Sound reinforcement in 2 and 3 dimensions using Wave Field Synthesis

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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

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

To be permanently installed, summer 2012

Final sound engineer student project
Thibault Husson, École Louis Lumière
Wave 1 installations

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

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

Permanent installation
Opening: summer 2012

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 $\Rightarrow 2 \frac{1}{2} \text{D WFS}$

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

Simp #1: 3D closed surface $\Rightarrow$ 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 $\Rightarrow$ horizontal open line
- Diffraction,
- Reduction of source positioning possibilities
Kirchhoff-Helmholtz integral: continuous 3D closed distribution of ideal omnidirectional and bi-directional.

**Simp #1**: 3D closed surface $\Rightarrow$ 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) $\Rightarrow$ also valid for 3D
- Diffraction

**Simp #3**: finite number of loudspeakers $\Rightarrow$ what sampling strategy?
- Spatial aliasing above a given Nyquist frequency

**Simp #4 (optional)**: horizontal closed line surface $\Rightarrow$ 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

- Green triangles: Large width centered
- Pink triangles: Small width centered
- Black crosses: Target position

Graphs show the pointer source elevation versus target source elevation for different source widths and positions.
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 ($2.1^\circ$ 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