# Generation of Far-Field Head-Related Transfer Functions using Virtual Sound Field Synthesis

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## Introduction

Head-related transfer functions (HRTFs) or impulse responses (HRIRs) capture the acoustic transmission path from an acoustic source to the ears. For ease of illustration we restrict our considerations to HRTFs $H_{\{L,R\}}(\alpha_0, R, \omega)$ captured from sources in a plane, were $(\alpha_0, R)$ denotes the position of the sound source. Note, the generalization of the proposed technique is straightforward. HRTFs are typically measured for a fixed source distance in the range of $R = 1.5 - 3$ m. For virtual auditory environments extrapolation to other distances than the measured ones is desirable in order to be able to place virtual sources at arbitrary positions within the virtual space. For some applications far-field HRTFs are of interest. These are defined as the transfer function $\bar{H}_{\{L,R\}}(\alpha_{pw}, \omega)$ of a plane wave with incidence angle $\alpha_{pw}$ to the ears. Far-field HRTFs can be beneficial for dynamic data-based binaural synthesis were plane wave representations of sound fields are combined with HRTFs [1]. A least two different strategies have been presented in the past to perform range extrapolation of measured HRTFs: (1) extrapolation using a representation of HRTFs in terms of spherical harmonics/Bessel functions [2] and (2) virtual higher-order Ambisonics [3]. In this paper, we present an approach which is closely related to the latter category.

## Virtual Sound Field Synthesis

Sound field synthesis (SFS) techniques like Wave Field Synthesis (WFS), near-field compensated higher-order Ambisonics (NFC-HOA) and the spectral division method (SDM) aim at the synthesis of a desired sound field within an extended area using an ensemble of individually driven loudspeakers (secondary sources). As outlined above, HRTFs represent the transfer functions from an acoustic source to the ears. Datasets of HRTFs are typically measured for a fixed distance $R$ of the source and varying incidence angle $\alpha_0$. Consequently, such datasets can be interpreted as a virtual circular loudspeaker array. Refer to Figure 1 for an illustration.

The basic idea of the proposed technique is to drive these virtual sources such that the sound pressure of a desired virtual source is synthesized at the ears. The range extrapolated HRTFs are given by the transfer function from the virtual source to the left/right ear. For the synthesis of far-field HRTFs the required virtual source is a plane wave (see Fig. 1).

The sound field $P(\mathbf{x}, \omega)$ synthesized by a continuous circular distribution of secondary monopole sources is given

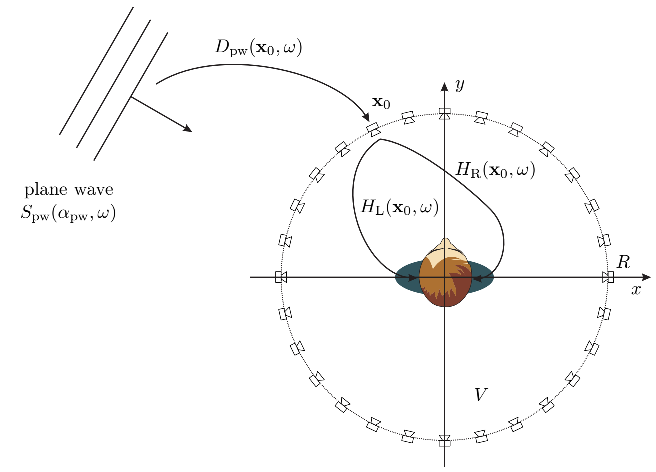



**Figure 1:** Principle of extrapolating HRTFs by virtual sound field synthesis.

as

$$P(\mathbf{x}, \omega) = \int_0^{2\pi} D_{pw}(\alpha_0, R, \omega)\, G(\mathbf{x} - \mathbf{x}_0, \omega)\, R d\alpha_0 \,, \quad (1)$$

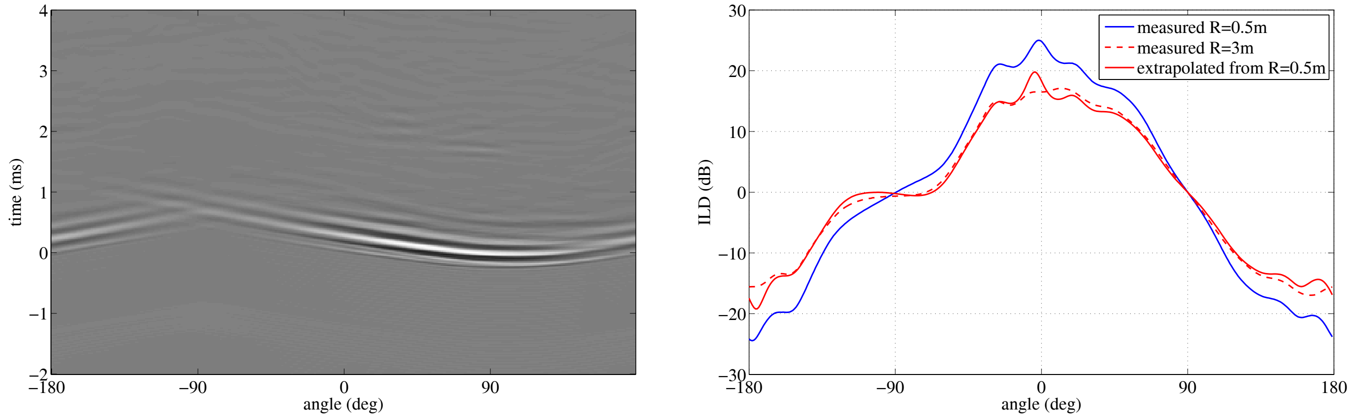
were $\mathbf{x}_0 = R\,[\cos\alpha_0 \;\; \sin\alpha_0]^T$ denotes the position of a virtual secondary source, $D_{pw}(\alpha_0, R, \omega)$ the driving signal for a plane wave and $G(\mathbf{x} - \mathbf{x}_0, \omega)$ the Green's function characterizing the sound field of a monopole source located at the position $\mathbf{x}_0$. Replacing the Green's function in (1) by the left/right HRTFs respectively and driving the virtual plane wave by a Dirac pulse yields the plane wave HRTFs as

$$\bar{H}_{\{L,R\}}(\alpha_{pw}, \omega) = \int_0^{2\pi} D_{pw}(\alpha_0, \omega) H_{\{L,R\}}(\alpha_0, R, \omega)\, R d\alpha_0 \,. \quad (2)$$

In principle, any suitable SFS technique can be used. Due to the underlying circular geometry, WFS and NFC-HOA are natural candidates for this purpose. We illustrate the computation of far-field HRTFs using WFS. This technique has a number of benefits like numerical stability and computational efficiency. However, similar considerations as given in the next section hold also for the application of NFC-HOA.

## Far-field Head-Related Transfer Functions

Equation (2) assumes that the measured HRTFs are available for all possible angles $\alpha_0$. In practice however, only a limited number of measured HRTFs is available.




**(a)** synthetic far-field HRIRs

**(b)** ILDs of measured/extrapolated HRTFs

**Figure 2:** Far-field HRTFs (left-ear) computed by virtual WFS from HRTFs measured at a distance of $R = 0.5$ m.

This constitutes a spatial sampling of the virtual secondary source distribution that may lead to spatial sampling artifacts in the extrapolated HRTFs [4]. However, even when the measured HRTFs are available only at a limited number of angles $\alpha_0$ the incidence angle $\alpha_{\text{pw}}$ of the virtual plane wave used to compute the far-field HRTFs can take arbitrary values.

The considered scenario of a circular distribution of virtual secondary sources constitutes 2.5-dimensional synthesis. The properties of WFS (and other techniques) in this respect are well researched [5]. Most prominent are amplitude deviations in the synthesized sound field. In this context a synthesized plane wave shows an undesired systematic amplitude decay that has to be compensated for for the computation of far-field HRTFs. If this amplitude decay is not compensated for, the interaural level differences (ILDs) will not be correct for the synthesized HRTFs. Compensation for these deviations is straightforward using the results from [5].

The preparation of the simulation results is described below. The measured HRTFs were pre-filtered by the pre-equalization filter of WFS, these pre-filtered HRTFs were then weighted and delayed individually and summed up for each ear. Note, the pre-equalization filter has to be adapted to the spatial sampling and distance of the virtual secondary sources.

A custom dataset of horizontal plane HRTFs [6] measured for four different source distances with an angular resolution of one degree was used for evaluation. Figure 2a shows the left-ear far-field HRIRs that have been computed from a dataset that has been measured at a source distance of $R = 0.5$ m. Listening examples are available at `http://audio.qu.tu-berlin.de/?p=612`. Figure 2b shows the ILDs of the far-field and measured HRTFs. Additionally ILDs for a source distance of $R = 3$ m are shown for reference. It it clearly observable that the ILDs of the synthetic far-field HRTFs are close to the $R = 3$ m measurements. This suggests that the ILD is considered correctly in the proposed approach.

## Outlook

The presented technique can be extended straightforward to cope for different head orientations. In this case the measured HRTFs $H_{\{\text{L,R}\}}(\alpha_0, R, \omega)$ have to be replaced by $H_{\{\text{L,R}\}}(\alpha_0, \varphi, R, \omega)$ in the respective equations. $\varphi$ denotes the head orientation. An extension to HRTFs captured for a spherical distribution of sources is also straightforward by using three-dimensional SFS techniques. The theory of three-dimensional WFS has been presented in [5]. A formal perceptual evaluation of the proposed approach is in preparation.

## References

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