...*: If *relative to direct time of graph* is selected then the values for *early time* and *late time* are interpreted as relative to the arrival time of the direct sound for each receiver separately. The direct sound is set as the straight line distance from the source point to the receiver point, regardless of whether surfaces obstruct this path or not. If *absolute* is selected then the time values are interpreted as from zero time.
- *Early Time based on...*: If *time value* is selected then the early time is set as from time zero to the value in the *early time* box. If *reflection order* is selected then the early time is set as up to the number of reflection in the *reflection order transition* box. For secondary source simulations the *reflection order* option should be selected. For ray traced simulations the *time value* should be selected.

- *Early Time* value: This value determines the maximum time for reflections to be considered in the early time. It is only used if the *early time based on time value* option described above is selected.
- *Late Time* value: This value should be ignored.
- *Reflection Order Transition*: This specifies the maximum number of reflections a ray can have to remain classified as being in the early time. It is only used if the *early time based on reflection order transition* option described above is selected.

2.2.5. Operations (Op) Simulation Parameters

The operations page of the simulation parameters box is the most complicated and detailed page (Figure 25). It governs the most detailed workings of the simulation program. In order to understand most of the options on this page it will be necessary to have an understanding of the simulation mechanism as explained in the body of the associated thesis. A summary of the most commonly used settings will be given after an explanation of each of the options.

University of Cape Town

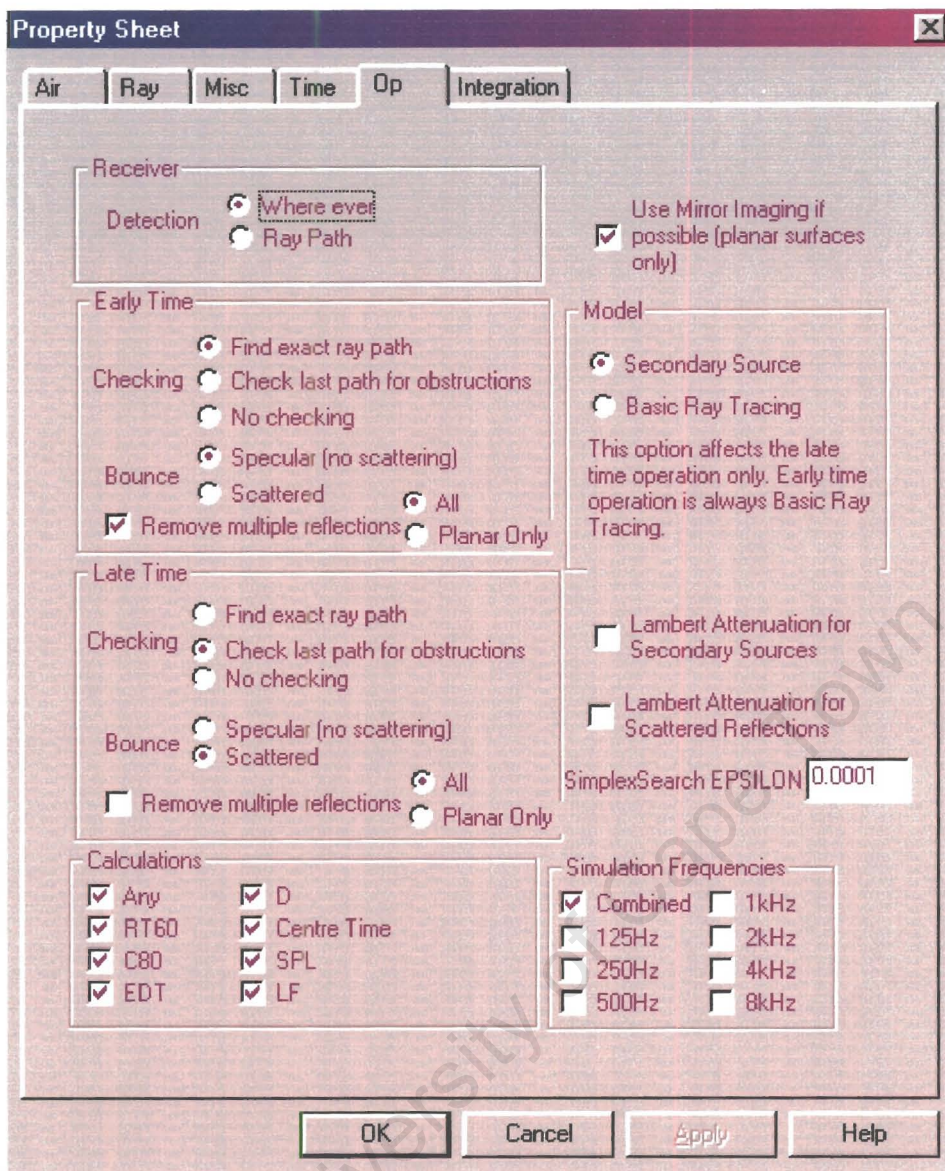


Figure 25: Simulation Parameters Box: Operation Page

2.2.5.1. Receiver Group

There are two possible receiver detection methods: *Wherever* and *RayPath*. *Wherever* should be user for secondary source simulations and *RayPath* should be used for ray path simulations.

2.2.5.2. Early Time & Late Time Groups

Both the early time and late time groups have the same options and operate in the same manner. The early time group describes how reflections in the early time are treated (see also 2.2.4) and similarly the late time group describes how reflections in the late time are treated. The options are:

- *Checking: Find exact ray path* forces the simulation to find the exact ray path for such a ray. This option should be selected for the early time group. *Stop Press: If*

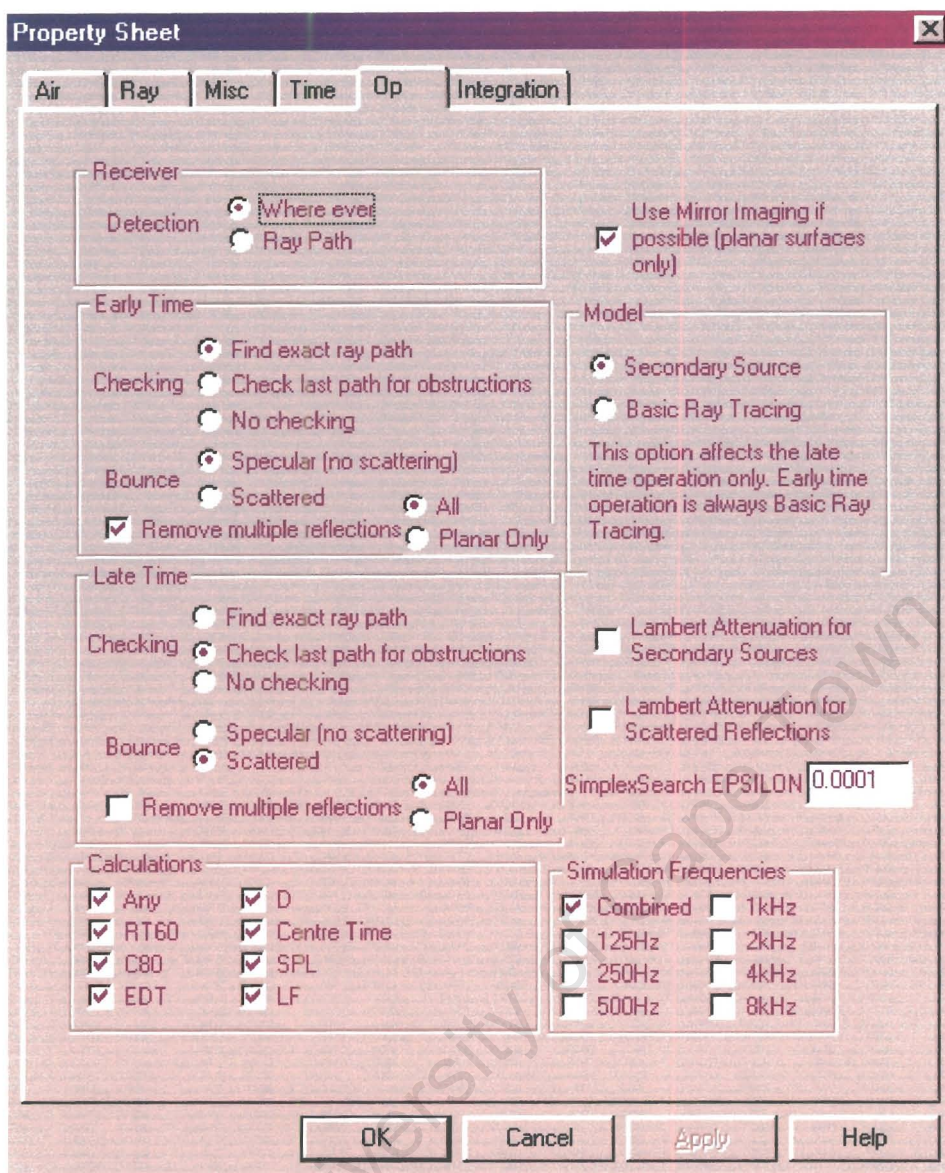


Figure 25: Simulation Parameters Box: Operation Page

2.2.5.1. Receiver Group

There are two possible receiver detection methods: *Wherever* and *RayPath*. *Wherever* should be user for secondary source simulations and *RayPath* should be used for ray path simulations.

2.2.5.2. Early Time & Late Time Groups

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- **Checking:** *Find exact ray path* forces the simulation to find the exact ray path for such a ray. This option should be selected for the early time group. *Stop Press:* If

the check option next to the *find exact ray path* is checked (not shown in Figure 25) then all rays in the early time will be checked after each bounce. This option should be checked in the early time group.

- *Checking: Check last path for obstructions* should be selected in the late time for ray path simulations.
- *Checking: No Checking* should be selected in the late time for secondary source simulations.
- *Remove Multiple Reflections*: This option should always be checked in the early time, and the sub-option *planar-only* should be selected. This also applies for the late time for ray path simulations. For secondary source simulations the *remove multiple reflections* option should be unchecked in the late time.

2.2.5.3. Simulating Model

This selects between the two basic simulation types, basic ray tracing or secondary source. Take note of the comments associated with most of the simulation parameters to ensure that all parameters are set correctly for the simulation type.

2.2.5.4. Calculations

This group specifies which room acoustic parameters are calculated. All of the options should be selected, although in this version of RoWena not all the parameters are calculated properly, if at all.

2.2.5.5. Simulation Frequencies

This group specifies which frequencies are to be simulated. Usually only the option *combined* should be selected. However in the case of scattering where the scattering coefficient is different for each frequency only the frequencies of interest should be selected and the option *combined* should not be selected.

2.2.5.6. Other Options

The thus far unnamed options are:

- *Use mirror imaging if possible*: This option should always be unchecked.
- *Lambert attenuation for secondary sources*: This option should always be unchecked.
- *Lambert attenuation for scattered reflections*: This option should always be unchecked.
- *SimplexSearch EPSILON*: This value should be about 0.0001.

2.2.6. Integration Simulation Parameters

The integration parameters page governs the resolution of the simulated graph and is shown in Figure 26.

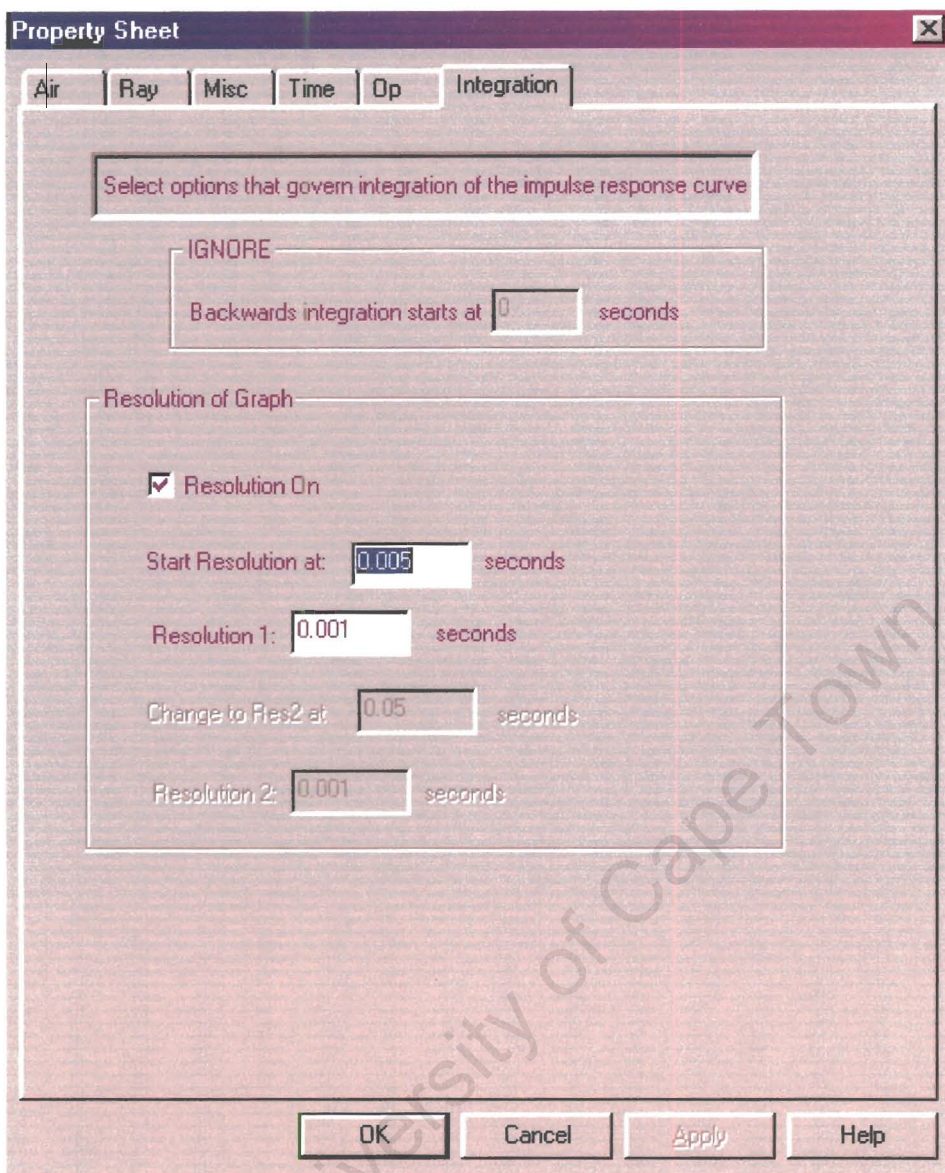


Figure 26 Simulation Parameters Box: Resolution Page

Since the sound field in a room is generally considered to be diffuse it is allowable to add the intensities of reflections arriving simultaneously together. From this page the interval within which reflections are assumed to be simultaneous can be specified.

In most cases it is advisable to leave resolution off, i.e. to ensure that the option *Resolution On* is unchecked. Doing this has no effect on the simulation results and means that the ray paths of individual reflections can be inspected. If resolution is on the resultant simulated impulse response graph may look more accurate but individual reflections cannot be inspected.

3. Running the Simulation

Once the room model is correct and the simulation parameters have been set, it is time to begin the simulation. To do this select *Simulate|Begin Simulation* from the menu. A confirmation box as shown in Figure 27 will appear.

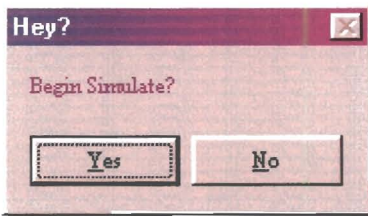


Figure 27: Begin Simulation Confirmation Page

Select *No* to abort starting the simulation or *Yes* to begin the simulation.

If *Yes* is selected then the organiser page as described in 1.5 will appear. The user is required to select a group into which the graphs produced by the simulation will be placed. To do this select a group by clicking on it and pressing the *Select* button. It is also possible to create a new group by pressing the *New Group* button as described in 1.5.12.

Once the *Select* button is pressed the simulation will begin. Depending on circumstances and the type of simulation selected it may be necessary to calculate the mean free path length before the simulation proper can begin. If this is so a box as shown in Figure 28 will appear.



Figure 28: Mean Path Progress Box

When the calculation of the mean free path length has completed the box shown in Figure 29 will appear.

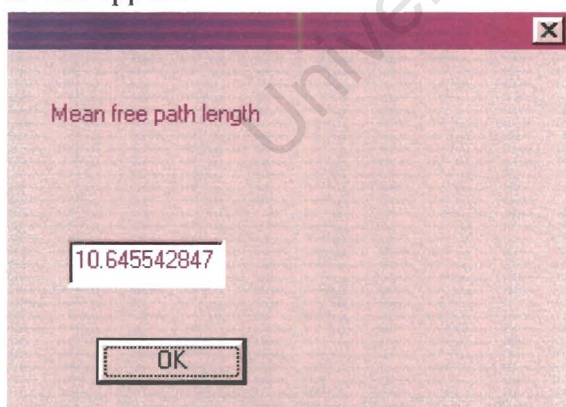


Figure 29: Mean Path Length Box

Press the *Ok* button. If the user is aware of what the mean free path length is and wishes to modify the value at this stage this may be done. Also if while the mean free path length is being calculated and the value shown in the title bar of the progress box (for example

the value is 10.882 in Figure 28) appears to remain constant then the *Cancel* button can be pressed during this calculation. It is recommended however that the process be allowed to continue to completion.

At this stage, either the mean free path length has been calculated or it was not necessary to calculate it. In either case the simulation proper will begin. A progress box as shown in Figure 30 will appear.

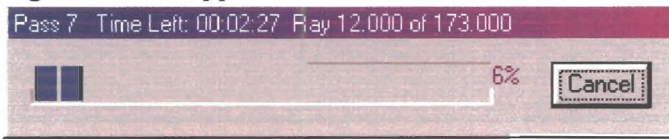


Figure 30: Simulation Progress Box

It is not possible to interact with the program while a simulation is in progress. The simulation may be aborted by pressing the *Cancel* button at any time, although the response to the button may take some time. Also note that if another window is made active by the user and then the user changes back to RoWena, it may take a few seconds before RoWena is displayed. Be patient.

The progress box contains the following information:

- *Pass x*: This can be ignored
- *Time Left*: This is the estimated simulation time remaining.
- *Ray x of y*: x is the number of the ray currently under simulation and y is the total number of rays to be simulated. Note that this number may be less than the number of rays specified in the ray parameters page (see 2.2.2).
- $x\%$: This shows the percentage of the rays already simulated.
- *Swivel*: This is a rotating symbol. As long as it rotating the simulation if progressing ok.

Once the simulation is complete, which may take some time, the box shown in Figure 31 will appear.

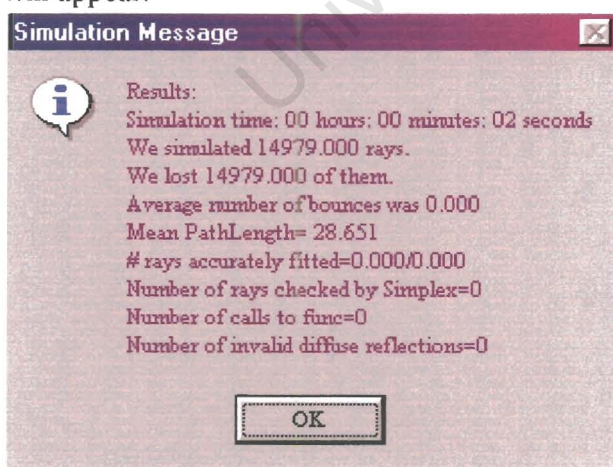


Figure 31: Simulation Completed Box

If while the simulation has been in progress the user has changed to another application, it may be necessary to select the 'Simulation Message' box from the task bar in order to see this box.

The box contains the following information, most of which is intended for the system programmer and all of which can be ignored by the user:

- *Simulation Time*: The actual time to completion of the simulation
- *The number of rays simulated*
- *The number of lost rays*: This values should usually be zero. In the example in Figure 31 the simulation was an exceptional case where an intentional gap in the hall model was left. If the value is less than 0.1% of the total rays simulated then the simulated results will not be adversely affected.
- *Average number of bounces*: This is the number of bounces for each simulated ray averaged over the number of rays simulated, excluding lost rays.
- *Mean Path Length*: The mean path length as calculated by the simulation program.
- *# rays accurately fitted*: This is the number of rays for which exact simplex searched rays path were found.
- *Number of calls to func*: this is the number of times the simplex search algorithm called the ray-tracing algorithm in total.
- *Number of Invalid Diffuse Reflections*: This is the number of scattered reflections for which the scattered reflection direction was calculated incorrectly. This value should be zero.

Press *Ok* to close this box.

At this stage the simulation is complete. A number of graphs will have been created dependant on the number of active receivers specified.

4. Simulated Impulse Response Graphs

The simulated impulse response graphs are the end result of the simulation. Since they are a vital part of the program there are a very large amount of commands and manipulations that can be performed on them. This guide will describe only a small amount of them. The user is encouraged to experiment and to discover the various means in which the information on the graph can be presented.

An example graph is shown in Figure 32. Simulated graphs created with different simulation parameters or different room models may have different shapes or density of reflections. However some basic similarity should be discernable.

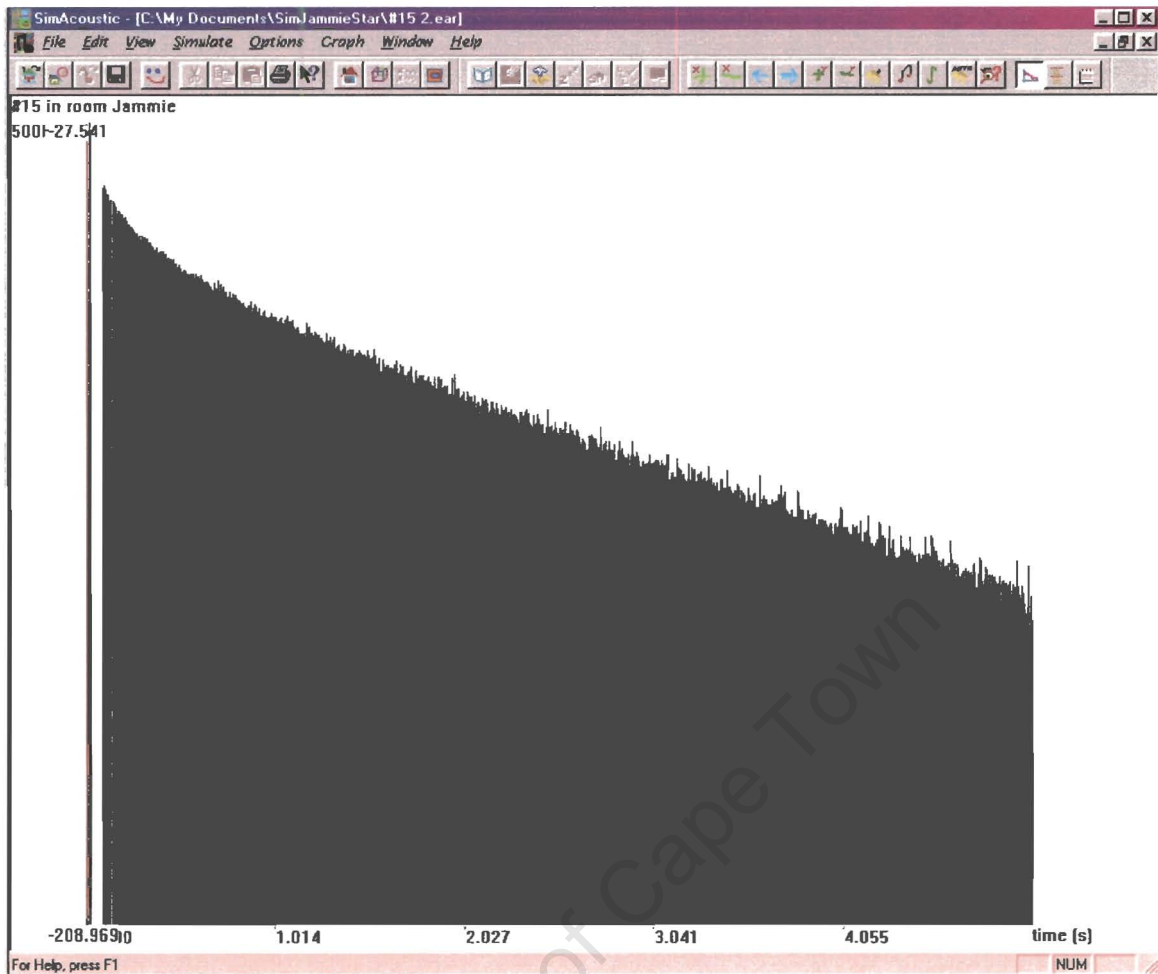




Figure 32: Simulated Impulse Response

4.1. Calculating the Reverberation Times

In this version of RoWena the only valid(?) measurement obtainable from the graph is the reverberation times. To obtain this value perform the following steps:

- *View the graph:* The graph must be visible on the screen and selected. If necessary open the *Window* menu item and select the desired graph. The graphs will all have the same name as the receiver name they are associated with.
- *Integrate the graph:* Press the integrate button (). The integration may take some time.
- *Turn the integration graph on:* A small integration toolbar will have appeared, which looks like . The first button has the word *on* written on it. If the button is pressed the integration curve will be drawn. Pressing it again will hide the integration curve.
- *Set the integration limits:* If the integration curve is visible then the two arrow buttons on the integration tool bar will be active. Choose the longest straightest part of the integration curve by clicking the left arrow button and then clicking on

the left part of the straight section on the integration, and similarly for the right part. An example of the result is shown in

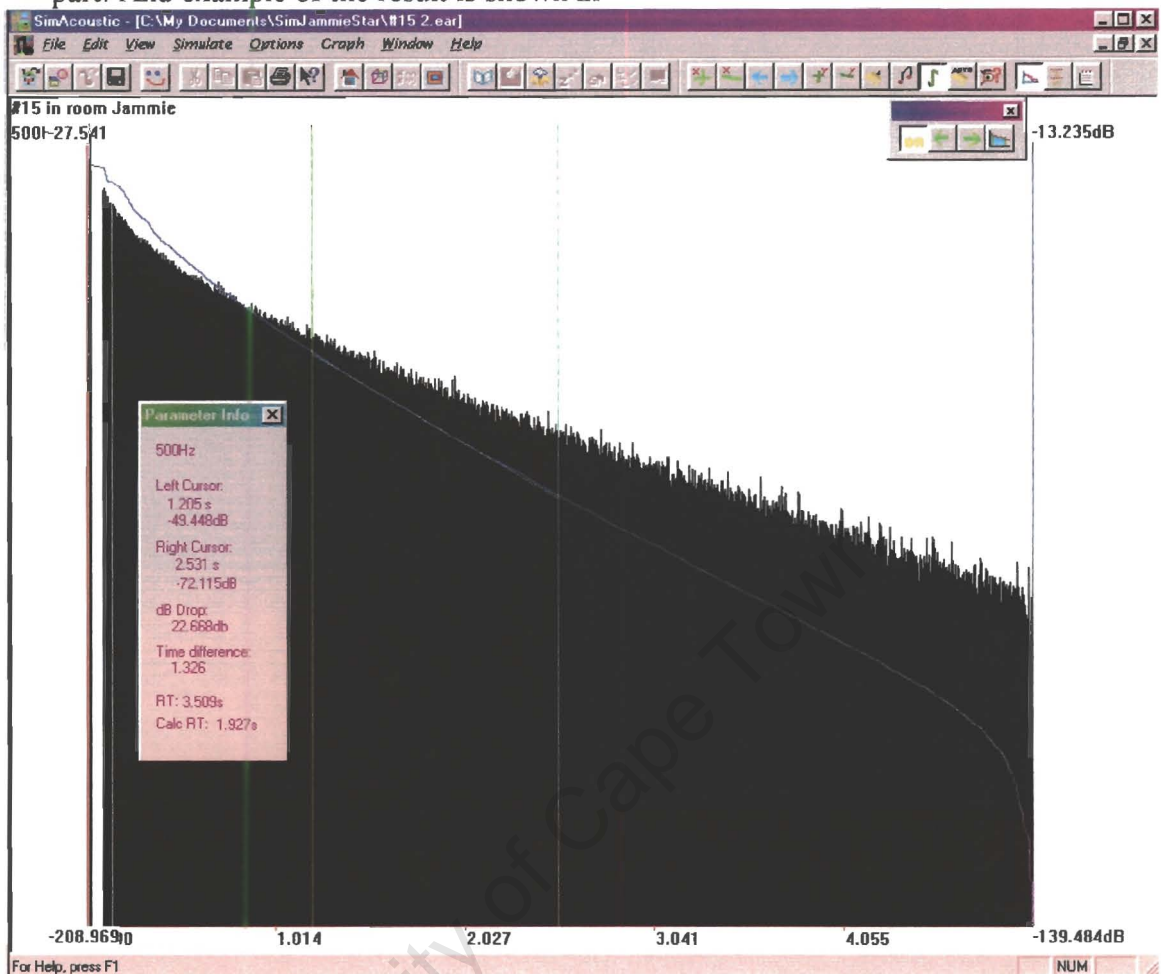


Figure 33: Backwards Integrated Impulse Response Graph



- *Read RT60 (Reverberation) Time:* The tall box called *Parameter Info* shows the frequency of the displayed graph (e.g. 500Hz), the position of the left and right cursor, and at the bottom the reverberation time (e.g. RT=3.509s). The calculated reverberation time is beneath for comparison (see 1.4). In the example shown in Figure 33 the calculated time is incorrect because of errors in the calculation of the area of the dome.
- *Repeat for Other Frequencies:* To view the reverberation times for other frequencies select *Graph|Active Graph*. The box shown in Figure 34 will appear.



Figure 34: Frequency Selection Box

From this box select the frequencies to display and then repeat from the *set the integration limits* step.

4.2. Other Acoustical Parameters

RoWena automatically calculates EDT, C50, C80, Center-Time, Definition and Sound Pressure Level. The accuracy of these calculations has not been verified, though informal inspection indicates that they are not useful values. To view the values press the  button in the graph toolbar. The graph will disappear and will be replaced by a table showing these results. To show the graph again press the  button.

4.3. Scaling the Graph

To zoom in or out of the graph select *Graph|Scale*. The box shown in Figure 35 will appear.

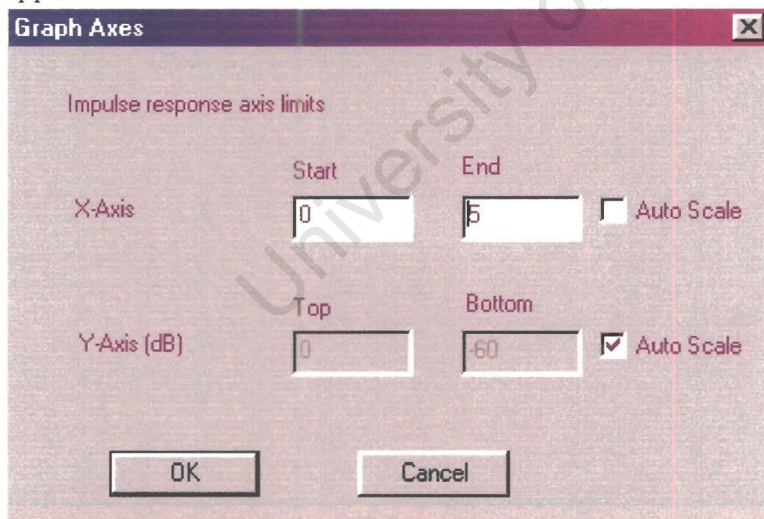


Figure 35: Graph Scaling Box

In this box the user can either select the limits of both the x- and y-axis, or select auto scale that scales the graph so that all reflections are visible.

An alternative method of scaling the graph is to use the mouse. To enlarge a portion of the graph on the x-axis, hold down the *left mouse button* at the left hand side of the

portion and then drag the mouse to the right while holding down the *left mouse button*. When the mouse button is released the selected portion of the graph will be scaled to fit the screen. The same technique can be used to scale the y-axis.

See also 8 for another method of scaling the graph.

4.4. Inspecting Individual Reflections

Any of the reflections in the graph, unless *resolution* was on (see 2.2.6), can be inspected. To do this scale the graph so that the reflection to be inspected is visible. Then place the mouse pointer over the reflection and click with the right mouse button. A small box should appear with a description of the reflection as shown in Figure 36. If the graph contains a lot of reflections then it might take a few seconds for the program to find the reflection.

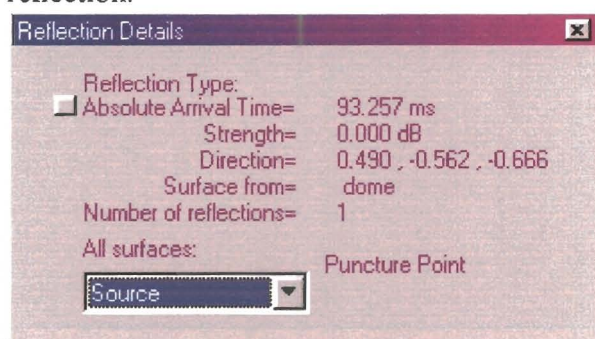


Figure 36: Reflection Details Box

This box shows:

- The *arrival time* of the reflection.
- The *intensity* of the reflection
- The *direction* of the reflection as seen from the last surface reflected from
- The *last surface* reflected from before hitting the receiver.
- The *number of reflections* of the ray, which is equivalent to the number of surfaces in the ray path.
- A list of *all surfaces* hit, which is contained in the drop down list in the order that the ray encountered them.

Also if the hall diagram box is open then the ray path of that reflection will be shown (see 5.3).

An alternative method is to select *Graph|All Reflections*. The box shown in Figure 37 will appear.

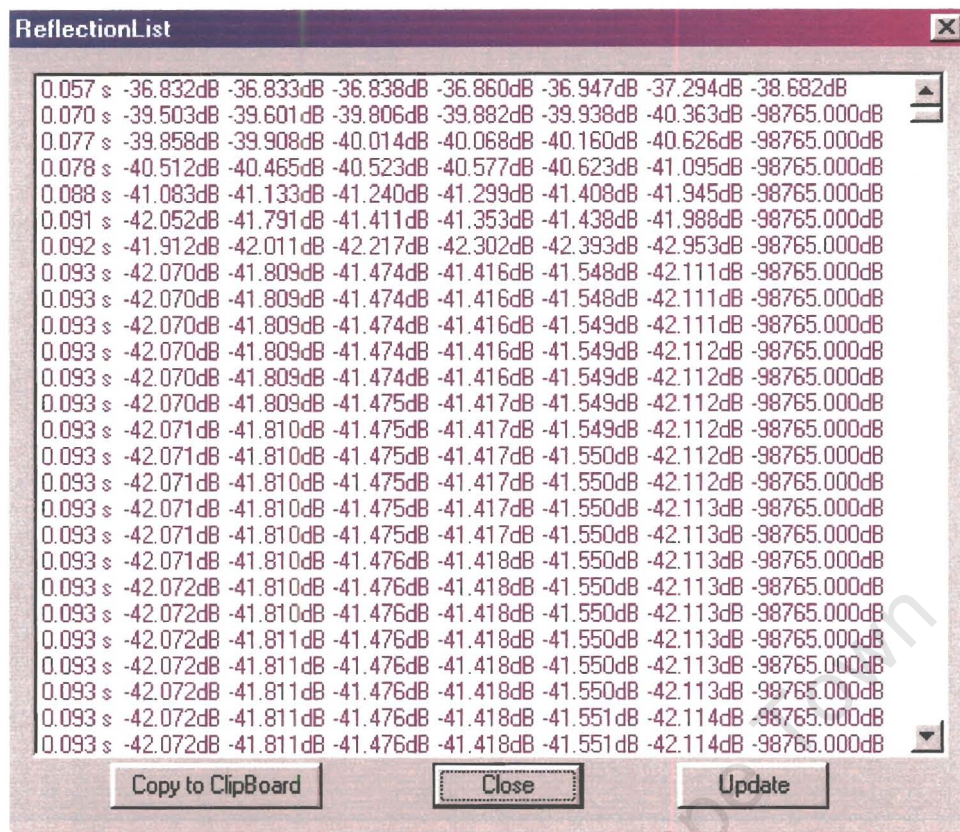


Figure 37: All Reflections Details Box

This box contains basic details on all the reflections in the graph. If the user clicks on one of the reflections in the box it will be selected in the graph in the same manner as described above.

Pressing the *Copy to Clipboard* button will cause all the reflections to be copied to the clipboard in a manner suitable for pasting into an Excel worksheet.

4.5. Size of Graph Files

Some simulated impulse response graph files can become very large. For this reason it may be more efficient to simulate a small number of receivers at a time, say 5. A computer with more memory will cope with more graph files in memory simultaneously. Once the memory is full Windows will automatically start to use the hard drive to make space in the memory. This can slow down the simulation dramatically and also cause potential errors.

5. The Hall Diagram Box

The hall diagram box was originally intended simply for a visual confirmation that the hall in memory was correct. Its functionality has since been extended dramatically to become an integral part of the prediction package. To view the hall diagram box select *View|Hall Diagram*. Figure 38 shows the hall diagram box displaying the Jameson Hall in isometric view.

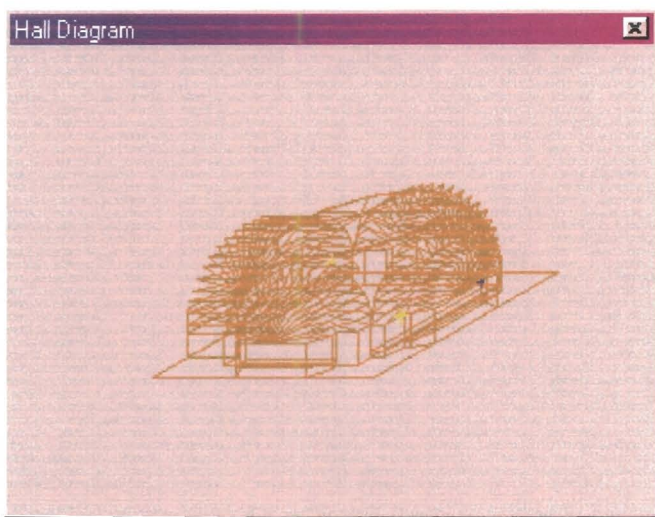



Figure 38: Jameson Hall Diagram Box

5.1. Ensuring the Hall Diagram Displays the Hall Model

If there is no hall in memory then this window will be blank. Alternatively it may be necessary to rescale the hall model so that it is displayed correctly in the hall diagram box. To do this observe that when the hall diagram box is on a toolbar appears on the right of the screen. This toolbar contains buttons that control the functionality of the hall diagram box. If this toolbar is not visible select *Options|General Options*, then the *Toolbar* page and ensure that the *hall diagram toolbar* check box is ticked.

Press the button . The box shown in Figure 39 will appear.

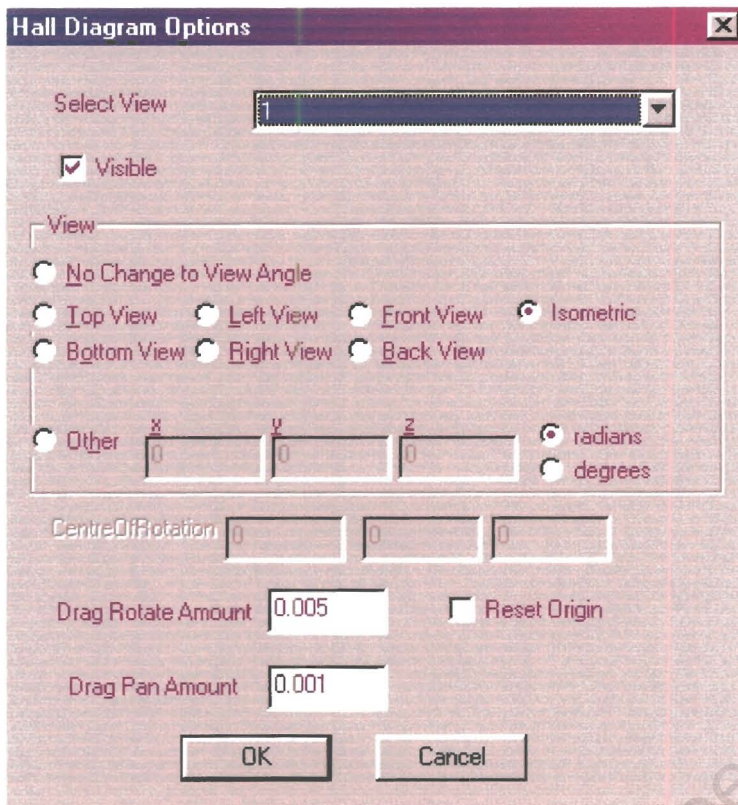


Figure 39: Hall Diagram Options Box

The hall diagram window may show up to six different views of the hall diagram. The user may experiment with the different options. For now, in order to ensure that at least one view is visible ensure the following:

- *Select View*: displays a 1 as shown in Figure 39.
- *Visible*: is ticked as shown in Figure 39
- *View*: Can be any of *Top View*, *Left View*, *Front View*, *Isometric*, *Bottom View*, *Right View*, *Back View* and *Other* are not operational.
- *Reset Origin*: is ticked, as NOT shown in Figure 39. Ticking this option causes the hall diagram to rescale the currently selected view (#1 in this example). Whichever view is selected when the *Ok* button is pressed will have its origin reset.
- *Drag rotate Amount* and *Drag Pan Amount*: leave them as shown in Figure 39.
- *Press the Ok button*
- *Zoom In*: Because the hall diagram view was rescaled it may have become very small, too small to be seen. To enlarge it either click repeatedly on the  button in the hall diagram toolbar or hold down the *control* key on the keyboard and simultaneously press the left mouse button while the mouse pointer is over the hall diagram box and move the mouse down.

5.2. Manipulating the Hall Diagram View

The currently selected hall diagram view can be zoomed in and out, moved around the hall diagram box and rotated around any primary axis.

5.2.1. To Change the Currently Selected View

If only one view of the hall diagram is visible this section does not apply. To display more than one view of the hall diagram follow the steps in 5.1 but instead of using view #1 select a different view, up to a maximum of 6. For example Figure 40 shows three different views of the Jameson Hall.

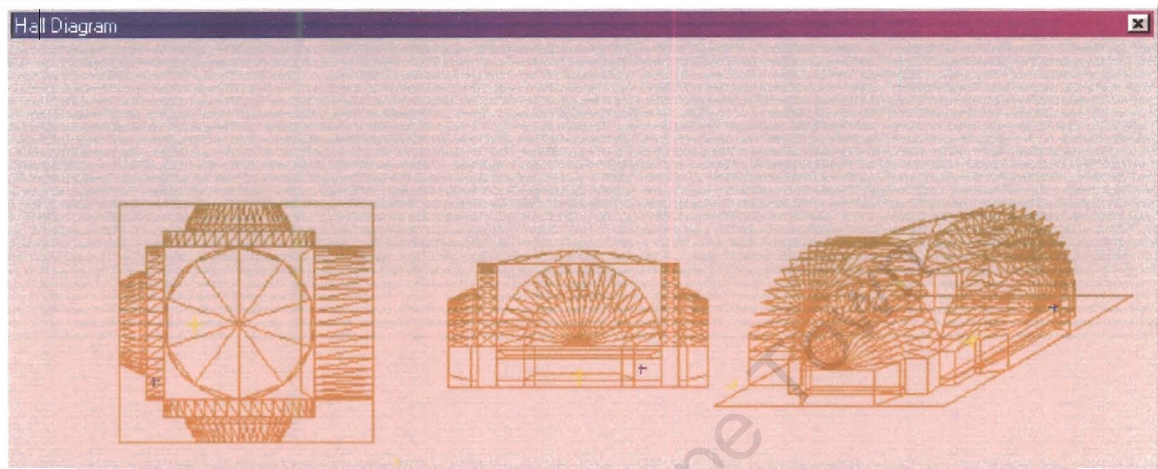





Figure 40: Three views of the Jameson Hall

Only one of the views is active at any one time, meaning that only one of the views can be moved, scaled or rotated. The active view can be changed by pressing the  button on the hall diagram toolbar. Pressing this button cycles through the currently visible views.





5.2.2. To Zoom In or Out of the Hall Diagram View

There are three means to enlarge or reduce the selected hall diagram view:

- Repeatedly press the  and  buttons to zoom in and out respectively.
- Hold down the *control* button and the left mouse button while simultaneously moving the mouse downwards or upwards.
- If the mouse has a mouse wheel then rolling this will zoom the hall diagram in and out.

5.2.3. To Move the Hall Diagram View

There are two means to move the selected hall diagram view around the hall diagram box:

- Repeatedly press the , ,  and  buttons on the hall diagram toolbar.
- Hold down the *left mouse button* while the mouse pointer is over the hall diagram box and move the mouse in any direction to make the selected hall diagram view move in that direction.


5.2.4. To Rotate the Hall Diagram View


The selected hall diagram view can be rotated about any of the x-, y- or z-axes. Isometric views cannot be rotated.

- To rotate the hall about the x- and y-axes hold down the *shift* key and the *left mouse button* and move the mouse in any direction to make the selected hall diagram view rotate.
- To rotate the hall diagram about the z-axis hold down the *shift* key, the *control* key and the *left mouse button* simultaneously which the mouse pointer is over the hall diagram box, and then move the mouse up to rotate the hall diagram view clockwise or down to move the hall diagram view anticlockwise.

5.2.5. To Show or Hide the Receiver and Source Positions

Usually the hall diagram views show not only the hall model but also the positions of the receiver and source points. These are both drawn in the shape of a star. The size of the receiver stars is the same as the size as specified in the receiver page (see 1.2.2) while the size of the source is set at 1 meter though this has no bearing on the simulation.

To toggle or switch between displaying the receiver on the hall diagram views press the  button on the hall diagram toolbar.

To toggle between displaying the source on the hall diagram views press the  button on the hall diagram toolbar.

5.2.6. Changing the Size of the Hall Diagram Box

Like any windows box the hall diagram box can be enlarged or reduced by dragging on the border of the window. The positions of the hall diagram views will move when the hall diagram box is resized in this manner, though they may disappear off the edge of the hall diagram box.

5.2.7. Help: All the Hall Diagram Views are Lost

Sometimes when the RoWena program is closed and restarted the hall diagram views are not displayed correctly. To remedy this error it is necessary to redo the steps described in 5.1.

5.3. Viewing Ray Paths in the Hall Diagram Box

Sometimes the hall diagram box will display a ray path, usually because it has been selected in the graph view (see 4.4) or because it has been sent there during a simulation (see 2.2.3). This section explains the nature of these ray paths and also how to manipulate them.

5.3.1. Single Ray Paths

Sometimes only a single ray path is shown on hall diagram. This ray path may be one of a group (see 5.3.2). The ray path is made up of a number of segments, one of which is selected at a time. In Figure 41 such a ray is shown.



Figure 41: A ray path in the Jameson Hall

The colours of the hall diagram have been changed to improve clarity for this example (see 7.2). The selected ray segment in this example is number 1 of 2 and is shown in white. Information about the selected ray segment is given at the top of the hall diagram box.

To change to the next or the previous ray segment press the < and > buttons on the hall diagram box. The smaller < and > buttons go to the first and last ray segment respectively.

5.3.2. Ray Path Groups

Sometimes a group of ray paths is displayed. This usually occurs when ray paths have been sent to the hall diagram box during a simulation (see 2.2.3). Figure 42 shows the hall diagram box with a ray path group consisting of 6 rays displayed simultaneously.

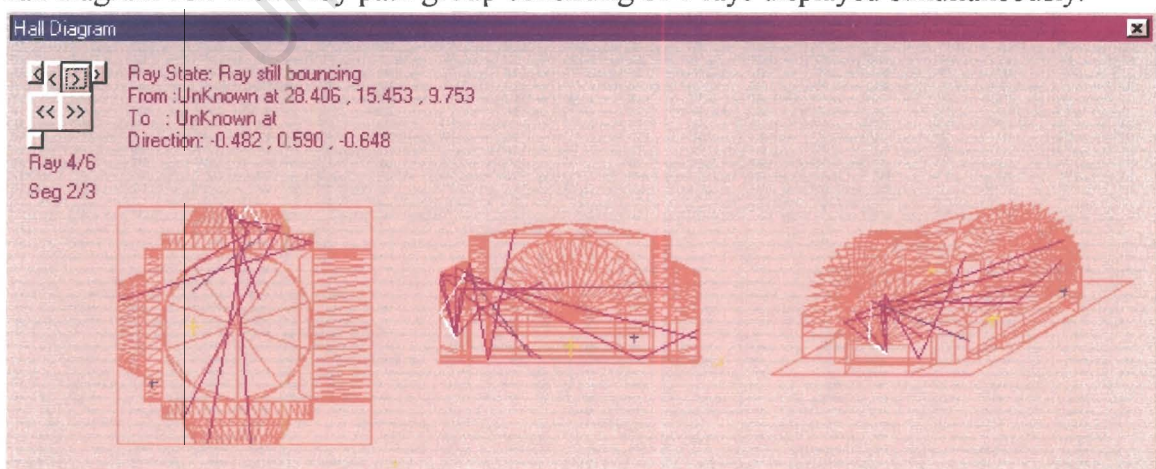




Figure 42: A ray path group in the Jameson Hall

One of the ray paths in the group will be selected, which in this example is #4 out of 6. The selected ray path acts as described in 5.3.1.

5.3.2.1. Showing a Single Ray Path in a Ray Path Group


Showing all the ray paths in a group may cause the hall diagram view to become cluttered. To display only one ray path in the group press the  button on the hall diagram toolbar. To display all the ray path in the group press the button again.

5.3.2.2. Turning Display of the Ray Path Group On and Off

To disable displaying the ray path group press the  button. To turn display of the ray path group on again press the button again.

If a ray path group is displayed it is not possible to show individual reflections as described for example in 4.4. To do this it is necessary to either turn display of the ray path group off or to delete the ray path group (see 5.3.2.3).

5.3.2.3. Deleting a Ray Path Group or a Single Ray Path in the Group

To delete either the entire ray path group or a single ray in the ray path group press the  button on the hall diagram toolbar. The box shown in Figure 43 will appear.

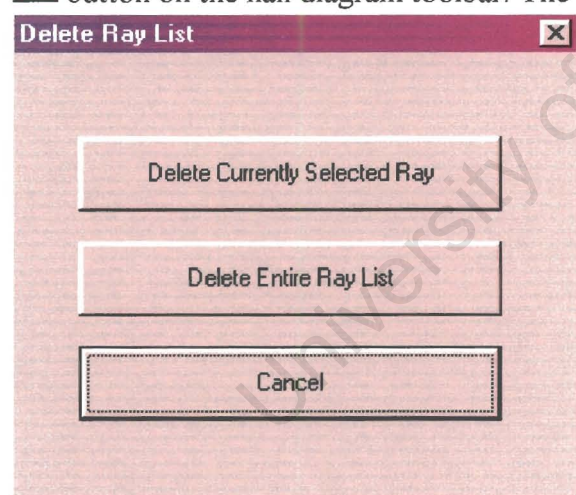



Figure 43: Deleting a ray group confirmation box


To delete the entire ray path group press the *Delete Entire Ray List* button. To delete just the currently selected ray path press the *Delete Currently Selected Ray* button. Press the *Cancel* button to close this box without performing any deleting.

5.3.2.4. Adding a Ray Path to a Ray Path Group

If a single ray path is shown which does not belong to a ray path group it can be added to the ray path group, or be the first of a new ray path group. To do this ensure that the ray path to be added is visible. Then press the  button on the hall diagram toolbar. If this

button is not visible or available then the required conditions have not been met. The ray path will immediately be added to the ray path group or be the first of a new ray path group. In this way a user selected group of rays can be created.

5.3.2.5. To Save a Ray Path Group


A ray path group can be saved and inserted into the organiser page (see 1.5). To do this press the  button on the hall diagram toolbar. If this button is unavailable then no ray path group is in the hall diagram's memory.

When the button is pressed the organiser page will appear and the *Select* button will be visible. Click on the organiser group in which to save the ray path and press the *Select* button.

A new box will appear in which a name to save the ray path under must be typed. Type a name for the ray group and press the *Ok* button. The ray path will have been saved to the organiser page. Now press the *Save All* button at the bottom of the *Hall Sheet* box to ensure that the information in the organiser page has been saved.

5.3.2.6. Editing a Ray Path Group

Because ray path groups are sometimes used for presentation purposes it is often necessary to edit the ray paths in the group. It was already explained how to delete a single ray in the group (see 5.3.2.3).

To remove all ray segments in the selected ray path after the selected ray segment press the  button in the hall diagram toolbar. The ray path will immediately be concatenated.

To remove all rays with a certain property press the *right mouse button* while the mouse pointer is over the hall diagram box. A menu will appear. Select the option *Edit Ray List*. A box as shown in Figure 44 will appear.

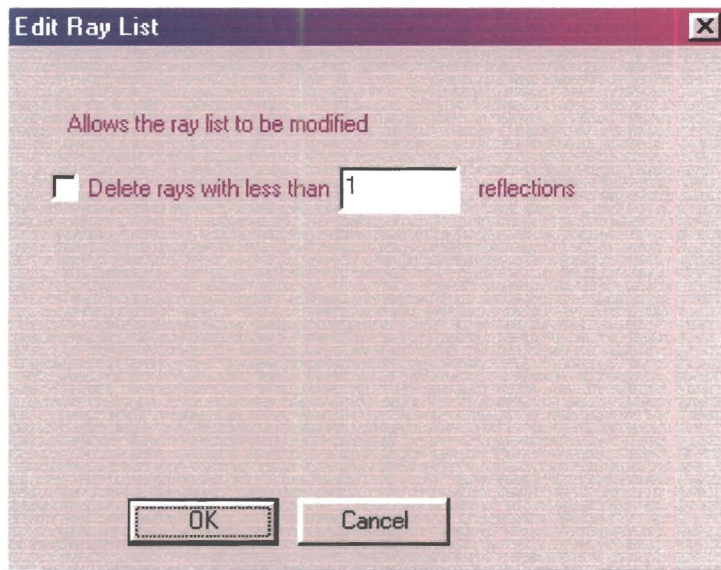


Figure 44: Edit a ray group options box

To delete all rays with less than x segments, type in the desired number of segments and ensure that the *Delete rays with less than* check box is ticked. Then press the *Ok* button. All rays with fewer than x segments will be deleted.

In more recent versions of the program more options may be added to this ray group editing box.

6. Simulating a Single Ray Path

It is possible to perform a restricted simulation where only a single ray path is simulated. This is useful where the user wishes to see whether a potential ray path exists, and was used extensively when examining PET graph reflections (as explained in the main thesis section).

6.1. Creating a Blank Graph

To simulate a single ray it is necessary to have an already simulated graph visible and active. If the user does not wish to use an already existing graph then a new blank graph can be created. To do this select *Simulate|Create Blank Graph* from the menu. The box shown in Figure 45 will appear.

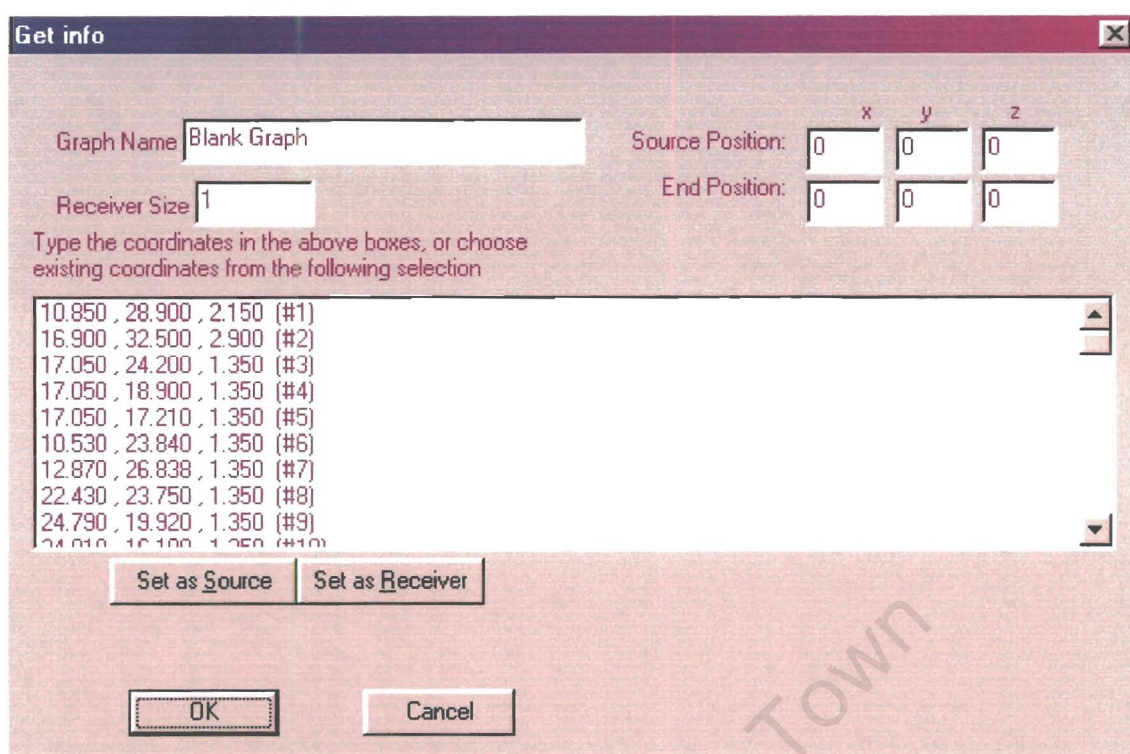


Figure 45: Create a blank graph box

It is necessary to specify:

- The *name* of the new graph, which is automatically chosen as 'Blank Graph'
- The *size* of the new graph, which is automatically chosen as 1 meter and should be left at that size.
- The *Source* and *Receiver* position of the new graph. These values can either be type into the relevant fields or one of the vector point positions in the large window can be chosen. To choose a point from the list click on the desired point and press either the *Set as Source* button or the *Set as Receiver* button to set the point as either the source or receiver point respectively.

Press the *Ok* button to create the graph. The new graph will be automatically added to the organiser page (see 1.5) under a new group named as the current date and time.

6.2. Perform a Restricted Simulation

Once a suitable graph is active select *Simulate|Restricted Simulation* from the menu. A box as shown in Figure 46 will appear.

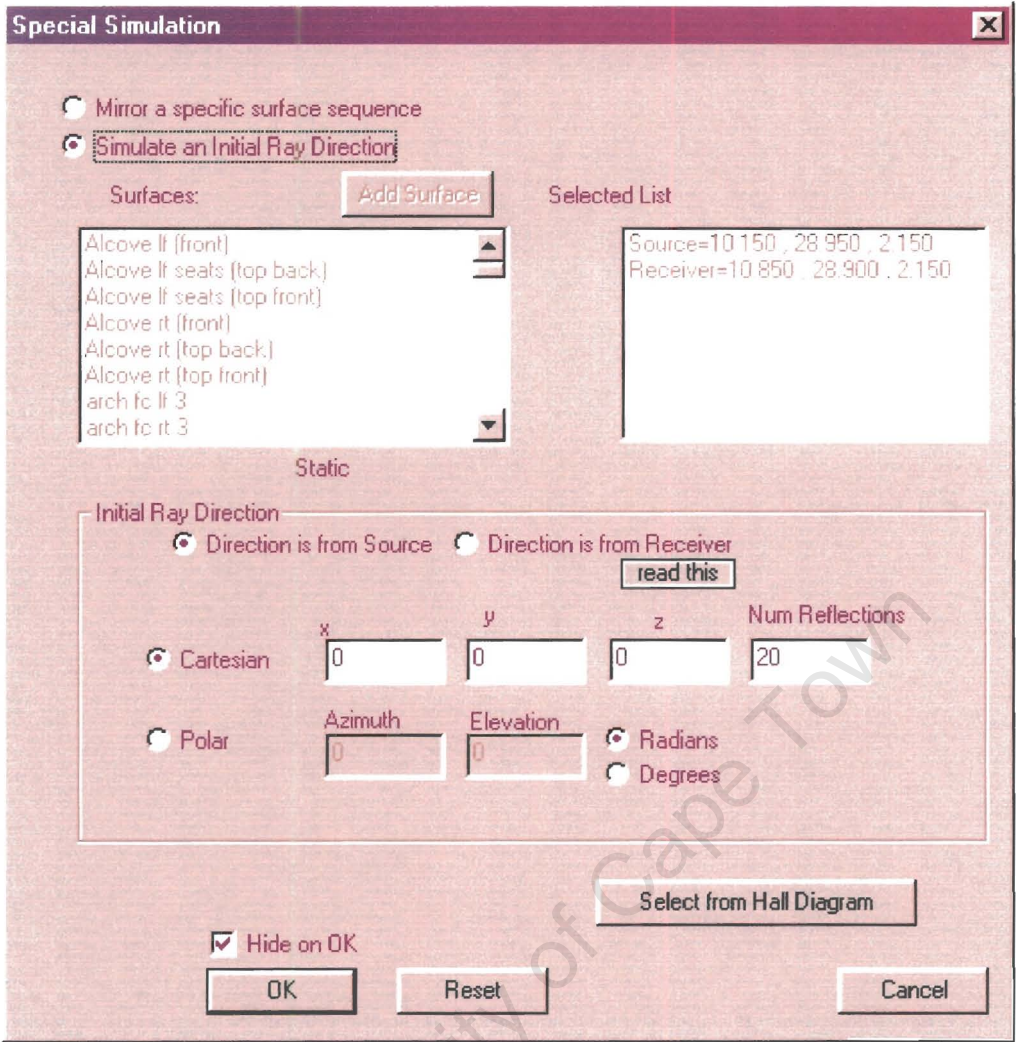


Figure 46: Restricted simulation box

This box is a modeless box, which means that other parts of the program are still operational while the box is visible. There are two types of restricted simulations that can be performed, based on a desired surface sequence or an initial ray path direction.

6.2.1. Simulating a Desired Surface Sequence

This option is not operational at present. When operational it allows the user to search for a ray path that passes from the source point through a specified sequence of surfaces and then to the receiver point.

6.2.2. Simulating a Ray with a Particular Starting Direction

To simulate a ray with a particular starting direction ensure that the option called *Simulate an Initial Ray Direction* at the top of the box is selected. The options for simulating a ray with a particular starting direction are as follows:

- *Direction is from Source*: If this option is selected then the direction of the simulation ray is assumed to refer to the source point of the graph.

- *Direction is from Receiver*: If this option is selected then the direction of the simulated ray is assumed to refer to the receiver point of the graph.
- *Cartesian Coordinates*: If this option is selected then the initial direction of the ray is specified in Cartesian coordinates. This direction will be normalised before simulation.
- *Polar Coordinates*: If this option is selected then the initial direction of the ray is specified in polar coordinates. *Azimuth* is the direction along the horizon and *Elevation* is the vertical angle.
- *Radians & Degrees*: These two options specify whether the *Polar Coordinates* are to be interpreted as radians or degrees.
- *Num Reflections*: The number of reflections the ray is allowed to make before being terminated.

The *select from hall diagram* button can be used if a ray path is selected in the hall diagram box. Pressing this button causes the *From* direction of the selected segment of the selected ray path in the hall diagram box to be set as the *Cartesian coordinate* direction in this box.

Pressing the *Ok* button causes the ray path to be simulated. If a suitable ray path could be found then it will be displayed in the hall diagram box and also added to the graph as a reflection. If the ray path could not be found then an information box will appear. The ray path will still be displayed in the hall diagram box up to the point where it could not be simulated further.

If the *Hide on Ok* check box is ticked then when the *Ok* button is pressed the restricted simulation box will disappear. However all information in the box is remembered and will be displayed again when the restricted simulation box is shown again.

If the user wishes to examine exactly how the simulation is performed then the *debug mode* option in the miscellaneous parameters page of the *simulation parameters* box can be selected (see 2.2.3). Other simulation parameters also effect the restricted simulation so it is important that the desired simulation parameters have been selected, especially as regards the *Operation* page (see 2.2.5).

In order for the ray paths created using the restricted simulation box to be displayed in the hall diagram box the ray path group option must be off as explained in 5.3.2.2. Ray paths created using the restricted simulation box can be added to a ray path group as explained in 5.3.2.4.

7. General Options

Some options that have no direct bearing on the simulation but are useful from a user interface point of view are available by selecting the *Option|General Options* menu option. The general options box will appear which contains a number of pages.

7.1. General Options Page

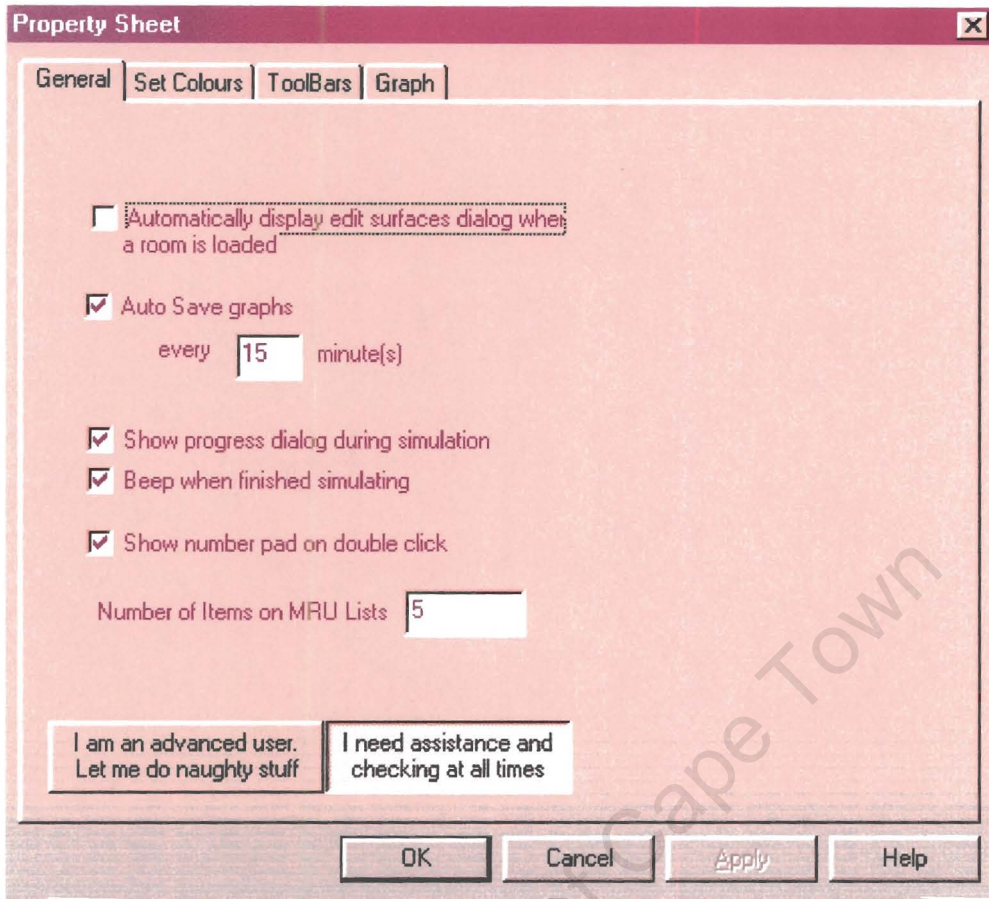


Figure 47: General Options Box: General Page

This page contains miscellaneous general options. A large number of options are unoperational.

- *Automatically display edit surface dialog*: If ticked then the hall diagram box will be displayed when a new hall is loaded. This option is operational
- *Auto Save Graphs every x minutes*: This option is unoperational.
- *Show progress dialog during simulation*: This option is unoperational
- *Beep when finished simulating*: This option is unoperational.
- *Show number pad on double click*: If ticked then when the mouse is double clicked on an edit box into which a number should be typed a small box appears as shown in Figure 48.



Figure 48: Number Pad

This box can be used to enter a number if the user's feet are on the desk and the user cannot reach the keyboard. Not all edit boxes have this capability.

- *Number of Items on MRU lists*: This option is unoperational.
- *I am an Advanced User/I Need Assistance*: This option is unoperational.

7.2. Set Colours General Options Page

The *set colours* page allows the user to change the colour of most objects in the program. The set colours page is shown in Figure 49.

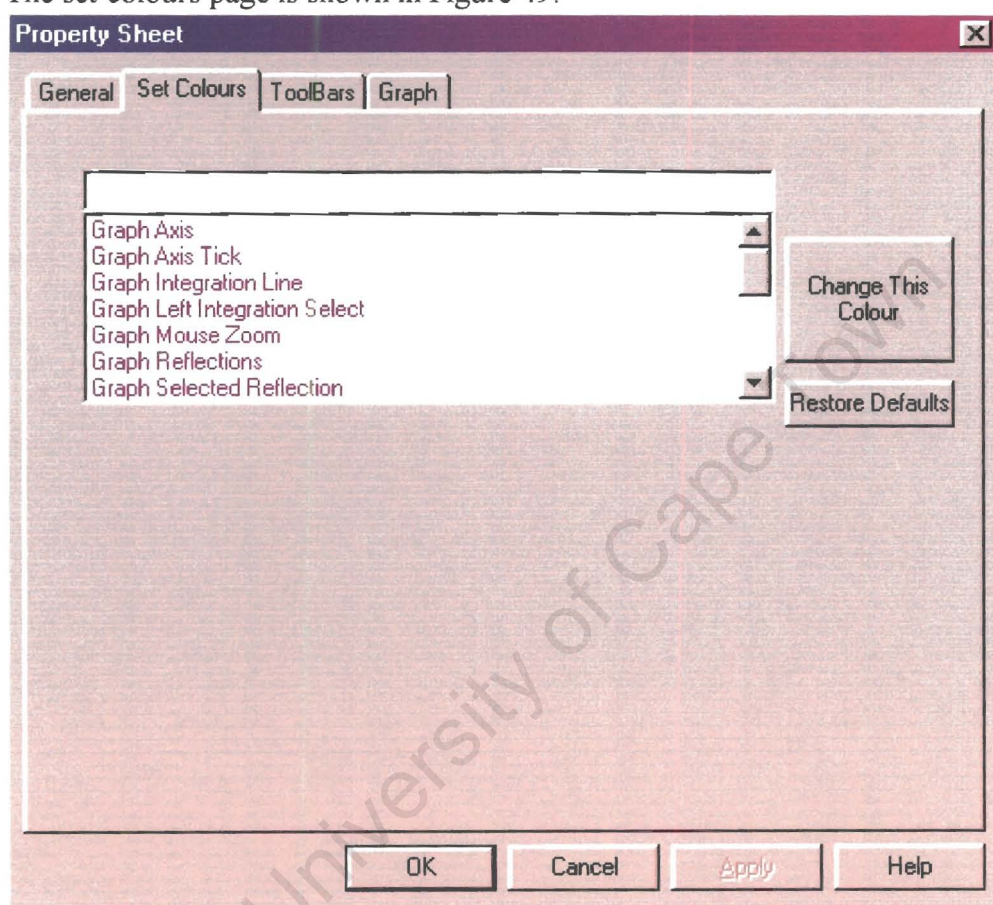


Figure 49: General Options Box: Set Colours Page

To change an item's colour click on the item whose colour is to be changed and press the *Change This Colour* button. A box will appear as shown in Figure 50.



Figure 50: Set Colours Box

The present colour of the item is selected (in the example it is blue). The user can select any other colour by clicking on the colour. Press *Ok* to accept the new colour. The item's colour will have changed. In most cases it will be necessary for the user to go to the item that has changed and click it. For example the hall diagram box will not show the new colours until the user clicks on the hall diagram box. Similarly for graphs where the user may have to rescale the graph to show the new colour.

The item's whose colours can be changed are self explanatory as listed in the window.

7.3. Toolbar General Options Page

The toolbar options page is shown in Figure 51.

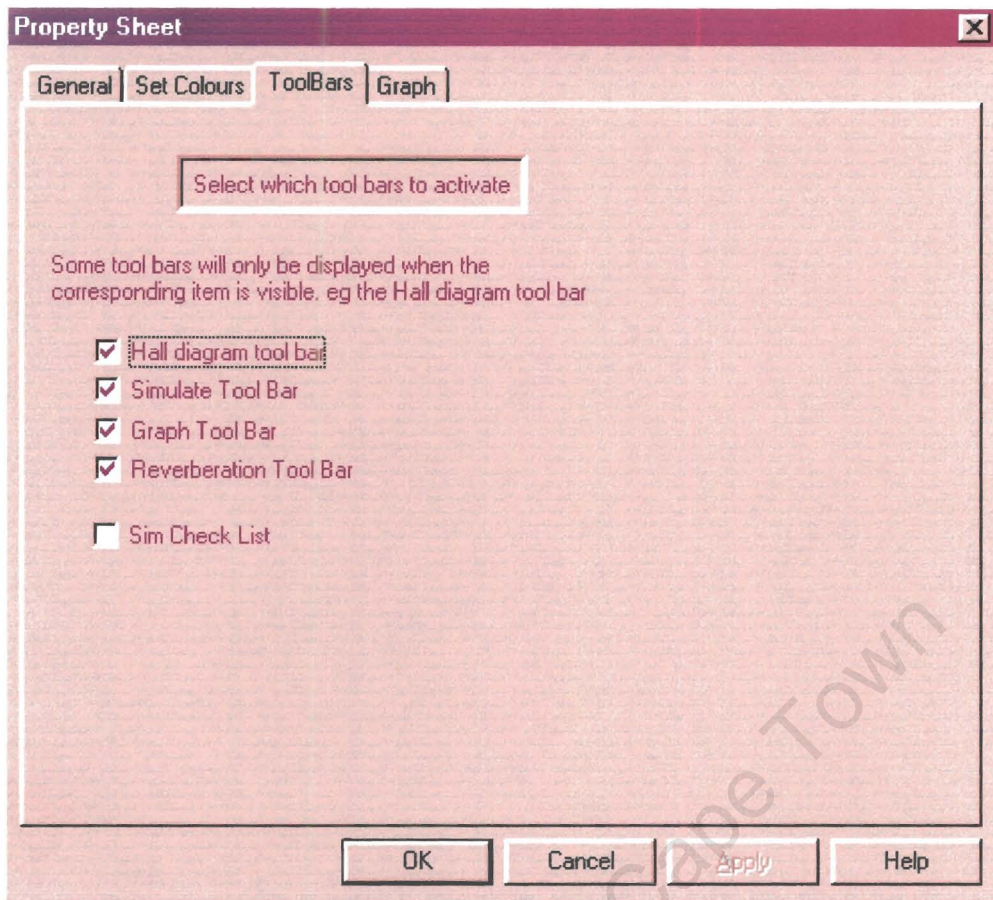


Figure 51: General Options Box: Toolbars Page

This page determines which toolbars are displayed. It is recommended that all the toolbars options are ticked. A toolbar option that is not ticked will not be displayed. Even if a toolbar option is ticked the toolbar may not be displayed. For example when the hall diagram box is off the hall diagram toolbar is not shown, even if the item on this page is ticked.

The SimCheckList option should be unticked.

7.4. The Graph General Options Page

The graph general options page is shown in Figure 52.

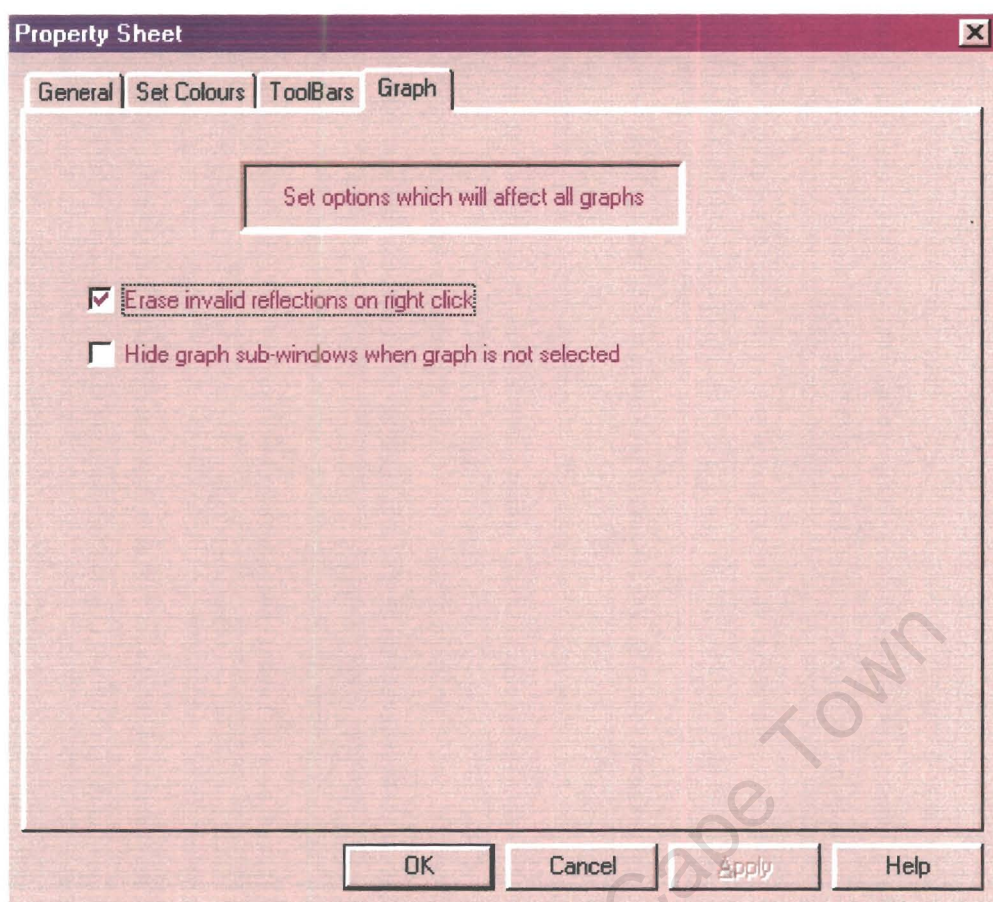


Figure 52: General Options Box: Graph General Options Page

These options should be left as they are. Changing them may produce unexpected results.

8. Icon Functions

There are many functions whose operation is accessed by means of menu items. The most commonly used operations are also accessible from the toolbar at the top of the screen. Some of these are described here:



Open a previously saved hall.



Open the most recently saved or opened hall (see also 9.5)



Save the currently active graph or room model. The use of this button is not recommend. Save the hall model and graphs using the save button on the *hall settings* box. (see 1.1.3). This button can be used however if the user wishes to save a graph under a specific name rather than allow the organiser page to choose one.



Allows the user to print the surfaces in the room model. (see 9.1).



Toggle showing the *hall settings* box (see 1.1.2).



Toggle showing the *hall diagram* box (see 5).



Show the *Simulation Parameters* box (see 2.2).



Show the *SimWizard* box (see 2.1).



Begin a Simulation (see 3).



Zoom in and out of the x-axis of the selected graph.



Shift the selected graph left or right along the x-axis without changing the scale.



Zoom in and out of the y-axis of the selected graph.



Select the frequency of the selected graph (see 4.1). If the user's mouse has a mouse wheel then rotating the wheel will also cause the frequency of the selected graph to change.



Integrate the selected graph (see 4.1).



Find a reflection in the selected graph (see 9.3).



Display the graph proper. This is selected the first time a graph is shown.



Display automatically calculated simulation results. These have not been tested yet and are probably incorrect.




Display a comments box where the user can type comments about the currently selected graph. The comments in this box are saved when the graph is saved and can be viewed again by pressing this button.

9. Miscellaneous Functions

There are a number of functions available in the program which have not already been described elsewhere. Some of these are described here.

9.1. *Print the Hall Model*

The surfaces in the hall model can be printed by pressing the  button on the main toolbar usually situated near the top of the screen. When this button is pressed a box as shown in Figure 53 is shown.

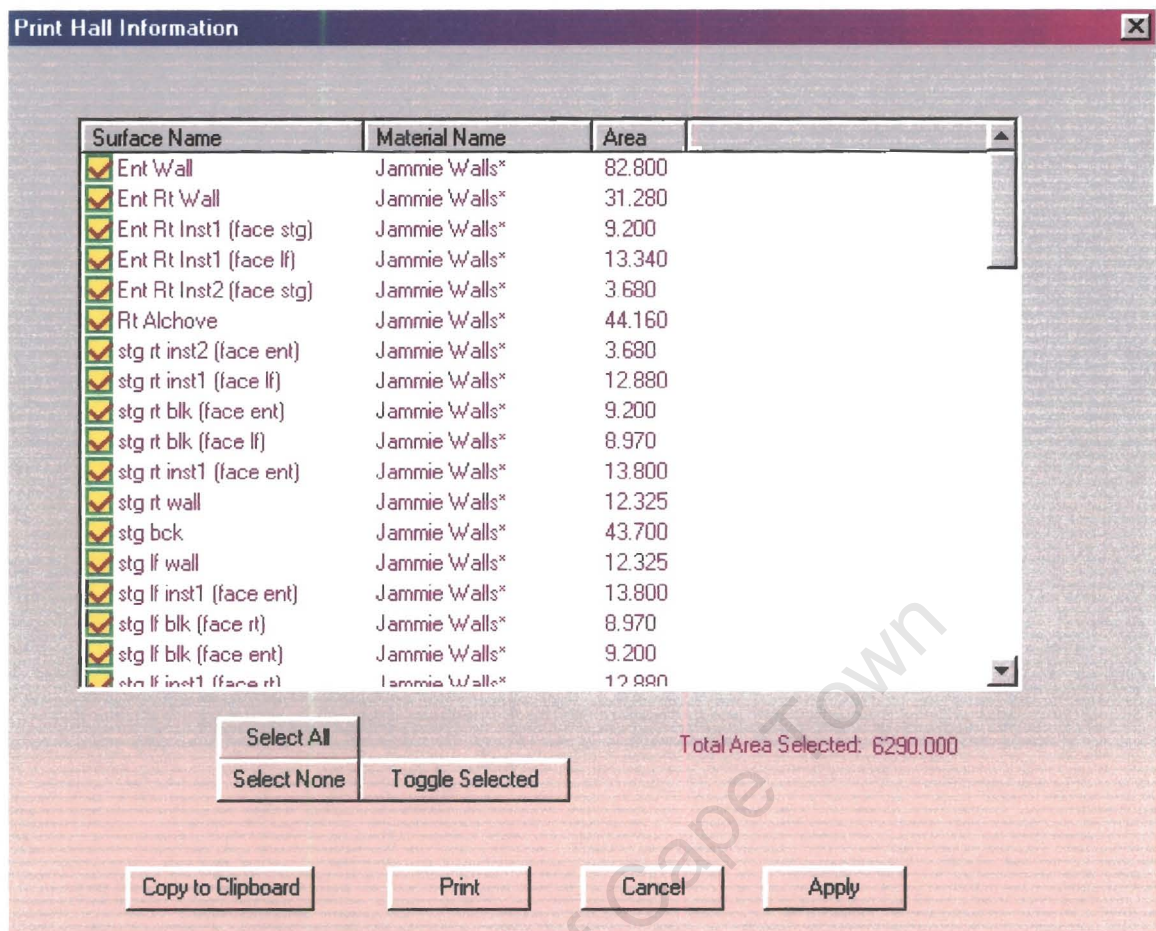


Figure 53: Print Surfaces Box

From this box the user is able to do more than just print the hall model surfaces. Three columns are shown in the main window in the box. These columns contain respectively the name of each surface, the surface's material name and the calculated area of the surface. The surfaces can be sorted in ascending or descending order by clicking on the header name of any of the columns.

The ticks to the left of the surface name determine whether the surface is selected for printing or not. Only surfaces with a tick will be printed. Also the *total area selected* information at the bottom right of the box shows the total area of all the selected surfaces (in this example it is 6290m²). To select or deselect a surface double click with the left mouse button on the surface.

Alternatively press the *Select All* or the *Select None* buttons to select all or none of the surfaces respectively. Press the *Toggle Selected* button to make all the selected surface deselected and visa versa. To toggle selection of a number of surface hold down the *left mouse button* while moving the mouse to draw a rectangle around the desired surfaces. When the *left mouse button* is released then the selection of the surfaces within the rectangle will be toggled.

Press the *Copy To Clipboard* button to copy the information in this box to the clipboard in a format that can be pasted into an Excel worksheet.

If the user does not wish to print the information but wants the surface selections to be remembered then the *Apply* button must be pressed and then the *Cancel* button.

9.2. Perform a Modal Analysis

RoWena can be used to perform a modal analysis on a rectangular shaped room. This analysis is a fully calculated impulse response using equations presented in the body of the thesis. Ray tracing or geometrical acoustical principles are not used.

To perform a modal analysis select *Simulate|Modal Analysis*. The box shown in Figure 54 will appear.

You may perform a simple modal analysis graph on a simple rectangular room.

Dimensions		Position		Nodes	
x max	7.371	Enter the measurement position. The origin is in the centre of the room.		Num x nodes	10
y max	5.715	x	3.6855	Num y nodes	10
z max	4.405	y	2.8575	Num z nodes	10
		z	2.2025		

Time
Maximum Length (seconds) 0.25
Resolution (seconds) 0.008

Frequency
Minimum 0
Maximum 125

Impedance
Enter the impedances of the walls. If you only know the absorption coefficients enter that instead.

	real	imaginary	coefficient
x=0 (front)	4.763	22	0.01
x=max (back)	4.763	22	0.01
y=0 (left)	4.763	22	0.01
y=max (right)	4.763	22	0.01
z=0 (floor)	4.763	22	0.01
z=max (roof)	4.763	22	0.5

Close

Figure 54: Modal analysis Box

Also a new blank graph will have been created. This graph is not added to the organiser list.

The modal analysis box contains the following fields that must be filled in by the user:

- *Dimensions*: These are the maximum dimensions of the sides of the room along each axis. The room is centered about the origin and is perfectly regular rectangular.
- *Position*: This specifies the position of the receiving point. The source point is always in the corner of the room. If the *Set To Corner* button is pressed then the *position* is set to the corner of the room. Such a position guarantees that all excited modes are detected.
- *Nodes*: Here specify the maximum number of nodes to compute in each axis direction. All combinations of nodes up to this maximum value will be calculated. If the limiting factor for the simulation is to be the frequency limit of the graph (see below) then enter a suitably large number here. The exact figure will depend on the size of the room.
- *Impedance*: Here the user must enter the absorption coefficients of the 6 surfaces in the room. Although strictly speaking the complex impedance should be entered this has not been implemented yet. The program assumes that the surfaces are hard and impose no phase change.
- *Maximum Length*: This is the maximum time of the calculated impulse response. The longer the value here the longer the calculated time.
- *Resolution*: Here the user may specify the interval between calculated points in the impulse response. A very small value here will mean the graph of the impulse response is very smooth but the calculation time will increase correspondingly, and visa versa.
- *Frequency*: Here the user may specify the minimum and maximum frequencies to be incorporated into the calculation. This over-rides the maximum mode selection.


Once all these parameters have been set correctly press the *Simulate* button. Depending on the length of the calculation the cursor may turn into an hourglass while the calculation takes place. Once it has finished the cursor will resume its normal state. Press the *Close* button.

The user must now perform a few steps to make the graph of the calculated impulse response visible:

- *Correct frequency*: No matter what the limits set in the frequency field of the modal analysis box were, the calculated impulse response graph is placed in the 125Hz frequency of the graph. Therefore select *Graph|Active Graphs* and ensure that 125Hz is ticked and no other.
- *Correct Graph Type*: To make the graph visible select *Graph|Simple Graph On*. The graph should now be visible but probably to the wrong scale. The automatic scaling functions do not work with this type of graph and the user must scale the graph using either the toolbar buttons (see 8) or selecting *Graph|Graph Scale*.

The modal analysis graph cannot be integrated. If the graph appears overly simple try decreasing the resolution. To do this a new modal simulation will have to be performed.

9.3. Find a Reflection in a Graph

As an alternative means to selecting a reflection the user may search for a reflection with some limited attributes. To do this press the  button on the graph toolbar. The box shown in Figure 55 will appear.

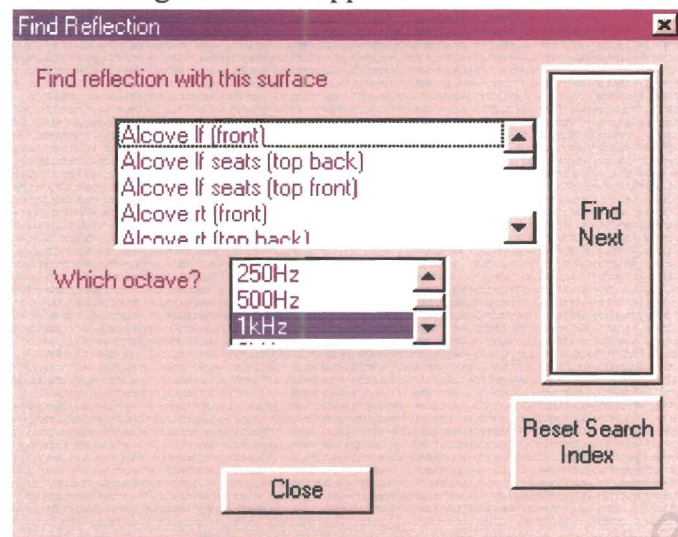



Figure 55: Find A Reflection Box

The attributes of a reflection that can be searched for are a single surface forming part of that reflection's ray path and also the frequency in which that reflection occurs. From the windows near the top of the box select the surface which the reflection's ray path must contain, and from the window below it selected the frequency to search through.

Now press the *Find Next* button. If a suitable reflection is found it will be automatically selected as described in 4.4. If the *Find Next* button is pressed again then the next reflection in time order will be search for. To begin the search from the beginning of the graph again press the *Reset Search Index* button.

To hide this box press the *Close* button. The *Find Reflection* box is modeless, which means that other parts of the program are accessible while the box is visible.

9.4. Simple Vector Manipulation

Sometimes it is useful to be able to perform cross products and dot products on two vectors. To do this press the  on the main toolbar of the program which is usually near the top of the screen. A box as shown in Figure 56 will appear.

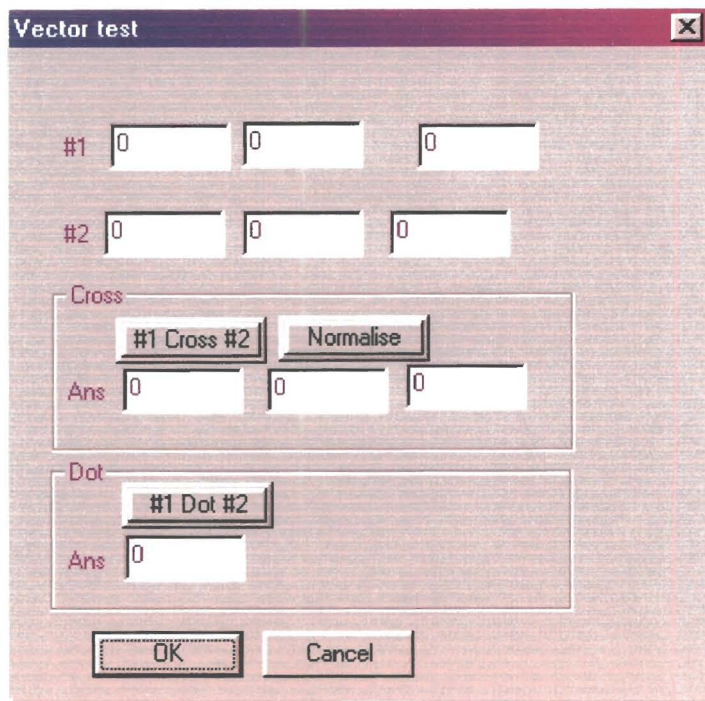



Figure 56: Simple Vector Calculations Box

In this box two vectors can be types, at positions #1 and #2.

- To obtain the cross product of these two vectors press the *#1 Cross #2* button. The cross product of the two vectors will immediately be shown in the cross product *Ans* field.
- To obtain the dot product of the two vectors press the *#1 Dot #2* button. The dot product of the two vectors will immediately be shown in the dot product *Ans* field.
- To normalise a vector type the vector into the Cross *Ans* field and press the *Normalise* button. This button will also work on the results of a *#1 Cross #2* operation.

Press *Ok* to close the box.

9.5. To Load the Most Recently Used Hall Model

Rather than selecting the hall model to load from the menu options, the user may press the  button on the main toolbar that is usually situated near the top of the screen. This button immediately loads the hall file that was last opened or saved. It is useful when the RoWena program is first run if the user wishes to continue editing the last room model without having to move through menu items or read message boxes.

10. Problems and Errors

The RoWena program is very large and constantly changing. This user guide is not large enough to explain all the details and potential problems. This section explains some of

the more important errors the user might encounter. Consider it a reference to come to if things are not going right.

10.1. Wrong Hall File

The only way to open graph and ray group files is through the organiser page (see 1.5.5). This ensures that any files that are open are related to the hall model in memory, which further ensures that any information in the open files is relevant and correct.

However it is possible to add graph and ray group files to the organiser page that may be unrelated to the hall model (see 1.5.7). This is allowed because there are occasions when it may be necessary to do so. The user must therefore be extremely wary when doing this. RoWena assumes that all open files are consistent with each other and if this is not the case the program might crash.

Potential problems to watch out for are:

- Adding a graph or ray path file created with an old version of a room model to the organiser page of a newer version of the room model. The files may not be consistent with each other. This will only be a problem if the surfaces of the room model have changed. Modifying the receiver and source positions will cause no problems. Modifying the materials associated with the surfaces will cause the graph reflection strength to be incorrect but no further errors will be caused.
- Removing a file from disc using one room model's organiser list when the file is also included in another room model's organiser list. Only one copy of a file is stored on disk at a time and deleting the file will make it unavailable to any room model. If the user wants more than one copy of a graph or ray group file then the user must manually make a copy, using windows explorer or similar. To find out the file name of a file select the file from the organiser page and press the *Summary* button (see 1.5.2).

10.2. Commands are Not Available

There are different commands and menu items applicable to graphs and to the room model itself. Therefore when a graph window is active some of the commands in the program may be deactivated. In order to switch between having the graphs active or having the room model window active use the *Window* menu item. In this menu is a list of all the currently open windows, including the graphs. From here any open window can be made active. The room model window is the one shown in Figure 57 and has the words "Welcome to RoWena" written at the top.

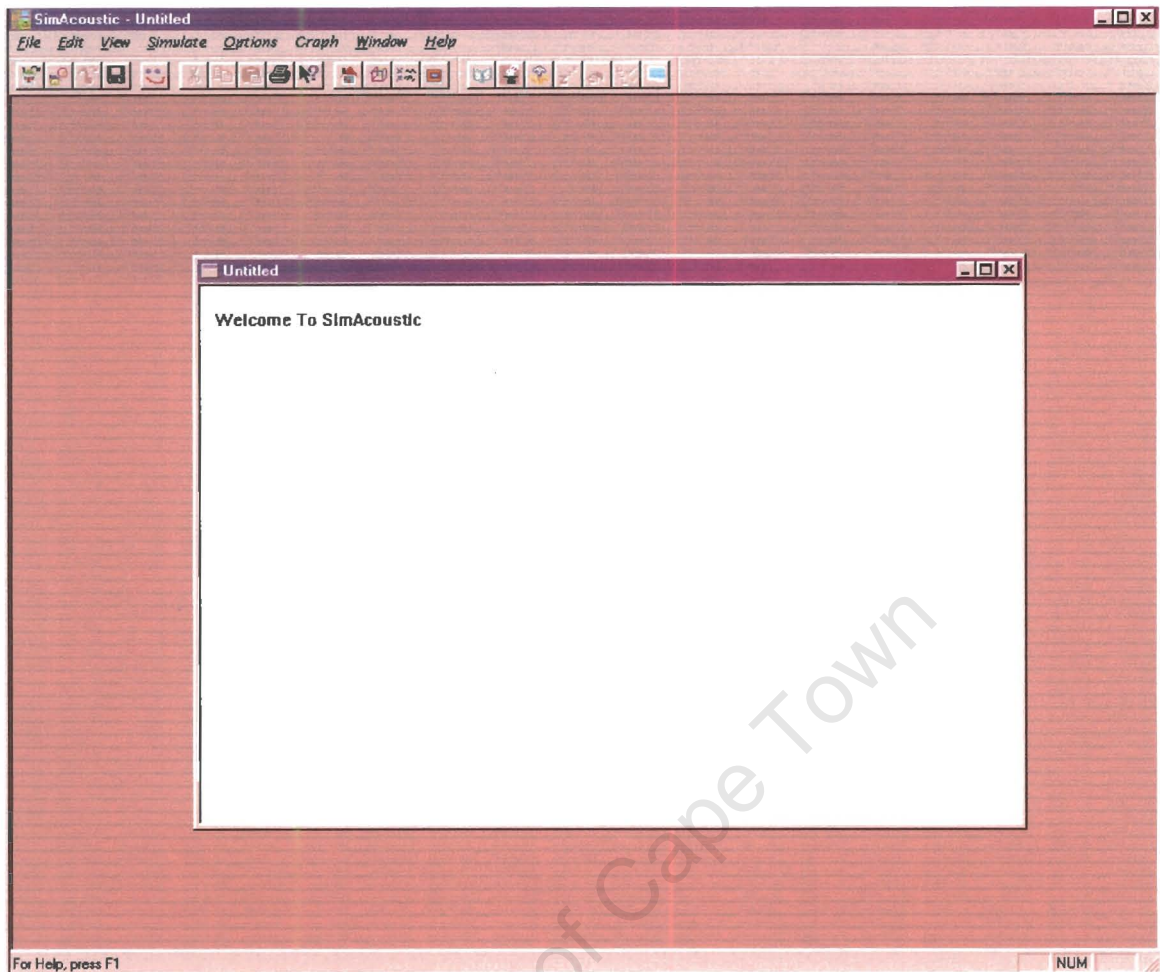


Figure 57: Room Model Window

10.3. Cannot View Reflections with the Right Mouse Button

As explained in 4.4 it is possible to select a reflection with the *right mouse button*. However sometimes this does not work, due to a bug in the program that hasn't been fixed yet. An alternative method to viewing a reflection is also explained in 4.4 and entails selecting the menu item *Graph|View All Reflections*. From here any particular reflection can be chosen. Although this method is less intuitive than clicking on the reflection it is guaranteed to work.

10.4. Reflections Viewed on the Hall Diagram are Incorrect

When a reflection is selected from a graph for viewing on the hall diagram (see 4.4), RoWena must recreate the ray path. This is because the complete description of the ray path is not stored with the graph file, as this would make the file excessively large. Instead the initial direction and number of reflections of the ray path is stored which is sufficient information to recreate the entire ray path.

However because there are many different simulation techniques, such as ray tracing or secondary source, with or without scattering, the ray path may be entirely different with

each simulation method or be completely invalid. For this reason it is important that the user first ensure that the correct simulation parameters are set when a reflection is viewed. This can usually be done quite simply by following the guidelines in 1.5.13.

If the reflection was simulated using scattering, which is a random process, or secondary sources, where the ray path is not specular, then a specular and geometrically exact ray path may in all likelihood not exist.

Assuming the user would like to see the specular ray path or the reflection, if one did exist, then the simulation parameters should be set as follows:

- *Air Page*: nothing relevant
- *Ray Page*: nothing relevant as long as enough reflections and time limit are specified.
- *Misc Page*: nothing relevant
- *Time Page*: Set *Early Time relative to Reflection Order* and reflection order equal to the number of reflections in the ray path, usually less than 200.
- *Op Page*: early time bounce must be *specular*, all the rest is irrelevant.
- *Integration Page*: nothing relevant.

10.5. Room Model File is Invalid

It is possible that RoWena might crash while saving, or through some other reason the room model file might become invalid and cannot be loaded. If RoWena crashed while saving then the user can refer to 1.1.3 for assistance.

If the room model has become invalid for some other reason then it is very likely that much information has been lost. Hopefully the user has made a backup somewhere. At the very least however all the graph and ray group files will probably still be accessible. It will only be necessary to include them in the new room model's organiser page.

As an aid to doing this each graph or ray group file has stored with the file the name of the organiser group in which it was first placed. To view this name *add* the file to the organiser page (see 1.5.7) and press the *Summary* button (see 1.5.2). The box that appears should show the group name.