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## Review Papers

# Virtual Acoustics

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Virtual Reality (VR) systems are used in engineering, architecture, design and in applications of biomedical research. The component of acoustics in such VR systems enables the creation of audio-visual stimuli for applications in room acoustics, building acoustics, automotive acoustics, environmental noise control, machinery noise control, and hearing research. The basis is an appropriate acoustic simulation and auralization technique together with signal processing tools. Auralization is based on time-domain modelling of the components of sound source characterization, sound propagation, and on spatial audio technology. Whether the virtual environment is considered sufficiently accurate or not, depends on many perceptual factors, and on the pre-conditioning and immersion of the user in the virtual environment. In this paper the processing steps for creation of Virtual Acoustic Environments and the achievable degree of realism are briefly reviewed. Applications are discussed in examples of room acoustics, archeological acoustics, aircraft noise, and audiology.

**Keywords:** acoustic virtual reality, simulation, auralization.

## 1. Introduction

More than 20 years ago, in 1993, Kleiner *et al.* published an overview on the emerging technique of auralization (Kleiner *et al.*, 1993). The basis for auralization is the landmark paper about the calculation of an acoustical room response by means of a sound-particle-based simulation technique almost 50 years ago, published by Krokstad *et al.* (1968). The state of the art, the methods, the challenges and implementation techniques required for auralization and virtual acoustics have become a rather complex field of research, particularly with the rapid progress in real-time processing and integration in virtual reality systems.

Complex acoustical simulation methods were established and applied in the sound field analysis of rooms and buildings on standard Personal Computers (Vorländer, 1989; Naylor, 1993; Dalenbäck, 1993) since the 1990s. The simulation times in the beginning were in the ranged of hours but meanwhile they arrived at fractions of seconds (Savioja *et al.*, 1999). In parallel to the progress in room acoustics, complex models for simulating vibro-acoustic problems such as sound insulation of buildings and transfer path analysis and synthesis in automotive industry were developed (Lyon, 1994; Gerretsen, 1986; Vorländer, Thaden, 2000). Thus the variety of applications have broadened as not only music and the quality of concert halls, or other performance spaces, are to be evaluated but also the perception of sound and noise in general (Vorländer, 2008). Accordingly building acoustics, automotive acoustics and machinery noise became areas of application, too.

Other fields of rapid progress are a) Virtual Reality (VR), which is – from a technical point of view – the representation and simultaneous perception of reality and its physical attributes in an interactive computer-generated virtual environment, and b) Numerical Wave Acoustics, which still has rapidly growing importance due to improved mesh methods and computational efficiency. It is obvious that in architectural applications such as a virtual walk through a complex of buildings, auditory information helps to assign meaning to visual information and the overall impression.

In this contribution the real-time simulation and signal processing tools for acoustics are reviewed and discussed concerning the integration in VR systems. For the sake of brevity, the design of a virtual reality system is explained in the example of the aixCAVE system implemented at RWTH Aachen University. Of course, several other options for system design, filter methods, rendering techniques, and spatial audio approaches can be used. A complete overview of all those concepts, however, cannot be presented in this rather brief review paper.

## 2. Fundamentals of auralization

The process of auralization contains the separation into the processes of sound generation, sound propagation and sound reproduction into system blocks, and the corresponding representation of these blocks with tools from system theory (see Fig. 1, from (Vorländer *et al.*, 2014)). In the figure, the discrete source signal, s(n), is called a "dry" sound. The resulting signal after sound propagation in (between) rooms, g(n), contains the features of both the sound source and the sound propagation or transmission system. The performance of a sound propagation system is represented by the system's impulse response, h(n). The sound signal at the receiver position is then achieved by convolving the original dry sound signal with the impulse response (the impulse response is usually represented by a digital filter).

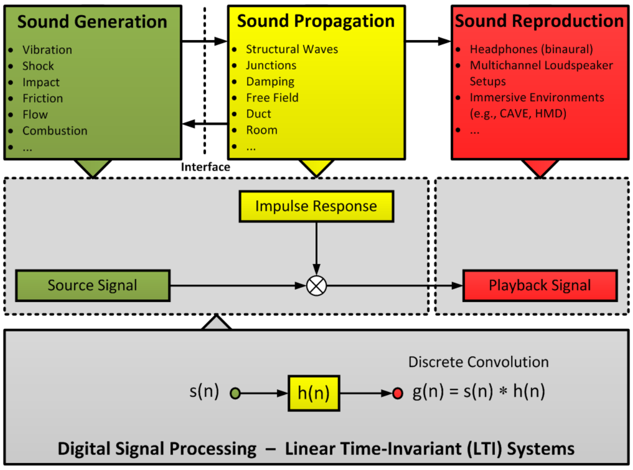


Fig. 1. Generation and propagation of sound and its representation in the physics domain (top) and in the domain of acoustic signal processing (bottom), from (Vorländer *et al.*, 2014).

## 3. Digital signal processing

At first, it is important to mention that after discrete Fourier transform (DFT) the convolution can also be efficiently performed in the frequency domain because this domain drastically increases the efficiency of mathematical operations from convolution integrals to a simple multiplication scheme (Gardner, 1995; Wefers, Vorländer, 2011), see Fig. 2.

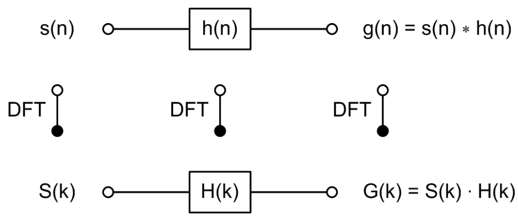


Fig. 2. Convolution of audio signals in time domain (top) or frequency domain (bottom).

### 3.1. Filter techniques

The process illustrated in Fig. 2 is filtering of an input audio signal, s(n). Virtual sounds can be created for a limited duration of the audio example. But usually the audio stream is quasi-continuous whereas the filter impulse response is finite in length. A standard class of algorithms used for such finite impulse response (FIR) filtering with long impulse responses and short input-to-output latencies are non-uniformly partitioned fast convolution methods. Here, a filter impulse response is split into several smaller sub filters of different sizes.

Small sub-filters are needed for a low latency, whereas long filter parts allow for more computational efficiency. Finding an optimal filter partition that minimizes the computational cost is not trivial. Optimization algorithms, however, are known. Usually the FFT transform sizes are chosen to be powers of two, which has a direct effect on the partitioning of filters. Recent studies reveal, that the use of FFT transform sizes which are not powers two has a strong potential to lower the computational costs of the convolution even more. Real-time low-latency convolution algorithms exist, which perform non-uniformly partitioned convolution with freely adaptable FFT sizes. Alongside, optimization techniques were developed that allow adjusting the FFT sizes in order to minimize the computational complexity for this new framework of non-uniform filter partitions (Wefers, Vorländer, 2012).

### 3.2. Binaural and spatial audio technology

Considering Fig. 2 again, it should be emphasized that the signal processing is usually not a simple monochannel filter processing. Virtual acoustics is impossible without 3D audio technology. The consequence is that h(n) and H(k) have an internal structure with multiple channels. The fundamentals of 3D audio – spatial hearing – start with two major head-related processes that are the physical diffraction of sound at the listener's head and torso at wave incidents on the listener from various directions. This part can be described by convolution filters as well, using the well-known dual-channel Head-Related Transfer Functions (HRTFs) in the frequency domain and Head-

Related Impulse Responses (HRIRs) in the time domain. HRTFs are different for the angles of sound incidence, and they are specific for each individual person (Blauert, 1996). Today, a large variety of HRTF databases of dummy heads exist (first standardized as the famous KEMAR IEC TR 959 (Burkhard, Sachs, 1975). And promising methods for the rapid determination of individual HRTFs are in progress (Katz, 2001; Pollow *et al.*, 2012).

Multi-channel loudspeaker arrays may serve as alternatives to binaural reproduction. The sound field can also be reproduced with 2D or approximately 3D spatial features in a certain area of listener a "sweet spot". Loudspeakers arranged around the sweet spot then serve as an amplitude- and phase-controlled array to reproduce a spatially distributed incident sound field (Wave Field Synthesis, WFS or higher-order Ambisonics, HOA).

## 4. Acoustic simulation techniques

Acoustic computer simulations are applied in various design processes already with great success. Sophisticated simulation algorithms help to gain information about room acoustics, building acoustics, vehicle acoustics, noise control already during the early design and planning. Mostly geometrical methods are used but in case a significant wave effect such as diffraction is present in the sound propagation paths, which is not masked by reflections or a diffuse reverberation, wave effects must be taken into account properly, at least in approximation (see below).

From a psycho-acoustical point of view, the impulse response of the propagation path (in the following referred to as Impulse Response (IR)) can be divided into three parts – the direct sound, early distinct reflections and the late (diffuse) reverberation. These parts require not the same attention or precision. Following the human's perception of sound, each part of the IR features individual requirements. For instance, small deviations of temporal and spectral information for the direct sound and distinct reflections affect the subjective sound source localization. In contrast, our hearing evaluates the late part of the IR (e.g. late reverberation) with a much lower temporal resolution, where only the overall intensity by diffraction and specular and scattered reflections in a certain time slot has to be energetically correct (Pelzer *et al.*, 2014; Schröder *et al.*, 2010).

### *4.1. Simulation of large spaces*

In large rooms, above the Schroeder frequency (Schröder, 1954), room modes are statistically overlapping and the methods of Geometrical Acoustics, GA, can be applied. Until today, all deterministic simulation methods based on GA utilize the physical model of Image Sources (ISs) (Allen, Berkley, 1979), where each IS represents a specific sequence of specular reflections on the room's faces. A definite low-frequency limit for applicability of IS cannot be given, as the errors made depend on many factors such as the room shape and the specific boundary conditions. In (Aretz *et al.*, 2014) it is shown that the errors are usually below 1 dB when the frequency limit is chosen at the Schroeder frequency in its original definition of "ten modes within the average half-width"[1]. The construction of IRs from image-like models is straightforward: ISs are represented by corresponding filtered Dirac delta functions, arranged accordingly to their delay and amplitude, and sampled with a high temporal resolution.

Several approaches exist for incorporating diffraction into deterministic and stochastic simulation methods, where the deterministic secondary source model by Svensson *et al.* (1999) and the uncertainty-based diffraction model by Stephenson (2010) have proven in various test scenarios to provide quite accurate results when integrated in methods of GA.

In order to overcome the limitations of GA generally, however, wave models must be used. This is true for small spaces in first place but also for other cases where the dominant propagation path contains wave effects which are not masked.

### *4.2. Simulation of small spaces*

For the acoustic rendering of rooms in flats, offices, vehicle cabins, or small rooms in general, wave-based models cover the relevant parts of the frequency response – a significant modal structure below the Schroeder frequency (Schröder, 1954). This applies for room smaller than 50 $m^2$ in case of significant components of the excitation signal spectrum are located below the Schroeder frequency.

For example, the finite-difference time-domain method (FDTD) (Botteldooren, 1995; Savioja, 2010), and a combination of the finite element method (FEM) and GA are applicable. With extensive measurements and modelling of the acoustic characteristics of the wall, floor and ceiling materials a very good agreement between measured and simulated results can be achieved (Pelzer *et al.*, 2011). However, further investigations regarding the boundary and source representation, and the phenomenon of sound diffraction are required to improve the simulation accuracy. The lack of data of boundary conditions is a common problem in all acoustic simulation methods based on wave models (Vorländer, 2013).

[1] In the original definition of the Schroeder-frequency from 1954 it is assumed that ten modes fall into an interval of one half-width, and accordingly a factor of 4000 is used in the original equation. Today, the Schroeder frequency is applied in Schroeder's modified form referring to a factor of 2000 and the assumption of "three modes within the average half-width".

### *4.3. Simulation of coupled rooms*

A virtual acoustic scene in a building consists of a finite number of rooms R1, ..., R$k$, which are interconnected by a finite number of openings, so-called "portals" P1, ..., P$l$ (Fig. 3). The topological structure of this problem is described by an undirected graph, the acoustic scene graph (ASG). Here, nodes present rooms and edges represent portals. Figure 4 depicts the according ASG for the example scene in Fig. 3, considering coupling via doors only.

The sound propagation paths are then identified in the ASG in the direction of the sound waves from a sound source to a listener. For this purpose the ASG is unrolled starting from the room node of the sound source. For each room that is reached on a constructed sound path the valid sound paths are constructed. Finally only those sound paths are auralized, which are audible to the user.

Directed acyclic graphs (DAGs) are well suited to describe the sound propagation in the scene. For each pair of sound source and listener the sound propagation through the scene using a transfer-path DAG (TP-DAG). The semantic of TP-DAGs differs from the ASGs: Here, nodes correspond to the scene objects (sources, listeners, portals), whereas the directed edges state the sound propagation between two scene objects. Figure 5 shows the according TP-DAG for the ringing phone and listener in Fig. 3.

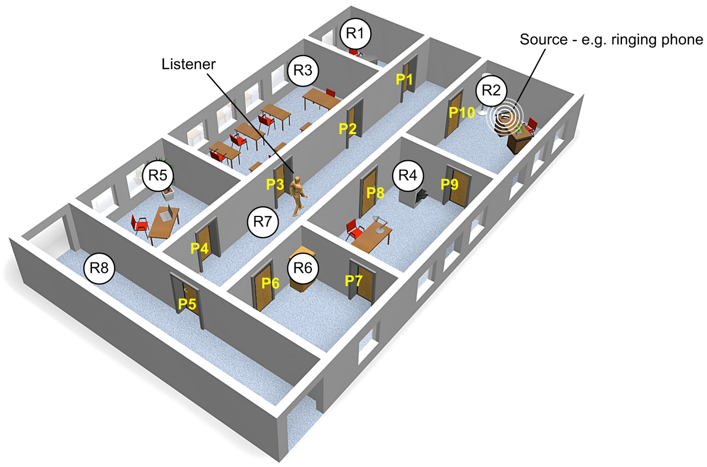


Fig. 3. An example scene with coupled rooms, Rl–R8, within an office building with coupling through portals P1–P9, after Wefers *et al.* (2009).

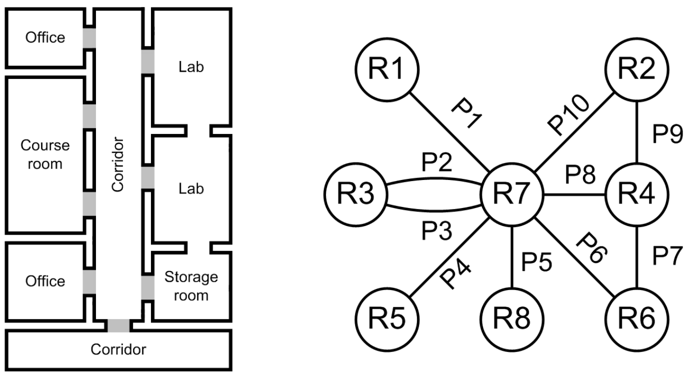


Fig. 4. The topological structure of the scene (acoustic volumes and their coupling through openings) in Fig. 3 described using an acoustic scene graph (ASG) (after Wefers *et al.* (2009)).

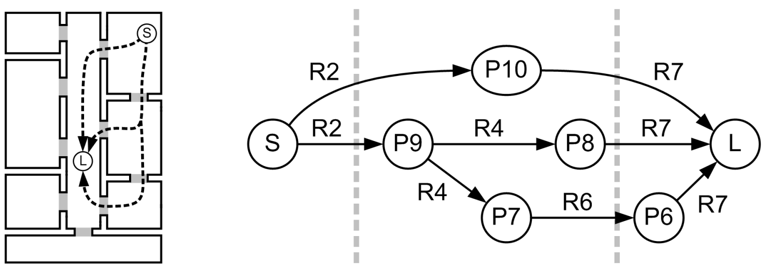


Fig. 5. Resulting transfer-path DAG (TP-DAG) for the sound source and listener in the example scene depicted in Fig. 3.

### *4.4. Simulation of sound transmission through partitions*

In a typical room-to-room situation the perceived signal of a listening event, for instance, music or speech is perceived "through the wall". This, way, the portals (Fig. 3) are not just openings between two rooms but they can represent any surface (door, wall) transmitting sound. The sound event has the main perceptive features of loudness and timbre, rather than spaciousness. Hence the focus should be set to a precise calculation of the sound energy, while the final 3D impression a finally plausible add-on of a "diffuse" reverberant field can be assumed.

A physical model that is available for the task of sound transmission calculation is the Statistical Energy Analysis, SEA. Here, the sound energy is considered by its flow through the partitions and sub-structures, the energy exchange between adjacent elements and the respective energy losses. Under steady-state conditions the energy balance requires just knowledge of the mean energy, the mean losses and the coupling mechanisms of the systems. The basic publications in building acoustics which were used for development of the European harmonized standard in buildings EN 12354 are papers by Gerretsen (1986). In other scenarios such as vehicles (cars, trucks, aircrafts, ships), a more general SEA approach (Lyon, 1994) can in principle be used in a very similar way.

In all of these cases, the relevant transfer paths transmitting most of the sound energy to the receiver, their filter functions, and their contribution to the total sound at the receiver must be superposed (added).

In Fig. 6, a sound source is located in room R4, while the receiver R is located in room R7. At first, all relevant propagation paths are determined and encoded in a graph structure (shown on the top left-hand side of the figure). In a subsequent step, this graph serves as a construction plan for the respective filter network (shown at the bottom of the figure) that represents the overall sound propagation from the source to the receiver.

In listening tests related to noise perception and speech intelligibility in buildings it was shown that state-of-the-art sound insulation auralization produces realistic sounds with respect to timbre and level (Vorländer, 2000).

### *4.5. Simulation of outdoor scenarios*

A plausible outdoor simulation can be considered as being similar to a large space simulation as introduced in Subsec. 4.1. It is usually based on a simplified free-field ray propagation model such as ISO 9613-2 and appropriate noise mapping software. It involves a landscape or city model including reflection and diffraction models, atmospheric conditions and appropriate source data. Typically all effects

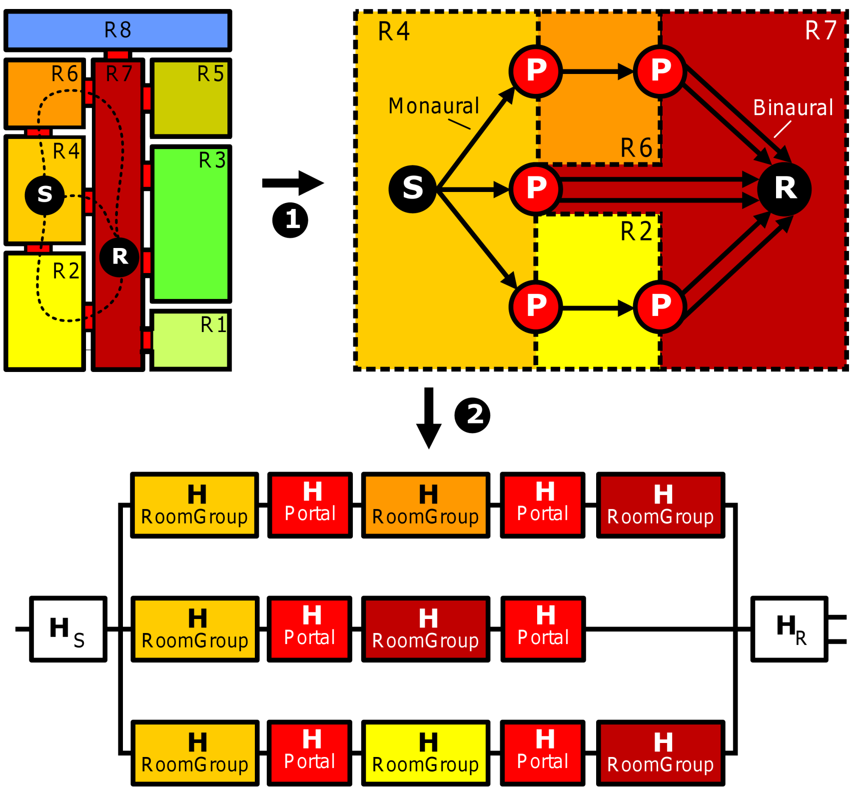


Fig. 6. Example of tracking sound propagation paths throughout an office floor and constructing a corresponding filter network (from (Schröder, 2011)).

can be considered energetically in attenuation factors in frequency bands. For given noise source positions of vehicles, aircrafts, etc. and a listener within the virtual scene, the intersected volume elements (voxels) on the direct line between both objects are determined within the meteorological model.

Similarly to the flanking path auralization, the relevant paths connecting the source and the listener, their filter functions, and their contribution to the total sound field must be superposed (added) with correct temporal lags.

In this case diffraction plays an important role because it cannot generally be expected that diffracted sound is masked by reverberation. For this reason wave models such as FDTD by Botteldooren (1995) are required as a reference for checking the validity of approximations of ray diffraction models.

## 5. Real-time auralization

With today's CPU speed and memory sizes the acoustic simulation can be processed within a fraction of a second and, thus, the method of auralization can be integrated into the technology of "Virtual Reality". As new challenge, the latency in the input-output auralization chain from tracking, audio hardware, signal convolution, and audio reproduction further reduce the maximum permissible computation time for both acoustics simulations and reproduction (rendering). Real-time processing is only possible with significant reductions of complexity. Here, physical and psychoacoustic evaluations help to find the balance between simplification and the precision. In the following, data management and convolution problems are briefly discussed with respect to real-time processing.

The convolution engine processes the monaural audio signals of the virtual sources with the filters applied for 3D audio reproduction (Vorländer *et al.*, 2014). For each listener, the signals of adjacent sound paths are summed up. As the sound propagation changes (e.g. movement or rotation of the listener), the room acoustic simulation is re-run and the filters, or parts of them, are exchanged. The non-uniform filter partitioning is chosen to support the required filter update rates for the application (Wefers, Vorländer, 2011).

Direct-sound and early reflection filters are updated with high rates (> 25–100 Hz). For the diffuse reverberation tail significantly lower rates (1–5 Hz) do mostly not diminish the perceived quality of the simulation, as the diffuse sound field changes slowly only with respect to a walking user for instance. A smooth changeover of filters without any audible artifacts is achieved by crossfading in between the convolution results of the current and the next filter.

Unlike time-domain filters, partitioned frequency-domain filters are subject to restrictions when it comes to assembling them into networks of filters (parallel and serial structures). When a large throughput (a multitude of virtual sound sources) is desired, the real-time filtering for each sound path should have the lowest possible computational requirements and consist of a low number of cascaded filters only. Using advanced rendering strategies, which make use of memorizing intermediate results, also complex sound propagation and transmission scenarios can be auralized and interactively altered in real-time (Vorländer *et al.*, 2014; Wefers *et al.*, 2009; Schröder, 2011; Chandak *et al.*, 2010). This, for instance, allows a user to perform a virtual walkthrough in a wide-range building environment, where he can open and close windows and doors.

In this overview paper, however, it is not possible to explain all details of the very complex task of real-time auralization. For details it is referred to literature. In the following it is illustrated in examples the benefits and limitations of virtual acoustics.

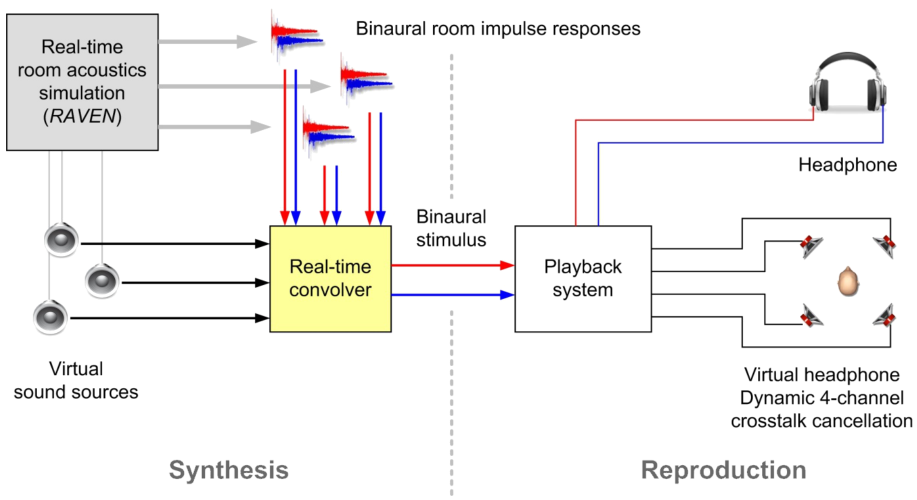


Fig. 7. Overview of Acoustic Virtual Reality system integrated in the aixCAVE (Vorländer *et al.*, 2014).

## 6. Applications

### *6.1. Concert hall acoustics*

Concert hall acoustics is one of the classical examples where auralizations for research, planning and teaching were first introduced. There are several software tools available which help to create optimized acoustic conditions interactively (an example is given in Fig. 8).

In the area of concert hall modelling two new aspects are in the focus interest, which are both related to input data of boundary conditions for the room surfaces. In numerical wave modelling the question of complex material impedances and of locally versus non-locally reacting surfaces is an interesting question. With a new wave based 3-D acoustical simulation algorithm non-locally reaction can be modelled (Opdam *et al.*, 2013). Results show that non-locally reacting boundaries do affect the acoustical space and not only close to the boundaries. How much this affects the auditory impression is subject to further work.

In geometrical acoustics models the crucial problem is surface input data of absorption as well. This was discussed in detail in a recent review paper (Vorländer, 2013). Furthermore there are doubts that wave effects can be neglected above the Schroeder frequency. The is related to pronounced wave effects which correspond not to the statistical features in the room transfer function but rather to the local wave effects, such as the seat dip effect, which depends in the spacing and the height of seating and the shoulders of sitting persons in the audience (Schultz, Watters, 1964).

Two large-scale projects of ongoing research in virtual room acoustics should be mentioned, "SEACEN" (Vorländer, 2013) and the study of the research group led by Lokki (2013). Both aim at a better understanding of the auditory perception in performance spaces. In the area of perception the focus is on binaural models and on audiovisual interaction, too. It is hoped to achieve an auditory frontend that predicts discriminability of different room acoustical simulations, and a cognitive model that predicts perceived room acoustical attributes (Blauert, Raake, 2014; Maempel, Jentsch, 2013).

### *6.2. Historic spaces*

This example is part of a research project which aims at the virtual restoration of the sound of the Old Hispanic Rite, auralizing the Mozarabic Chant in Pre-Romanesque churches of the Iberian Peninsula. The church considered is Santa María de Melque. The project was performed in collaboration with the Polytechnic University of Madrid, UPM. For this purpose, an acoustic virtual model was created according to archaeological documentation of the original building conditions. Anechoic recordings of several early

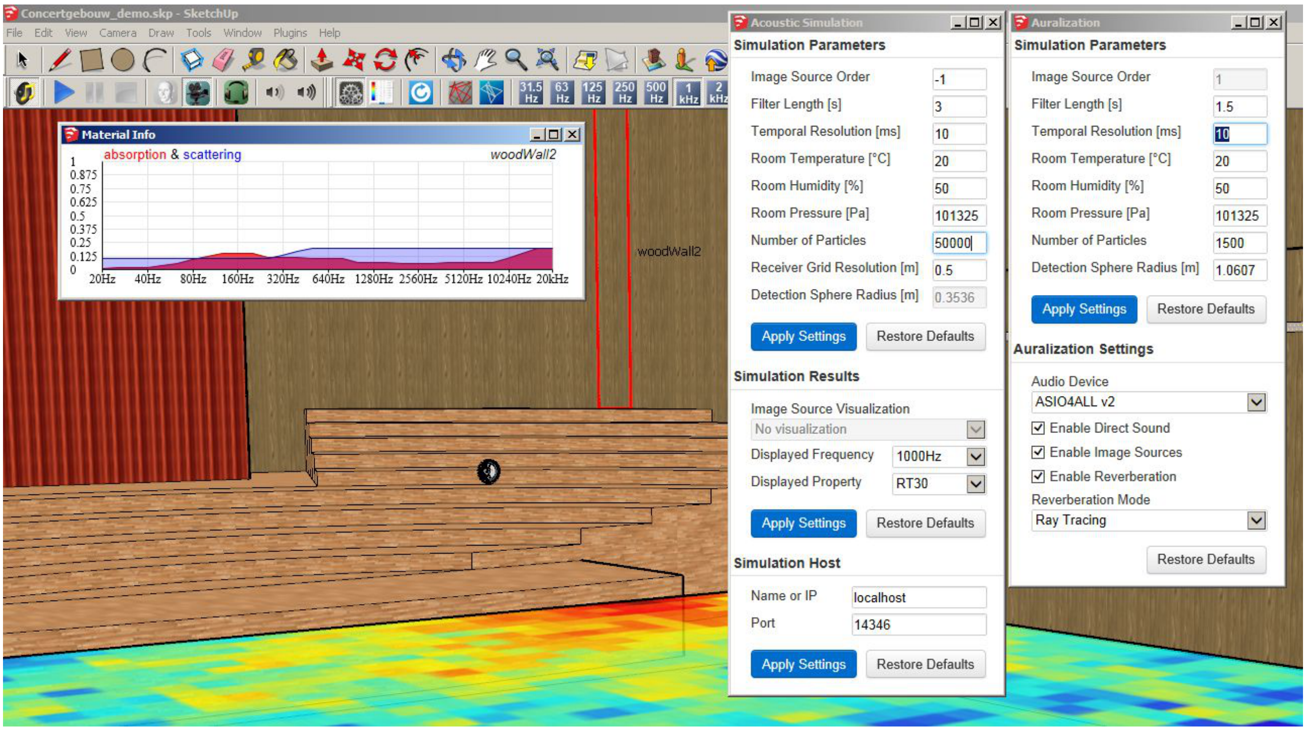


Fig. 8. Room acoustics simulation of a concert hall and calculation of room acoustical parameters using a plug-in for the CAD modeler SketchUp (Pelzer *et al.*, 2014) that triggers the real-time room acoustics simulation framework RAVEN (Schröder *et al.*, 2010).

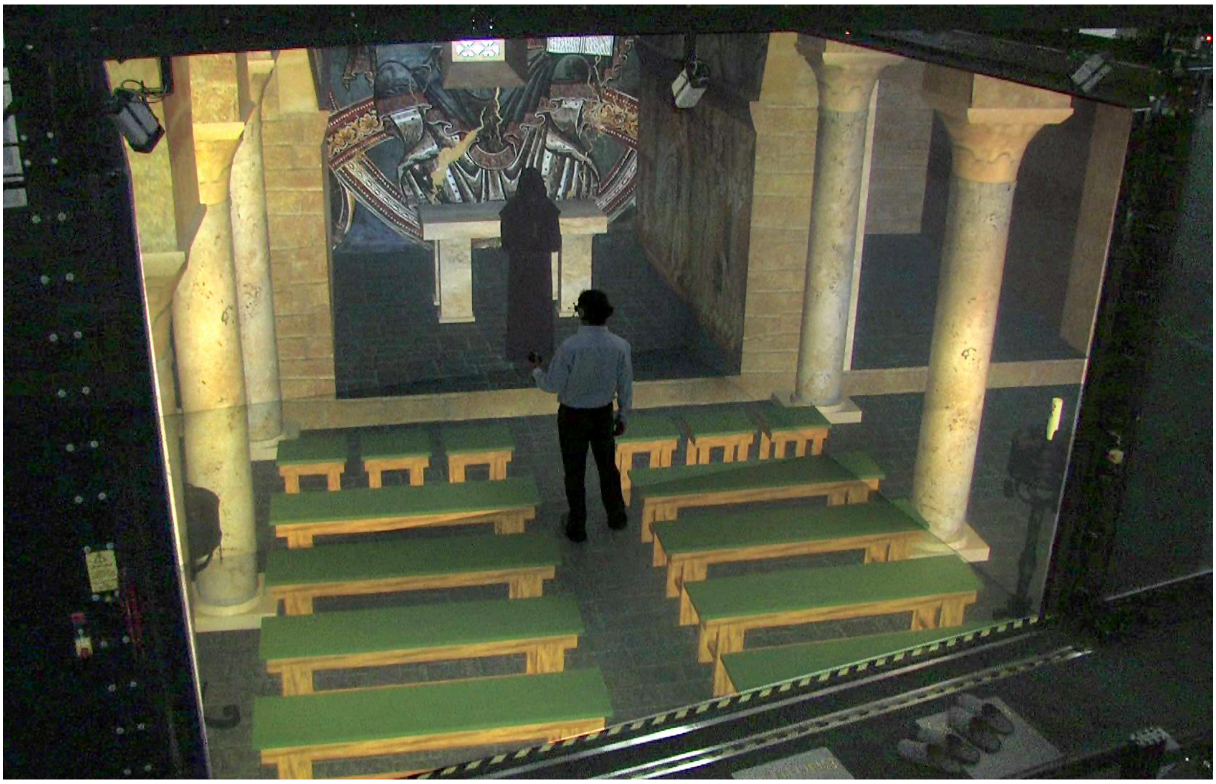

Fig. 9. Simulation of a historic church in the aixCAVE environment of RWTH Aachen University (five-sided 3D image projection and 3D audio rendering).

Mozarabic Chant musical pieces were recorded and auralized corresponding to old Hispanic liturgical rites in multiple settings (Pedrero *et al.*, 2012; 2013).

Similar auralizations were made in European projects such as ERATO and they are surely the basis for more applications of virtual acoustics in studies of cultural heritage.

### *6.3. Traffic planning*

A very interesting project with integration of auralization was an audio/video demo tour organized in the United Kingdom. It aimed at information of the public for acceptance of a high-speed train connection planned between London and Birmingham (ARUP acoustics, 2012). Auralizations were performed based on free-field recordings of the French high-speed train, TGV, and subsequent filtering and adaptation to the situation (landscape, speed, etc.) in the English landscape/soundscape in the particular cities and villages. This way the public could much better contribute and comment on the solution proposed.

In a similar way the problem of aircraft noise experienced by residents in the airport's neighborhoods is one of subjective annoyance and a presentation of noise intensity in decibels alone might not be sufficient to give a clear understanding of noise abatement measures being carried out or the effect of constructing a new runway of an airport. For this reason, an auralization of complete aircraft movements could be one such way of better capturing the annoyance due to noise caused by aircrafts.

The interdisciplinary project "Virtual Air Traffic System Simulation" of RWTH Aachen University has the aim of presenting the effect of complete aircraft movements via visualization and auralization of aircraft noise in 3-D Virtual Reality environments for the subjective assessment of aircraft noise. This work is an interdisciplinary collaboration of the Institute of Technical Acoustics with the Institute of Aerospace Systems, ILR, of RWTH Aachen University. The noise from turbofan engines is modeled for take-off and landing procedures with an auralization technique based on a tonal/noise synthesizer, which is adapted to models of standard noise emission spectra from aircraft engineering.

The bottleneck in this application is the limited availability of sufficiently accurate source signals. Noise prediction models for jet and fan engine, wing and landing wheel noise and the excitation of the aircraft body deliver noise levels in frequency bands but not generally data, which lead to time signals required for convolution. The post-processing steps for generating the phases of the rotational and fluid-dynamic components in detail are subject to research.

Fig. 10. Virtual reality representation of an aircraft approach to a regional airport.

### *6.4. Psychoacoustics and audiology*

The potential of visual and acoustic VR systems will also contribute to create real-world situations for advanced psychoacoustic experiments on localization, attention, and higher-level cognition and for psychoacoustic research and audiologic diagnostics. Up to now, such tests are performed in rather simple environments such as an approximated free or diffuse sound field. The corresponding sound propagation paths in terms of impulse responses or transfer functions, however, can also be precisely simulated for a human listener

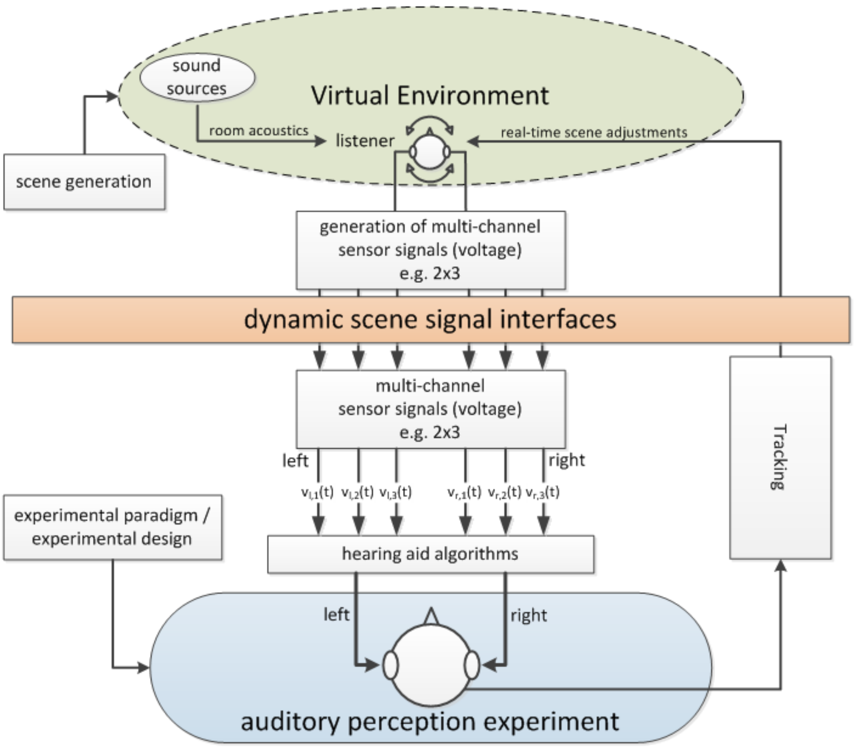


Fig. 11. Simulation of a virtual environment for auditory scenes reproduced by multi-channel hearing aids or cochlear implants.

with or without hearing aids or cochlea implants, and in this respect the binaural synthesis technique will be extended to an innovative audio reproduction system that allows an evaluation of different auditory scenes through either the audio-input of hearing aids and/or by simulation of the correct sound field at the ear of the hearing-impaired person using an expanded binaural technology. For hearing aids with more than two microphones this approach can be extended towards a multi-channel HRTF database and integrated into real-time dynamic room auralization software.

Then, the dynamic virtual test environment can be freely chosen as an outdoor rural or urban or indoor environment with multiple dynamic sources and a head-tracked listener. This approach is not only relevant for better diagnostic assessments of hearing impaired subjects but also for other patient groups suffering from marked deficits to concentrate and communicate in noisy environments (Fels, Vorländer, 2014). Current research focuses on the connection of hearing aids and cochlear implant technology to the interfaces of the Virtual Reality system.

## 7. Summary and conclusions

After decades of development in acoustics simulation a significant progress has been made indeed. This fact is related to the results of the activities in many groups working in the field of room acoustics and virtual reality systems. The developed simulation programs are successfully applied in numerous applications for room acoustics design. Virtual reality concepts in acoustics allow for new perceptual studies, investigations of well-being, annoyance and comfort in integrated design processes.

General user guidelines and user interfaces, however, are still uncertain, and they do not provide a sufficient basis for acoustic simulation software being used by non-acousticians. Software specifications differ particularly as regards the transition of the early-to-late response modelling and the treatment and combination of specular and diffuse reflections. As long as the user is not sure how many sound particles shall be chosen, how the resolution of the geometrical CAD model is to be defined, how the scattering coefficients are found and the transitions order between early and late parts is chosen, uncertain results may occur. However, it is not a task of the user to find out those differences. Instead it should be an automatically robust parameter setting in the applied simulation software.

Wave effects (diffraction, interferences) can play an important role at low/mid frequencies, and accordingly robust guidelines for merging wave models and geometrical models and in consequence automatic hybrid software must be developed (Savioja, 2014).

For auralization of vibro-acoustic problems, research and development is still required. This is related to the fact that several approximations are made in calculating the total transmission loss including multiple paths, the vibro-acoustic source characterization, and the auralization of structure-borne sources. These problems are not trivial at all. The biggest shortcoming in general is presently the lack of precise material data and databases integrated in professional design software in architecture and other disciplines such as noise control engineering.

Other new research focuses on the important question of plausibility and authenticity with reference to the auditory event in the real world. This involves the development of quality metrics similar to PEAQ (PEAQ, 1999) and extensions towards 3D audio, and psychoacoustic models of plausibility and corresponding psychometric tests vocabulary and test methods (Lindau, Weinzierl, 2012; Lindau *et al.*, 2014).

Looking at the current activities in research and development, the field of Virtual Acoustics seems to be still at the state of an emerging technology, even after two decades of work.

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