NEWS FROM ROOM ACOUSTICS

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1 INTRODUCTION

Room acoustics is an established field with exciting connections to architecture and music. Efficient planning tools are available. Experience with solutions for various applications is the basis for daily work in acoustic consulting. Finally, room acoustic planning and consulting is a fairly straightforward process. This statement is true if one considers the elementary design rules and the creation of acceptable room acoustic conditions. In rooms for speech and music, however, acceptable acoustic conditions do not always exist because standards and guidelines of room acoustics are not sufficiently taken into account. In ISO 3382 [1] we find definitions and guidelines for the measurement and interpretation of room acoustic quantities. In famous textbooks, the best known by Beranek [2] and by Barron [3], we find a large amount of data from concert halls and opera houses, and these data give target values and tolerance ranges for successful acoustic designs.

In this article, it is briefly summarised and updated the information about the history of room acoustics, revisited the state of the art, and discussed open research questions (see also [4]). These relate to the cross-disciplinary exploration of classical room acoustics with psychoacoustics and array signal processing.

2 A BRIEF HISTORY OF ROOM ACOUSTICS

Wallace Clement Sabine created the first scientific approach to understanding the acoustics of performance spaces. His famous "Collected Papers" [5] form the basis for the room acoustics we are still using today. The relationship between reverberation, volume and absorption was clarified and explained empirically. A little later, in the 1930s, Norris [6] and Eyring [7] presented a theory with more correct factors in the equations, known today, of course, as the reverberation equations of Sabine and of Eyring.

After that, the "fine structure of reverberation" became the focus of interest. In the first edition of his book [8], in 1948, Lothar Cremer illustrated sound reflections using geometric constructions of rays and image source, a methodology that is still one of the standard methods in room acoustics today. He already recognised the importance of reflections, their arrival series, their density and their global late decay.

With these findings and the availability of instruments for measuring impulse responses, acoustic consulting was put on a scientific footing. From the 1950s onwards, consultancies could rely on a deeper understanding of sound fields and advise architects accordingly. But still the specific subjective effects in impulse responses were in the dark.

2.1 Impulse responses

The physical aspects of room acoustics were first studied in the 1950s. The subjective impressions were related to the physical properties of the room impulse responses. One of the first observations regarding early reflections was made in 1952 by Rolf Thiele [9], who established the basis for the objective description of the ratio of early to late energy ("clarity"). This finally became possible with the availability of multi-channel loudspeaker systems in anechoic chambers. Today we consider the concept of early decay also to be well understood. This knowledge came from Vilhelm Jordan [10], who discovered the relationship between reverberation and subjective reverberance. In addition, studies on the correlation of subjective impressions and objective parameters were carried out during this period. Numerous publications originate from the research groups around Erwin Meyer (Göttingen), Walter Reichardt (Dresden) and Lothar Cremer (Berlin). In Göttingen, Manfred Schroeder contributed to room acoustics with two very famous studies, one on the statistics of frequency curves [11] (also [12], with Heinrich Kuttruff), and one on the integrated impulse response method [13]. With these pioneering works, room acoustics was clearly removed from the influence of black magic. In the following years, the defined quantities were tested in laboratory environments and applied in measurements in halls.

2.2 Spatial impression

By the early 1970s, many modern concepts for "good" room acoustics related to classical music performances, operas and theatre had been proven in theory and accepted as best practice. However, at that time many halls were designed with modern architecture and construction. The use of open concrete, mostly large flat and smooth surfaces, large and wide halls, especially fan-shaped halls, was favoured. And some of these halls had bad reviews, although reverberation time, sound level and clarity were in the right order of magnitude.

James West [14] noted in 1966 that acoustically good concert halls (Musikvereinssaal Vienna and Boston Symphony Hall) had a low width-to-height ratio. In 1968, Harold Marshall [15] confirmed that the spatial impression is created by side wall reflections, which are particularly strong in narrow halls. In the early 1970s, Michael Barron [16] in Southampton (1971) and Peter Damaske and Yoishi Ando [17] in Göttingen (1972) found that the importance of side reflections had been underestimated. They pointed out the importance of the early lateral reflections for the spatial impression. They influence the accuracy of source localisation and give the impression of diffuse sound incidence. Even today, the spatial impression is among the most interesting components of multidimensional listening in rooms ("auditory awareness").

The fan-shaped hall indeed shows a lack of early side sound. One consequence was to incorporate side walls with sloping segments or terraces or vineyards to split side wall reflections and direct them laterally to the audience.

2.3 Best practice in room acoustic design

After the 1970s, acousticians and architects could rely on a fairly stable and complete knowledge of the general principles of room shape and their effects on early and late reflections. Heinrich Kuttruff's book [18] already contained the current state of knowledge on room acoustics in the first edition of 1972. After that, details could still be studied, but the general insight into room acoustics was considered kind of complete.

It is interesting that the findings in room acoustic research directly are reflected in the hall shapes built. Jürgen Meyer [19] evaluated 157 halls with seating capacity >1000. He points out that the majority of room shape is rectangular, fan-shaped, hexagonal or in arena style, see figure 1. Thus, the hall shape determines a large amount of the acoustic performance. Many details such as surface corrugations, stage, balcony and reflector design are important as well, and consideration of the directional radiation of musical instruments.

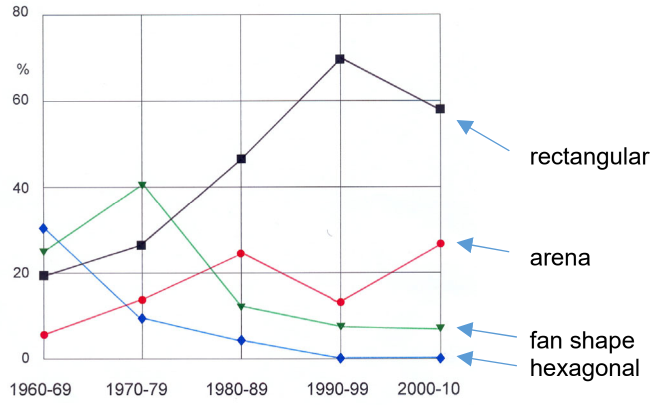

Figure 1. Percentage of room shapes chosen for concert halls built between 1960 and today (after Meyer [19]).

2.4 Standards

Under the leadership of Fergus Fricke from University of Sydney, an extended edition of the international standard ISO 3382 "Measurement of the reverberation time of rooms with reference to other acoustical parameters" was developed and finally published in 1996 [1]. It contained not only guidelines for the measurement of the reverberation time in lecture halls, but also definitions for other room acoustic parameters: Early Decay Time EDT, Strength G, Clarity C80, Definition D50, Centre time t_c, Lateral energy fraction LF, Interaural cross correlation coefficient IACC.

Nevertheless, other milestones in room acoustics are worth mentioning. These relate to signal processing in measurement technology, advances in computer simulation and further clarification of spatial impression. In 1995, John Bradley and Gilbert Soulodre [20] investigated the subjective effects of early and late room reflections. They found two independent effects of spatial impression: apparent source width and envelopment. And they were able to correlate the results of the subjective tests with two simple but meaningful objective measures: the early lateral sound ratio (more or less in Barron's definition) and a new quantity, the late lateral strength, G_{LL}.

2.5 Computers

The dawn of the digital age has led to significant advances in room acoustics, as in all areas of science and technology. The 1990s saw the initial introduction of analogue-to-digital conversion and measurement technology, including complex broadband sensor calibration. Computational acoustics, which is now widely used alongside high-performance computing in computer centres, represents another major push in powerful tools in acoustic research and engineering.

The introduction of computers in digital acoustic measurement technology has enabled sophisticated measurement techniques for impulse response measurements. This applies both to measurements in real rooms and to scale models. Impulse responses could be measured with high reproducibility and thus comparability. In the first ISO 3382 there was already a reference to ISO 18233 to the use of broadband excitation and post-processing to obtain impulse responses. There is no need at all to use interrupted noise method for measuring reverberation times. Also for material testing, there are powerful methods based on swept-sine signals, digital sequences, or interleaved sweeps, which allow for quick and precise signal acquisition ad processing [29].

Computer simulations have been developed in parallel with model measurements and brought to a high quality level. Based on pioneering work by Krokstad, Strøm, and Sørsdal in 1968 [30], independently, Dirk van Maercke in Grenoble [31] (originally developed as EPIKUL at KU Leuven), Michael Vorländer in Aachen [32], Bengt-Inge Dalenbäck in Gothenburg [33] and Graham Naylor and Jens Holger Rindel [34] in Copenhagen worked on algorithms for simulating room acoustics based on architectural CAD input data. These and other programs are still in use successfully today. Round-robin tests [35-37] evaluated their performance, and also the limits of room acoustic computer simulation. This led, among other things, to the definition and implementation of scattering coefficients [38] in simulation procedures. Similar to observations in real sound fields with purely specular reflections (rooms with large flat concrete walls), it was found that artificial decays based on purely specular models sound unnaturally cold and too contrasted.

3 CURRENT RESEARCH

Room acoustics is far from being a solved problem, though. Despite standards and planning tools, there is a need for research and knowledge transfer to other technical disciplines. Too many boardrooms, classrooms, auditoriums, offices, train stations and airports have unacceptable acoustic conditions.

3.1 Room acoustics and psychoacoustics

Regarding the need for research on subjective impression, Anders Christian Gade [39] has already provided an excellent overview and outlook in 2004. He noted that multidimensional room-acoustic impression requires a much larger statistical base of rooms, seats, and subjects than is commonly applied and published. Each study captures one variable and attempts to hold others constant. The relationship between clarity and loudness or ASW and bandwidth, music style and dynamics, for example, remains unclear because the test conditions of different studies are not identical. Tapio Lokki and his group, for example, have approached the multidimensional problem by developing techniques for creating individual vocabulary profiles [40], which finally revealed the underestimated importance of loudness dynamics. In this case, the basis for reproducible research is an artificial orchestra that can reproduce musical excerpts in exactly the same way in different rooms. Spatial audio reproduction technology enables reproducible listening tests in an anechoic chamber. Pätynen and Lokki [41] generated this anechoic orchestral signal with variations in music dynamics and reproduced it with a loudspeaker array. The underlying impulse responses were measured in a series of concert halls at several locations. The results of the listening experiments confirmed that concert halls reproduce the dynamics of the music played differently and with different perceptual aspects. It has already been established that concert halls that enhance dynamics evoke high subjective preference. The adage that the concert hall is the "instrument" of the orchestra can also be expected because musical instruments which support a wide variation of dynamics offer the musician a wider range of expression. This work is a striking example of how the use of digital technology, i.e., multichannel processing, can provide new insights into the complex problem of spatial acoustic perception.

Barron [42] also emphasised the importance of sound level distributions in halls as early as 1988. Later, further data were collected and confirmed that the subjective assessment of loudness in concert halls is not only influenced by the sound level but also by the distance between source and receiver. The total level (strength) decreases typically more than expected for diffuse fields but nevertheless the loudness perception is rather constant in the whole space. In [43], Barron suggests a strength rating which should be based rather on a function of the distance between the source and the listener, because listeners are compensating their judgement of loudness on the basis of either visual or other auditory information.

Densil Cabrera and colleagues asked why reverberation must be based on level decay rather than loudness decay [44]. Time-dependent loudness includes both spectral masking and the temporal effects of cochlear sound processing. There are models from psychoacoustics (Fastl and Chalupper [45], Moore and Glasberg [46]) that have already been adopted into a standard [47].

Cabrera's loudness decay rates actually correlate well with subjective reverberation. Moreover, the loudness decay rates may contain signal properties if the decay curve is derived from signals convolved with impulse responses rather than from the impulse response. Accordingly, reverberation can be expressed in two aspects: a) reverberation in signal transients and its effect on signal modulation, and b) reverberation after the final chord.

Regarding binaural aspects, auditory models of binaural processing are a powerful tool for assessing localization, envelopment, and spatial impression. Based on the Jeffress model of cross-correlation [48], there are several modeling approaches (including Lindemann [49], Dau [50], Breebaart [51], van Dorp Schuitman [52]) that are increasingly used in spatial acoustics research.

3.2 Uncertainties of room-acoustic measurements

A fairly new area of research is the evaluation of measurement procedures (typically application of ISO 3382) with respect to measurement uncertainty (Peters [53]). The measurement uncertainty can then be compared with the just perceptible differences, jnd, to determine the significance of results. Using the framework of GUM [54], it is possible to examine the sources of error affecting a measurement result and to specify the quantitative influence of each source of error on the overall uncertainty. In room acoustics, the placement and directivity of dodecahedron loudspeakers have been shown to be critical, as have the specifications of the microphone and artificial head [55, 56].

Witew [57] described a GUM-compliant strategy to obtain the main uncertainty contributions in the measurement of room impulse responses. In ongoing work, he created a hierarchical list of the most important uncertainty contributions in measurements of room impulse responses (to be published in [58]), for example see figure 2 in a diagram with room-dependent clusters. Based on this list, efforts to obtain accurate measurements can be focused on the most important influencing factors can be directed to improve the efficiency of the measurements.

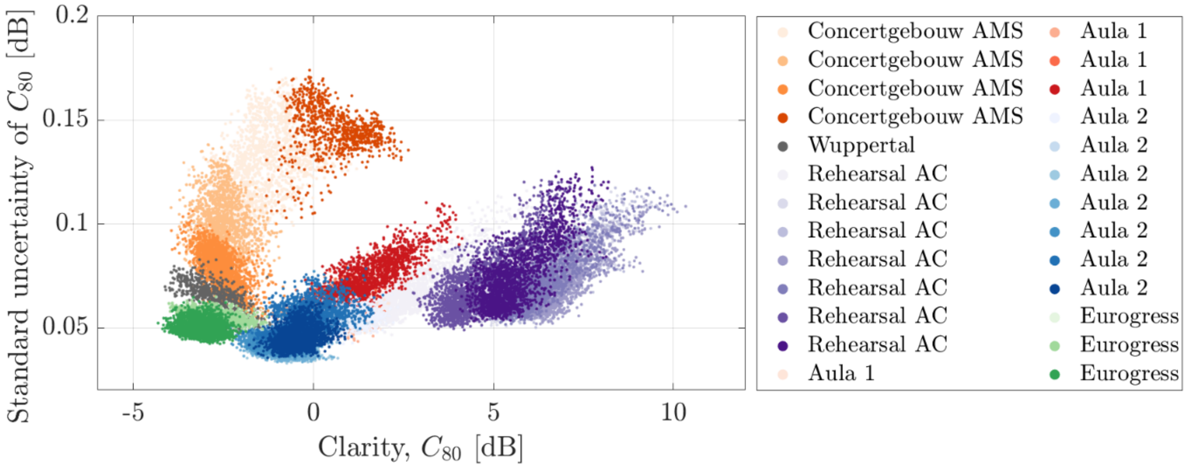

Figure 2. Broadband clarity index C80 and the associated standard uncertainty in different auditoria. (after Witew [58])

The uncertainty of room acoustic parameters due to uncertain room impulse responses is very small and in most cases not a significant factor. Differences in the data due to variations of source and receiver positions are by far the largest uncertainty contribution to room acoustic parameters, even when very small distance variations are considered. Results of the parameters quantities (T30, EDT, C80, D50, t_c, G) may differ not only between seats but also within the dimension of one seat. The uncertainty due to spatial fluctuations must be taken into account independently of the source and the receiver. Thus, a sufficiently precise specification of the measurement locations of source and receiver are required.

3.3 Auralization

The basic algorithms for computer simulation and auralization in room acoustics were developed in the 1990s. Also at that time, the importance of scattering was recognized, thus leading to implementations of hybrid models. Their feature is that deterministic specular components in the impulse responses is calculated separately from stochastic (diffusely scattered) parts. Both parts are combined in the end. It is important to mention that the physical sound field can be separated into those two parts as well. The simulation results are post-processed in order to provide output signals with appropriate sampling rate, frequency bandwidth and spatial resolution for audio reproduction. Auralizations using such kind of hybrid models are in perceptive aspects close to recordings, as usually described with the term “plausibility”. To quantify the differences and to understand the reason of differences, though, is subject to research.

Besides the development of algorithms describing the physical sound propagation in room, many ideas from computer graphics were also applied to room acoustic modelling, such as space partitioning or other methods to speed-up the algorithmic kernel of ray intersection point with polygons. Due to severe differences of (narrow-band) light propagation in contrast to broadband sound propagation and differences in the ratio of room and object sizes in comparison with wavelengths, the algorithms used for creation of computer images cannot be applied in room acoustics. Nevertheless, data management and dynamic object handling developed in computer graphics makes real-time auralization possible (Acoustic Virtual Reality).

Based on a developed database (BRAS [59]), a round robin test was performed with five simple scenes and all four complex rooms as test scenarios. Here, the software tools (anonymously labelled A, C, D, E, F) were used to predict the impulse responses and transfer function in high resolution suitable for auralization. The simple scenes included single reflection on purpose in order to study the effects of reflection contributions and digital filter construction individually, before complex room impulse responses are considered. In [60] and in the dissertation by Aspöck [61], the results were analysed. First, large deviations of results submitted by some participants in the simple scenes were very surprising, see figure 3. This means that various software tools create rather different comb filter patterns or linear/minimum, etc. phase impulse responses for a “simple” reflection at a rigid surface.

Also, the reflection from a one-dimensional diffusor could not be accurately modelled by most participants. Second, the results of the complex rooms once again demonstrated that it is still a challenge to determine adequate absorption and scattering coefficients for simulations when the user does not have the knowledge about the real acoustics of the studied room. This, however, is a problem caused by insufficient material data, insufficient material models, such as for lightweight walls or other structures with complex vibration patterns, not to mention the problem of characterizing sound reflection and diffraction of concert halls seats.

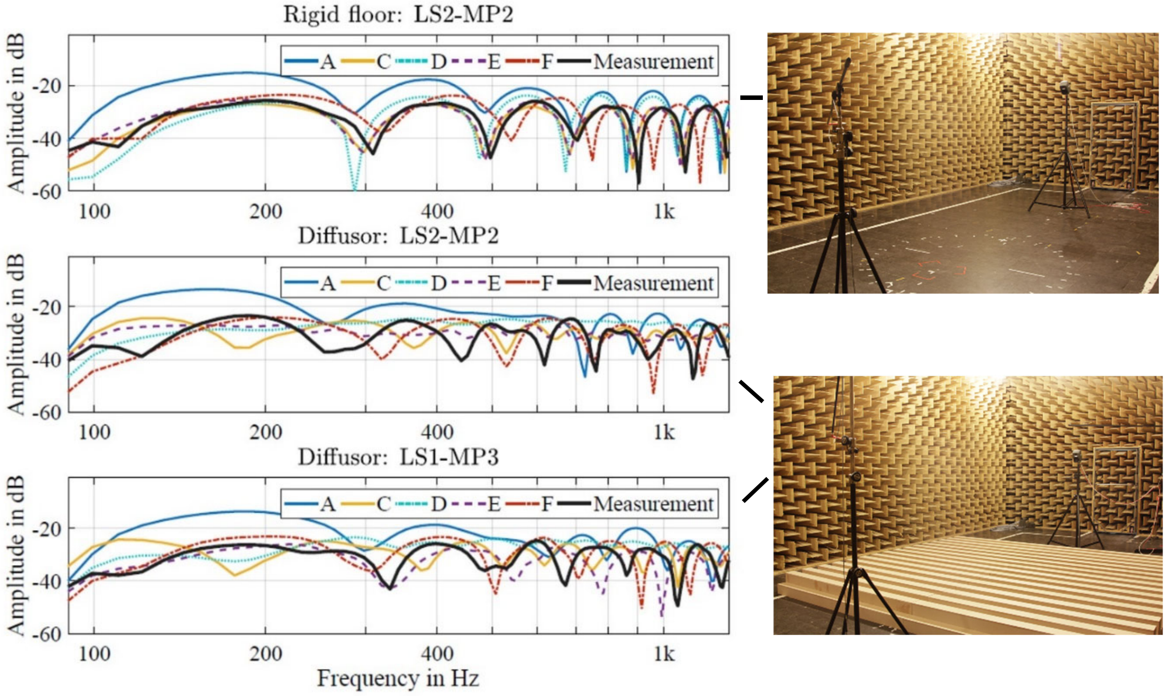

Figure 3. Comparison of simulated and measured sound field (magnitude) of direct sound and reflection at infinite flat surface (top) and corrugated surface (middle and bottom), after Aspöck [61].

3.4 Array technology for wave field analysis

The development of linear, circular and spherical arrays for 3D sound field analysis has inspired much research in room acoustics. Arrays can be used for decomposing complex sound fields into a sum of plane or spherical waves. These waves are naturally generated by reflections. The advantage of the technique is that not only the temporal and spectral characteristics of room sound fields are captured, but also their directional distribution. And apart from the possibility of multi-channel sound recording, this technique is very interesting for the analysis of room sound fields and reflection patterns.

One of the first findings with linear arrays was that clarity, C80, is very sensitive to small changes in microphone position, see also section 3.2. When impulse responses are evaluated for adjacent array microphones that are only a few centimetres apart, the clarity data differ more than the difference that can just be perceived [63]. This would indeed mean that the subjective impression of clarity differs significantly within a concert hall space. This in no way corresponds to the listening experience, and accordingly the definition of the clarity index is too sensitive a result.

Another example is the application of the concept of wave field analysis, WFA, to room acoustics. In this way, rooms can be compared with respect to their wave propagation patterns [64], providing valuable insights into wave incidences and thus into the relationship between pronounced specular wave fronts and the more blurred diffuse components.

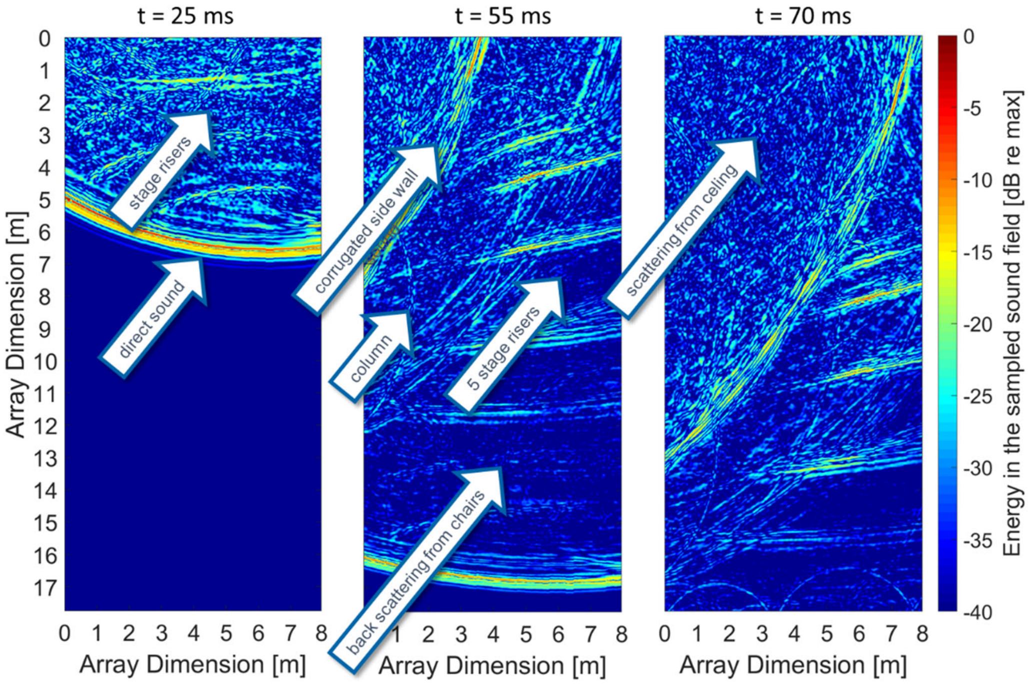

Figure 4. Wave field analysis in Concertgebouw Amsterdam, snapshots at 25 ms (left), 55 ms (middle), 70 ms (right) (after [65])

3.5 Array technology for spatial analysis

The basic definition of the "diffuse sound field" is that it is isotropic, i.e., the sound field consists of infinitely many sound waves from uncorrelated sources whose directions of arrival are uniformly distributed over a sphere. Studies about measurement of isotropy go back to Thiele [9] but they were intensified with the availability of array technology and multi-channel digital processing. Gover et al [66] discuss the distribution and spatial variation of incident energy measured with a directional receiver in a room to study the isotropy of a sound field at steady state. Nolan et al. applied this approach to determination of the state of diffuse field in reverberation chambers [67]. Similarly, Berzborn and Vorländer studied in [68] the diffuseness and the effect on directional decay curves by analysing the spatial variation of directional energy decay curves (DEDCs) derived from directional spatial impulse responses (DRIRs).

A DRIR measured with a spherical microphone array is expanded into spherical harmonics (SH) coefficients. When decomposed into plane waves, this can be interpreted as a spatial filtering that yields a DRIR for each direction incident at the measurement point. Applying Schroeder integration to the DRIR yields a directed energy decay curve (DEDC).

In complex geometries, especially in rooms with reverberation reservoirs such as chambers for the purpose of variable acoustics, or dome structures, the temporal reverberation process may exhibit specific features of directional sound incidence and mixing process during decay. In a simulation study, the directional characteristics of the DRIR and the DEDC for impulse and noise excitation, respectively, were investigated, as shown in one example of a baroque church (Frauenkirche Dresden) in figure 5.

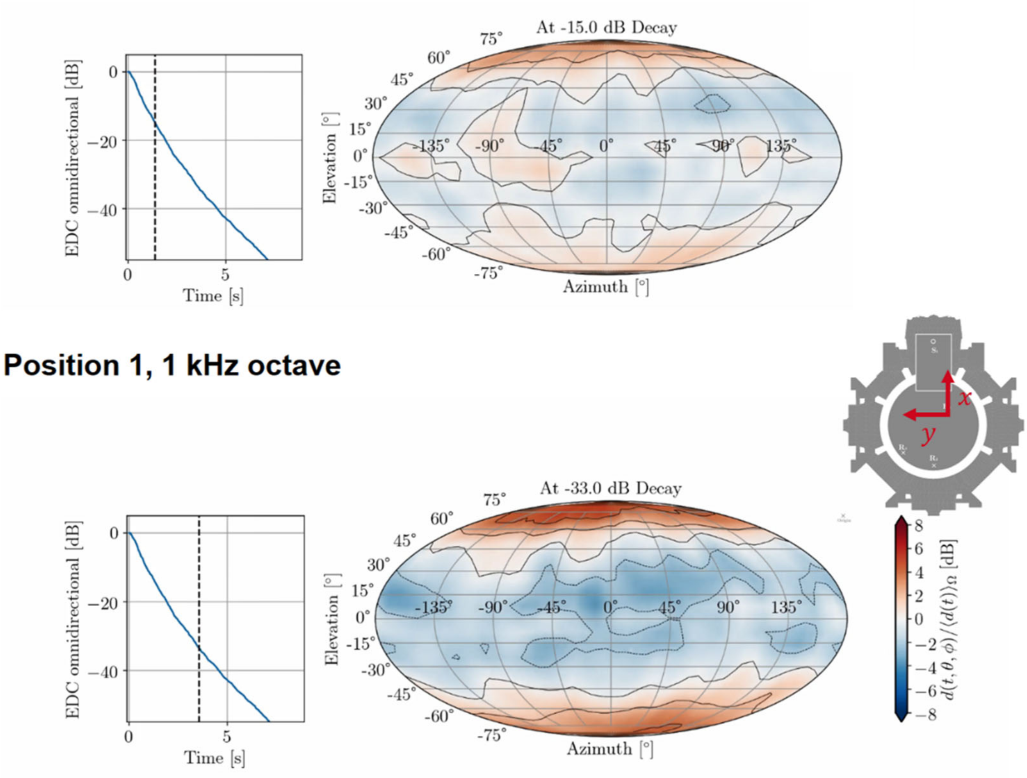

Figure 5. The DEDCs normalized by their directional mean for the 1 kHz octave band at an exemplary receiver position and at two decay states of 15 dB (top) and 33 dB (bottom) in sphere projections. The contour lines represent the levels marked in the colour bar. At the left, the traditional decay curve with the corresponding time cursors are shown. The grey sketch on the right shows the ground plan of the Frauenkirche (after Berzborn et al. [68]).

The sound field in the baroque church shows a fairly isotropic sound field up to the time corresponding to a decay of about 15 dB (graph above). After this time, an increasing concentration of the incident energy from the poles can be observed, as shown in the graph below. The global maximum, which deviates by more than 6 dB from the mean, is observed towards the north pole, indicating that the dome roof structure acts as a reverberation reservoir with a longer reverberation time than the main volume of the church. The second maximum towards the south pole is caused by reflection from the floor and is less similar to the north pole than the maximum incident energy at the north pole. It goes without saying that these effects correlate with a non-straight decay curve.

4 SUMMARY AND CONCLUSIONS

In room acoustics, several dimensions of the overall auditory impression were determined, which show a good correlation with corresponding objective measurement data. In summary, standardized room-acoustic parameter correlate well with the three most important factors (loudness, reverberation and room impression) explain most of the statistical variance when comparing acoustic conditions in auditoriums. Aspects of dynamics are still being investigated, as are robust descriptors of stage acoustics.

Auralization tools are well developed, including for use in consulting practice. The main challenge is the uncertainties in the input data, which are mainly the boundary conditions of the room. For modelling with geometrical acoustics, this concerns the development of broadband filters for specular reflections and even more so for filters intended to represent reflection from scattering surfaces. Wave models are nominally more correct, but even suffer from unknown or inaccurate boundary conditions when it comes to simulating real surfaces, too.

In addition to the definition of the most important perceptual factors, another crucial issue is the listener's sensitivity to changes in a sound field with respect to these subjective aspects (jnd) and to the robustness and significance of measurement results in comparison with the jnd.

The collaboration of room acoustics with psychoacoustics and spatial audio engineering will generate further ideas and innovations in research and in the design of concert halls. Today, room acoustics is far from being black magic. Rather, it is a strictly scientific, interdisciplinary concept that certainly needs to be further developed. And finally, methods, findings and guidelines from classical room acoustics will also be used for purposes other than the acoustics of performance spaces, such as for railway stations or airports, factory halls and office spaces, thus also for noise control and soundscape applications.

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