Hybrid Method for Numerical Simulation of Room Acoustics: Part 2 – Validation of the Computational Code RAIOS 3

Roberto A. Tenenbaum
Emeritus Member ABCM
tenenbaum@iprj.uerj.br
Mech. Eng. Dept., Instituto Politécnico
Universidade Estadual do Rio de Janeiro
28630-050, Nova Friburgo, RJ. Brazil

Thiago S. Camilo
thiagosc@petrobras.com.br;
Engenharia de Logística, Logística de Gás
Natural, PETROBRÁS

Julio Cesar B. Torres
juliotorres@ufrj.br
Graph. Eng. Dept., Escola Politécnica
Universidade Federal do Rio de Janeiro
21949-900 Rio de Janeiro, RJ. Brazil

Leonardo T. Stutz
ltstutz@iprj.uerj.br
Mech. Eng. Dept., Instituto Politécnico
Universidade Estadual do Rio de Janeiro
28630-050 Nova Friburgo, RJ. Brazil

In the companion paper "Hybrid method for numerical simulation of room acoustics with auralization: Part 1– Theoretical and numerical aspects" a new hybrid method for numerical simulation of room acoustics, implemented by the software RAIOS 3, was presented. Here, the software itself and its main features are discussed. It will be shown that the proposed method actually results in very reliable and accurate predictions of the main acoustical parameters: T30, EDT, C80, D50, TS, G, LF and LFC. The performance of RAIOS 3 was assessed in an international intercomparison, coordinated by the Physikalisch-Technische Bundesanstalt, in Germany, where measured acoustical parameters where compared to those predicted by 9 different software. Due to the hybrid method proposed, the comparative results shown a very good agreement between the parameters predicted by our software and the measurements, even in a somewhat diffuse condition. In a statistical evaluation, the results obtained by the numerical code RAIOS 3, stayed among the top 10%. The strong dependency of the predicted acoustical parameters on reliable room data, especially absorption and diffusion coefficients, is also discussed.
***Keywords**: computer modeling, room acoustics, hybrid method; numerical intercomparison*

Introduction

The use of computer simulation for predicting the sound quality in rooms has been a very powerful design tool among engineers, architects, and acousticians (Rindel *et al.*, 1992). Many numerical techniques for modeling the sound propagation (Embrechts, 1982; Kruzins *et al.*, 1982; Farina, 1995; Alarcão *et al.*, 2000), the sources of sound (Tenenbaum *et al.*, 1992; Lewers, 1993) and the receiving apparatus (Camilo, 2003) – going from non-directional microphones to human or dummy heads with binaural characteristics (Blauert, 1997) – have been published. Some commercial software was also developed and is continuously being improved. However, computer simulation of room acoustics is not a trivial task, because of the great number of phenomena to be taken into account: Modes, damping, reflection, diffraction and diffusion, just to mention a few. Besides, the simulation results must be validated by reliable measurements for a variety of rooms with distinct acoustical characteristics. For the same room, different algorithms may yield unlike results. Of course, looking at the impulse responses themselves, not too much information about the differences can be recognized; but the values of the acoustical parameters computed from them — like T_{30}, EDT, C_{80}, LF, and so on — pinpoint the differences in an unmistakable way.

That was the main motivation of the Acoustics Department of the *Physikalisch-Technische Bundesanstalt* (PTB), the German metrologic institute, to start, in 1994, the first project for acoustical simulation intercomparison, called *Round Robin* 1 (RR1), with 16 participants from 7 different countries. An auditorium pertaining to PTB was taken as the reference room to the simulations. Then, the participant teams should compute the acoustical parameters T_{30}, EDT, C_{80}, D_{50}, TS, G, LF and LFC, in the octave band centered at 1 kHz. The results of RR1 showed so great discrepancies that, in principle, a numerical prediction of these parameters seemed to be almost impossible (Vorländer, 1995).

In 1996, another international intercomparison project was proposed by the same group in PTB, the *Round Robin* 2 (RR2), with 16 participants from 9 countries using 13 different software. In this project, the reference room was the Swedish concert hall Elmia, in Jönkping. The process finished only in 1998. The results of the RR2 were much better than the ones of the RR1, but the room complexity, associated with the software state of the art at that time, introduced some inconsistencies. However, with no doubt, the *Round Robin* became a reference to software developers.

A third project, called *Round Robin* 3 (RR3), was launched by the same group in 1999. For the RR3, the adopted reference room was a music recording studio in PTB. Despite its quite simple boundary geometry, the room comprises many diffusors. Besides testing the software capacity to simulate diffusion, another novelty was the fact that three phases of crescent complexity were introduced in the intercomparison. The process finished only in 2002 due to the three phases, the inclusion of interaural cross correlation (IACC) calculus, and to the fact that two room configurations (open and closed curtains) were given. The RR3 had 21 teams from 15 different countries, involving 9 different software (users and developers were accepted). Very good results were obtained by some of the participant teams, confirming the maturity of numerical simulation as a reliable tool for acoustic design of rooms.

The software RAIOS 3 was one of the participants of the RR3, being the only representant from Latin America in this project. A brief overview of the software, a detailed description of the RR3 and some comparative results obtained by all participants of the project, along with a statistical analysis of them, will be presented and discussed in the sections that follows.

Paper accepted December, 2006. Technical Editor: José Roberto de F. Arruda.

The Computational Code RAIOS 3

The computational code RAIOS 3 implements the hybrid method for numerical simulation of room acoustics, whose theoretical and numerical aspects were discussed in (Tenenbaum *et al*., 2007). The software was developed in C++ language on a Microsoft Windows platform. The software interface includes a computer graphics module that allows the user to edit and visualize the virtual room. It's principal screen is depicted in Fig. 1.

As can be seen in Fig. 1, the screen comprises five modules. The largest one is the edition module; the upper-right module is for data input; the lower-right module contains a command area; the lower-central module consists in a graphical area for checking the correctness of the input data and, finally, the lower-left module shows the simulation results in a graphical form (as a function of time or frequency). In the data input module, the reverberation time can be previously calculated by one of the approximate formulas of Sabine, Eyring (Pierce, 1991), and Fitzroy (1959). The auralization module is not shown in the software's principal screen and will not be discussed here.

The software input data are: information about each sound source, including the power spectrum in octave bands, directivity, position, orientation, number of rays emitted NR, among other; information about each receiver, including the geometrical diameter, position and other; and information about the room geometry, including size, position, orientation and material of each plane surface (other shapes are discretized into small plane surfaces). The surface materials are associated with absorption and scattering coefficients in the eight octave bands between 63 and 8000 Hz. Some other input data must also be furnished: the atmospheric conditions, including temperature, humidity and barometric pressure; the stopping criteria or maximum decay ΔL, in dB, before abandoning the remaining energy of each ray; the number of elements N_E for the spatial discretization; and the impulse response discretization time Δt, in milliseconds.

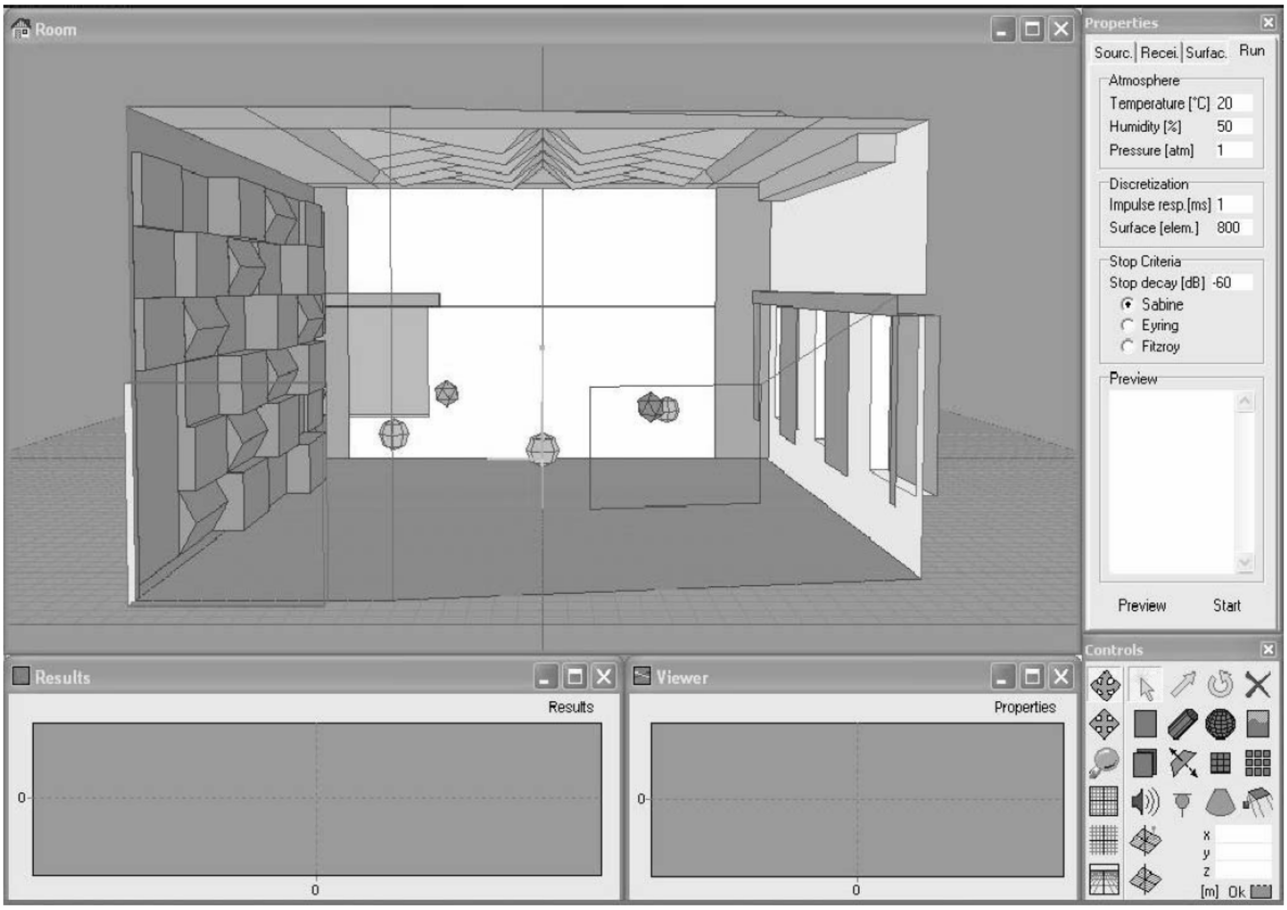

Figure 1. Principal screen of RAIOS 3.

Numerical tests of convergence showed that typical values, for a simulation with good accuracy in a room with reasonable complexity, are: NR ≈ 500k; $\Delta L \approx 60$ dB; $N_E \approx 1$k; and $\Delta t \approx 1$ ms. For auralization purposes the time discretization must be more refined.

Essentially, the software computes the squared room impulse response (echogram) at different source-receiver combinations, being also capable of computing the binaural impulse response of a virtual human head at a given position. From the echogram, the decay curves are computed by the Schröeder back-integration method (Schröeder, 1965). These curves can be obtained globally or in octave bands, as well as the room quality parameters, as defined by ISO 3382. The main available parameters are: the reverberation time T_{30}; the early decay time EDT; the clarity factor C_{80}; the definition D_{50}; the centre time TS; the strength factor G; the lateral fraction LF; the bass ratio BR; and the interaural cross-correlation family IACC, IACCE and IACCL, among other.

Figure 2 depicts the initial part of the squared specular impulse response, without filtering, computed by RAIOS 3, at one source-receiver combination in the room shown in Fig. 1. The amplitude scale is arbitrary and the time scale was limited to 300 ms. Observe that there is no specular energy beyond, approximately, 200 ms. Note that the vertical amplitude scale is linear.

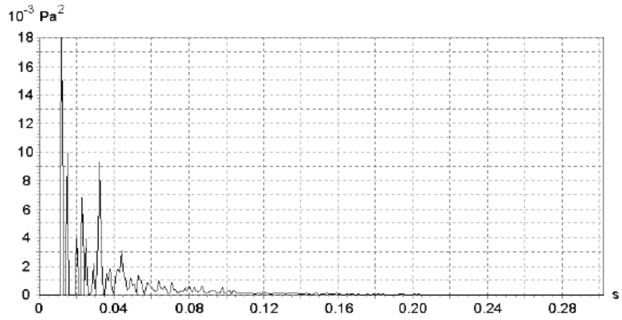

Figure 2. Initial part of the squared specular impulse response.

The initial part of the squared diffuse impulse response, computed by RAIOS 3 at the same source-receiver combination, is depicted in Fig. 3. It is worth noting that the amplitude scale – also linear – is quite different from that of Fig. 2 since the initial diffuse energy level is noticeably less than the specular one. Although, there is much more energy in the reverberant tail of the squared diffuse impulse response, captured by the energy transition method. For instance, at 200 ms, the energy level represents around 25% of the maximum level of the diffuse energy.

The superposition of the squared impulse responses (the specular and diffuse ones) leads to the squared hybrid impulse response, whose initial part is shown in Fig. 4. The magnitude scale is the same as in Fig. 2 and the time is shown up to 300 ms. Comparing Figs. 2 and 4, one can see a noticeable increase in the amplitude and, most of all, in the time duration of the impulse response tail. As commented before, even if the general aspects of the impulse responses do not change too much, the acoustical parameters computed from the hybrid IR and from the specular IR may differ dramatically.

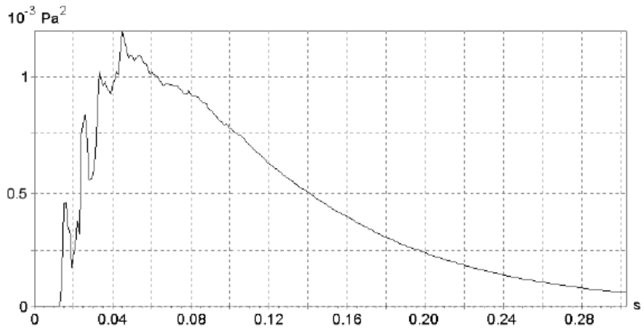

Figure 3. Initial part of the squared diffuse impulse response.

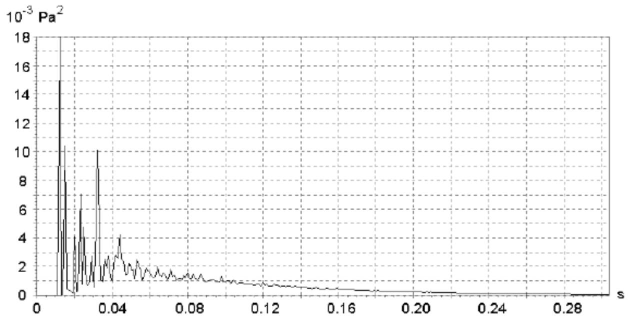

Figure 4. Initial part of the squared hybrid impulse response.

The octave band decay curves computed by RAIOS 3 are shown in Fig. 5. Since no random noise was considered in the simulation (it could be included), the decays are a bit longer than actual ones (where some background noise is always present). Observe the frequency dependent slopes, with higher decay in higher frequencies, as would be expected. The sudden fall down at the right side of each decay curve is very similar to what happens in practice (measurements), when using the back-integration technique (Barron, 1973).

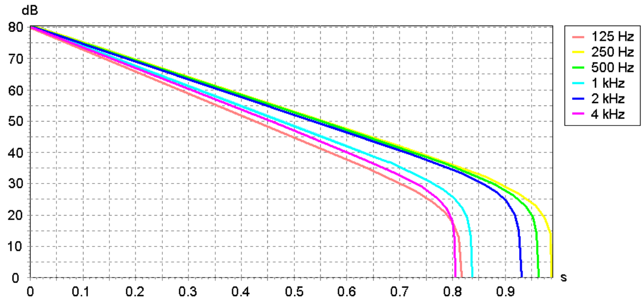

Figure 5. Octave band decay curves computed by RAIOS 3.

The Round Robin 3

The 3rd Round Robin on room acoustics computer simulation, launched in 1999, had 21 participants, from 15 countries, using 9 different software. The participants were software developers as well as typical users. For this project, the music recording studio of PTB was adopted as the reference room and it was intended to be analyzed in three phases of increasing complexity. In the first phase, the music studio was physically modeled with a very crude configuration. The model consisted in seven plane walls with equal absorption and scattering coefficients in all octave bands (from 125 Hz to 4 kHz). Two source and three receiver positions were considered (six source-receiver combinations) and nine acoustical parameters: T_{30}, EDT, C_{80}, D_{50}, TS, G, LF, LFC and IACC were then required for each simulation, resulting in 324 values to be furnished to RR3 coordinators. This phase was intended for checking the software under well-defined conditions and it was useful to establish a communication protocol between the project organizer (PTB) and the participants. Figure 6 shows the provided room geometry along with the source (S) and receiver (R) positions.

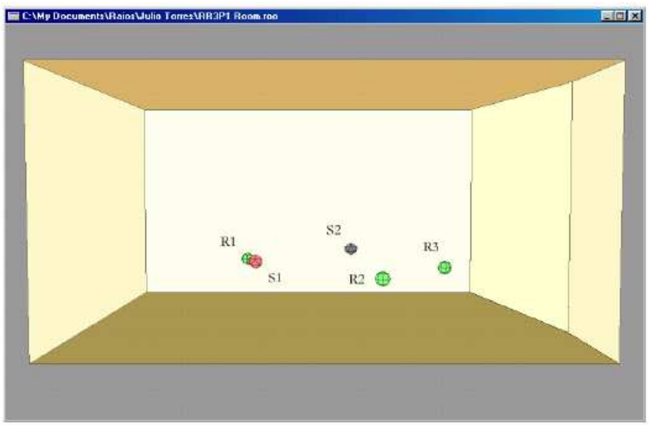

Figure 6. Model of the room for phase 1 of the RR3: Simplified geometry.

In the second phase, the actual (measured) absorption and scattering coefficients were given and some geometrical details of the room were also included, as shown in Fig. 7. In this phase, differently from the first one, two configurations were considered: room with open curtains and with closed curtains, doubling, therefore, the number of simulations to be performed (648 results).

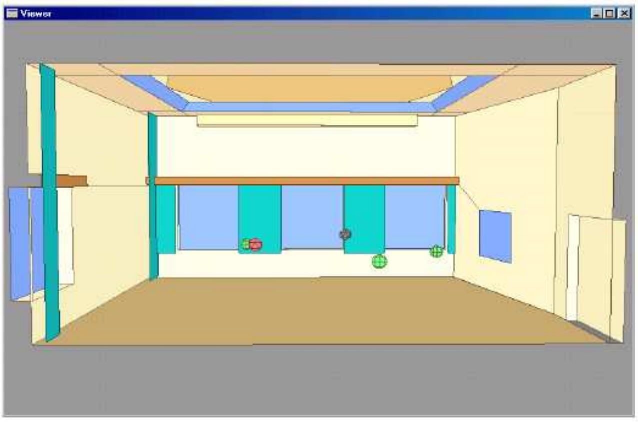

Figure 7. Model of the room for phase 2 of the RR3: Intermediary geometrical complexity.

Finally, in the third phase, almost all geometrical details of the music studio were given, including the diffusers profiles of the roof and of one of the room walls, as can be seen in Fig. 8. All plane surfaces of the diffusers was modeled with the same absorption coefficient as in phase 2 and the scattering coefficient was modeled as being 0.2 for all frequency bands.

Each participant team in RR3 received an identification number, known only by the organizers and, of course, the participant himself. The number 16 identified the software RAIOS 3. At the end of each phase, the results furnished by all participants were available in the project website (www.ptb.de), so anyone could evaluate, by comparison, if some parameter was misadjusted. This was, anyway, a relative analysis, and resulted in no information at all for the next phase, since, as a matter of fact, three very different rooms were in consideration. In the last phase, after divulging all participants results, the experimental data were also published, giving the actual possibility to verify the results of the numerical simulations against the actual data, offering a reliable validation of the proposed methods and software.

Figure 8. Model of the room for phase 3 of the RR3: Detailed geometry.

The first two phases of the RR3 acted as "warming up" stages for the software RAIOS. Much of its "bugs" were corrected during these phases. In fact, the software RAIOS 2 was used in phase 1 and the version RAIOS 2.2 was used in phase 2. None of these versions included the diffusion effect as described in (Tenenbaum *et al.* 2007), which was only taken into account by the version RAIOS 3, used in phase 3 of the RR3. From the initial number of 21 participants, only 17 of them returned data to the three phases.

In the next section, the results obtained by RAIOS 3, in comparison with the ones obtained by all other participants of RR3, phase 3, and with the measurement data, will be presented and discussed.

Numerical Results

All the results presented here refer to the third phase of the RR3, where a detailed model of the reference room was considered. The computation time spent by RAIOS 3 on each simulation, with maximum accuracy, including all parameters and the whole frequency range, was around 90 minutes in an Athlon 1.2 GHz PC, requiring 100 MB of RAM. In the present technology (2005), this computation time is reduced to about 15 minutes.

At the moment of RR3, the software was not able to calculate the binaural acoustic response at the receiver position and, hence, no IACC coefficient was provided for intercomparison. In fact, only 6 of the 21 participants presented IACC calculations (which does not mean, necessarily, six different softwares, since only nine softwares participated in the intercomparison). For this reason, no interaural data will be discussed here.

Since there is a huge amount of data, it was decided to present a selection of them in two kinds of graphics. In the first one, the parameter magnitude versus the six source-receiver combinations at one frequency band is shown. In the second one, the parameter magnitude versus the six frequency bands at one source-receiver combination is depicted; the lines themselves being a linear interpolation of the data.

Acoustical Parameters

In the graphics that follow, numerical results obtained by RAIOS 3 are presented as thick doted lines; numerical results obtained by other participants are presented as thin lines; and the measurement results as thick solid lines. The measurement uncertainty is indicated, as usual, by thin vertical lines. All curves available in RR3 website are reproduced here for each selected parameter. In Fig. 9, a label is shown at the right of the figure. This label is the same for Figs. 10–20. The acoustical parameters presented and discussed below are: T_{30}, EDT, C_{80}, D_{50}, TS, and LF.

Figure 9 depicts the reverberation time T_{30} as a function of the source-receiver combination in the 2 kHz octave band, for the closed curtains condition. It is clear that the curve computed by RAIOS 3 is the one that more consistently approximates the experimental one. It is worth noting that all curves present lower values for the reverberation time than the experimental ones. Our main finding from this figure is that the simulated decays, for this frequency band, are shorter than the actual ones, which means that the impulse responses do not consider the remaining energy due to the scattering effect, simulated quite well by the hybrid method implemented by RAIOS 3.

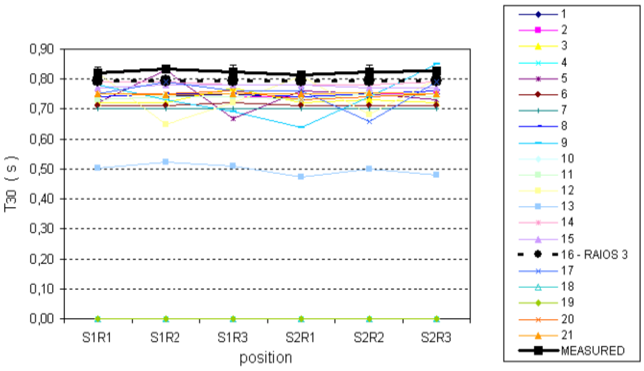

Figure 9. Reverberation time T_{30} at all source (S) and receiver (R) combinations in the 2 kHz octave band. Closed curtains condition.

The reverberation time T_{30} as a function of the frequency band, at the source-receiver combination S1R3 and for the closed curtains condition, is presented in Fig. 10. The values obtained by RAIOS 3 are now slightly greater than the experimental ones in the three lower octave bands (125, 250 and 500 Hz) and slightly lower in the three higher bands (1, 2 and 4 kHz). Even though, the obtained values are close to the measured data, with an average error around ± 0.04 s.

From Fig. 10, it is interesting to observe that, at this source-receiver combination, the reverberation time curve is almost flat. This is mainly due to the high degree of room diffusion. Indeed, in the high frequency bands (1 to 4 kHz), the measurement data presented greater magnitudes than the simulated ones. In this frequency region, the good scattering prediction provided by the hybrid algorithm yielded the results obtained by RAIOS 3 closer to the measured data. In the lower frequency band, where the scattering effect is not so important, the results obtained by RAIOS 3 were also close to the measured data, except in the 500 Hz octave band.

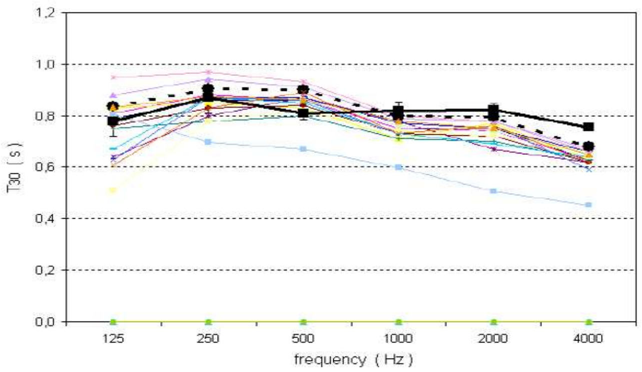

Figure 10. Reverberation time T_{30} in all octave bands at S1R3 combination. Closed curtains condition.

Next, we will examine the results for the clarity factor C_{80}. It is recognized that the clarity factor – an energy rate, expressed in dB, between the initial and final parts of the impulse response at a source-receiver pair – is an important room quality attribute, giving an idea of how much the music performed in the room will became sufficiently perceivable, not blending too much complex harmonic passages (Barron, 1993; Forsyth, 1985; Beranek, 1996).

Looking at the results plotted in Fig. 11, stands out the fact that, except at S1R1 combination, the magnitudes of almost all predicted values are greater than the measured ones. The clarity factor obtained by RAIOS 3 showed to be one of the most accurate, considering the small deviation from the measurement data. It is worth noting that differences among the curves in Fig. 11 are significant, since a logarithmic scale (dB) is used. The results obtained by RAIOS 3 are not so good at combinations S1R1 and S2R3, showing a deviation of around 0.8 dB.

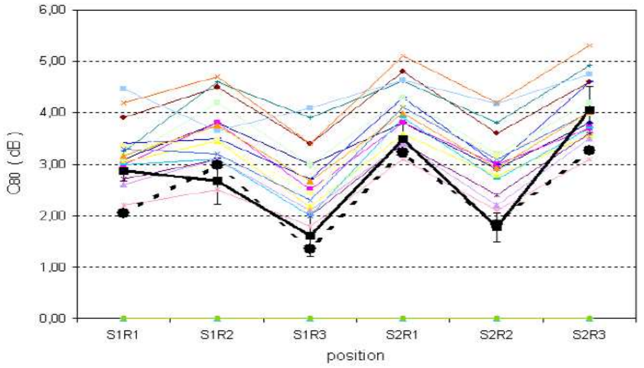

Figure 11. Clarity factor C_{80} at all source-receiver combinations in the 250 Hz octave band. Open curtains condition.

Figure 12 presents the results of C_{80} as a function of frequency band, at S2R2 combination and for open curtains condition. As can be seen, all predicted values presented a noticeable error in the lower frequency band (125 Hz), but, on the other hand, the measurement uncertainty was ± 1.5 dB in this band. For all other octave bands, the results obtained by RAIOS 3 were very close to the experimental ones.

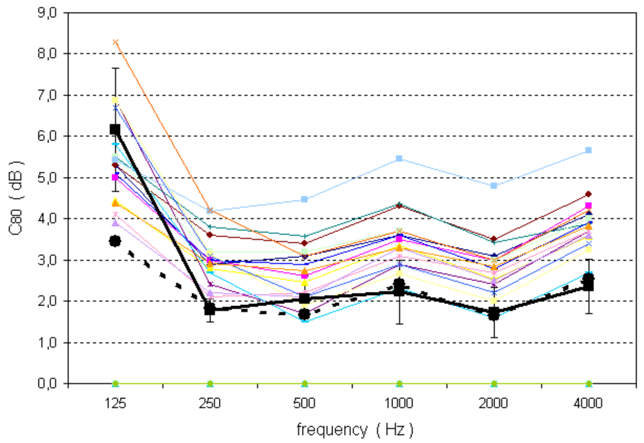

Figure 12. Clarity factor C_{80} in all octave bands at S2R2 combination. Open curtains condition.

Here, a comment on the errors in the 125 Hz octave band is appropriate. It seems that no one of the participant software – including RAIOS 3 – predicts well at the lower frequency band, probably, due to the fact that none of them has a modal analysis algorithm for predicting the effects of the room modes, predominant at low frequencies. In other words, neither the ray-tracing model nor the energy transition model considers the interference effect. The modal behavior yields a strong dependency of the acoustical parameters on the receiver position in the room. This is, of course, a limitation for predicting with good accuracy the room acoustics in the lower frequency band. A model for this phenomenon will be considered and implemented in the new program version (RAIOS 4).

In the following, we will examine the centre time TS, which is the first moment of the squared impulse response and it is roughly correlated with speech intelligibility (Kuttruff, 2000). Despite not being a linearly independent parameter (Ando, 1998), the centre time is important since it defines another useful to detrimental energy ratio, based on the barycenter of the squared impulse response curve.

Figure 13 depicts the centre time TS as a function of the source-receiver combination in the 1 kHz octave band, for the open curtains condition. A difference of up to 20 ms relative to the measurement data at all source-receiver combinations can be seen in the plot. The results obtained by RAIOS 3 fit quite well the experimental data.

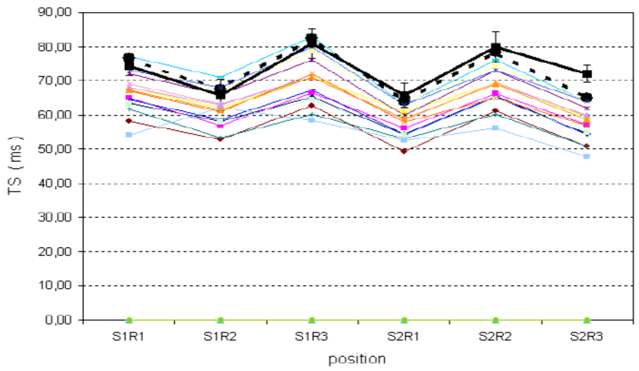

Figure 13. Centre time TS at all source-receiver combinations in the 1 kHz octave band. Open curtains condition.

In Fig. 14, the simulation results for TS, at S2R2 combination, in all frequency bands and for the open curtains condition, are presented. It is worth noting that some differences between predicted and measured values are as great as 25 ms, in the lower frequency band. The results presented by RAIOS 3 were one of the closest ones, except in the 500 Hz octave band, where the difference was around 7 ms. Looking at Figs. 13 and 14, it seems that the hybrid method, discussed in (Tenenbaum *et al.*, 2007) and implemented by the computer code RAIOS 3, reconstructs the impulse responses quite well, by considering the existing scattering surfaces in the room.

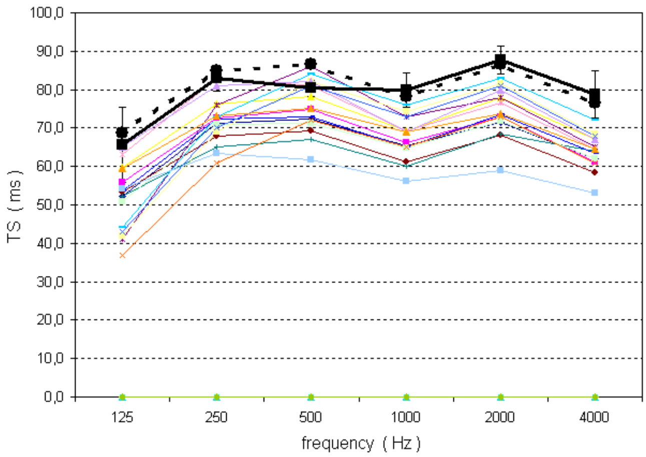

Figure 14. Centre time TS in all octave bands at S2R2 combination. Open curtains condition.

The lateral energy fraction parameter LF is the ratio of the early energy (within the first 80 ms) arriving laterally at the receiver to the non-directional average energy, arriving at the same point, at the same time interval (Beranek, 1996).

This parameter is associated with the acoustical intimacy, attribute that is provided by the room, at a certain neighboring seat (Ando, 1998). Since only the early energy is involved in this computation, all the simulations — even if using only the ray-tracing technique or, equivalently, the virtual-source method — presented good results.

Figure 15 depicts the LF parameter as a function of the source-receiver combination in the 4 kHz octave band, for closed curtains condition. As stated before, almost all participants provided good results. The results obtained by RAIOS 3 showed a good agreement with the experimental data.

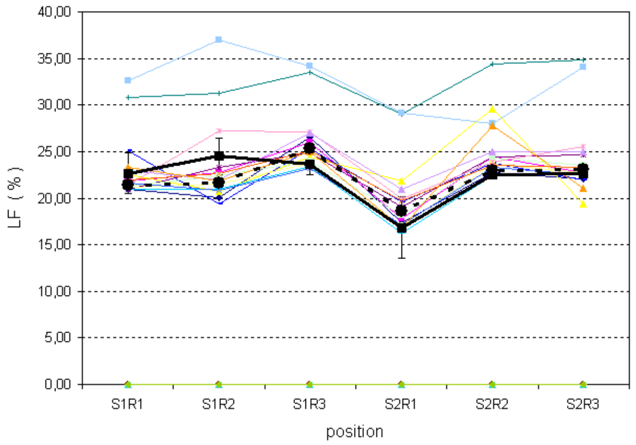

Figure 15. Lateral fraction LF at all source-receiver combinations in the 4 kHz octave band. Closed curtains condition.

The LF parameter as a function of frequency band, at the source-receiver combination S1R2 and for the open curtains condition, is presented in Fig. 16. The 250 and 1000 Hz octave bands are the ones that, for almost all participants, presented the largest discrepancies. It is worth noting that the majority of the software — including RAIOS 3 — provided almost flat curves, with regard to frequency, while the experimental data show some magnitude fluctuation between 15% and 25%, which is not too much but noticeable. In the average, RAIOS 3 provided a rather good result, but this parameter deserves a deeper analysis.

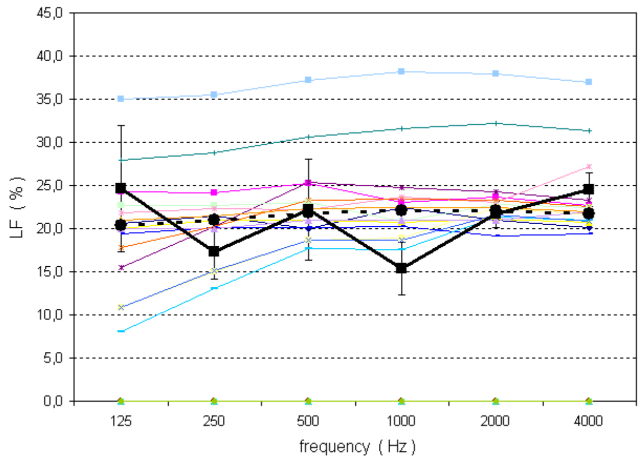

Figure 16. Lateral fraction LF in all frequency bands at S1R2 combination. Closed curtains condition.

The coordinator of the Round Robin 3 project, Ingolf Bork, published recently a report on the results obtained by some programs (Bork, 2005). In the article, from the 21 participants (nine programs) that contributed to the project, the "non-commercial" programs were discarded, and only the results of six "commercial" programs (an author's choice) were retained. RAIOS 3 was considered as a "non-commercial" program by the author, being not included in the presented results. In Figs. 17 to 20, we show some results discussed in the report – but including *all* participants, as can be found in the project website (www.ptb.de). The RAIOS 3 curve and the measurement one are highlighted, as before.

In Fig. 17 the comparative results for the EDT parameter, at all source-receiver combinations in the 1 kHz band and open curtains condition, is presented. As can be seen, the standard deviation among the results is rather large. The average difference between the simulation results obtained by RAIOS 3 and the measurement data is around 0.1 s, with similar oscillatory behavior (among the six source-receiver combinations). At the S2R3 position, the discrepancy is greater, staying around 0.15 s.

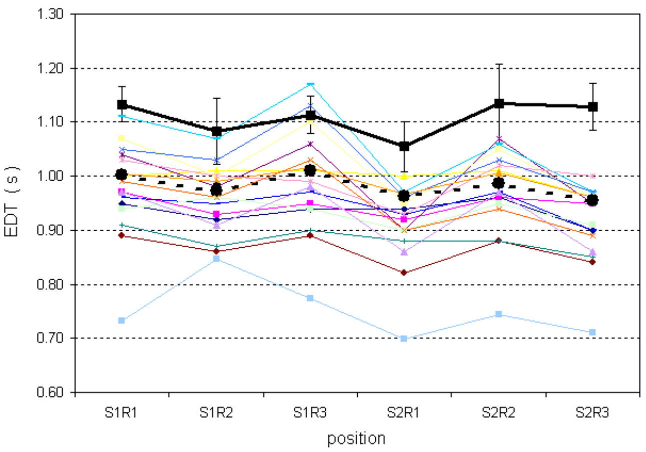

Figure 17. Early decay time EDT at all source-receiver combinations in the 1 kHz octave band. Open curtains condition.

Looking to Fig. 18, the same parameter is shown — EDT, at all source-receiver combinations in the 1 kHz band — now for the closed curtains condition. The measurement curve shows a strong oscillatory behavior, while almost all simulated data present a small variation with the source-receiver combination, including the RAIOS 3 curve. This plot also shows how much the early decay time depends on the receiver position, a dependence not well predicted by simulations.

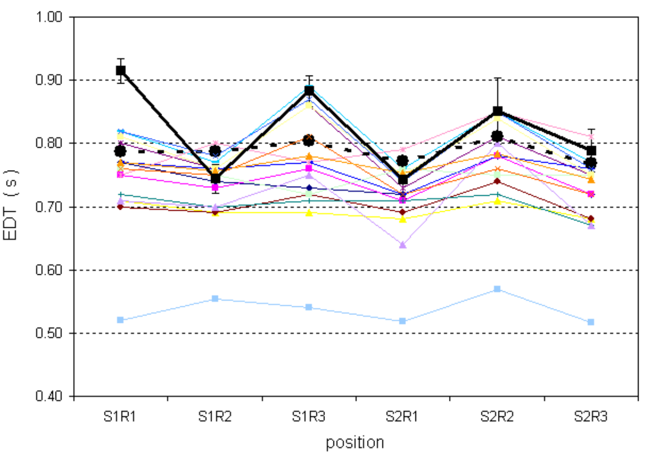

Figure 18. Early decay time EDT at all source-receiver combinations in the 1 kHz octave band. Closed curtains condition.

Figure 19 shows another parameter, the definition, D_{50}, at all source-receiver combinations in the 1 kHz octave band and open curtains condition. This parameter, which is somewhat associated with the room intelligibility (Kuttruff, 2000) is strongly dependent on the balance of the initial (useful) to late (detrimental) energy of the room quadratic impulse response. Since the hybrid method increases the energy of the reverberant part of the IR, as can be seen comparing Figs. 2 and 4, the balance of useful to detrimental energy is changed, leading to the results for D_{50} to become very close to that of the measurements. It is worth noting that this parameter showed a great difference among the results presented by the different participants. For instance, at S1R3 combination, this difference was around 20%.

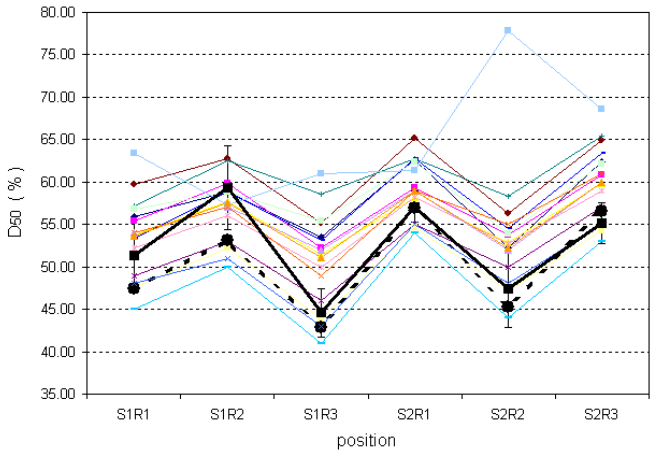

Figure 19. Definition D_{50} at all source-receiver combinations in the 1 kHz octave band. Open curtains condition.

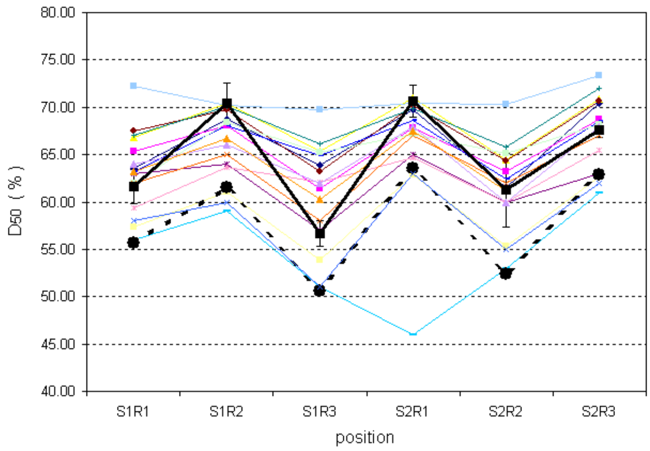

Figure 20. Definition D_{50} at all source-receiver combinations in the 1 kHz octave band. Closed curtains condition.

We must recognize that the results presented in Fig. 20 somehow seems to contradict the previous paragraph, being one of the worst results obtained by RAIOS 3. However, the dependence of the measured data on the source-receiver combination was quite well reproduced, but with a difference varying from 9% (maximum) to 4.5% (minimum).

The full data with all results of the Round Robin 3 project can be found in (www.ptb.de).

RELATIVE MEAN ERROR (%) For all source-receiver combinations and frequency bands

Ranking: 1st, 2nd, 3th, 4th

OPEN CURTAINS PARTICIPANT	1	2	3	5	6	7	8	9	11	12	13	14	15	16	17	20	21
T30	10.16	8.98	5.38	15.08	12.02	13.78	9.12	10.62	11.26	11.04	10.70	8.89	6.61	7.72	12.30	13.58	7.19
EDT	12.70	12.23	8.97	12.73	18.33	15.33	11.81	9.53	13.04	11.32	24.19	11.45	12.37	10.10	10.35	16.16	10.73
D	12.23	12.41	9.47	11.14	17.25	16.87	12.27	10.30	13.84	9.31	26.24	9.56	9.01	10.52	9.89	15.44	10.44
C	43.81	40.50	27.44	31.76	62.31	58.55	40.92	26.89	45.40	28.56	82.56	25.72	26.75	32.17	28.90	51.23	35.59
TS	15.36	14.36	9.15	13.95	21.14	19.82	15.00	12.41	16.54	12.64	22.14	9.76	8.63	11.52	12.03	19.23	12.53
G	4.24	4.10	3.84	6.61	4.62	5.74	3.96	8.42	4.24	6.81	3.26	4.16	3.90	4.13	6.97	4.57	3.80
LF	18.75	20.52	24.07	22.07		57.30	21.46	21.91	20.84	20.17	61.55	23.44	24.76	21.30	21.10	18.46	17.42
LFC	22.95	25.04	26.85			45.16	25.69		25.83		21.18	25.56	27.86	25.19			21.51
IACC	26.13	18.81					24.18		21.74		39.83	21.09					
MEAN T30-LF	16.75	16.16	12.62	16.19		26.77	16.36	14.30	17.88	14.26	32.95	13.28	13.15	13.92	14.50	19.81	13.96
MEAN T30-LFC	17.53	17.27	14.40			29.07	17.53		18.87		31.48	14.82	14.99	15.33			14.90

CLOSED CURTAINS PARTICIPANT	1	2	3	5	6	7	8	9	11	12	13	14	15	16	17	20	21
T30	8.82	8.59	9.06	13.52	10.47	11.14	8.11	14.24	8.69	14.01	27.08	9.58	8.50	6.64	11.02	13.82	7.54
EDT	13.68	14.48	14.96	12.51	14.92	14.08	12.85	12.24	13.22	11.86	26.98	16.72	16.64	12.96	11.73	11.55	13.16
D	9.02	8.70	8.98	10.51	9.50	10.16	8.27	13.99	8.96	11.06	12.95	9.08	8.47	7.77	11.19	9.15	7.92
C	19.24	18.17	20.70	19.87	22.57	22.48	17.63	21.45	18.99	19.28	43.82	17.47	17.12	15.08	19.67	19.29	16.53
TS	12.21	11.86	12.95	15.39	14.58	13.35	11.46	14.00	12.27	13.71	21.61	12.95	11.97	10.38	13.60	13.77	10.84
G	4.49	4.48	4.50	5.42	4.57	4.20	4.50	6.62	4.64	5.58	5.61	5.09	5.81	4.89	5.82	4.87	4.66
LF	23.74	25.69	30.03	26.15		69.53	32.51	21.22	26.67	21.50	76.21	28.48	28.74	26.11	22.68	26.39	23.45
LFC	31.04	32.67	35.67			54.68	37.74		33.77		29.44	31.90	34.13	32.72			33.40
IACC	19.84	12.88					18.93		15.48		39.24	22.39					
MEAN T30-LF	13.03	13.14	14.45	14.77		20.70	13.62	14.82	13.35	13.86	30.61	14.20	13.89	11.97	13.67	14.12	12.02
MEAN T30-LFC	15.28	15.58	17.10			24.95	16.63		15.90		30.46	16.41	16.42	14.57			14.69

OPEN AND CLOSED CURTAINS PARTICIPANT	1	2	3	5	6	7	8	9	11	12	13	14	15	16	17	20	21
MEAN T30-LF	14.89	14.65	13.53	15.48		23.74	14.99	14.56	15.61	14.06		13.74	13.52	12.95	14.09	16.96	12.99
MEAN T30-LFC	16.40	16.42	15.75			27.01	17.08		17.39			15.61	15.70	14.95			14.79

Figure 21. Relative mean errors averaged over all source-receiver combinations and all frequency bands.

Relative Mean Error

A simple comparative analysis of the results obtained by the participants of the Round Robin 3 can be done evaluating the averages of the relative mean errors of the predicted results with respect to the experimental ones. For each participant and for each predicted acoustical parameter, the relative mean errors were averaged out over all source-receiver combinations and all frequency bands. This calculus provides a rough comparative ranking of the simulation accuracy, for the room under consideration, of the participants.

Figure 21 presents the average of the relative mean errors of each acoustical parameter predicted by the 17 participants that remained in phase three. This figure is divided into three blocks: the first one considers the open curtains condition; the second one considers the closed curtains condition; and the average of the errors, considering both curtains conditions, is presented in the last block. A gray scale was used for identifying the ranking (1st to 4th). Since only five participants provided results for the IACC parameter (and, as stated by Ingolf Bork in (Bork, 2005): "only one of the six commercial programs was able to do these calculations"), these results were not included in the statistics presented. The results provided by the participant identified by number 13 were also not considered due to their inconsistency.

Looking with care to Fig. 21, one can verify that there was no simulation software at Round Robin 3 that predicted the acoustical parameters clearly better than the others, considering all frequency bands, source-receiver combinations and room conditions. However, for the room simulated with open curtains, the minimum average of the relative mean errors was clearly obtained by participant number 3. For the room simulated with closed curtains, the minimum average was obviously obtained by participant number 16, RAIOS 3. Considering both conditions (open and closed curtains), it can be observed that participants 16 and 21 presented the best scores (minimum average of the relative mean errors), with a slight advantage to participant 21.

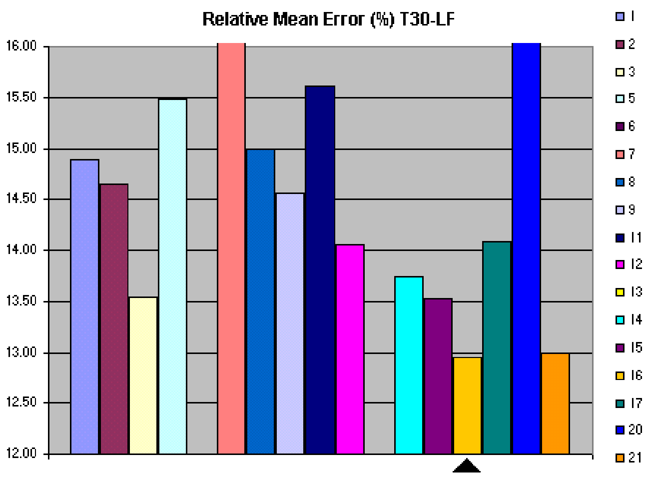

Figure 22. Relative mean errors averaged over the parameters T_{30} to LF.

In Figs. 22 and 23, the average of the relative mean errors, considering both curtain conditions, are plotted as bar graphics. Figure 22 depicts the average performed over the parameters T_{30}, EDT, C_{80}, D_{50}, TS, G, and LF obtained for each participant team. In Fig. 23 the average also included the parameter LFC. The software RAIOS 3 is identified by a black triangle at the bottom of these graphics. As can be seen in these figures, a relative mean error around 13 to 15% is the general result obtained by RAIOS 3. From Fig. 22, it can be concluded that RAIOS 3 achieved the minimum average value among the 17 participants, considering all parameters except the LFC. From Fig. 23, one can see that RAIOS 3 obtained the second best score, when the LFC parameter was taken into account in the average. It is worth noting that only ten participants was able to furnish this data.

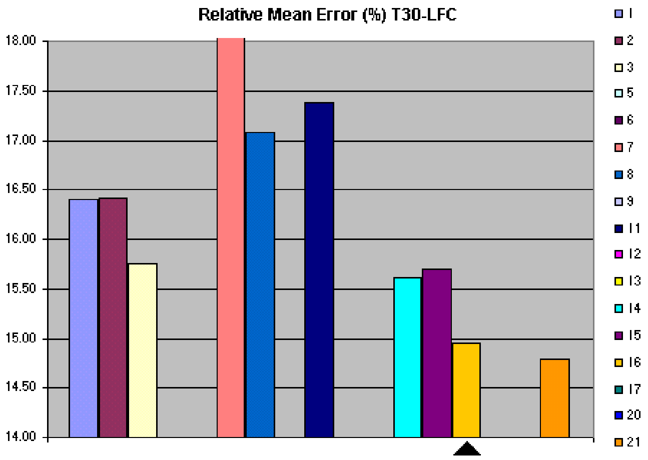

Figure 23. Relative mean errors averaged over the parameters T_{30} to LFC.

Some aspects about the influence of the input data on the predicted acoustical parameters should be commented. The results obtained in phases 1 and 2, not discussed here, and were rather different than that obtained in phase 3 of the RR3. This was mainly due to the geometrical simplification of the room model. Besides, the incompleteness of the absorption and scattering data also played an important role in these differences. Indeed, some numerical tests showed that the simulation results present a considerable sensibility to variations on the absorption and scattering coefficients. This means that, for a reliable simulation, the accuracy of these data is a very important issue.

Conclusions

User-friendly software, called RAIOS 3, which implements the hybrid method for numerical simulation of room acoustics discussed in (Tenenbaum *et al.*, 2007), was briefly presented. As stated before, the acoustical parameters are the best way to verify the accuracy of a simulation method, since they are values and functions computed from the impulse responses, which reveal distinct aspects of the echograms, in spite of not being mutually orthogonal. A simple example was considered for giving an idea of how much the reverberant tail changes, when one takes into account the scattering effect.

A representative set of results obtained by RAIOS 3 in the intercomparison with other participants of Round Robin 3 (RR3) and measurement data was presented. Considering the acoustical quality parameters, it was demonstrated that the hybrid method, proposed in the companion paper (Tenenbaum *et al.*, 2007) and implemented by the program code RAIOS 3, predicted with good accuracy the room acoustics. The results obtained are found to be in acceptable agreement with the measurements. Some of the plots presented are similar to the ones included by the Round Robin coordinator, Ingolf Bork, in his report (Bork, 2005), just for comparison. However, the plots presented in the report include only the results obtained by the six commercial programs, chosen by the author, while our graphs include all participants, as the ones found in RR3 website (www.ptb.de).

Considering the statistical data, computed based on the mean relative errors (with regard to the measurements) of all acoustical parameters, except the IACC, averaged over all octave bands and all source-receiver combinations, the program code RAIOS 3 showed one of the best results in accuracy, in a global ranking.

This good general result – around 13 to 15% of relative mean error – is due to the suitability of the hybrid method for predicting the involved phenomena and to the correctness of the software implementation, which leaded to the algorithm accuracy. Some slight improvements discussed in (Tenenbaum *et al.*, 2007), saving CPU time and computer memory, collaborated to run the program with a heaviest configuration (number of rays, number of surfaces etc.).

One of the remarkable handicaps of RAIOS 3 (and other computer codes) is the lack of good sound field estimation in the low frequency band, where the interference phenomenon must be considered. This deserves the implementation of a good and simple model for the modal behavior of a room, which is predominant in this frequency range. This will be our next step.

Of course, for a 'quality seal' to be applied to a program code, many other simulations must be performed and compared with experimental results for different rooms. The sensibility of the results to absorption and scattering coefficients requires that these coefficients should be carefully measured, which is not a trivial task and can yield results with a rather large uncertainty (Araújo, 2005).

Up to the last moment that final results were required by the Round Robin 3 organizers, the binaural impulse response algorithm was not ready, so that no IACC data was furnished by RAIOS 3. Now, not only the IACC algorithm is available, but also the head related transfer functions (HRTF) modeling, discussed in (Tenenbaum *et al.*, 2007), and is handy. Now, we wait for Round Robin 4, probably with auralization.

References

Alarcão, D., Bento Coelho, J.L., Tenenbaum, R.A., "On modeling of room acoustics by a sound energy transition approach", *Proceedings of EEA Symposium on Architectural Acoustics*, Madrid, October 2000.

Ando, Y., "Architectural Acoustics: Blending Sound Sources, Sound Fields, and Listeners", Springer-Verlag New York, Inc., 1998.

Araújo, M.A.N. and Tenenbaum, R.A., "Uncertainty in sound absorption measurements in diffuse fields", *Proc.Managing Uncertainty in Noise Measurement and Prediction*, Le Mans, 2005.

Barron, M. "Growth and decay of sound intensity in rooms according to some formulae of geometric acoustics theory", *Journal of Sound and Vibration*, 27(2): 183–196, 1973.

Barron, M. *Auditorium Acoustics and Architectural Design*. 1st ed. London, E & FN Spon Chapman & Hall, 1993.

Beranek, L., "Concert and Opera Halls: How They Sound", 1st ed. New York, Acoustical Society of America, 1996.

Blauert, J., "Spatial Hearing", *The MIT Press*, Cambridge, 1997.

Bork, I., "Report on the 3rd Round Robin on room acoustical computer simulation – Part II: Calculations", *Acta Acustica united with Acustica*, 91(4):753–763, 2005.

Camilo, T.S., "Método híbrido para simulação numérica de acústica de salas: Combinação dos métodos de traçado de raios e transição de energia" (in portuguese). *Master Thesis*, COPPE, UFRJ, Brazil, March 2003.

Embrechts, J.J., "Randomly traced sound ray techniques", *Acustica*, vol. 51, pp. 285–295, 1982.

Farina, A., "RAMSETE – A new pyramid tracer for medium and large scale acoustic problems", *Proceedings of Euro-Noise 95 Conference*, Lyon, March 1995.

Fitzroy, D., "Reverberation formula which seems to be more accurate with no uniform distribution of absorption", *Journal of the Acoustical Society of America*, 31(7): 893–894, 1959.

Forsyth, M., "Buildings for Music: The architect, the Musician, and the Listener from the Seventeenth Century to the Present", MIT Press, Massachusetts, 1985.

ISO 3382, "Acoustics – Measurement of the reverberation time of rooms with reference to other acoustical parameters", 2 ed., June 1997.

Kruzins, E., Fricke, F., "The prediction of sound fields in non-diffuse spaces by a 'random walk' approach", *Journal of Sound and Vibration*, 81(4): 549–564, 1982.

Kuttruff, K.H., "Room Acoustics", 4th ed. London, Spon Press, 2000.

Lewers, T., "A combined beam tracing and radiant exchange computer model of room acoustics", *Applied Acoustics*, vol. 38, pp. 161–178, 1993.

Pierce, A.D., “Acoustics: An Introduction to its Physical Principles and Applications”, *Acoustical Society of America*, Woodbury, 1991.

Rindel, J.H., Naylor, G., “Computer modeling of sound fields in rooms – The state of the art and outlook to the future”, *Proceedings of 14th International Congress on Acoustics*, F2-1, Beijing, September 1992.

Schröeder, M.R., “New method of measuring reverberation time”, *J. Acoust. Soc. Am.*, 37:409–412, 1965.

Tenenbaum, R.A., Camilo, T.S., Torres, J.C.B., Gerges, S.N.Y., “Hybrid method for numerical simulation of room acoustics: Part 1 – Theoretical and numerical aspects”, *J. Brazilian Soc. Mech. Sci. and Eng*, vol.29, (2), 222–231, 2007.

Tenenbaum, R.A., Slama, J.G., Balesteros, M.L., “Numerical simulation of room acoustics: A new approach for source modeling”, *Proceedings of 14th International Congress on Acoustics*, F6-11, Beijing, September 1992.

Vorländer, M., “International Round Robin on Room Acoustical Computer Simulation”, *Proceedings of 15th International Congress on Acoustics*, Trondheim, 1995.

www.ptb.de/de/org/1/17/173/roundrob3 1.htm.