COMPUTER MODELLING WITH CATT-ACOUSTIC – THEORY AND PRACTICE OF DIFFUSE REFLECTION AND ARRAY MODELING

Adrian James, Adri an James Acoustics, UK (adrian@adrianjamesacoustics.co.uk)
Bengt-Inge Dalenbäck, CATT, Sweden (bid@catt.se)
Amber Naqvi, IoSR University of Surrey and Adrian James Acoustics, UK
(amber@adrianjamesacoustics.co.uk)

1. INTRODUCTION

This paper describes the room acoustics prediction and auralisation software CATT-Acoustic. It concentrates on topics relevant to prediction quality rather than on features such as use of colour and similar that instead will be exemplified during the presentation. Although important for the user, abundant features are of limited value if the underlying prediction algorithms fail to predict well in many important cases. Specifically, the paper will focus on the handling of frequency dependent diffuse reflection and loudspeaker array modelling. Frequency-dependent diffuse reflection is essential for the prediction of fundamental parameters such as the reverberation time (RT), while handling the sometimes very long nearfields are as essential for the prediction of sound from arrays.

2. SOFTWARE BACKGROUND

To serve as a backdrop for the prediction method discussion below, the software background is briefly outlined in this section.

The initial DOS-based software was written in 1989 and was used a combination of the image source model (ISM) for early reflections and global ray-tracing for the late decay. Already in the initial versions frequency-dependent diffuse reflection was taken into account. In 1990 the first auralisation implementation, using Lake DSP hardware, was finished [1]. During the years 1990-94 features were added but no major method changes took place.

In 1995 a software convolver was included so that the complete auralisation process could be performed on a standard PC, although the close relationship with Lake DSP continued with head-tracked auralisation [2] and Ambisonic replay options. Essentially the same method was used up to and including the first 16-bit Windows version in 1996 (v.6.0), and was successful in the first international round-robin on room acoustics prediction [3] where CATT was one of only three programs that were judged to give reliable and useful results. Of these three, 5 of the 8 predicted measures were best evaluated by CATT-Acoustic. With v.6 also classical ray-tracing [4] was added for audience area colour mapping. However, during 1990-95, B-I Dalenbäck also worked half-time in the Chalmers Room Acoustics Group [5] developing a more advanced prediction and auralisation method resulting in a Ph.D. thesis [6].

In 1998, v.7 for 32-bit Windows was released introducing Randomised Tail-corrected Cone-tracing (RTC), a simpler but more robust variant of the research method. The RTC, detailed below, is a very general method useful for prediction of acoustic parameters as well as for auralisation, and remains the main prediction method in CATT-Acoustic. Also released in 1998 was a fundamental functionality related to array modelling: the DLL Directivity Interface (DDI) that enabled run-time array-modelling including handling of the nearfield and DSP-settings for beam-steering.

3. DIFFUSE REFLECTION

Before the prediction methods employed are described a question has to be answered. *Why is diffuse reflection so important in room acoustics prediction?* For the answer it is useful to characterise rooms according to:

- their *mixing properties* : i.e. basically to what degree the room shape and surface orientations are such that rays risk being locked into particular directions (e.g. between parallel walls).
- their *absorption distribution* : i.e. if all surfaces have similar coefficients, or if some surfaces are hard while other are very absorbent.

First we have the simple cases: rooms where the shape acts as mixing and where the absorption distribution is even. Here classical Sabine theory works very well and prediction using specular-only methods can be quite successful. Then we have the other extreme: rooms that are non-mixing and with uneven absorption distribution. In these rooms Sabine will dramatically *under*-estimate the actual RT while specular-only methods will dramatically *over*-estimate the RT. To illustrate this a case from consultant practice is used, see Figure 1.

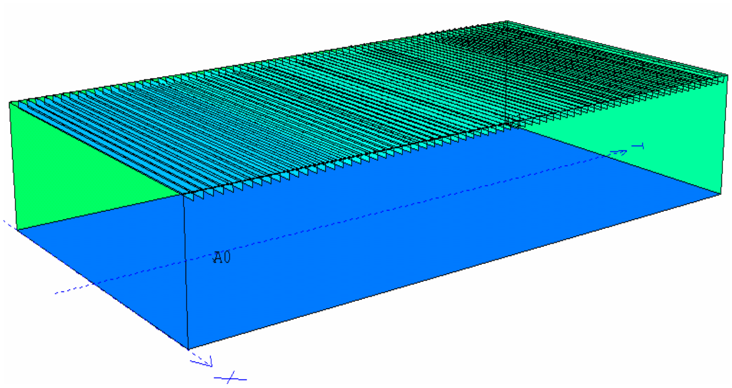

Figure 1 Sports hall 43 x 23 x 7 m^3. The ceiling is mostly covered with high-absorbing material, remaining surfaces are hard. T_{Sabine} @ 1 kHz was 1.9 s while the actually measured T_{30} was 5.7 s.

The acoustic consultant involved [7] recommended placing high-absorbing material between every second beam pair in the ceiling (ca. 50% coverage giving an effective ceiling absorption coefficient of 0.43 @ 1 kHz) and additional high absorption on at least one end wall and one side wall. However, to save money the contractor instead chose to use only the ceiling absorption and to leave the rest basically as concrete. With only the ceiling used for absorption T_{Sabine} @ 1 kHz was 1.9 s but when the RT was actually measured it was 5.7 sec. This is a clear case of a non-mixing shape where handling of diffuse reflection is absolutely necessary. Table 1 lists the RT predictions at 1 kHz using various methods and room models.

Method/model	Scattering coefficient (s @ 1 kHz)	RT @ 1 kHz (T_{30})
Sabine, detailed model [1]	N/A	1.9 s
Sabine, simple model [2]	N/A	2.1 s
Measured	N/A	5.7 s
Detailed model [1]	$s_{beams} = 0.22^3$, $s_{rest} = 0.08$	5.1 s (10% error)
Simple model [2]	$s_{ceiling} = 0.80$, $s_{rest} = 0.08$	5.9 s (3% error)
Detailed model [1]	specular-only, $s = 0$	13.0 s
Simple model [2]	specular-only, $s = 0$	12.0 s

Table 1 Predicted and measured RTs for the sports hall. [1]with beams as in Fig. 1, [2]flat ceiling with high diffusion, [3]auto edge diffusion (see below).

An interesting note here is that the sports hall project (ca.1995) was initially calculated with CATT-Acoustic v.6 as well as the consultant's own in-house ray-tracing software, which also handled diffuse reflection. The results were very similar to those in Table 1, which were modelled in CATT v.7.2. However, the frequency dependence of diffuse reflection has not yet been addressed since the example above only holds for 1 kHz. Generally the frequency dependence has to be included for purely physical reasons, and Figure 2 schematically illustrates why. For a more general discussion about diffuse reflection in computerised prediction, see [8].

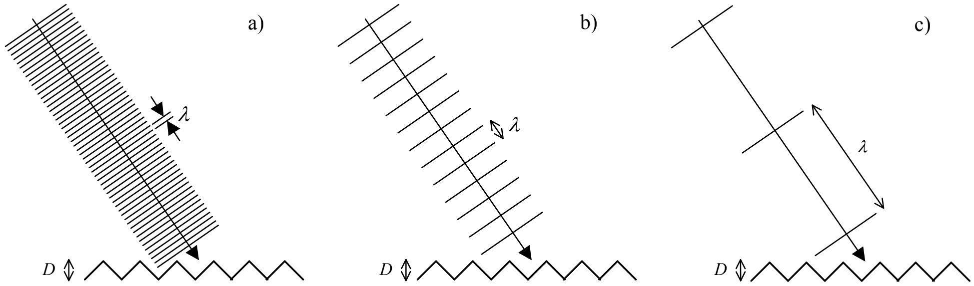

Figure 2 Schematic description of how the ratio between surface roughness (D) and wavelength (λ) determines the diffusion. **a)** $\lambda << D$: geometrical mixing (effectively acts as diffusion), **b)** $\lambda = D$: high diffusion, complex actual behavior, **c)** $\lambda >> D$: low diffusion.

4. PREDICTION METHODS

With the example in the previous section in mind, we can now look at the two main prediction methods employed by CATT-Acoustic ; ray-tracing and randomised tail-corrected cone-tracing.

RAY-TRACING FOR AUDIENCE AREA MAPPING

Audience area mapping is based on classical ray-tracing with fixed-sized spherical receivers placed in a grid over defined audience areas. Frequency-dependent diffuse reflection using the Lambert distribution [4] is taken into account by randomising the directions of those rays which are determined to reflect diffusely off a surface (as dependent on the scattering coefficient). An exception is that direct sound is handled deterministically without rays. When frequency-dependent diffuse reflection is taken into account (and only when it is taken into account) ray-tracing is a very robust prediction method. However, the echogram from ray-tracing is difficult to use for auralisation since, unlike with the RTC, the reflection density growth over time is unnatural. Hence, ray-tracing is only used for mapping of measures such as C_{80} but not for auralisation or a detailed echogram. However, room acoustical measures predicted in CATT using frequency-dependent diffuse ray-tracing are virtually identical to those predicted by the more elaborate RTC.

RANDOMISED TAIL-CORRECTED CONE-TRACING FOR DETAIL AND AURALISATION

The unique RTC is a combination of three different methods, compensating and correcting for weaknesses in each of these three methods. The program uses scattering coefficients which are normally estimated based on general guidelines and input by the user in the same way as absorption coefficients, but an automatic edge diffusion can also be used. For hard smooth objects like tables and reflectors, a size- and frequency- dependent scattering coefficient is optionally calculated automatically

1) Image Source Model (ISM) for 1st and 2nd order specular reflection so that the most important early reflections are always included independent of how many rays are used. A weakness of the ISM is its inefficiency for high-order reflections, but up to 2nd order it is always fast.
2) Direct diffuse radiation for 1st order diffuse reflection. Many small diffusely radiating surface sources are distributed over each diffusing surface. From the actual sound source, vectors are drawn to each diffuse surface source and from each of those to the receivers (taking occlusion into account). To give the highest geometrical accuracy where it is needed, the number of these surface sources is increased for surfaces with low absorption coefficients and high scattering coefficients.
3) Randomised cone-tracing for higher order reflections where ray directions are randomised like in ray-tracing so that, unlike with specular cone-tracing, diffuse reflection can be taken into account.

A weakness of ray-tracing is that the receiver sphere must be fairly large and the early part detail therefore suffers. The use of cone-tracing and the ISM compensates for this lack of detail. Cone-tracing also gives a reflection density which grows with t^2 (t=time) which makes the resulting echograms well-suited for natural-sounding auralisation. On the other hand, a weakness of cone-tracing is a ray-density dependent late reflection loss and that is corrected for by an automatic reflection growth extrapolation [6]. However, the more rays/cones that are used the less the extrapolation needed.

5. ARRAY MODELLING INCLUDING THE NEARFIELD

The methods described above perform very well for estimation of reflected sound and thus the full echogram. However, with non-simple sound sources the directivity also needs to be handled in sufficient detail. Manufacturers and researchers are now measuring full space directivity at ever-increasing resolutions, going from 10º and 1/1-octaves to 5º and 1/3-octaves. In some cases even higher resolutions including phase is discussed.

However, with this focus on higher resolutions a fundamental property of loudspeaker *arrays* appears to have been forgotten even in dedicated sound system software: *the extended nearfield*. The now very popular line arrays (e.g. Duran Audio Intellivox and Target systems, L-Acoustics V-DOSC/dV-DOSC, JBL VERTEC and several other under development) are essentially cylindrical

1/r-radiators up to very large values of r (often > 100 m). Many commercial sound-system modelling programs still treat these as spherical $1/r^2$-radiators. In other words, these programs take the farfield directivity of the array and apply it in the nearfield. This method may work for single speakers but can give wildly incorrect results for arrays such as column loudspeakers or large central clusters. To remedy this, in 1998 CATT developed a "DLL Directivity Interface" (DDI) that did not just create an equivalent far-field balloon from coherent summation of the array elements but where the summation was done “live” during run-time at each distance, azimuth and elevation required, thus also handling the nearfield.

Since a DLL is an actual program it can also handle beam-steering. The first commercial line array that used the DDI was the Duran Audio Intellivox where DSP-settings for AZIMUTH, FOCUSDISTANCE and OPENINGANGLE simply can be selected in the CATT DLL interface, in much the same way as they are selected on site when the loudspeaker is programmed. Even if farfield-only modelling of such an array worked, it would be extremely cumbersome to create an equivalent balloon for all possible DSP settings since each of the three parameters can be selected in very fine increments (0.1 unit steps). Figure 3 shows a comparison of predicted polar diagrams at different distances for an Intellivox 2c. Note that not only the on-axis *level* (as compared to $1/r^2$) changes with distance but also the *shape* of the balloon. Figure 4 shows a validation of the modelling as compared to an outdoor measurement.

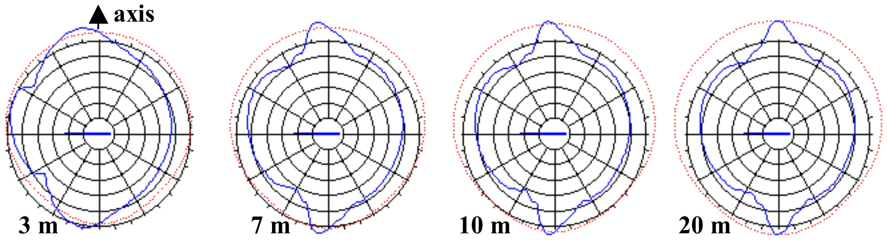

Figure 3 Duran Audio Intellivox 2c*,* 2.7 m long DSP-controlled column array. DSP settings: AZIMUTH = -1º, FOCUSDISTANCE = 40 m, OPENINGANGLE = 6º. Polars are plotted at 2º resolution, 10 dB/div**.**

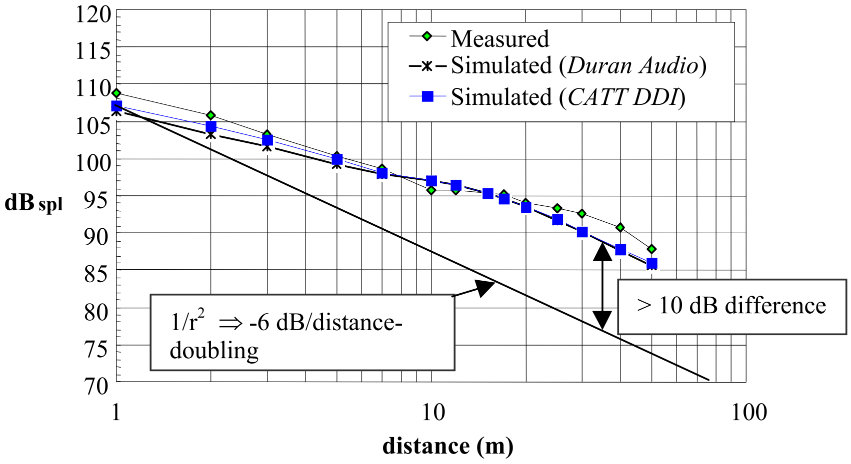

Figure 4 Validation of Duran Audio Intellivox 2c DDI prediction at 1 kHz, free-field on-axis.

Another line array that uses the DDI is the L-Acoustics V-DOSC/ dV-DOSC range. Here, instead of DSP settings, the number of cabinets and their relative inclinations are selected in the interface. Since the DDI has a defined programming interface, and acts much like a plug-in, it is possible for manufacturers of loudspeaker arrays to write their own DLLs where proprietary beam-steering methods are completely hidden and where the array summation can use any kind of angular resolution and measured "phase balloons". Indeed, angular resolution is not an issue with the DDI but polar plots are made at a reasonable 2° and 3D balloons at 5°. The Duran DLL was written by CATT based on DSP specifications from Duran, and was validated by Duran Audio, while the L-Acoustics DLL was completely developed and validated by L-Acoustics.

6. IMPLICATIONS AND APPLICATIONS

All of the above means that CATT-Acoustic can be used for an unusually wide range of acoustic modelling applications, both for "pure" room acoustics and sound system testing. We use the term "testing" rather than "design" advisedly ; modelling programs allow us to test proposed designs, but do not generate designs for us. Although in principle they could be looked on as tools in a trial-and-error process, this is not an efficient mode of design and they do not replace the need for a good understanding of acoustics. What they do is allow us to test different (often unorthodox) designs and to investigate the effects of changes to surfaces, elements and loudspeakers in a given acoustic environment.

Adrian James Acoustics have been using CATT-Acoustic since 1994 and the following illustrations of projects show applications of a modelling system which is accurate and realistic in spaces from small listening rooms. The correct modelling of diffusion and of source directivity are fundamental to all of the following practical projects, but many of these will be discussed in separate papers at a later date.

6.1 DERRY MILLENNIUM THEATRE - THE FLEXIBLE AUDITORIUM

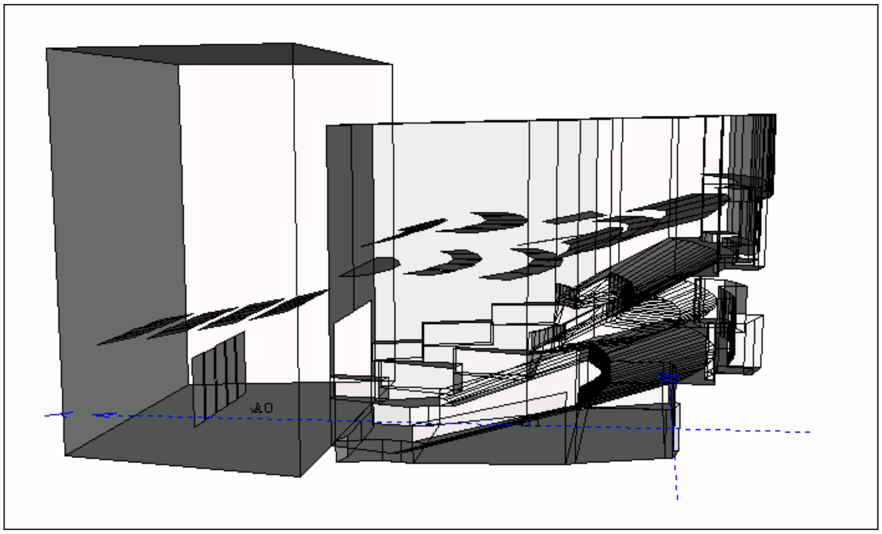

Figure 5 Model of the Derry Theatre with overhead reflectors in intermediate position .

Figure 5 shows a simplified CATT model of a 1,000 seat auditorium built on a traditional proscenium theatre layout, but with a complex series of reflectors over the auditorium and stage. Some of these reflectors are omitted for clarity in the illustration. The stage reflectors form part of an orchestra shell which can be varied in size and height to suit different types of musical ensemble. The reflectors over the auditorium have a number of positions at which they can drop down to close off conceal balconies and slip seating, allowing a 1,000 seat auditorium to be reduced in apparent size to 670 or 300 seats. Completely closing off the upper volumes was impractical within a limited budget and the model was used to assess the effect of different sizes and coverage of reflectors both on speech clarity and also on reverberation time. In practice, the reflectors are curved and the effect of different diameters of curvature was also estimated by changing the diffusion coefficients of the reflectors – a much simpler process than re-modelling the reflectors as multiple complex planes, but one that relies on accurate frequency-dependent diffusion modelling. The theatre was commissioned in September 2001 and the results of measurements accord well with the modelling results.

6.2 NORWICH MILLENNIUM PROJECT

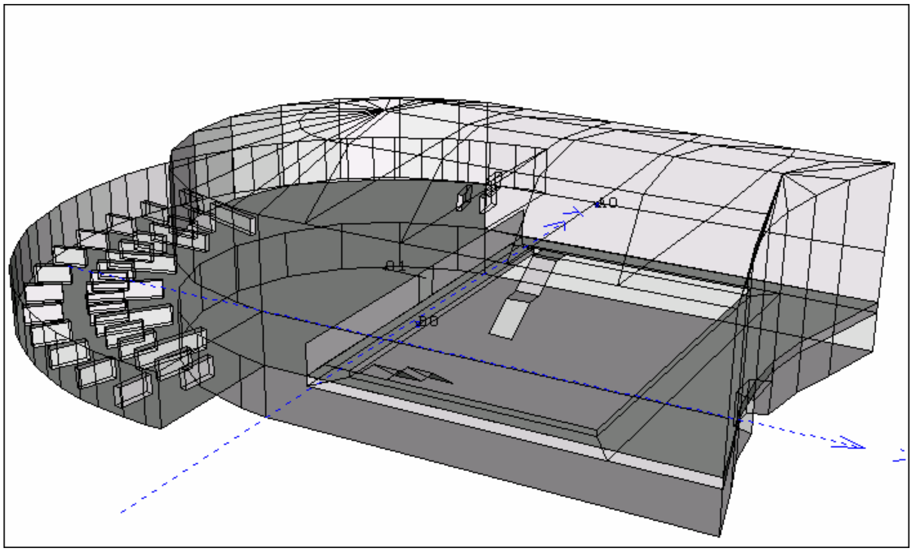

Figure 6 Norwich Forum with Intellivox 2c overhead reflectors in intermediate position .

Figure 6 shows a simplified CATT model of the Norwich Forum, another Millennium project which includes a library open to a 30,000 m^3 atrium made largely of glass and concrete. The model was used for room acoustic calculations as well as to predict coverage and intelligibility of a Public Address and Voice Alarm system using two Intellivox 2c loudspeakers, each with “split beam” technology to cover two separate floors, using the method described in Section 5 of this paper.

6.3 TOTTENHAM COURT ROAD UNDERGROUND STATION

Figure 7 shows RASTI mapping for a proposed refurbishment of the main concourse at Tottenham Court Road Underground station in London, using a distributed sound system with loudspeakers at two ceiling heights. The concourse has all of the acoustic absorption concentrated on the walls, with very little absorption at the centre of the concourse, so that again standard Sabine theory for reverberation time does not apply and the only way of predicting intelligibility was to create a computer model. The whole model, including escalators and tunnels, comprised some 70 loudspeakers, making initial calculation times relatively long (2 hours on a Pentium 600) for a full calculation, but the ability to test changes to individual sources without having to re-run the whole calculation procedure saves a great deal of time in this modelling of distributed systems.

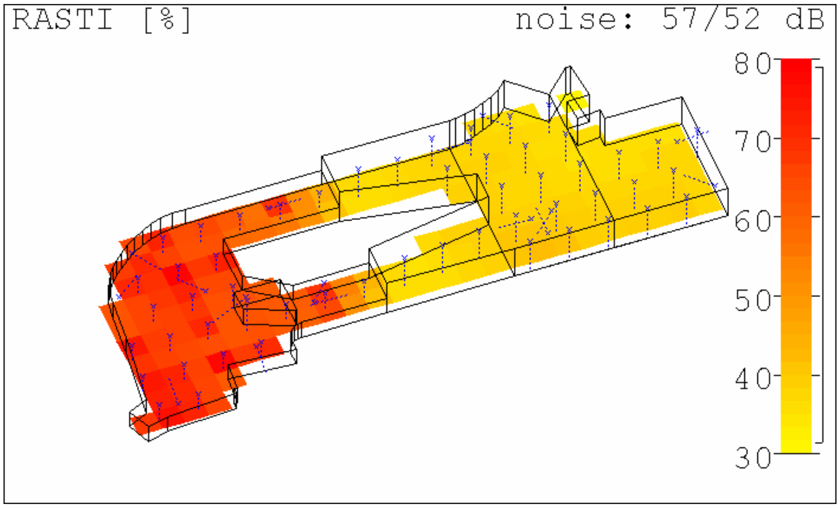

Figure 7 RASTI mapping, underground station concourse

6.4 OTHER PROJECTS

Projects in progress at the time of writing include the “Virtual listening Room” research project at Surrey University, where CATT was used to model different layouts of passive reflectors and flat panel loudspeakers to create an ITU-compliant listening room in a large space [9,10] a replica of the Shakespearean Rose Theatre, and the use of different diffusers in BBC Radio control rooms.

7. REFERENCES

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