Wave Field Synthesis in Three Dimensions By Multiple Line Arrays

Matthew N. Montag

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Presentation Outline

- Background
  - What is Wave Field Synthesis?
  - Theory of Wave Field Synthesis
  - Limitations of Wave Field Synthesis
- Objectives
- Original Contributions
  - 48-Channel Low-cost, Modular Loudspeaker Array
  - WFS Visualizer
  - WFS Designer cross-platform application
- Proposed System: WFS with Multiple Line Arrays
- Listening Test
  - Hypothesis
  - Test Setup
  - Results
- Conclusion and Future Work

A Little Background…

- Wave field synthesis was introduced by seismologist A.J. Berkhout in 1988
- WFS is established in research and commercial applications
- Over 50 installations around the world
  - Recording studios
  - Theaters
  - Auditoriums
  - Disney World's Haunted Mansion

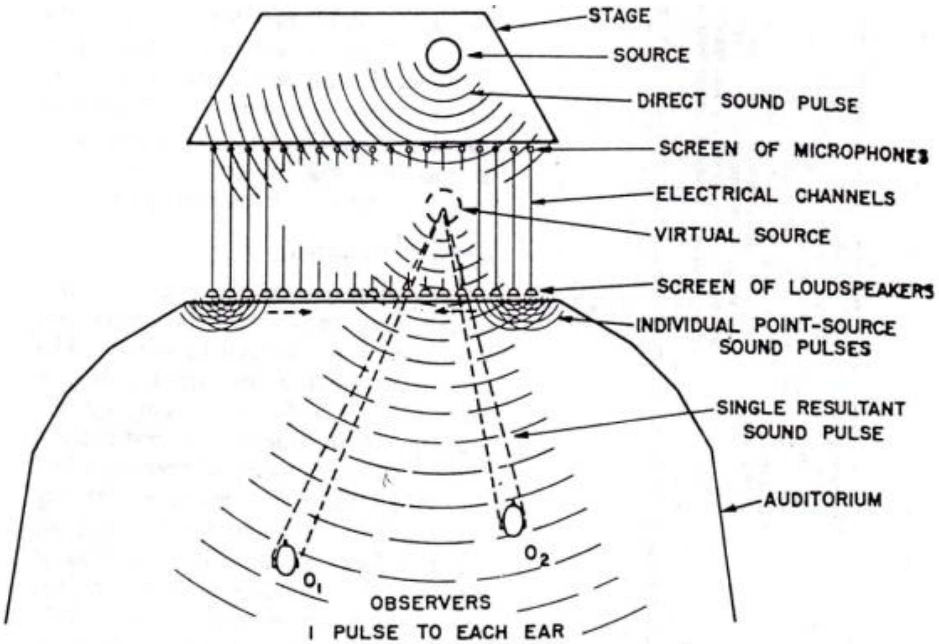
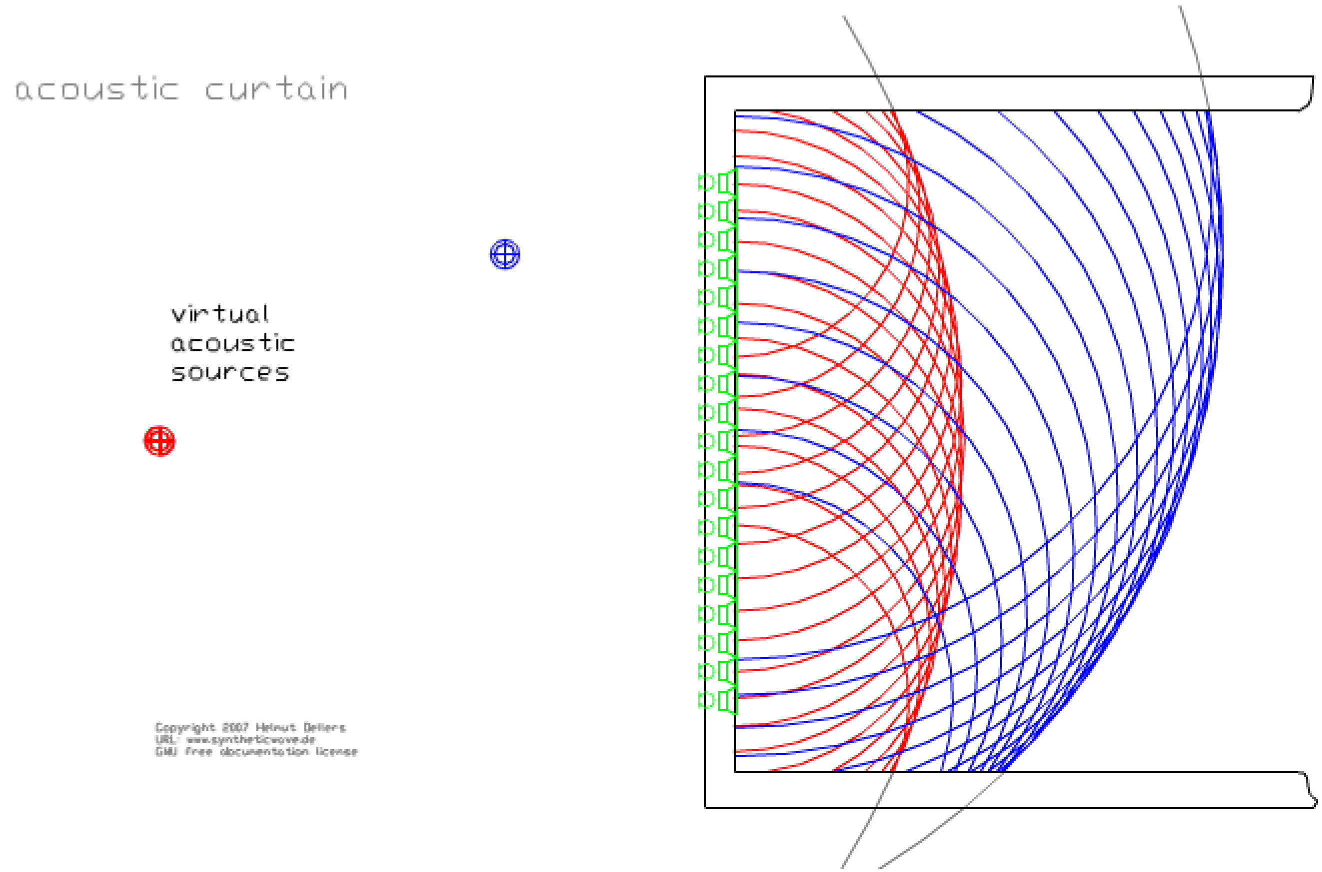


Fig. 2. Ideal stereophonic system. A very large number of very small microphones and loudspeakers would give a perfect reproduction of the original sound.

Steinberg and Snow originally proposed the "acoustic curtain" in 1934.

What is Wave Field Synthesis? A Visual Explanation



Helmut Oellers, www.syntheticwave.de

Stereo vs. Wave Field Synthesis

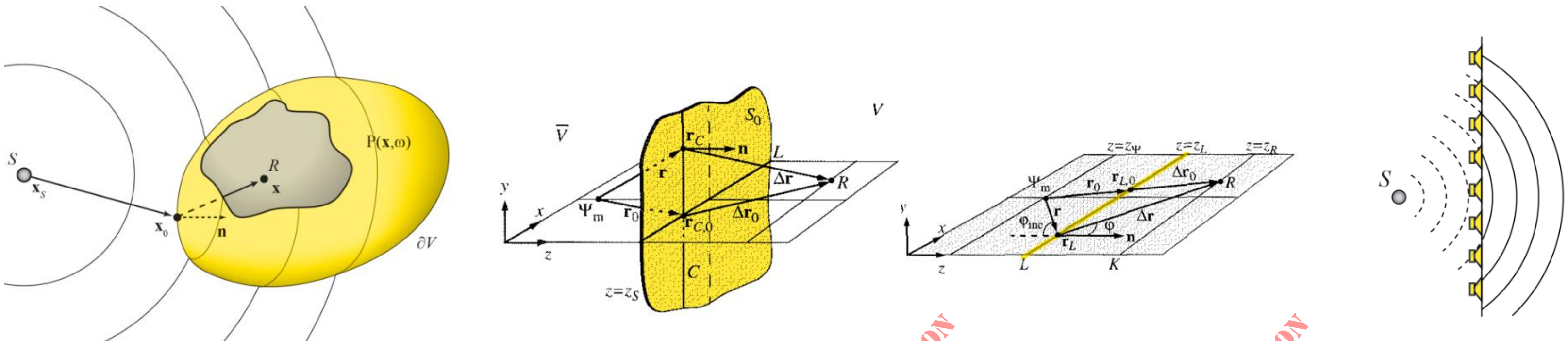
- Conventional stereo and surround sound use amplitude panning and produce a phantom source
- Optimal spatial impression is only achieved in a small area (sweet spot)
- Source position is an “illusion”

- Wave field synthesis produces a stable virtual source image throughout an entire listening area
- Virtual sources can be placed inside the listening area
- Source is physically approximated by wave field

For the purposes of this thesis,

- A **virtual source** is defined as a source produced by physical reconstruction of the wave field (as in WFS).
- A **phantom source** is a source produced by conventional amplitude panning.

Theory of Wave Field Synthesis



surface → *plane* → APPROXIMATION *line* → APPROXIMATION *discrete line*

KIRCHHOFF-HELMHOLTZ | RAYLEIGH 3D | RAYLEIGH 2.5D | WFS DRIVING FUNCTION

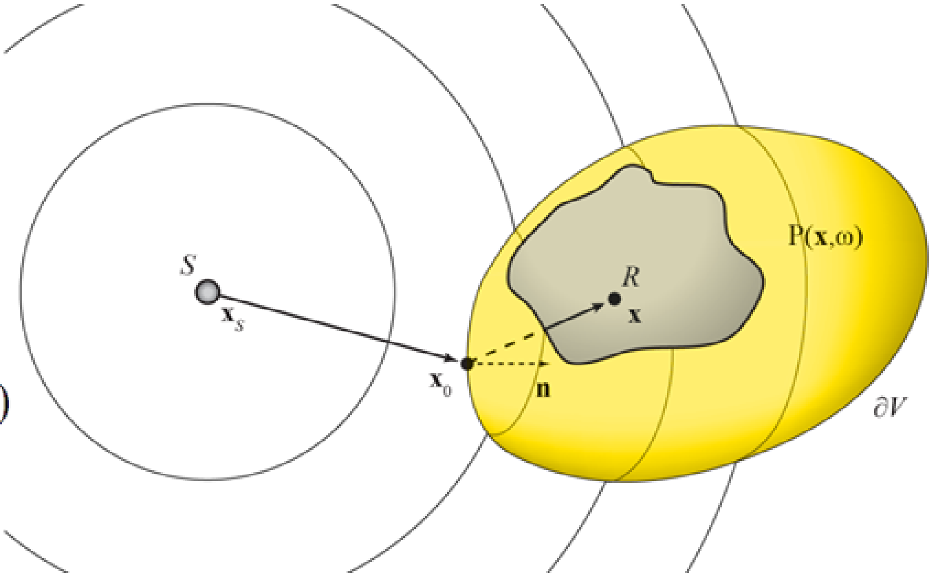
- WFS is based on the Huygens principle: a wave front can be recreated by adding smaller wave fronts.
- The Kirchhoff-Helmholtz integral states that a perfect reconstruction of a source wavefront is possible inside a volume.
- WFS introduces basic approximations to sound field reconstrucition:
  - Reduction from a **plane** to a **line** of secondary sources
  - Reduction from **continuous** to **discrete** secondary sources
- These approximations result in amplitude and spectral errors in the wave field, but can be optimized.

WFS Discrete Driving Function

$$D(\mathbf{x}_0,\omega) = S(\omega)\cdot H(\omega)\cdot w(\mathbf{x}_0)\cdot e^{-j\omega\tau_0(\mathbf{x}_0)}$$

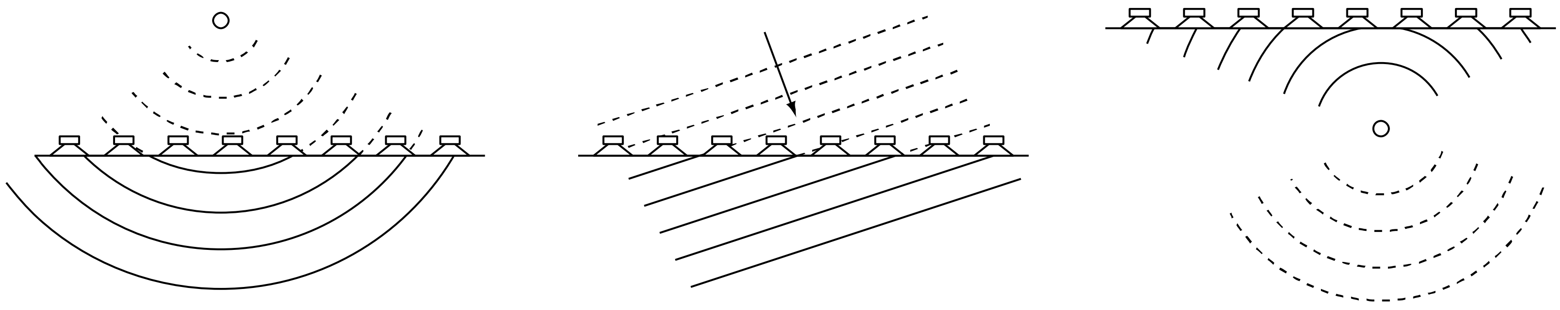
Inverse Fourier transform

$$d(\mathbf{x}_0,t) = s(t) * h(t) * w(\mathbf{x}_0) * \delta(t-\tau_0(\mathbf{x}_0))$$



- The driving function $d(\mathbf{x}_0,t)$ defines what the array loudspeaker at position $\mathbf{x}_0$ should be doing at time t.
- $s(t)$ is the virtual source signal at time t.
- $h(t)$ is a static pre-equalization filter to correct for WFS approximations.
- $w(\mathbf{x}_0)$ is the amplitude factor.
- $\tau_0(\mathbf{x}_0)$ is the time delay factor.
- $\tau_0(\mathbf{x}_0)$ is the time it would take sound to travel from the source at $\mathbf{x}_S$ to the array position $\mathbf{x}_0$: generally $\frac{|\mathbf{x}_0-\mathbf{x}_S|}{c}$.
- $w(\mathbf{x}_0)$ amplitude factor incorporates virtual source distance attenuation and angle of incidence of the source wavefront on the array contour (oblique wavefronts are attenuated).

Characterization of Virtual Sources



Spherical source, plane wave source, and focused source.

Three types of virtual source:

- Spherical Source
  - A virtual point source behind the array.
- Plane Wave Source
  - A virtual plane wave source without a position, only defined by direction.
- Focused Source
  - A virtual point source in front of the array.

Distinction is important because each type of virtual source requires a different driving function.

Limitations of Wave Field Synthesis

- Amplitude error
  - Line array produces cylindrical instead of true spherical wave; 3dB rolloff per doubling of distance instead of 6dB
  - Resolve by optimizing amplitude for a reference listener distance
- Truncation /diffraction effects
  - Solve by gradually rolling off gain at edges of array (tapering) or by completely surrounding listener with speakers
- Spatial aliasing
  - Occurs when the wavelength of the signal is shorter than the loudspeaker spacing. 1 to 3 kHz in most configurations. Results in spatially-varying coloration and pre-echo
  - Resolve by bandlimiting the signal or redirecting high frequency content for simple amplitude panning; "sub-band mixing method"
- Room acoustics
  - Reflections of the secondary source off listening room walls do not correspond to virtual source reflections.
- Restriction to horizontal plane
  - Virtual sources can only be presented through the window of loudspeakers. Virtual source space is restricted to the plane for linear loudspeaker arrays. Practical limitation – too many loudspeakers required for a plane array

Research Objectives

Three complementary goals:

1. Build a low-cost, modular loudspeaker array suitable for research and creative applications beyond wave field synthesis
2. Create an open source, cross-platform wave field synthesis software environment
3. Enhance wave field synthesis by practically extending the virtual source space to the vertical dimension

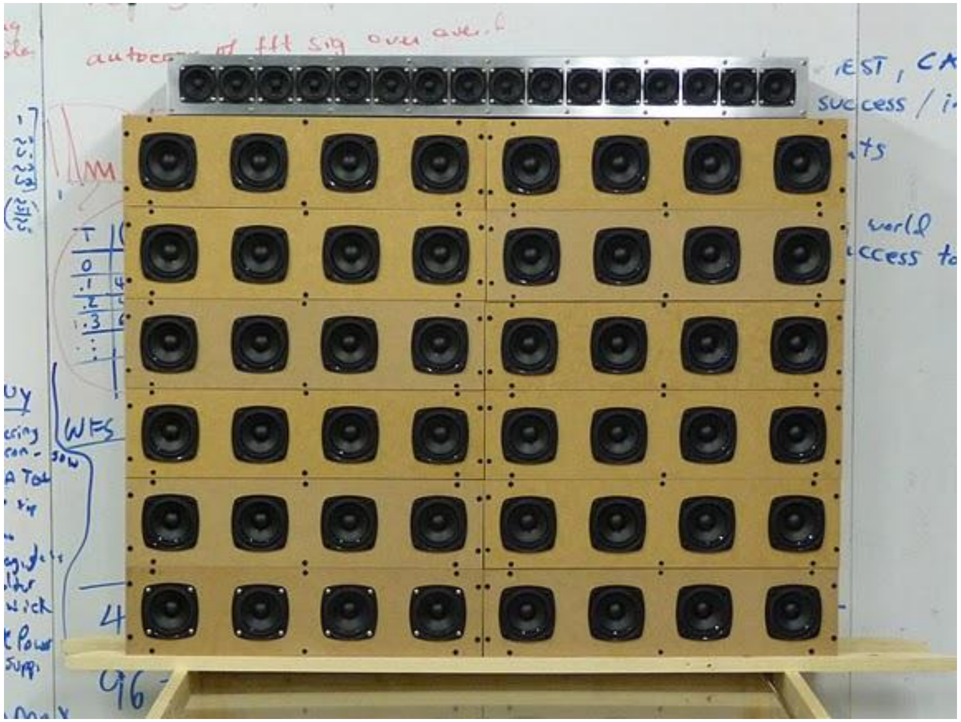
48-Channel Loudspeaker Array

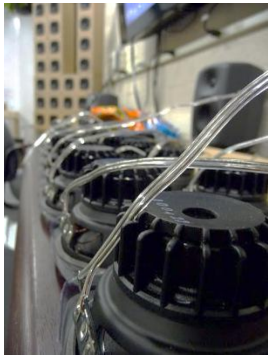
- Competing design constraints:
  - Easily reconfigurable
  - Flexible
  - Stackable
  - Low-cost
  - High spatial aliasing frequency (speakers need to be closely-spaced)
  - Wide array coverage

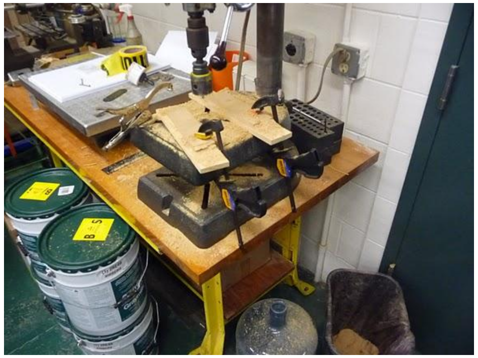
48-Channel Loudspeaker Array

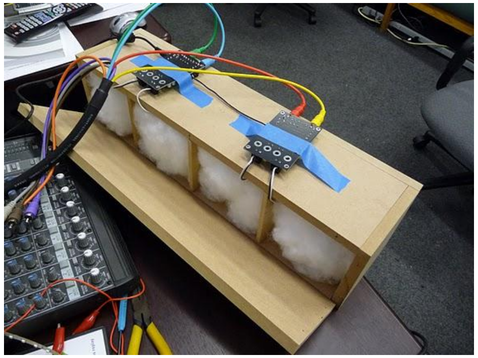
Solution:

- 12 four-speaker modules
- 5” spacing – 2.7 kHz f_{alias}
- Materials: $15 per channel
- Amplification: $7 per channel

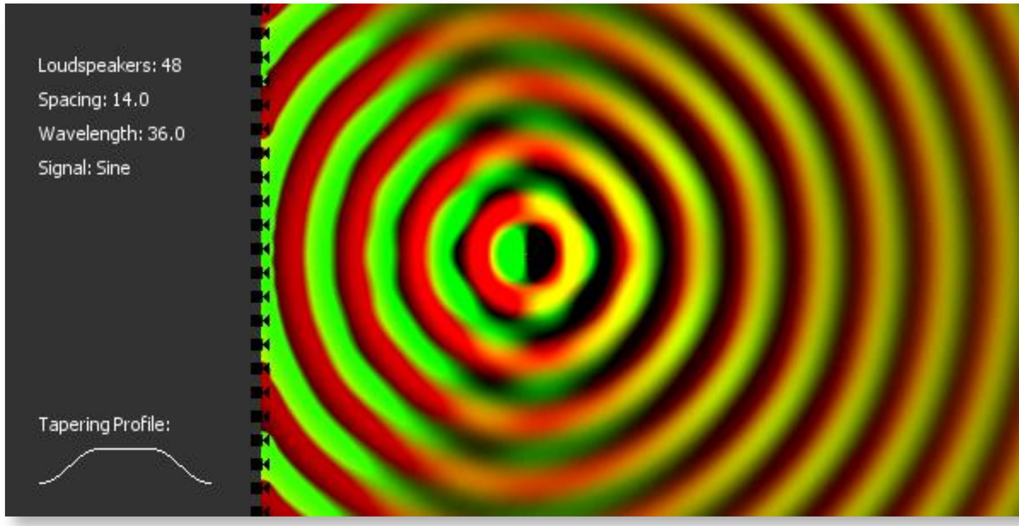








WFS Visualizer Java Applet



WFS Visualizer is a Processing sketch/Java applet that simulates wave field synthesis. A virtual source follows the position of the mouse cursor. It is useful for visualizing the behavior and limitations of WFS.

p	Toggle primary wave
1/2	Increase/decrease resolution
q/w	Adjust tapering profile ($\cos^n$)
Left arrow/Right arrow	Decrease/increase number of loudspeakers
Up arrow/Down arrow	Increase/decrease array spacing
[/]	Decrease/increase signal wavelength
S	Change signal waveform (sine, noise, and saw)

WFS Designer

WFS Designer is a cross-platform, open source wave field synthesis software environment.

(Demonstration after presentation.)

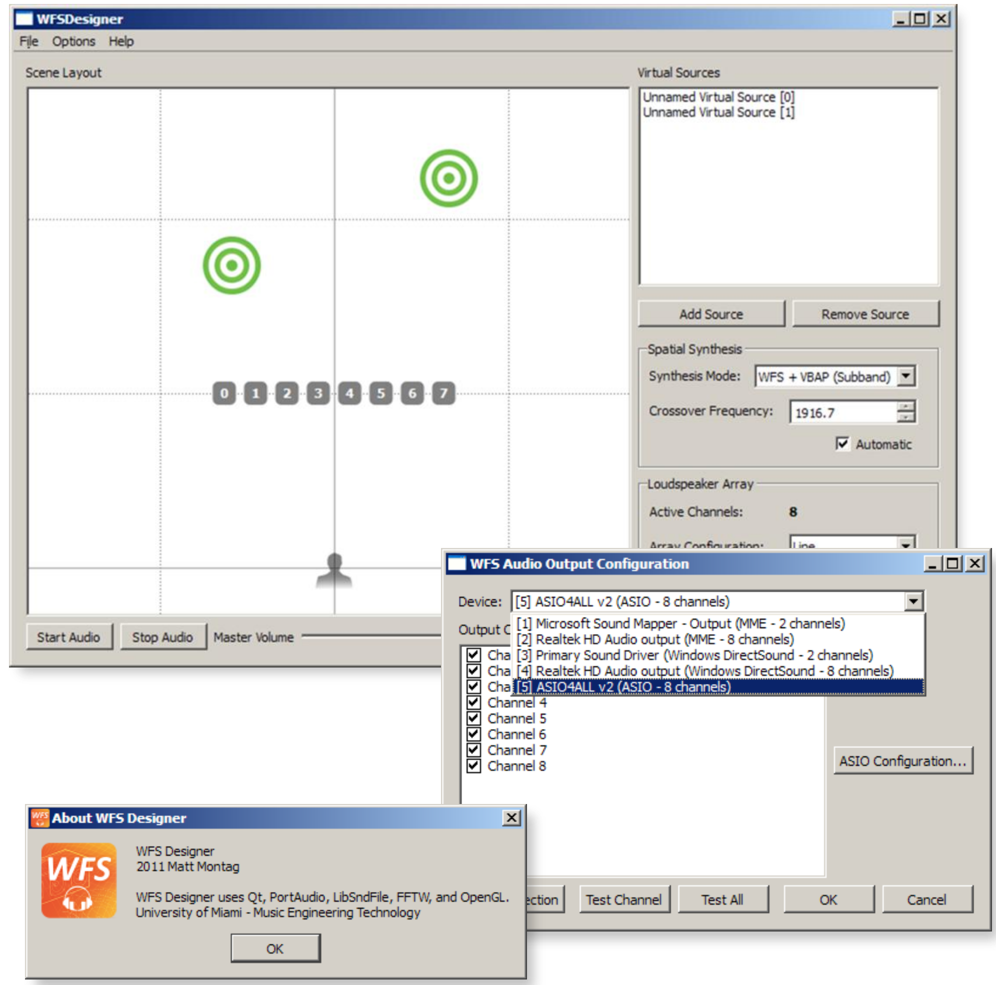
Makes use of:

- Qt framework, OpenGL, Libsndfile, PortAudio, FFTW

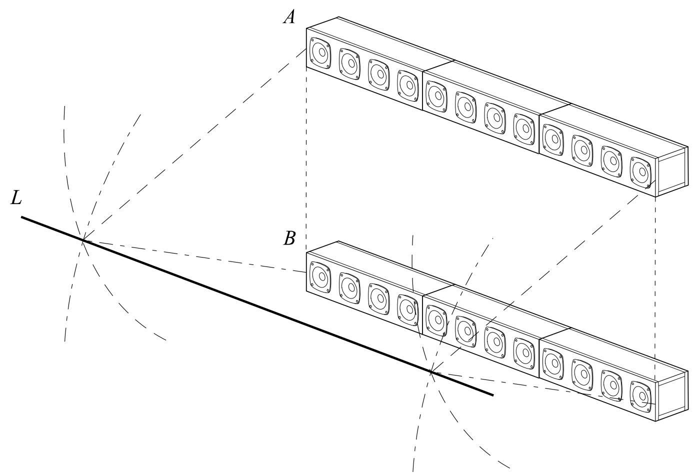
WFS Designer

Features:

- Position any number of sources in graphical interface
- Automatically configure several array geometries
- Four synthesis options
  - WFS+VBAP (Sub-band mixing)
  - WFS
  - Bandlimited WFS
  - VBAP
- Flexible loudspeaker positioning
- FIR convolution and delay-line implementations of WFS
- ***True 3-dimensional virtual source manipulation space***



Proposed System: Multiple Line Array Wave Field Synthesis



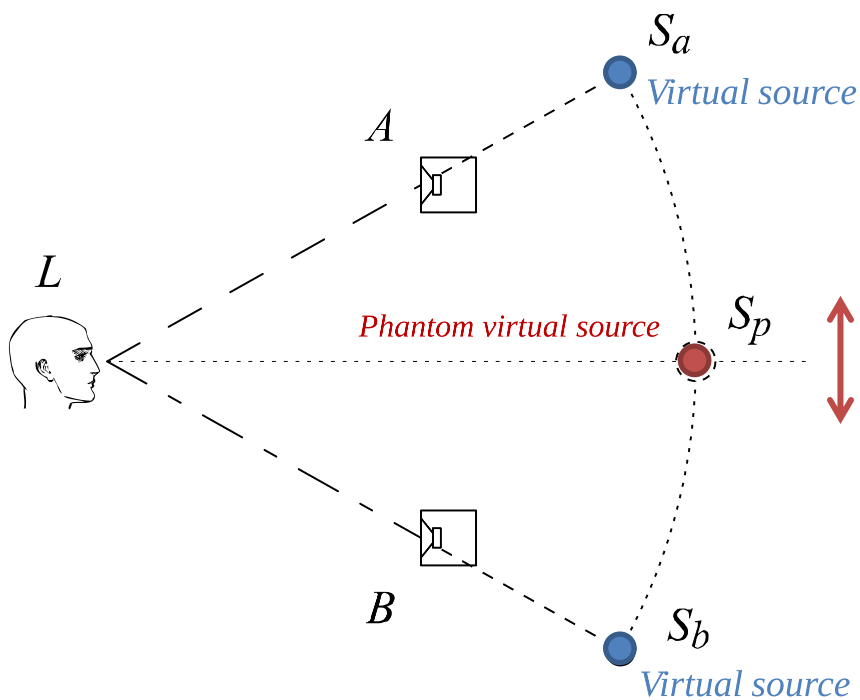
- Purpose: extend WFS in vertical direction
- Achieved by stacking two or more arrays vertically.
- Removes the restriction to the horizontal plane without using a complete plane array.
- Sources are steered with wave field synthesis in the horizontal direction, and with amplitude panning in the vertical direction.
- Multiple line array WFS is implemented in WFS Designer.

Proposed System: Multiple Line Array Wave Field Synthesis

Example:

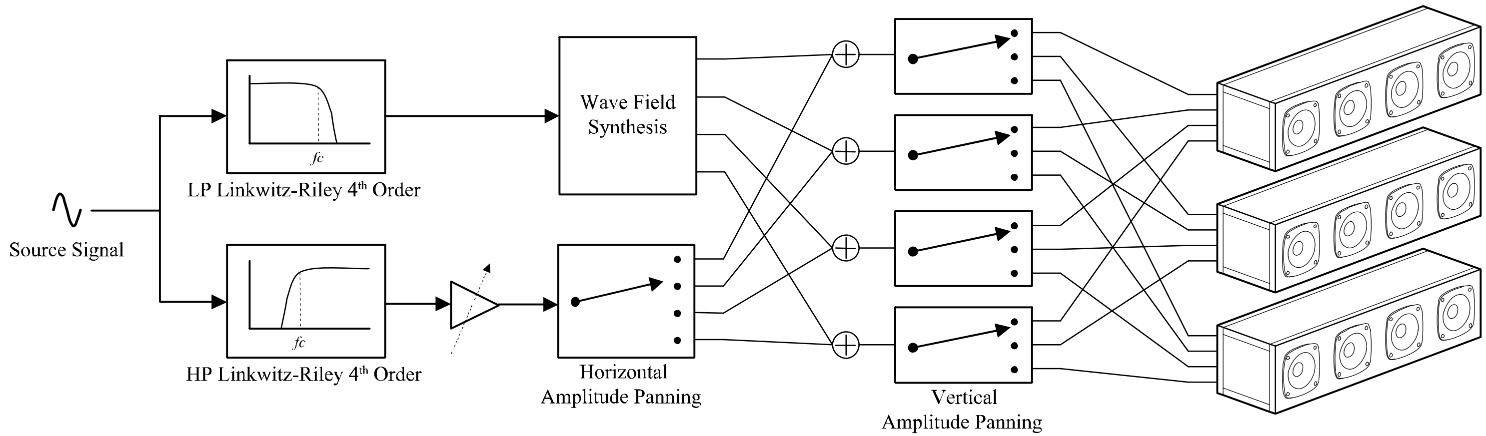
- If a virtual source is positioned between a line array and another identical line array duplicated 6 feet above it, a single horizontal WFS solution is calculated and emitted at equal gain from both top and bottom line arrays.
- If the virtual source moves closer to the top array, the WFS solution is attenuated in the bottom array and intensified in the top array, just as the phantom source in conventional stereo amplitude panning.

Therefore, the virtual source, based on the description of its synthesis method, is now both a phantom source and a virtual source. For convenience, we will refer to it as a ***Phantom Virtual Source***.



S_a and S_b perceptually merge at position S_p.

Signal Flow in Multiple Linear WFS



This example pertains to the sub-band mixing method.

- Signal is separated into low-frequency and high-frequency content
- Low-frequency content is sent for horizontal wave field synthesis (WFS)
- High-frequency content is sent for horizontal amplitude panning (VBAP)
- Result is mixed at each channel
- WFS+VBAP solution is amplitude panned vertically across array rows

Purpose of Listening Test

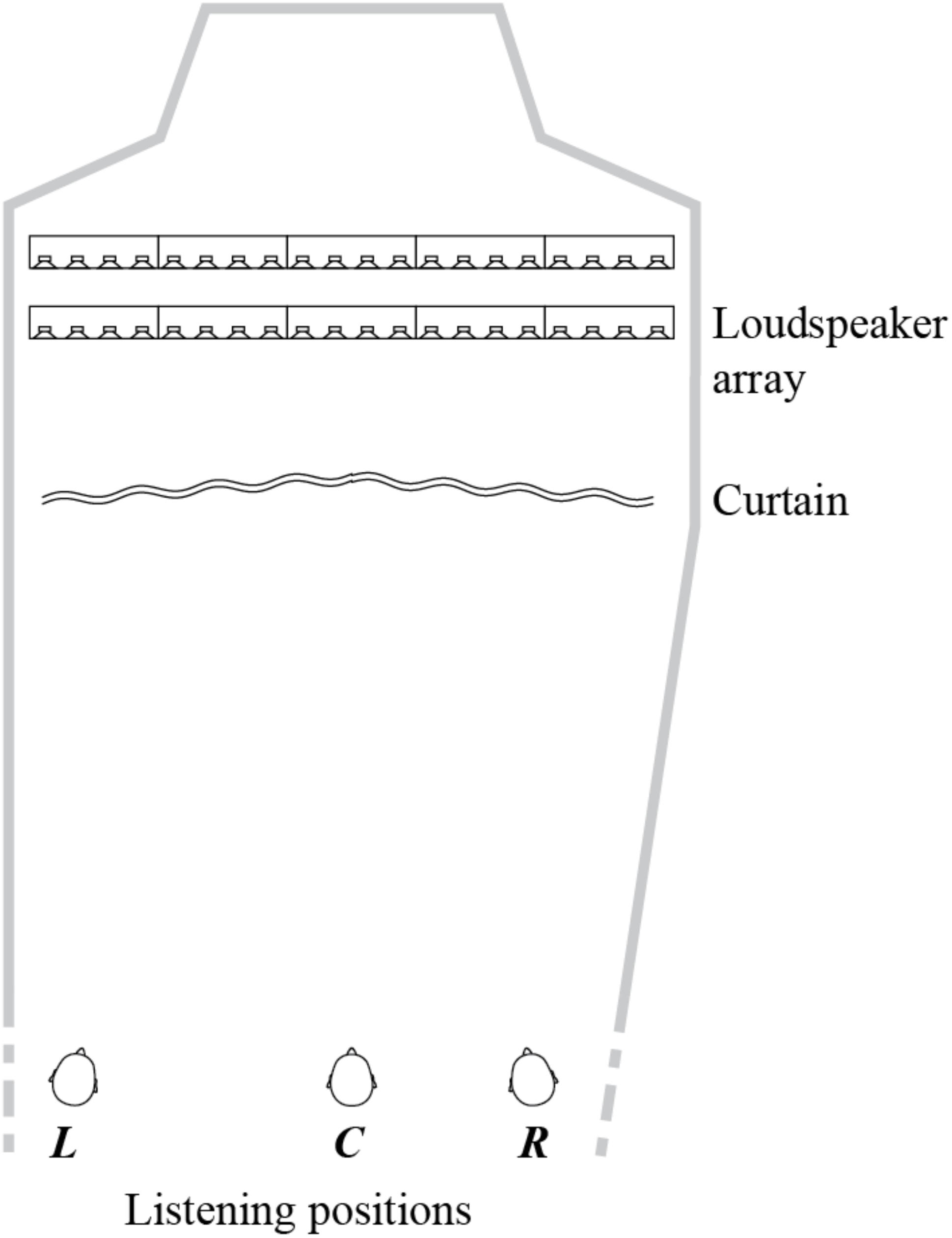
The purpose of the listening test was to test two hypotheses:

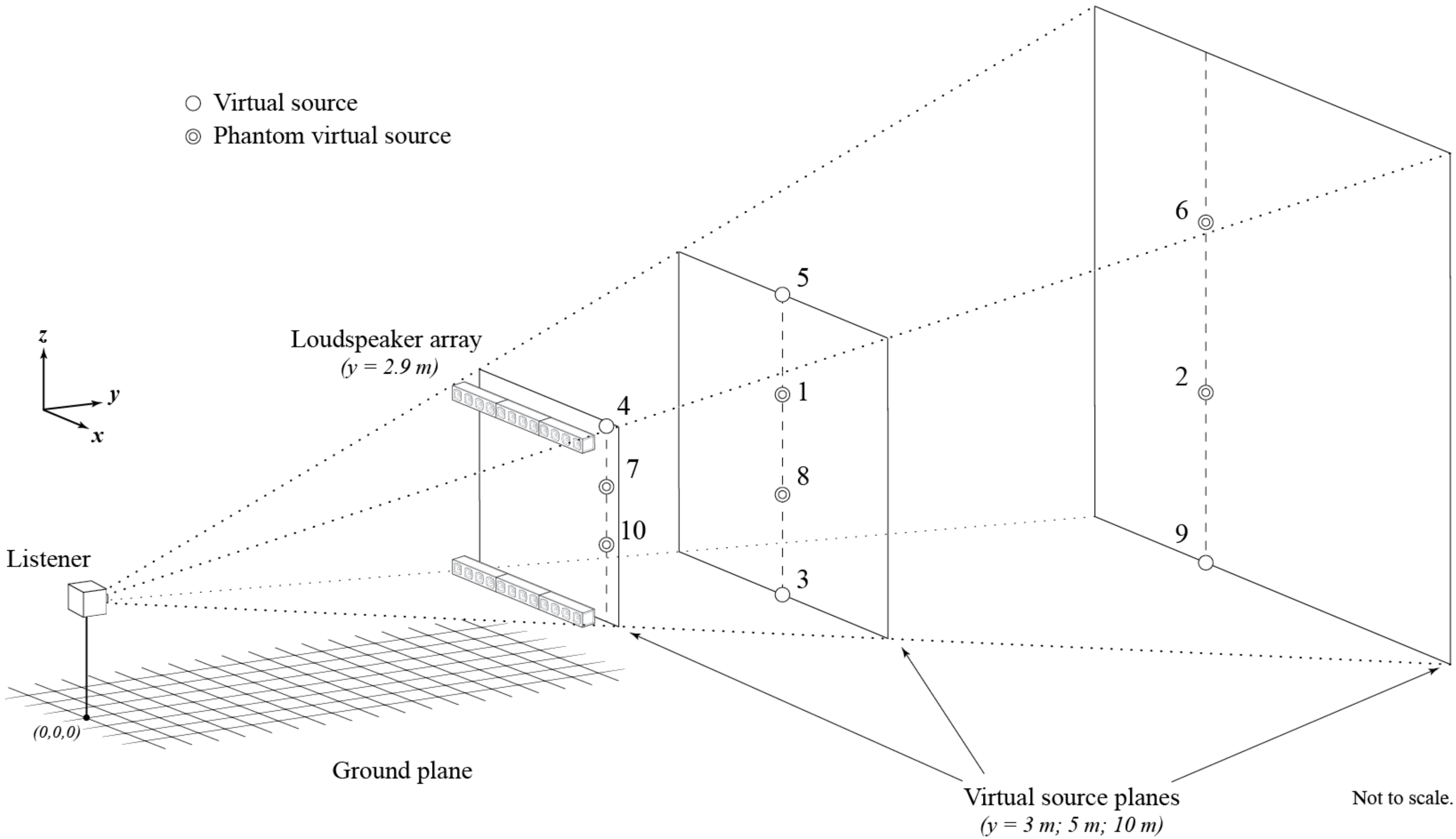
1. Localization cues of wave field synthesis are preserved under the multiple line array method. No significant error is introduced.
2. Vertical localization of virtual sources is at least as accurate under the multiple array method as under traditional single-array horizontal wave field synthesis.

Listeners were asked to localize 10 different test tones, indicating the perceived direction on a curtain with a laser pointer. Thirteen subjects participated and performed 170 total evaluations.

Listening Test Setup

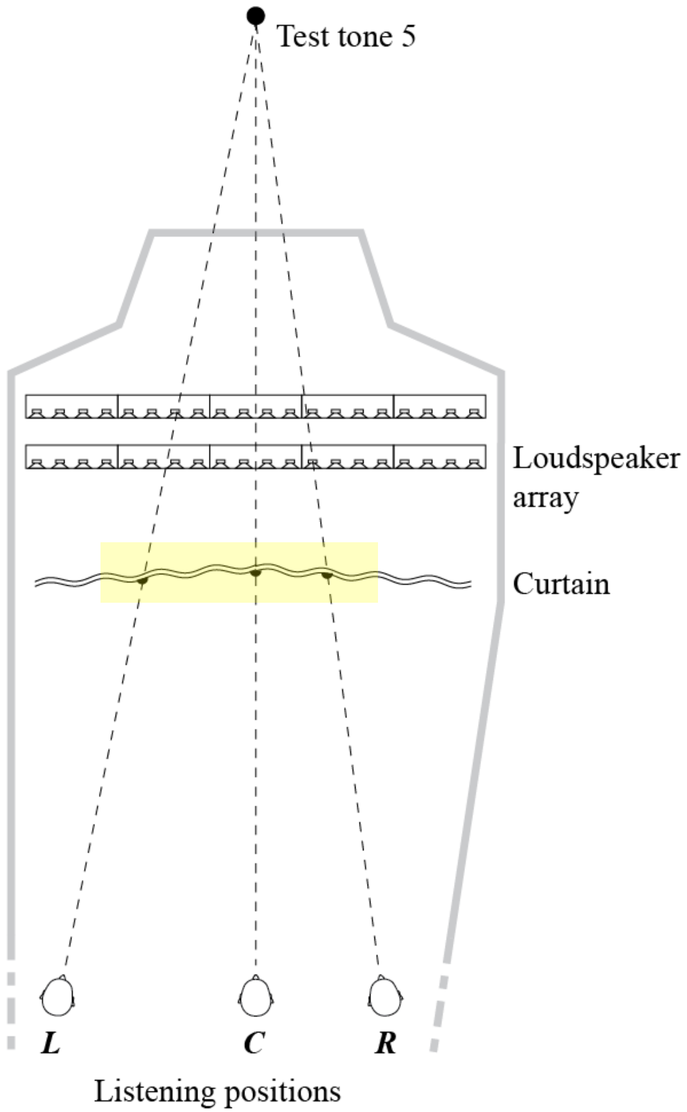
- 40-loudspeaker array in 2 rows
- Array width: 254 cm (8’4”)
- Array height: 82 and 216 cm (2’8” and 7’1”)
- Distance: Listeners seated 2.9 meters (9’6”) away from loudspeaker array
- Three listening positions
- Test signal: white noise limited to 2.7 kHz



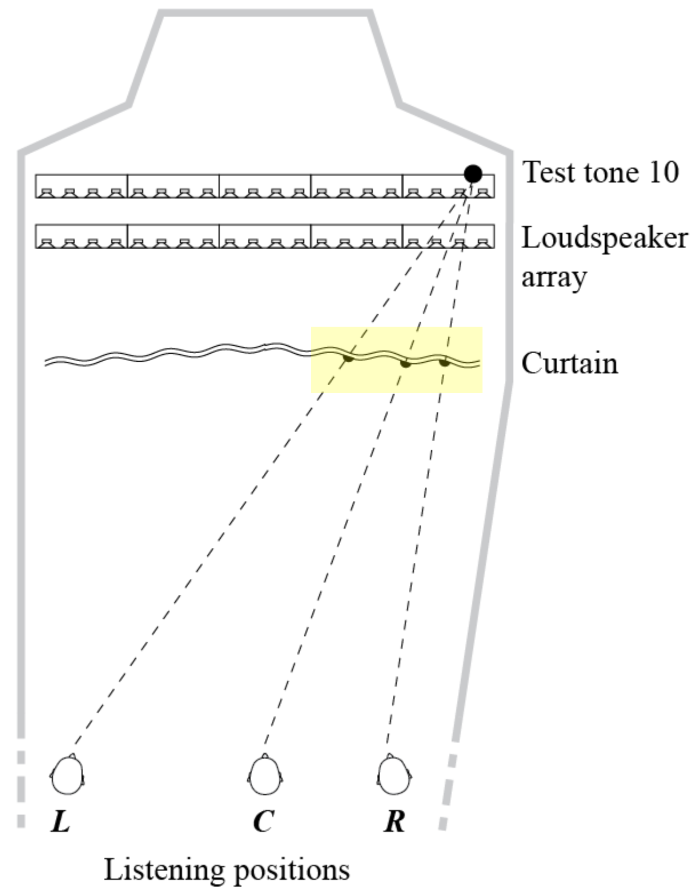


Test Tone Virtual Locations

- Tones 3, 4, 5, 9 are virtual sources because they are on the listener-array plane
- Tones 1, 2, 6, 7, 8, 10 are phantom virtual sources because they are between the listener-array planes



Validation of WFS: Stable source position



Validation of WFS: Stable source position

Localization Results

Overall **horizontal** localization error:
σ = 3.4 degrees

Overall **vertical** localization error:
σ = 6.6 degrees

ANOVA horizontal axis:

$F = 0.23$

$F_{crit} = 3.90$

ANOVA vertical axis:

$F = 1.51$

$F_{crit} = 3.90$

$F < F_{crit} \rightarrow$ **accept** null hypothesis.

	A	B	C	D	E	F	H	I	J	K	M	N	O	P	R	S	T	U	X	Y	Z
1			VIRTUAL SOURCES																	PHANTOM	
2			3, 4, 5, 9																	1, 2, 6, 7, 8, 10	
3			3				4				5				9					1	
4		distance	250.0				10.0				250.0				750.0				distance		
5		reference	**114.5**	**121.0**			**191.0**	**33.5**			**114.0**	**33.0**			**88.5**	**117.0**			reference	**114.5**	**62.0**
6			105.5	105.5	0.5	-36.6	194.0	32.0	3.3	1.0	108.0	53.5	-5.1	20.0	74.0	124.5	-15.3	-12.2		106.5	60.5
7	Center		107.0	102.0			201.5	14.0			92.0	41.0			46.0	156.0				107.5	47.0
8			121.0	94.0	12.6	22.6	199.5	34.5	8.5	13.2	104.5	14.5	11.8	27.1	91.5	90.0	17.5	34.8		120.5	30.0
9			107.0	64.5			196.5	45.0			120.5	72.5			85.0	80.5				142.0	35.0
10			134.5	56.0			180.0	47.0			119.5	83.5			69.5	73.0				137.0	69.0
11		reference	**61.5**	**121.0**			**156.0**	**36.0**			**61.0**	**34.5**			**19.5**	**116.0**			reference	**60.5**	**63.5**
12			58.0	117.0	16.8	-26.6	149.5	23.0	3.9	16.6	58.0	46.0	-1.9	14.0	4.5	126.5	25.1	-17.2		38.0	89.0
13			79.5	122.0			168.5	22.5			56.0	33.5			56.5	139.0				71.0	104.0
14	Left		80.0	107.5	13.3	30.3	172.0	20.5	10.5	34.7	55.5	28.0	8.6	25.5	67.5	118.5	23.3	34.7		81.5	87.0
15			88.5	102.5			162.0	88.5			56.5	23.0			49.0	101.5				49.5	39.5
16			68.0	90.0			166.5	93.0			78.5	42.5			24.0	94.0				58.5	31.5
17			75.0	90.0			143.0	86.5			55.0	74.5			67.5	75.5				68.5	31.5
18			99.0	31.5			158.0	34.5			54.5	92.0			43.0	36.5				74.5	25.0
19		reference	**144.0**	**121.0**			**207.5**	**34.0**			**143.5**	**33.5**			**129.5**	**116.0**			reference	**144.0**	**62.5**
20			137.5	121.5	12.1	-2.5	202.0	33.5	0.0	15.3	173.5	40.0	14.7	42.3	134.0	122.0	7.8	18.1		128.5	68.5
21	Right		145.5	115.0			208.0	37.0			165.0	60.5			130.5	131.0				150.5	127.5

X	Y	Z	AA	AB	AD	AE	AF	AG	AJ	AK	AL	AN	AN	AO	AP	AS	AT
	PHANTOM VIRTUAL SOURCES																
	1, 2, 6, 7, 8, 10																
	1				2				6				7			8	
distance		250.0				750.0				750.0				10.0			
reference	**114.5**	**62.0**			**88.0**	**88.0**			**88.5**	**60.5**			**190.5**	**59.5**		**113.5**	**92.0**
	106.5	60.5	8.2	-13.7	65.0	115.0	-13.5	-13.9	84.0	60.0	-8.2	-2.4	193.0	65.0	8.0	1.2	105.5	125.5
	107.5	47.0			82.5	69.0			88.5	65.0			193.0	77.5			102.0	95.5
	120.5	30.0	16.4	16.5	91.0	68.0	11.7	23.4	80.0	67.5	9.1	8.8	214.5	102.0	12.9	34.1	105.0	64.0
	142.0	35.0			69.0	61.0			84.0	50.0			209.0	48.0			115.5	64.0
	137.0	69.0			65.0	57.5			65.0	48.0			183.0	11.0			118.0	92.5
reference	**60.5**	**63.5**			**18.0**	**90.0**			**19.0**	**62.5**			**156.5**	**62.0**			**61.5**	**93.0**
	38.0	89.0	2.6	-5.3	50.0	105.5	37.5	-32.6	25.0	24.0	12.5	-7.8	136.5	85.5	4.6	-12.5	72.5	94.0
	71.0	104.0			55.5	101.5			24.5	20.0			153.5	109.0			87.0	104.0
	81.5	87.0	15.3	33.5	47.5	86.5	9.3	38.3	42.5	21.0	20.9	34.0	151.0	43.5	15.7	34.1	57.5	137.5
	49.5	39.5			45.0	29.5			73.5	66.0			160.5	20.0			85.5	81.0
	58.5	31.5			54.5	26.5			27.5	102.0			167.5	26.5			69.5	77.0
	68.5	31.5			67.5	28.5			15.5	90.5			178.5	28.0			74.5	44.0
	74.5	25.0			68.5	24.0			12.0	59.5			180.5	34.0			80.0	48.0
reference	**144.0**	**62.5**			**128.5**	**89.0**			**129.0**	**62.0**			**207.5**	**61.0**			**143.0**	**92.0**
	128.5	68.5	17.8	11.0	128.0	125.5	16.0	-7.5	120.0	47.0	7.4	18.4	212.5	62.0	5.3	-21.2	123.5	72.5
	150.5	127.5			139.5	106.0			138.0	43.5			214.0	66.0			146.5	109.5
	171.5	116.0	22.5	47.3	134.0	88.0	15.7	36.7	140.5	98.0	9.4	33.1	204.0	25.5	5.3	22.6	148.5	126.5
	173.0	26.5			154.5	46.0			143.5	96.5			216.5	29.0			166.0	83.5
	185.5	29.0			166.5	42.0			140.0	117.0			217.0	16.5			165.5	66.0
x-mean			9.5				13.3				3.9				6.0			
y-mean			-2.7				-18.0				2.7				-10.8			
x-stdev			18.0				12.2				13.1				11.3			
y-stdev			32.4				32.8				25.3				30.2			

Localization Results

Overall **horizontal** localization error:

σ = 3.4 degrees

Overall **vertical** localization error:

σ = 6.6 degrees

ANOVA horizontal axis:

$F = 0.23$

$F_{crit} = 3.90$

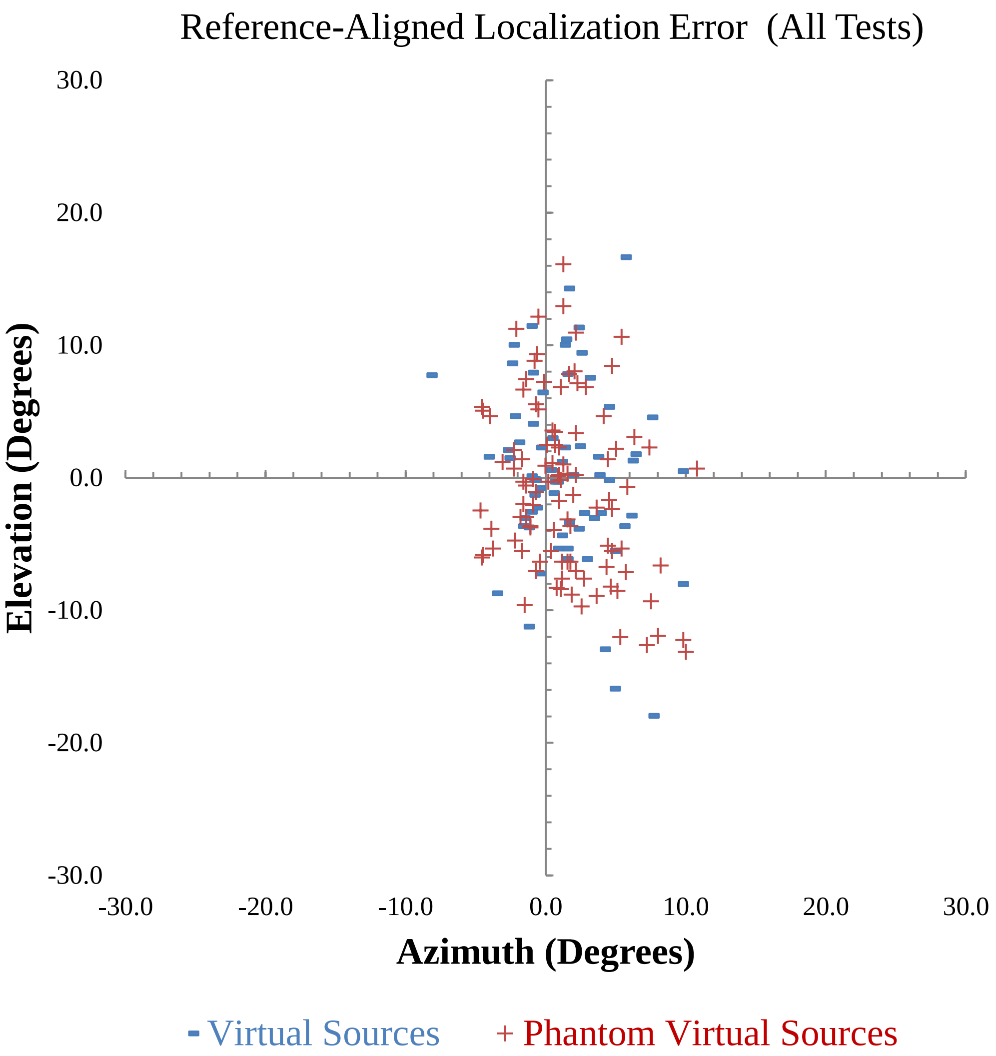
ANOVA vertical axis:

$F = 1.51$

$F_{crit} = 3.90$

$F < F_{crit} \rightarrow$ **accept** null hypothesis.

No significant difference between localization error of virtual sources and phantom virtual sources



Results of Listening Test

The hypotheses are **confirmed**.

- ✓ Localization cues of wave field synthesis are preserved under the multiple line array method. No additional error is introduced.
- ✓ Vertical localization of virtual sources is at least as accurate under the multiple array method as under traditional single-array horizontal wave field synthesis.

However, vertical localization is poor overall. Can this be improved?

Conclusions and Future Work

- Multiple line array wave field synthesis improves wave field synthesis by expanding the virtual source space
  - Viable method for theaters
  - Virtual reality
- Future Work
  - Test effects of varying the vertical spacing; how many speaker rows are necessary?
  - Enable ASIO input routing in WFS Designer
  - Other research with speaker modules
    - Active noise control
    - Active room compensation

Acknowledgements

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- All listening test participants

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