

Predicting Room Acoustical Behaviour with the ODEON Computer Model.

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ABSTRACT

The ODEON model for room acoustics is implemented for general use on a PC. Technical features of the program relevant to the acoustical design process include interactive visualizations of reflection paths and sequences, mapping of overall energy distributions and of coverage provided by individual reflectors, and minimized recalculation times. In this paper the modelling process is discussed. Comparisons are then made between predicted room acoustical indices and values measured in full-size and model halls, and reasons for discrepancies are discussed. These discrepancies indicate areas in which the computational model has to be improved, and highlight some shortcomings of current room acoustical survey methods. The effects of various calculation parameters (e.g. number of rays, early reflection order) are also briefly considered.

1 INTRODUCTION: THE MODELLING PROCESS

The principal subject of this paper is to present and discuss comparisons between measured and calculated values of various room acoustical indices. The calculations were performed using ODEON version 2.0, which is described in a companion paper [1]. Before making the comparisons, it is worthwhile briefly to consider a few aspects of the process of modelling a room and making calculations with that model room.

Like virtually all computer models, ODEON works from a description of a room's geometry and absorption. The results of a calculation will obviously depend on how these are approximated.

Absorption

Obviously, a reliable value for reverberation time (understood here as the final rate of sound decay) will only be obtained if the absorption coefficients of the major surfaces are well approximated. Apart from this, our experience is that minor variations in absorption coefficients have very little effect on other indices. Quite large changes of absorption coefficient are required on primary reflecting surfaces to produce significant changes in the value of C80, for example.

Geometry

Geometrical modelling is a more critical process, and must be done with consideration for the calculation method to be employed. With calculation models based wholly or partially on image source theory, one should avoid numerous small surfaces, especially in areas of the room which are important for early reflections. Otherwise, too much early energy will be received, since the laws of geometrical acoustics assume that all surfaces are infinitely large (for the purpose of determining reflection level). Generally speaking, when modelling for ODEON 2.0, one should aspire to accuracy in the modelling of primary reflecting surfaces, but otherwise avoid unnecessary small surfaces and aim for a replication of the general proximities and forms in the room. This argues against the use of geometries translated automatically from CAD drawings, whereby one typically obtains far too many and far too small surfaces.

1.1 Choosing Calculation Parameters

There are three principal parameters which have to be chosen when carrying out a calculation in ODEON 2.0, and which can have a significant effect on the results. Although a lot more experience is needed before definitive rules can be laid down, it is possible to give some indication of how these should be set for best results.

Number of Rays

We usually find that a number of rays between 25 and 100 times greater than the number of surfaces in the room produces robust and convincing results. This is quite a low number of rays in comparison with typical particle tracing methods. The end results of calculations are generally not very sensitive to the number of rays used.

Order of Transition from Early to Late Reflections

The optimal choice of this parameter depends on the complexity of the modelled room geometry. We wish to avoid including image sources from combinations of surfaces which in reality would contain negligible energy. The risk of doing so increases with the order of early reflections and with the number of small surfaces in the room. Therefore one should as a rule choose a lower transition order, the more complex the room model is. Transition orders above about 4 should probably be avoided except when investigating high-order echoes and such like. It is a weakness of the computer model that some of the results are rather sensitive to the transition order chosen.

Diffusion Coefficients

At the present state of experience, unless a surface in a geometrical model really represents a very large plane surface in the real room, we always give it a diffusion coefficient of 1, and the results seem satisfactory. The diffusion coefficients do not have a consistent or marked effect on any derived indices other than reverberation times.

2 COMPARING MEASURED AND CALCULATED ACOUSTICAL INDICES

Before presenting the results of studies comparing measured and predicted indices, it is worth considering a few of the factors which may affect the validity of any comparison. We will only consider here uncertainties which are inherent to the measurement or modelling process, not factors which depend on the choice of technique.

Measurement Uncertainties

A growing body of evidence [2, 3] indicates that the room acoustical survey methods employed hitherto are inadequate for the characterization of most rooms. In a nutshell, one needs to measure far more source-receiver combinations than has been normal to adequately sample the statistics of a room's acoustical indices. The task here however is to achieve an accurate estimate of the conditions local to a given receiver position from a given source position.

Some uncertainty arises from the limited reproducibility of measurements. This will vary between measurement systems. Bradley [2] presents standard deviations for repeated re-placement of source and microphone as follows (all figures are for 1000 Hz):

C80: 0.25 dB G: 0.4 dB EDT: 0.075 s RT: 0.02 s LF: 0.015

Pelorson's results are similar [3].

Further problems arise because there is often a strong local positional variation in the values measured, and one is as a rule not quite certain of the absolute position of the source or receiver when transferring between a real hall and its model description. For example, Bradley [2] obtained maximum standard deviations for various common indices when receivers were moved within a radius of 30 cm as follows (all figures are for 1000 Hz):

C80: 0.75 dB G: 0.6 dB EDT: 0.1 s RT: 0.04 s LF: 0.05

Again, Pelorson's results are of the same order of magnitude [3]. A positional accuracy of +/-30 cm in transferring from a real hall to a geometrical model description is probably only rarely achieved. Thus we may regard the above figures as a lower limit to the level of agreement one may demand between measured and predicted indices.

Further sources of uncertainty which have as yet not been adequately quantified and which are difficult to exclude from the modelling process include detailed transducer directivity and detailed characteristics of the immediate vicinity of source and receiver.

Modelling Uncertainties

Geometrical simplifications and distortions will often cause a given phenomenon (e.g. a reflection or interference effect) to occur at a slightly different location in the room or in the reflection sequence. This can for instance cause a reflection to occur just before 80 ms instead of just after, thus disturbing the C80 value.

The comment above regarding the detailed form of the vicinity of the source and receiver also applies in modelling. In particular, the seating area has a very complex structure, which is always greatly simplified for modelling purposes. The attenuation of sound passing over such a structure is very difficult to model in a general way.

3 CASE STUDY 1: FULL-SIZE CONCERT HALL

The first case study concerns the Royal Festival Hall in London. Figure 1 shows a plan and section of the real hall (including the organ case), and Figure 2 shows the corresponding views of the ODEON model. Figure 3 shows an orthogonal view of the model, which contains 140 surfaces. Note the numerous relatively small surfaces on the side walls.

Measurements from this hall (with the 'Assisted Resonance' turned off) have been published by Gade [4]. The absorption coefficients for the surfaces in the ODEON model were the original consultants' own [5]. All surfaces were assigned a diffusion coefficient of 1. Various combinations of calculation parameters were tried: the best overall results so far were obtained with 5000 rays, and an early-late transition at order 1. Explanations for the success of these seemingly very crude calculations are given later. Calculations were made for two source positions (S1 and S3 in Figure 1) and five receiver positions (R1-R5 in Figure 1).

Figure 4 shows the measured and calculated reverberation times, in each case the mean of the 10 source-receiver combinations. The agreement is satisfactory.

For all indices other than reverberation time, comparisons are presented here for the 1000 Hz octave band only. Figure 5 shows the 10 pairs of measured and calculated values of Level (The sound pressure level relative to that which would be measured at 10 m from the same source in a free field.) In view of the previous discussion concerning uncertainties, the agreement is generally excellent. The worst error is +1.5 dB for S1-R5.

Figure 6 compares measured and calculated Clarity C80. Here the agreement is less good, but still generally comparable with the inherent uncertainties. The error of +3 dB for S3-R5 remains unexplained.

Figure 7 shows the results for Early Decay Time EDT. The range of values covered is about right, and 6 out of 10 values agree within the expected minimum measurement uncertainty. EDT is problematic regarding its derivation from the decay curve, which is rather sensitive to the inherent limitations of an energy-based calculation method without filtering. The lack of filtering causes the typical drop after the direct sound to be much sharper than in reality. This in turn causes an EDT derivation based on fitting a regression line to the decay to virtually ignore the direct sound and fit a line to the following plateau. The resulting EDT values are too high. For this reason, ODEON 2.0 uses a simple level-crossing algorithm instead of a regression algorithm to determine EDT. Nevertheless, some problems remain.

So far, the use of only 5000 rays and an early-late transition after the first reflection seems to have led to good results. This may be put down to the relation between the geometries of the real and the modelled hall.

In the real hall there are actually very few large uninterrupted reflecting surfaces which will give 'clean' image sources. Using higher transition orders worsens the agreement between measured and calculated results. We can expect the energy transport around the room to become non-specular (if not fully diffuse) very quickly. Thus a low transition order is appropriate. Since image sources in small surfaces give too much specular energy, too much effort should not be expended in finding them. 5000 rays yield an angle of about 3° between rays, which is sufficient to resolve the most important first order image sources.

There is one room acoustical index for which a higher transition order gives much better results. This is the Lateral Energy Fraction LEF. Figure 8 shows the measured values along with two sets of calculated values; both use 5000 rays, but the transition order is 1 in one case and 4 in the other. A transition order of 4 reproduces the measured trends well, in addition to many of the values, whereas order 1 gives much weaker agreement. The explanation for this is to be found in the definition of LEF. LEF is only concerned with the first 80 ms of the response, so effects of diffusion or scattering are limited. Furthermore, almost all the reflections arriving within the 80 ms appear in both the numerator and denominator. Thus errors in the magnitude of the individual components are not so critical. What differs crucially between the numerator and denominator in the definition is the directional weighting of the contributions. Thus it is most important to get the balance between different directions correct. This can be achieved by ensuring that specular components (with very well-defined directions) dominate over diffuse components coming from all surfaces in every direction.

Errors which are not immediately explicable may be due to extreme occurrences of the variations mentioned in section 2, or to other effects. One obvious culprit is the use of energy instead of pressure as the primary variable, whereby under certain circumstances strong reinforcements or cancellations between reflections can occur, and where the addition of filtering would affect the smoothness of the decay curve and the energy-time distribution.

4 CASE STUDY 2: SIMPLE MODEL CONCERT HALL

The second set of comparisons was carried out against a physical scale model. This was a 1:50 model of a notional large concert hall (similar in dimensions to the Royal Festival Hall). Such an exercise is of interest because the 'real room' is much simpler than a full-size room. There are however extra uncertainties associated with the problems of making measurements at 1:50 scale.

Figures 9 and 10 show the model used in ODEON. This contains 30 surfaces, and is a fairly faithful copy of the real hall, except for the audience areas, which in the real hall were constructed of rows of metal angle covered with material. The same model has been the subject of another comparison study [6]. It should be noted that the designations of the receiver positions differ from those of Ref. 6. The receivers can be equated as follows: (Present 1 = 3 in Ref. 6), (2=2), (3=4), (4=5), (7=6), (8=7), (9=8), (10=9), (11=10).

The measurements results quoted here were made at the Dept. of Applied Acoustics, Salford University, England, using a prototype measurement system dubbed 'SUMMS'.

All the calculation results quoted here were obtained with both:

- (a) 1000 rays and a transition order of 4, and
- (b) 20000 rays and a transition order of 6.

Due to uncertainty about the absorption coefficients of the materials used in the model, there is poor agreement over reverberation times. In ODEON's favour is the fact that the calculated reverberation times fall between those given by Sabine's and Eyring's formulae provided with the supposed absorption coefficients.

Figure 11 shows the measured and calculated values of Level at 1000 Hz. The trends are generally followed quite well, although the calculated values vary less strongly than the measured ones. Receivers 10, 11 and 12 on the balcony show quite large and inconsistent errors. It is thought these may be connected with the fact that the line of sight to the source lies close to the balcony edge. The balcony edge may also significantly influence other wavefronts in the real hall. There is virtually no difference between the results for the two calculation conditions. This is attributable to the simplicity of the room model; 1000 rays discover almost as many images up to the third order as 20000 do.

In Figure 12 the 1000 Hz Early Decay Time values are compared. The calculated values are on average a little low; this is a by-product of the general disagreement about reverberation times. If receivers 2 and 6 are disregarded for a moment, the agreement is otherwise reasonable (using 20000 rays helps somewhat for receivers 9, 10 and 11). The large discrepancy at receiver 2 is probably due to the direct sound and two early reflections passing close to the front edge of the stage; diffraction in the real hall will attenuate these images' contributions, giving a higher EDT. Receiver 6 is on the stage and receives very strong, very early floor reflection. Experiments [7] have shown this to cause a dramatic cancellation of the direct sound, again leading to a raised EDT.

Results for Clarity C80 at 1000 Hz are shown in Figure 13. The large errors at receivers 2 and 6 have the same explanation as before. The agreement is acceptable for the remaining receivers other than 11. The errors at receivers 10, 11 and 12 may again be due to the influence of the balcony edge.

It was not possible to obtain measured values of Lateral Energy Fraction in the RECT-1 scale model.

5 CONCLUSIONS

It has been demonstrated that quite good agreement between measured and calculated results can be achieved without enormous computing effort.

In simple room models, ODEON provides stable predictions over a wide range of input parameters (number of rays, transition order). The ODEON calculation model requires improvement to reduce its sensitivity to choice of transition order for complex room models. Improvements also need to be made to the calculation model such that the optimum calculation parameters are the same for predicting all room acoustical indices.

A general conclusion here is that simple room models are to be preferred, perhaps even if they are rather gross simplifications of complex real rooms.

More thorough room acoustical survey methods are required to provide statistical data which can pose deeper and more meaningful tests of numerical predictions.

ACKNOWLEDGEMENT

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- [7] Lam, Y.W., personal communication.

Figure 1: Plans and section of the Royal Festival Hall, London (RFH), showing the source and

receiver positions used in the measurements and calculations.

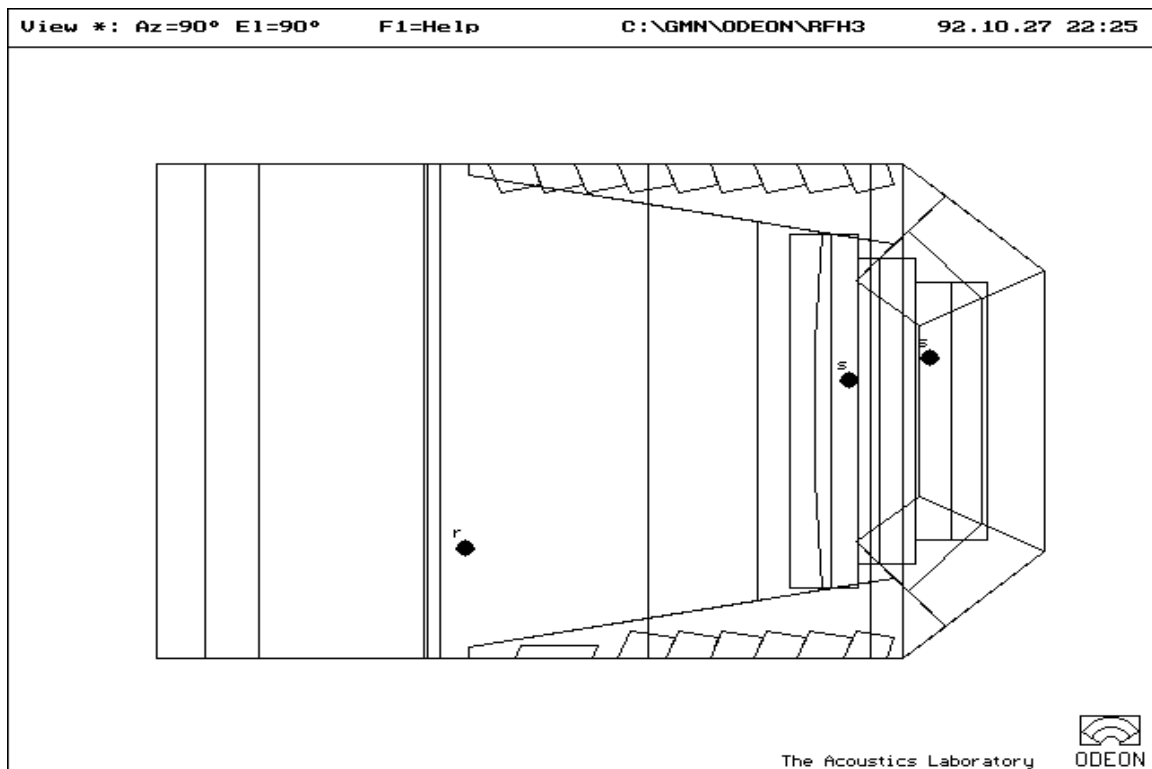
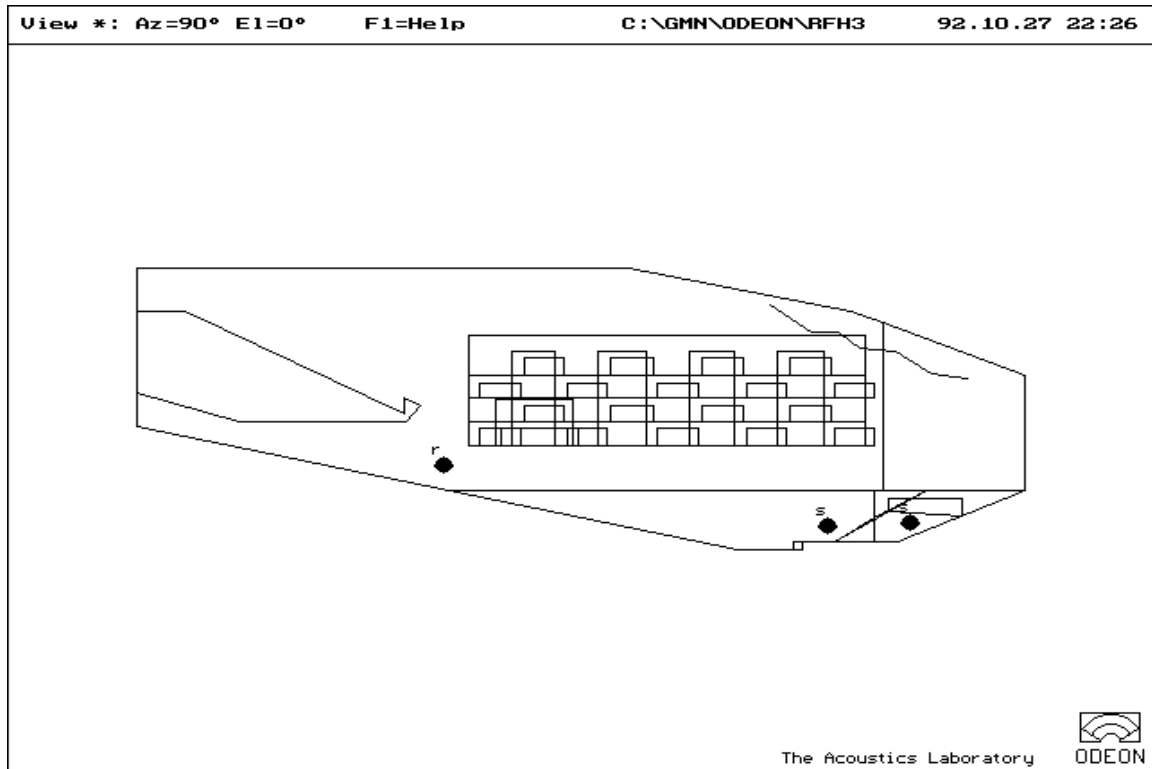


Figure 2: Plan and section (wireframe) of the ODEON model of the RFH.

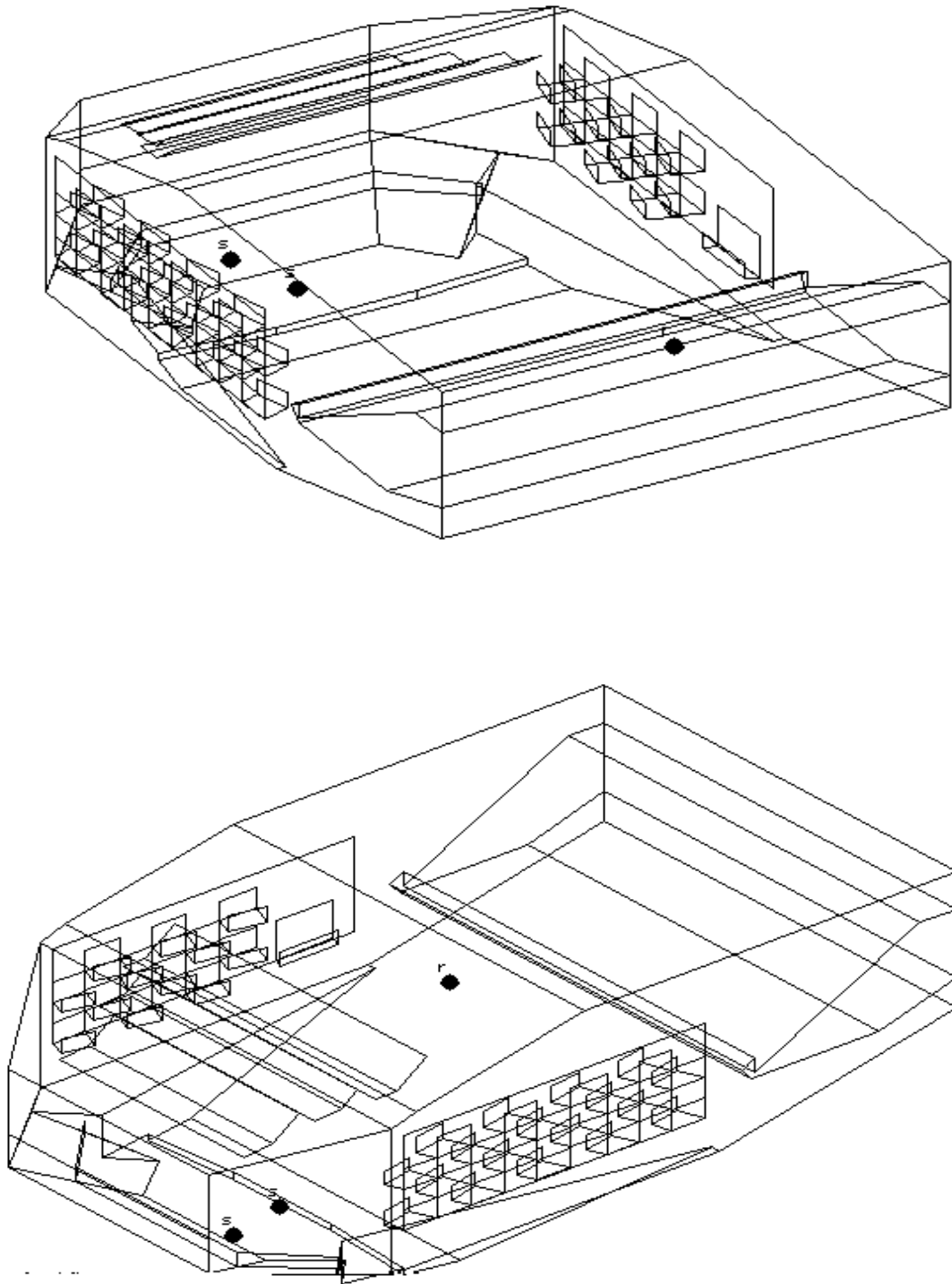


Figure 3: Orthogonal views of the ODEON model of the RFH.

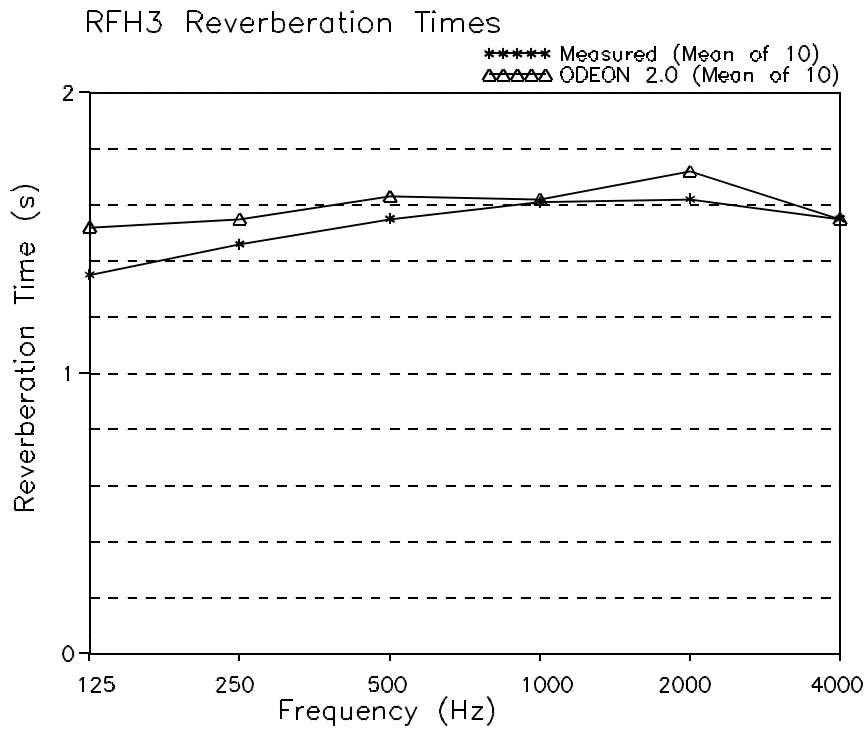


Figure 4: Measured and calculated mean reverberation times in the RFH.

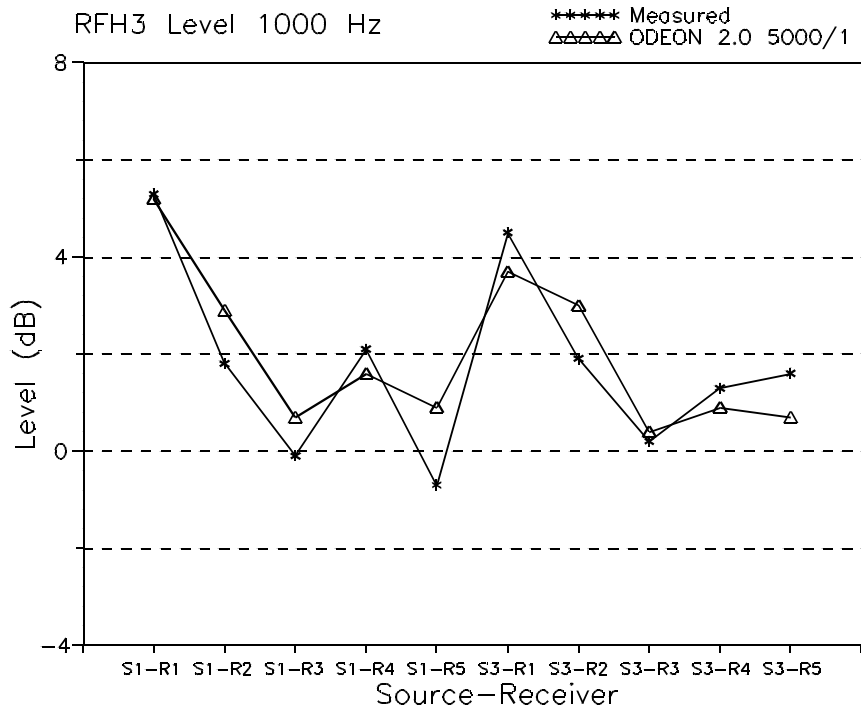


Figure 5: Measured and calculated Level at 1000 Hz in the RFH. The legend 5000/1 indicates

the use of 5000 rays with a transition order of 1.

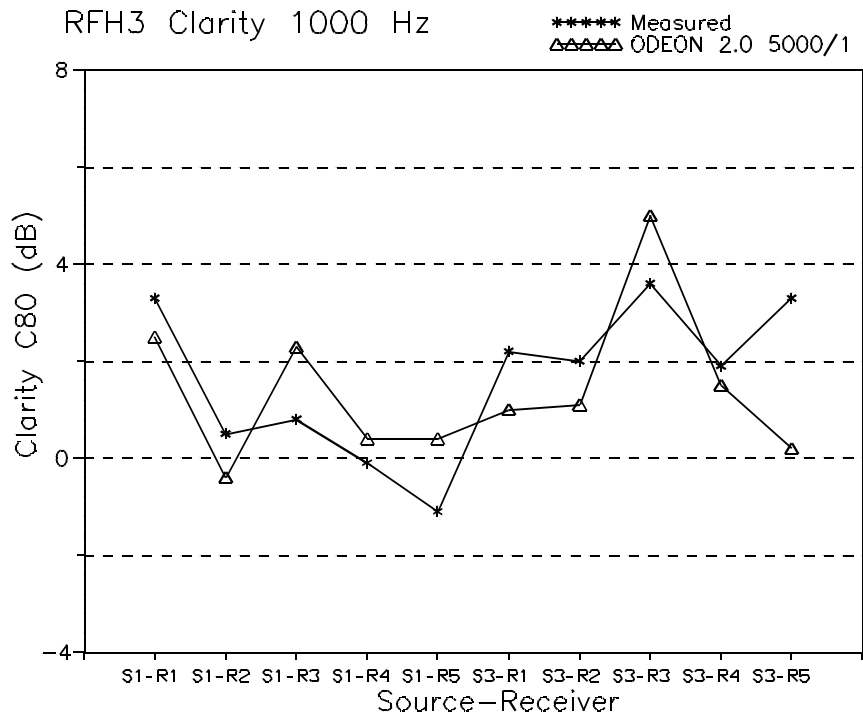


Figure 6: Measured and calculated Clarity C80 at 1000 Hz in the RFH.

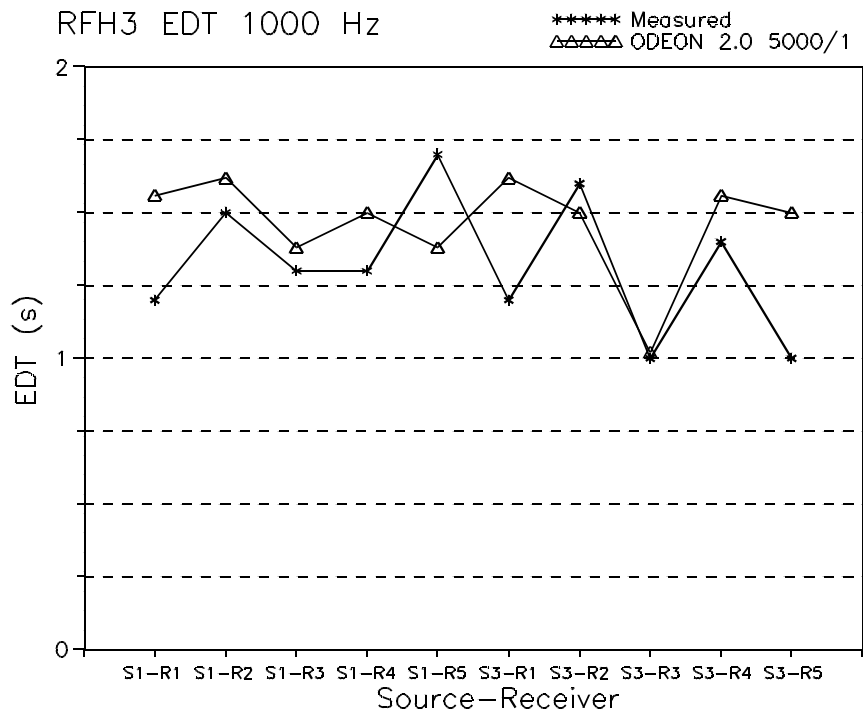


Figure 7: Measured and calculated Early Decay Time at 1000 Hz in the RFH.

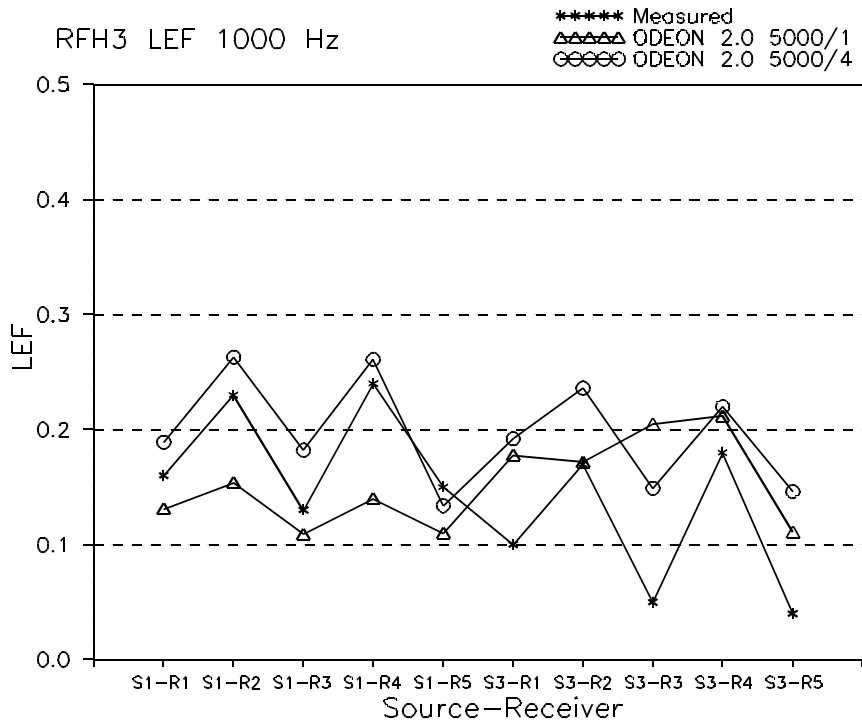


Figure 8: Measured and calculated Lateral Energy Fraction LEF at 1000 Hz in the RFH. Calculated with transition order 1 and 4.

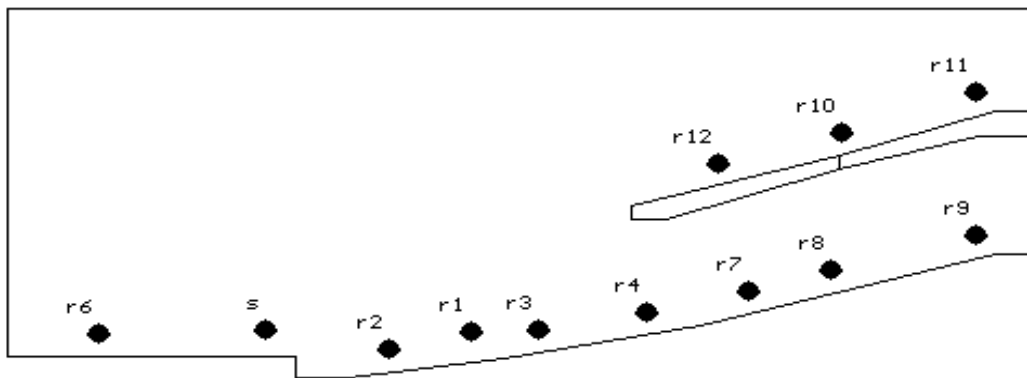
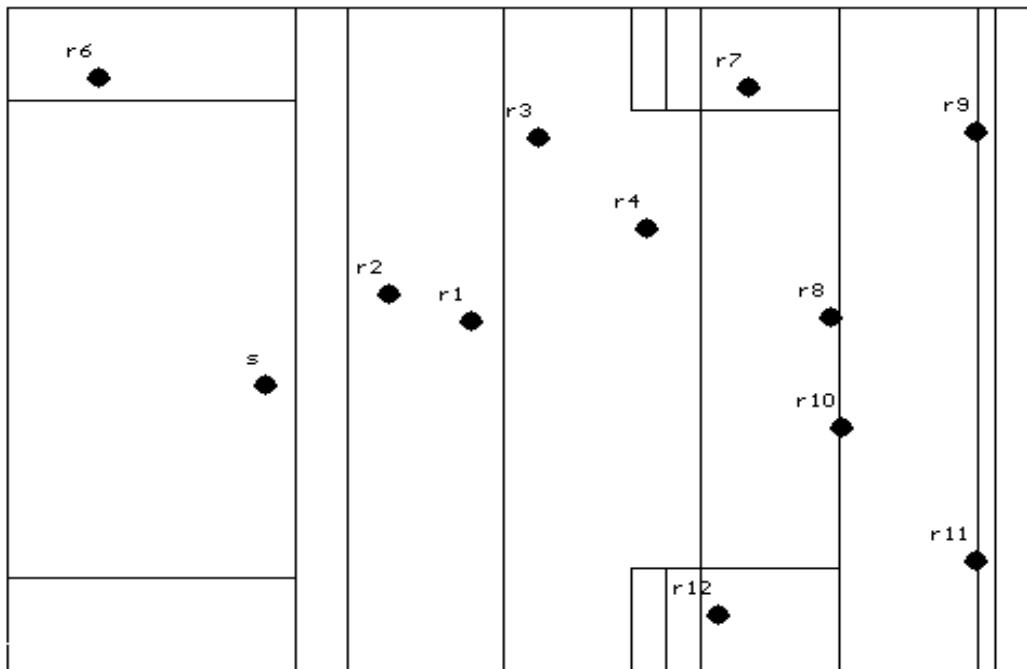


Figure 9: Plan and section of RECT-1 model, showing source and receiver positions.

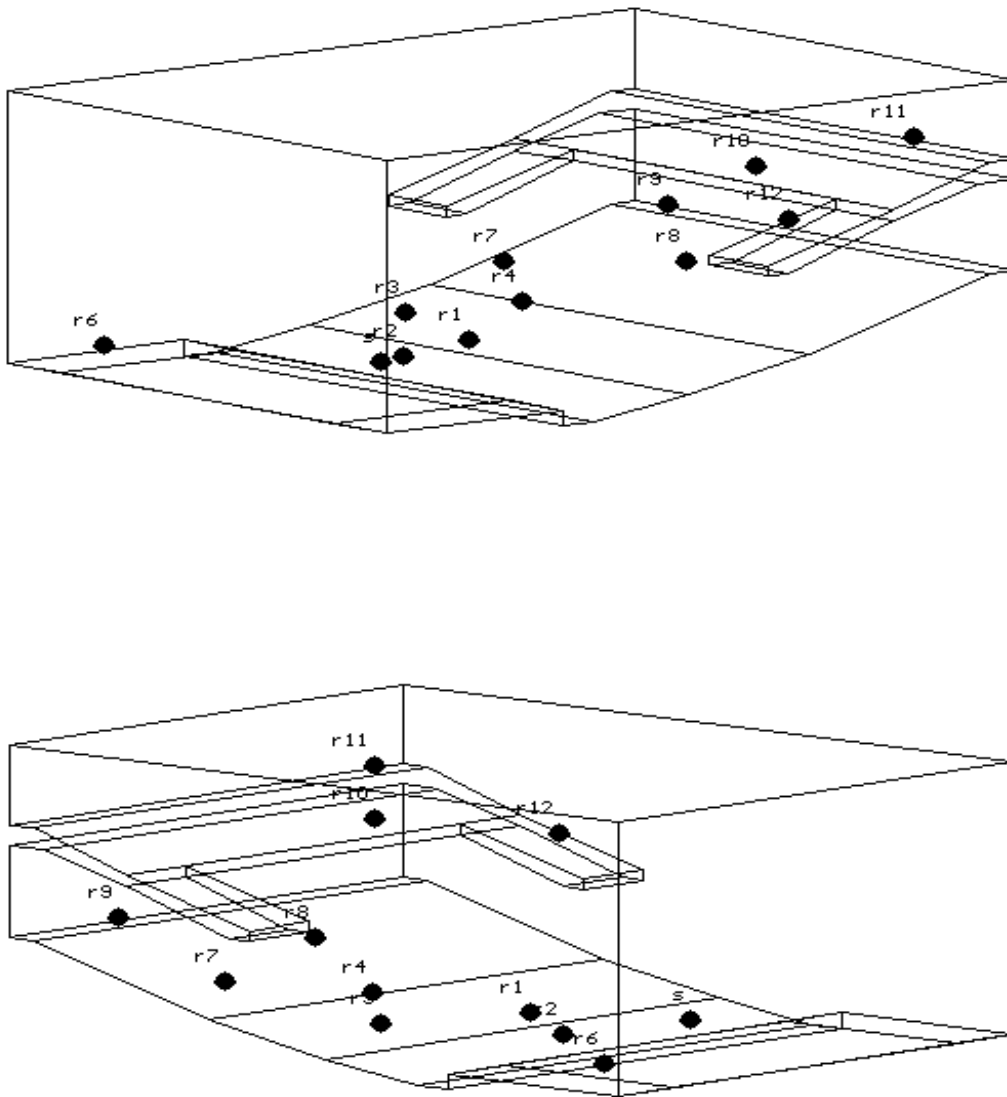


Figure 10: Orthogonal views of the RECT-1 model, showing source and receiver positions.

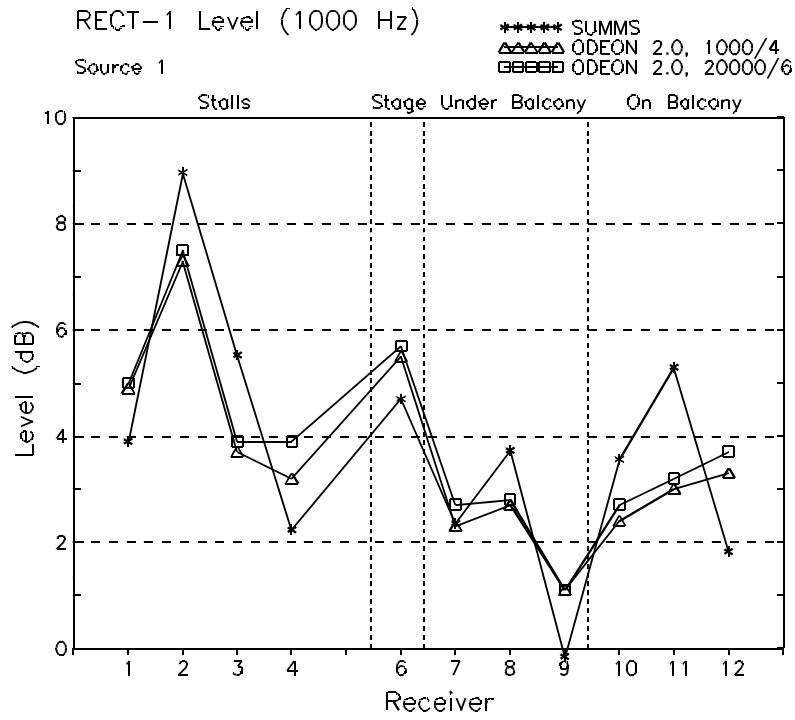


Figure 11: Measured and calculated Level at 1000 Hz in RECT-1. Calculated with 1000 rays / transition order 4 and 20000 rays / transition order 6.

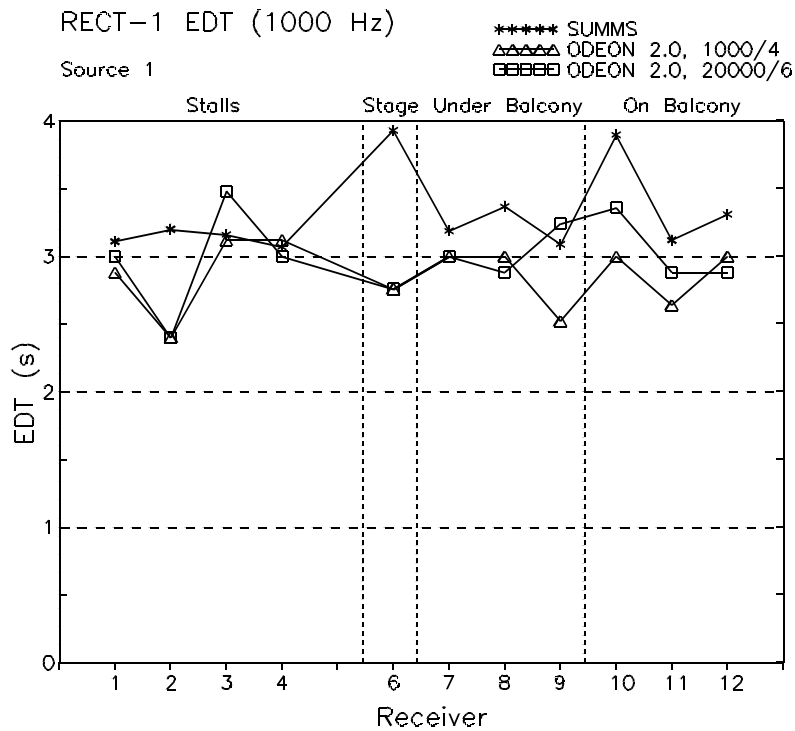


Figure 12: Measured and calculated Early Decay Time at 1000 Hz in RECT-1. Calculated with

1000 rays / transition order 4 and 20000 rays / transition order 6.

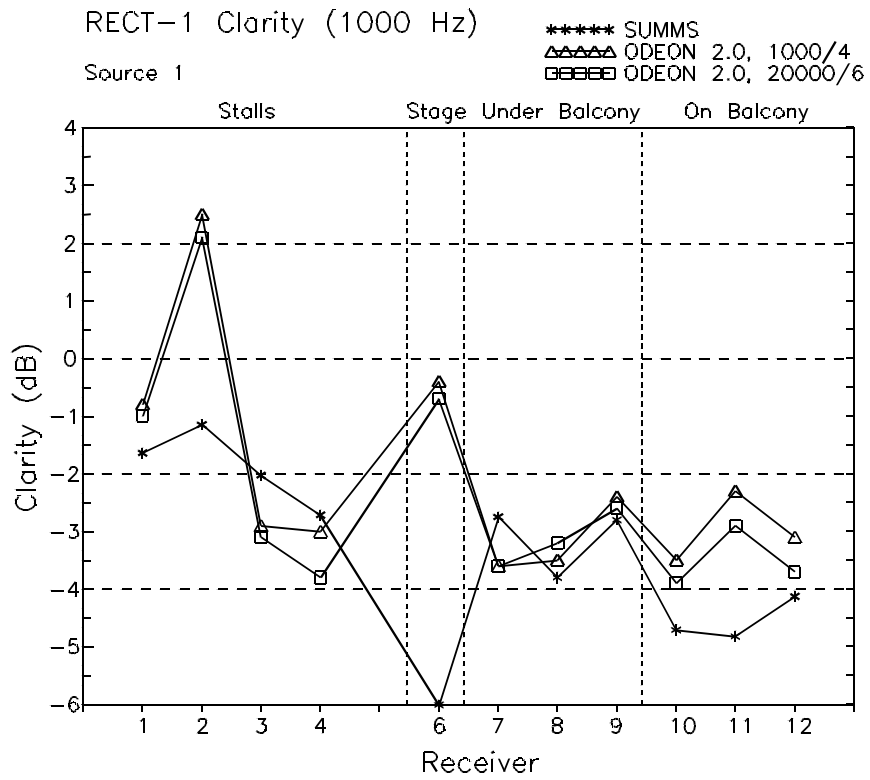


Figure 13: Measured and calculated Clarity C80 at 1000 Hz in RECT-1. Calculated with 1000 rays / transition order 4 and 20000 rays / transition order 6.