# AN APPROACH TO ORCHESTRAL CANOPY DESIGN OPTIMISATION

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## 1 INTRODUCTION

The ease in which orchestral musicians are able to hear their own instrument and others nearby within the orchestral ensemble is critical in order for them to give a performance that is both secure in intonation and convincing in ensemble. To improve the stage acoustic experienced by orchestral players an orchestral shell and overhead reflective canopy are often constructed around the orchestral stage to reflect energy back towards the musicians. However, a common criticism of overhead reflectors lies in their tendency to detrimentally colour the stage acoustic. Rindel[1] suggests that having a high number of smaller reflectors is preferable in this respect over fewer larger reflectors; this assertion is also consistent with the investigations by Halmrast[2], where strong discrete reflections between 5-20ms were found to create a 'Boxy' sound impression and more diffuse/ scattered reflections were found to reduce the perceived 'Boxyness' on the orchestral platform.

If many smaller reflectors are to be used within a rehearsal/ recording studio environment, their alignment would also need to accommodate the provision of an intimate and vividly rendered stereophonic image at the conductor and typical main microphone positions. In addition, if a seated audience were to be invited to rehearsals/ broadcasts their listening experience would also benefit from the provision of an intimate and wide stereophonic sound stage. The challenges of positioning and orienting many small reflectors to form an orchestral shell and canopy to assist the provision of all of the desirable acoustic conditions previously described become clear; the task would therefore lend itself to some form of optimisation process in order to help explore the possibilities.

This paper describes a computational approach towards the optimisation of heights and rotational orientation of arrays of overhead, side and rear reflective panels that comprise an orchestral shell and canopy within an orchestral rehearsal/ recording studio. To demonstrate the principle, the stimulus for optimisation was to provide a favourable stage acoustic, and then to augment this with the simultaneous provision of a favourable initial time delay gap and lateral fraction measure at the main microphone and audience seating positions.

The nature of iterative optimisation processes gives rise to the requirement for an efficient method of determining the current 'fitness' of a particular state. To this end, a geometric ray-tracing model was constructed to predict the error magnitude corresponding to each shell/ canopy reflector configuration. Although the ray-tracing modelling method provides an adequate approximation for the purposes of generating potential reflector orientation solution sets, it should be seen in the light of its inherent useful frequency range limitations and its neglect in the treatment of phase and diffraction about surfaces.

## 2 THEORY

### 2.1 Prediction of room acoustic parameters

A computationally efficient vector based ray-tracing algorithm was developed in order to predict the room acoustic parameters and hence the current 'fitness' of a particular orchestral shell/ canopy reflector set. In this instance due to the requirement for stability within the optimisation process, only specular reflections at surfaces were considered. As the calculation of the room acoustic parameters used to steer the optimisation process require only the first 100ms of predicted impulse response and the room in question has a fairly large mean free path, it was considered that the specular reflection assumption would allow a reasonable level of accuracy for the purpose of the optimisation. From vector mathematics specular reflection at a plane surface, see Figure 1 can be calculated using [1].

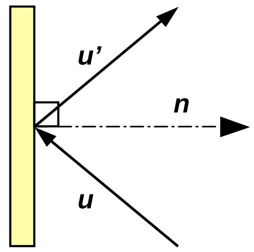


Figure 1 - Vector specular reflection at a plane surface

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

## 2.2 Room acoustic parameters

The room acoustic parameters calculated from the impulse response predictions at various receiver locations around the room are defined in the following sections.

### 2.2.1 Objective support (ST1)

Objective support is a measure of the amount of reflected energy returning to musicians from the orchestral shell and canopy. It is the ratio of energy reflected from the shell/ canopy between 20ms and 100ms after the onset of the source signal, as measured at a receiver 1m away and 1.2m from the stage floor, against the energy arriving directly from the source and first order floor reflections reaching the receiver within the first 10ms after the onset of the source signal.

Objective support is given by [2}.

$$ST1 = 10\log\left[\frac{\int_{.02}^{1} p^2(t)dt}{\int_{0}^{.01} p^2(t)dt}\right] \qquad [2]$$

From studies conducted by Beranek[3], measurements of orchestral stages and surveys of orchestral musicians indicate a preference for stage acoustics that possess on objective support of between –14.4dB and –12dB.

### 2.2.2 Initial time delay gap (ITDG)

The use of the initial time delay gap (ITDG) as a measure of the perceived intimacy of a concert hall acoustic was originated by Beranek. The ITDG is the duration between the arrival of the direct sound at the receiver and the onset of prominent early reflections (within 10dB of the level of the direct sound). From his extensive study of the acoustic characteristics of concert halls around the world Beranek noted that halls rated high on the quality scale possessed an ITDG of about 15 to 25ms.

### 2.2.3 Lateral fraction (LF)

In their derivation of the lateral fraction (LF), Barron and Marshall[4] developed a measure of the spacial impression of a concert hall acoustic. It is the ratio of energy received from the sides, determined from a figure of 8 polar response receiver over 5ms to 80ms, against the direct energy received at the receiver from all incidences up to 80ms after the onset of a signal.

The lateral fraction is given by [3],

$$LF = \frac{\int_{.005}^{.08} p_8^2(t)dt}{\int_0^{.08} p^2(t)dt} \quad [3]$$

Studies by Beranek indicate desirable early lateral fraction values of between 0.17 and 0.23.

## 2.3 Optimisation

The optimisation process was implemented using a standard Nelder-Mead[5] 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 (reflector heights/ rotation about axes 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.

# 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’ defines the room and generates sets of reflector geometries, from this, the corresponding error magnitude for each reflector geometry configuration is calculated via the ray-tracing model. The second ‘optimisation program’ reads in the generated sets of reflector geometries and their corresponding error magnitude, carries out an error minimisation process and exports the solution room geometry/ reflector set to ODEON .par or standard .obj 3D geometry file format for further investigation.

## 3.2 Set-up program

### 3.2.1 Ray-tracing model

A ray-tracing model forms the backbone of the error calculation process within the set-up program. All surfaces are defined as triangular elements so as to avoid potential planar twisting problems during the definition of room surfaces and any subsequent errors related to the accurate calculation of normals to surfaces. To allow for approximations of acoustic parameters to include elementary frequency considerations octave band absorption coefficients can be assigned to surfaces.

The number of omni-directional sources and their location within the room is able to be set, together with a global control of the number of rays to be emitted from each source.

The receiver size can be defined by the user or automatically be calculated by the program to take into account the room size, number of rays emitted by the source or distance between source and receiver, according to the methods described by Lehnert[6] or Xiangyang et al[7]. The number of receivers, their locations within the room and omni and figure of 8 polar receiver patterns are accommodated in order to measure the impulse response approximations at various room locations, from which the room acoustic parameters described in section 2.2 are calculated.

### 3.2.2 Definition of reflector panels

Each curved rectangular reflector panel is comprised of a mesh of triangular elements; the user is able to specify the density of the mesh and hence the accuracy of the defined panel curvature, albeit at the expense of increasing the duration of the surface impact search within the ray-tracing model.

To allow for the exploration of the use of alternative panel sizes and configurations, the x and y size of panels, depth of curvature and x and y spacing between adjacent reflector panels can be adjusted by the user. The number of panels constituting the arrays of overhead, side and rear reflector panels can also be defined.

The program allows for left to right symmetry about the front to rear room axis to be imposed on the reflector arrays (as used for the examples in this paper), but this can also be switched off to enable asymmetric reflector arrangements if desired.

### 3.2.3 Movement boundaries

In order to contain the solution domain, limits were imposed on allowable movement and rotation ranges, the boundaries used for the examples in this paper are highlighted in Table 1, but are free to be defined by the user.

Table 1 – Reflector movement boundary limitations used

| Reflector panel type | Movement limitation |
|---|---|
| Overhead reflectors | $5m \leq$ height $\leq 8m$ above room floor |
| Side reflectors | $\pm \pi/4$ rotation about the relative x- axis* and<br>$\pm \pi/4$ rotation about the z-axis |
| Rear reflectors | $\pm \pi/4$ rotation about the x- axis |

* The side reflector arrays are initially rotated about the z-axis to allow for a fan shaped stage shell arrangement.

### 3.2.4 Generation of initial reflector sets

The degrees of freedom within the reflector configuration determine the number of dimensions of reflector configurations for input into the optimisation process; $n+1$ time variant randomised reflector sets, confined within the above boundary limits are generated as part of the set-up process, prior to the initial error calculation and subsequent instigation of the optimisation program.

## 3.3 Optimisation program

### 3.3.1 Simplex routine

Following each trial solution within the simplex routine, boundary checks are performed and if exceeded the newly proposed reflector height or rotation is forced back to the boundary limit prior to calculation of its associated error. The process continues until the process converges at a minimum; in this case when all dimensions of reflector configurations 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 reflector configurations and the process is repeated to verify whether convergence to the same minimum occurs.

### 3.3.2 Error calculations

Measures of the error were developed for each acoustic parameter based upon achieving the favourable values for each given in section 2.2, these are shown in Table 2.

Table 2 – Acoustic parameter error functions

| Acoustic parameter | Error function |
|---|---|
| Support (ST1) | $$Error_{ST1} = \frac{\sum_{i=1}^{n}\left(ST1_T + ST1_i\right)^2}{n} \quad [4]$$ Where, $ST1_T$ is the target ST1; $n$ is the number of receivers. |
| Initial time delay gap (ITDG) | $$Error_{ITDG} = \sum_{i=1}^{n}\left(\frac{\left(1-w_f\right)\left(d-t_i\right)}{ITDG_T} + \left(w_f - 1\right)\right) \quad [5]$$ Where, $w_f$ is a weighting factor; $d$ is the direct time; $t$ is the time of arrival of the captured incident ray; $ITDG_T$ is the target initial time delay gap. |
| Lateral fraction (LF) | $$Error_{LF} = \sum_{i=1}^{n}\left(\left(\frac{1-w_f}{LF_T} \times LF_i\right) + w_f\right) \quad [6]$$ Where, $LF_T$ is the target lateral fraction. |

Combinations of the above equations are then able to be used to create error functions for multiple acoustic parameter optimisations. These combination error functions are then able to be weighted to prioritise optimisation at certain receiver locations, eg. to prioritise optimisation of acoustic conditions at the main microphone position, then on the orchestral stage and finally for the audience, a simple weighting as outlined in equation [7] could be used.

$$Error_{Total} = 100 \times Error_{Microphone} + 10 \times Error_{Orchestra} + Error_{Audience} \quad [7]$$

# 4 EXAMPLE OPTIMISATIONS

## 4.1 Optimisation A - Multiple ST1

To illustrate the optimisation process, the program was set the challenge of optimising a reflector set to provide a favourable ST1 in several areas across the orchestral stage. 3 sources were defined, with 4 receivers defined at 1m from each source. The mean ST1 value calculated according to equation [4] from all 12 receivers was used as the impetus for the optimisation. The associated optimised reflector set is shown in Figure 2.

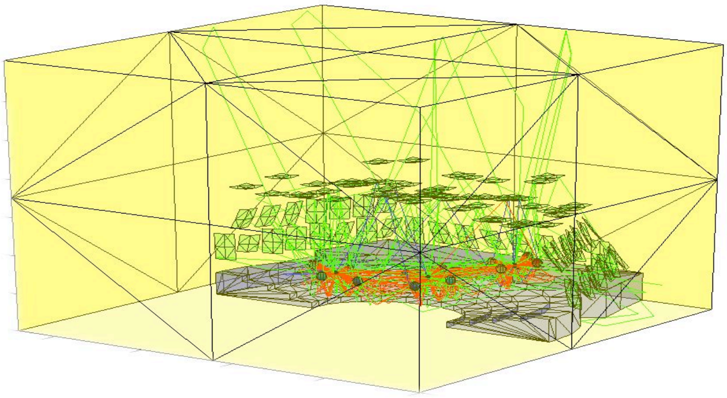

Figure 2 - 3D view of a multiple location ST1 optimisation

## 4.2 Optimisation B - Multiple ST1, ITDG and LF

In addition to achieving a favourable ST1 measure at several locations on stage, optimisation B was set the task of achieving favourable LF conditions at the main microphone and audience seating locations, together with a favourable ITDG at the main microphone location. The associated optimised reflector set is shown in Figures 3 and 4.

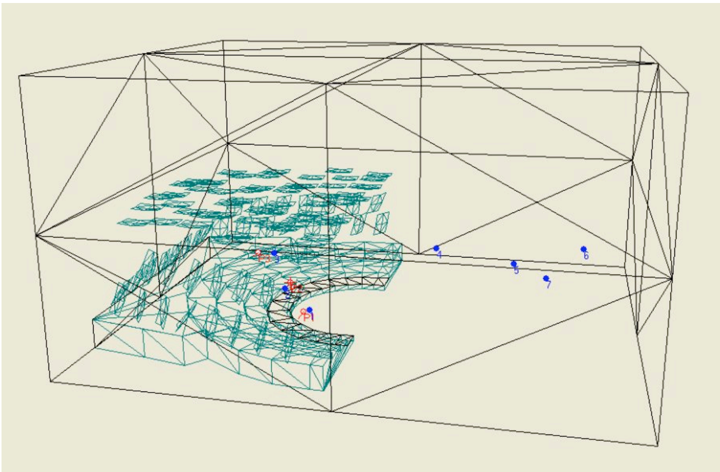

Figure 3 – 3D view of optimised reflector canopy/ shell (optimisation B)

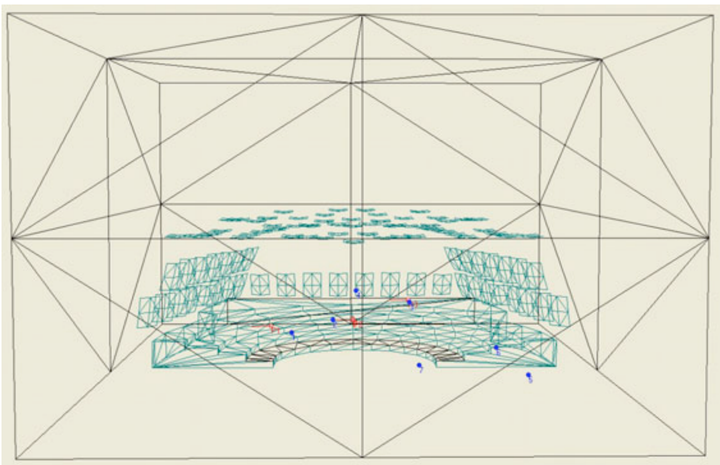

Figure 4 – End view of optimised reflector canopy/ shell (optimisation B)

## 4.3 Verification of achieved ST1 in optimised solutions

The solution geometries were imported into ODEON to verify the calculated ST1 values at the receiver locations. The mean four-band ST1 for optimisation A and B were calculated to be approximately -13.2 dB and –14.0 dB respectively, see Table 3 and 4; these both fall within the recommended ST1 design range as stated in section 2.2.1.

Table 3 - ODEON calculated ST1 at stage receivers 1, 2 and 3 (optimisation A)

| Receiver Number: 1 R1 | | | | (x.y.z) = (14.00. 10 00. 1 20) | | | | |
|---|---|---|---|---|---|---|---|---|
| Band (Hz) | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| STearly (dB) | -19.55 | -17.58 | -13.53 | -12.84 | -12.84 | -12.94 | -13.22 | -13.95 |
| **Receiver Number: 2 R2** | | | | **(x.y.z) = (11 00. 7.00, 1 50)** | | | | |
| Band (Hz) | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| STearly (dB) | -21.74 | -18.74 | -14.09 | -13.17 | -13.16 | -13.31 | -13.71 | -14.85 |
| **Receiver Number: 3 R3** | | | | **(x,y,z) = (8.00, 6.00, 2.10)** | | | | |
| Band (Hz) | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| STearly (dB) | -18.82 | -18.08 | -13.87 | -12.88 | -12.86 | -12.95 | -13.26 | -14.03 |

Table 4 - ODEON calculated ST1 at stage receivers 1, 2 and 3 (optimisation B)

| Receiver Number: 1 R1 - Violin | | | | (x,y,z) = (14.00, 10.00, 1.20) | | | | |
|---|---|---|---|---|---|---|---|---|
| Band (Hz) | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| STearly (dB) | -12.31 | -15.70 | -14.78 | -13.66 | -13.32 | -13.37 | -13.32 | -13.49 |
| **Receiver Number: 2 R2 - Viola/ Flute** | | | | **(x,y,z) = (10.00, 8.00, 1.50)** | | | | |
| Band (Hz) | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| STearly (dB) | -12.56 | -16.96 | -15.58 | -14.08 | -13.73 | -13.47 | -13.22 | -13.41 |
| **Receiver Number: 3 R3 - Bassoon** | | | | **(x,y,z) = (8.00, 6.00, 2.10)** | | | | |
| Band (Hz) | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| STearly (dB) | -13.52 | -18.55 | -15.64 | -13.92 | -13.45 | -13.45 | -13.25 | -13.11 |

## 4.4 Verification of achieved LF in optimisation B

The ODEON calculated four-band LF80 values were found to be 0.14 at the main microphone position and a mean of 0.27 at the audience seating positions; these fall slightly below and above the desired design range as stated in section 2.2.3 respectively, see Table 5.

Table 5 – ODEON calculated LF80 at receiver positions 4, 5, 6 and 7

| Receiver Number: 4 R4 - Mic | | | | (x,y,z) = (11.00, 16.20, 4.00) | | | | |
|---|---|---|---|---|---|---|---|---|
| Band (Hz) | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| LF80 | 0.163 | 0.131 | 0.136 | 0.141 | 0.143 | 0.141 | 0.132 | 0.145 |
| **Receiver Number: 5 R5 - Audience 1** | | | | **(x,y,z) = (4.40, 20.00, 1.20)** | | | | |
| Band (Hz) | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| LF80 | 0.319 | 0.303 | 0.303 | 0.300 | 0.300 | 0.298 | 0.291 | 0.296 |
| **Receiver Number: 6 R6 - Audience 2** | | | | **(x,y,z) = (6.30, 24.00, 3.00)** | | | | |
| Band (Hz) | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| LF80 | 0.288 | 0.285 | 0.282 | 0.276 | 0.275 | 0.272 | 0.266 | 0.271 |
| **Receiver Number: 7 R7 - Audience 3** | | | | **(x,y,z) = (8.80, 22.00, 2.00)** | | | | |
| Band (Hz) | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| LF80 | 0.236 | 0.219 | 0.220 | 0.218 | 0.218 | 0.214 | 0.206 | 0.211 |

Although the measured LF at the main microphone position (R4) was slightly below the desired value, the model did not account for the extra absorption from seated musicians directly in front of the conductor, these would be expected to attenuate more of the direct on-axis sound relative to the lateral sound than is presently allowed for, and so in practice the LF value here would be expected to improve.

The sidewalls of the studio are as yet untreated and as such the ODEON predicted reverberation time is in the region of 3.5 seconds; this is longer than would be typically suited for orchestral repertoire performance and so with the addition of treatment to the sidewalls it would be expected that the audience measured LF values would reduce slightly.

## 4.5 Verification of ITDG at main microphone position

From the ODEON predicted reflectogram below, several prominent reflections seem evident within the first 20 ms, however, as 3 sources were used in the model, 2 of the apparent reflection images are direct arrivals from other sound sources and the remaining images (within 10dB below image at 30ms) are from floor reflections in front of the conductor; here as discussed previously, musicians would be seated and so attenuation of these reflections (not taken into account within this model) would be expected. The first prominent reflection occurs at 32ms and is a first order reflection from the sidewall.

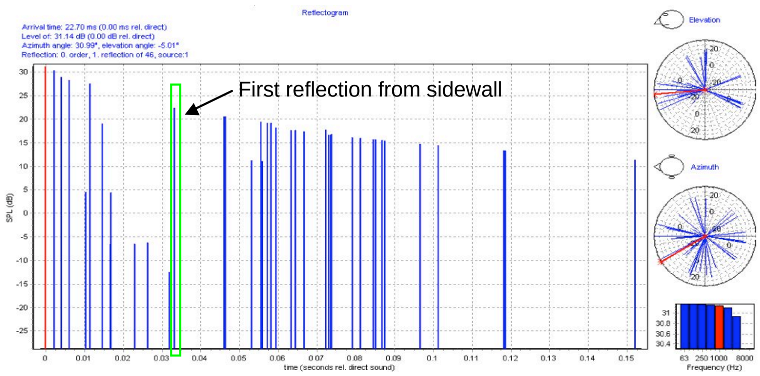


Figure 5 – ODEON predicted reflectogram at the main microphone position

# 5 CONCLUSIONS

A computer based method of optimising the orientation of arrays of reflector panels that form an orchestral canopy and shell, to achieve multiple favourable acoustic conditions at various locations throughout an orchestral rehearsal/ recording studio has been described. Two example optimisations have been presented and both appear to indicate that the method is capable of suggesting solution reflector canopy/ shell arrangements worthy of further investigation.

# 6 REFERENCES


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