A Spatial Audio Impulse Response Compilation Captured at the WDR Broadcast Studios

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Abstract

Spatial audio techniques are in the focus of interest for recording and production purposes. Within the scope of a research project at the Cologne University of Applied Sciences in cooperation with the WDR (Westdeutscher Rundfunk) a large set of room impulse responses (RIRs) has been captured in different control rooms and auditoria of the WDR radiobroadcast studios. The RIRs have been recorded using a high-resolution spherical scanning microphone array system, a rotating Neumann KU100 artificial head (Norbert) and classical stereophonic microphone setups like MS, ORTF, AB and XY. Furthermore spherical panorama photos and basic CAD data of the corresponding venues have been captured for visualization and modeling purposes. The measurement datasets can e.g. be used to create virtual acoustic environments. The recorded control rooms and auditoria can be auralized employing binaural synthesis, wave field synthesis or any common reproduction technique. Furthermore typical acoustic properties can be derived from the classical measurements and can be compared to the corresponding array measurements. Whereas the array datasets are expected to resolve more detailed spatial information and to give a deeper insight to room acoustics than it is possible employing current state-of-the-art methods.

1. Introduction

Spatial audio recording and reproduction is a popular topic for research and increasingly gains the attention of media production companies. Additionally, some of the new methods offer highly promising approaches for the analysis and prediction of room acoustics [1]-[9]. While in media production[1] the channel based and psychoacoustically motivated surround techniques have already been established for a long time, different completely new approaches for the recording, editing and reproduction are under investigation [10]-[14]. Some important key topics are e.g. object-based or field based descriptions of audio scenes, new methods to enable a high resolution spatial capturing of sound fields or the synthesis of sound fields by means of complex reproduction techniques that are based on physical models instead of a solely reliance on psychoacoustic phenomena. Even the binaural recording and reproduction currently seem to undergo a certain renaissance. This is reasonable as the reproduction of media via headphones has gained considerable importance due to the broad prevalence of mp3-players and smartphones. A broad range of new approaches and applications has been already investigated and even market-ready solutions involving new spatial audio techniques are available in the meantime. But there is still substantial need for further research and development in the full production chain involving recording techniques, editing and production processes, spatial audio codecs and the appropriate reproduction methods. Regarding this, a large set of room impulse responses

[1] especially in the cinematic sector

(RIRs) has been captured in different control rooms and studios of the WDR[1] radiobroadcast facility. The recordings have been conducted in the scope of the research project MARA[2] at Cologne University of Applied Sciences, in cooperation with the WDR, the Technical University of Berlin, the Deutsche Telekom Laboratories (Berlin) and the IOSONO GmbH (Erfurt). The respective rooms are introduced in section 2. The RIRs have been recorded using different measurement systems and recording techniques. These are discussed in section 3. Furthermore, spherical panorama photos and basic CAD data of the corresponding venues have been captured for visualization and modeling purposes, which are presented in section 3.4 and section 3.5. The presented collection of impulse responses is mainly intended for research purposes, i.e. to develop and evaluate new spatial audio technologies for recording and reproduction as well as for the analysis of room acoustics. Besides this, some of the material, e.g. the binaural room impulse responses, can directly be involved in current production and media creation processes. In order to fulfill the valuable aim of freely accessible and reproducible science, the complete data collection is published under a Creative Commons license and available to the scientific community. More detailed license information and the download link are presented in section 6.

2. Rooms

The compilation covers four different rooms of the WDR radio broadcast facility[3] that is located in the plain city center of Cologne, Germany. On the one hand, two classical control rooms for audio mixing and production and on the other hand two larger broadcast studios used for performance and recording of music have been captured. The involved rooms and their respective basic geometric key data are listed in **Table** 1.

Room	Denotation	Floor area	Volume	Height
Control Room 1	CR1	37,57 m^2	92,79 m^3	2,47 m
Control Room 7	CR7	59,97 m^2	167,91 m^3	2,90 m
Small Broadcast Studio	SBS	201,09 m^2	1246,77 m^3	6,20 m
Large Broadcast Studio	LBS	578,09 m^2	6461,56 m^3	11,16 m

***Table 1** Basic description of the involved rooms*

2.1. Control Room 1 (CR1)

Control room 1 (CR1) is part of the production and broadcast complex 1 (PK 1)[4] and is mainly used for the production and recording of classical music. It is located adjacent to the large broadcast studio[5] to enable the recording and mixing of live concerts or to produce studio recordings of large orchestras. A *Lawo mc²82* digital console is positioned at the center of the room. Close behind the sound engineer's position a slightly elevated table for the Tonmeister is provided. Attached to CR1 there are an ancillary control room for cutting

[1] WDR - Westdeutscher Rundfunk Köln
[2] MARA - **M**icrophone **A**rrays for **R**oom Acoustics and **A**uralization; A research project funded by the Federal Ministry of Education and Research in Germany
[3] German name: "Funkhaus"
[4] German name: "Produktionskomplex 1" (PK1)
[5] German name: "Klaus-Von-Bismarck-Saal"

and editing and a small rest room. The acoustical properties of the CR1 are well balanced and very appreciated by both sound engineers and Tonmeisters of the WDR.

Figure 1 *Control Room 1 (CR1) [Source: Hagmayer]*

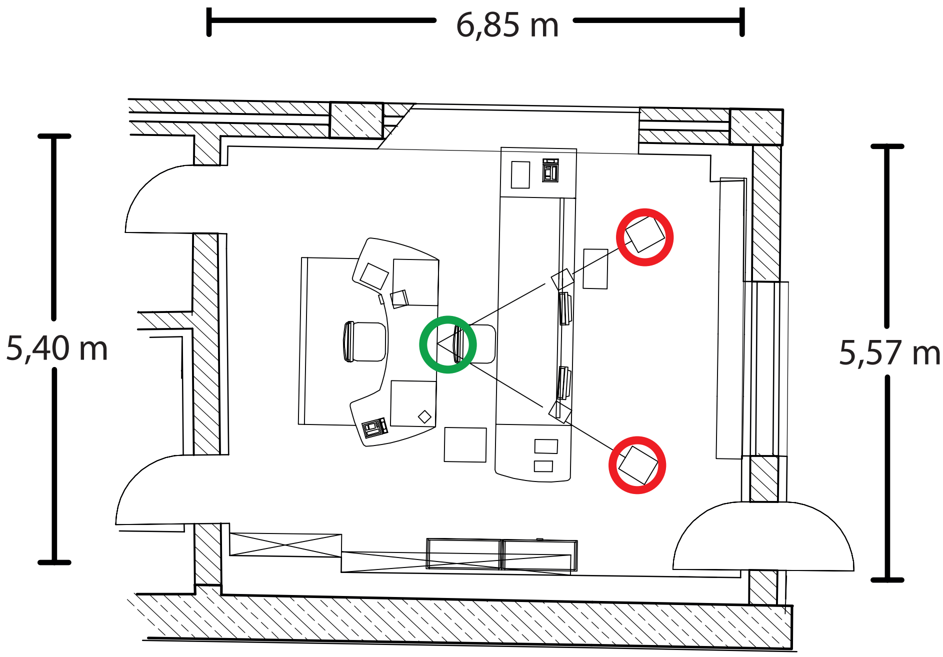

Figure 2 *Sketch of the CR1 (green circle = listener position (receiver) / red circle = sound sources)*

2.2. Control Room 7 (CR7)

Figure 3 *Control Room 7 (CR7) [Source: WDR/Maurer]*

Control room 7 (CR7) is the main control room of the production and broadcast complex 7 (PK 7)[1] and is used for radio drama production. Directly attached to CR7 there are an ancillary control room for cutting and editing as well as a large recording room. A *Lawo mc[2] 66* digital mixing console is located at the center of the room. Next to and behind the sound engineer's position, different tables for audio technicians or producers are located. In contrast to CR1, CR7 involves several height differences and constructional irregularities. The latter can be observed in **Figure 4**.

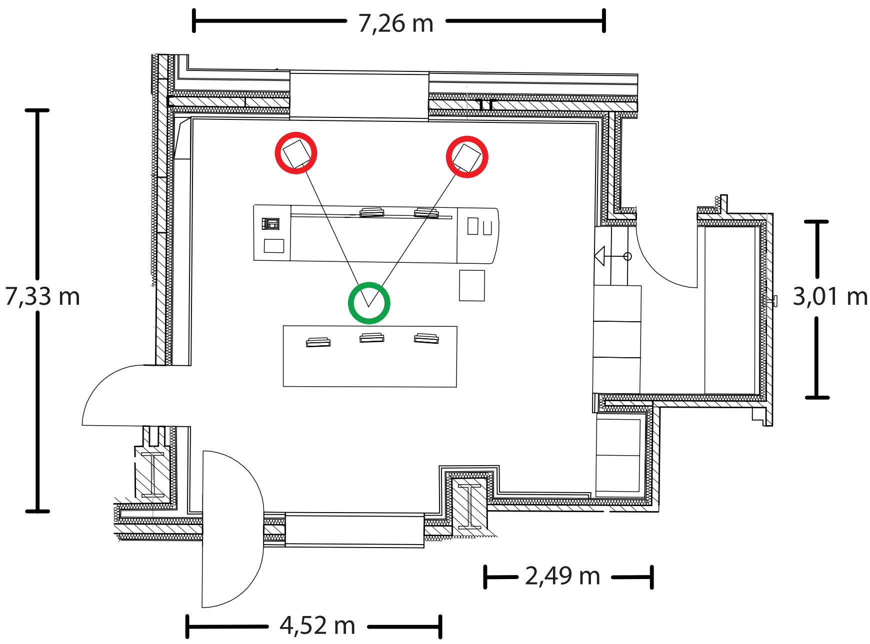

Figure 4 *Sketch of the CR7 (green circle = listener position (receiver) / red circle = sound sources)*

[1] German name: "Produktionskomplex 7" (PK7)

2.3. Small Broadcast Studio (SBS)

Figure 5 *Small Broadcast Studio (SBS)*

The small broadcast studio (SBS) is a concert room for chamber music and small ensembles. The number of seats can be varied or the seats can be removed completely, as they are not firmly integrated. During the presented recordings, the room was equipped with around 160 seats. The room has a short reverberation time and remarkable early reflections. The architectural layout is slightly asymmetrical and the stage edge is curved and slanted as depicted in **Figure 6**.

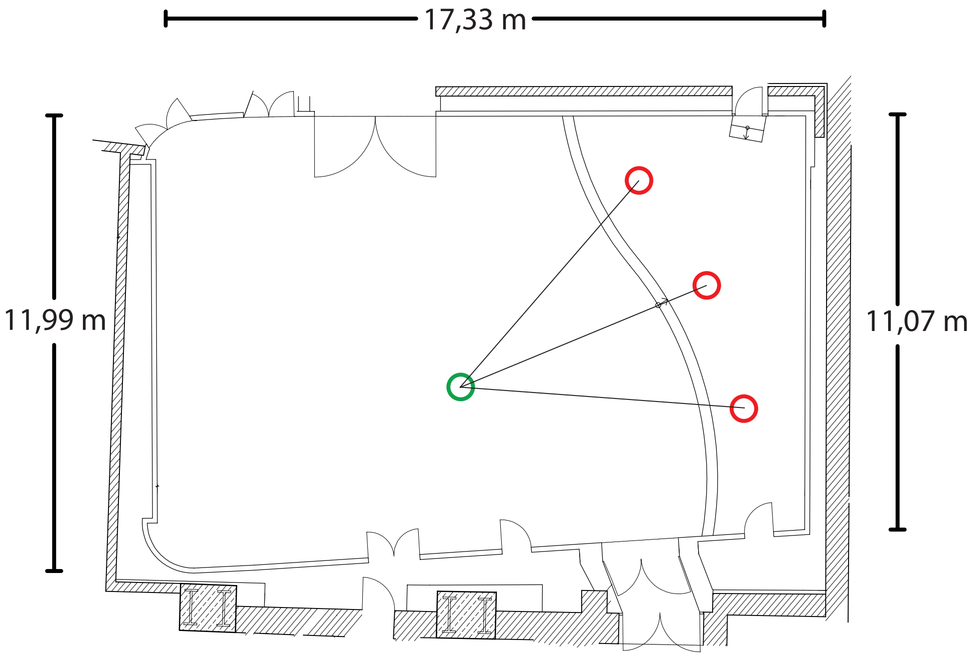

Figure 6 *Sketch of the SBS (green circle = listener position (receiver) / red circle = sound sources)*

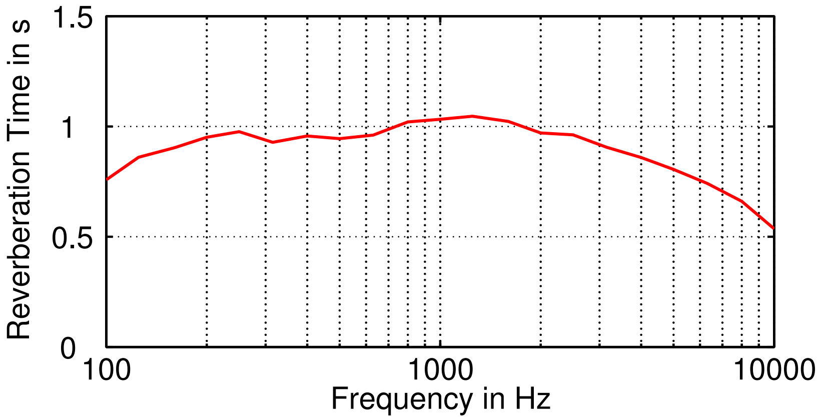

***Figure** 7 Average Reverberation Time (RT60) SBS*

2.4.Large Broadcast Studio (LBS)

***Figure 8** Large Broadcast Studio (LBS)*

The large broadcast studio (LBS), named "Klaus-Von-Bismarck-Saal"[1], is a classical concert hall for the performance and recording of orchestral music. It offers 637 seats that are distributed over a main listening area and a balcony. The venue includes a huge stage of approximately 210 m² for large orchestras and choirs and provides an electro-pneumatic *Klais* pipe organ with 62 registers installed in 1950 and restored in 1990. The architectural layout is completely symmetrically as can be observed in the sketch, **Figure 9**.

[1] Klaus von Bismarck *1912-†1997, was the director of the WDR from 1961-1976 and president of the ARD (Consortium of public-law broadcasting institutions of the Federal Republic of Germany) from 1963 to 1964.

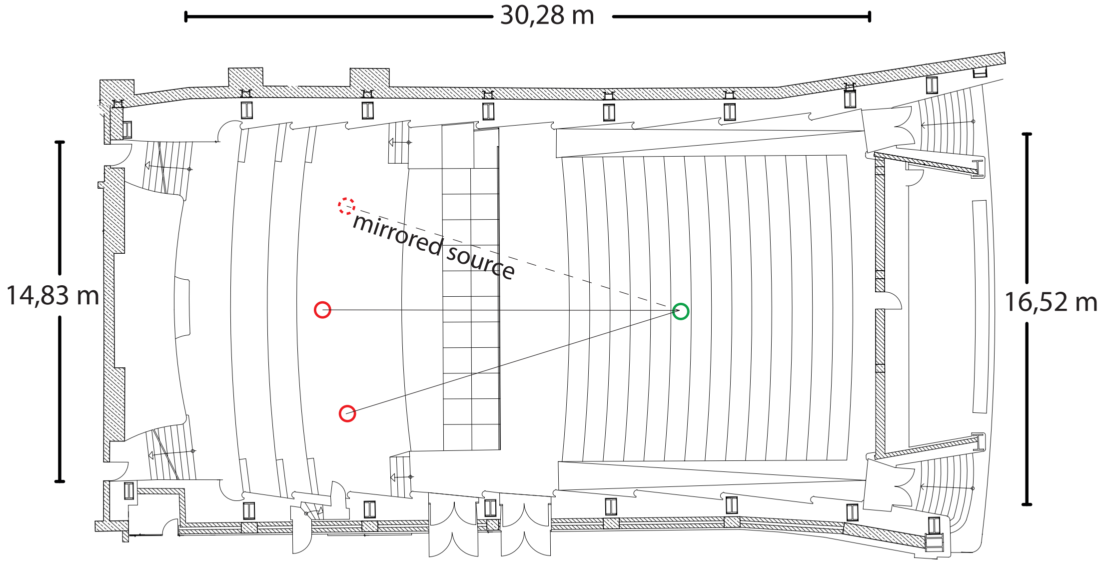

Figure 9 *Sketch of the LBS (green circle = listener position (receiver) / red circle = sound sources)*

The WDR maintains different proprietary professional orchestras (WDR Symphony Orchestra, WDR Broadcast Orchestra, WDR Big Band and the WDR Broadcast Choir). The WDR orchestras frequently rehearse, perform and record in the large broadcast studio, involving the attached control room 1 (CR1) that was presented in section 2.1.

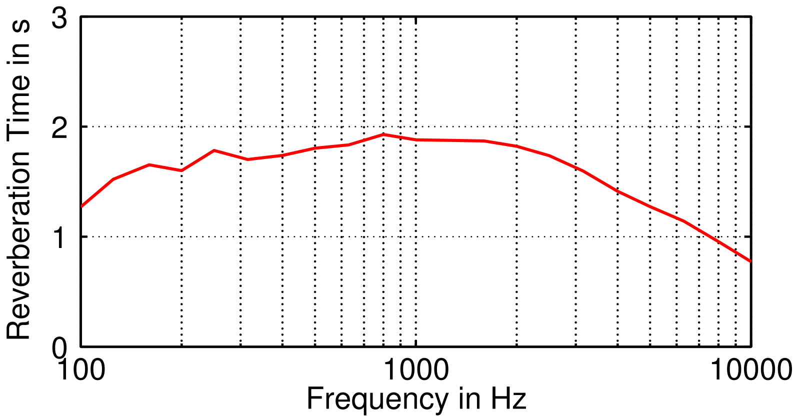

Figure 10 *Average Reverberation Time (RT60) LBS*

3. Measurement Systems

In order to obtain a versatile 3D audio database, different measurement systems and configurations were employed. The collection involves impulse responses that were captured using classical stereophonic microphone setups, a rotated dummy head and a scanning microphone array in different configurations. All systems and setups were placed at the same location (listener position) and are referred to a common pivot point. The positioning of the different systems was done very accurately, in order to enable reasonable comparisons between different configurations.

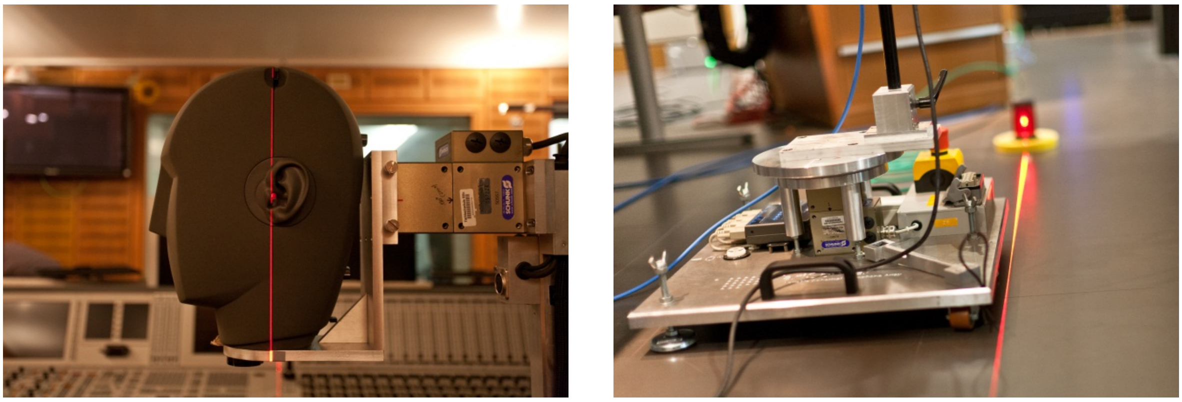

Figure 11 *Examples for a very accurately conducted laser based calibration.*
(left picture: Neumann KU100 in CR1; right picture: VariSphear ground plane in CR7)

In the control rooms, the measurement systems were placed in a typical audio engineer's position, right in front of the mixing consoles and very well-adjusted to be in the center of the left and right main monitor speakers. In the broadcast studios, a comfortable listening position within the audience area was chosen. The selection of the positions was based on recommendations of the local WDR engineers combined with an extensive listening to reference sound examples. The final positions are indicated as a green circle in the sketches depicted in **Figure 2**, **Figure 4**, **Figure 6** and **Figure 9**. The heights of the respective pivot points are listed in **Table 2**.

Room	**Height of the virtual listening position**
CR1	127 cm
CR7	127 cm
SBS	127 cm
LBS	123 cm

Table 2 *Heights of the virtual pivot points*

For the acquisition of the room impulse responses and the motion control, a proprietary software tool was employed, that is based on MATLAB and C routines and has been entirely developed and implemented at the Cologne University of Applied Sciences. The software includes an impulse response measurement core that is based on the approach proposed in [15]. For all measurements, colored sine sweeps (+20dB lowshelf @ 100Hz) with a FFT degree NFFT=19 at a sampling rate of FS=48 kHz were employed for excitation. The high temporal extension of approximately 11 seconds plus an additional gap time of the single excitation signals lead to a considerable temporal accumulation and thus a high temporal expense concerning the overall measurement sessions. However, the excitation time was intentionally chosen high to generally deliver high signal to noise ratios on the one hand and to be comparatively robust against extraneous noise contributions in the building on the other hand. The measurement software environment used for the sequentially captured array and dummy head recordings automatically compensates for the latency in the audio chain and involves a quality control and error detection stage to validate the captured impulse responses. Nevertheless, every single captured impulse response has been manually revised to minimize the risk of unrecoverable results due to measurement errors.

A RME Fireface UCX audio interface including the built-in microphone preamplifiers and a Lenovo R500 Laptop computer were employed to run and control the measurements. The full measurement system was remotely controllable and accessible via the Internet.

Furthermore, a web camera enabled the visual surveillance of the robotic measurement system during the absence of a technician. The complete measurement session took approximately 14 days (day and night) including all setups, adjustments and recordings. The final compilation involves more than 35,000 impulse responses.

3.1.VariSphear

VariSphear is a spherical scanning array measurement system that was developed und built at the Cologne University of Applied Sciences in 2009 [16]. The *VariSphear* system is a fully automated robotic system that sequentially acquires room impulse responses employing a single microphone only. During a sound field capture session, the microphone is moved by two motors (azimuth and elevation) to different positions on a real or virtual sphere. The system allows for a free configuration of the sphere radius and the quadrature, i.e. the distribution and positioning of the spatial sampling nodes. Furthermore a rigid sphere body extension with a diameter of 17.5 cm is available.

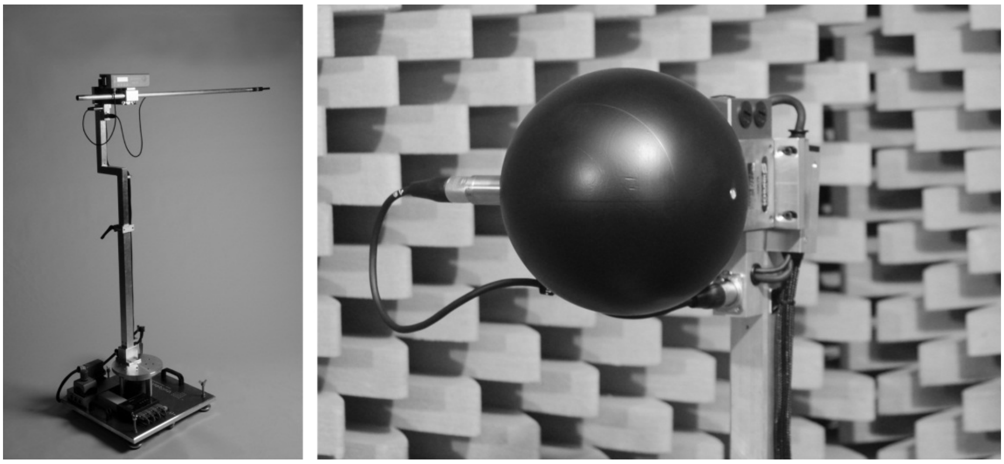

Figure 12 *VariSphear scanning array system in an open sphere configuration (left picture) and with the rigid sphere extension and the Earthworks M30 microphone (right picture).*

For the compilation, different Lebedev quadratures of each 50, 86, 110 and 1202 nodes using the rigid sphere extension were captured. The 1202 nodes grid on the diameter of 17.5 cm is stable up to around 18 kHz by theory. But this configuration was simulated in advance and turned out to be sufficiently stable up to more than 20 kHz. For the rigid sphere configuration an Earthworks M30 omnidirectional measurement microphone was employed. Additionally, an open sphere configuration at a diameter of 50 cm was involved, using a Microtech Gefell M900 large diaphragm cardioid microphone. The grid density (Lebedev) was varied during the session (CR1: 110 nodes, CR7: 146 nodes, SBS/LBS: 194 nodes).

3.2. Neumann KU100

A *Neumann KU100* dummy head[1] was used to capture binaural room impulse responses (BRIRs). The head was mounted on the *VariSphear* system for rotation. It was rotated in one degree steps in the horizontal plane. For each source, two different full horizontal datasets were captured. For the first set, the head was mounted on top of a simple and thin microphone stand. The respective BRIR sets can directly be applied e.g. for head-tracked binaural synthesis. For the second set, the head was mounted on a more complex and thicker

[1] Norbert.

rotation mount that basically allows for a full sphere head rotation, even if only the horizontal plane was involved. The intention here was to establish identical physical conditions to the corresponding full sphere HRTF/HRIR (head related transfer function/impulse response) sets captured inside an anechoic chamber[1].

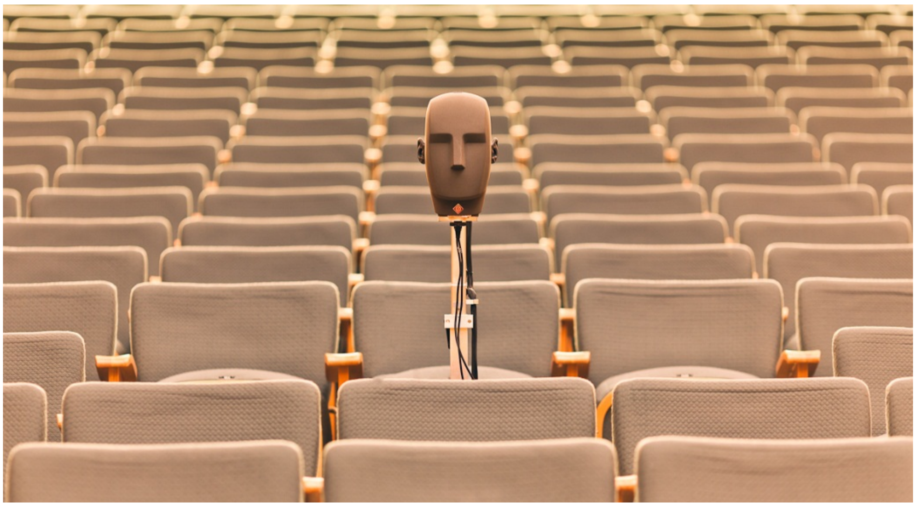

Figure 13 *KU100 mounted on the VariSphear system (ROTM) in the large broadcast studio*

3.2.1. Headphone Compensation

In a binaural playback system, the complete transducer chain consisting of dummy head and headphones must be compensated in order to enable a natural reproduction; whereas the headphones typically tend to have a considerably stronger impact than the other components due to their physical construction and the resulting deviations in the frequency response. Even headphones models explicitly advertising free field equalization [17] do usually not meet the requirements for a highly natural and color-free reproduction that is needed for an immersive binaural listening experience. Hence the frequency response of the headphones, respectively the full transducer chain, must be explicitly compensated by application of appropriate compensation filters [18]. In order to make this highly specific compensation filters accessible to a broad range of different users, around 20 different common headphone models were analyzed to create specifically adapted compensation filters. The respective models are listed in **Table 3**. To create the filters, each headphone was put on the KU100 head and replaced 12 times in order to capture stable and representative transfer functions. The corresponding compensation filters were computed based on a semi-automatic log-spline inversion algorithm that was developed at the Cologne University of Applied Sciences. The resulting compensation filters are available either as linear phase or minimum phase FIR filters. The proprietary *miro* data type (refer to section 5) enables a direct inline processing of the headphone compensation filters.

[1] The respective HRTF/HRIR sets will also be freely available to public and will be presented at the AIA-DAGA Conference on Acoustics 2013 in Meran, Italy.

Manufacturer	Model	Recommended[1]
AKG	K702	****
AKG	K701	*****
AKG	K601	*****
AKG	K271 Studio	**
AKG	K271 MKII	**
AKG	K240 MKII	****
AKG	K240 DF	****
AKG	K141 MKII	**
Audio Technica	ATH M50	**
Beyerdynamic	DT990PRO	****
Beyerdynamic	DT880PRO	*****
Beyerdynamic	DT770PRO	**
Beyerdynamic	DT250	**
Presonus	HD7	****
Sennheiser	HD650	*****
Sennheiser	HD600	*****
Sennheiser	HD565	****
Sennheiser	HD560 ovation II	****
Sennheiser	HD480	****
Sennheiser	HD430	***
Shure	SRH940	**

Table 3 *Included Headphone compensation filters*

3.3. Classical Stereophonic Microphone Setups

In addition to the different microphone array and binaural configurations, several classical stereophonic microphone configurations (Small AB, Large AB, XY, M/S and ORTF) were involved for the acquisition of stereophonic room impulse responses. The pivot point is in the center of the microphone setup. In the large broadcast studio, some of the fix-mounted microphone setups were captured additionally.

Configuration	Microphone Types
Small AB (17 cm)	Schoeps MK2, Neumann KM83
Large AB (34 cm)	Schoeps MK2, Neumann KM83
XY	Neumann SM69, Neumann U89
M/S	Neumann SM69, Neumann U89
ORTF	Schoeps MK4

Table 4 *Stereophonic microphone configurations*

[1] **Carefully:** This rating is informal. This recommendation only refers to the presented dataset and to the provided compensation filters and shall not give any general recommendation or depreciation of the listed headphones. It is based on the optical revision of the measured frequency responses and the quality of the achievable compensation filters, as well as on a very short subjective listening impression. In general, open headphones with native diffuse field equalization deliver the best results for the purpose of binaural reproduction.

Figure 14 *Example for a stereophonic configuration (left picture: Small AB with Schoeps MK2, right picture: ORTF with Schoeps MK4)*

3.4. Spherical Panorama Photos

High-resolution spherical panorama photos were captured in every location using a *Canon EOS 5D* digital single-lens reflex (DSLR) camera (*Canon EF 50mm f/1.2 L USM* lens) mounted on the *VariSphear* system. Special software that is part of the *GIXEL* spherical panorama viewer[1] calculates the required picture grid based on the respective focal distance and takes control over the *VariSphear* system as well as over the camera exposure settings and release control section. Thus the entire panorama shot runs fully automated. For CR7 a picture set of 70 images was involved, all other rooms were captured with a set of 98 pictures to obtain an increased overlapping area.

Figure 15 *Canon EOS 5D camera mounted on the VariSphear system*

The *GIXEL* viewer is based on a geometrical stitching algorithm [19] that merges the single pictures to a seamless panorama. The viewer allows the user to do full spherical pan and tilt operations and to zoom in and out. A very special feature of the *GIXEL* viewer is the interface to import datasets that are produced by sound field analysis processing based on

[1] The *GIXEL* (**G**iga p**IXEL**) spherical panorama viewer has been developed and implemented within the scope of a master student's project at the Cologne University of Applied Sciences in 2012.

the microphone array datasets. These techniques can be used e.g. to visualize single reflections in a concert hall or control room. For more information on the combination of sound field analysis methods and spherical panorama photography, the reader is referred to [9].

3.5. CAD model

The *VariSphear* system (refer to section 3.1) allows for a semi-automatic acquisition of a basic CAD model using an integrated laser sensor. The CAD models involve listener and source positions, the relevant measures as lengths, surfaces and the room volume and dedicated interior furnishings. The models are stored in a vector-based format and can be visualized in MATLAB using a simple viewer that is provided for free in addition to the database.

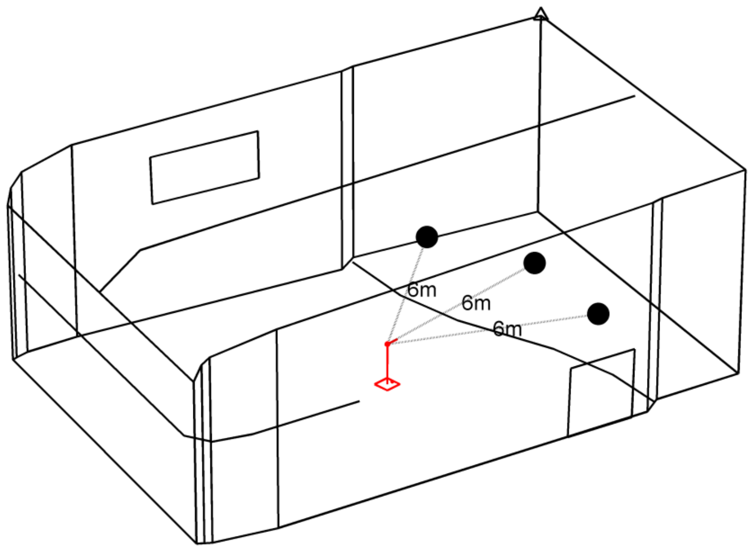

Figure 16 *Exemplary CAD model of the small broadcast studio. Additionally the measures like lengths, surfaces or the room volume could be included, but for the ease of exposition the presented model is kept simple. The three bubbles on stage demark the sources and the red structure in the center depicts the array.*

4. Sound Sources

Depending on the location and purpose, different speaker systems and setups were used to excite the room and to capture the respective impulse responses. In the control rooms, the main monitor speakers (Stereo, left and right) were used. CR1 is equipped with a pair of *Genelec 8260a* 3-way active systems and CR7 provides some *Bowers & Wilkens 803D* 3-way passive speakers driven through external *Linn Chakra* power amplifiers. The respective speaker systems were directly connected to the audio interface of the measurement systems in order to avoid unnecessary routing and AD/DA conversions. The speakers left and right were captured in separate runs. The center (pivot point) of the measurement system was adjusted very accurately by employing speaker measurement software in order to have a consistent phase relation and to avoid comb filter effects, in case that the two signals are combined. The use of the integrated main monitor systems for excitation combined with a typical a sound engineer's position for the measurement systems e.g. allows for the creation of a headphone-based virtual control room by employing a dynamic binaural render like e.g. the Sound Scape Renderer [20].

Figure 17 *The used main monitor systems: Genelec 8260A in CR1 (left picture) and B&W 803D in CR7 (right picture)*

Obviously for the broadcast studios a different concept concerning the sources had to be applied. In order to emulate virtual sources, two different speaker types were involved and placed on stage. On the one hand an omnidirectional source and on the other hand a directional source with a nominal pattern of 75° x 50° (at high frequencies) were involved. The positions of the sources are indicated by red circles within the sketches of the broadcast studios, compare **Figure 6** and **Figure 9**. The omnidirectional source was a special high power wideband dodecahedron called *Sonic Ball* that was designed and built at Cologne University of Applied Sciences in 2011 [21]. The directional source was a full PA stack involving an *AD Systems Stium*[1] Mid/High unit combined with 3 *AD Systems Flex 15* subwoofers controlled by an *XTA* speaker controller and driven through *Camco Vortex* amplifiers. This rig delivered a considerably solid signal and enabled to achieve comfortable signal to noise distances. The controller presets were previously optimized in the anechoic chamber and were later in situ only slightly optimized and adapted to the rooms. In contrast to the studio monitors in CR1 and CR7, both of the high power sources used in SBS and LBS had a roll-off at the very high frequencies due to their physical construction, which cannot be compensated by the system controlling.

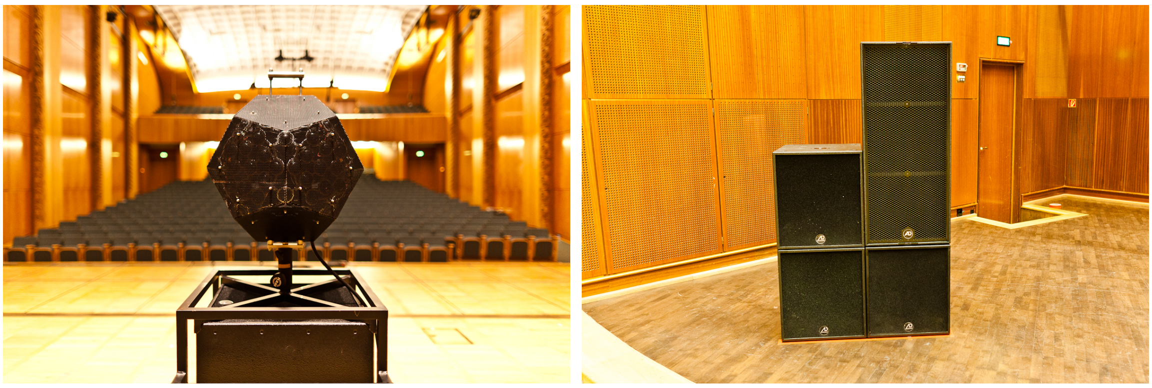

Figure 18 *Omnidirectional source: The high power wideband dodecahedron "Sonic Ball" (left picture) and the horn loaded PA rig from AD-Systems (right picture)*

[1] AD-Systems Stium: Horn loaded 2x12" + 1.4" Mid/High Unit

5. Data Format

The presented compilation comprises several thousands of impulse responses. The subsequently produced HRTF/HRIR datasets[1] will involve another several thousands of impulse responses. The appropriate storage, organization and representation of such complex data combined with an urgently required method set to enable the comfortable access and basic treatment of the involved signals is a sophisticated problem. A proprietary and versatile data type was developed for that purpose in order to fulfill the latter claims in a best possible way. The new data type is a very simple object based MATLAB data type called *miro*[2]*; miro* integrates three stages: It combines the storage of raw impulse response, the access to around 50 meta information properties and a method set for the access to the impulse response as well as for the treatment and conversion of the signals. Every rotated binaural or array measurement session produces a separate object instance of the class *miro*. A closer description of the data type can be downloaded. The on-board method set involves several useful functions. At the moment of a concrete impulse response request, the raw data internally runs through a basic pseudo real time signal processing block that enables versatile operations. Some method examples are:

- Finding the closest available impulse response to a given angle
- Defining an arbitrary (reduced) number of return taps with adapted windowing
- Setting headphone compensation filters to the output signals
- Dropping impulse response wave files
- Quick Pre-listening of the impulse response for a passed stimulus
- Re-sampling of the output signals
- Showing grid and coordinate system information
- Direct export of HRIR or BRIR sets to the *Sound Scape Renderer* [15]
- Direct export to the *SOFiA sound field analysis toolbox* [22] to enable a seamless connection to spherical acoustics and spherical harmonics processing.

6. Access und License

6.1. Access

The dataset can be downloaded at: **http://www.audiogroup.web.fh-koeln.de**

6.2. License Information

The complete compilation is freely available under a Creative Commons (CC BY-SA 3.0)[3] license. The user is allowed to copy, distribute and transmit the work or to adapt the dataset to his needs. Even the commercial use of the data is permitted. Additional and more concrete information can be found at: *http://creativecommons.org/licenses/by-sa/3.0/legalcode* .

[1] Presented at the AIA-DAGA Conference on Acoustics 2013 in Meran, Italy.
[2] miro: **m**easured **i**mpulse **r**esponse **o**bject.
[3] Attribution-ShareAlike 3.0 Unported

7. Acknowledgements

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