Sound reinforcement in 2 and 3 dimensions using Wave Field Synthesis

Etienne Corteel[1], Lukas Rohr[2]

[1] sonic emotion labs, Paris, France

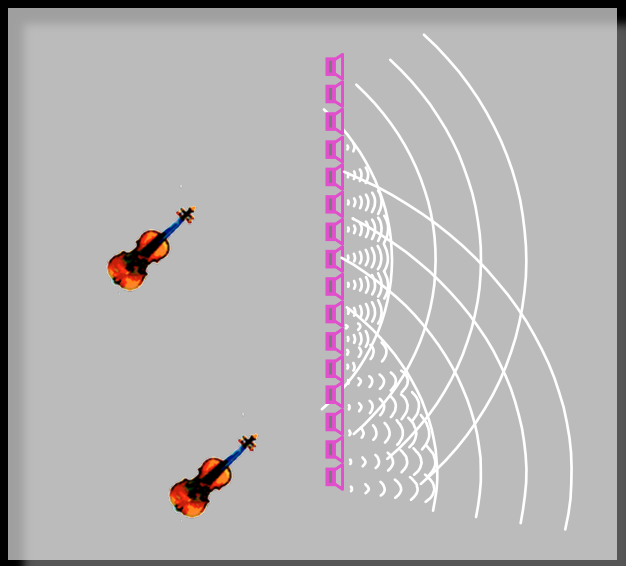
[2] LEMA, EPFL, Lausanne, Switzerland

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

i3D music

sonic emotion ABSOLUTE 3D

Wave Field Synthesis (WFS)



- Wave Field Synthesis: adaptation from Rayleigh 1/ Kirchhoff-Helmholtz integrals to a *finite number of regularly spaced* loudspeakers
  - ➔ source at an arbitrary position/directivity
  - ➔ listening *area* ➔ *no sweet spot*
  - ➔ delays/gains/filtering

➔Acoustical window

- Restricted to 2D with practical formulations (sources, listeners)
- Requires tens to hundreds of speakers (in theory…)

Can this principle be used for sound reinforcement?

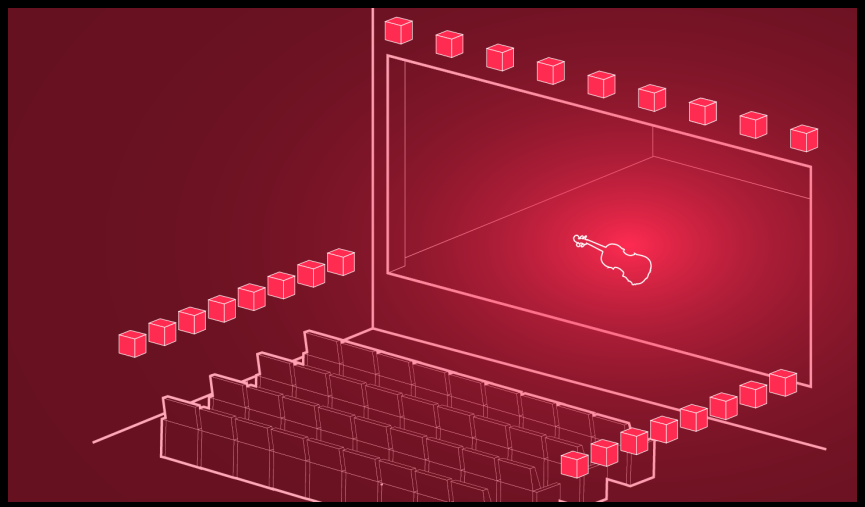
Can this principle also be used extended for 3D sound reproduction with a reasonable number of speakers?

Wave 1: WFS for sound reinforcement

High consistency between musician/actors visual and auditory location

➔ improved intelligibility of sound stage

- 24 inputs, freely adjustable position (direct input or bus feed for mixing desk)
- Compatible with most available formats: 2.0 5.1, 7.1, 9.1, ...
- 16 (stage portal) to 48 loudspeakers
- Processors can be stacked for up to 500 outputs
- Easy to interface
- Also applicable to cinema/home cinema/installed sound
- Worldwide distribution



« School book » WFS installations, sonic emotion

IRCAM, Paris, *2002-2009*
3 systems: 48, 56 and 128 channels

Neue Aula Detmold, Deutschland, *2009*
340 channels, active room acoustics (Rt from 1.3 to 5s)

Wave 1 installations

Institut du Monde Arabe, Paris, *2011*
16 loudspeakers above + 6 subs

To be permanently installed, summer 2012

Concert OK Baby, Paris, *2011*
8 loudspeakers above + 2 subs

Final sound engineer student project
Thibault Husson , École Louis Lumière

Wave 1 installations

Staatstheater, Stuttgart, Germany, *2011*
48 channels, surround system

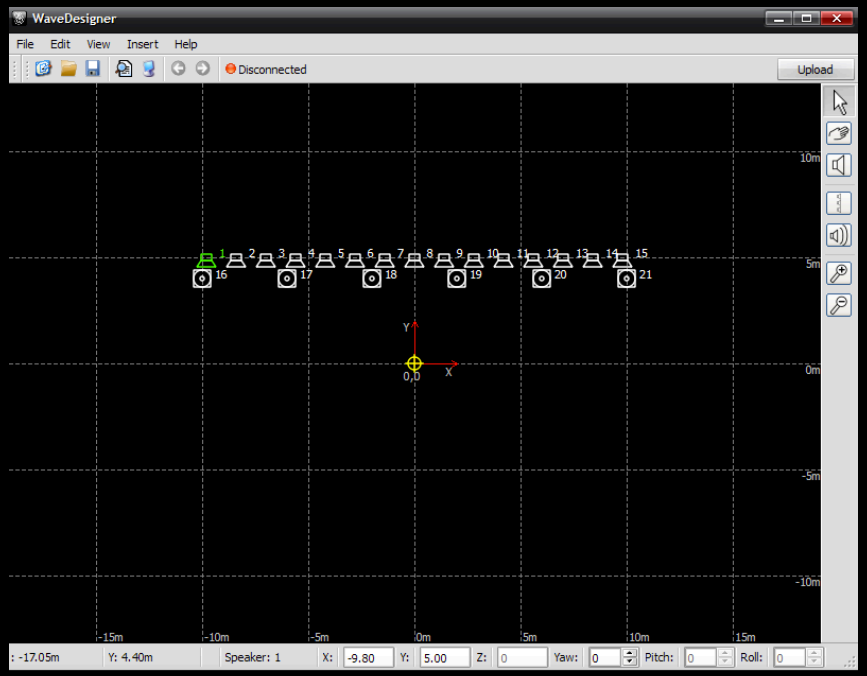
Permanent installation
Opening: summer 2012

Salle pleyel, Paris, *2011*
12 channels for front fill support

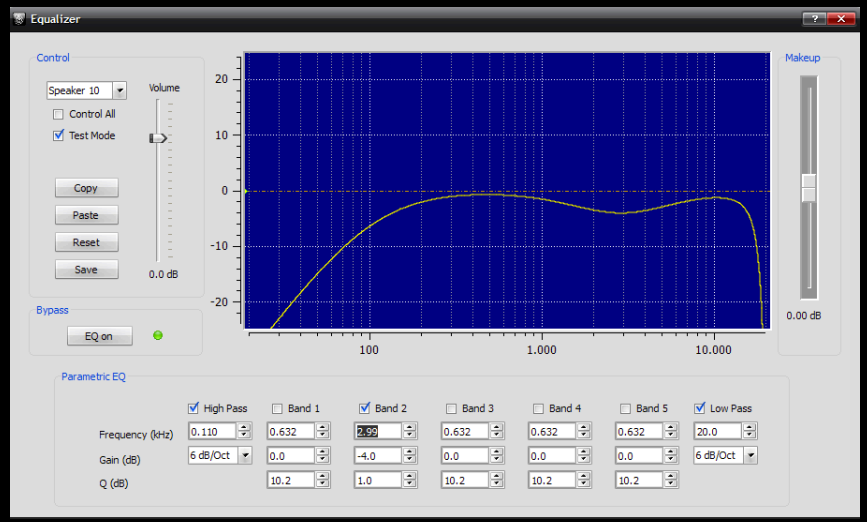
Test installation

Interfaces
System setup: Wave Designer

Loudspeaker positioning



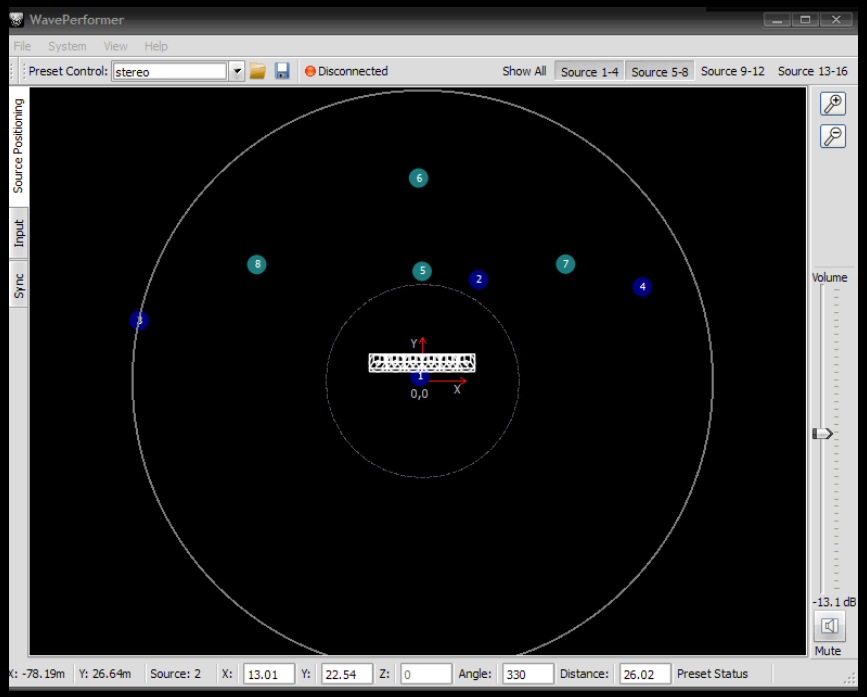
Equalizer (for each output)



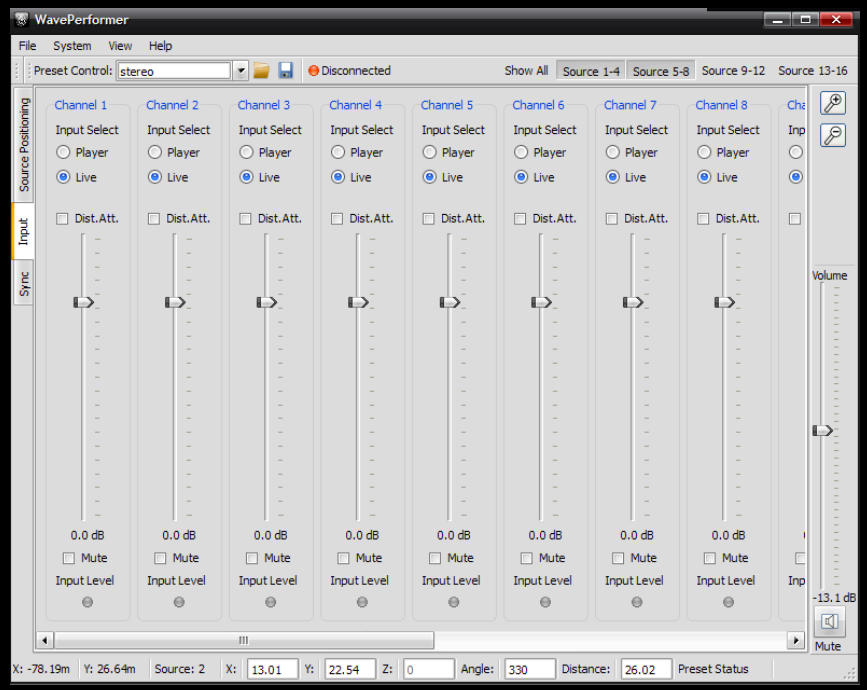
Installer interface, parameters not accessible for final user

Interfaces
Real-time integration: Wave Performer

Source positioning



Input



Upcoming Q3 2012: user EQ, independent from system setup EQ

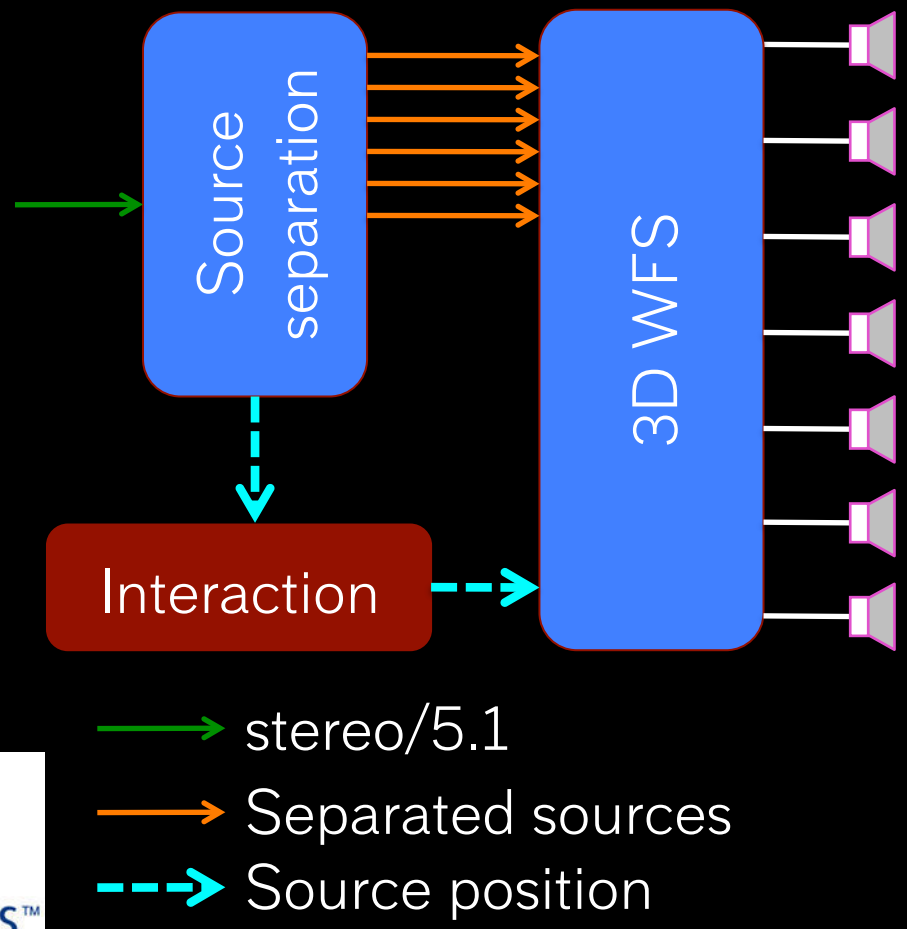
More interfaces with standard DAW (Logic, MaxMSP) and standard VST (upcoming Q3 2012)

3D WFS Context: i3d music project

Real-time Interactive 3D Rendering of Musical Recordings

4 Partners:

- France: Audionamix (Leader), INRIA (Metiss team)
- Switzerland: sonic emotion, EPFL (LEMA)



Kirchhoff-Hemlholtz → WFS

Physically accurate sound reproduction

Kirchhoff-Hemlholtz integral: continuous 3D closed distribution of ideal omnidirectional and bi-directional secondary sources.

2 ½ D Wave Field Synthesis :

Hypotheses:

- Virtual omnidirectional point sources → extended to directional sources (Verheijen 97, Corteel 07)
- Virtual sources/listeners → horizontal plane → 2D reproduction

Simplifications: limited number of loudspeakers distributed along an open line of the horizontal plane

Kirchhoff-Hemlholtz ➔ 2 ½ D WFS

Kirchhoff-Hemlholtz integral: continuous 3D closed distribution of ideal omnidirectional and bi-directional

Simp #1: 3D closed surface ➔ horizontal closed line *(reduction to 2D)*

➔ Erroneous spatial characteristics of sound field out of horizontal plane

➔ Modified attenuation

Simp #2: selection of omnidirectional sources only: source selection criterion (Spors et al. 2008)

➔ Diffraction

Simp #3: finite number of loudspeakers

➔ Spatial aliasing above a given Nyquist frequency

Simp #4 (optional): horizontal closed line ➔ horizontal open line

➔ Diffraction,

➔ Reduction of source positioning possibilities

Kirchhoff-Hemlholtz ➔ 3 D WFS

Kirchhoff-Hemlholtz integral: continuous 3D closed distribution of ideal omnidirectional and bi-directional

~~Simp #1: 3D closed surface ➔ horizontal closed line *(reduction to 2D)*~~

~~➔ Erroneous spatial characteristics of sound field out of horizontal plane~~

~~➔ Modified attenuation~~

Simp #2: selection of omnidirectional sources only: source selection criterion (Spors et al. 2008) ➔ also valid for 3D

➔ Diffraction

Simp #3: finite number of loudspeakers ➔ what sampling strategy?

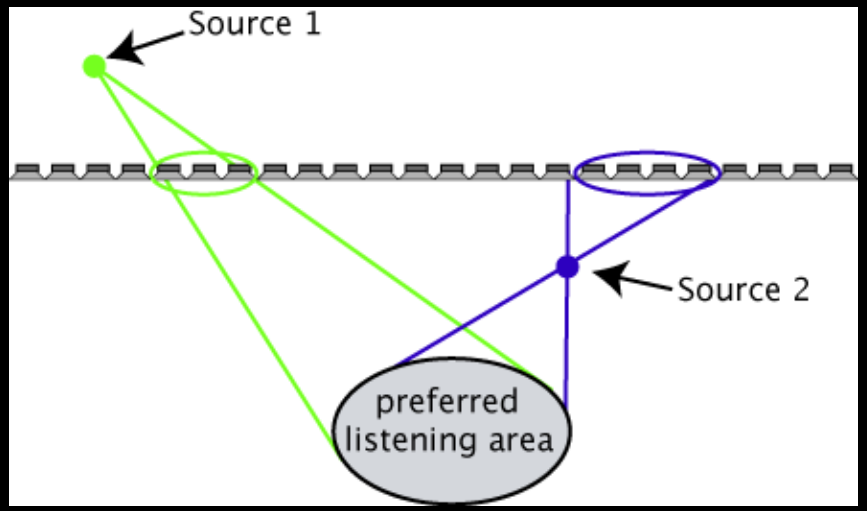
➔ Spatial aliasing above a given Nyquist frequency

Simp #4 (optional): ~~horizontal~~ closed ~~line~~ surface ➔ ~~horizontal~~ open ~~line~~ surface

➔ Diffraction

➔ Reduction of source positioning possibilities

2 ½ D WFS in a preferred listening area



- Loudspeaker selection :

  ➔ synthesis of the target sound field in the preferred listening area according to visibility criteria

  ➔ depends on source position
- Selection of loudspeakers in the direction of the virtual source ➔ increase of aliasing frequency
- Adapted WFS driving functions

  ➔reduce the level of other loudspeakers

  ➔frequency dependent windowing

Loudspeaker array sampling (3D WFS)

What sampling strategy for 3D WFS?

- Same as 2D: square the number of loudspeakers!!
- Localization accuracy is lower in elevation than in azimuth (Blauert 1999)

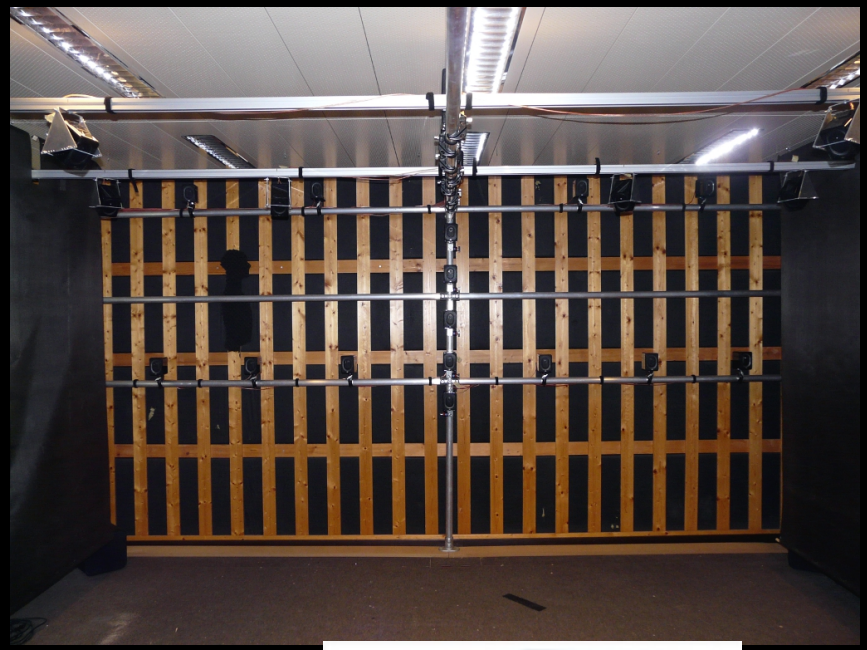
Proposed loudspeaker distribution strategy:

- Concentrate loudspeakers in horizontal plane (localization most accurate)
- Reduce loudspeaker density in elevation
- Compensate for irregular sampling by accurate loudspeaker weighting and filtering

3D WFS, 24 loudspeakers

sonic emotion labs
3 levels, upper half sphere

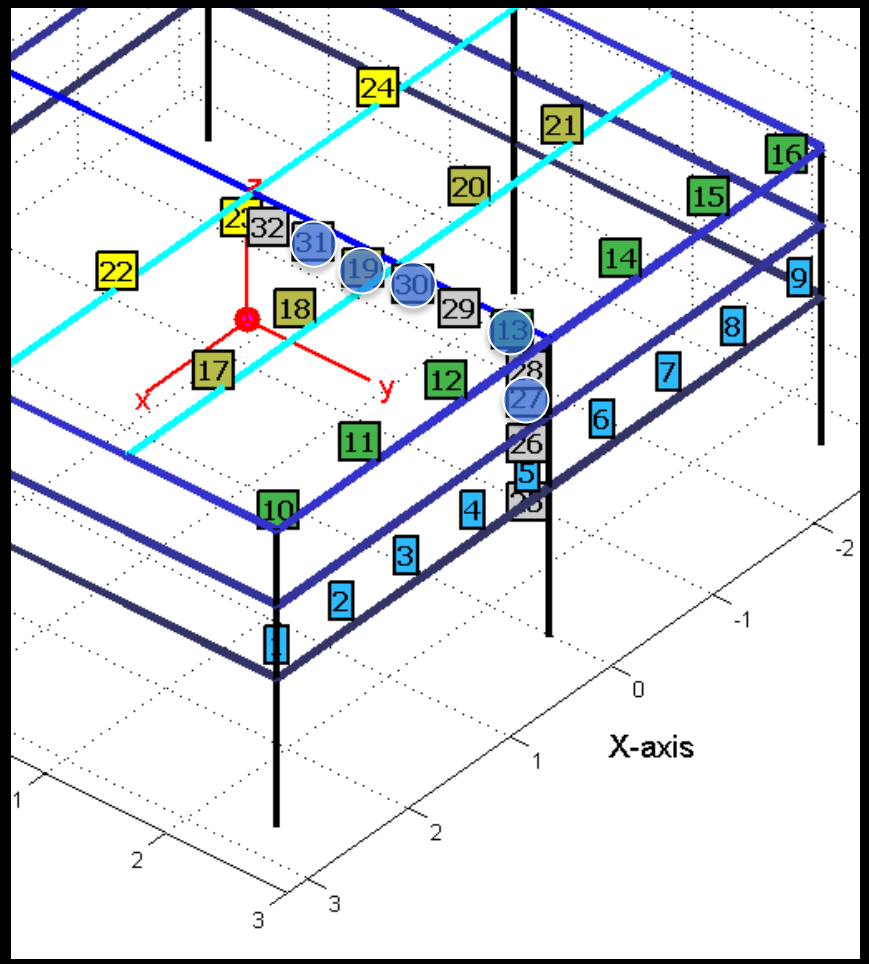
EPFL
4 levels, frontal upper space



Wave 1

3D WFS, vertical localization

- Setup:
  - 5.5*5.5 m installation, four levels:
    - 0, 25, 45, 90 degrees elevation
    - 9, 7, 5, 3 loudspeakers
  - 24 loudspeakers (3D WFS, or individual speaker)
  - 8 additional speakers (25 to 32) monitored (individual speakers only)
- Two sounds:
  - *Target* on 1 reference speaker (14°, 26°, 36°, 43°, 58°) ➔ modulated pink noise, 15 Hz
  - *Pointer* manipulated with 3D WFS (0 to 90° elevation at 5.4 m distance) ➔ modulated pink noise, 20 Hz

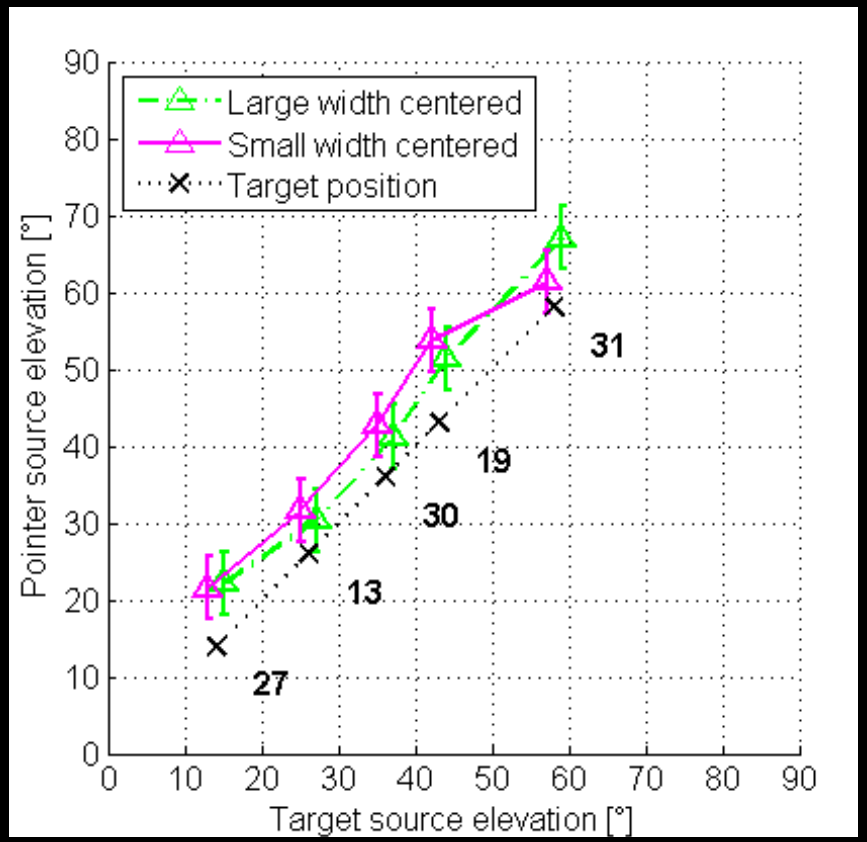


3D WFS, vertical localization

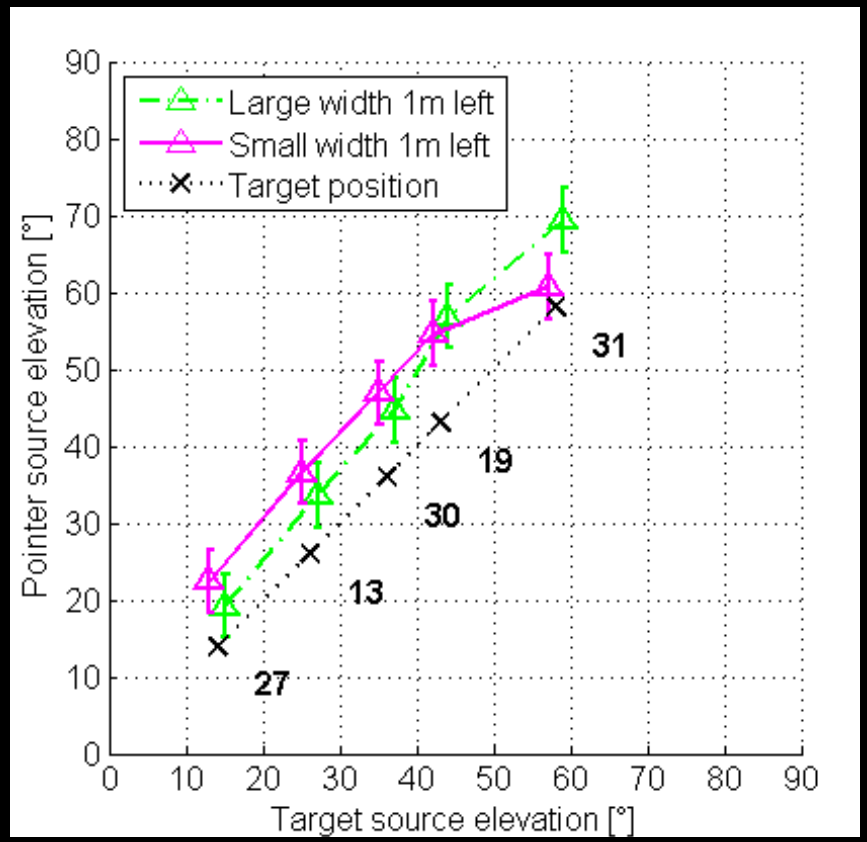
- Task:
  - align pointer to target with keyboard
  - switch between target and pointer
  - no time limit
- Conditions:
  - 2 listening positions (center, 1 m to the left)
  - 5 target locations: 14°, 26°, 36°, 43°, 58° elevation
  - 2 WFS 3D rendering mode:
    - Large source width
    - Small source width (extension of optimization in preferred listening area to 3D WFS)
- 5 repetitions per condition : 50 stimuli per participant
- 11 participants (2 women, 9 men) 23 to 37

3D WFS, vertical localization results

Centered position



1 m to left



3D WFS, vertical localization results
Localization accuracy (Median)

- Systematic bias (3 to 10 degrees depending on target elevation) ➔ can be remapped for better accuracy
- Significant effect of *target elevation* ($p<0.001$)
- Significant effect of *listening position* (2.1° elevation difference in average)
- All source pairs are significantly discriminated, except:
  - *left listening position, small width*: 19 and 31 ($p=0.337$)
  - *center listening position, small width*: 19 and 30 ($p=0.088$), 19 and 31 ($p=0.098$)
  - *center listening position, large width*: 13 and 27 ($p=0.58$)

➔4 levels discriminated for each listening position

➔3D WFS works!

3D WFS, vertical localization results
Localization blur (half inter-quartile range)

- Significant effect of width control ($p<0.001$) ➔ less blur with small width (4.1° against 6.1° for large width on average)
- Significant effect of source width and source number ($p<0.01$)

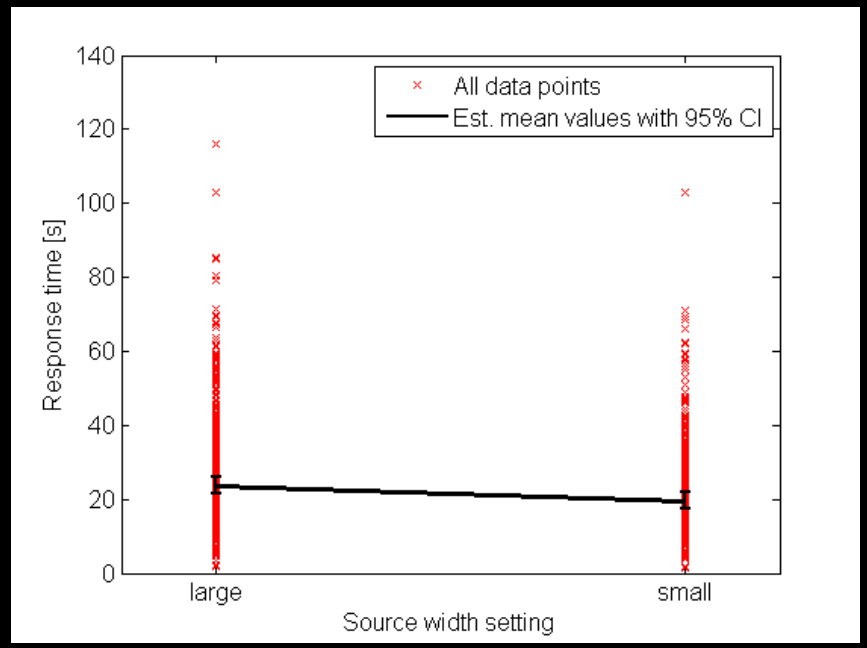
➔ significant effect of *source number* factor for *large width* at the left listening position ($p<0.05$)

- Almost significant interaction between source position and source width control

3D WFS, vertical localization results
Response time

- Significant effect of width control ($p<0.05$)
  - Small width: 23.4 s
  - Large width: 27.5 s
- No significant effect of listening position or source number

➔ Small width provides better performance localization



3D WFS

Proposed formulation of *3D WFS* works !

- 4 levels significantly discriminated between 14° and 58° elevation
- Source width control enables to reduce localization blur
- Source positioning: full 3D or reduced subspace depending on installation requirements
- Very few constraints for loudspeaker positioning:
  - Irregular setup possible
  - Non closed surfaces possible
- 24 to 48 loudspeakers are sufficient for typical installation

Conclusion
WFS for sound reinforcement

- Immersion for entire audience with possibly dynamic sounds at 360 degrees (+ elevation)
- Fusion between player/singer/actor on stage and corresponding amplified sound
- Improved intelligibility of sound scene
- Playback versatility, backward compatibility
- Limit audibility of individual speakers:
  - Sound field rendering
  - Improved power distribution over entire audience
- Improve loudspeaker/room interaction (Eq of individual speakers)
- Integrated audio/video/light solution (with Coolux)

Thank you for your attention

Headquake - binaural iPhone app for music library listening
Available on the appstore since janvier 2012
Headphones compensation