ACOUSTIC GEOMETRY SCULPTOR – A COMPUTER PROGRAM FOR OPTIMISING ROOM SURFACES

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1 INTRODUCTION

The Live End Dead End[1] (LEDE™) and Reflection Free Zone[2] (RFZ) control room design paradigms have been time-tested to offer the stereo mix engineer with a work setting conducive to the exacting nature of their task. However, with the increasing requirement for surround sound mixing environments, some adaptation of the design paradigms is now required. It is commonly current practice to introduce large amounts of absorptive treatment to surfaces within the control room in an attempt to control the level of early reflections falling within the Initial Time Delay Gap (ITDG). Consequently the acoustics within surround sound control rooms move closer to effective anechoic conditions, which can be fatiguing to work in over extended periods of time and inherently lack any diffuse spacious character.

While this might be considered a 'necessary evil' within a control room for the mix engineer, a listening room for the enjoyment of recorded music/ home cinema would arguably provide a more relaxing environment if it possessed a longer Reverberation Time (RT) perhaps in the region of 0.4 seconds (closer to that of a standard living room).

If we consider the first 15ms window of time immediately following the arrival of the direct sound at a listening position from a loudspeaker configuration within such a room, the reduced use of surface absorption treatments in order to create a longer RT would give rise to an increase in prominence of early reflected energy. If the listening room designer were tasked with creating an ITDG of 15ms in such a room for a 5-satellite speaker surround system, careful consideration of reflection paths from all speakers, typically up to 4th orders, may be needed.

This paper gives an overview of Acoustic Geometry Sculptor, a computer program to automatically optimise ceiling and wall surface geometries to provide favourable acoustic conditions (determined from an approximated impulse response) at the listening position within a critical listening room. To illustrate the approach, solution room geometries are presented for mono, stereo and 5-channel loudspeaker listening rooms, each possessing an ITDG of 15ms (excluding first order floor reflections) and an RT of approximately 0.4s; the presence of a 15ms ITDG in the associated impulse responses for the 5-channel solution is confirmed using ODEON room acoustic software.

2 THEORY

A brief overview of some of the theoretical ideas associated with the design of the geometry sculpting program and background to critical listening room design concepts are described in this section.

2.1 Initial Time Delay Gap (ITDG)

The ITDG is the duration between the arrival of the direct sound at a receiver and the onset of prominent early reflections. In the case of small rooms (such as recording studio control rooms or home cinema rooms), Davis and Davis[1] suggest an ITDG of 15ms, with any early reflections arriving within the ITDG being attenuated by at least 20dB when compared to the direct sound; the application of the concept is described further in the following section.

2.2 Prediction of room impulse response approximation

A computationally efficient vector based ray-tracing algorithm was developed in order to predict the room impulse response approximation at the listening position for the current room surface geometry. In this instance due to the requirement for stability within the optimisation process, only specular reflections at surfaces were considered.

From vector mathematics specular reflection at a plane surface, see Figure 1 can be calculated using [1].

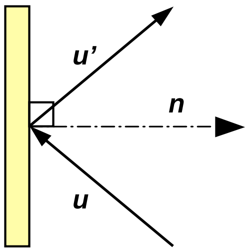

Figure 1 - Vector specular reflection at a plane surface

$$\mathbf{u'} = \mathbf{u} - 2\,(\,\mathbf{u} \cdot \mathbf{n}\,)\,\mathbf{n} \qquad [1]$$

The residual intensity of a single ray is reduced according to the square of its distance travelled and the energy lost due to surface absorption during each reflection, given by [2].

$$I_{ray} = I_{source} - 20\log_{10}\left(path\ \ length\right) + \sum_{i=1}^{n} 10\log_{10}\left(1-\alpha_i\right) \qquad [2]$$

where, I_{ray} is the intensity of the reflected ray (dB);
n is the number of surfaces the ray has impacted with during its flight path;
α_i is the absorption coefficient of the i'th reflection surface.

2.3 Optimisation process

The optimisation process was implemented using a standard Nelder-Mead[3] simplex routine. The main strength of the simplex method lies in its ability to minimise a scalar valued nonlinear function of n variables, using only the function values (vertex co-ordinate sets and their corresponding error values in this case), without the need of any derivative information. It has been used extensively in the field of chemical engineering and has been proven over the past 40 years to be robust and reliable even when strict limitations of the solution domain are imposed upon it.

2.4 Traditional control room design paradigms

2.4.1 Live End Dead End (LEDE™)

The LEDE™ design concept combines the creation of an ITDG of approximately 15ms and a diffuse rear sound field at the listening position. This is able to provide the mix engineer with the detailed transients from the loudspeaker playback and a sense of space normally associated with a larger room, without noticeable distortion from the control room acoustic.

The ITDG is achieved by applying absorptive treatment to the loudspeaker 'Dead End', of the room. The spacious rear field 'Live End' is achieved by the human auditory system being able to integrate the later arrival of many scattered reflections. An illustration of the concept is shown in Figure 2.

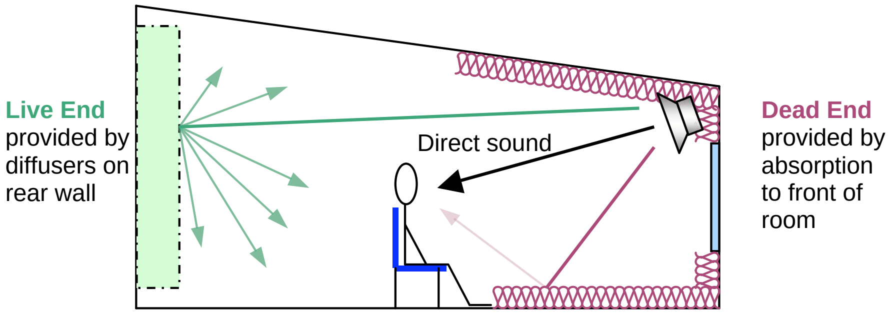

Figure 2 - Illustration of LEDE™ Control Room Concept

2.4.2 Reflection Free Zone (RFZ)

The LEDE™ concept effectively creates a Reflection Free Zone (RFZ) by absorption of early energy from surface reflections falling within the ITDG. A further development of this idea was to reduce the absorption treatment within the control room in favour of geometrically profiling the front sidewalls and ceiling to direct the unwanted early reflections away from the mix engineer onto a diffusing rear wall, in doing so creating a RFZ around the mix engineer. An illustration of the plan view of a control room design with such a principle can be seen in Figure 3.

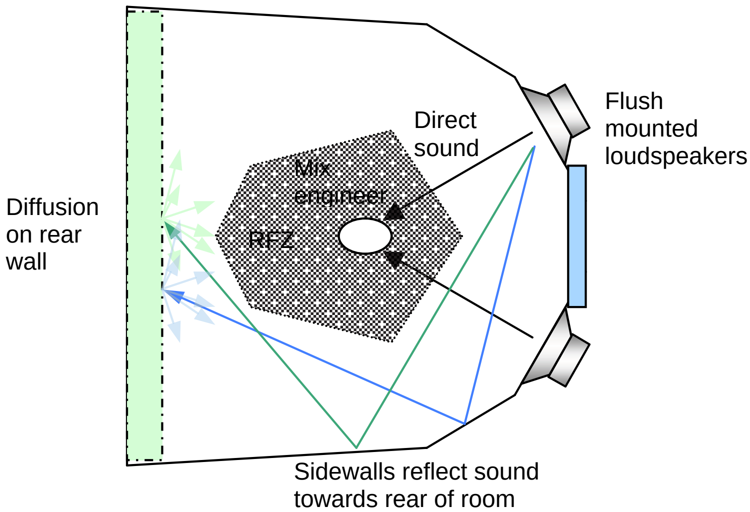

Figure 3 - Illustration of RFZ Control Room (Plan View)

3 DESIGN

3.1 Overview of approach

The design was facilitated using an array mathematics programming language and is split into two sub-programs. The first 'set-up program' discretises the room surfaces into triangular surface elements, generates alternate room surface geometries and calculates a corresponding error magnitude for each geometry set using the ray-tracing model.

The second 'optimisation program' reads in the generated sets of surface geometries and their corresponding error magnitude, carries out an error minimisation process and exports the solution room geometry set to ODEON .par or standard .obj 3D geometry file format for further investigation.

3.2 Set-up program

3.2.1 Initial settings

The program first acquires the user-input room dimensions, approximate indication of the size of the triangular surface elements the room surfaces are to be discretised into and the intended loudspeaker configuration, the speakers are then arranged according to ITU-R BS.775-1[4] about the listening position.

3.2.2 Generation of initial room geometries

From the initial settings the number of degrees of freedom to be used within the optimisation process is calculated and an appropriate number of randomised alternative room surface geometries are generated. The vertex co-ordinates of the alternative room surface geometries have boundary limitations imposed upon them to prevent impossible room geometries being created and symmetry is forced about the front to rear room axis.

3.2.3 Ray-tracing model

The sets of vertices corresponding to each room geometry are passed into a ray-tracing model, from which an error magnitude is calculated according to how close the current surface geometry set is to providing the desired energy characteristics within its impulse response approximation (an ITDG of 15ms at the listening position in this example case). This level of 'fitness' is stored along with the vertex coordinate sets for input into the optimisation program.

3.2.4 Error calculation

The error calculation used to determine the current 'fitness' of each room vertex set is given by [3].

$$\text{Error}_{\text{ITDG}} = \sum_{i=1}^{n}\left(\frac{\left(1-w_f\right)\left(d-t_i\right)}{x}+\left(w_f-1\right)\right) \qquad [3]$$

valid for $\left(t_i \leq x + d\right)$

where,
- t is the impulse arrival time;
- d is the direct time;
- w_f is a weighting factor >1;
- x is the ITDG required;
- n is the number of sets of impulse entries.

A weighting factor w_f is included to introduce a control on the gradient of the error with regard to the captured impulse time of arrival; the higher the weighting factor, the steeper the gradient towards the desired ITDG. This allows for the introduction of a combination of cost factors, each with a priority determined by their corresponding weighting factor.

3.3 Optimisation program

The sets of vertex co-ordinates and their corresponding errors are ranked and passed into the simplex minimisation routine. Following each trial solution proposed within the routine, vertex co-ordinate boundary checks are performed and if exceeded the newly proposed vertex position is forced back to the boundary limit prior to calculation of its associated error. This is to prevent the room geometry expanding beyond the desired solution domain and to prevent planar conflicts within the solution geometry. The process continues until it converges at a minimum; in this case when all sets of vertex co-ordinates possess the same error value.

To reduce the probability of finding false minima, the set-up program is then restarted with the previously found best error solution as one of the initial set of vertex co-ordinates and the process repeated to verify whether convergence to the same minimum occurs.

4 RESULTS

Example optimisations for mono, stereo and 5-channel surround loudspeaker playback configurations are presented for a room with properties given in Table 1

Table 1 - Listening room parameters

Room characteristic	Value
Initial dimensions: (Length x Width x Height)	5m x 6m x 3m
Inter-node distance (approx)	2m
Number of room surfaces	97
Weighted absorption coefficient of surfaces	0.25
Number of rays used in ray-tracing	10000
Approximate Initial RT_{60}	0.4s
Distance: loudspeakers to listener	2m
Surround loudspeaker azimuth and elevation relative to listening position (where appropriate)	110˚, 0˚

4.1 Mono room

An optimised solution room impulse response approximation and surface geometry for a mono playback listening room can be seen in Figure 4 and Figure 5 respectively.

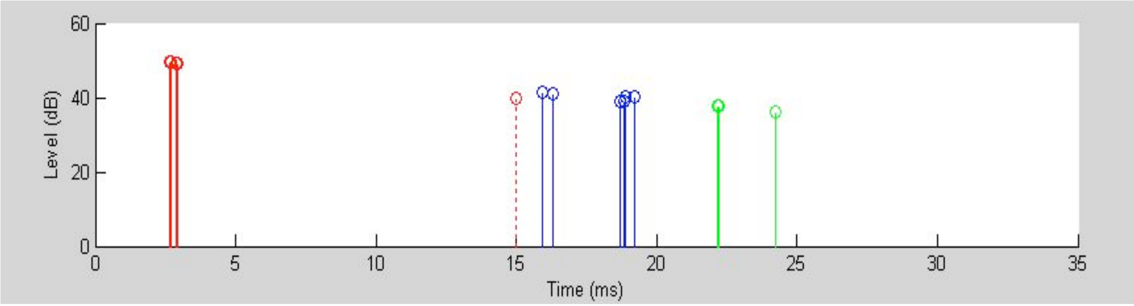

Figure 4 - Impulse response approximation for optimised mono listening room

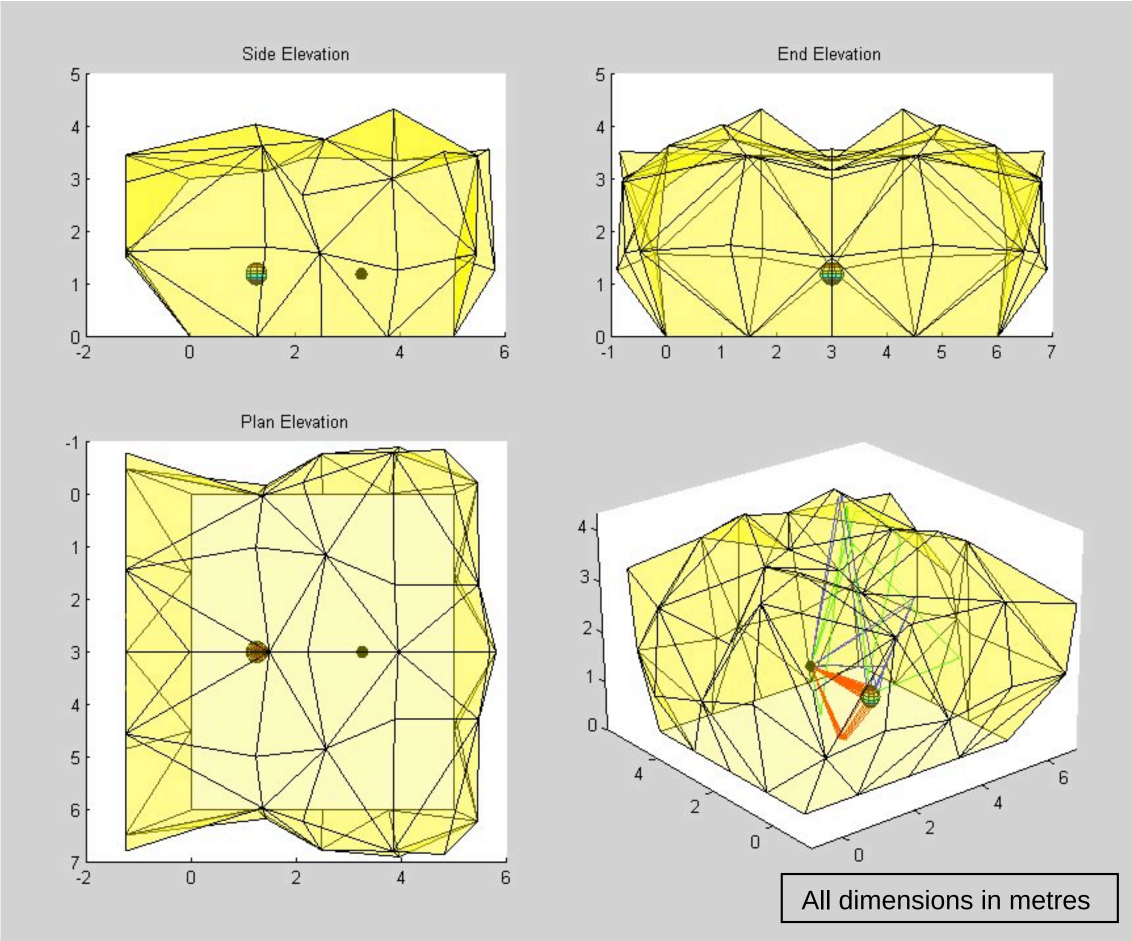

Figure 5 - Solution surface geometry for optimised mono listening room

Excluding the first order floor reflections at around 2-3ms it can be seen that the solution geometry satisfies the 15ms ITDG criteria, marked by the dashed red stem in Figure 4. The ray flights corresponding to the red, blue and green coloured impulses in Figure 4 can be seen in the bottom right figure of Figure 5.

4.2 Stereo room

An optimised solution room impulse response approximation and surface geometry for a stereo playback listening room can be seen in Figure 6 and Figure 7 respectively.

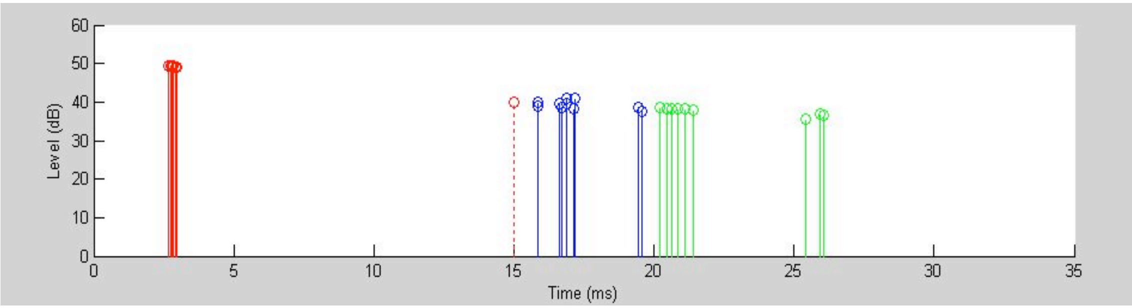

Figure 6 - Impulse response approximation for optimised stereo listening room

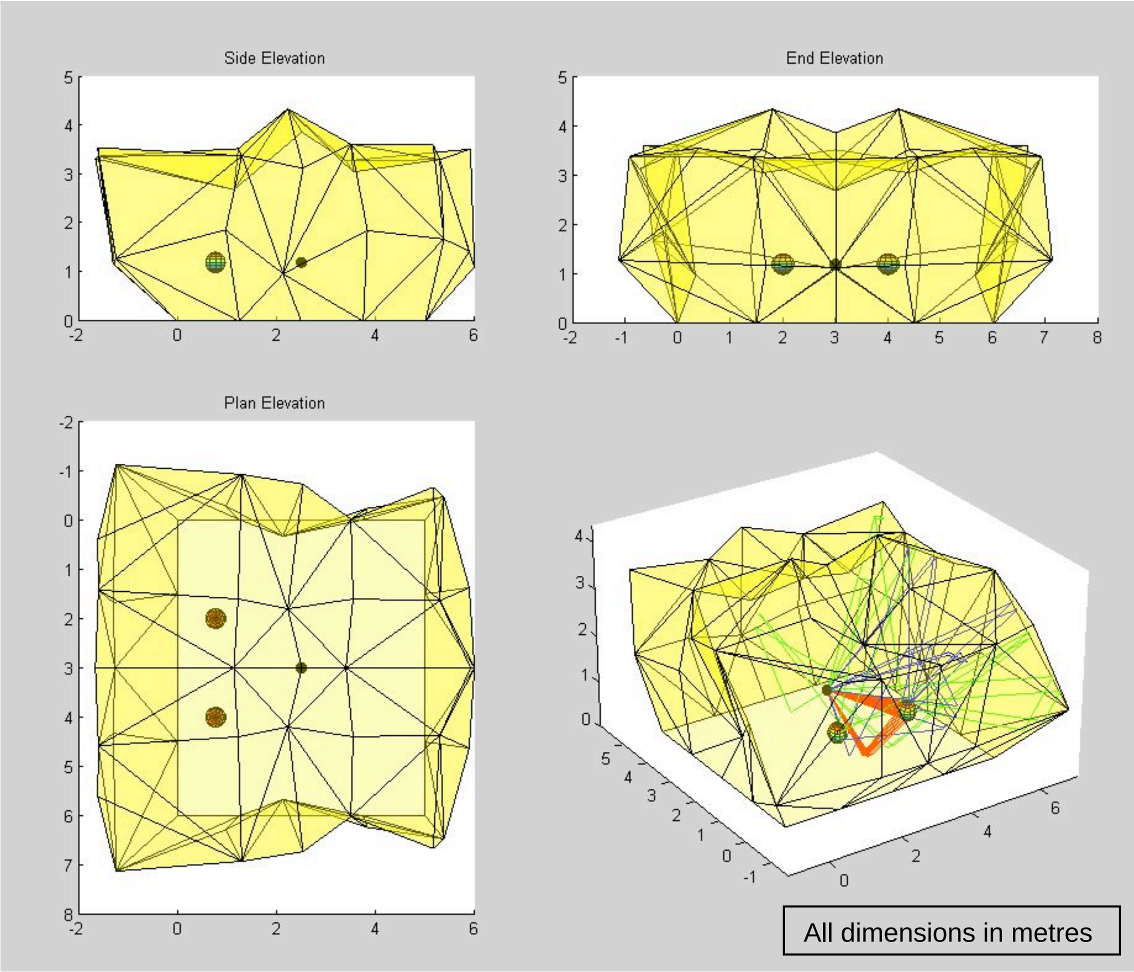

Figure 7 - Solution surface geometry for optimised stereo listening room

Again, excluding the first order floor reflections at around 2-3ms it can be seen that the stereo playback listening room solution geometry satisfies the 15ms ITDG criteria.

4.3 5 – Channel surround room

An optimised solution room impulse response approximation and surface geometry for a 5- channel playback listening room can be seen in Figure 8 and Figure 9 respectively.

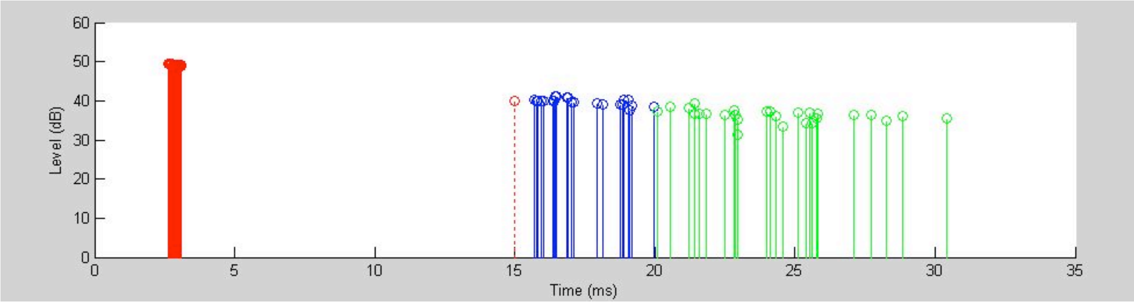

Figure 8 - Impulse response approximation for optimised 5-channel listening room

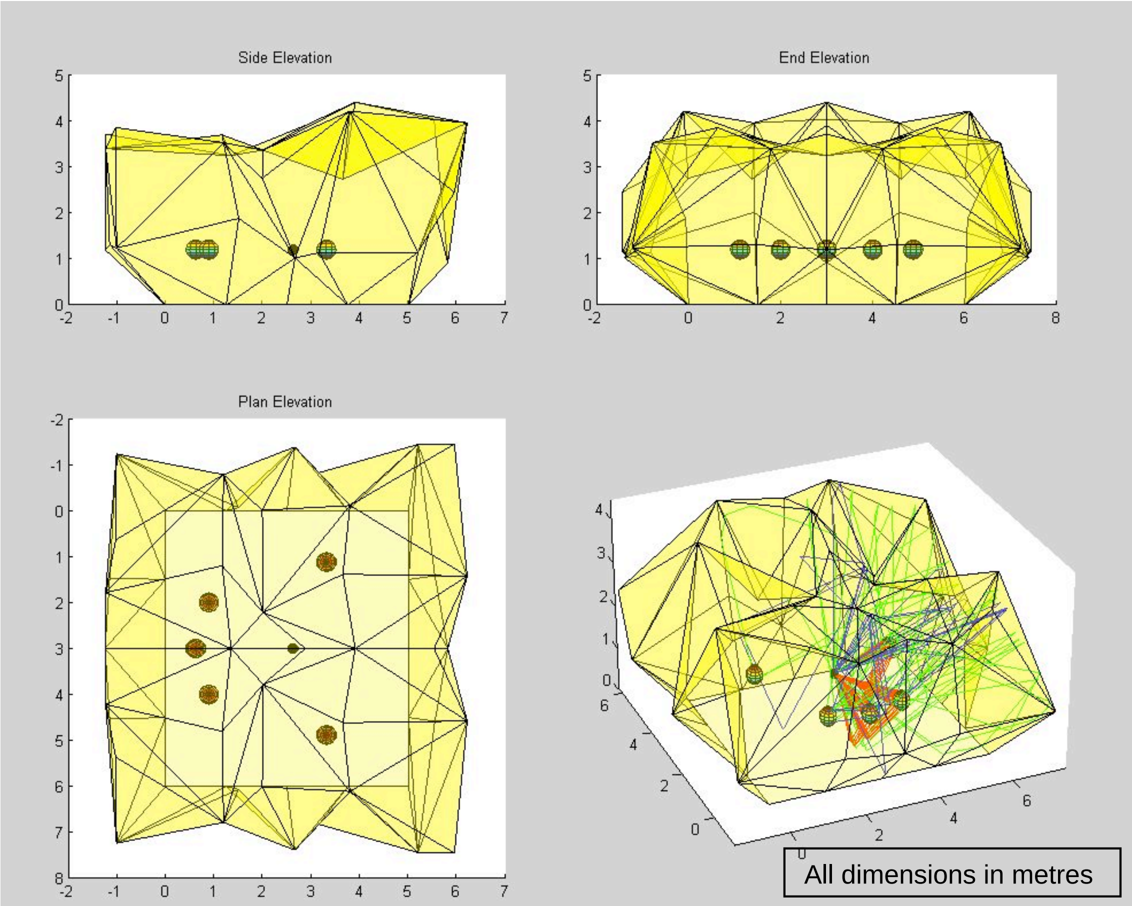

Figure 9 - Solution surface geometry for optimised stereo listening room

Excluding the first order floor reflections at around 2-3ms it can be seen that the 5-channel control room solution geometry satisfies the 15ms ITDG criteria. The number of early reflections and hence complexity is clearly seen to increase as we move from mono through stereo to 5-channel playback listening room geometries.

4.4 General observations

It can be seen by the solution impulse responses, that the program was successful in converging towards room geometries to give a 15ms ITDG, excluding first order floor reflections, at the listening position for each loudspeaker configuration.

It is clear that the 5-channel control room solution would also satisfy the ITDG requirement for mono and stereo playback.

From the plan views of the control rooms, see Figure 5, Figure 7 and Figure 9 the sidewalls can be seen to generally constrict slightly in front of the line of the loudspeaker(s), this has the effect of re-directing potential first reflection paths, away from the listening position.

The ceiling surface elements that would normally give a first reflection path to the listener were generally lower in height along the central axis, running from the front to the rear of the rooms; this would cause incident rays to be reflected out towards the sidewalls or floor instead of directly towards the listening position.

As the floor nodes were fixed in position, the walls tended to “billow” outward enabling incident rays at low level to be reflected upwards, again with the effect of elongating the reflection path. One of the reasons for imposing outward movement limitations on the vertex nodes was to try to contain the room within a guide room volume, instead of allowing it to merely expand outwards to a geometrical solution.

4.5 Verification of ITDG using ODEON

As further verification of the validity of the solution geometries, the 5-channel control room solution geometry was imported into ODEON room acoustic software. The geometry showing the source and receiver locations and the modelled impulse response set are shown in Figure 10 and Figure 11 respectively.

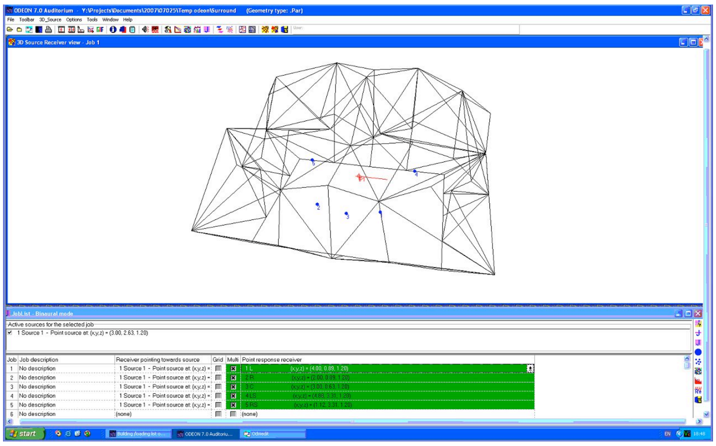

Figure 10 - 5-channel listening room solution geometry in ODEON

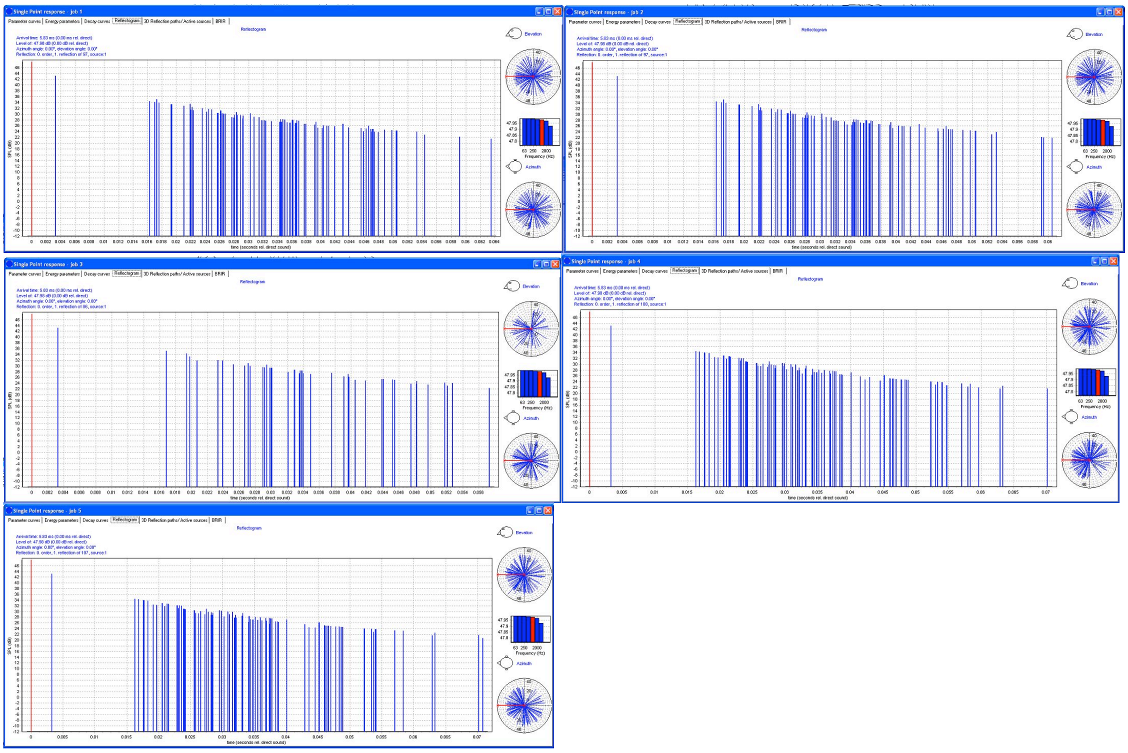

Figure 11 - ODEON modelled impulse response set

The first order floor reflections at 3ms and ITDG of at least 15ms can be seen in each plot in Figure 11. This concurs with the solution geometry presented by Acoustic Geometry Sculptor.

5 CONCLUSIONS

An overview of the design of a computer program that can be input with a desirable acoustic quality in terms of a property within an impulse response, and automatically generate a room geometry that would possess the input desirable acoustic quality has been described. This was achieved through the creation of a ray-tracing model and through utilisation of the Nelder-Mead Simplex Method for function minimisation.

To illustrate its operation, solution impulse responses and room geometries possessing an ITDG of 15ms, ignoring first order floor reflections, were presented for a typically sized mono, stereo and 5-channel control room with an RT60 of approximately 0.4 seconds; the validity of the 5-channel room geometry was confirmed using ODEON room acoustic software.

The program was shown to successfully converge to solution geometries for each input loudspeaker configuration for a room with 97 surfaces and would indicate that the Acoustic Geometry Sculptor was capable of generating valid geometries worthy of further investigation. However, it should be borne in mind that although the ray-tracing modelling method used within the program is capable of providing an adequate approximation of the impulse response at the listening position for the purpose of generating the error associated with a particular room geometry, it should be seen in the light of its inherent useful frequency range limitations (spectral reflection assumption) and its neglect in the treatment of phase and diffraction at and around surfaces.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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