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## Measurements of musical instruments with surrounding spherical arrays

G. K. Behler, M. Pollow and M. Vorländer

RWTH Aachen University, Institute of Technical Acoustics, Templergraben 55, 52056 Aachen,  
Germany  
[gkb@akustik.rwth-aachen.de](mailto:gkb@akustik.rwth-aachen.de)

The directivities of natural sound sources such as musical instruments are often neglected in auralization, both when working with measured or simulated acoustical environments. This is due to the complex nature of both the radiation of musical instruments and the post-processing involved in this task. However, as the directivity patterns constitute an audible part of the tonal characteristic of a musical instrument in a room, it is advisable to take their directivities into account.

To conduct the measurements, a large surrounding spherical microphone array was constructed that allows to fully encompass the musician in an anechoic chamber. Hereby great care has to be taken in the design process of the recording device in order to obtain a broad-band omnidirectional sensitivity of the used microphones. The acquired multi-channel audio data can be then used to analyze the directivities of the recorded instrument.

## 1 Introduction

In auralization of acoustic scenery consisting of source, transfer path and receiver, the directivity patterns of the sound sources are often neglected and thus implicitly assumed to be of omnidirectional type. The international standard for room acoustical measurements ISO 3382-1 even demands omnidirectional sources for the use in such measurements in order to make different measurements comparable.

New studies, however, show that the directivity of sound source matters more than commonly expected [1]. Even in the late part of the impulse responses the influence of the radiation pattern can still be noticed, even if the sound field is already highly diffuse at that time [2]. Musical instruments owe a part of their character to their tonal color, which varies for different directions [3]. Including these specific spectral differences for the sound radiation in different directions, the auralization is expected to be enhanced in terms of natural perception. Any measured or simulated room impulse responses for omnidirectional sound sources are lacking these varying directional dependent tonal color and cannot be modified afterwards to include the described effect.

In order to take the directivities of musical instruments into account, the radiation patterns need to be measured and prepared for the use in room acoustical measurement and simulations. For the analysis of these instrument specific properties, a large surrounding spherical microphone array was constructed to record the sound radiation of a source in many directions simultaneously. This paper deals with questions regarding hardware setup, full calibration of the measurement chain and issues as how to obtain clean and correct data of the emitted sound. These data can be used later on for studies to analyze data such as the emitted sound power of instruments or the radiated directivity patterns.

## 2 Previous work

The first approach to collect data for a directivity database goes back to the 1970s with Jürgen Meyer publishing the measured radiation of various instruments in averaged octave bands [4]. More recently Otondo and Rindel measured the directivity with a set of microphones distributed around the musician, using 13 microphones distributed on the median plane and on the horizontal plane [5]. In 2010 Pätynen and Lokki [6] used a slightly denser distribution of 22 microphones and recorded pieces of music.

A spherical microphone array with 64 channels was constructed in Graz, Austria, designed for optimal spherical harmonic processing [7].

## 3 Surrounding spherical microphone array

In order to capture the radiation of naturally excited musical instruments, all directions have to be measured simultaneously, due to the lack of repeatability. This motivates the construction of a lightweight and transportable spherical microphone array. The chosen geometry of the array is a truncated icosahedron, distributing 32 microphones regularly on the surface of a sphere with a diameter of 4.20 m. In Figure 1 a sketch of the geometry is depicted.

The array consists of 90 flexible fiber glass sticks that can be connected to hold the microphones on a spherical surface. With some attached strings the whole array forms a light but very stable construction. The complete setup can be placed in an anechoic chamber in order to avoid any reflections from the walls and the ground floor, as depicted in Figure 2. If the height of the anechoic chamber is not sufficient for the full array, a reduced version can be used by omitting the highest and/or the lowest microphone of the array. Each of the two microphones save about 40 cm in the required height.

In the center of the array an adjustable chair is placed that can be used to place the musician approximately into the geometrical center. The stand can be extended in height to quickly to set the height of the musician in order to move them as close as possible to the geometric center of the array. However, for large instruments as the contrabass the placement is too low; this has to be accounted for in post-processing. [12]

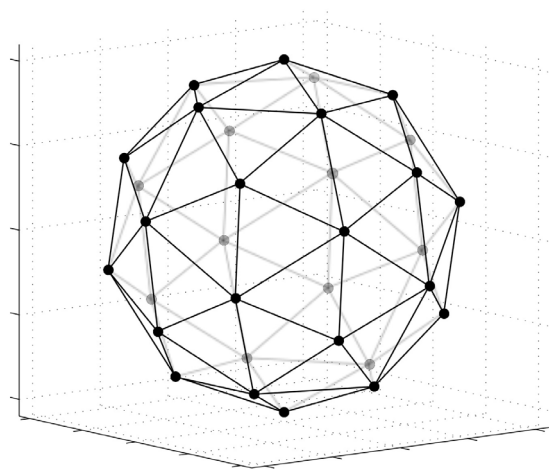


Figure 1: Sketch of the geometry of the spherical microphone array with a diameter of 4.20 m

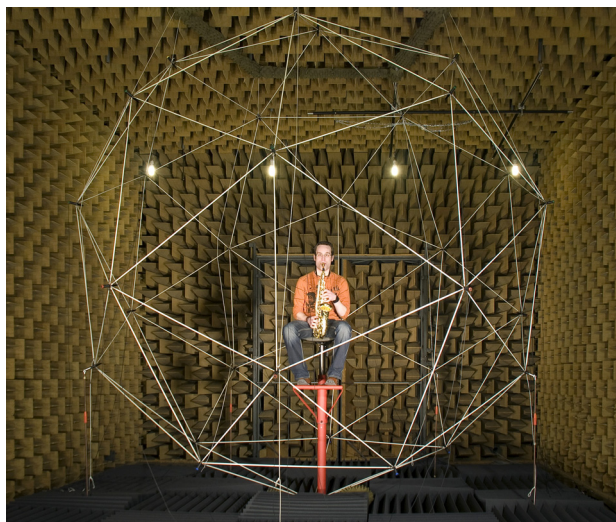


Figure 2: Mounted surrounding spherical microphone array with 32 microphones

## 4 Calibration of the microphones

The correct calibration of the microphones is crucial for precise measurements. This includes both the sensitivities of the capsules as well as the mounting situation, e.g. the housing of the microphones. The captured sound is supposed to consist purely from direct sound radiation without any reflections or diffraction of objects in the vicinity that do not belong to the musician or the musical instrument. An acoustical transparent behavior of the array is thus desirable.

### 4.1 Housing of the microphones

The housing of the microphones is very important as any additional sound path arriving at the microphone (e.g. due to reflections on the housing) can cause highly frequency dependent comb-filter effects. As the array is highly symmetric several small reflections can sum up to arrive at the same time instance and cause significant interference, so great care has to be taken to avoid any reflection on the mechanical structure.



Figure 3: Close-up of the microphone array without additional absorbers, electret capsule at the narrow end of the conical shape, preamplifier in the rear end

Even the thin structure as shown in Figure 3 is sufficient to cause on-axis comb filter effects starting from frequencies as low as 2 kHz. Sensitivity measurements of the

microphones revealed that this is caused by the reflexion at the fiberglass sticks attached to the microphone housing. Whereas any regular frequency deviation from a flat frequency spectrum can easily be compensated (or can even be ignored for directivity measurements as it occurs on all microphones), this symmetry yields a sensitivity which is highly dependent on the angle of incidence. This was further verified using a boundary element method simulation of the housing as depicted in Figure 4, confirming the strong influence of the direction of sound incidence. This effect cannot be compensated for later on, an aligned sound source can thus help to minimize such deviations between the effective microphone sensitivities encountered for a given direction of incoming sound. [8]

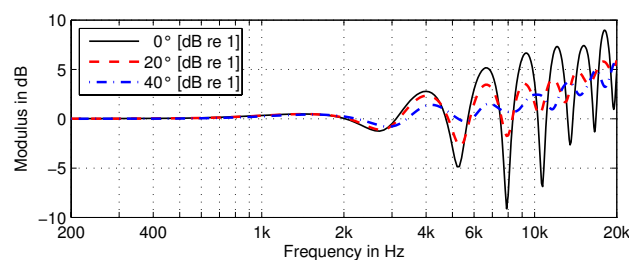


Figure 4: Boundary-element simulation to quantify the influence of the microphone housing without attachment for different angles of incidence, cf. [8]

In order to improve the array in terms of constant sensitivity over the angle of sound incidence several attachments for the microphones were tested: a solid drop shaped material (as used in a similar project [9]) and several types of acoustical foam in different shapes. Finally, a dense acoustic foam in sphere-like shape was chosen due to its smooth frequency response over a range of sensible angles of incidence.

### 4.2 Calibration of the electret capsule

To measure the individual sensitivities of the used electret microphones, each capsule was mounted in a rigid wall in the floor of an hemi-anechoic chamber, so that the front face of the microphone is aligned with the rigid wall. A reproducible sound pressure was applied and the resulting spectrum was compared with a high quality G.R.A.S. quarter inch pressure microphone (type 40BP) with a flat frequency response. This measurement procedure allows to derive the microphone sensitivities as functions of frequency. In general the obtained sensitivity spectra show very similar characteristics but differ in their absolute levels. An equalization of the sensitivities as measured at a single frequency is thus sufficient for high quality electret microphones such as the used Sennheiser KE 4-211-2. However, the broad band sensitivities were used as measured for the evaluation of this data. The result is a frequency dependent microphone sensitivity that accounts for the sensitivity of the individual electret capsule as well as for the influence of its housing.

## 5 Recording setup

The recording setup consists of a standard workstation PC or Laptop running a multitrack recording software of

choice. Each of the microphones is connected to a preamplifier and from there to the sound card which is connected with the computer.

Studio quality microphones can be added to obtain a track of higher quality for auralization of the recorded data. A calibration of the setup including the studio microphones can be performed to allow correct sound tracks in terms of referenced sound pressure level at the distance of the array microphones. Alternatively, these microphones can also be placed at closer ranges than the array microphones to obtain a near-field recording of the emitted sound.

The additional high quality microphones are suitable for auralization, as the array microphones have a rather high self-noise level (approx. 35 dBA) rendering them insufficiently noisy when used for recordings at a distance of 2 m from the source.

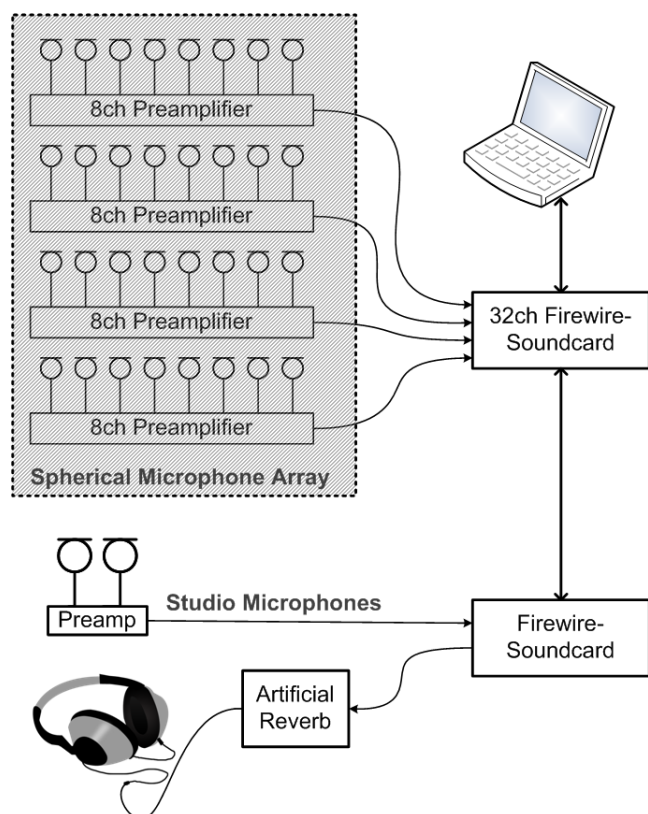


Figure 5: Exemplary setup of the recording hardware

To measure the directivity of a musical instrument, the musician is placed on an elevated seat as centered as possible within the array. This positioning can be problematic due to practical limitations in the setting as mounted in the full anechoic chamber. Large instruments, such as the contrabass, the timpani or the harp, had to be measured out of center with the help of additional structures to keep musician and instrument in a position in the array. Perspective photos help to track down the location and to compensate for the de-centered position.

For each instruments the electrical levels are adjusted and re-calibrated if necessary to be suitable for the emitted levels of the measured instrument. After starting the recording, the musicians can be instructed to play either chromatic scales (to get the full range of possible tones) or a piece of music (to obtain a dynamic recording to be used as is for auralization).

All the musicians were asked to play clean and steady

tones without any vibrato or tremolo and to keep in a steady position to be able to compare the directivities of sequentially played tones.

## 5.1 Artificial reverb via headphones

Musicians usual find it strange to perform in the acoustical environment of an anechoic chamber. To avoid disturbances the recording of their sound radiation was looped back through a reverberator and presented to the musician by headphones. In-ear headsets or closed headphones are suitable in order not to contribute to the measured radiation pattern during the recording.

## 5.2 Recorded audio material

Contrarily to some other studies, each instruments was recorded with clean single tones, encompassing all possible pitches and (depending on the instrument) also the playing style. All these tones were recorded in two different levels, pianissimo (as soft as possible) and fortissimo (as loud as possible). This choices were motivated due to the focus of TU Berlin to measure the sound power of both historical and modern symphonic instruments. [10, 11]

With the described setup it is possible to record the musician simultaneously with fully calibrated microphones. Depending on the desired results, it can make sense to record individual tones of chromatic scales or a full piece of music [12].

- **Woodwinds** (Bassoon, Contrabassoon, Oboe, English horn, Clarinet, Bass clarinet, Alto saxophone, Tenor saxophone)
- **Brass instruments** (Trumpet, Tenor trombone, Bass trombone, Tenor saxophone, Tuba, French horn)
- **Percussion** (Timpani)
- **Singer** (Soprano, Gregorian choir)
- **String instruments** (Viola, Violin, Cello, Double-action pedal harp, Contrabass, Classical guitar)
- **Flutes** (Western concert Boehm flute)

Except for the Gregorian choir (which was recorded at the University of Madrid) the recordings were performed in a joint project at anechoic chamber at the Audio Communication Group, TU Berlin.

## 6 Conclusion

A high quality set of data was obtained, using a surrounding microphone array with 32 channels. Full calibration allows the determination of the actual sound pressure values at the microphone positions. These data can be used to gain knowledge about the distinct characteristics of musical instruments, like radiated sound power and directivity.

The directivities obtained from this study can be used to measure or simulate the room impulse response with respect to a specific directivity. A method for the measurement can be found in [13], algorithms for the use in simulation software can be found in [14].



The results are used in the virtual reality system at RWTH Aachen University, where directivity patterns are usually applied in third octave bands to allow for computation in real time. Furthermore, only the absolute value is needed, as the simulated data is based on a stochastic model.

The data can also be used to gain knowledge about the distinct characteristics of musical instruments, like radiated sound power and directivity.

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