HARMAN

Beam Steering & Shaping

dr. ir. Evert Start
Senior Principle Engineer
Duran Audio/JBL Pro
The Netherlands

July 2015

AKG harman/kardon Infinity JBL mark levinson lexicon REVEL

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CONTENTS

1. INTRODUCTION
2. BASIC ARRAY PHYSICS
3. DIRECTIVITY CONTROL
4. CONTROLLING BASS

Array myths

Arrays *must* be curved to shape the lobe…

FIR filtering to optimise the directivity of arrays is new…

Arrays can be put anywhere, the software will do the rest…

You cannot control bass…

BASIC ARRAY PHYSICS
What?

WHAT IS AN ARRAY?

A loudspeaker array is a collection of sound sources (or complete enclosures) that is assembled to achieve a coverage pattern that cannot be achieved with a single loudspeaker.
The combined array is more powerful and can have a wider or narrower beam than the individual elements

Line array

BEAMFORMING

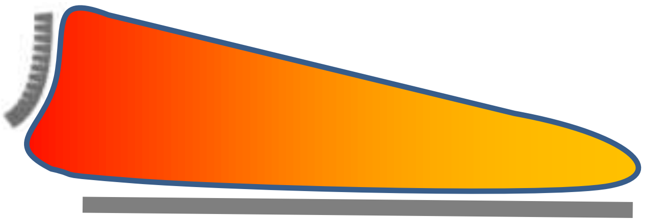
- **Mechanical**
  - Minimum interference
  - Beam controlled by shape of array
- **Electronical**
  - Maximum interference
  - Beam controlled by (digital) signal processing of loudspeaker signals

Beam steered/shaped column

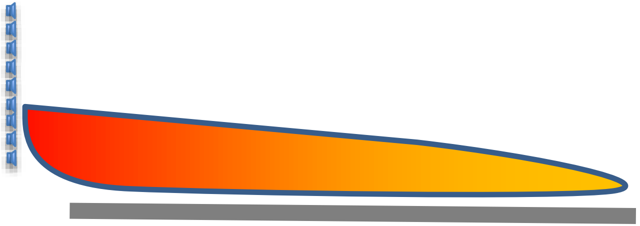
ARRAY PHYSICS

Beamforming Concepts

- **Mechanical beamforming**
  - Line arrays: Radiation pattern dictated by shape of array.
  - Minimum interference. HF horns are designed to have minimum mutual interference at higher frequencies.
  - Low driver density.
  - No multi-channel signal processing.



- **Electronical beamforming**
  - Radiation pattern determined by (digital) filtering of output channels (i.e., loudspeaker signals)
  - High driver density.
  - Maximum interference: Deliberate, controlled interference for obtaining desired radiation pattern.



ARRAY PHYSICS

Sound Waves

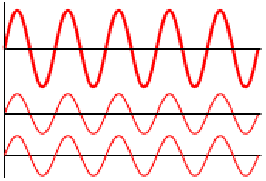
KEYWORDS:

$$\lambda = \frac{c}{f}$$

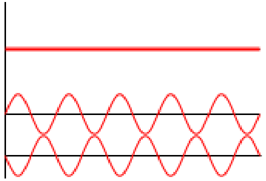
- Sound is a wave phenomenon
  - Frequency f
  - Wave length λ
  - Speed of sound c (=340 m/s)

f [Hz]	20	50	100	200	500	1000	2000	5000	10000	20000
λ [m]	17.0	6.8	3.4	1.7	0.68	0.34	0.17	0.068	0.034	0.017

- Waves interfere



Constructive



Destructive

ARRAY PHYSICS

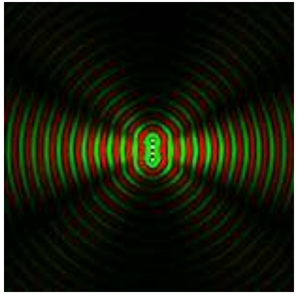
Interference

- A small loudspeaker (monopole) radiates sound in all directions (omni-directional sound wave).
- By combining several loudspeakers in an array, the radiation pattern becomes directional.
- In the target direction the sound waves sum, in other directions they (partially) cancel.

1 monopole

2 monopoles spaced at $\lambda/2$

4 monopoles spaced at $\lambda/2$



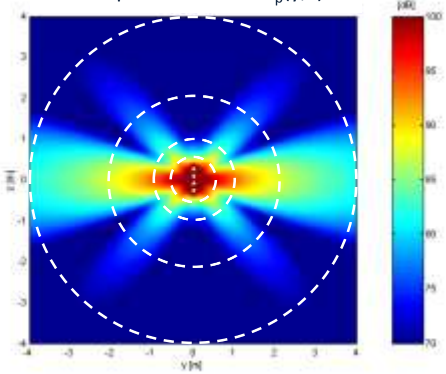
ARRAY PHYSICS
Interference

4 monopoles (f=1kHz, spacing=λ/2)

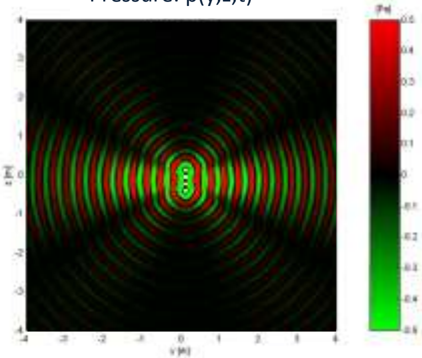
Representation:

- Space-time (yz-t)
- Space-frequency (yz-f)
- Angle-frequency (rθ-f)

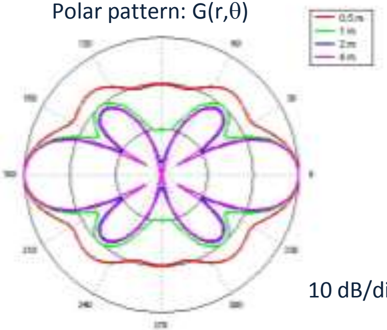
Sound pressure level: $L_p(y,z)$



Pressure: p(y,z,t)



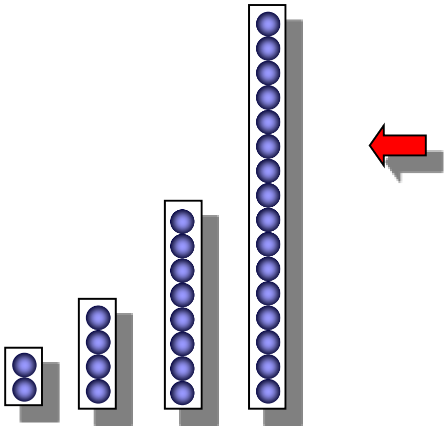
Polar pattern: G(r,θ)



ARRAY PHYSICS

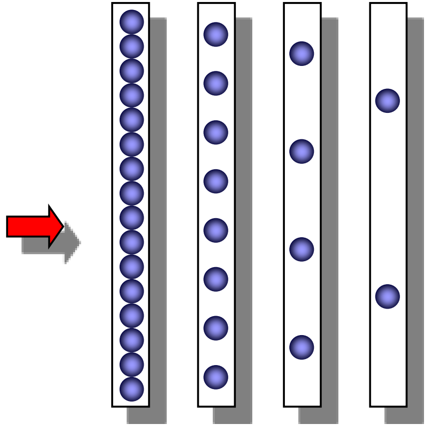
Length and Spacing

BEHAVIOUR OF A PARALLEL-DRIVEN POINT SOURCE ARRAY

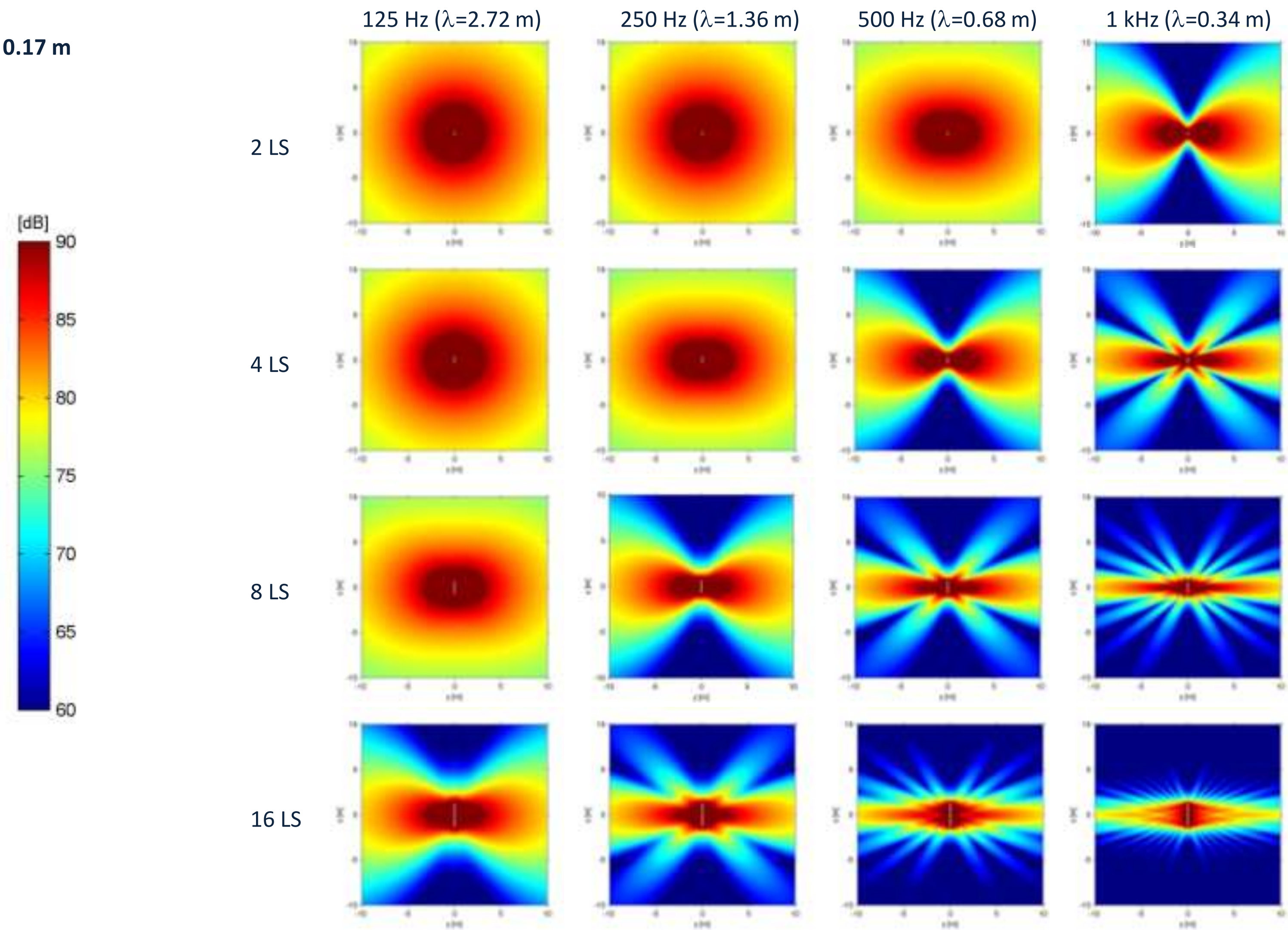


Fixed driver spacing,
variable array length

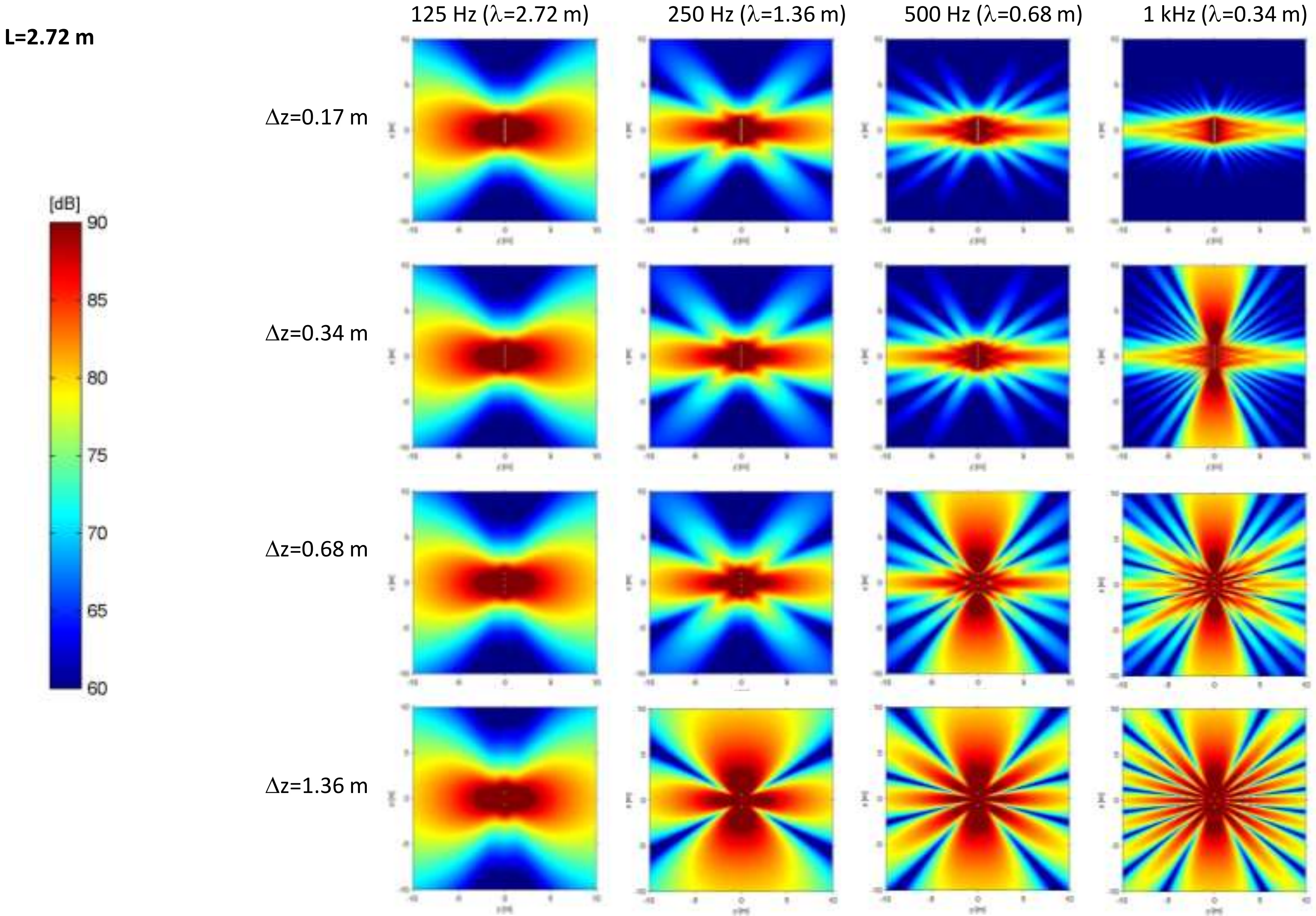
Fixed array length,
variable driver spacing



Δz = 0.17 m



125 Hz (λ=2.72 m)
250 Hz (λ=1.36 m)
500 Hz (λ=0.68 m)
1 kHz (λ=0.34 m)
2 LS
4 LS
8 LS
16 LS
[dB]
90
85
80
75
70
65
60


L=2.72 m
125 Hz (λ=2.72 m)
250 Hz (λ=1.36 m)
500 Hz (λ=0.68 m)
1 kHz (λ=0.34 m)
Δz=0.17 m
Δz=0.34 m
Δz=0.68 m
Δz=1.36 m
[dB]
90
85
80
75
70
65
60

ARRAY PHYSICS

Basic Laws

- Effect of array size and wave length:

$$Beam\,width \sim \frac{\lambda}{L}$$

- Spatial sampling (i.e. driver spacing):

$$\Delta z \leq \frac{\lambda}{2}$$

(Nyquist criterion)

❖ Note: For directional sources like waveguides this anti-aliasing criterion can be relaxed

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DIRECTIVITY CONTROL

Beamforming technology

AS SHOWN, THERE IS A NEED FOR DIRECTIVITY CONTROL

Objectives:

- Consistent radiation pattern over frequency
- Uniform coverage and frequency response
- Minimize “spill” (e.g., avoid reflective surfaces or reduce outdoor noise pollution

Methods:

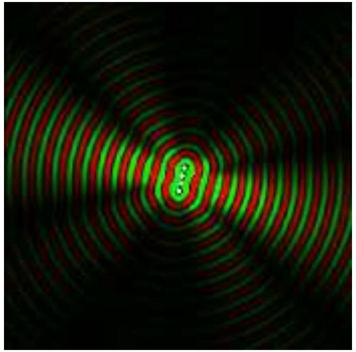
- Mechanical line array optimisation → Minimum interference
- Signal processing → Maximum interference
  - “constant-λ” design, i.e. $L_{eff} = C \cdot \lambda$
  - Beam steering
  - Beam shaping

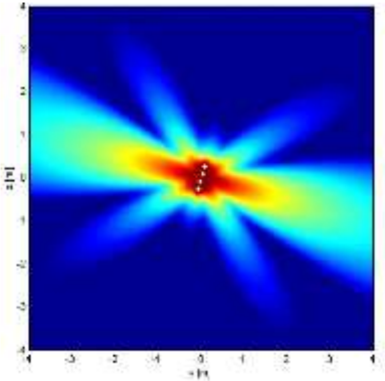
DIRECTIVITY CONTROL

Beam Steering

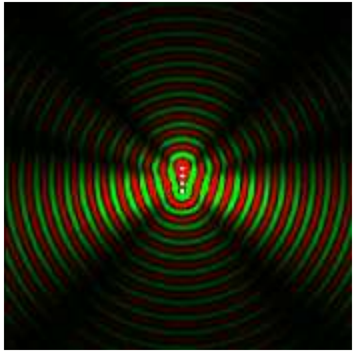
Mechanical Aiming
versus
Electronic Steering

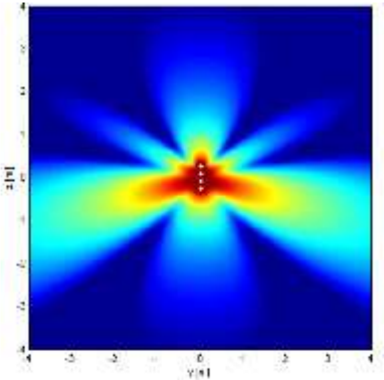
Mechanical aiming





Electronic steering

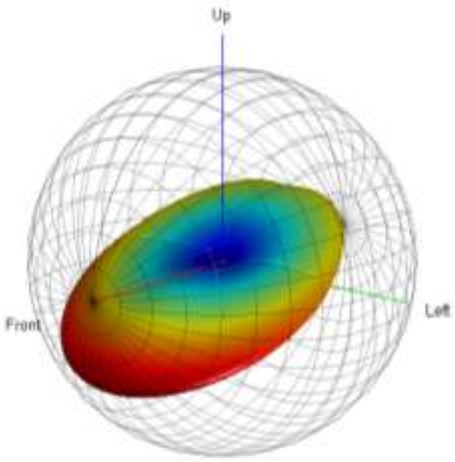


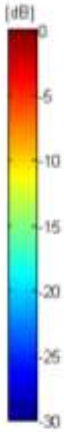


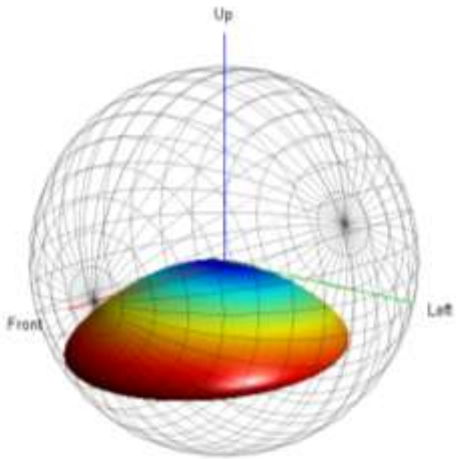
DIRECTIVITY CONTROL

Beam Steering

Mechanical aiming versus electronic steering







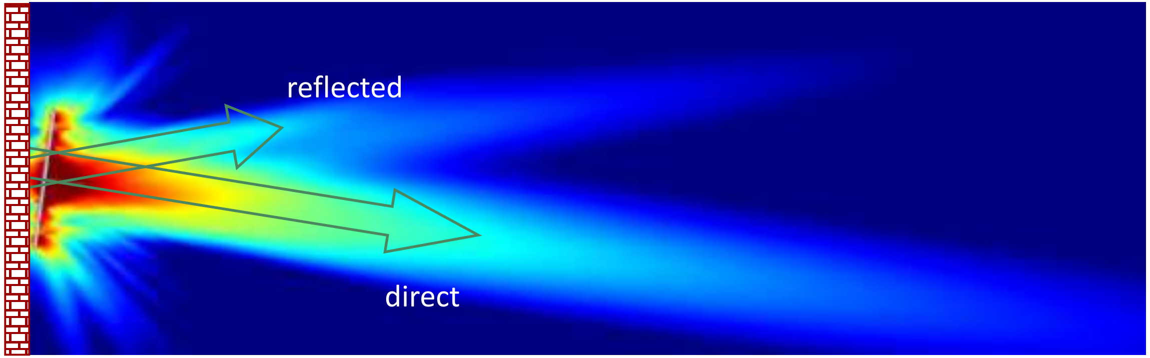
Mechanical aiming

Electronic steering

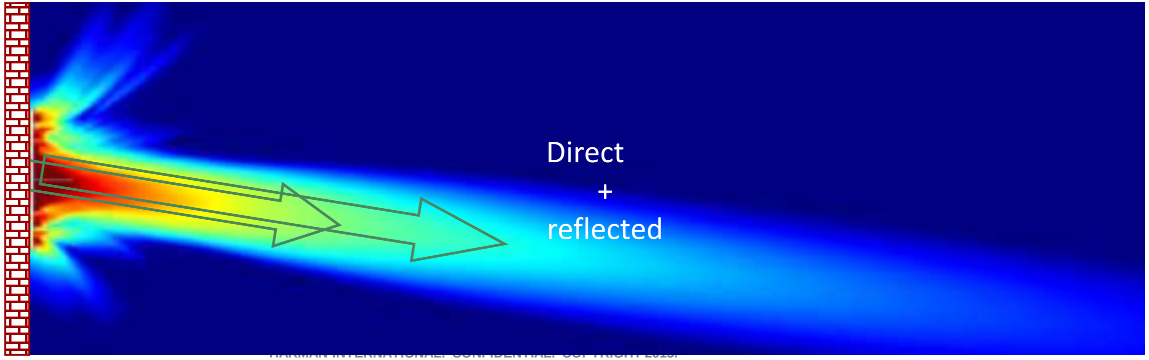
DIRECTIVITY CONTROL

Beam Steering

Mechanical aiming



Electronic steering



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DIRECTIVITY CONTROL

Some History

Early attempts to control the opening angle ("constant-λ"):

- Electrical Low-pass filter circuit
- Mid/wide band loudspeaker arrangement
- Barber pole
- Acoustic low-pass filtering

DIRECTIVITY CONTROL

Some History

Electro-Voice LR-4S (1950s)

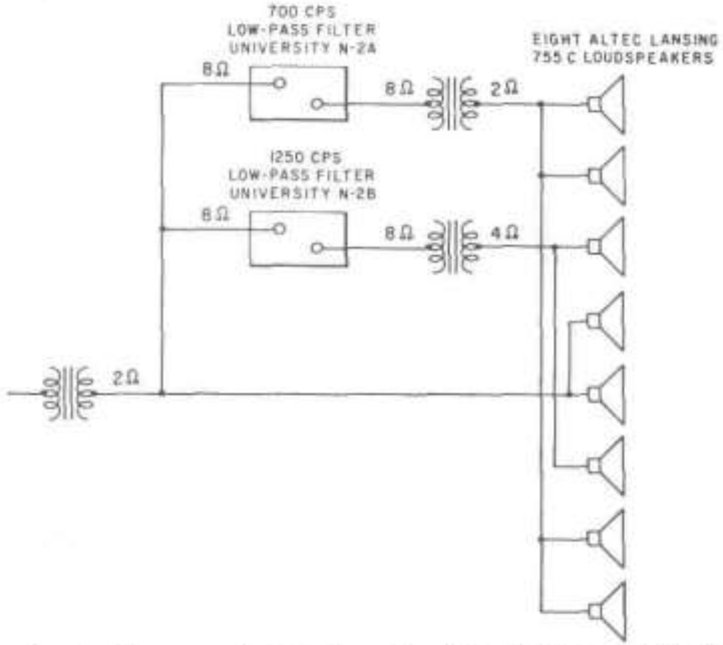


FIG. 1. Line-source loudspeaker with electrical filtering at Franklin Hall, Franklin Institute, Philadelphia, Pa.

DIRECTIVITY CONTROL

Some History

UL (1950s)

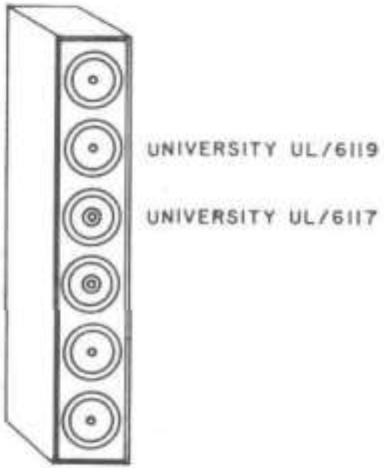


FIG. 2. Line-source loudspeaker with omission of high frequency "whizzer" in outer loudspeakers: University loudspeaker UCS-6.

DIRECTIVITY CONTROL

Some History

“Barber pole” (Philips 1958)

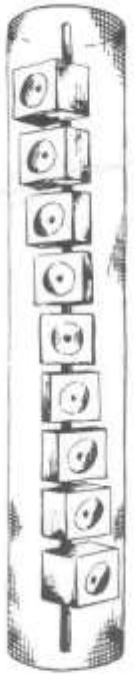


FIG. 3. “Barber pole” line source: Palais Chailot, Philips system.

DIRECTIVITY CONTROL

Some History

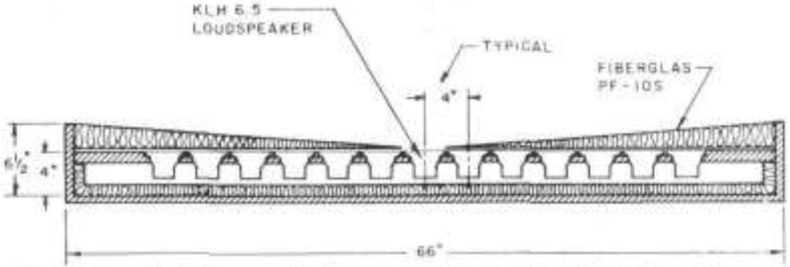


Fig. 4. Section through line-source loudspeaker (enclosure is made of ¾ in plywood).

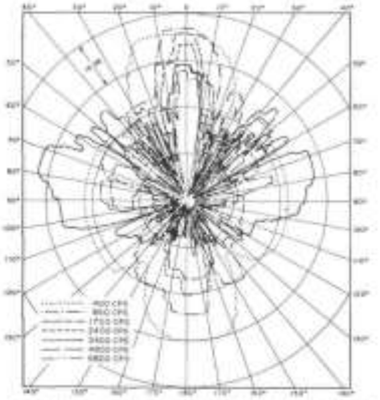


Fig. 6. Polar plot line source containing 13 4-in loudspeakers, no glass fiber.

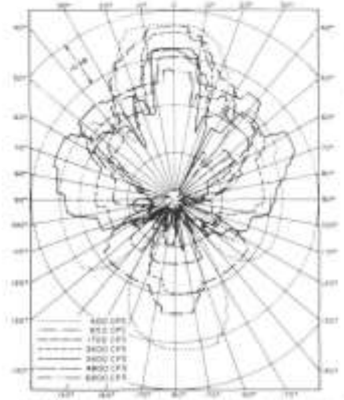
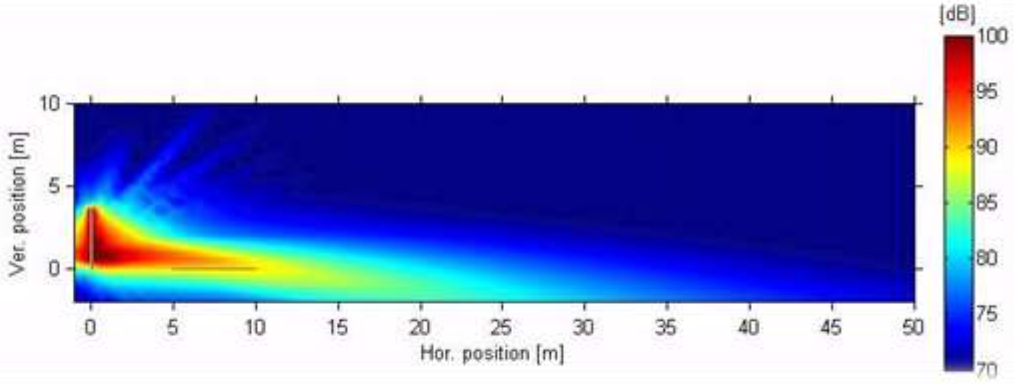


Fig. 7. Polar plot line source containing 13 4-in. loudspeakers with glass fiber wedges.

DIRECTIVITY CONTROL
Advanced techniques

1. **DDC – BEAM STEERING** (Developed and introduced in the early 90-ies by Duran Audio)

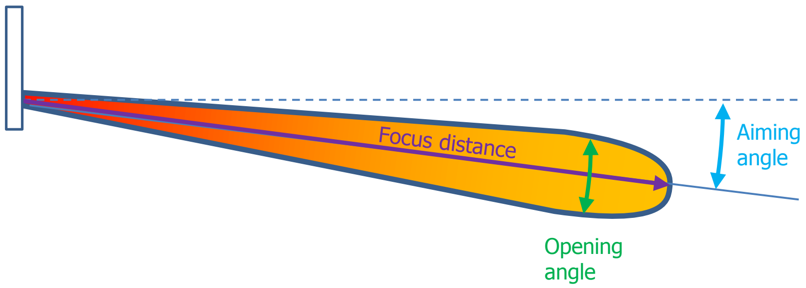
2. **DDS – BEAM SHAPING** (Developed and introduced in 1999)



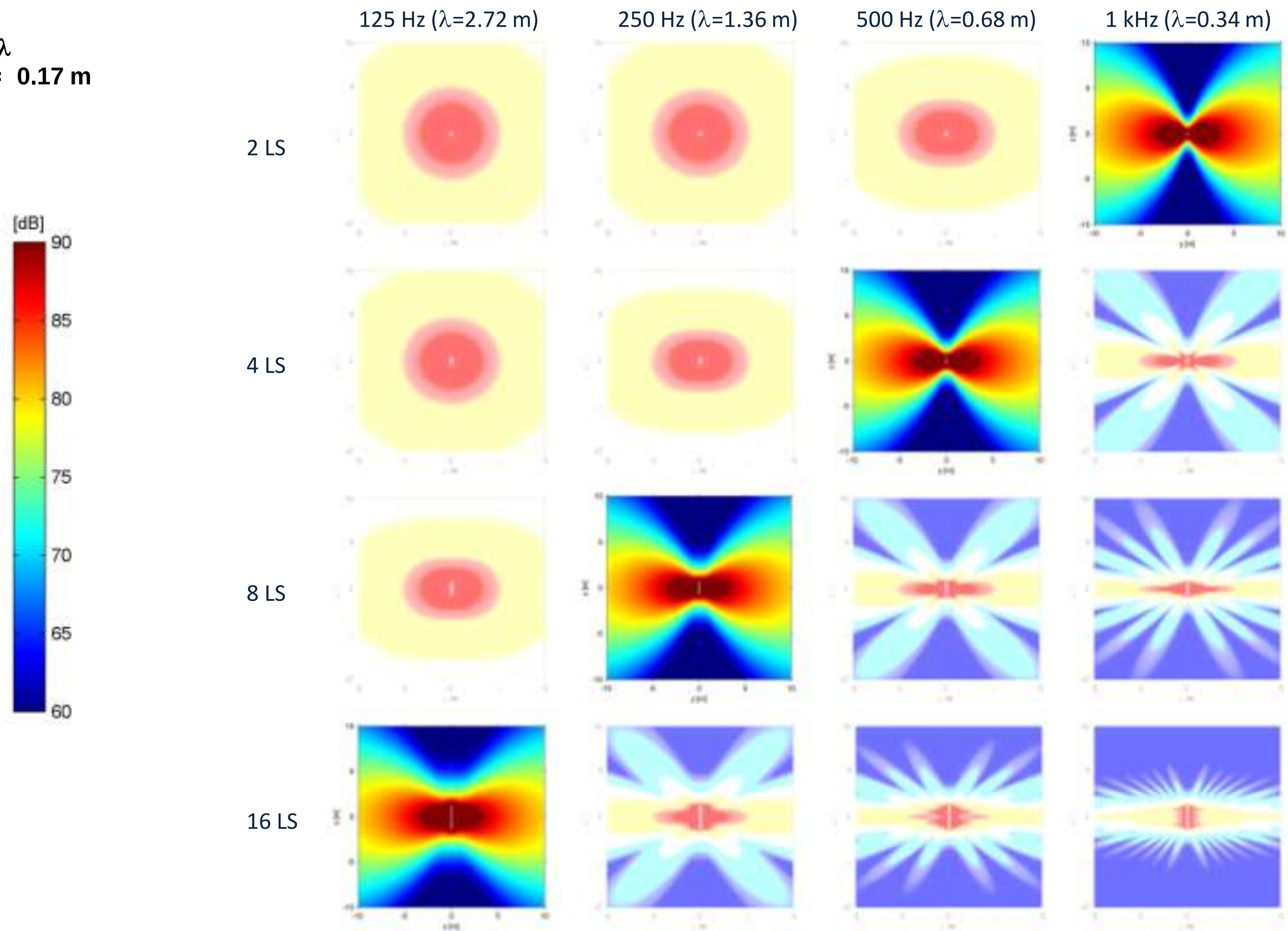
DDC
BEAM STEERING

Digital Directivity Control (DDC)

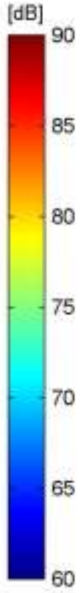
- "Beam Steering"
- Parametric beam control
- Applied in:
  - Intellivox-DC range



L=1λ
Δz = 0.17 m

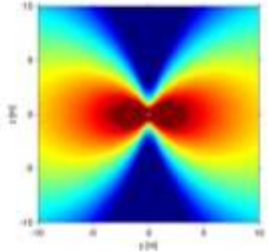

125 Hz (λ=2.72 m)
250 Hz (λ=1.36 m)
500 Hz (λ=0.68 m)
1 kHz (λ=0.34 m)
2 LS
4 LS
8 LS
16 LS
[dB]
90
85
80
75
70
65
60

L=1λ
Δz = λ/2

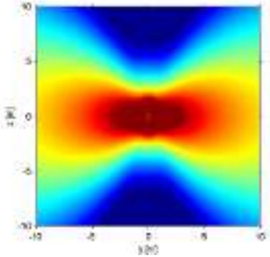


125 Hz (λ=2.72 m) | 250 Hz (λ=1.36 m) | 500 Hz (λ=0.68 m) | 1 kHz (λ=0.34 m)

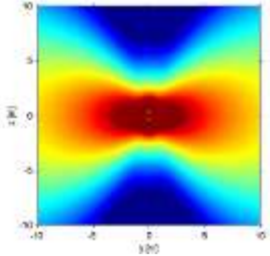
2 LS



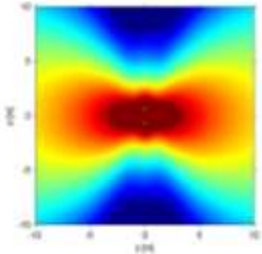
4 LS



8 LS



16 LS



DDC - BEAM STEERING

Transducer spacing

Frequency independent:

$$L_{eff}(\lambda) = const \cdot \lambda$$

+

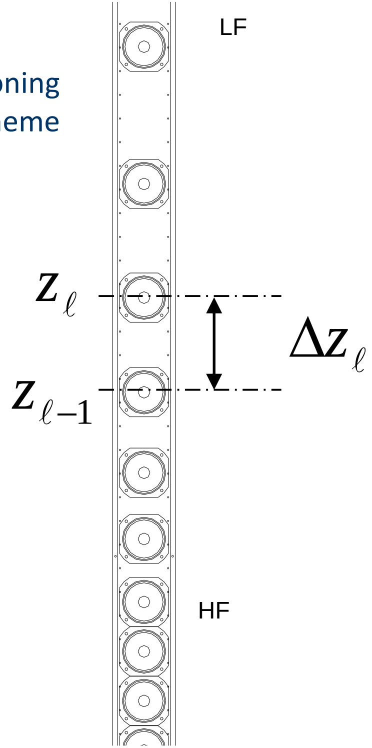
Logarithmic positioning:

$$\Delta z_{\ell} \leq \frac{\lambda_{\min}}{2}$$

$\Downarrow$

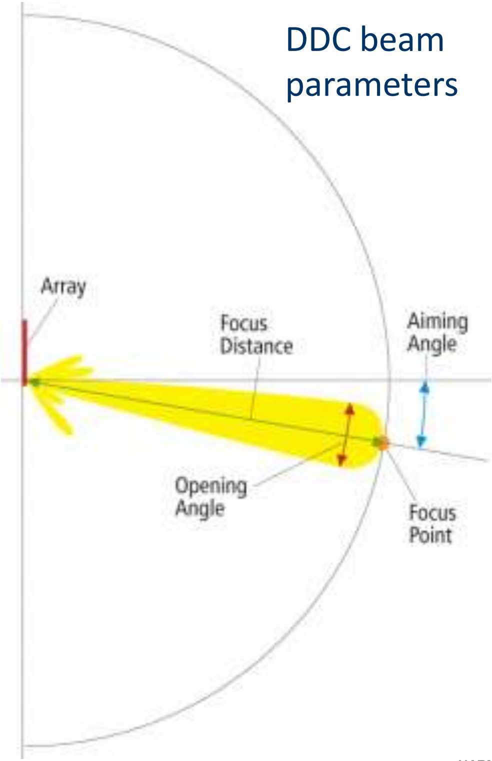
Reduction of the number of loudspeakers and signal processing for a given array length

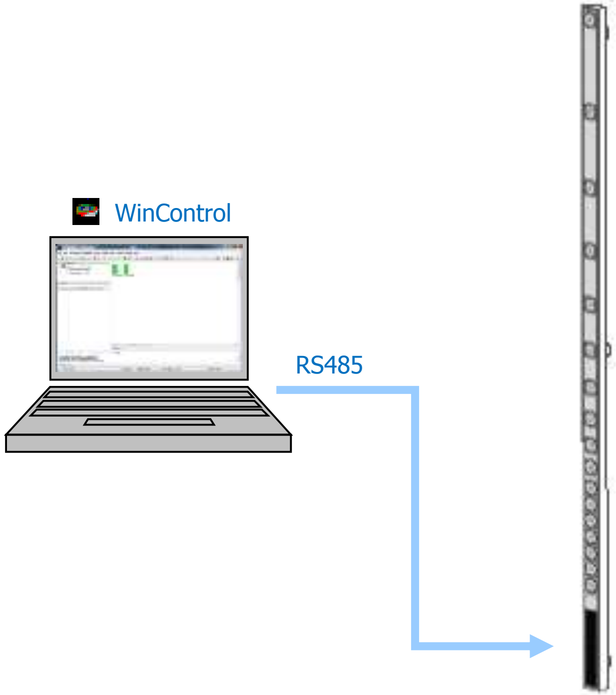
Patented positioning scheme



DDC - BEAM STEERING

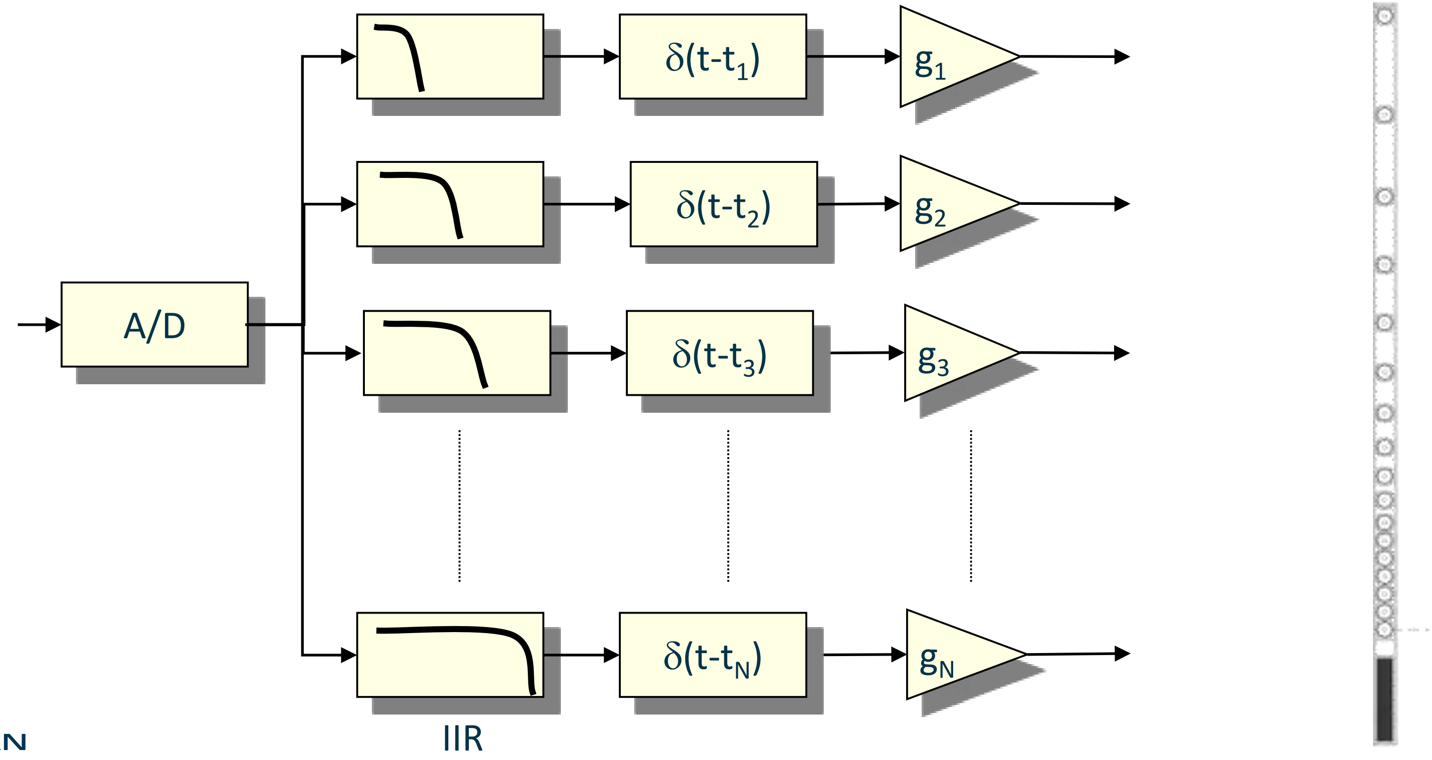
Beam parameters





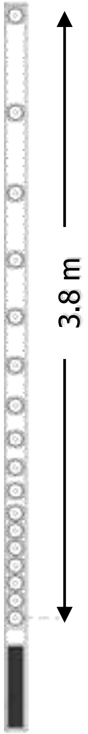
DDC - BEAM STEERING

Block diagram



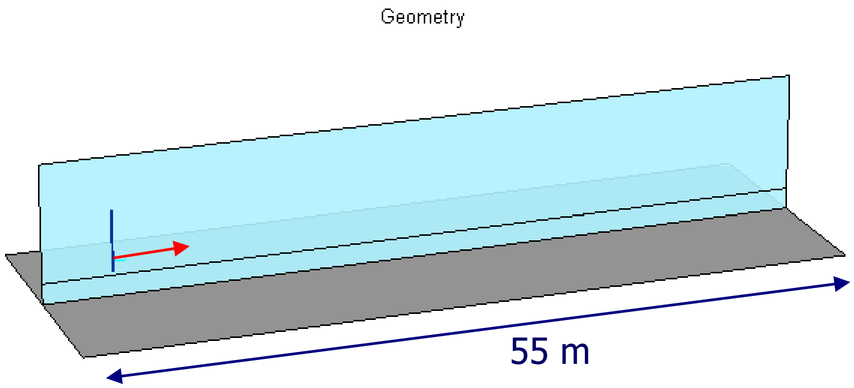
DDC - BEAM STEERING

Example



z_c=2.5 m

z_{li}=1.7 m



Plan view

Side view

Opening Angle: 6°

Elevation: -1°

Focus distance: 50 m

Opening Angle: 14°

Elevation: -1°

Focus distance: 50 m

Opening Angle: 6°

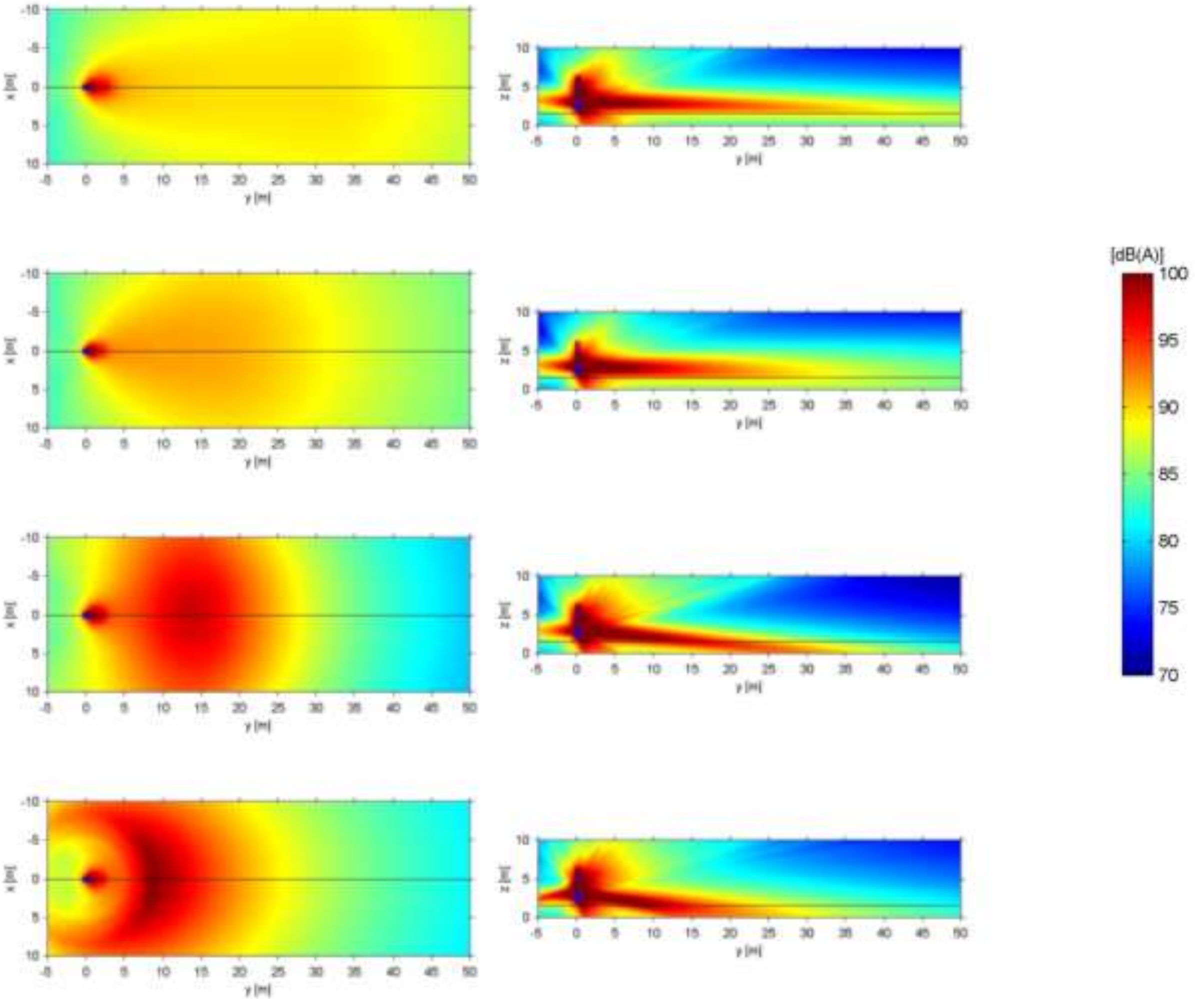
Elevation: -5°

Focus distance: 50 m

Opening Angle: 6°

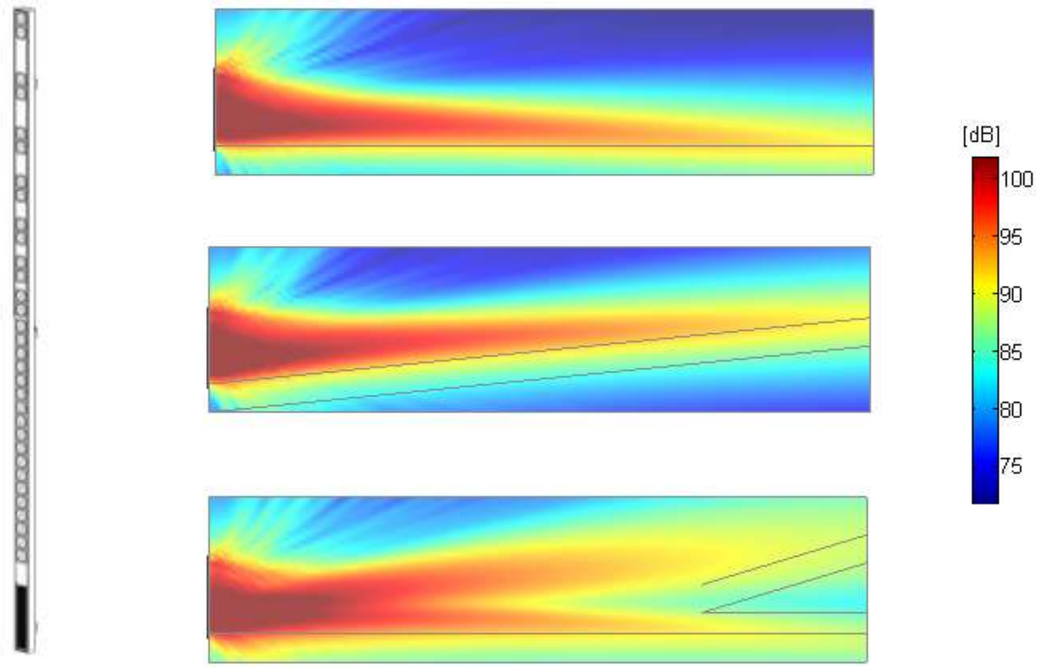
Elevation: -1°

Focus distance: 10 m



DDC - BEAM STEERING

Typical use



Single lobe,

horizontal plane

Single lobe,

tilted plane

Dual lobe,

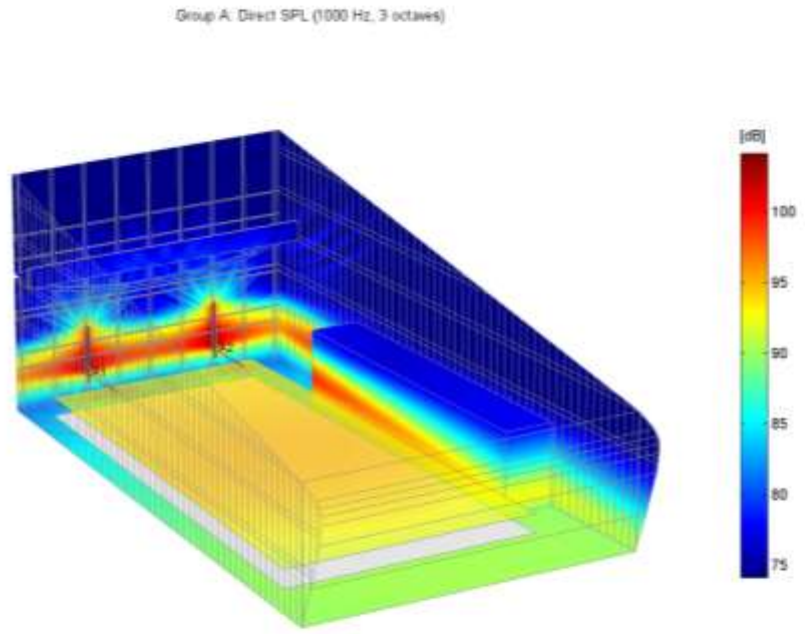
horizontal + tilted plane

DDC - BEAM STEERING

Features

- Simple and intuitive parametric control
  - Opening angle
  - Aiming angle
  - Focus distance
- Constant SPL over distance (up to 70m)
- Large direct-to-reverberant ratio
- High speech intelligibility

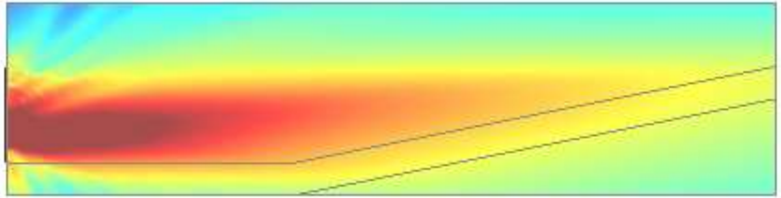
- Most suitable for flat audience areas
- Mounting height restrictions:
  - Offset between acoustic center and audience plane 0.3-0.6 m (~ 1-2 ft.)

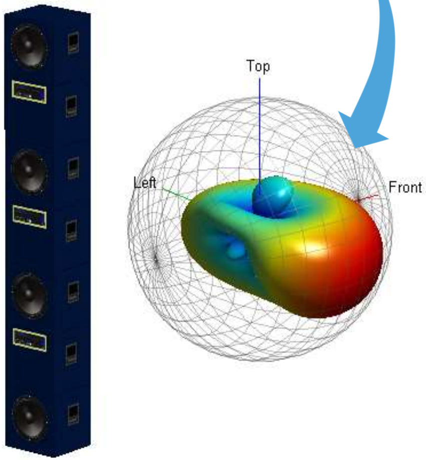


BEYOND BEAM STEERING…

What if:

- we could not only steer but also **shape** the beam?
- we could **extend** the frequency response?
- we could control **bass**?

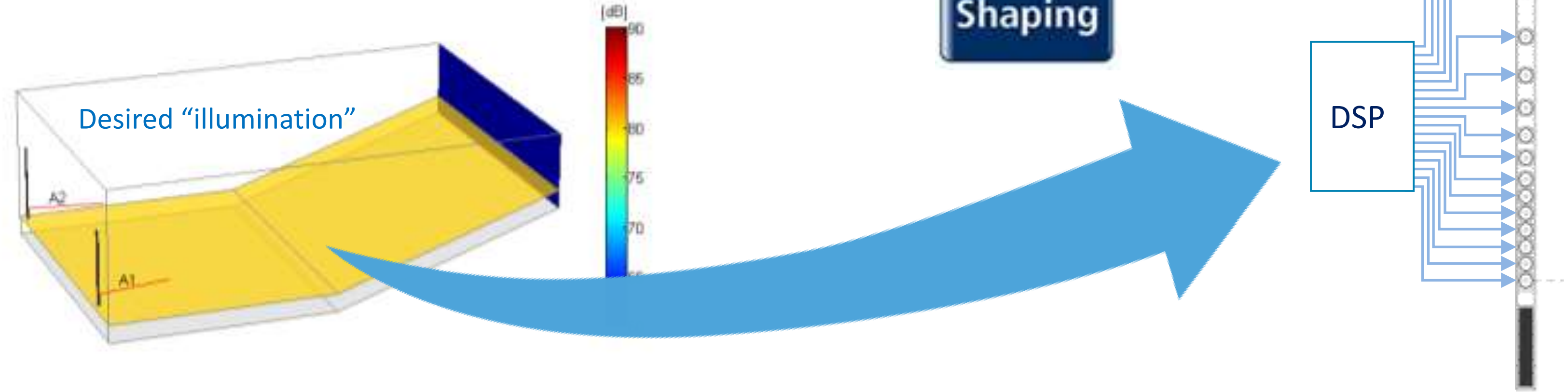




DDS - BEAM SHAPING

The Inverse Approach

- Digital Directivity Synthesis (DDS)
- Invert the desired “illumination” of the room to the array.
- Boundary conditions:
  - Minimum sound power
  - minimum “spill”
  - Robustness & Stability



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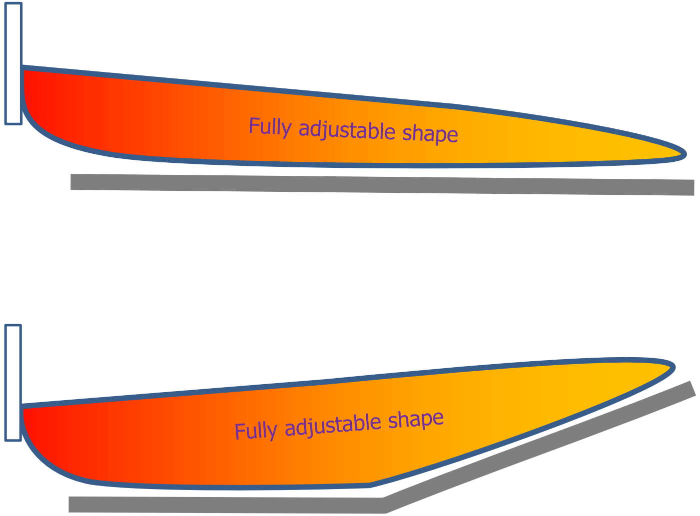
DDS
BEAM SHAPING

DDS Shaping

Digital Directivity Synthesis (DDS)

- “Beam Shaping”
- Beam can be adapted to geometry of the room
- Applied in:
  - Intellivox-DS(X) range



DDS - BEAM SHAPING

The Inverse Approach

- Digital Directivity Synthesis (DDS)
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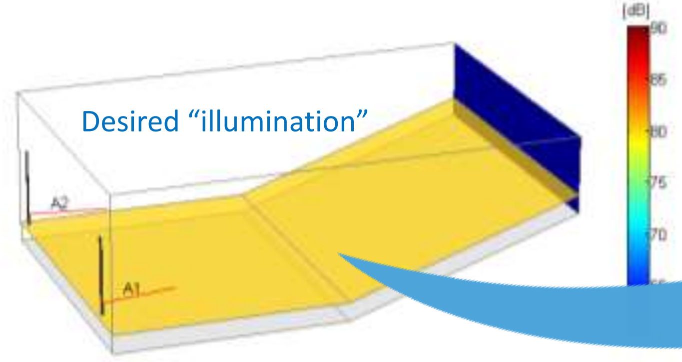
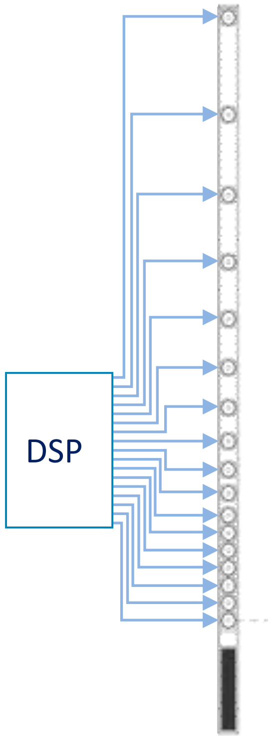
  - Robustness & Stability

DDS Shaping





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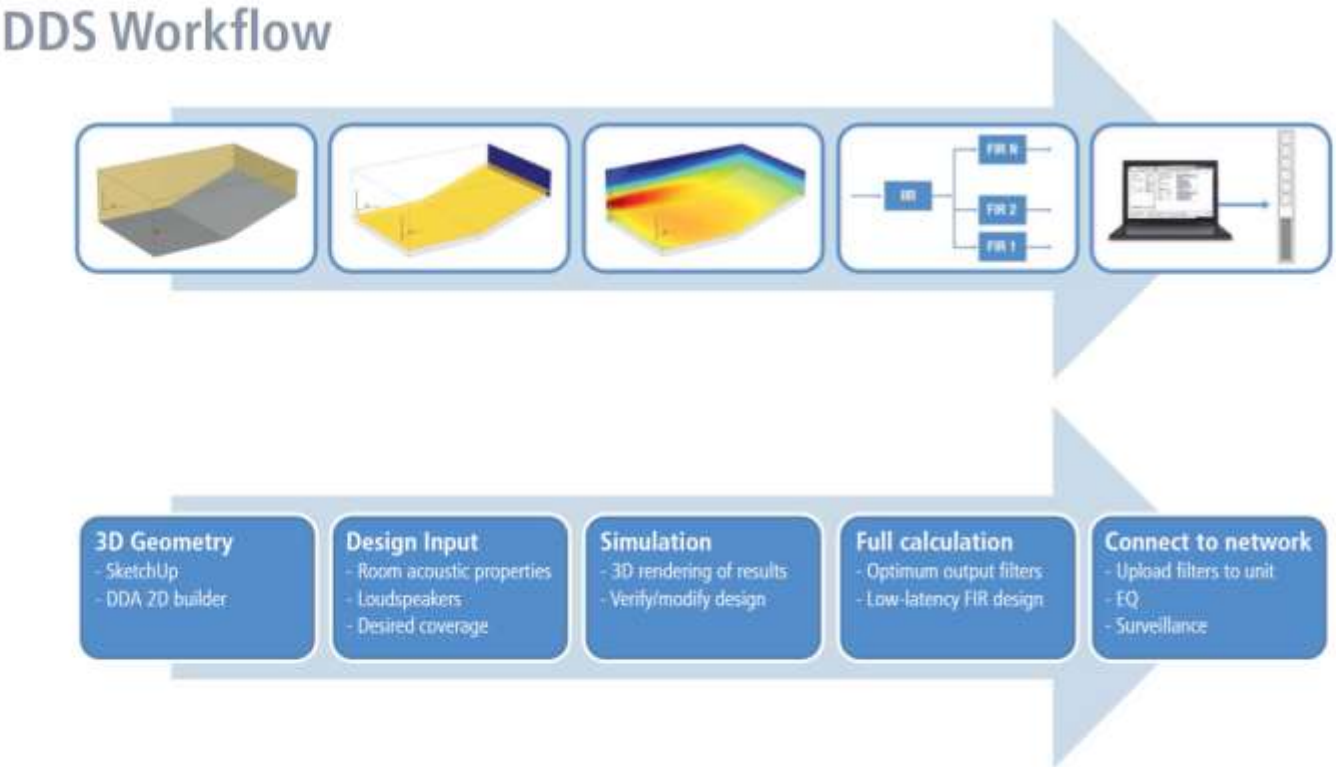
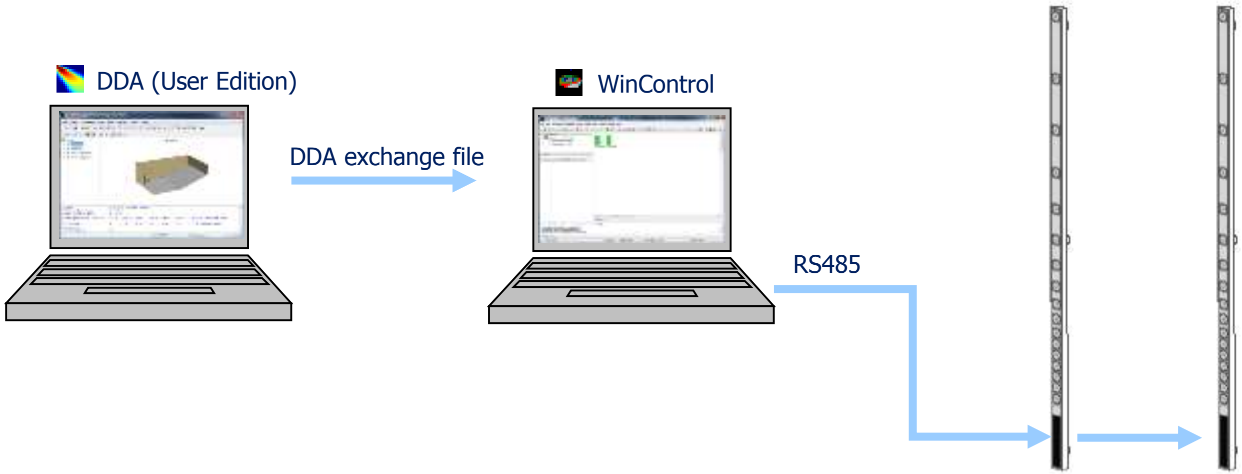
DDS - BEAM SHAPING



DDS - BEAM SHAPING

Upload Process



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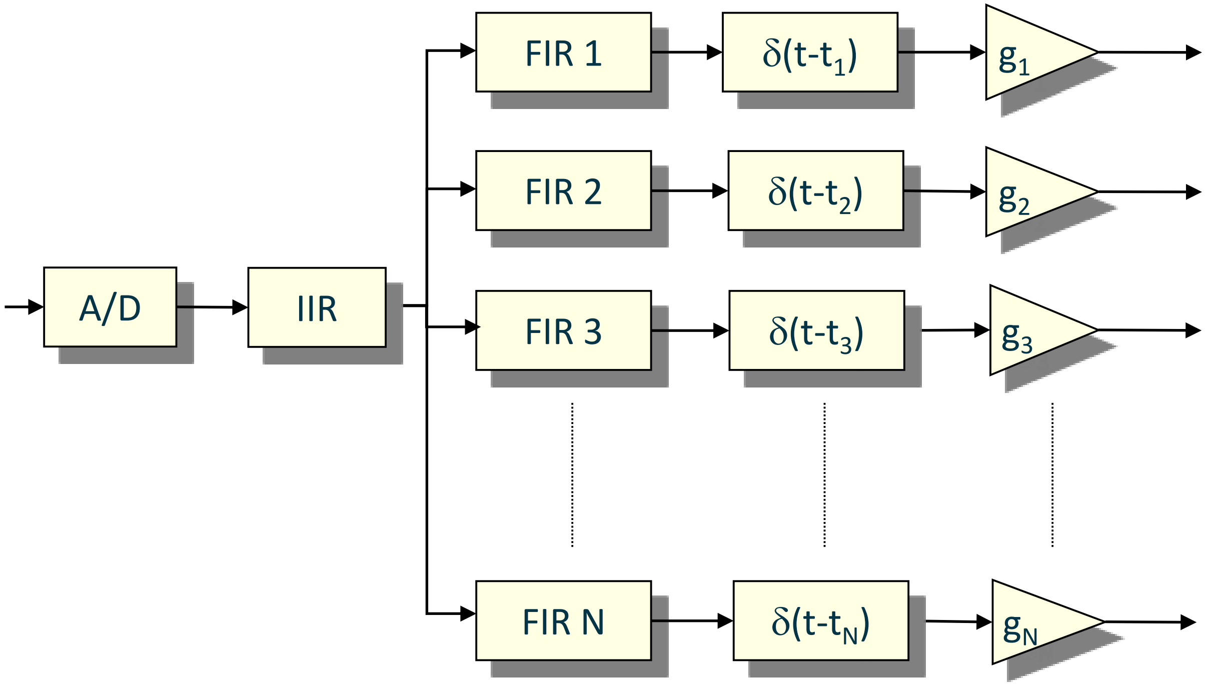
DDS BEAMFORMING

Block Diagram

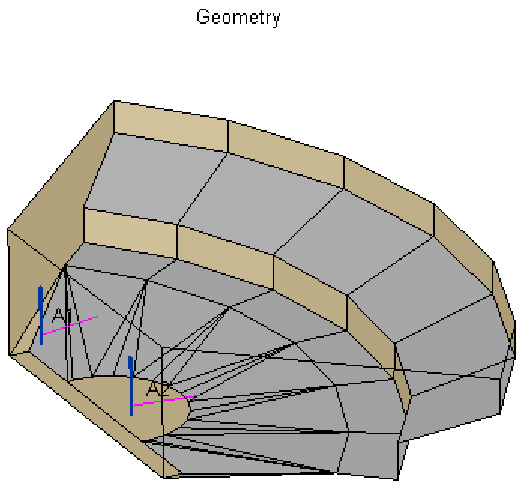


DDS - BEAM SHAPING

Intellivox Application Example

SWEDISH PARLIAMENT

- Fan-shaped hall
- Reflective curved back wall
- 2x Intellivox-4c-XL (predecessor of Intellivox-DS430)



DDS INTELLIVOX

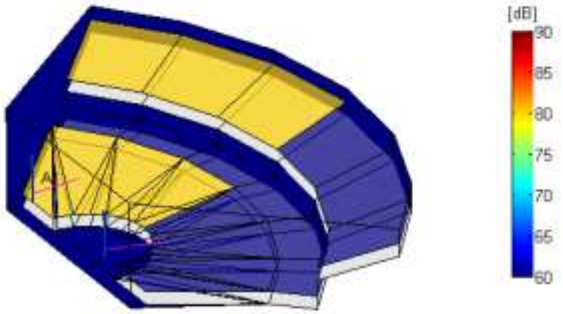
Intellivox Application Example

- Swedish Parliament
  - Fan-shaped hall
  - Reflective curved back wall

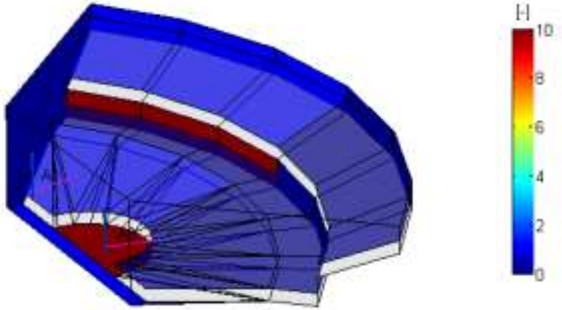
DDS - BEAM SHAPING

Intellivox Application Example

Desired direct SPL distribution



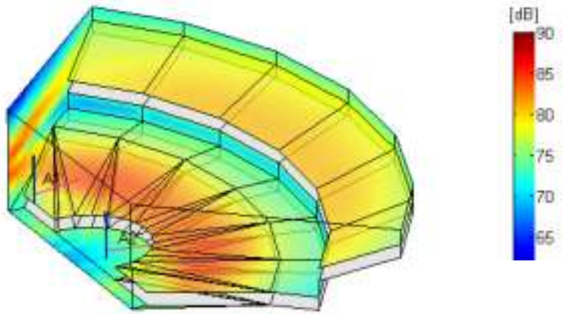
Weights (priority factors)

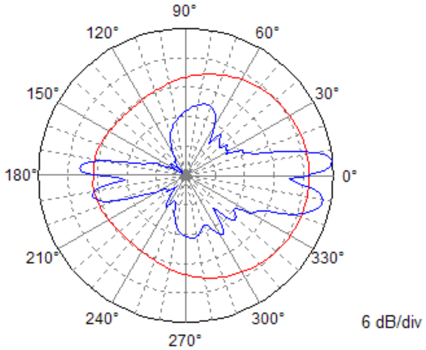


DDS - BEAM SHAPING

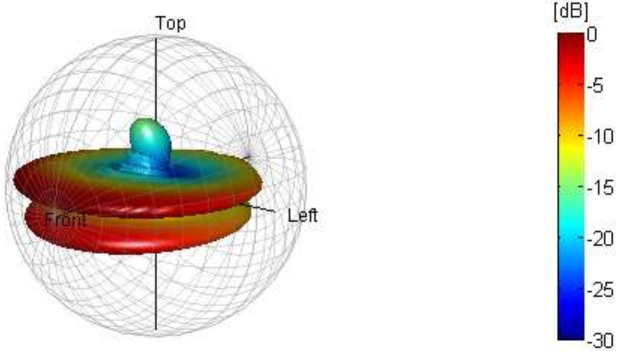
Intellivox Application Example

Realized direct SPL distribution





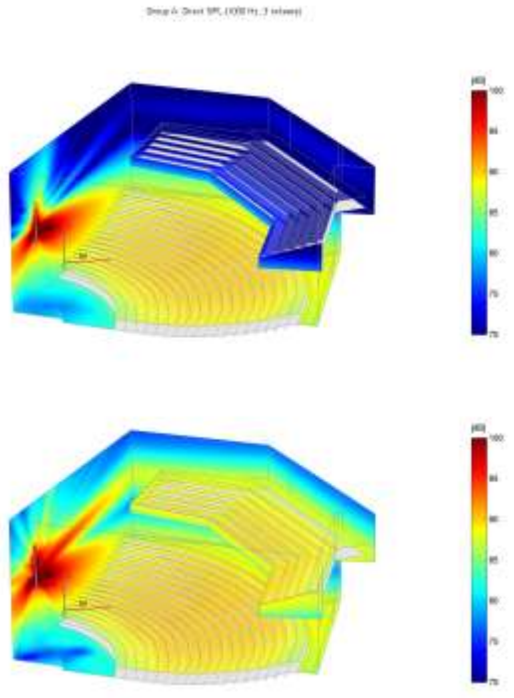
Far field polar pattern



DDS - BEAM SHAPING

Features

- Flexible array set-up
- Tailor-made directivity pattern
  - Requires (basic) 3D geometric model of space → SketchUp ® + Plugin
- Constant spectral balance for all listening positions
- Optimum direct-to-reverberant energy ratio
- Both far field and near field control
- Directivity pattern can be changed by software, i.e., without re-angling the boxes

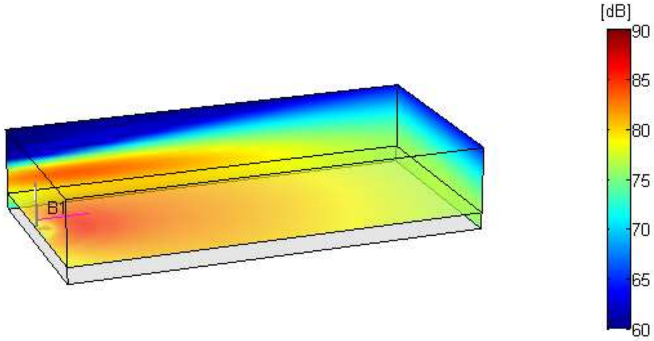


DDS - BEAM SHAPING

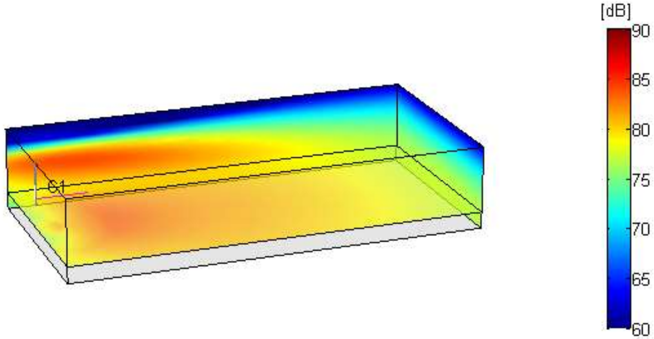
Mounting height vs. Coverage

Intellivox-DS430

H=2.5 m
Δz = 0.8 m



H=4.5 m
Δz = 2.8 m



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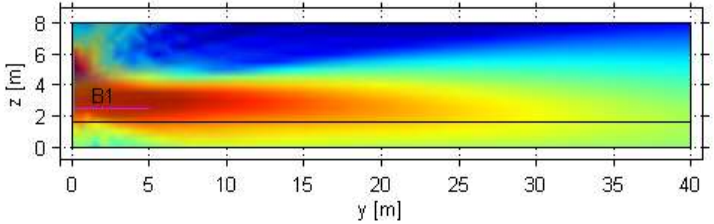
DDS - BEAM SHAPING

Mounting height vs. Dispersion

Intellivox-DS430

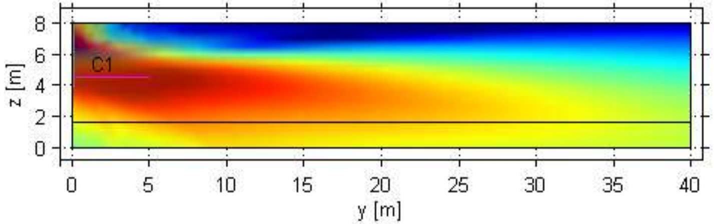
H=2.5 m

Δz = 0.8 m



H=4.5 m

Δz = 2.8 m



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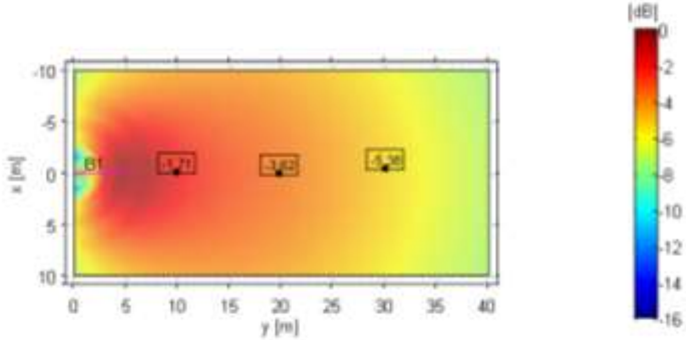
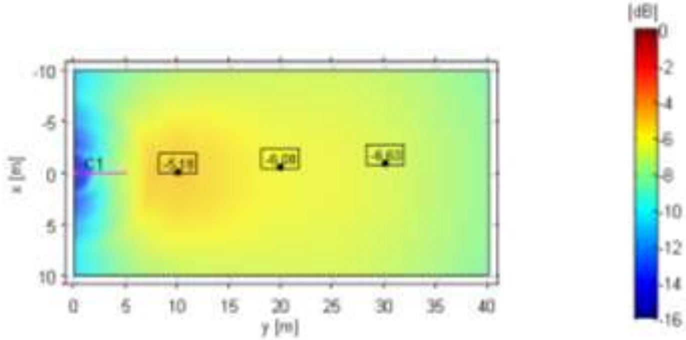
DDS - BEAM SHAPING

Mounting height vs. D/R ratio

<D/R>= -4.6 dB



<D/R>= -7.0 dB



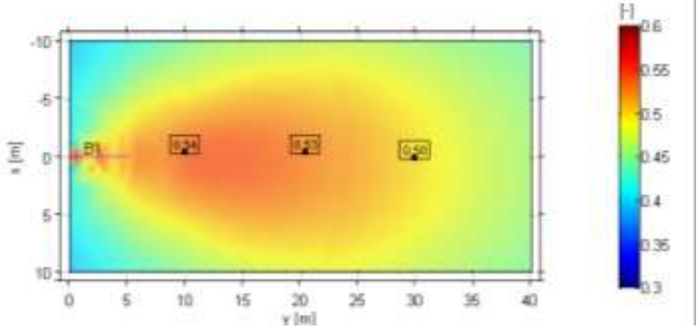
V=6,400 m^3

RT=3 s

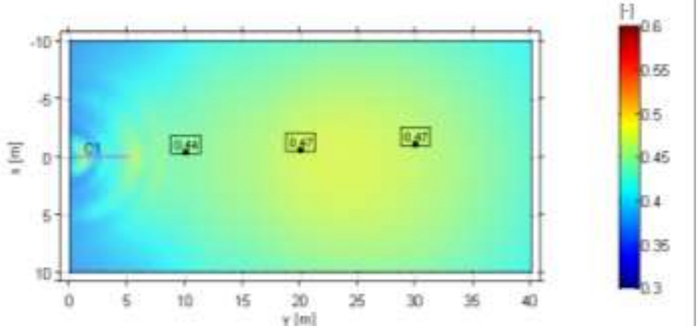
DDS - BEAM SHAPING

Mounting height vs. Intelligibility

<STI>=0.50



<STI>=0.45



V=6,400 m^3

RT=3 s

DDS - BEAM SHAPING

Mounting height

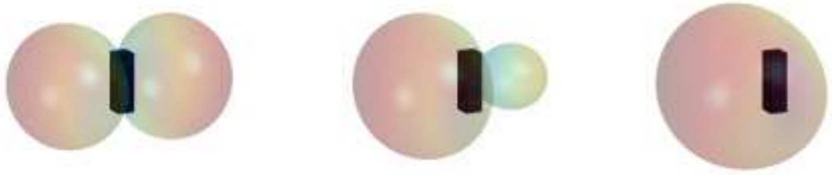
Conclusion:

- Larger mounting height
    - Larger steering angle & wider dispersion
    - Lower D/R ratio
    - Poorer speech intelligibility and musical clarity

Extremely large steering angles don't make sense!

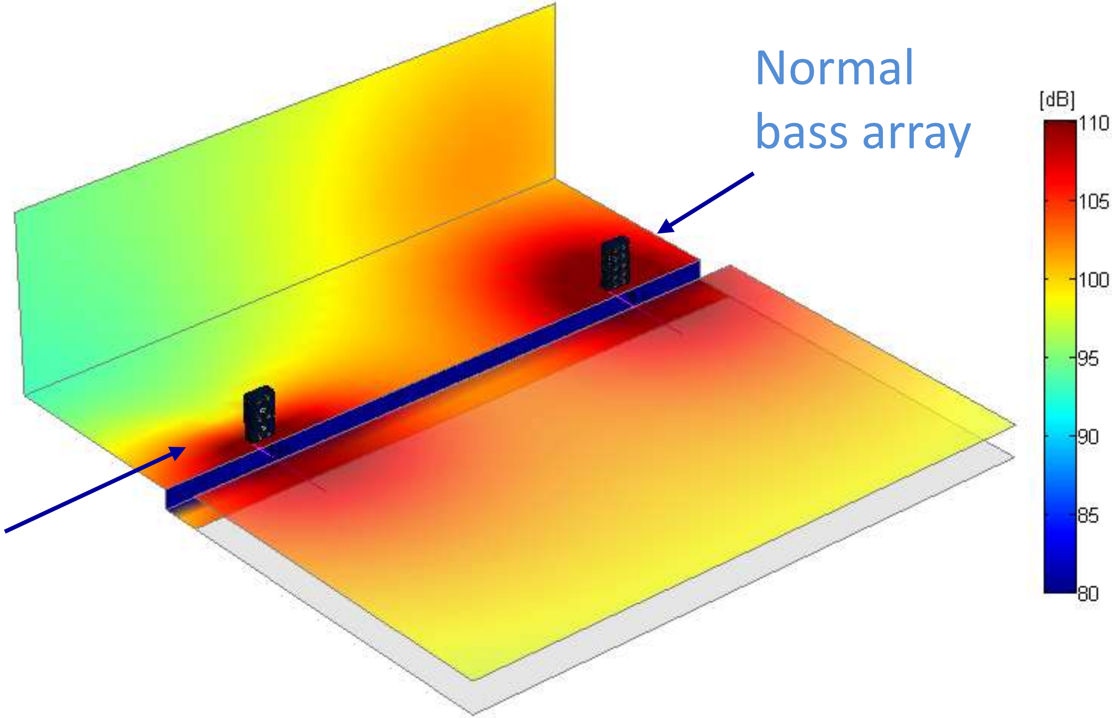
CONTROLLING BASS

1. **WHAT ARE BEAM-SHAPED DIFFERENTIAL SUBWOOFER ARRAYS?**
2. **ACOUSTIC MODELLING BY PSM-BEM**
3. **VALIDATION OF PSM-BEM BY MEASUREMENTS**
4. **SUMMARY AND CONCLUSIONS**



Normal versus cardioid bass arrays

Normal
bass array



Cardioid
bass array

SUBWOOFER ARRAYS

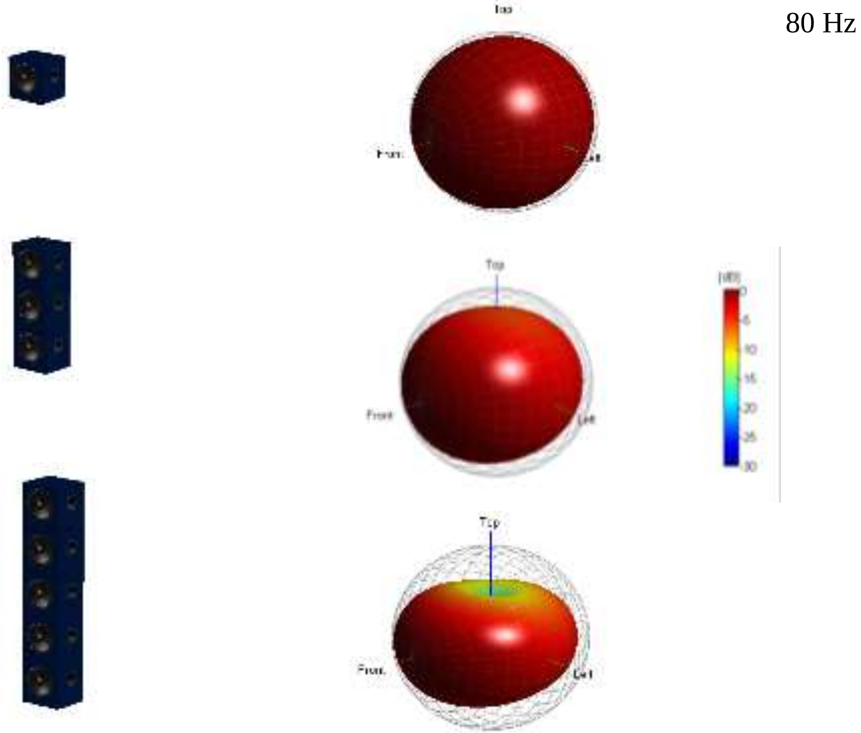
"Summing"

Directivity:

$$Q \propto \frac{L}{\lambda} \qquad DI = 10\log(Q)$$

Gain and robustness:

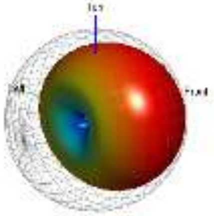
$$G_{array} = 10\log\left[\frac{P_{array}^2(f)}{\sum_{l=1}^{L} P_l^2(f)}\right]$$



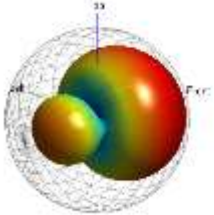
SUBWOOFER ARRAYS

“Differential”

80 Hz



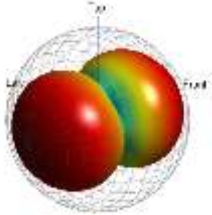
+ “Superdirectional”, i.e., high Q for small L/λ
- Less robust than delay-and-sum arrays



1x B-215DIFF

Front

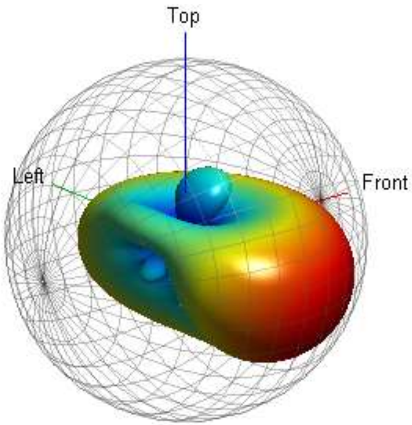
Back



3x B-07

BEAM-SHAPED DIFFERENTIAL SUBWOOFER ARRAYS

- **Combination of delay-and-sum and differential array**
- **DDS-optimised**
  - **Requires an accurate model of each box**

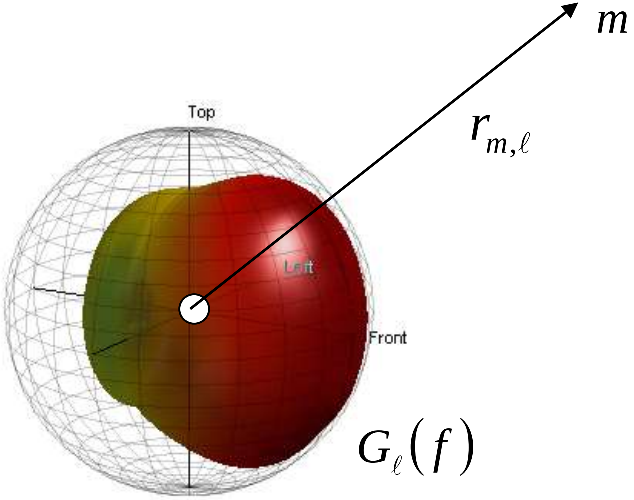


ACOUSTIC MODELLING OF SUB ARRAYS

Point Source Model (PSM)

- Each loudspeaker in the array is represented by a point source with a certain directivity
- Radiation into free space (free field conditions)

$$L_{m,\ell}(f) = G_{\ell}(f, \theta_{m,\ell}, \varphi_{m,\ell}) \frac{e^{-jkr_{m,\ell}}}{r_{m,\ell}}$$



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POINT SOURCE MODEL (PSM)

Benefits:

- Computationally efficient
- Only one directivity function for each loudspeaker type

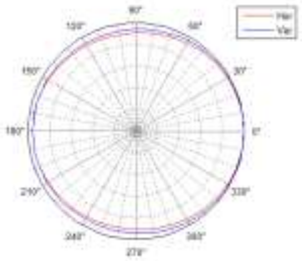
Shortcomings:

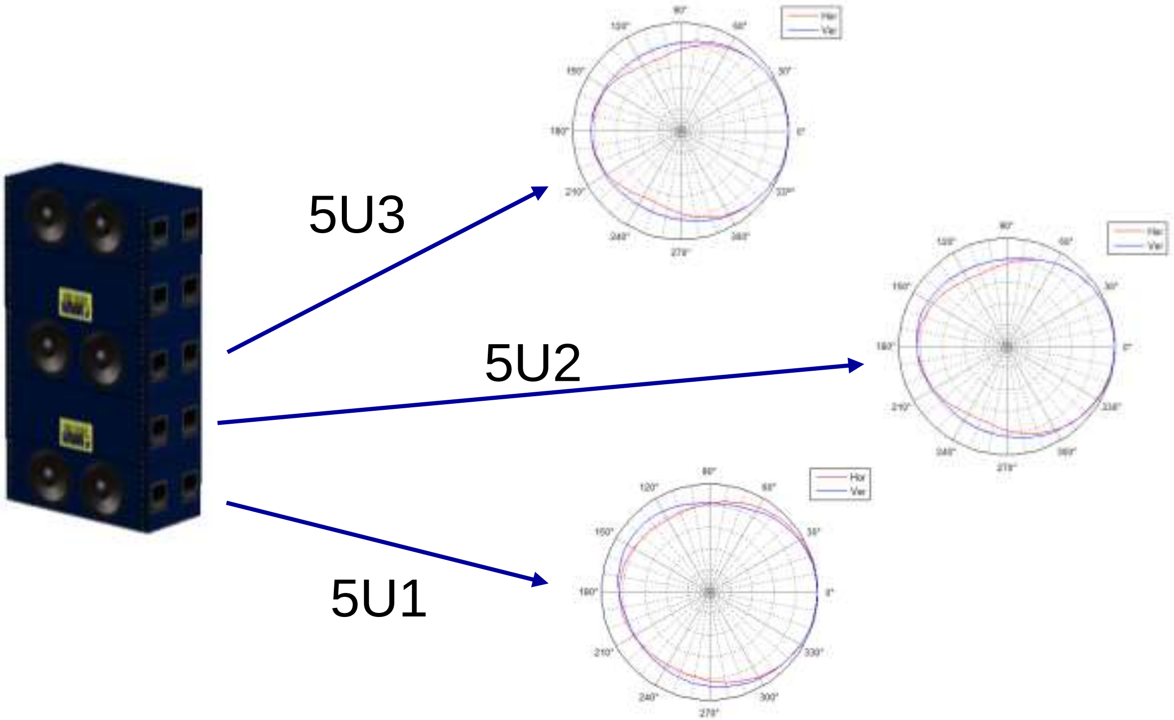
- No LF 'coupling' between stacked subwoofers
  - In reality, sensitivity of each box depends on stack size
- No modelling of LF diffraction around array
  - In reality, directivity and F/B ratio of each box depends on stack size
- No accurate ground plane modelling (i.e., half-space) possible with simple mirror image source model

COUPLING EFFECTS

ARRAY SIZE AND LOUDSPEAKER POSITION

Free field





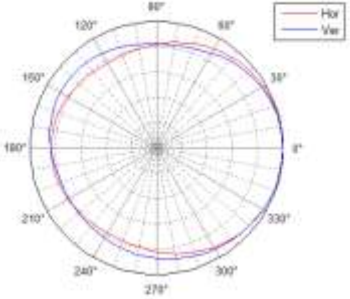
Magnitude (6 dB/div)

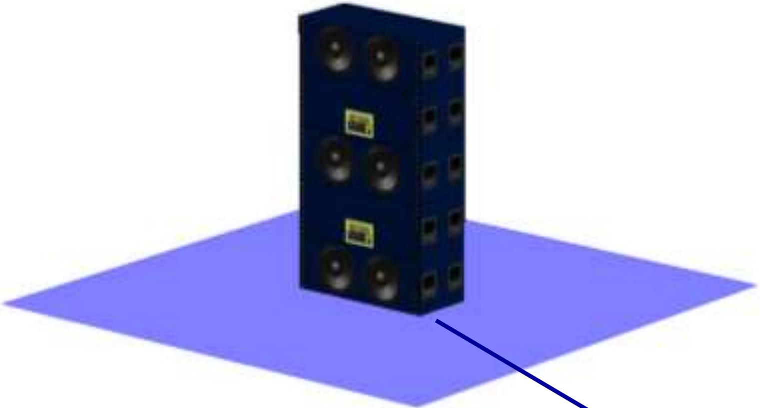
COUPLING EFFECTS

Boundary plane

Full-space

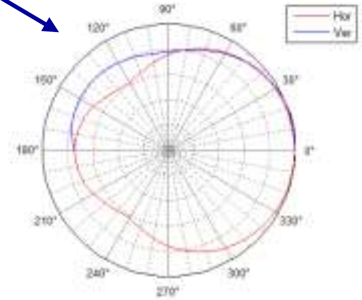
5U1 FS





Half-space

5U1 HS



Magnitude (6 dB/div)

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HYBRID PSM-BEM MODEL

Idea:

- Each loudspeaker in the array is modelled as a directional point source
- BEM is applied to calculate directivity functions of loudspeaker facing the actual Acoustic Boundary Conditions (ABC), including half space conditions

Benefits:

- One-time only calculation of directivity library for various ABC
- Library can be easily extended
- Computationally efficient simulation

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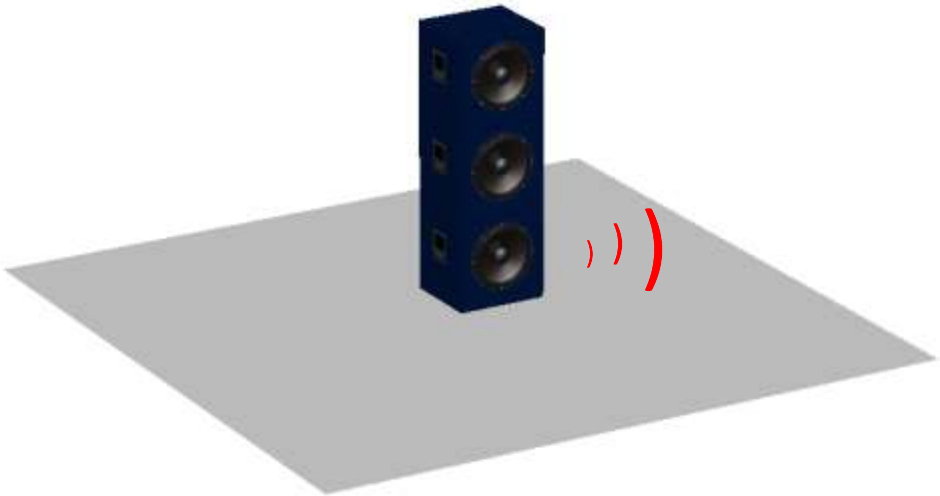
BEM CALCULATIONS

Procedure:

- Measure normal component of particle velocity in front of cone and ports of subwoofer
- Make finite boundary element model of subwoofer array
- Calculate pressure distribution on boundaries using either full-space or half-space version of Helmholtz Integral Equation (HIE)
- From the measured velocity and the calculated pressure distribution, calculate directivity balloons for active subwoofer

BEM CALCULATION EXAMPLE

Set-up



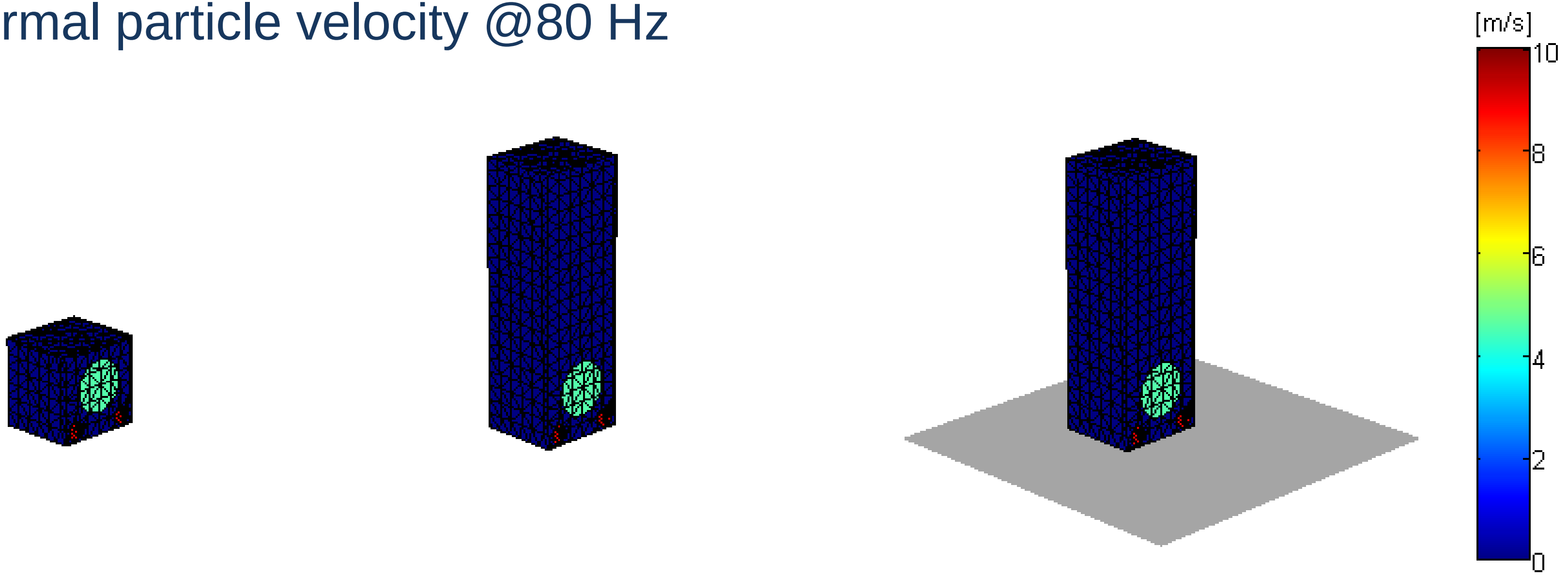
Free-Field

3U1 full-space

3U1 half-space

BEM CALCULATION EXAMPLE

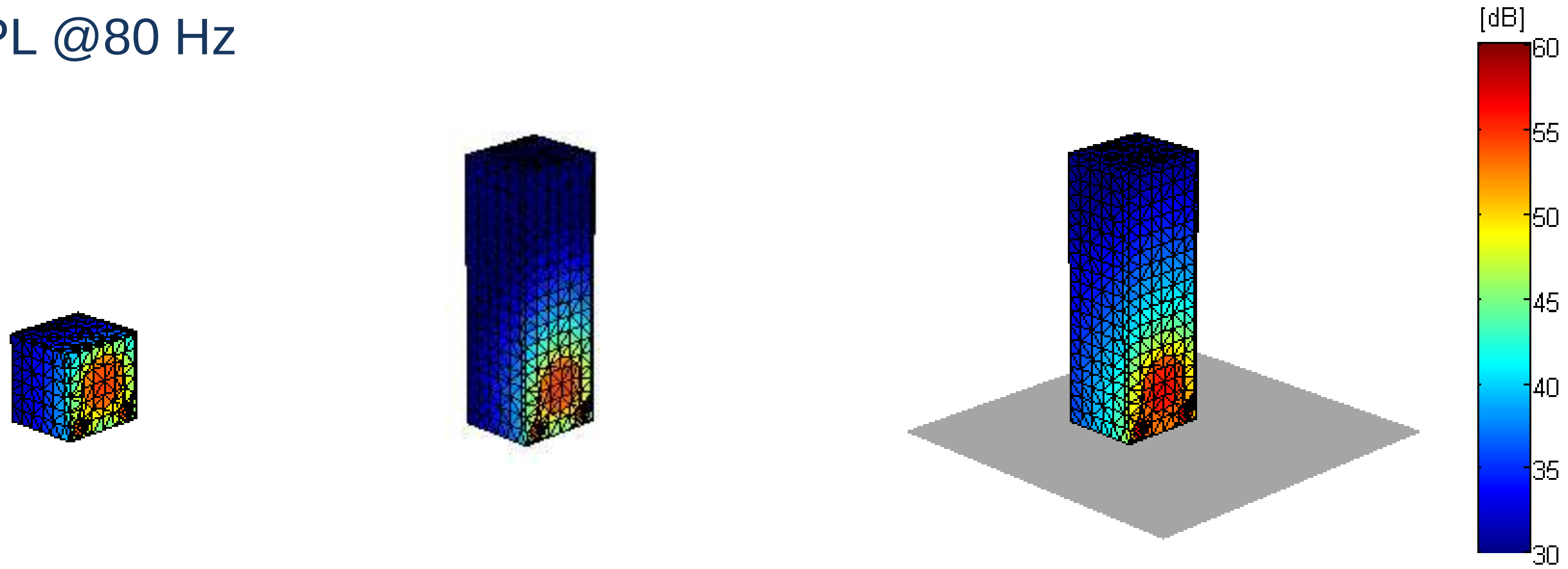
Normal particle velocity @80 Hz



Free-Field	3U1 full-space	3U1 half-space

BEM CALCULATION EXAMPLE

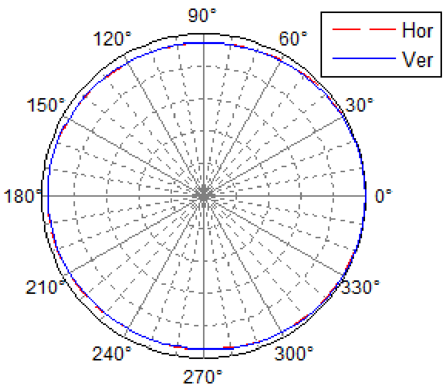
SPL @80 Hz



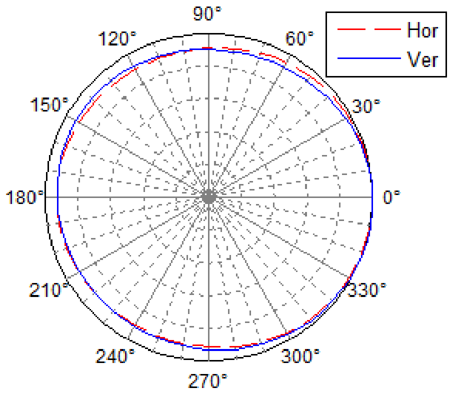
Free-Field 3U1 full-space 3U1 half-space

BEM CALCULATION EXAMPLE

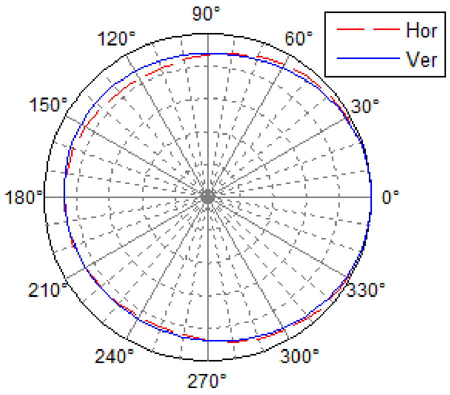
Balloon @80 Hz



Free-Field



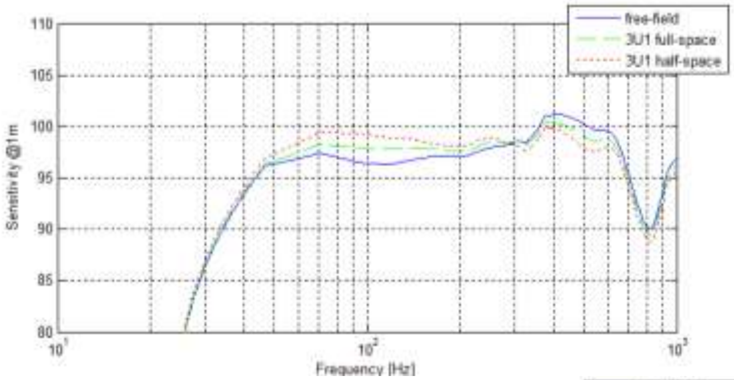
3U1 full-space



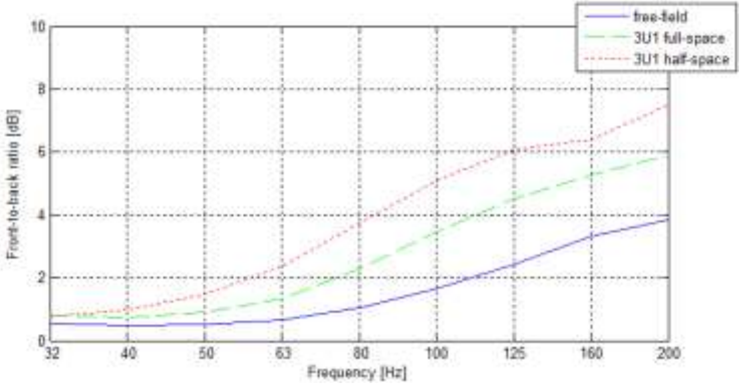
3U1 half-space

BEM CALCULATION EXAMPLE

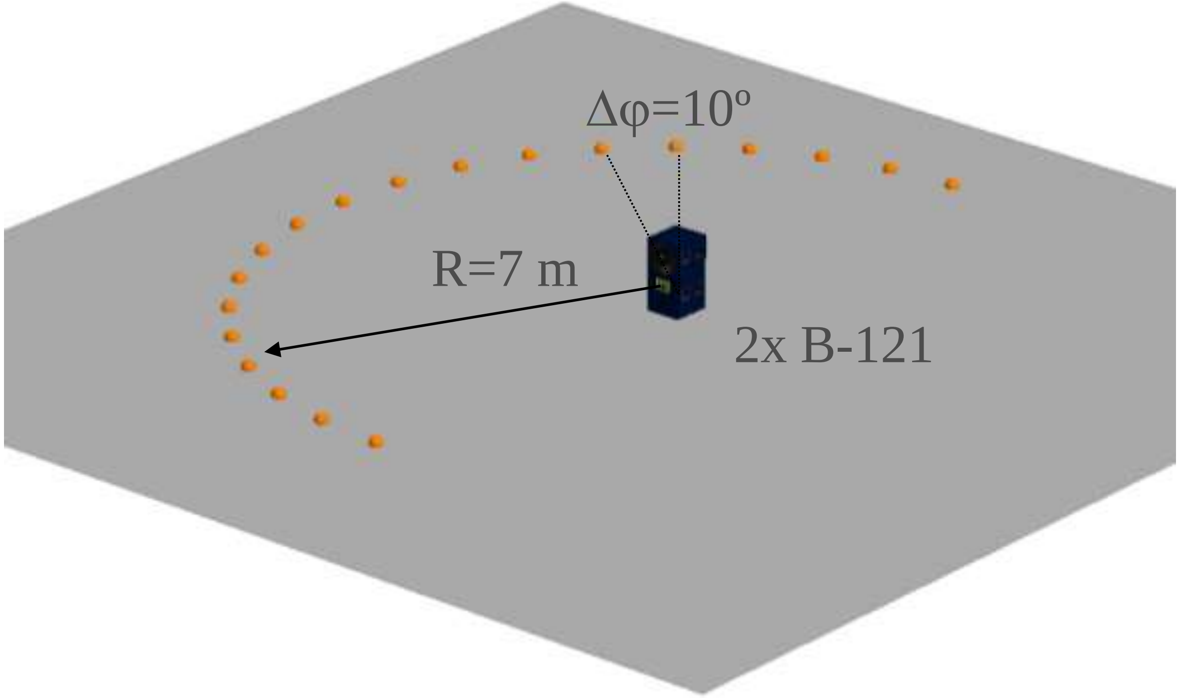
Sensitivity



Front-to-back ratio



VALIDATION PSM-BEM MODEL

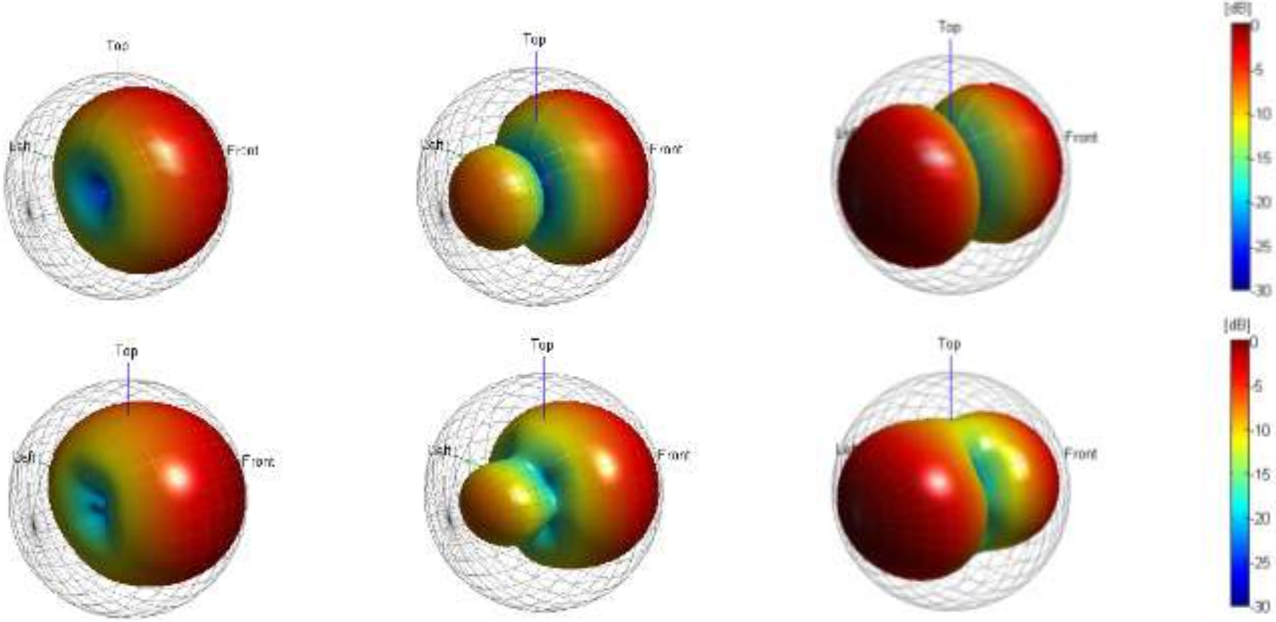


VALIDATION PSM-BEM MODEL

Cardioid | Hyper-cardioid | Dipole

Theoretical

Predicted
(63 Hz octave)



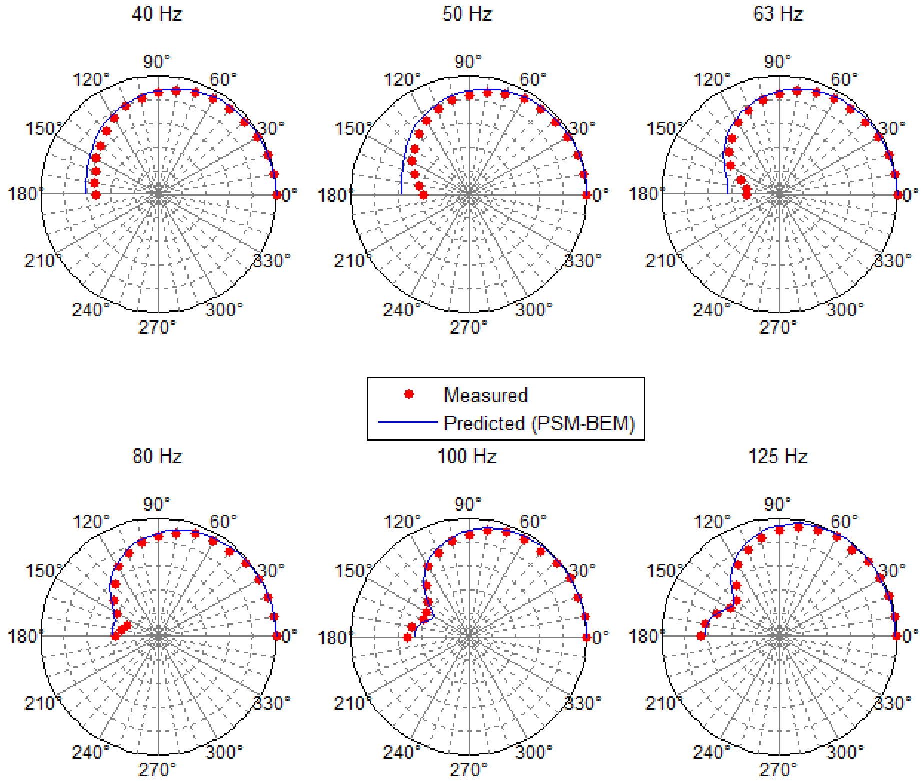
MEASUREMENT RESULTS

Cardiod setting

Mean array parameters:

DI = 4.9 dB

G_{array} = 1.4 dB



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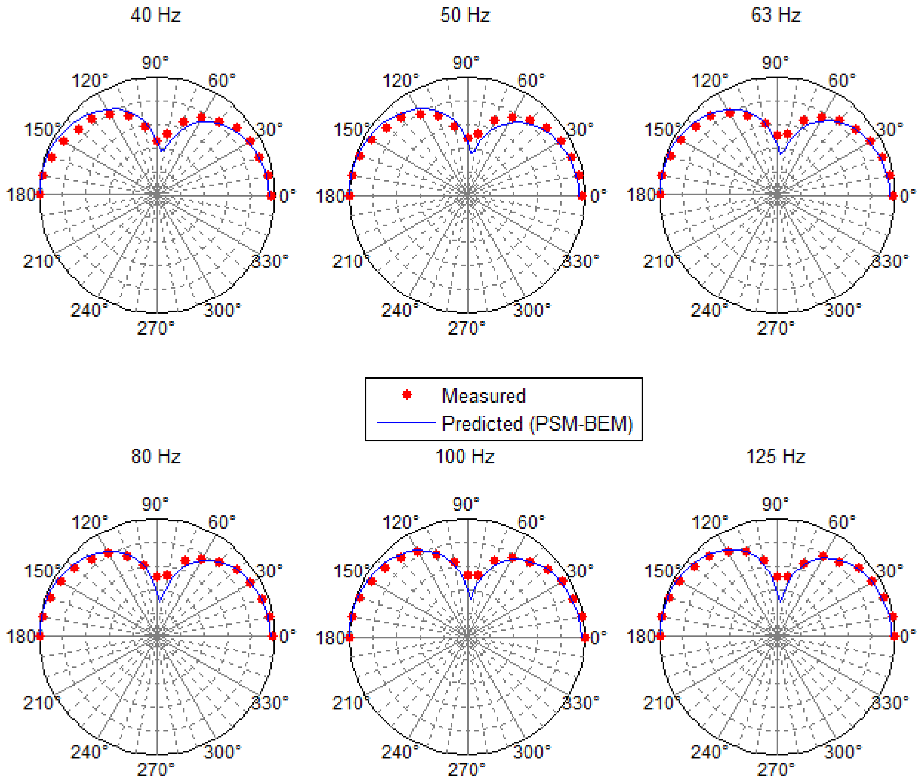
MEASUREMENT RESULTS

Dipole setting

Mean array parameters:

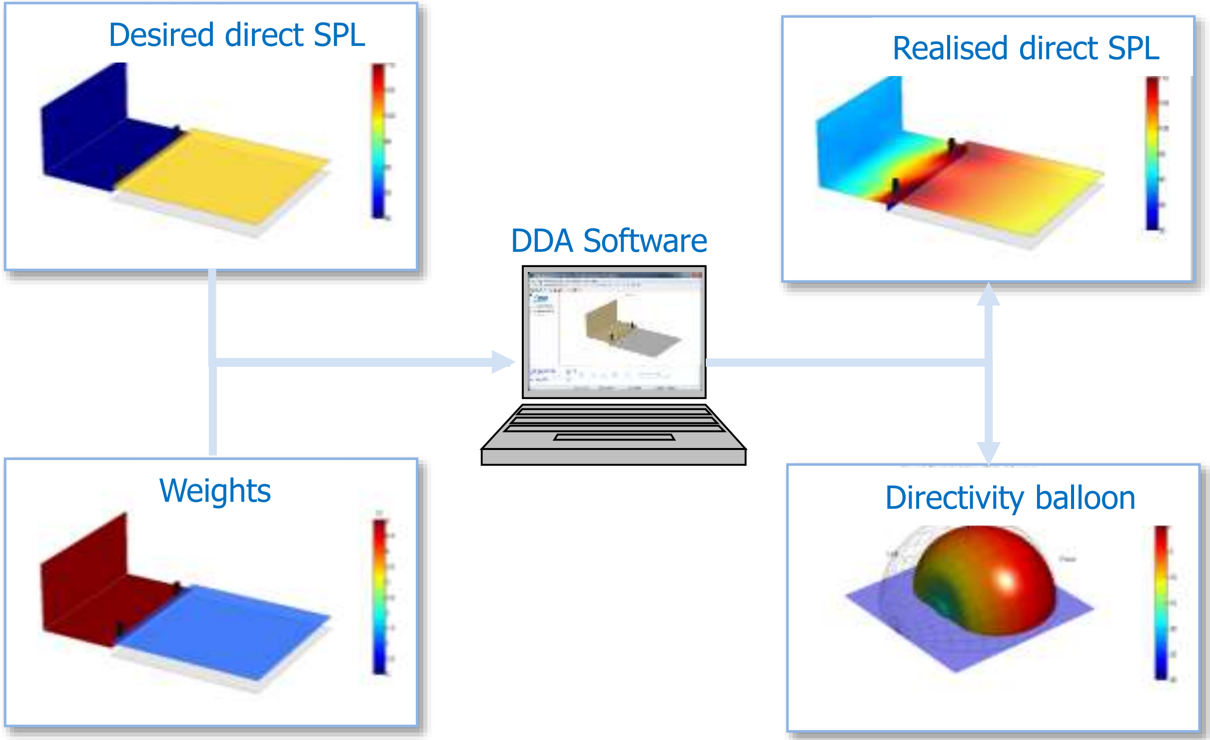
DI = 5.3 dB

G_{array} = -0.5 dB



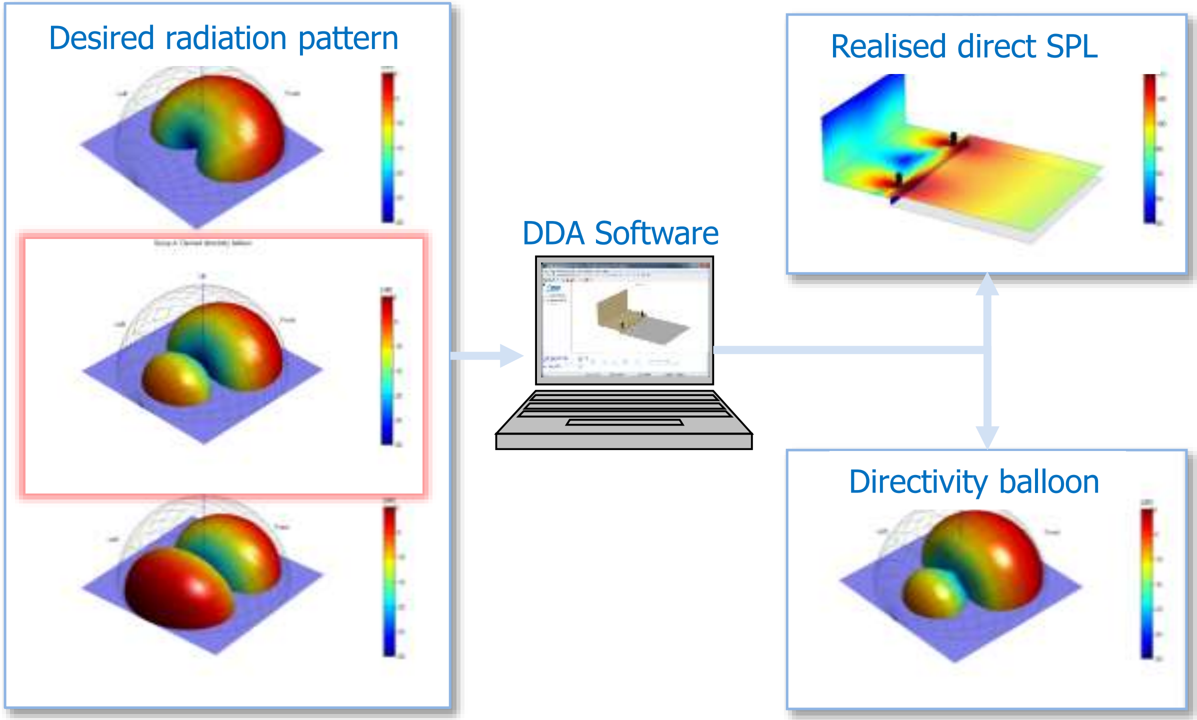
HOW DOES IT WORK IN PRACTICE?

DDS Geo method



HOW DOES IT WORK IN PRACTICE?

DDS Balloon method



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Summary & Conclusions

- Hybrid PSM-BEM model handles
  - Full-space
  - Half-space
  - Various array lengths
- Very accurate modelling of beam-shaped differential subwoofer arrays
- Large front-to-back ratio of cardioid subwoofer arrays
- Good Robustness, i.e. array response not sensitive to small deviations in sensitivity of individual drivers