HOW SPHERICAL LOUDSPEAKERS CAME INTO AURALIZATION

M Vorländer Institute of Technical Acoustics, RWTH Aachen University, Germany

1 INTRODUCTION

Auralization combines source recording, sound propagation modeling and sound reproduction in a way that components of this chain can be changed, their auditory impression compared, and their optimum constellation be found. For dynamic scenes such as Virtual Reality environments, auralization requires an extremely quick update rate. This can only be achieved with either multi-processor or GPU computational power, or with low-cost computers, large memory spaces and pre-processing. When it comes to the analysis of the most used interaction movement of listeners in virtual environments, head rotation is far ahead of all translations. Those head movements, too, contribute significantly to source localization, even unconsciously. The order of magnitude of such significant head rotations is below a degree in angular resolution. The challenge for auralization systems is implementation of head rotations very efficiently.

Source movements may be of interest as well, if a more life performance is concerned. Thus also for musical instruments rotations must be considered.

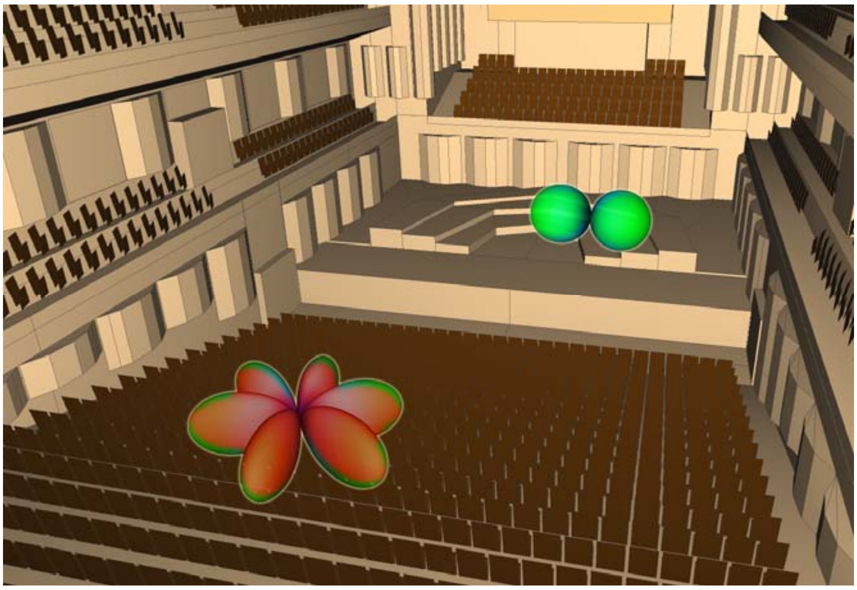


Figure 1. Transfer function representation between a dipole source and a higher-order receiver.

The approach depicted in figure 1 is actually the logical continuation of Michael Gerzon's invention of ambisonics and B-format recording on the one hand, with another spherical harmonic decomposition for the source. In classical recording, a monopole or any specific directional radiation is captured at the receiver side in a four channel B-format, or a higher number of channels in higher order ambisonics, HOA. In the representation proposed here, instead of monopole radiation a second spherical harmonic decomposition for the sound source is used. The signals obtained do

not belong to a specific source and a spherical receiver, but to any source to any receiver, both coupled by a matrix of transfer paths for all combinations of SH coefficients.
The question is how to obtain such complex data by using spherical microphone arrays and spherical loudspeaker arrays at the same time. If, however, this is successful, the acoustic transfer functions are easy to be changed for a) varying directivities and b) rotational cues in dynamic scenes.

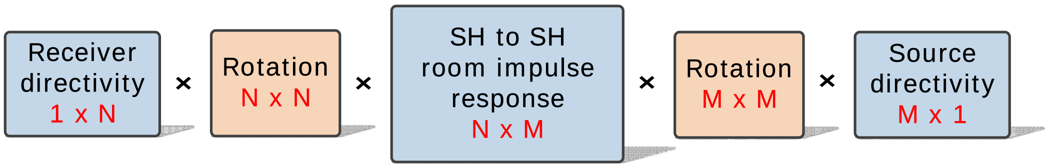


Figure 2. Acoustic transfer path between arbitrary sources and receivers.

In order to compute or measure the central matrix, it is necessary excite the room with a spherical array and the record with a spherical array. The question which array represents the real source and which one the real listener, is up for discussion. The arrangement is reciprocal, so that we have a free choice. The decision finally depends on the complexity of the directivity of the source and the receiver, and the best choice is made for the higher-order transducer is used for that part which requires more spatial resolution.

The basis for this technique is the simulation or the measurement of the SH-SH room impulse response. In this overview paper it is summarized which progress was recently made in designing spherical loudspeaker arrays for measurement of SH-SH room impulse responses. It is reported about a new approach of a segmented array which can be used for linear and time invariant systems in subsequent excitation, after all allowing the decomposition into spherical harmonics of up to 23rd order.

2 THEORETICAL BACKGROUND

For combining the angular components in both azimuth and elevation, a set of orthonormal base functions called spherical harmonics (SH) are defined. The spherical harmonic base functions can be defined as

$$Y_n^m(\theta,\phi) = \sqrt{\frac{(2n+1)}{4\pi}\frac{(n-m)!}{(n+m)!}} \cdot P_n^m(\cos\theta) \cdot e^{jm\phi} \qquad (1)$$

with n and m describing the order and degree of the spherical harmonics, respectively. P_n^m is the associated Legendre function whose definition can be found in mathematical textbooks [1].

Any kind of directional pattern is then decomposed into contributions of the base function, the SH components. They represent monopole, dipole, quadrupole etc. patterns which must be added in an appropriate way in order to obtain a best match with the specific directional pattern of interest. Similar to the correspondence between time signals and frequency spectra, there exists a transformation between the spatial (balloon) domain and the SH coefficient. Due to orthogonality, a weighted sum of SH coefficients is a complete and unique representation of the spatial pattern.

More detailed definitions of spherical harmonics for the decomposition of spherical functions can be found "Fourier Acoustics" by in Earl Williams who gives a concise overview of the methods with a focus on acoustics [2].

3 SPHERICAL LOUDSPEAKER ARRAYS

3.1 Previous work

Using loudspeakers for outgoing spherical waves, sound sources with adjustable radiation patterns can be designed. Hereby a set of speakers is mounted into a spherical chassis being able to create the radiation of sound sources with a specific directivity pattern. The achievable spatial resolution is limited by the number of loudspeakers used, similar to what we find with limited sampling rates and corresponding aliasing effects. Due to the physical size of the single transducers and the requirement for different membrane sizes for a full spectral coverage, the resolution is usually severely limited with these speakers, see also [3,4,5].

3.2 System development

In Figure 3, the recently developed measurement equipment at ITA is depicted. It is used for the measurement and auralization of room impulse responses with arbitrary and in post-processing adjustable directivity pattern of the sound source. With its multi-band excitation the audible frequency range can be covered up to a spherical harmonic order of 23, cf. [6].

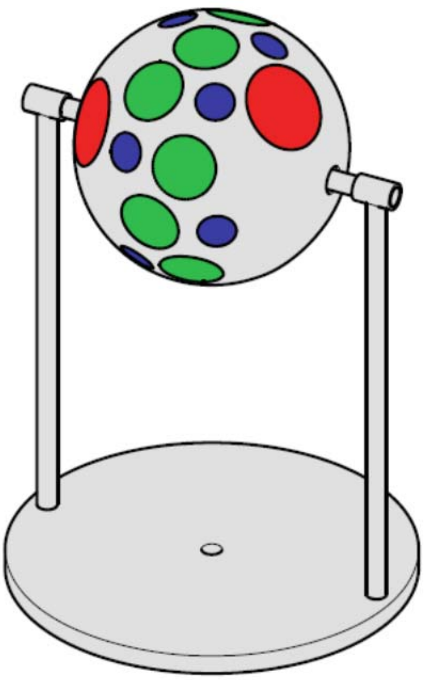


Figure 3. Measurement device with 28 transducers of three sizes (after [6] and [7]).

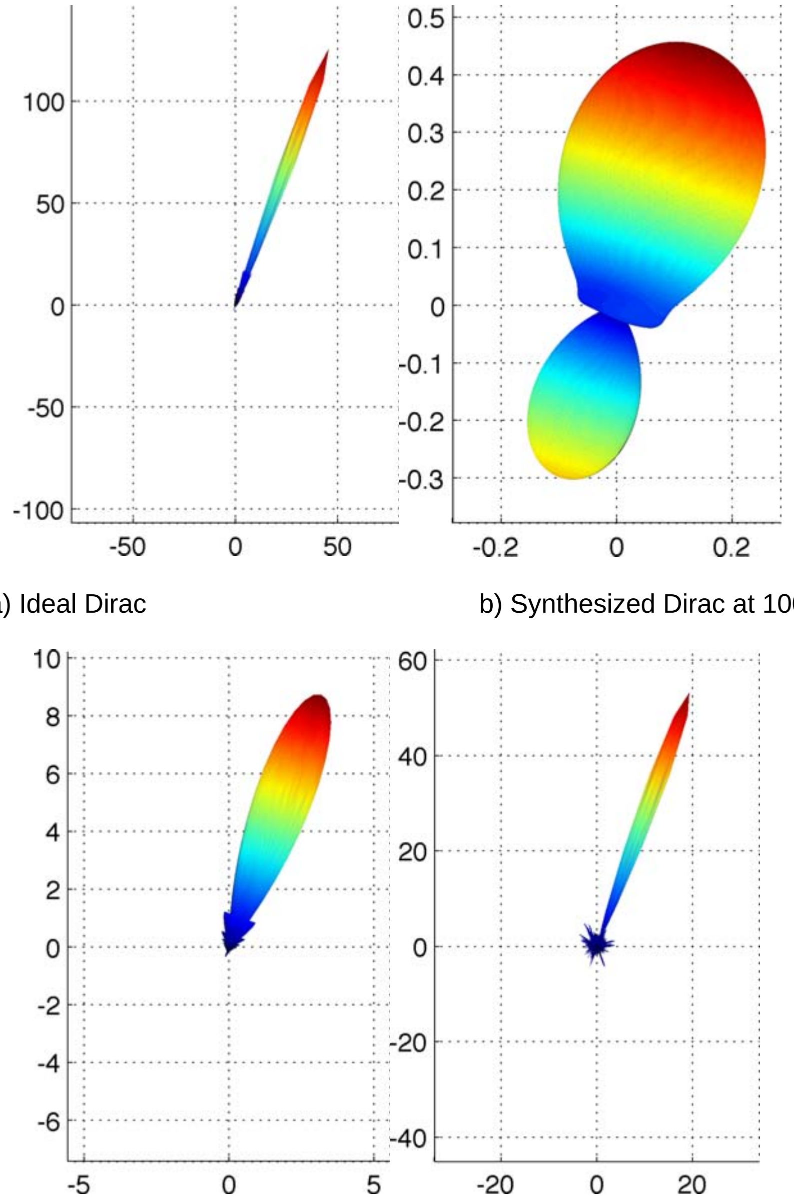
In the process of source development a simulation model based on a set of analytical descriptions of spherical sound sources was applied. This model allows the analysis of the radiation processes of all individual drivers involved. From this it was achieved an optimum between the transducer size distribution for the various frequency ranges and their distribution on the sphere. Then a SH-based composition was made with a position optimization on the sphere depending on the transducer radius and the space necessary for mounting and separation of the magnets, etc.

Instead of fully covering the sphere with transducers the concept is to use a free rotation in order to cover the whole sphere in an automatic sequential measurement procedure. This design opens the theoretical ability for a synthesis of spherical harmonic orders up to n_{max} = 23 at about 8 kHz.

In a master project [6] a first prototype of the new measurement system has been built to evaluate its performance in real measurements. The transducers have been chosen according to the aperture concept.

3.3 Applications

In first applications, this source should serve as a Dirac pointer source as recently presented by Pollow [7] or as a HRTF source for reciprocal binaural measurements, as recently presented by Klein [8]. From both studies some sample figures are given as examples (figures 4 and 5). Both studies are based on fast sequential measurements with interleaved sweeps suggested by Majdak [9] and improved by Dietrich [10].



a) Ideal Dirac

b) Synthesized Dirac at 100 Hz

c) Synthesized Dirac at 1 kHz

d) Synthesized Dirac at 10 kHz

Figure 4. Ideal spherical Dirac function and generated Dirac beams from 672 transducer positions calculated by Tikhonov regularized inversion for different frequencies (after Pollow et al. [7]).

When applied to room acoustic measurements, distinct early reflections can be evaluated and auralized. This allows innovative studies on the perception of reflections regarding their spatial and spectral contributions. Evaluation of scattering surfaces will be of interest as well, and possibly new approaches to an in-situ measurement of wall absorption and scattering.

In another study it is tried to synthesize HRTF and to apply the source as a binaural receiver in reciprocal measurements. Room impulse responses are reciprocal between source and receiver. Accordingly the question of best choice for the best-obtainable spatial resolution must be discussed. Usually ISO 3382 measurements are done with omnidirectional sources and monopole, dipole or binaural receivers. In any case, the challenge to listener directivity is rather high, whereas the omnidirectionality of dodecahedron loudspeakers is far from being perfect.

With the source presented and a ½ inch microphone, a quasi-perfect constellation can be found in the reciprocal approach: A perfect omnidirectional transducer on the stage (equivalent to the "source") and an adaptive SH source (equivalent to a monopole, dipole, or HRTF "receiver") in the audience.

Figure 5. Prototype of the spherical loudspeaker array (after Klein et al. [6]).

Thus there is the task to post-process the SH response in order to obtain the desired equivalent listener directivity. It should be noted that this procedure requires just one measurement session in the room, while all data are obtained in post processing, including the possibility to construct binaural room impulse responses for individual listeners.

4 CONCLUSIONS AND FURTHER WORK

A spherical loudspeaker array is introduced which allows a spatial resolution of up to 23rd SH order. Under non-ideal conditions due to time variances, measurements are possible using just one rotational degree of freedom and an SH order of up to 11. With this approach it is possible to measure SH to SH room impulse responses for quick implementation of head rotations during real-time playback for auralization of measured rooms. Furthermore, auralization of individual reflections including their manipulation or comparison with regard to changes in absorption or scattering is possible, and finally post-processing into individual HRTF seems to be a very promising technique.

All applications, however, must be tested in future in much more detail. The biggest problem of the technique is the necessity of sequential measurement, during which the room under test must be time invariant. Any speed-up of the multi-channel excitation is therefore significant. The limits of this technique are still under investigation.

5 REFERENCES

1. M. Abramowitz. Handbook of mathematical functions with formulas, graphs, and mathematical tables, Science, vol. I, 1964.
2. E. G. Williams. Fourier Acoustics: Sound Radiation and Nearfield Acoustical Holography. 1999.
3. O. Warusfel, P. Derogis, R. Causse. Radiation Synthesis with Digitally Controlled Loudspeakers, Preprints-Audio Engineering Society, 1998
4. F. Zotter. Analysis and Synthesis of Sound-Radiation with Spherical Arrays. pp. 1-192, 2009.
5. M. Pollow, G. K. Behler. Variable Directivity for Platonic Sound Sources Based on Spherical Harmonics Optimization. Acta Acustica united with Acustica, vol. 95, no. 6, pp. 1082–1092, 2009.
6. J. Klein. Optimization of a Method for the Synthesis of Transfer Functions of Variable Sound Source Directivities for Acoustical Measurements, Diploma thesis, RWTH Aachen, March 2012.
7. M. Pollow, J. Klein, P. Dietrich, G. Behler, M. Vorländer. Optimized spherical sound source for room reflection analysis. Proc. IWAENC 2012, Aachen, September 2012.
8. J. Klein, M. Pollow, J. Fels, M. Vorländer. Reciprocal binaural room impulse response measurements. J. Acoust. Soc. Am., Vol. 132, No. 3, Pt. 2, September 2012, p. 1912.
9. P. Majdak, P. Balazs, B. Laback. Multiple exponential sweep method for fast measurement of headrelated transfer functions. J. Audio Eng. Soc. 55, pp. 623–637, July-August 2007
10. P. Dietrich, B. Masiero, M. Pollow, B. Krechel, M. Vorländer. Time Efficient Measurement Method for Individual HRTFs. Proc. DAGA 2012 Darmstadt, Germany.