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SIMULATION AND MEASUREMENT OF AUDITORIUM ACOUSTICS - THE ROUND ROBINS ON ROOM ACOUSTICAL SIMULATION

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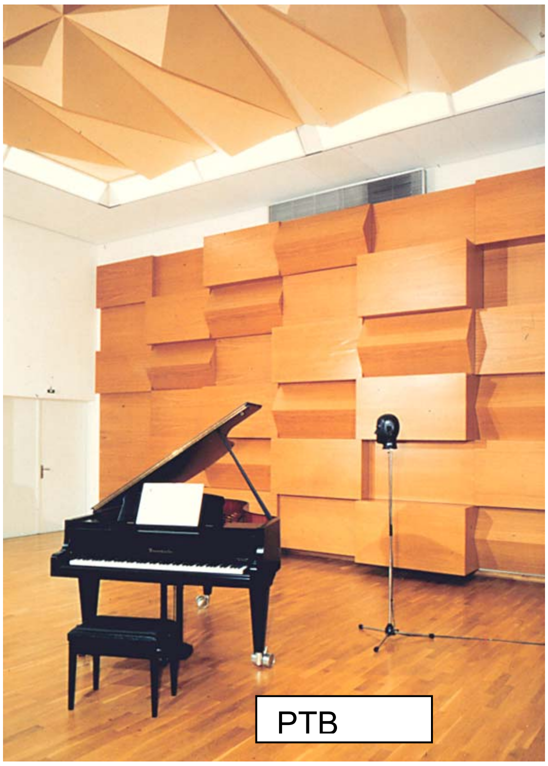
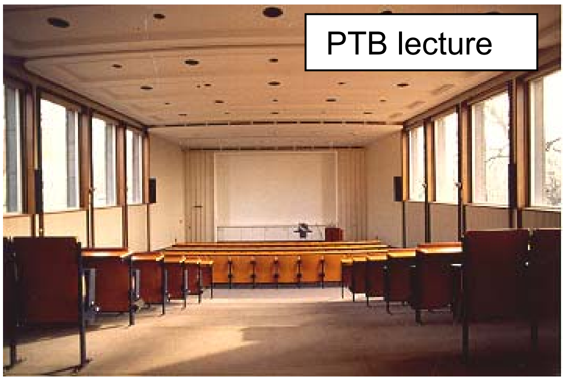
1 INTRODUCTION

In 1994 the 1^{st} International Round Robin on Room Acoustical Computer Simulation was launched by the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany, with the intention of giving software developers the chance of comparing the results of calculation with those of reliable measurements. The great interest this project has found was the reason for another two such Round Robins of this kind, the last of which has just finished this summer of 2002. Three rooms of very different size and purpose were the objects of these comparisons:

1. the Lecture Hall of the PTB (Vorländer[1]), 1,800 m^3 volume, 274 seats
2. ELMIA hall in Jönköping (Bork[2]), Sweden, 11,000 m^3 volume, 1,100 seats, multipurpose hall
3. the music recording studio of the PTB, 400 m^3 volume.

Photos are shown in Figure 1. In the following the conclusions will be described which can be drawn from the experience gained in these three Round Robins as regards the precision of the room acoustical measurement technique and that of the room simulation software. During these eight years, software was increasingly improved, and thus also the number of octave bands increased from one (1 kHz) for the 1^{st} Round Robin (RRI) to six, including one more parameter (IACC) and the scattering behaviour in the 3^{rd} Round Robin.





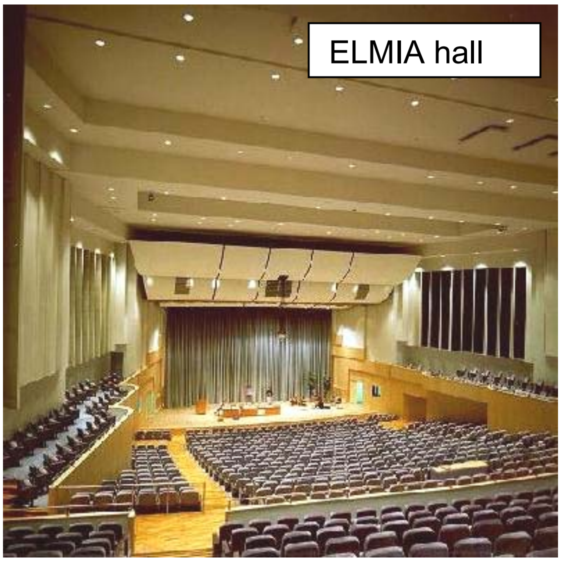


Figure 1: Photos of the Round Robin objects

2 AIMS OF ROUND ROBINS ON COMPUTER SIMULATION

The main purpose of the Round Robin was to compare calculations with reality, especially for rooms not accessible to all participants. The situation of an acoustics consultant, who only knows the room under test from photos should be simulated, apart from the fact that for buildings in the planning stage only drawings are available. Therefore, in the first phase of RRI and RRII only verbal descriptions of the surface material were given, and the participants had to estimate the absorption coefficients in the first phase based on these descriptions. In the second phase material properties were given, which unfortunately had also to be estimated by the organiser but were unique for all participants. The reason for this restriction is, that even today no reliable in-situ measuring technique likely to furnish the required data for all relevant surfaces in the test rooms is available. The Round Robin, therefore, turned out to be a comparison of software dealing with the same object and equal input data.

On the other hand, according to the new (in 1994) ISO 3382, measurements had to be carried out which should not only furnish the reference for the calculation but also serve as a test of the practical relevance of the nine acoustic parameters defined by ISO. Therefore, the measurements by different teams built the base of another Round Robin test on measuring technique[1].

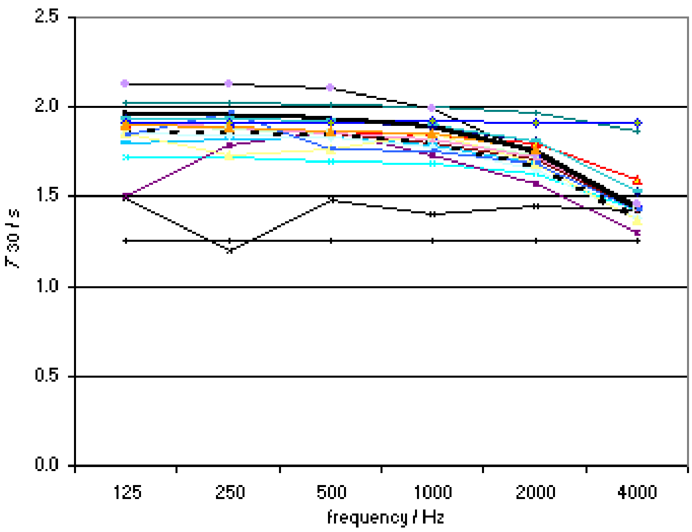
The Round Robins were expected to show the state of the art of computer modelling, and the differences between the different simulation software should be revealed. The relation between the individual result and the name of its software was not published since anonymity had been promised to the participants. Although this is often called for, there will be no winner in the Round Robin test and a fair rating of the results submitted is hard to achieve because of the uncertainties in the prescribed material parameters. Further, the group of participants was expanded to include interested users of commercial software. This made it possible to identify the influence of the user and the problems of application involved. It could also serve as an additional feedback to the developers as regards not only the calculation properties but also the usability of their software.

3 EVALUATION OF SOFTWARE QUALITY

It is one of the most important questions to know how the quality of calculation and the precision of different programs can be compared and evaluated. It is not possible for a single person to use all programs in parallel, because it takes a long time, to get skilled in each of the very specific programs some of which are available only in a research version without any user support or manual etc. It was therefore decided, to let the developers or users do the modelling work, i.e. the input of the geometry data, properties of sources and receivers, absorption and scattering coefficients of all surfaces. As results of the calculation, the nine parameters defined in ISO 3382 were selected: decay time T_{30}, early decay time *EDT*, clarity C_{80}, definition (in German: “Deutlichkeit”) D_{50}, centre time *TS*, sound strength *G*, lateral energy fractions *LF* and *LFC* and interaural cross correlation coefficient *IACC*. For the determination of the software quality these nine parameters were calculated at several source and receiver positions (e.g. for RRIII, two sources and three receivers were chosen) and compared with the corresponding measured data.

4 UNCERTAINTIES OF COMPUTER MODELS

An objective rating of the software is possible only if reliable measured data for the ISO 3382 parameters are available which may serve as a reference for rating. These data, of course, should not be accessible to the participants before the end of the calculation phase. It was found in Round Robins I and II that the choice of the surface properties by the users in the first phases influenced the results in such a way that the individual differences of the software were hidden. E.g., the estimation of chair absorption at the ELMIA hall varied from 0.1 to 0.8 in the 125 Hz octave and 0.36...0.80 (250 Hz) up to 0.48...0.91 in the 4 kHz octave (Bork²). Only after relevant absorption coefficients had been specified in phase II could a true comparison be carried out. For estimating the variance of the calculation results, in the first phase of the 3rd Round Robin, a very simple room consisting of seven walls had to be modelled with all given geometry, absorption and scattering data. It had the dimensions of the PTB Studio and a volume of about 416 m³, with a total surface area of 345 m². For simplicity, the absorption and scattering coefficients were chosen independent of the frequency (10 % each). Using Sabine's well-known formula, the results for T_{30} could be obtained within a few minutes. The results submitted by the 21 participants showed that not everyone checks the software output with such simple and old-fashioned tools. Figure 2 shows the frequency dependence of the decay time obtained by the participants. It is evident that some did not even consider the frequency dependence of sound propagation attenuation.



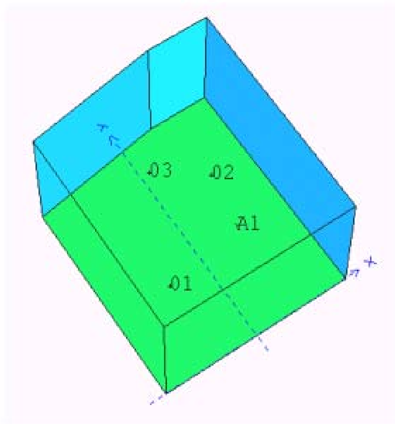
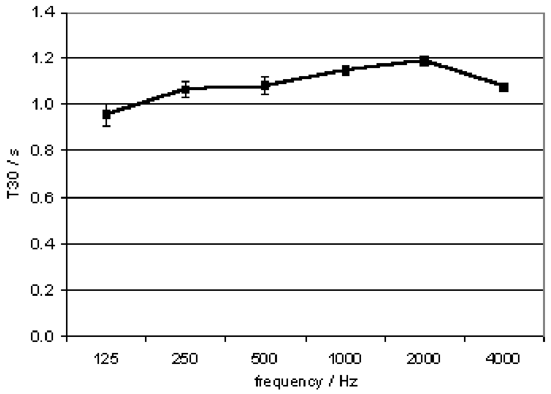


Figure 2: Calculation results for the decay time T_{30} / s for a simple room with seven walls

The variance of the calculated decay times also shows that even the simplest geometry with defined surfaces for some programs leaves some problems to be solved. It should be mentioned that most of the 21 curves concentrate around the Sabine values (black solid line, Eyring: dashed line), and that also some new research programs were involved. More detailed results can be downloaded from the PTB Website³.

5 UNCERTAINTIES IN MEASUREMENTS

The measurements and their uncertainties for the first Round Robin were published by Lundeby[4] et al.. The results of the determination of the measurement accuracy are given there, indicating the standard deviation of the parameters, measured in the 125 Hz, 1 kHz and 4 kHz octave bands, measured by seven teams. As is mentioned there the standard deviation was 5 to 10% for T_{30}, *EDT, D, TS*, and approximately 0.5 dB for C_{80} and *G*. For *LF* it was larger than 10%. Similar results were found in Round Robin II (three teams); especially the *LF* and *LFC* values showed discrepancies which could not be completely explained. In Round Robin III, the measurements of four teams were evaluated, one team (PTB) with two measurements carried out in 1997 and 2001. Examples of these measurements are shown in Figure 3.



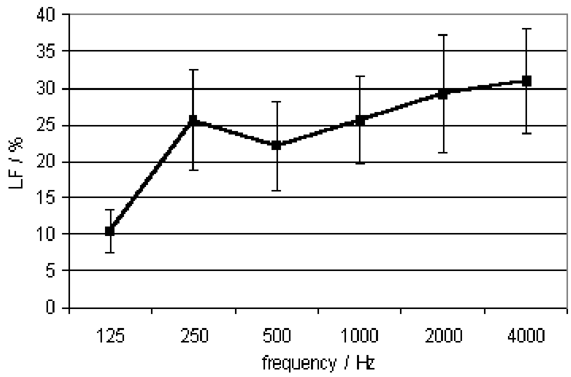


Figure 3: Measurements at the PTB Studio, mean values and standard deviation of T_{30} and *LF* for five measurements (source 1, receiver 1, curtains open)

While the T_{30} values show relatively good agreement for the five measurements, the *LF* values again show discrepancies which need to be further discussed. It could be ruled out by detailed measurements that spatial fluctuations as reported by De Vries[5] were responsible for this error. Instead, it was found that some figure-of-eight microphones, which are required according to ISO 3382 for measuring *LF* and *LFC,* showed frequency-dependent differences of more than 4 dB in the front and rear side sensitivity, which cannot be compensated for. This means that the result of a measurement depends also on the orientation of the microphone. Figure 4 shows how far the two possible orientations can differ in the *LF* value evaluated. A more precise specification for the microphones applied has therefore to be given in ISO 3382.

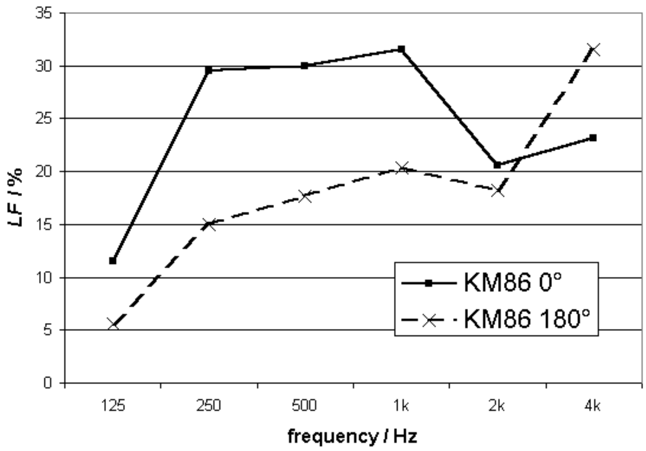


Figure 4: Different *LF* values measured when the microphone is turned by 180°

In Figure 5, the standard deviation of the measurements for all nine parameters is given. These are mean values averaged over six source/receiver combinations, displayed in six octave bands. For display on a unique scale normalisation has been applied with reference to the subjective limen (*JND*).

This choice proved to be more meaningful than using measured values as reference, because in the latter case one scale each for percent and dB values would be required. Since these measured data serve as reference for the evaluation of the calculation results, it is evident that the variance of some parameters (esp. *LF, LFC*) is too large for this purpose.

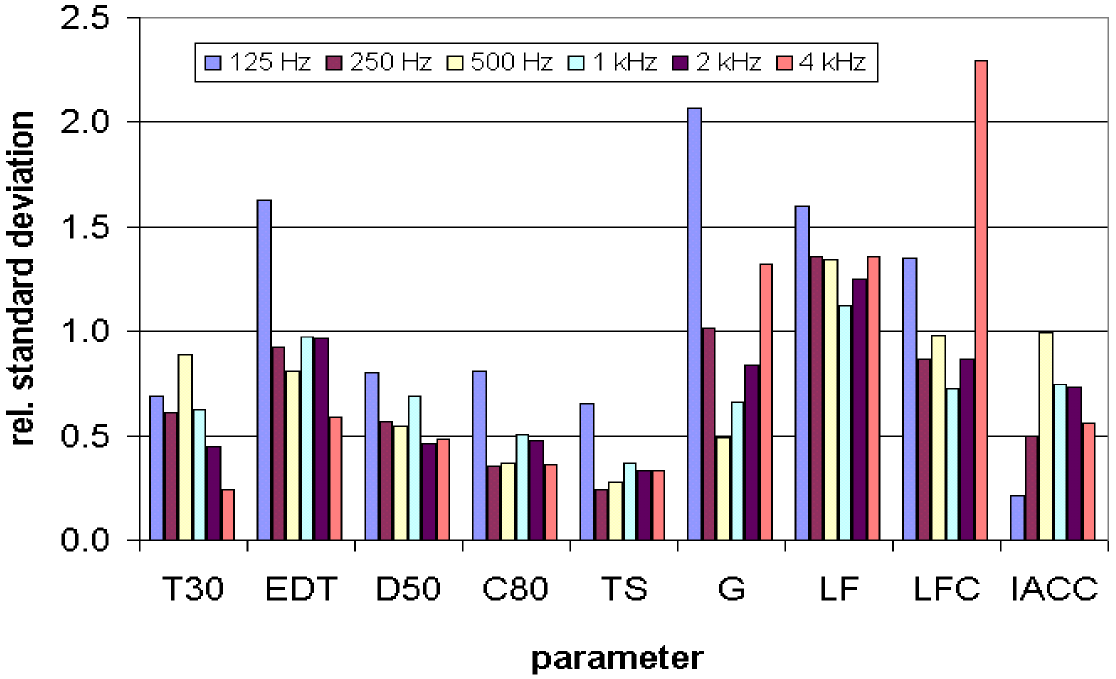


Figure 5: Relative standard deviation for the nine parameters measured in the six octave bands, reference: subjective limen (see Table 1)

Parameter (ISO 3382)	**Symbol**	***JND***
Decay time	T_{30}	50 ms
Early decay time	*EDT*	50 ms
Deutlichkeit	D_{50}	5 %
Clarity	C_{80}	1 dB
Centre time	*TS*	10 ms
Sound strength	*G*	1 dB
Lateral energy fraction	*LF*	5 %
Lateral energy fraction (cosine)	*LFC*	5 %
Interaural cross correlation coefficient[6]	*IACC*	0.08

Table 1: Reference values for the ISO 3382 parameters

6 COMPARISON BETWEEN CALCULATION AND MEASUREMENT

The huge amount of data acquired during all phases of the Round Robin makes a compact display of selected data necessary here (9 parameters, 6 octaves, 6 positions, 2 curtain positions (opened - closed) and 21 participants = 13608 figures). The complete data files are available on the Project's Website[3]. In phases 2 and 3, the structure of the diffusing ceiling and the wooden wall (see Figure 1) had to be simulated first as two single planes (phase 2) and then with a detailed surface geometry (all co-ordinates were made available by the organiser). The aim was to find out, whether a detailed structure improves the calculation details or - as assumed by some software developers - decreases the accuracy of the model.

For an example, in Figure 6, the phase 2 calculation results for T_{30} (f) at S1R1 and the D_{50} in the 1 kHz octave are shown. Although the individual curves may not be distinguished, it can be seen to what extent the calculations deviate from the measurements. The very low standard deviation of the measurements are indicated. The too low value for the calculated decay time at 1000 Hz is representative for all positions. It agrees with a relatively high value (0.78) for a special absorbing material in the outer region of the ceiling, which was taken from the manufacturer's data sheet. Some experiments with this material showed that the absorption for oblique angles is significantly smaller than for perpendicular incidence.

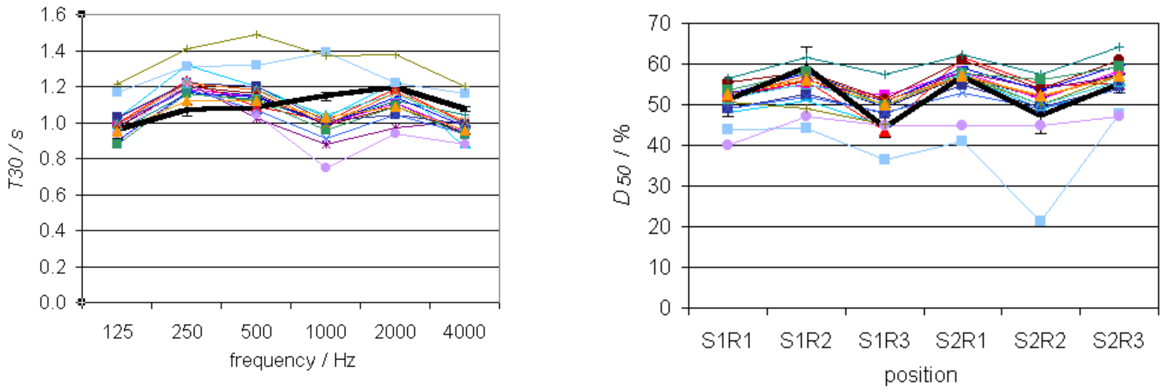


Figure 6: Calculations compared with measurements $T_{30}(f)$ at S1R1 and D_{50} (position) at 1 kHz, curtains open

The curves for D_{50} generally follow the measured values along the changing positions, i.e. the calculations seem to represent the locally varying properties fairly well. This tendency could also be seen for other parameters like e.g. *G* . Only in the 125 Hz octave is the error increased, which may be due to the restriction to geometrical acoustics (see Figure 7).

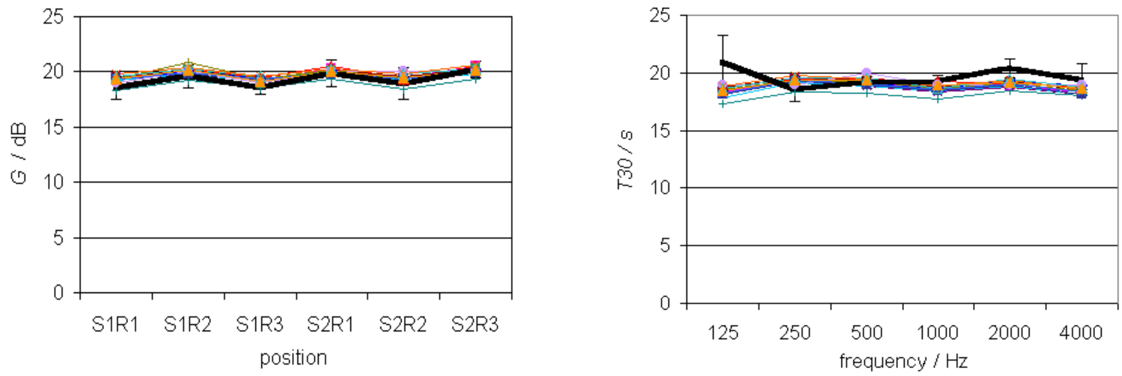


Figure 7: Calculated *G*-values *G*(250 Hz) and *G* (S1R1) open, measured values black curve

For a more global representation of the calculation quality, in Figure 8 the T30 error magnitudes in the six octave bands are displayed for all participants. In contrast to the location-dependent quantities, the error in the lowest octave is quite small. The errors for the 1 kHz octave are significant and can be attributed to the absorber error mentioned above. By most participants the decay time in the 250 Hz octave is estimated too low. This may be due to a standing wave effect which could be measured best under special conditions but did not appear in the evaluation of the measurements: When all wall reflections are suppressed by movable absorber elements, an impulsive excitation furnishes a response with a relatively long decaying frequency component at 210 Hz. This is visible in a sonagram as displayed in Figure 9. Thorough investigation delivered a standing wave between ceiling and floor, which at this quite low frequency obviously was not affected by the diffusing elements on the ceiling.

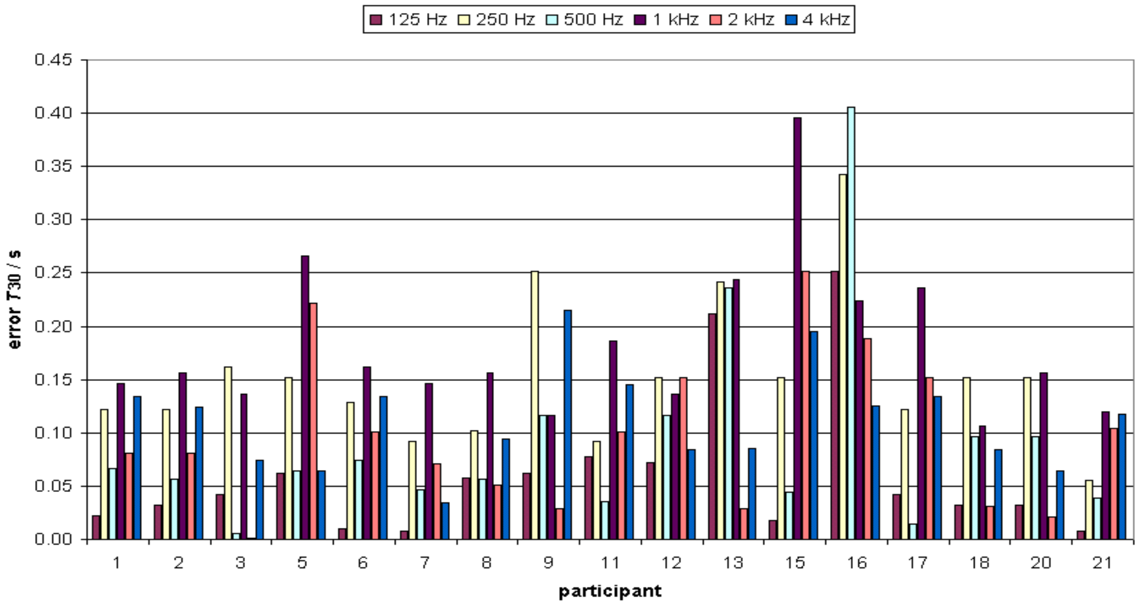


Figure 8: Differences between calculation and measurement for T_{30} , S1R1 curtains open, phase 2

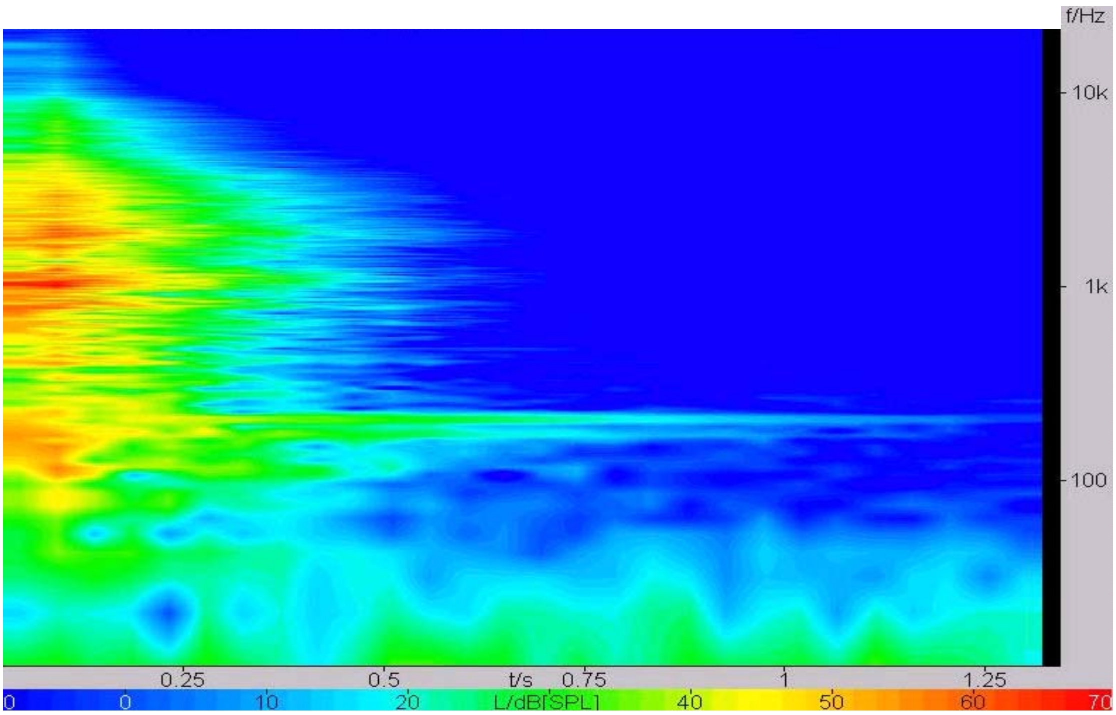


Figure 9: Sonagram of an impulse response at the studio with absorbing walls

This is an example of an effect which is clearly audible, especially when the critical frequency is excited by humming (also under reference conditions). Neither the measurement of the room acoustical parameters nor a simulation are capable of detecting such an acoustic deficiency, which becomes particularly annoying as a coloration of male speech.

In Figure 10 the results for D_{50} are presented at a position in which the error is maximum in the lowest octave. In contrast to this, at other positions, the magnitudes of the error are smaller than, and comparable to, that in the higher octaves. This shows one of the problems of presenting results of such a project: If a single mean value for all positions is taken, a lot of individual information is lost. But the display of absolute differences instead of signed values also makes it difficult to assess, whether a calculation furnishes too high or too low values; on the other hand, forming mean values from positive and negative deviations might cancel the error completely.

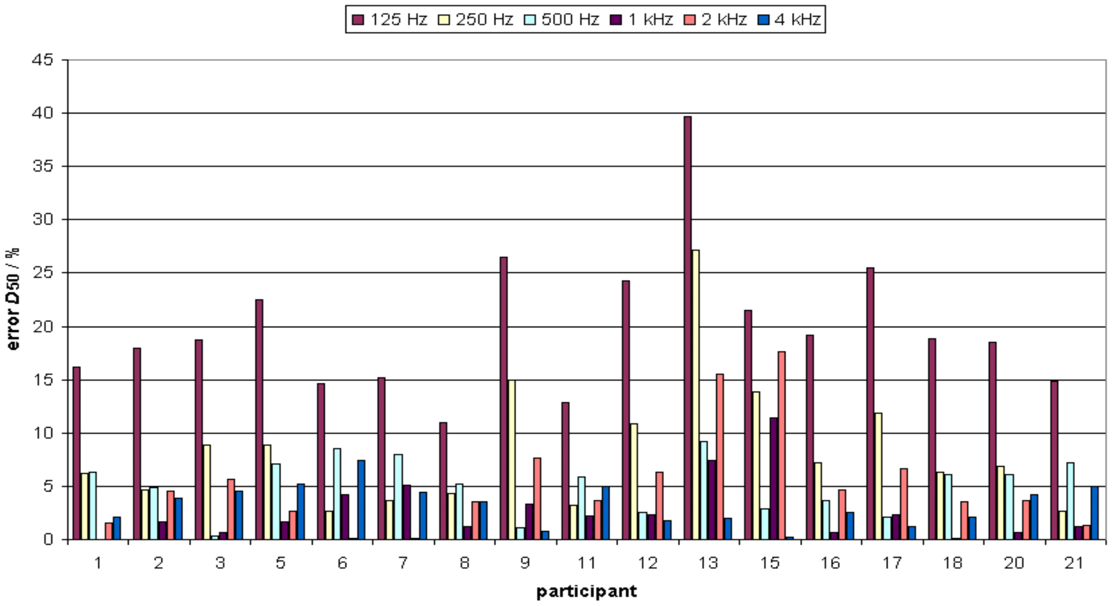


Figure 10: Difference between calculation and measurement for D_{50} at S1R1 (curtain open, phase 2)

7 DISCUSSION OF RESULTS

It can generally be resumed that the reliability of room simulation software has increased even for small rooms, although the limitation to geometrical acoustics still persists and other solutions like FEM/BEM even today are not fast enough for practical applications. Commercial programs show good agreement with measured values and in most cases the dependence on position follows the measurements fairly well. Due to the uncertainties of LF/LFC measurements, the calculated values cannot yet be judged reliably, but further measurements will follow. Everybody is therefore invited to perform measurements at the PTB Studio.

In this paper only a few details of the results could be outlined. More evaluations of the influence of the curtains and the calculations for the detailed structure will be published soon.

8 FUTURE PROJECTS

For future projects it is intended to extend the comparisons also to auralisations, which will give rise to some more problems as regards a common base for sound processing, beginning with the virtual sound source character (frequency response, directivity, expansion) and ending with the listening conditions for presenting the sounds generated in the computer (HRTF of the virtual dummy, headphone equalisation etc.). Further detailed information about the Round Robins and new activities can also be found and downloaded from the PTB Website[3].

9 REFERENCES

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