# Wave Field Synthesis with increased aliasing frequency

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## Introduction

Wave Field Synthesis (WFS) is a holophonic technique that targets the reproduction of physical properties of sound fields in an extended listening area. WFS typically relies on a finite number of regularly spaced loudspeakers arranged in a linear array. WFS synthesizes target sound fields within a large portion of the horizontal plane up to a corner frequency referred to as "spatial aliasing frequency". This corner frequency generally increases with the number of channels for a given loudspeaker geometry. Spatial aliasing is usually regarded as the main limitation of WFS. It creates physical inaccuracies in the synthesized sound field which may lead to perceptual artefacts such as localization bias [1] [2], increase of source width [3], sound coloration for fixed [4] and moving listeners [5]. The audibility of these artefacts mostly depend on the frequency content of the sound material [2] [3] [5]. An aliasing frequency of 1.5 kHz is usually considered sufficient to limit localization errors and coloration artifacts for voice signals[5]. Coloration artefacts may still be perceived for such an aliasing frequency with music signals [4] and localization bias may still exist for off centered sources or listening positions with critical signals (broadband and high pass filtered noise) [2].
Perceptual enhancement techniques have recently been proposed to limit coloration artefacts. They consist in either using strereophonic means at high frequencies [4] or decreasing the correlation of driving signals at high frequencies [6]. They enable to limit coloration artefacts for fixed and moving listeners but at the cost of an increase of source width and possibly introduce localization bias for large listening areas while using strereophonic means. Therefore, high quality sound reproduction using WFS requires an aliasing frequency of at least 1.5 kHz which correspond to a large amount of loudspeakers. The concept of spatial bandwidth reduction was proposed by Start and Verheijen to increase the aliasing frequency with a fixed number of channels. It basically consists in using sources and loudspeakers that have specific directive characteristics. However, nowadays available loudspeakers don't have the required directivity characteristics and the approach may lead to sound coloration for most source/listener configurations.
In this paper, we propose a new approach that enables to increase the aliasing frequency of WFS reproduction within a preferred listening area. Unlike spatial bandwidth reduction, our approach does not put constraint on the directivity of the loudspeakers or the source.

## Spatial Aliasing in Wave Field Synthesis

Spatial aliasing results from the spatial under sampling of the required linear continuous loudspeaker distribution. The "spatial aliasing frequency" is the Nyquist frequency of the spatial sampling process.
Classical description of spatial aliasing in WFS rely on the decomposition of the WFS driving function and synthesis in the Spatial Fourier domain (plane wave decomposition) [3]. This description assumes loudspeaker arrays of infinite length. The spatial aliasing frequency $f_{al}$ is given as :

$$f_{al} = \frac{c}{\Delta x(|\sin(\theta_{max,\Psi})| + |\sin(\theta_{max,ls})|)}, \qquad (1)$$

where $c$ is the speed of sound, $\Delta x$ is the loudspeaker spacing, $\theta_{max,\Psi}$ is the maximum plane wave component of the virtual source $\Psi$, and $\theta_{max,ls}$ is the maximum plane wave component of the loudspeakers.

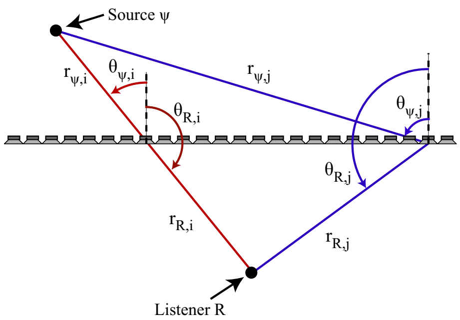



**Fig. 1:** Description of propagation time for each loudspeaker from the source $\Psi$ to the listener position $R$ using WFS

The aliasing frequency depends on the loudspeaker array extension and the listener's position in practical setups. This can be described using an alternative definition of aliasing in the time domain [7]. Assuming that the source and the listener are in the far field on the loudspeakers, the spatial aliasing frequency can be defined as :

$$f_{al}^{temp}(R,\Psi) \simeq \frac{g_{al} \times c}{\Delta x \max_{n \in \mathcal{N}_R^{\Psi}} |(\sin(\theta_{\Psi,n}) + \sin(\theta_{R,n}))|}. \qquad (2)$$

where $g_{al}$ is a weighting factor. $\mathcal{N}_R^{\Psi}$ is a subset of loudspeaker indices whose contribution at listening position $R$ is higher in level than a certain threshold $tr_{al}$[7].

## Wave Field Synthesis with increased aliasing frequency

According to equations 1 and 2, the aliasing frequency can be raised by decreasing $|\sin(\theta_{max,\Psi})|$ (resp. $\max_n |(\theta_{\Psi,n})|$) and/or $|\sin(\theta_{max,ls})|$ (resp. $\max_n |(\theta_{R,n})|$). This corresponds to the concept of spatial bandwidth reduction which requires more directive loudspeakers and sources.
The alternative definition of spatial aliasing in the time

domain (cf. equation 2) which consists in minimizing $|(\sin(\theta_{\Psi,n})+\sin(\theta_{R,n}))|$. This sum is null for loudspeaker $i$ in figure 1. Loudspeaker $i$ is in the alignment of source $\Psi$ and listening position $R$ which is referred to as the "point of stationary phase".

WFS a priori does not make any assumption of the listener's position. However, in many situation, listeners might remain seated at a given position or might wander only in a restricted (preferred) listening area. Figure 2 proposes a method to select loudspeakers for a restriction of WFS in a preferred listening area. It is based on a simple visibility criterion which is similar to the one commonly used to describe the restriction of the listening area due to finite length array in WFS. Selected loudspeakers are thus in the vicinity of the point of stationary phase for any listening position in the preferred listening area. It can thus be expected that the aliasing frequency may increase with the proposed selection.

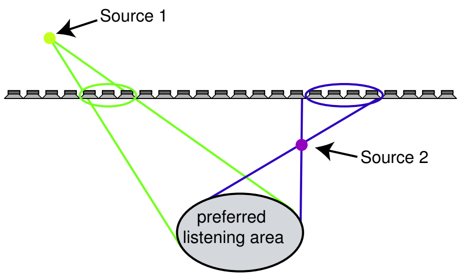


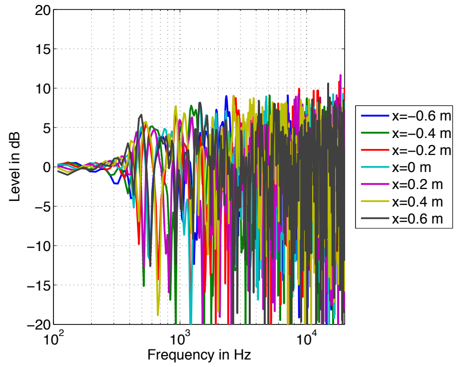

**Fig. 2:** Selection of loudspeakers for WFS in a preferred listening area

## Simulation

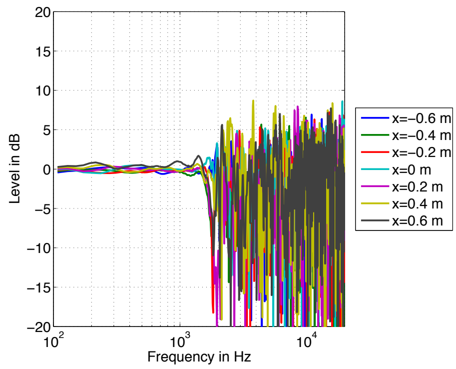
We consider here a 6 m linear array with only 12 loudspeakers (50 cm spacing). We define a 1.2 m wide preferred listening area centered towards the loudspeaker array along a line located at 2 m from the loudspeaker array. The target virtual source is located at 10 m distance and 30 degrees to the right from the center of the preferred listening area.

Frequency responses of the loudspeaker array are displayed in figure 3(a) for conventional WFS and in figure 3(b) for WFS in the preferred listening area. The aliasing frequency can be significantly raised from 350 Hz to about 1.5 kHz using the proposed method independently of the lateral listening position. Using conventional WFS, a similar aliasing frequency would be obtained with 48 channels and a loudspeaker spacing of 12.5 cm. The proposed method enables thus very significant reduction of the number of channels for WFS which may largely reduce entry cost for home entertainment applications.

A more complete description of the method and additional simulations and application scenarios can be found in a companion paper [8].




(a) Conventional WFS, $f_{al}$ = 350 Hz




(b) Proposed method, $f_{al}$ = 1.5 kHz

**Fig. 3:** Frequency responses of the 6 m long 12 channels loudspeaker array (50 cm spacing) at 7 positions within the preferred listening area

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