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Concert Acoustics Criteria in the Frauenkirche Dresden

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ABSTRACT
After a short introduction to the history of the building, measurements of the room acoustic parameters of the church are discussed. Here, dummy head measurements are compared with monaural and figure –of-eight ones.
In the reconstruction period impulse responses have been calculated by using the so-called CAESAR algorithm implemented in the AURA module in EASE. Briefly the specialties of this calculation method are explained.
By comparing the measured results with the simulated ones, the largest deviations were found between the measured ones derived from the monaural and the binaural recordings. In the seventies of the last century the classical objective measures like clarity or strength have been defined for monaural recordings only. But human beings hear binaurally, so the Concert Acoustics Criteria have to be updated to reflect this binaural impression. First proposals are given.

1. INTRODUCTION

The rebuilt Frauenkirche was inaugurated in fall 2005 and in the preliminary phase all were eager to know whether the legendary acoustics had also been restored. Expert opinions of contemporary witnesses were hardly available and just a few sound recordings of concerts performed by the organist Hanns Ander-Donath at the organ in 1944 after its renovation from 1939 to 1944, have survived. Nevertheless, these scarce sources kindled high expectations which in terms of acoustic quality proved true after the inauguration. Many scraps of information, stories and also anecdotes about the building process under George Bähr from 1726 to 1738 and thereafter until the completion of the church in 1743 are preserved, whereas nearly nothing can be found about its acoustical design. From a modern point of view one would even have dissuaded George Bähr from the rotunda style of the church building or at least signaled that difficulties could arise. But fortunately this could not be the case, since the scientific fundamentals of acoustics had not yet been established in the baroque age so that one often took recourse to well-known examples with the intention of excelling them in design and ornamentation.

2. ROOM ACOUSTICS

2.1. Measurements

The lavish structure as well as the projecting pillars and the recessed galleries prevent the formation of acoustical focuses frequently occurring in rotundas, see Fig. 1. Only above on the gallery under the inner dome which, however, is accessible for the public only in exceptional cases, it is possible to experience the whispering gallery effect well known also from other church buildings as, for instance, St Paul's Cathedral in London or Isaak's Cathedral in St Petersburg.
Typical room acoustic treatment was thus not necessary for the reconstruction. Neither the volume was reduced for possibly diminishing the reverberant component, nor the room structure was modified for avoiding acoustical problems possibly induced by the circular primary structure. A painstaking selection of the building materials was meant to help ensure the historical reconstruction from the very beginning. This resulted in guaranteeing that the traditional acoustic qualities got restored.

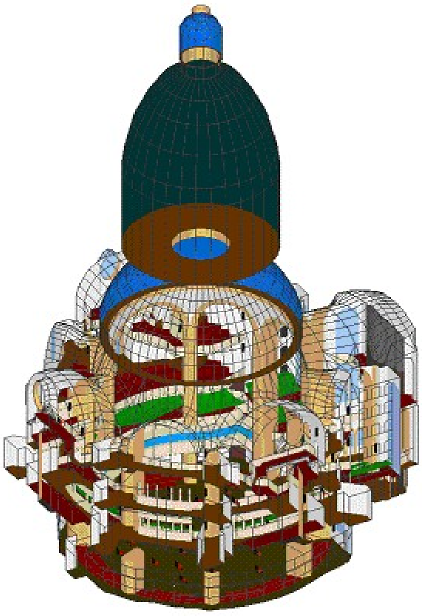

Fig. 1 EASE-Model of the interior of the Frauenkirche

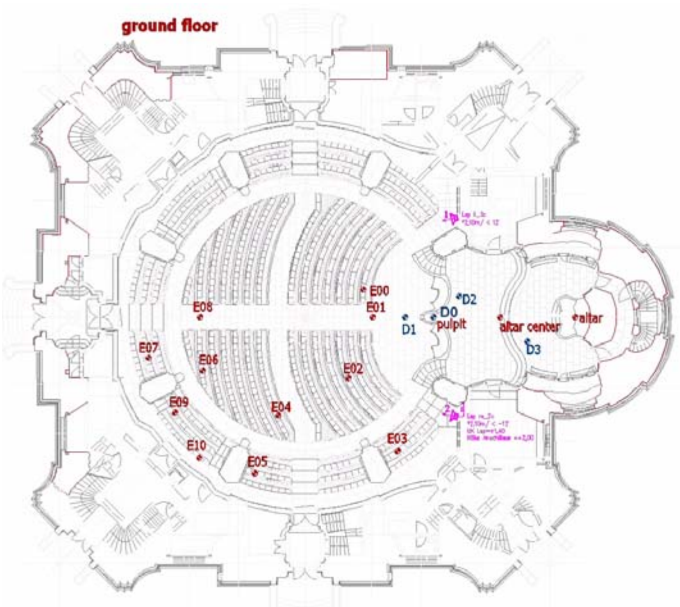

Fig. 2: Measurement places in the ground floor

The simulations for assessing the room acoustic behavior of the church room were carried out in EASE [1] by means of the model shown in Fig. 1. Details of concern were the reverberation time to be expected as compared with the original building on the one hand, and possible disturbing acoustic effects, such as sound concentrations and echoes, on the other.

In the course of the remodeling of the church (1938 to 1942) by the firm Gebr. Jehmlich, modernization work was carried out also on the organ (until 1943). With this new 85-register instrument numerous recordings for radio transmission were made with cathedral organist H. Ander-Donath at the manuals. After tapes could be retrieved in the post-war period, a remastering was carried out in 1968 and today a corresponding CD is available which was explored for decay processes allowing reverberation times to be deduced.

After completion and intonation of the new Kern organ in the reconstructed church, Mr. Güttler jun. recorded an organ concert from the 16th to the 20th of September 2005, which is now also available as a CD and was evaluated in the same way as the historic recording. At the end of September 2005 we made measurements of our own (by means of EASERA [2]) in the empty church room, comp. "Measurement places in the ground floor" (Fig. 2). In Fig. 3 the RT behavior is listed for these evaluations.

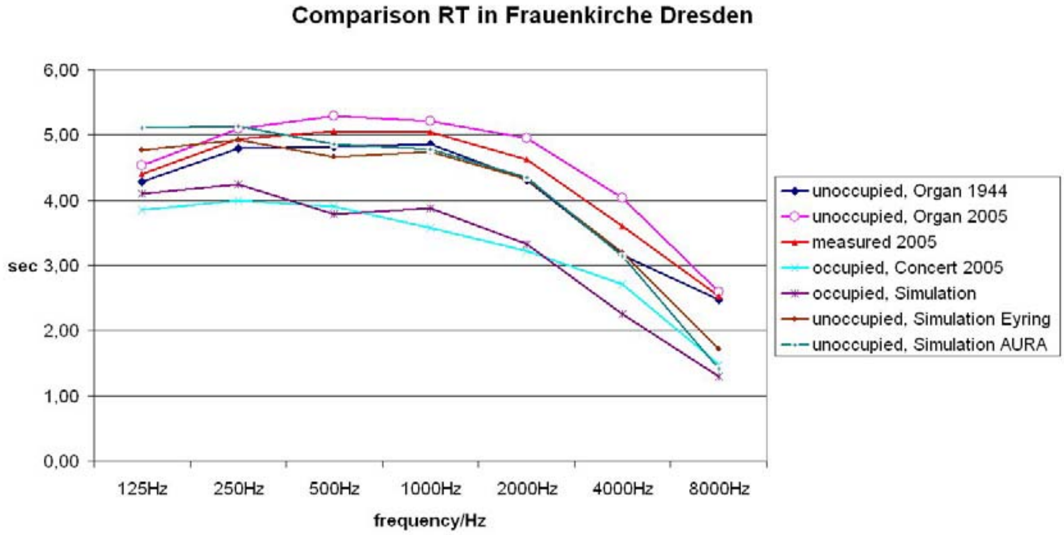

Fig. 3: RT comparison

2.2. Comparisons of measured and simulated results

To determine the acoustic properties in advance in 2002-2004 acoustic calculations have done in EASE using the advanced calculation module AURA developed together with the Institute of Technical Acoustics, ITA, of RWTH Aachen University. The older versions of EASE were focused on Sound reinforcement calculations and could not be compared with pure room acoustic calculation routines available especially from Scandinavian universities. So the **A**nalytic **U**tility for **R**oom **A**coustics was derived from the CAESAR module and expanded from omni-directional sources to directed ones. The main features of AURA are thus including the tradition and experience of the developments of ITA [5], [6]. The main feature of this algorithm is a combination of the image source and the ray tracing model which is independent of a forced choice of transition order from one model to the other. Instead, the transition is inherently given by random-incidence scattering coefficients, a purely physical quantity according to ISO 17497-1. Accordingly the room model itself contains the information about the balance between specular and diffuse reflections. Of course, sources and receivers are treated in the data structure with relative power levels and directivities and head-related transfer functions, respectively. Data are used in third-octave bands or in octave bands in a chosen range.
Two impulse responses are created in parallel, one containing the purely specular part and another, containing reflections which are scattered at least once. The two impulse responses are then added with a proper relative calibration which can be derived easily from the algorithmic implementation of image source power and the number of rays traced. In fact, it is only the number of rays which is a free parameter to b chosen by the operator. Also here, information is available concerning the required number of rays corresponding to certain accuracy [7].
The accuracy of the temporal fine structure in the impulse response is given by the sampling rate, typically 44 kHz. The fine structure in the scattered part of the impulse response is not a-priori known and must be created artificially. This approach is well possible since the scattered part is perceptively of secondary importance (due to masking), as long as the spectral temporal envelope (kind of modulation spectrum) is correct. Due to the nature of a histogram of ray tracing results, the envelope is in fact known. Hence the spectral and temporal envelope in a resolution of some 1 to 10 ms is used as basis for artificially introduced spikes representing diffuse reflections which are introduced as "diffuse rain" [6]. The fine structure is, again designed for a scale of sampling rates. The diffuse sound incidence is accounted for by selecting HRTF from all directions with equal probability. Accordingly, the temporal precision in the late part is not physically but perceptually correct.
First versions of CAESAR and later AURA were also used in the round robin tests and they showed good results (among the "top three") [8], [9].
Additionally to the comparisons of the reverberation time at all 10 listener seats E01 to 10 the impulse responses have been calculated and compared with the measured ones. Fig. 4 to 6 show the results

for the acoustic measures C50, C80 and STI. Because of the huge amount of data we show here only some data for the selected pairs of listener E04 and dodecahedron positions D0 and D3.

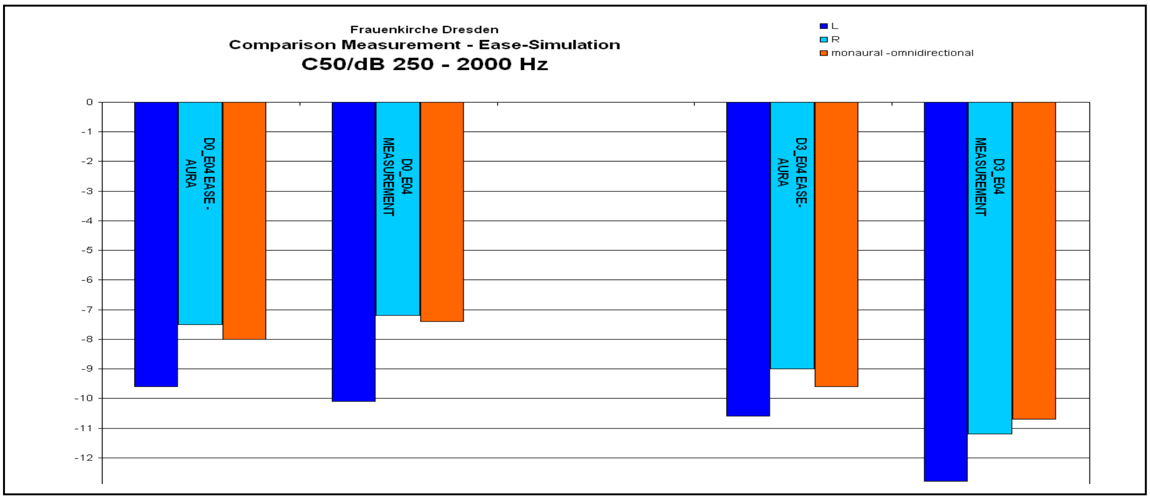

Fig. 4: Comparison for C_{50}

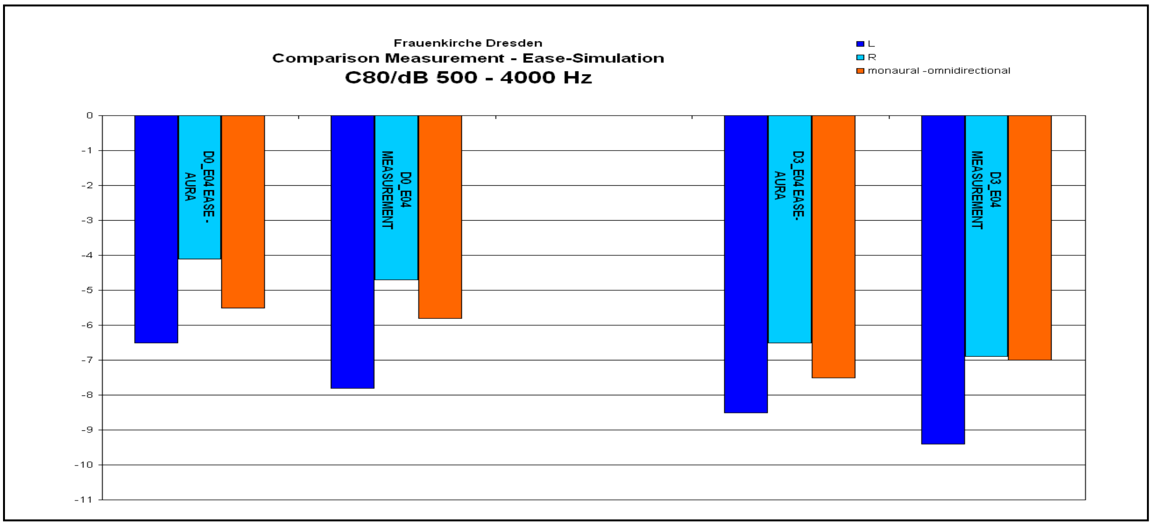

Fig. 5: Comparison for C_{80}

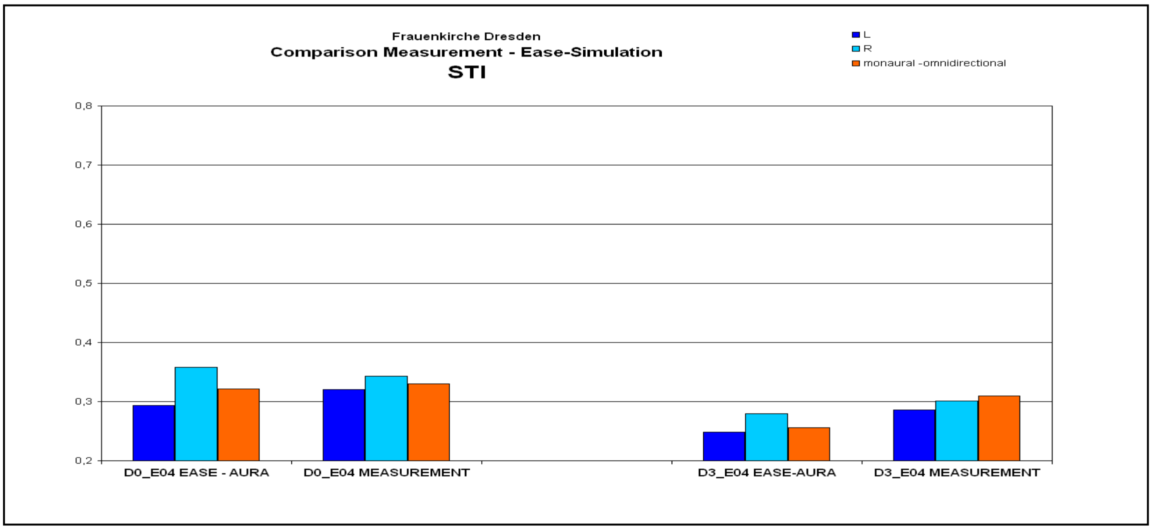

Fig. 6: Comparison for STI

In all 3 figures a comparison between the simulated and the calculated monaural and binaural values shows a high similarity. As to be expected we get with a point source like a dodecahedron a very low intelligibility (STI always < 0.4) and also negative clarity measures.

2.3. Use of binaural and monaural measurements to derive acoustic measures

All the measures like clarity, definition or STI have been introduced more than 30 years ago and they are developed for monaural derived impulse responses. If we compare the simulated values for STI for the speaker position D0 in figure 6 (left side) we recognize less than 0.3 for the left ear, mote than 0.35 for the right one and 0.32 for monaural derivations. What is now right and wrong?
By using the sound system in that church we got better results with STI numbers around 0,5 [3]. For this case we compared on the site also subjectively the results and obtained usable good scores, but monaurally calculated STI values have been lower than 0,5. With dummy head measurements only the louder ear showed STI values higher 0,5. So some researchers recommend using not the results of monaural measurements but the louder ear of binaural ones. Already in 1993 [4] has been proposed to use a kind of averaging to get right objective numbers for binaural measurements. So we checked three methods:

SQUARE SUM MEAN	Geometric Mean	Arithmetic Mean
$x_{rms} = \sqrt{\dfrac{x_L{}^2 + x_R{}^2}{2}}$	$x_{geom} = \sqrt{\lvert x_L \cdot x_R \rvert}$	$x_{arithm} = \dfrac{x_L(t) + x_R(t)}{2}$

In figure 7 the results for the measure C_{50} are shown. In one case the C_{50} values are calculated for the two binaural files separately and then the averaging above is applied in postprocessing. The other way was done in the measurement tool EASERA [2] by applying the math directly to the binaural impulse responses, t.e. for instance by squaring both impulse responses, adding the results and deriving the measures from the root of the sum.
The results are quite different. After checking the results we certainly may exclude the Arithmetic Mean from further considerations because of the fact, that here energy values are calculated based on the summation of impulse responses. This must lead to unpredictable results.
The Geometric Mean we obtain by multiplying the left and the right impulse response of a binaural file. This way energy-like values are obtained.
The last method is based on the Square Sum Mean calculation.
So future checks to find a general expression for energy measures derived from binaural files should be focused on routines like Geometric Mean, Square Sum mean or similar. Certainly psychoacoustic tests have to prove anyway the right relationship between subjective evaluation and an objective criterion reflecting the subjective behaviour.

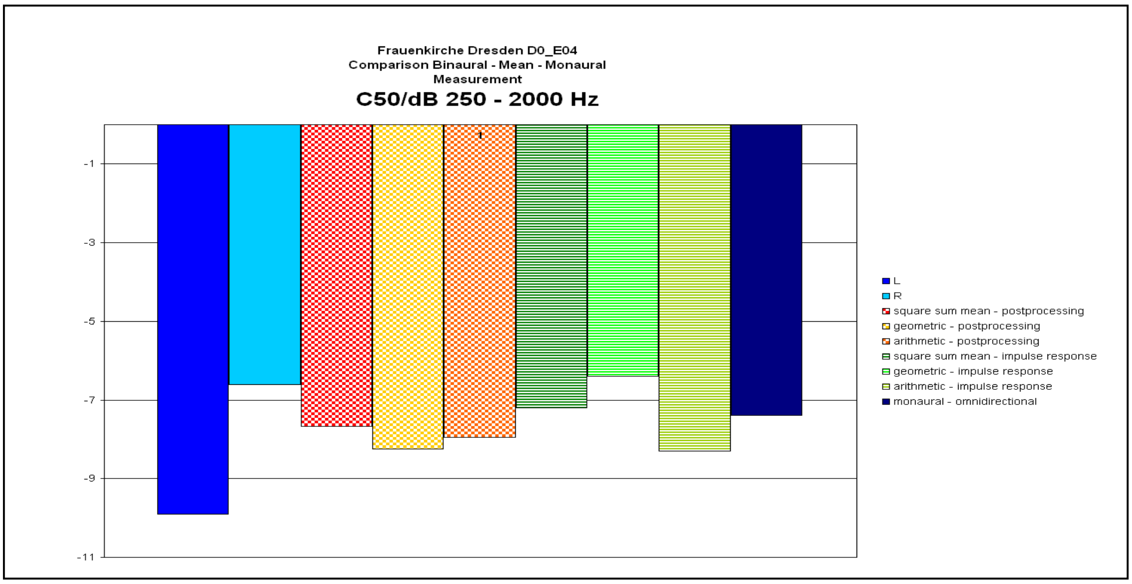

Fig. 7: Different approaches for evaluation of C_{50}

As visible in Fig. 7 an averaging of acoustic measures in post-processing doesn't make to much sense, the results are more or less the same and coming close to direct average values of the left and right channel. As already mentioned above the arithmetic averaging of impulse responses is also not meaningful.

Only the other two methods will lead to values, which are equal or even more positive as the two binaural ones or the value for the monaural measurement. The results of this calculation approach reflect the slight enhancement of definition by listening with two ears. Psychoacoustic investigations must show whether the common value may only reach the levels of the louder ear or even may exceed this threshold.

3. CONCLUSIONS

Measurements and simulation at the Frauenkirche showed a very good agreement for all the acoustic measures used for prediction and verification. In listening tests a bad agreement was found between the measures defined for monaural measurements and the subjective impression. Definition, clarity and intelligibility have been perceived in higher scores than shown by objective numbers. This means that the binaural perception is improving the scores expressed by monaurally measured measures. The paper will support any efforts to find a better correlation between objective measures based on binaural measurements and subjective impressions.

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