

# OPSI

( **O**ptimised **P**hantom **S**ource **I**maging  
of the high frequency content of  
virtual sources in Wave Field Synthesis )

*A Hybrid WFS / Phantom Source Solution to avoid Spatial aliasing*

(patentiert 2002)

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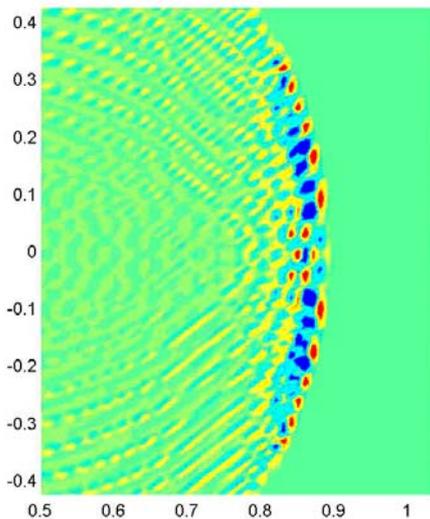
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Helmut Wittek, IRT, 11.4.2002

**1. Need for another solution ?**

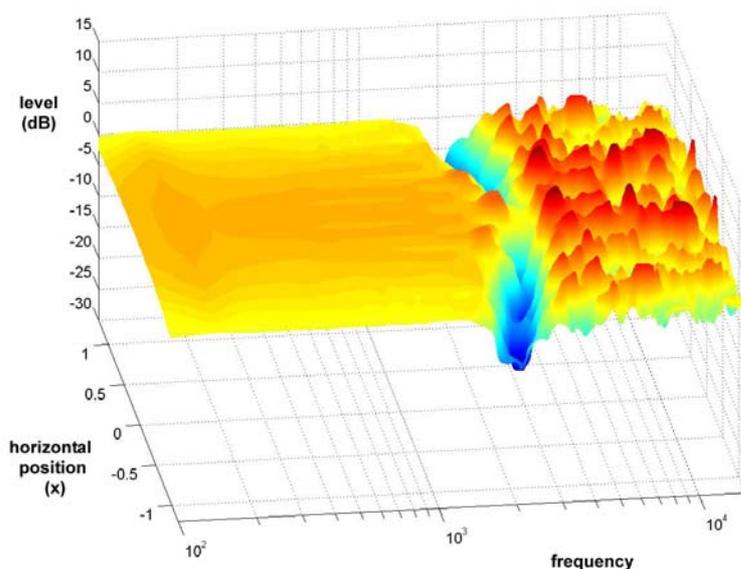
Reproduction via a WFS array suffers from one essential point: Due to the finite resolution of the array, reproduction free from spatial-aliasing is possible only for frequencies below one certain limit. This “spatial-aliasing frequency” depends on different parameters, as described in literature:

- spacing of the loudspeakers
- source distance, maximum incident angles
- listening distance, maximum angles to the array



**Figure 1:**  
*Aliasing in the x/y-domain: 6400 Hz-signal of a virtual monopole reproduced by an array with 15cm spaced loudspeakers*

Above the aliasing frequency, the original shape of the waveform will not be reproduced (Fig.1). The direction and the frequency response of the original source will not be reproduced correctly and will be strongly dependent on the listening position. Even small changes of the listening position cause immediate changes of the virtual source’s sound colour (Fig.2).



**Figure 2:**  
*Aliasing in the x/f- domain*

To improve the performance of a WFS array regarding sound colour and localization, an alternative should be investigated:

The combination of WFS at lower frequencies and phantom source imaging at higher frequencies.

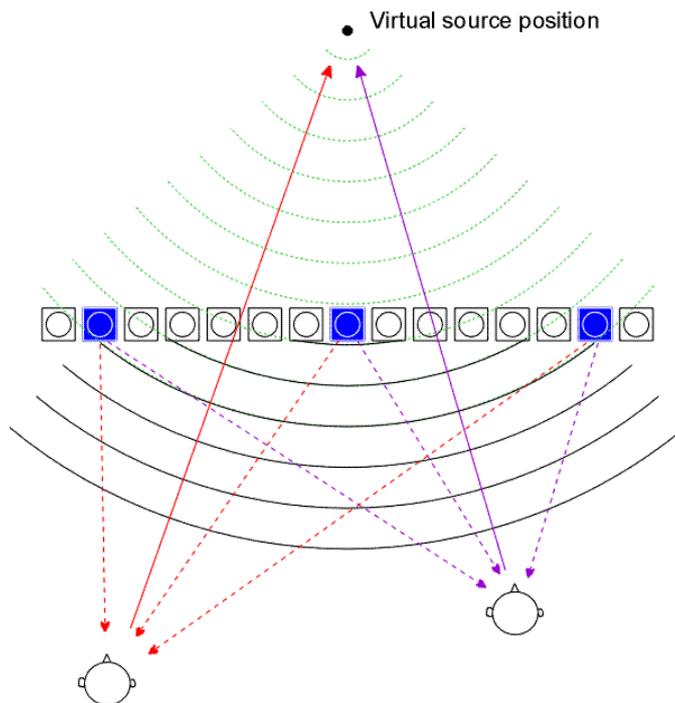
This method is called **OPSI = Optimised Phantom Source Imaging of the high frequency content of virtual sources in Wave Field Synthesis.**

## 2. Using OPSI

Instead of using the non-perfect WFS reproduction at frequencies above the aliasing frequency, a phantom source solution is used to achieve a high frequency image in the same direction as the virtual source.

Fig.3 shows the principle of this kind of imaging.

In this figure a virtual source can be seen that is reproduced with a combined WFS/phantom source solution. The WFS array uses the low-passed ( $< f_{alias}$ ) WFS signals to reproduce the accurate virtual source position. The phantom source generating single loudspeakers, indicated with blue color, are fed with high-passed ( $> f_{alias}$ ) signals and generate a phantom source that should be perceived in the same direction as the virtual source.



**Figure 3:** Combination of WFS reproduction below  $f_{alias}$  and phantom source imaging above  $f_{alias}$

These points will be required for this solution to make it a real improvement:

- The audibility of comb filtering caused by the overlap of the few loudspeakers needed for phantom source imaging is much lower than the audibility of the aliasing of a normal full range WFS array → The sound colour of the combined source is improved
- Localization errors between different frequency bands are comparably small with the combined solution than with the full range WFS array, i.e. the difference between phantom source direction and WFS virtual source direction at high frequencies is not bigger than the differences produced by a full range WFS array. Because localization errors cause blurring of the virtual source or even separation of the different parts of the virtual source, there is no loss of the focus of the combined source.
- The installation of significantly fewer tweeters (e.g. spaced 1 m) and a conventional woofer array can help reduce costs and increasing loudspeaker quality.

### 3. Generation of OPSI signals

To generate OPSI signals these steps are necessary:

1. Generate the conventional WFS loudspeaker signals for the virtual source
2. Split these signals into a low-passed and a high-passed part,  $f_{\text{split}} = f_{\text{alias\_min}}$
3. Use the low-passed parts for the woofer array
4. Use the high-passed parts of the WFS signals according to the tweeters' locations, omit the others
5. Optionally apply additional level differences between the tweeter signals to achieve optimum stability and decrease localisation errors. To optimise this level differences apply localisation simulations. However, no additional manipulation is usually O.K. for most cases. → chapter 6
6. Make level adjustment between high- and low-passed part of the phantom source, it's also possible to estimate that by calculations

If applied, the only sophisticated action might be point 5. In chapter 6 some simulations are depicted that can be used to find the suitable values.

The psychoacoustic consequences of splitting the source into a high- and a low-frequency part are considered within the next chapter.

### 4. Psychoacoustic properties of an OPSI source

Two simultaneous sound events are processed in the acoustical perception of the listener:

- a low-frequency virtual source, i.e. the authentic **physical** replica of the real waveform of the source
- a high-frequency phantom source, i.e. an imitation of the virtual source by means of **psychoacoustic** principles

The OPSI solution creates a superimposition of these two perception events.

Now, questions arise about the consequences that this superimposition will have on the localisation properties. The mixture between two totally (or not ?, an open scientific question) different perception mechanisms follows certain rules, which are not clear just now. Within this paper, some first little experiments are depicted which can be helpful for the design of an OPSI system, but don't solve these questions.

First of all, these questions are asked:

- Do the two sound events actually merge two one sound event ?
- Which localisation properties (sound color, focus) does the merged sound event have ?

A very clear answer is found quickly: Yes, they merge fine, but the merging and the localisation properties are highly dependent on differences in the direction of the two sound events.

**The quality of the merged sound event is dependent on the *OPSI localisation error*.**

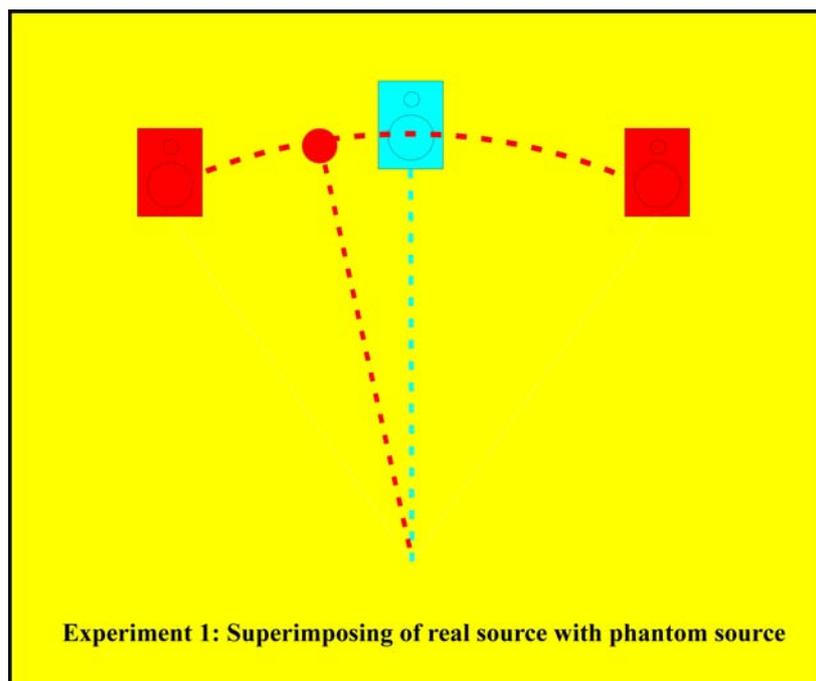
**The *OPSI localisation error* is defined as the directional difference between the low-frequency virtual source and the high-frequency phantom source**

The human perception mechanism is not able to distinguish between the two different sound events as long as the directions in which they are localized when reproduced separately coincide. If the sound events are coming from different directions they are perceived separately as they are not of the same “gestalt”. The intersection between these two possibilities, i.e. a small OPSI localisation error is expected to cause a blur of the localized virtual source, that is a decrease of the localisation focus of the source. First approximations of the magnitude of this “critical intersection OPSI localisation error” can be made out of the results of the following experiments.

## 5. Experiments considering the OPSI psychoacoustics

### A. Listening test 1

*In this test an average broad-band test signal (female voice, SQAM[]) was divided into a high-frequency part and a low-frequency part. The crossing frequency was chosen to be 1400 Hz (HP1) resp. 2300 Hz (HP2). Now, the low frequency (LF) part was reproduced via one loudspeaker (being the Center loudspeaker of a normal 3/2-Stereo setup). The HF part was reproduced as a phantom source between the left and the right loudspeaker (so at  $-30^\circ$  and  $+30^\circ$ ). Their level difference was varied to get different HF image directions. The test setup is illustrated in Fig. 4:*



*Figure 4: Experiment 1, Setup*

The panelists had in every example to toggle between two sound items:

- Reference: Superimposed sources from one direction  $0^\circ$  ( $\Delta L$  (L/R) = 0)
- Test item: Superimposed sources from different directions ( $\Delta L$  (L/R) = x dB)

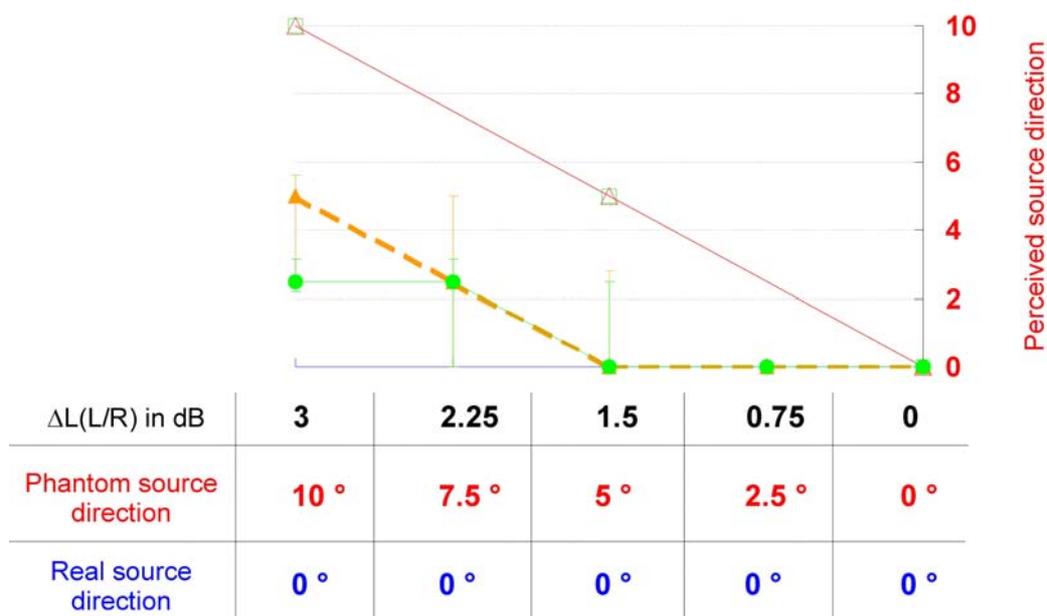
They were asked if there is a localization shift audible between these two examples.

The results are shown in Fig. 5.

It's obvious that the difference in localization can't be smaller than the localization accuracy. This limit is exceeded at a HF image of about  $7.5^\circ$ , quite independent of the shape of the HF/LF division. When the HF image is coming from  $10^\circ$  the 1.HP ( $f > 1400$ ) leads to an overall localization of about  $5^\circ$  (i.e. localization shift of ~50%) and the 2.HP ( $f > 2300$ ) leads to an overall localization of 2-3° (i.e. localization shift of ~25%).

It can be assumed that, using the 2.HP, a HF image that deviates less than  $7.5^\circ$  does not lead to an audible localization shift of the overall combined LF/HF image.

However, this result is only valid for this kind of test signal. It will be strongly dependent of the relationship of the LF and HF energy of the signal.



**Figure 5:** Listening Test 1: Perceived direction of

1. HF phantom source (red) created by level difference  $\Delta L$  (black)
2. LF real source (blue)
3. Merged source (orange and green)

The red numbers on the y-axis indicate the perceived source direction of the presented test item (in degrees)

**HF Phantom source shifting (Listening Test 2)**

The localization of a HF phantom source follows certain rules that differ significantly from the basic broadband phantom source theory. As it was already found out in related literature the phantom source shift caused by a level difference  $\Delta L$  is larger for pure HF signals. According to own, preliminary experiments, the well-known phantom source shift factor of 7.5 % /dB for broadband signals changes to ca. 12 % /dB for HF signals.

## B. Listening Test 2

*The results of this listening test can be read in the Master's thesis of Thomas Huber (IRT/ TU München, available on [www-hauptmikrofon.de](http://www-hauptmikrofon.de)). The main result: The localization focus of the perceived images does not change when instead of pure Wave field synthesis an OPSI solution applied. This proves the OPSI solution to be a useful alternative.*

### 6. Localisation performance in the entire listening area

It is desired to minimize the difference between the WFS virtual source direction and the perceived phantom source direction. This "OPSI localisation error" determines the magnitude of the localisation focus or even the separating of the different parts of the source. (→ chapter 4)

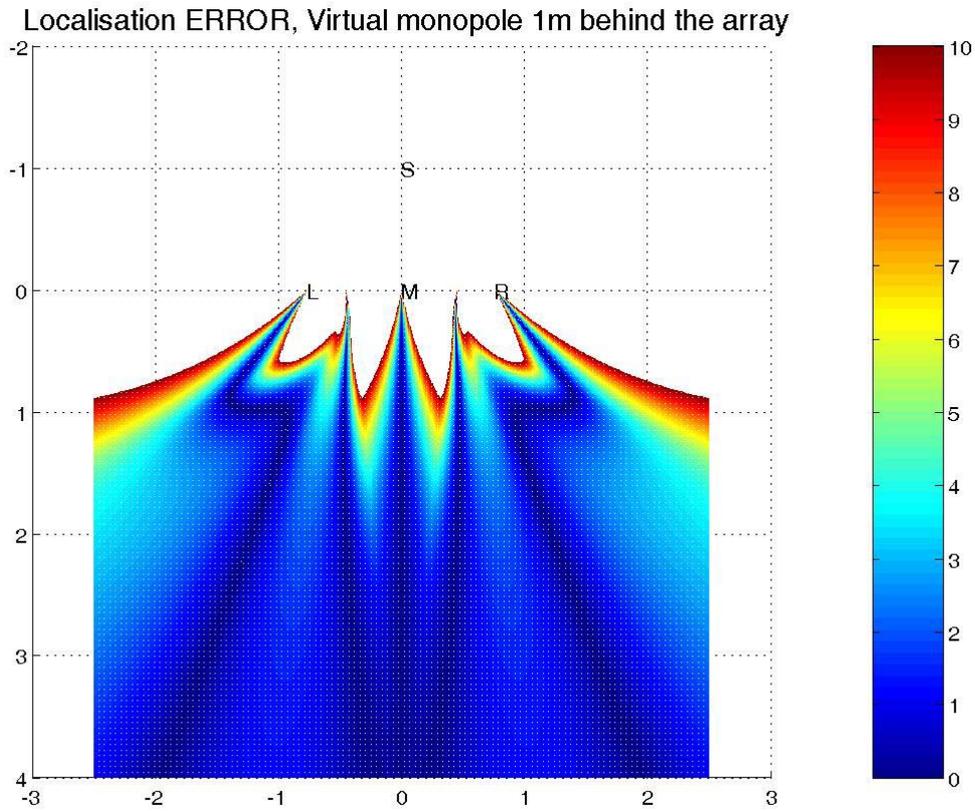
The OPSI localisation error can be simulated within a listening area. Therefore the direction of the virtual WFS source has to be calculated which is assumed to be congruent with the ideal of a real source. In addition an approximation of the perceived direction of the HF phantom source has to be made. This task requires knowledge of the psychoacoustic basis of phantom source shifting dependent on time and level differences of the phantom source loudspeakers. As depicted in the gray box ("HF phantom source shifting") of the latter chapter, the psychoacoustic basis changes for HF signals. Following basic relationships are used to approximate the phantom source direction:

LEVEL :	Phantom source shift $\Delta$ / level difference $\Delta L = 12 \% / \text{dB}$
TIME :	Phantom source shift $\Delta$ / time difference $\Delta t = 12 \% / 0.1 \text{ ms}$

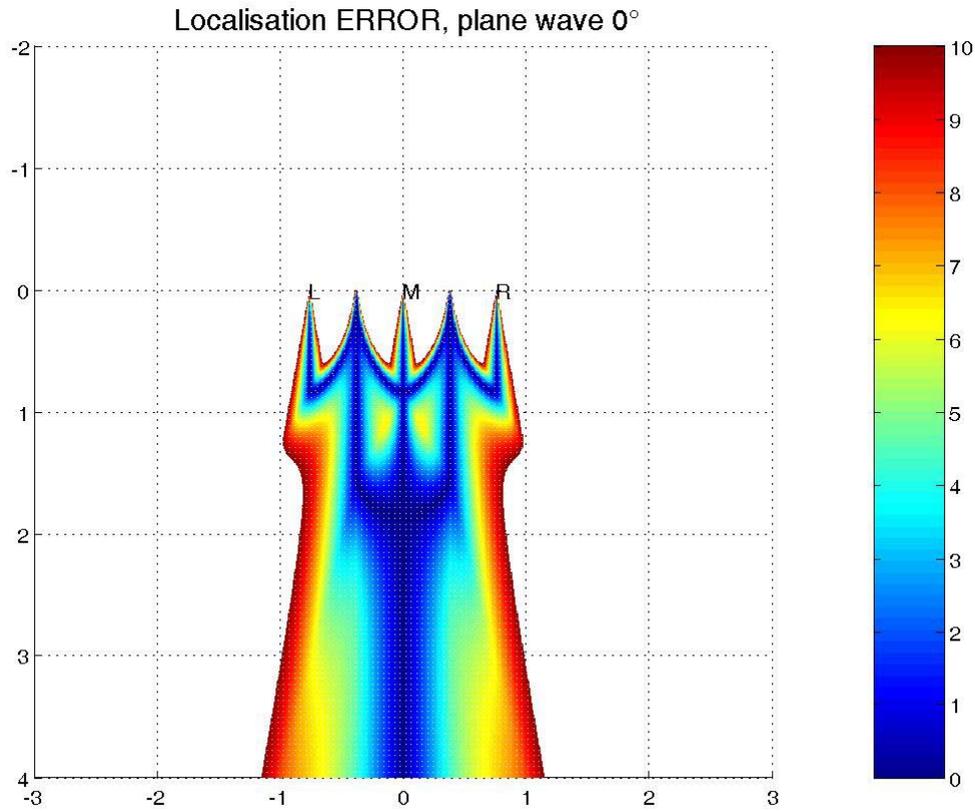
For every location within the listening area the time and level differences between the phantom source loudspeakers are calculated, and the corresponding phantom source shifts and respective corresponding phantom source directions are derived. Now, the OPSI localisation error can be derived as the difference of this direction to the WFS virtual source direction.

Some examples are shown here:

The figures show the OPSI localisation error (absolute values in degrees from  $0^\circ$  to  $10^\circ$ ), i.e. the difference between the true WFS virtual source direction and the perceived phantom source direction. So the figures show the deviation between LF and HF image. The diagram shows a big listening area of the dimension  $4 * 5$  meters. The virtual source (S) and the three phantom source speakers (L, M, R) are indicated within the figures. Three phantom source speakers are used, the distances to the Center loudspeaker are 0.75 m.



**Figure 7:** Simulation of the OPSI localisation error (in degrees),  
 x- and y-axis indicating dimensions in the listening room (meters)  
 Virtual source = monopole, 1m behind the array,  
 No additional level manipulation of the phantom source signals



**Figure 8:** Simulation of the OPSI localisation error (in degrees),  
 x- and y-axis indicating dimensions in the listening room (meters)  
 Virtual source = plane wave, 0°,  
 No additional level manipulation of the phantom source signals

The OPSI localisation error is dependent on the distance of the virtual source, the phantom source loudspeaker bases and the level manipulations of the phantom source loudspeakers.

In general, optimal reproduction is enabled when the virtual source is located between the phantom source loudspeakers out of the perspective of the listener. Additionally, a certain minimum distance to the phantom source loudspeakers is required for optimal localisation and level conditions. This distance is mainly dependent on the magnitude of the loudspeaker bases.

With these results the upper performance of the plane wave reproduction could be improved. One could e.g. use another two phantom source loudspeakers on the sides to enlarge the listening area.

## 7. Discussion

It has been shown that the “OPSI” method could be a good alternative to avoid artefacts on sound colour and localization. It could be a suitable compromise between pure WFS (with the emphasis on unchanged, pure reproduction) and loudspeaker stereophony (with the emphasis on optimisation of sound colour).

The advantages of WFS, such as the real acoustical perspective, the huge independence of the listener’s position and the impressive near-head localization, are still valid with the OPSI solution.

Further practical experience will show the usability of this system. The reduction of reproduction channels through OPSI has already been proven as a big advantage.