

WAVE FIELD SYNTHESIS – A PROMISING SPATIAL AUDIO RENDERING CONCEPT

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ABSTRACT

Modern convolution technologies offer possibilities to overcome principle shortcomings of loudspeaker stereophony by exploiting the Wave Field Synthesis (WFS) concept for rendering virtual spatial characteristics of sound events. Based on the Huygens principle loudspeaker arrays reproduce a synthetic sound field around the listener, whereby the dry audio signal is combined with measured or modelled information about the room and the source's position to enable the accurate reproduction of the source within its acoustical environment. However, theoretical and practical constraints of WFS systems limit the rendering accurateness and the perceived spatial audio quality to a certain degree, dependent on characteristic features and technical parameters of the sound field synthesis. Nevertheless recent developments have already shown that a number of applications could be possible in the near future. An attractive example is the synthesis of WFS and stereophony offering enhanced freedom in sound design as well as improved quality and more flexibility in practical playback situations for multichannel sound mixes. Furthermore, a novel application called "Binaural Sky" combines wave field synthesis and binaural techniques. Focused sources are rendered close at listener's ears by means of headtracking and a WFS-array above the listener, forming a virtual headphone. As a result, binaural (e.g. BRS) reproduction can be enjoyed without wearing a headphone and without any loudspeakers in the listener's field of vision.

1. INTRODUCTION

Three psychoacoustic fundamentally different spatial audio imaging methods should be distinguished:

- (Multichannel) loudspeaker stereophony
- Binaural reconstruction of the ear input signals
- Syntheses of the sound field around the listener

All known spatial sound systems can be traced back to one of these methods or can contain mixed forms thereof, whereby certain advantages of the methods are being exploited, respectively its disadvantages are avoided, dependent on the intended application area.

1.1. Loudspeaker stereophony

This is in principle based on the characteristics of localization in the superimposed sound field, generated by two loudspeakers [1].

Directional imaging is done in the imaging area between two adjacent loudspeakers [2]. In the case of 3/2 stereophony, with the help of surround channels the imaging area between the front loudspeakers can be extended. Therefore possibilities are offered for the reproduction of early lateral sound for imaging of spatial depth as well as reverberation, in order to produce the spatial impression and the envelopment. Details are described in [3].

1.2. Binaural reconstruction of the ear input signals

The original employment of this method is the known dummy head stereophony. It is not intended to reproduce a suitable sound field at the reproduction location. Instead, the effective ear signals at the recording location are recorded with the assistance of a dummy head – and replayed in principle via headphones. Under ideal circumstances, the reproduced binaural signals are identical to the original ear signals that the listener received in the recording location. In practice it is possible to reproduce auditory events with excellent realism regarding spatial characteristics and sound colour.

1.3. Synthesis of the sound field around the listener

The third approach was pursued within the framework of the European Research Project „CARROUSO“ [4]. It is based on the concept of Wave Field Synthesis (WFS, developed at the Technical University Delft, refer e.g. [5], [6]), i.e. the representation of a virtual source and a virtual room is achieved by rendering an acoustically correct sound field. The principle of WFS is based on the loudspeaker arrays which generate a complete sound field in the listening zone which is identical to an appropriate real sound event (see Chapter 2). This acoustical counterpart to the optical holography is also described as "holophony". The binaural ear input signals that are active for the auditory event thus arise in a natural way within the sound field, contrary to dummy head stereophony.

2. WFS PRINCIPLES AND PROPERTIES

2.1. WFS – the application of the "Huygens" Principle

The Huygens principle states:

"If from a point S of a homogeneous isotropic medium a spherical wave is emitted, one can imagine the procedure of the individual wave reproduction in that a particle brought into oscillation by external forces, transfers its movements to its neighbouring particles. This procedure then continues symmetrically in all directions and in this way gives cause to a spherical wave..." [7]. The Kirchhoff-Helmholtz integral, an

application of this fundamental principle, is used as the underlying mathematical formulation for WFS. Its fundamental conclusion is the fact that a wave field is known as soon as the wave front on a continuous surrounding surface is known.

The major step to put this theory into practice is the discretisation of the surface to a grid of positions and the reduction of the reproduction dimensions to the horizontal plane. Accordingly, the WFS principle states that a wave field in the horizontal plane can be synthesized when the signals on the positions of an array of transducers are known.

An example is depicted in Figure 1: From sound source S (which emits a sine impulse and is located in an infinitely large plane without demarcation of walls), a wave front results as illustrated in Figure 1a). If one now places an array of n microphones (M) in this primary sound field and one reproduces the recorded microphone signals via an equally arranged array of n loudspeakers (L) – special equalization has to be included according to the relevant physical basics – in a reproduction room (Figure 1b), one obtains the synthesized wave front in the (red dotted) listening area. At any place in the listening area the listener perceives a virtual sound source S, as he can move around freely; whilst the virtual sound source remains correctly localized in terms of its direction (see [5] or [8]).

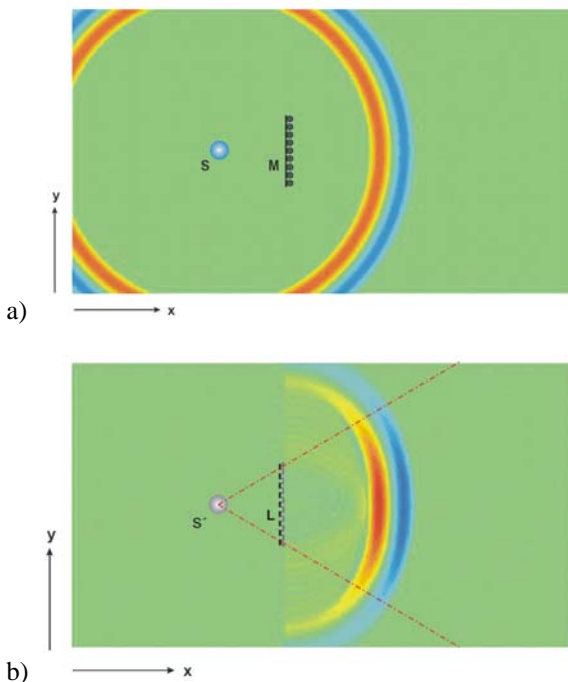


Figure 1: Principle of WFS

- a) ideal source response
- b) typical output of a finite WFS array

2.2. Special Properties of WFS

Through WFS the sound engineer has a powerful tool to design a sound scene. One of the most important (with respect to conventional techniques) novel properties is its outstanding capability of providing a realistic localization of virtual sources. Typical problems and constraints of a stereophonic image vanish in a WFS sound scene.

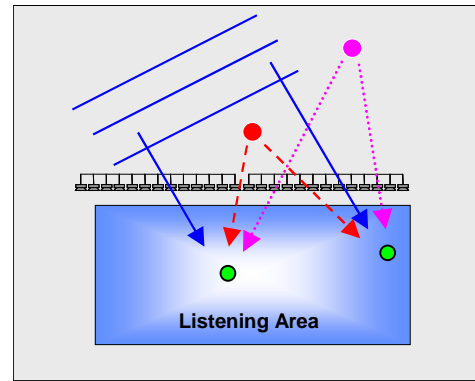


Figure 2: WFS is capable of reproducing both the stable positions of point sources (red and pink, dashed and dotted) and the stable direction of a plane wave (blue, solid)

In contrast to stereophony WFS is able to:

- produce virtual sources that are localized on the same position throughout the entire listening area, refer Figure 2: The red (dashed) and pink (dotted) arrows indicate the directions of the auditory events when the red and pink virtual point sources are reproduced.
- produce plane waves that are localized in the same direction throughout the entire listening area, refer Figure 2: The blue (solid) arrows indicate the direction of the auditory event when the blue plane wave is reproduced.
- enhance the localization of virtual sources and the sense of presence and envelopment through a realistic reproduction of the amplitude distribution of a virtual source. In other words, when the listener is approaching the location of a virtual source the amplitude increases in a realistic way. Accordingly, the amplitude of a plane wave - which can be seen as a source in infinite distance - changes least on different listener positions.
- produce focused sources. Focused sources that are in principal localized in front of the array. Figure 3 shows the wave fronts of a point source behind the array (a) and in front of the array (b) in a simulation. Naturally, the localization will not be correct for listening positions between the focus point and the array because the sound emission of the virtual source occurs here reversely.

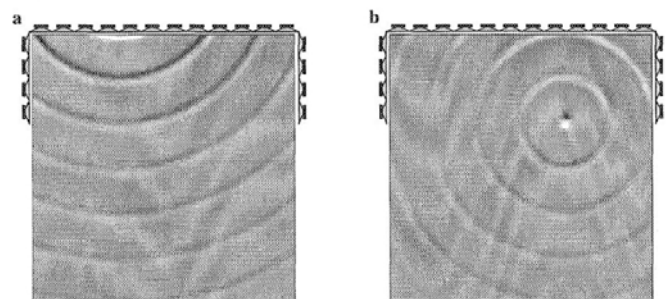


Figure 3: Wave fronts of virtual sources, after [10]

- a: behind the array
- b: in front of the array

These properties enable the synthesis of complex sound scenes which can be experienced by the listener while moving around within the listening area. This feature can be made use of deliberately by the sound engineer to realize new spatial sound design ideas. Moreover, it has been shown that the enhanced resolution of the localization compared with stereophony [9] enables the listener to easily distinguish between different virtual sources making the sound scene significantly more transparent.

3. WFS PRACTICAL CONSTRAINTS

Not surprisingly, in practice it is not possible to match all theoretical requirements for a perfect result. The rendered WFS sound field differs from the desired sound field to some degree for a number of reasons (for details see [11]):

3.1. Discreteness of the array (spatial aliasing)

Spatial aliasing produces spatial and spectral errors of the synthesized sound field due to the discretisation of the secondary source distribution. The wave field is produced erroneously above the spatial aliasing frequency f_{alias} which depends on the loudspeaker spacing and the source/listener geometry. Spatial aliasing gives rise to artefacts of colouration and localization.

3.2. Reflections of the reproduction room

A WFS array can not render the desired sound field perfectly if reflections of the reproduction room produce interference in spatial perception. In particular, perception of distance, depth and spatial impression are affected, because fragile distance cues of synthesised sources can be dominated by the stronger distance cues generated by the array speakers. They interfere with the desired reflection pattern of the synthesised source. Special room compensation algorithms being under investigation ([12], [13]) will perhaps be able to minimize this effect.

3.3. Restriction to the horizontal plane

Theory does not restrict WFS to the horizontal plane. However, the reduction of the array dimension to the horizontal plane is the practical approach, having a number of consequences. First, virtual sources can be synthesized only within the horizontal plane. This includes virtual reflections affecting the completeness of a natural reflection pattern and thus possibly resulting in impairments of perception of distance, depth, spatial impression and envelopment. Furthermore, horizontal arrays do not generate real spherical waves, but cylindrical waves. In the case of imaging a plane wave for example there results an error with respect to the level roll-off (3dB/doubling of distance), in comparison with the ideal plane wave (no roll-off) ([11], [14]).

3.4. Limitation of array dimensions (diffraction)

In practical applications the loudspeaker array will have a finite length. Due to the finiteness of the array, diffraction waves originate from the edges of the loudspeaker array ([11], [14]). These contributions appear as after-echoes (and pre-echoes respectively for focused sources), and – depending on their level and time-offset at the receiver's location – may give rise to colouration. Methods to reduce these truncation effects are known, e.g. by applying a tapering window to the array signals. This means that a decreasing weight is given to the loudspeakers near the edges of the array. In this way the amount of diffraction effects can substantially be reduced at the cost of a limitation of the listening area [14]. ...

3.5. Effects on perception

Although a number of authors have suggested methods to deal with the practical limits of rendering accurateness or to minimize their effects, there is still a lack of knowledge (some details can be found e.g. in [5], [6], [11], [15]). Several effects of the constraints on specific perceptual attributes are not known yet in detail. However, this knowledge is important for further developments of WFS systems in view of future applications.

Current psychoacoustic studies are concentrating on the subjective evaluation of principle characteristics of WFS systems in comparison with stereophonic or binaural systems. They are necessary to evaluate the resulting impacts on attributes of spatial perception not only with respect to the development of WFS systems for different applications but also in view of scientific knowledge. Particular attention should be turned to the perception of sound colour, direction, distance, spatial depth, spatial perspective, spatial impression, reverberance, and envelopment.

4. WFS APPLICATIONS

4.1. The European CARROUSO Project ¹

The European CARROUSO Project (“Creating, Assessing and Rendering in Real Time of High Quality Audio-Visual Environments in MPEG-4 Context”) intended to break several limitations of these current commercial systems by merging the new WFS rendering technique with the flexible coding standard MPEG-4, allowing object-oriented and interactive sound manipulation.

By means of the MPEG-4 format the signal of the source (“Gestalt”) and its spatial properties are transmitted separately. For reproduction, the dry source signal is convolved with the measured or modelled set of impulse responses (containing the spatial information), and emitted by a loudspeaker array. In contrast to stereophony WFS is able to

- produce virtual stable sources localized at the same position throughout the entire listening area,
- produce virtual sources in front of the loudspeaker array (“focused sources”)
- produce plane waves that are localized in the same direction throughout the entire listening area,
- enhance the sense of depth, spatial impression and envelopment through a realistic reproduction of the original room response

The key objective of the project CARROUSO was to provide a new technology that enables to transfer a sound field, generated at a certain real or virtual space, to another usually remote located space. The results have shown the possibility to capture, transmit and render sound sources and their related acoustic environment with more realism, compared to existing stereophonic methods. They are considered as a major milestone for immersive audio representation at public places and in private households. Two applications were targeted within this project. The first one concerns high quality spatial audio with associated video for broadcasting. The second application is related to cooperative and interactive work on immersive audio objects.

¹ EU-Project IST-1999-20993 (Jan. 2001 – June 2003): [4].

4.2. Synthesis of WFS and stereophony

For recording of orchestra and soloist closely spaced spot microphones are used. The stereophonic orchestra mix should be composed in a way that it contains as little room information (reverb, reflections, etc.) as possible; but it should contain the adequate spatial distribution of elements. This multi-channel stereophonic mix and the soloist signal are convolved with the appropriate spatial impulse responses (see Figure 4).

As a result, the rendered WFS sound field represents stable virtual sources located in the concert hall. Listeners within the listening area perceive a multi-channel stereophonic image of the orchestra and a point source image of the soloist, whereby the reproduced characteristics of the concert hall give a new sense of realism. On this basis apparent advantages of established conventional stereophonic recording techniques on the one hand and of WFS technologies on the other can, in principle, be utilized through a purposeful combination.

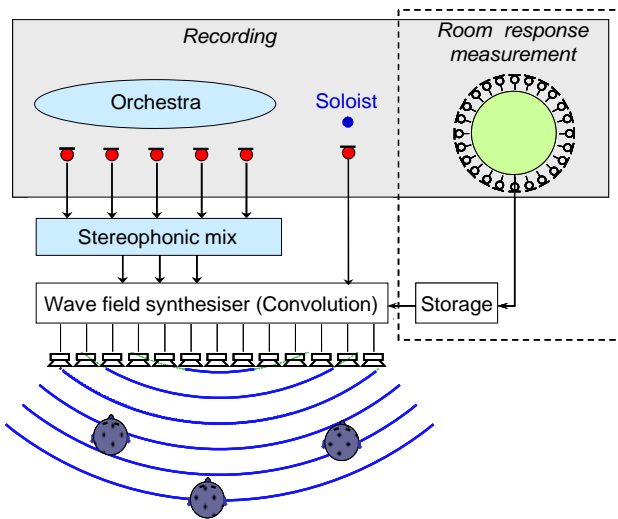


Figure 4:

WFS: Separate handling of sources and spatial information

4.3. Virtual Panning Spots (VPS)

The key tool is use of so-called Virtual Panning Spots (VPS) [16], virtual point sources to be applied for panning across any stereophonic imaging plane in the virtual WFS imaging area. VPS can be understood as virtual “loudspeakers” which reproduce the stereophonic sound image of a spacious sound source (e.g. a choir) in the recording room (see also [17], [18]). The suitable room impulse responses have to be measured in the original room or to be created artificially in a suitable way. In the example of Figure 5, the orchestra is imaged with the assistance of six VPS, which are reproduced via WFS and are relatively freely configurable with regard to localization, expansion and distance.

The sound design advantage of this concept is self-explanatory: The stereophonic recording of the orchestra according to Figure 4 produces a spacious sound image of the sources as there is an image between the VPS in accordance with the principles of phantom sources localization. The “loudspeakers” are virtual sources, generated through WFS and provided with the room characteristics of the recording room. The locations of the VPS behave directionally stable in the listening area. The known disadvantages of phantom source localization, especially the low directional stability can be easily avoided by employing a sufficient number of VPS.

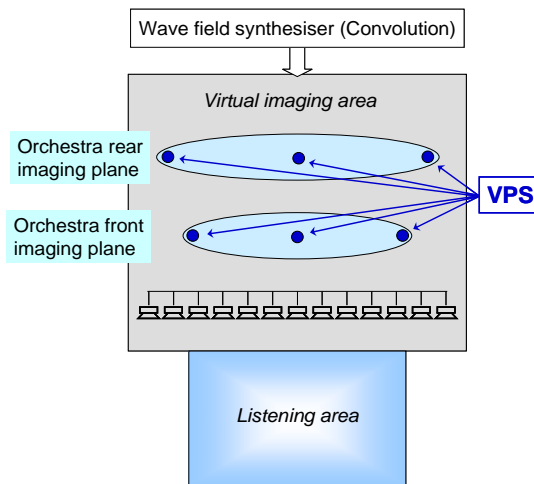


Figure 5: Use of Virtual Panning Spots (VPS)

The number of stereophonic imaging areas is in principle arbitrary. From an artistic point of view, one should orientate oneself towards the number of spacious instruments or instrument groups (in large ensembles, e.g. string groups, brass player groups, choir). The number and spatial distribution of the VPS depends on the following criteria:

- Size and shape of the homogeneous ensemble
- Circumstances of the production
- Artistic and sound balance-related intention of the sound engineer
- Available transmission capacity

Virtual Panning Spots, VPS, are selected points (“virtual loudspeakers”), which produce a stereophonic representation area. These can in principle be selected at choice in accordance with the recording situation and the desired sound image. The imaging area can be “spread out” by an arbitrary number of VPS in a random spatial expansion in accordance with the situation and intention.

The artistic arrangement of the ensemble upon the WFS transmission commences with the choice, dedication and positioning of the VPS. Three parameters should be mentioned, which lends the sound engineer to new possibilities of spatial sound design:

1. In the case that loudspeaker arrays are installed lateral to the listening area, there are in principal, no problems as far as directional stability is concerned, as a lateral stereophonic representation sector can be built up from a sufficient number of stable VPS. The same applies to the sector behind the listener.
2. A stereophonic imaging area does not only allow itself to be moved in all directions, stretched out or compressed, but can also be presented in an extensive range with different distances. The representation of depth is thus easily recognizable.
3. With certain constraints (see Section 4), the VPS can be placed in a distance between the listener and the loudspeaker array and also with the stereophonic imaging field. Thus, the virtual imaging area theoretically reaches in dense closeness to the listener and allows for an expressive representation of depth.

4.4. Virtual loudspeaker reproduction

An important application of the VPS technique is a special preset of the VPS setup on the reproduction side, which enables the reproduction of conventional multichannel recordings in a virtual listening room [16]. For this purpose, two modifications are suggested for the WFS decoder, which can be activated in the event of need for application, see Figure 6:

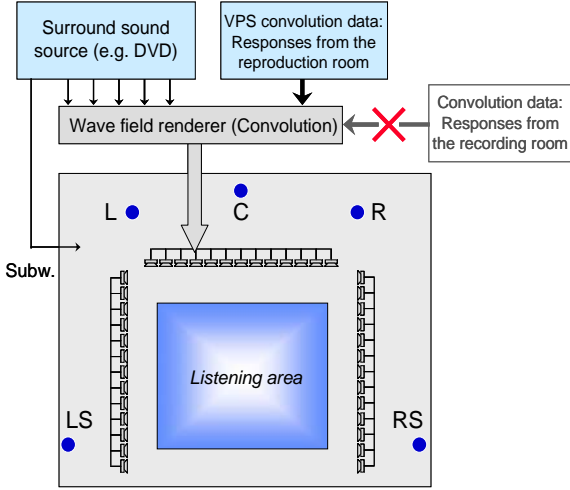


Figure 6: VPS configuration for rendering virtual 5.1 multi-channel loudspeakers

1. The configuration of the VPS with regard to room impulse responses and spatial arrangement is done in accordance with the preset setup of virtual loudspeakers in a virtual listening room. Arbitrary arrangements of the virtual loudspeakers can be preset and be activated dependent on the stereophonic format to be reproduced.
2. The virtual source signal is not received via the transmission channel, but from the multichannel decoder on the reproduction side (e.g. that of a DVD player).

The WPS reproduction unit operates completely detached from WFS transmission, and can principally offer three attractive advantages:

1. Diverse stereophonic multichannel formats can be easily reproduced optimal through the selection of a VPS preset, without having to appropriately adjust the loudspeaker arrangement within the living-room.
2. The virtual loudspeakers can also be placed outside the living-room, i.e. also in a confined area situation, the listening area for multi-channel stereophony is sufficiently large.
3. A future high quality WFS reproduction unit will allow for an electronic compensation of diverse defects in the reproduction room [12], especially the reduction of the effect of the early reflections and the balancing of asymmetrical arrangements of the speaker array.

From the technical and practical point of view the application of WFS for multichannel stereo reproduction could be the first step towards acceptance in the market place. In this regard, the development of the so-called MAP technology (see [19]) is important. The flat panels, e.g. fed with glass fibre cables, can often be better integrated into the living-room and are more attractive than conventional loudspeakers.

4.5. Virtual headphone reproduction

The standard way to play binaural signals via loudspeakers is to use crosstalk cancellation (XTC) filters to eliminate the unwanted signal paths between speakers and ears (see e.g. [20]). Ideally, the head related transfer functions (HRTF) of the path between the loudspeakers and the ears of the listener have to be measured or calculated with a mathematical model (e.g. [21], [22]), and inverse XTC filtering must ensure that the resulting transfer function is neutral ($= 1$). The need for head-tracking results in the use of a whole set of XTC filters which have to be updated with every head rotation, see Fig. 7.

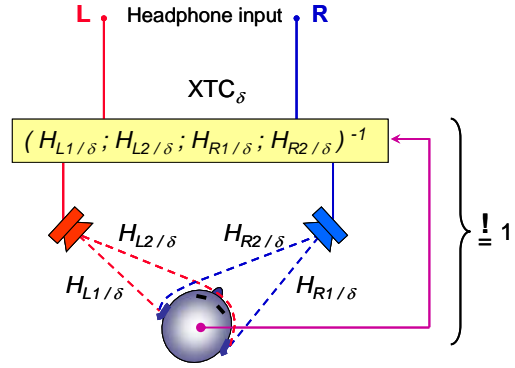


Figure 7:

Headtracking controlled inverse HRTF filtering (XTC_{δ}) to provide a neutral transfer function of the virtual headphone

4.5.1. Concept

The realization of a headtracking controlled inverse HRTF filtering is problematic particularly in case of larger head rotations. In the best case, the loudspeakers ought to move with the head rotation, so that the relative positions between the sound sources and the ears stay constant and only one set of XTC filters is needed. Of course this concept is not feasible with real loudspeakers.

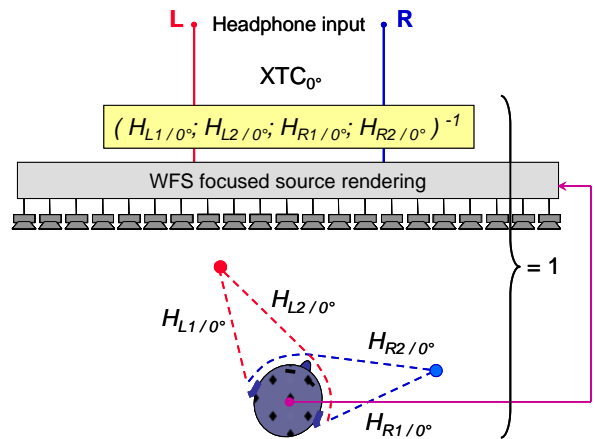


Figure 8:

Headtracking controlled WFS rendering of focused sources to provide a neutral transfer function of the virtual headphone without the need of adaptive XTC filters

WFS however enables to replace the real speakers by focused sources that act as the transaural loudspeakers and can easily be moved around by adjusting the driving functions (i.e. the delay times and attenuations) of the array loudspeakers. By synthesizing focused sources at a close distance to the listener's head a stable virtual headphone reproduction can be achieved without the need of adaptive XTC filters (Figure 8). The actual configuration of the focused sources is adaptable for optimum inverse filtering performance.

Instead of a standard linear WFS array however, a circular design ensures constant distances between the ears, the focused sources, and the array speakers. This leads to a constant (and high) aliasing frequency and greatly reduces audible sound colorations during head rotations. Figure 9 (left) shows a schematic view of the circular array rendering two focused sources (red and blue dots). The dashed circle indicates the path on which the focused sources move during a full head rotation.

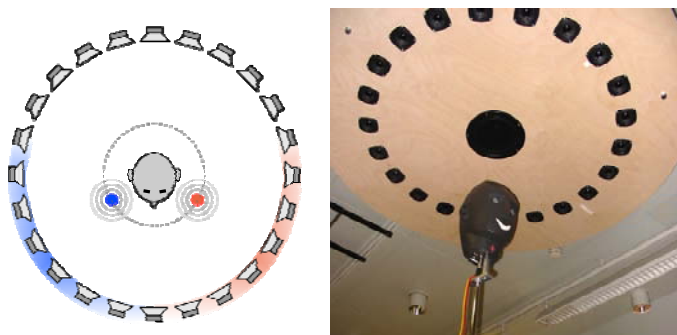


Figure 9: The circular array located above the listener synthesizes focused sources which act as transaural sources.

The array setup is suspended above listener's head and includes a low frequency driver in the middle of the circle (Figure 9, right). No loudspeakers in the listener's field of vision are obstructing the view on e.g. computer displays or TV monitors.

4.5.2. The Binaural Sky

An attractive application of the virtual headphone is reproduction of binaural signals, particularly reproduction of Binaural Room Synthesis signals (BRS, see e.g. [23], [24], [25]). The BRS headphone playback system was developed in the 1990s by the Institut für Rundfunktechnik IRT. Controlled by headtracking data, multi-channel audio signals are convolved with measured or modelled binaural impulse responses of a monitoring room. The resulting headphone input signals offer accurate room-related localization of the virtual loudspeakers in terms of direction and distance regardless of listener's head orientation.

The BRS-system is a perfect tool for accurate surround sound headphone reproduction. Irrespectively of the actual acoustic properties of an individual control room, like in a small OB-van, the sound engineer can work in a virtual acoustic environment which is identical to his familiar or preferred environment. Consumers can use a (virtual) high-quality studio for surround sound reproduction.

However, a drawback of the BRS system is the need to wear headphones. For a number of applications and situations, e.g. in a car or in a situation where real and virtual sources have to be mixed ("augmented reality"), a binaural reproduction without headphones would be desirable.

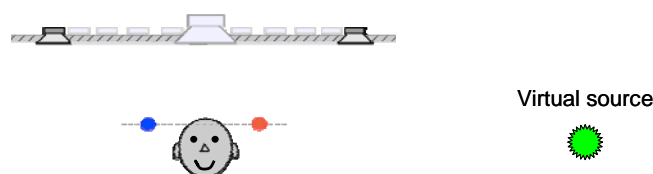


Fig. 10: The Binaural Sky concept BRS reproduction via WFS based virtual headphone

BRS reproduction without wearing headphones is the idea and intention of the novel system known as "Binaural Sky" [26] which is the combination of the two headtracking based concepts, BRS and virtual headphone as introduced in chapter 4.5.1. As indicated in Fig. 10, the WFS array above the listener generates focused sources close at the ears. They are applied as transaural sources forming a virtual headphone which is used for BRS reproduction. As a result, stable and accurate room-related localization of virtual loudspeakers in the horizontal plane is achieved. The location of the array loudspeakers is not perceivable.

Results of subjective and objective tests on a first realization of the Binaural Sky setup have been reported in [26]. In the upper hemisphere (above horizontal plane) they show good localisation of virtual sources in terms of direction and distance, comparable to BRS playback via real headphones or even real sound sources. However, similar to experiences with dummy head technique, sources in the horizontal plane are frequently heard about 10° too high, and below the horizontal plane perception of depth is problematic. Variations in sound colour between different virtual sources are uncritical.

BRS reproduction can be enjoyed without wearing a headphone and without any loudspeaker in the listener's field of vision. Thus the system is perfectly suitable for applications in the field of virtual reality.

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