Holographic directivity measurement of line sources and sound panels

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KLIPPEL

Abstract

Compared to a standard Hifi stereo system, new 3D listening experiences have increased the complexity of sound systems a lot. To realize immersive audio reproduction, many loudspeakers distributed in the listening room may be placed. Other methods use more complex sound sources like line arrays and sound panels to shape distinct beams, including controlled reflections from the room boundaries. The complex control algorithms necessitate directivity data of each individual transducer with highly accurate phase information.

The workshop will discuss the field of directivity measurement for multi-transducer sound systems and will compare the benefits and limits of a traditional far field measurement vs. new holographic measurement techniques.

Reproducing 3D sound

Distributed sound sources

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- Sound sources are distribute in the listening room
- Fixed installation

- Sound sources are relatively simple

Centralized audio system

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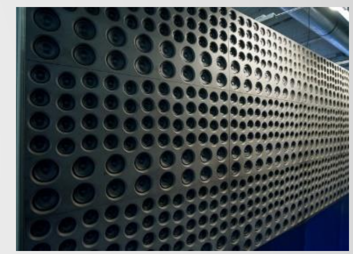

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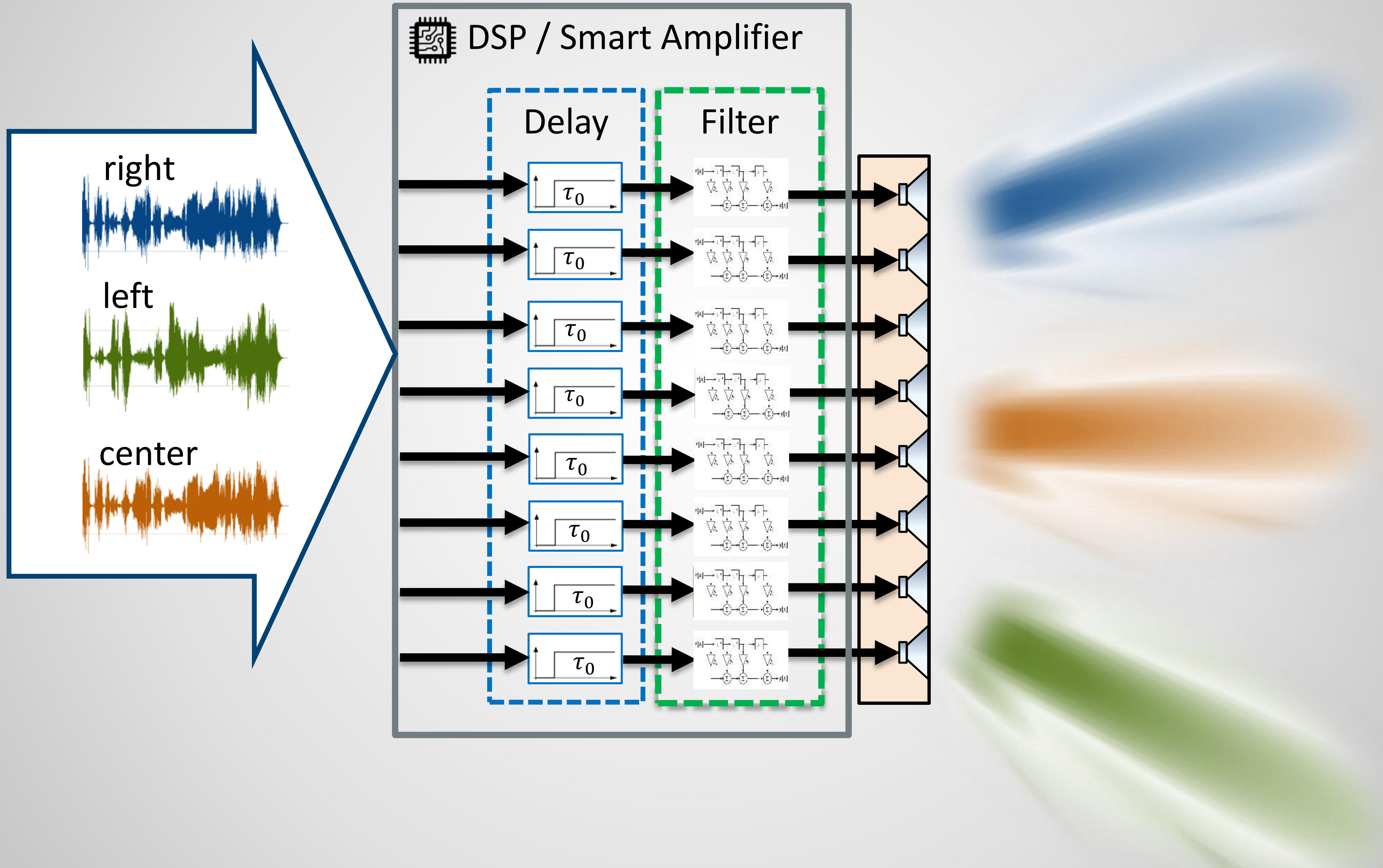
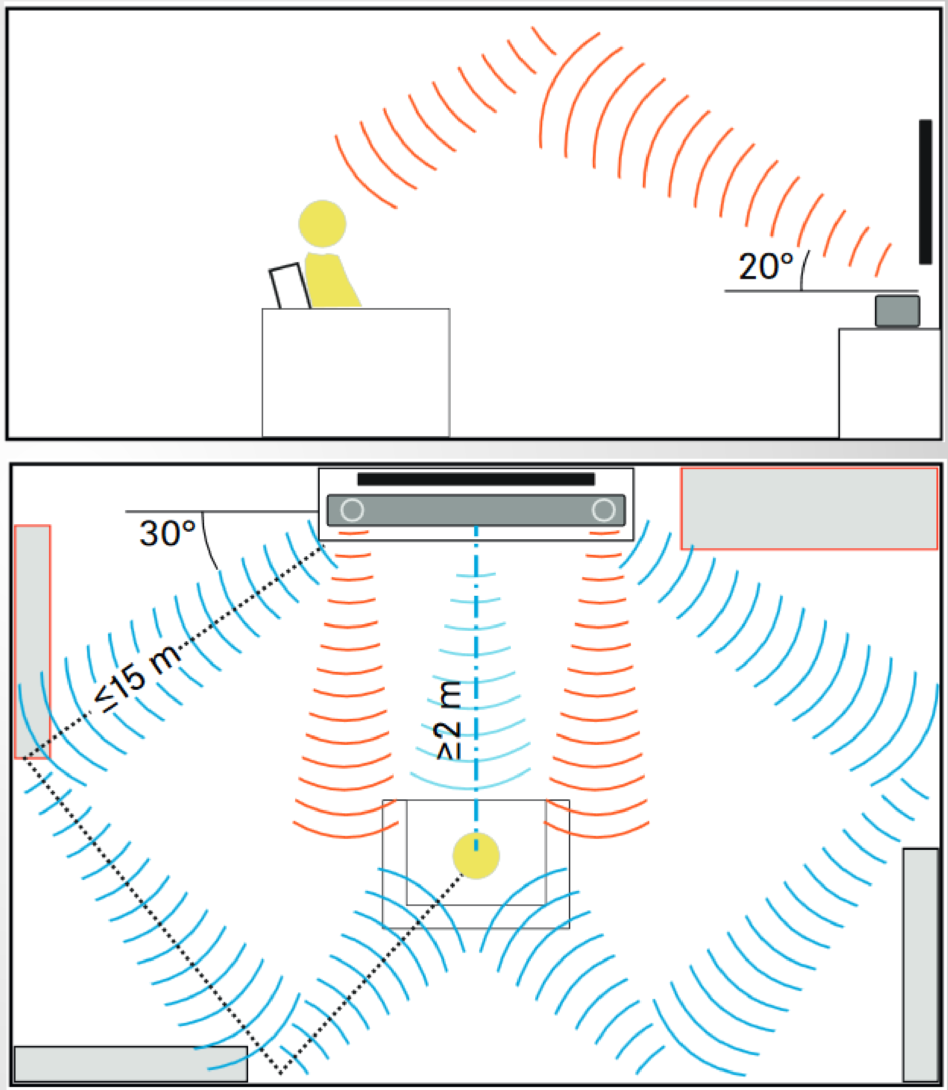
- sound system is at one spot in the listening room
- (e.g. TV, stage, etc.)
- Spatial perception generated by controlled reflections

- portable
- high complexity of the sound source
- many transducers, large dimension

Controlled directivity



Example: Sound Bar



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Home Cinema application

- Distinct beams for front channels
- Rear channel by controlled reflections

Measurement Requirements

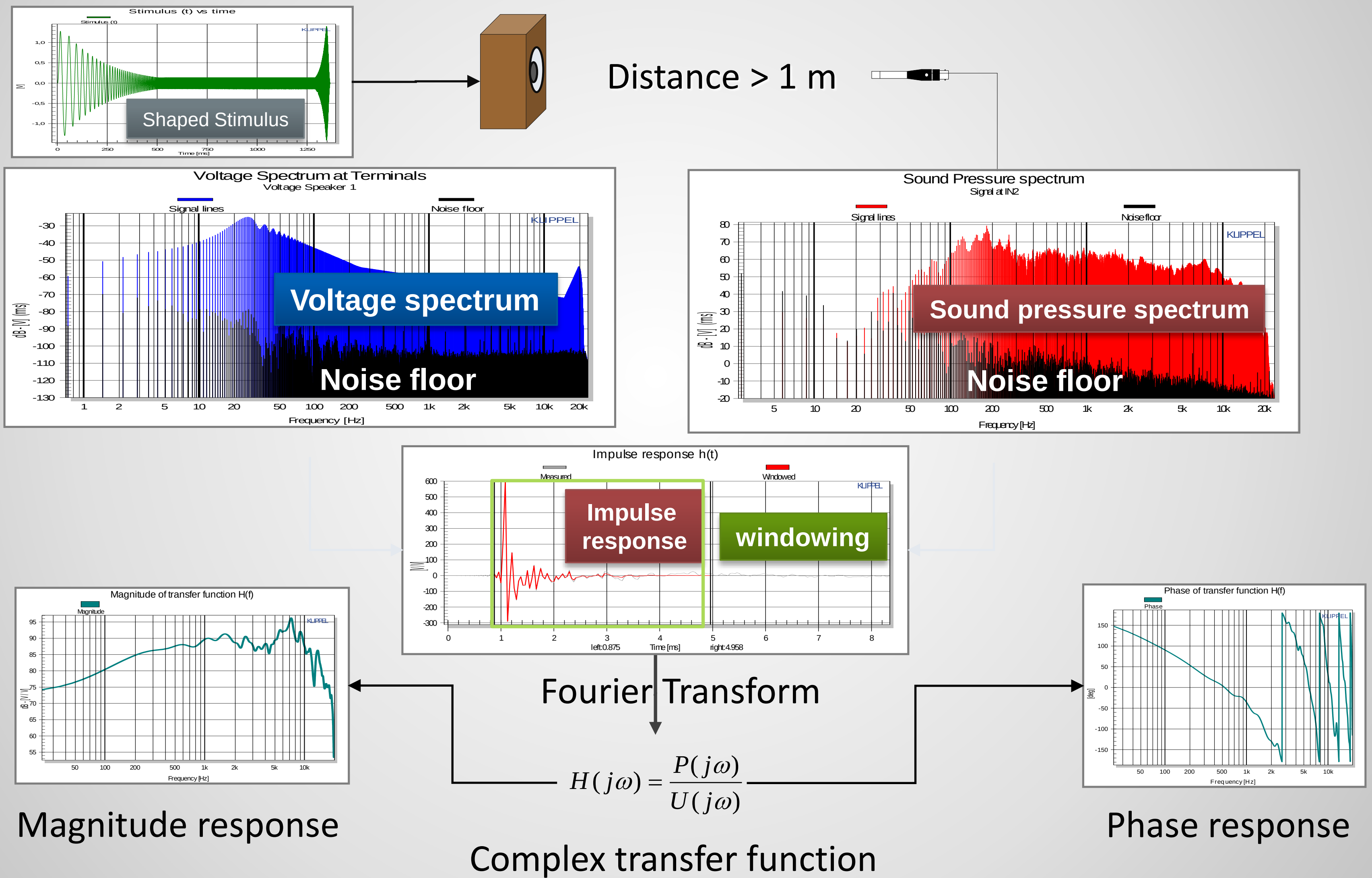
Targets:

- Directional characteristics of each transducer
- Including boundary effects from the cabinet
- Far field (Pro Audio Line Arrays)
- Near Field (e.g. sound bars, studio monitor)
- Accurate Phase information

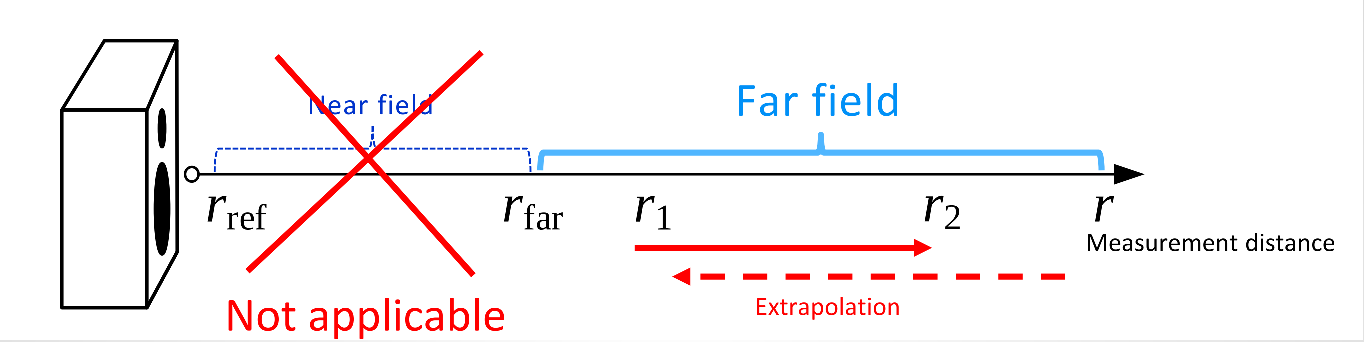
Measurement Particularities

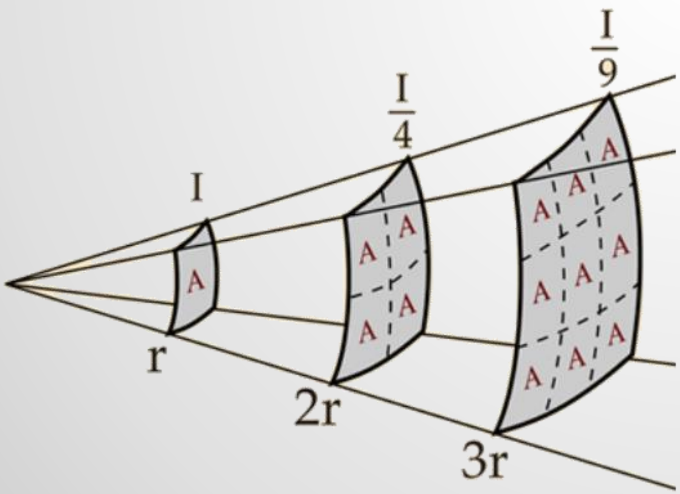
- Free field data
- Separate measurement of transducers
- Positioning of sources is critical
- Measurement distance? Near Field or Far Field?
- Sound radiation problems (e.g. humidity, temperature)
- Reasonable Time, minimum number of points

Measurement of Far Field Response



Extrapolation of Far Field Data





$$\underline{H}(f, r_2, \theta, \phi) = \underline{H}(f, r_1, \theta, \phi)\frac{r_1}{r_2} e^{-jk(r_2 - r_1)}$$

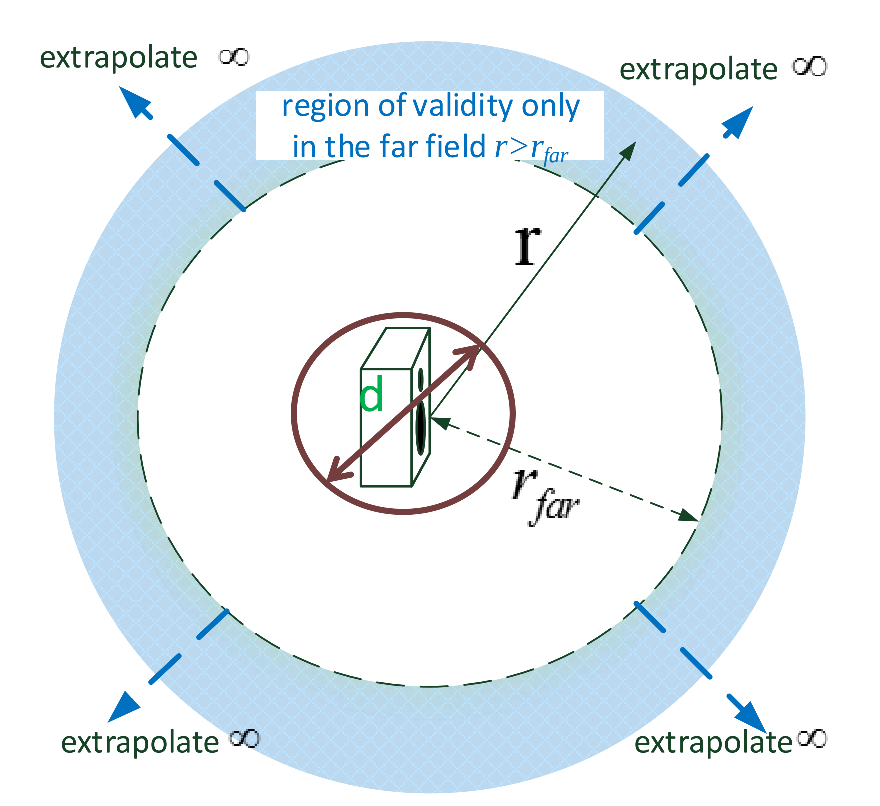
Requirements:

- free field condition (direct sound)
- *far field condition*
- same direction ($\phi_2 = \phi_1,\ \theta_2 = \theta_1$)

How to Ensure Far-Field Conditions ?

Requirements:

- *Distance* $r_{far} >> d$
  (critical for large geometrical dimension d)
- *Distance* $r_{far} >> \lambda$
  (critical at long wavelength λ*)*
- *ratio* $r_{far} / d >> d/\lambda$
  (critical at short wavelength λ*)*



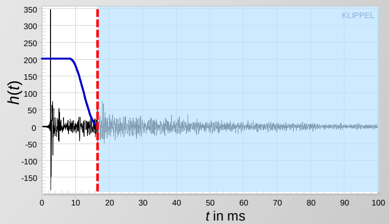
→ Large loudspeaker systems require large anechoic rooms ! (e.g. line arrays)

Conventional Far-Field Measurements

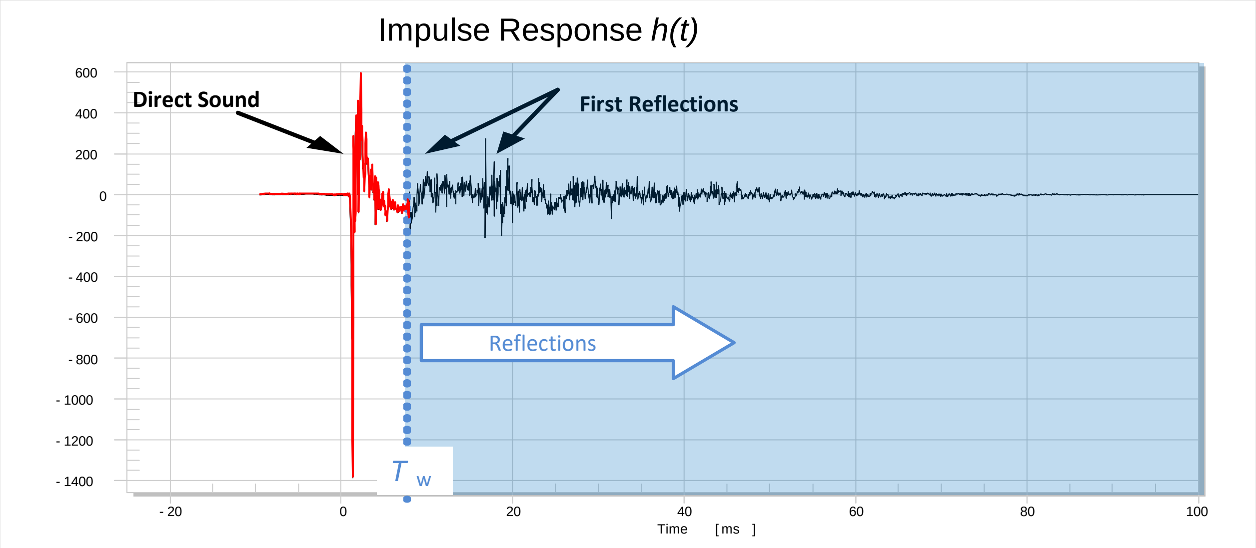
(a time line)

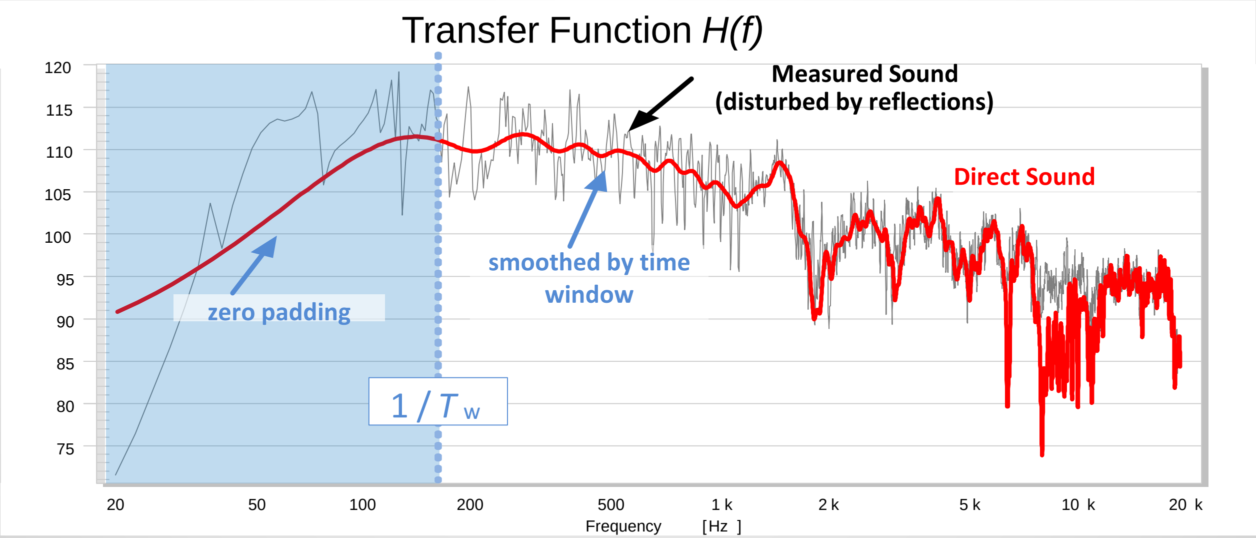
- **Far-Field Measurements in Anechoic Chambers** (1930's, Beranek and Sleeper 1946)
  - Realized as a half and full space
  - Good absorption of room reflections (> 100 Hz)
  - High ambient noise isolation
  - Controlled climate conditions and avoids wind effects

- **Far-Field Measurement under simulated free-field conditions** by gating or windowing the impulse response (Heyser 1967-69, Berman and Fincham 1973)
  - Good suppression of room reflections at higher frequencies
  - Higher SNR due to ambient noise separation
  - Limited low frequency resolution (depends on time difference between direct sound and first reflection)

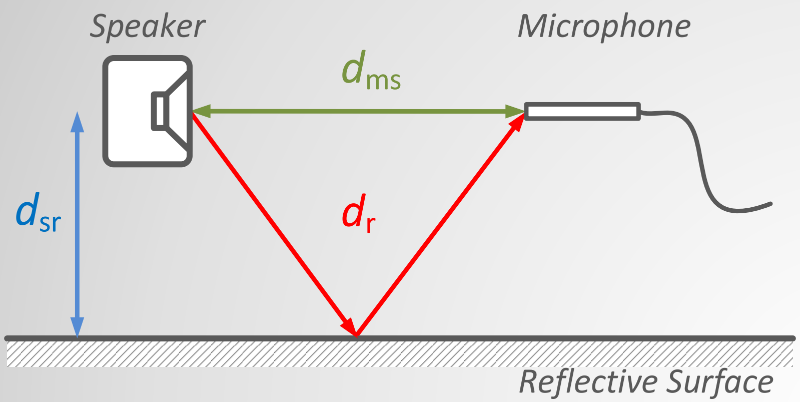


Time Windowing





Time Windowing



Path of the first reflection $$d_r = 2\sqrt{\left(\frac{1}{2}d_{ms}\right)^2 + d_{sr}{}^2}$$

Length of the time window $$T_W = \frac{d_r - d_{ms}}{c}$$

Frequency Resolution $$\Delta f = 1/T_W$$

d_{ms} - Distance microphone speaker
d_{sr} - Distance speaker room boundary

Example: d_{ms}=4m

d_{sr}	T_w	Δf	1/12 octave
2 m	4.8 ms	200 Hz	>1 kHz
5 m	19.7 ms	50 Hz	>500 Hz

- Room size is limiting the Frequency Resolution
- Not applicable for low frequencies

Angular Resolution limited by Sampling

Problem of the Far Field Measurement

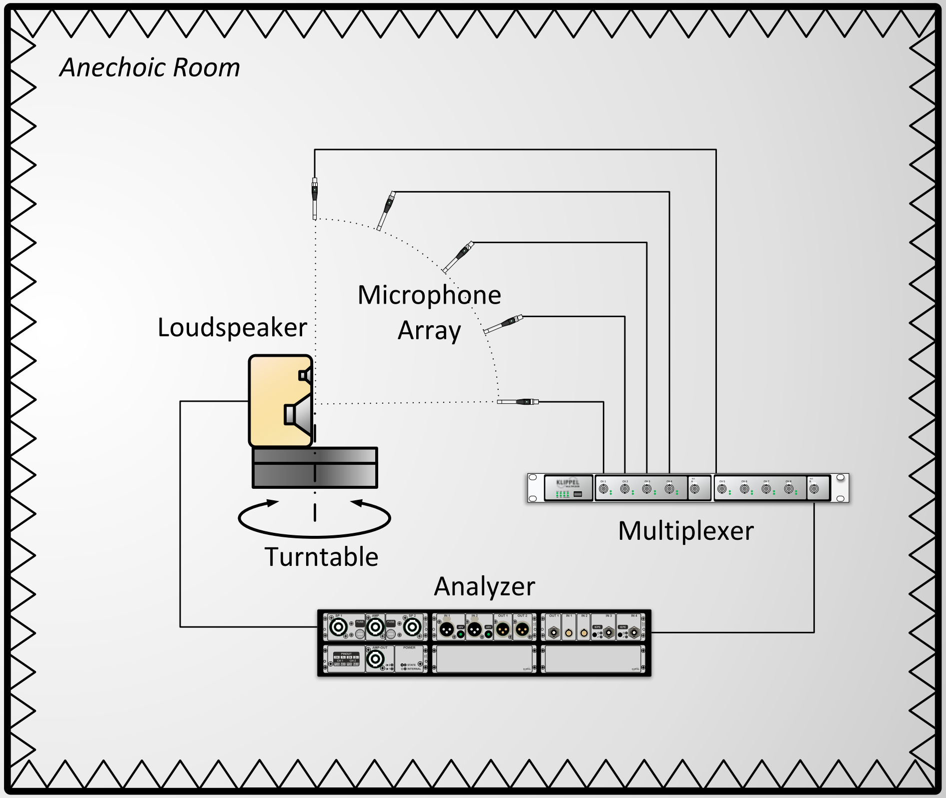
The sound pressure is measured at multiple measurement points located on a sphere with radius r. The # of pts. depends on desired resolution:

5 degree → 2592 points
2 degree → 16200 points
1 degree → 64800 points

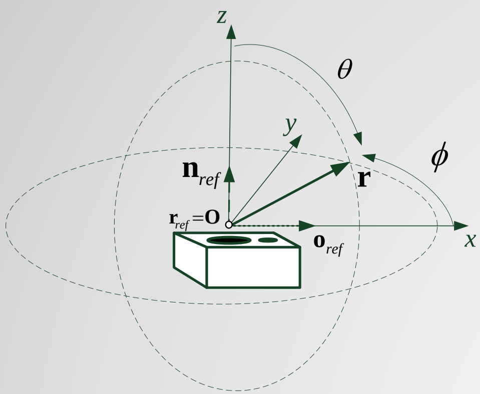
Not practical

Accuracy of measurement depends on:

- tolerance of microphone placement (both θ and r)
- DUT positioning while maintaining the acoustic center
- Sound reflections from turntable
- Room absorption irregularities

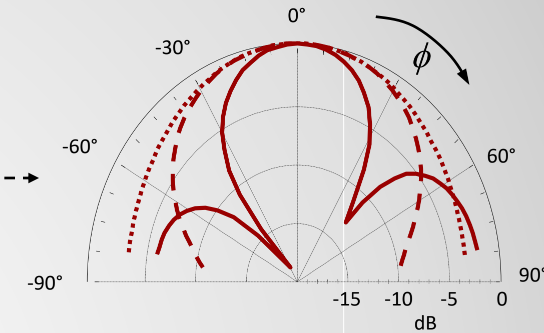


Directional Far Field Characteristics



Directional Gain

$$D(\theta,\phi) = 20\log\Gamma(\theta,\phi)\ dB$$



Far-Field Sound Pressure

$$p(r,\theta,\phi)$$

Directional Factor

$$\Gamma(r,\theta,\phi) = \frac{p(r,\theta,\phi)}{p_{ax}(r)}$$

Sound Power

$$\Pi = \frac{1}{\rho c}\int_S p(r,\theta,\phi)^2 dS$$

$$= \frac{p_{ax}^2(r)}{\rho c}\int_S \Gamma(r,\theta,\phi)^2 dS$$

$$= \frac{S}{\rho c}p_S^2(r)$$

Sound Pressure On-Axis

$$p_{ax}(r) = p(r,\theta=0,\phi=0)$$

Directivity Factor

$$Q = \frac{p_{ax}^2(r)}{p_S^2(r)} = \frac{S}{\int \Gamma^2(\theta,\phi)dS}$$

SPL On-Axis

$$SPL_{ax}(r) = 20\log\left(\frac{p(r,0,0)}{p_o}\right) dB$$

With p_0=20 µPa

Directivity Index

$$DI = 10\log_{10}(Q)\ dB$$

Sound Power Level

$$L_\Pi = 10\log_{10}\left(\frac{\Pi}{P_0}\right) dB$$

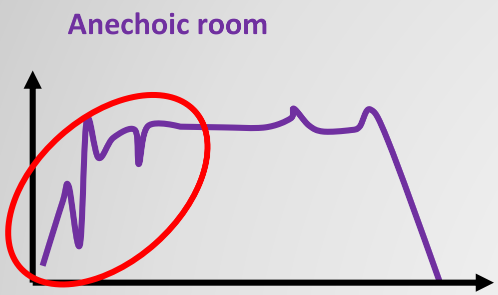
With $P_0=10^{-12}$ W

$$DI \approx SPL_{ax}(r=0.4m) - L_\Pi$$

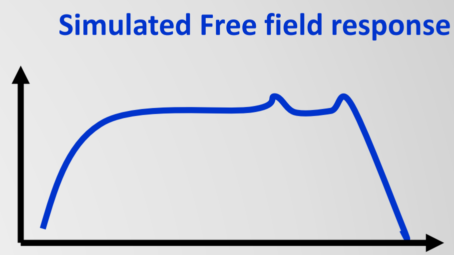
Radiation into half space (using baffle)

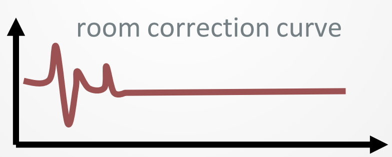
No anechoic room is perfect !

How to cope with limited absorption at low frequencies ?



insufficiently damped for frequencies below 100Hz





Room correction curve depends on loudspeaker properties !!

1. Select typical set of loudspeakers
2. Measure Loudspeaker in anechoic room and under free-field conditions
3. Calculate a room correction curve

Problems in the Far-Field

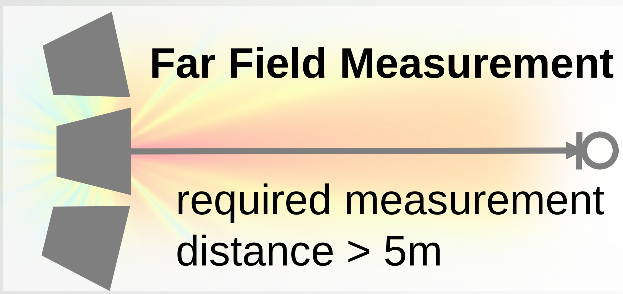
Phase response depends on air temperature

Speed of sound is dependent on air conditions (e.g. temperature)

$$\vartheta_1 = 20°C \rightarrow c_1 = 343.4 m/s$$
$$\vartheta_2 = 22°C \rightarrow c_2 = 344.6 m/s$$
$$\vartheta_3 = 24°C \rightarrow c_3 = 345.8 m/s$$

A temperature difference of $\Delta\vartheta$=2°C will change the speed of sound by Δc≈1.2 m/s

Depending on the distance, the temperature difference will influence the sound wave propagation time:



Deviation:

$$\Delta t = 0.05 ms$$
$$(\Delta r = 17.2 mm)$$

Phase error caused by temperature difference of 2°C during

Frequency	Wave length	Phase Error in 5 m distance
f=2kHz	λ=171.7mm	36° (0.1 λ)
f=5kHz	λ=68.7mm	90° (0.25 λ)
f=10kHz	λ=34.3mm	180° (0.5 λ)

Far field measurement are prone to phase errors !

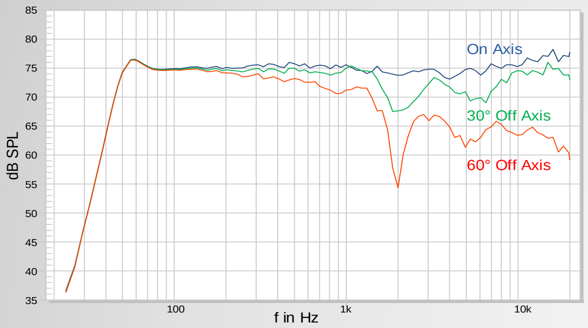
Problems of conventional techniques

- Low frequency measurements (accuracy, resolution) limited by acoustical environment
- Large loudspeakers need large measurement rooms
- High frequency measurements require far-field conditions
- Accuracy of the phase response in the far-field depends on temperature deviations and air movement
- An anechoic chamber is an expensive and long-term investment which cannot be moved easily
- Far field is not relevant for near field applications

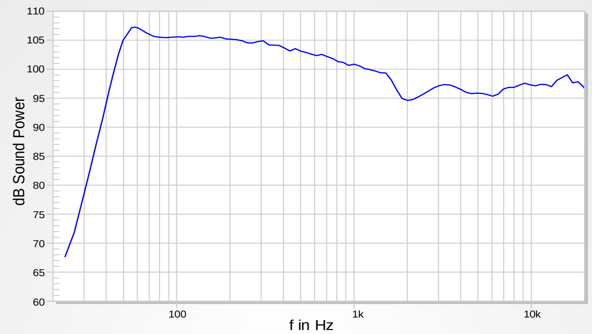
Sound Radiation

Far Field Characteristics

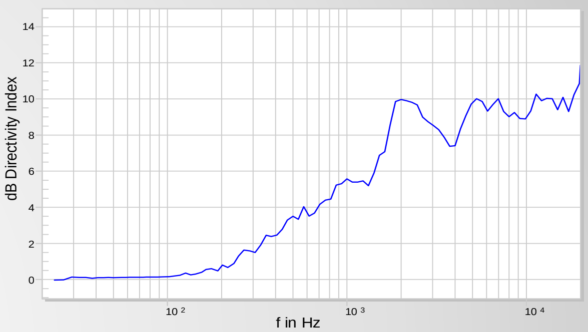
Frequency Response

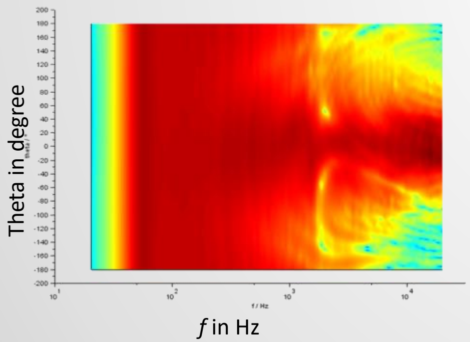


Sound Power

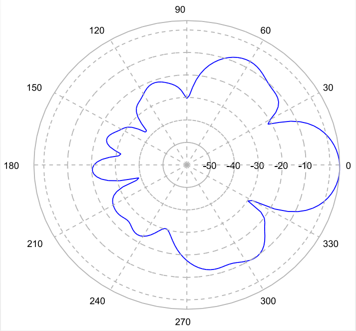


Directivity Index

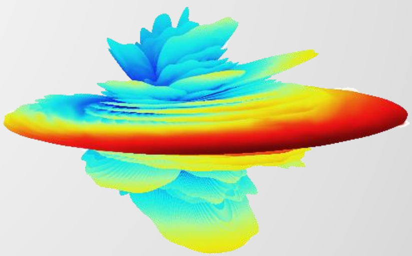




Contour Plot



Polar Plot



Directivity Balloon

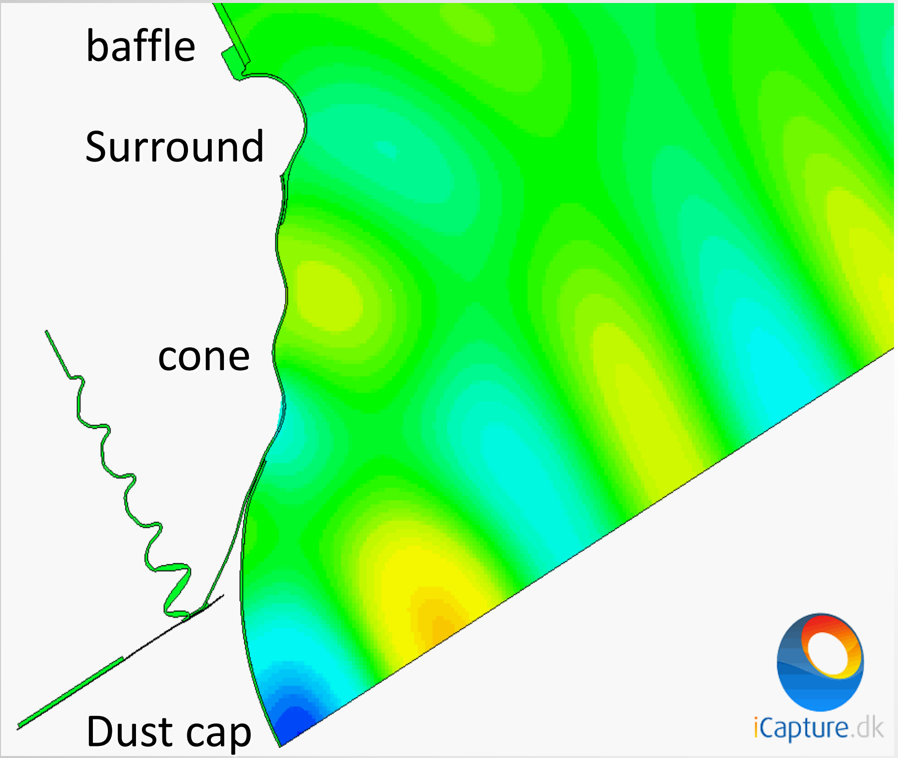
Measurement Requirements

Targets:

- ✓ Directional characteristics
- ✓ Including boundary effects from the cabinet
- (✓) Far field (Pro Audio Line Arrays)
- ✗ Near Field (e.g. sound bars, studio monitor)
- ✗ Accurate Phase information,
- ✗ Reasonable Time

Measurements in the Near Field

Sound Pressure Field at 10 kHz



Advantages:

- High SNR
- Amplitude of direct sound much greater than room reflections providing good conditions for simulated free field conditions
- Minimal influence from air properties (air convection, temperature deviations)

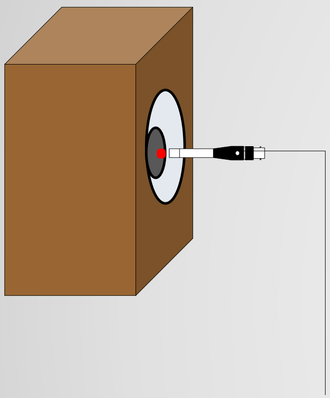
Disadvantages:

- Not a plane wave
- Velocity and sound pressure are out of phase
- 1/r law does not apply, therefore, no sound pressure extrapolation into the far-field (holographic processing required)

Solution → Scanning + Holographic Postprocessing

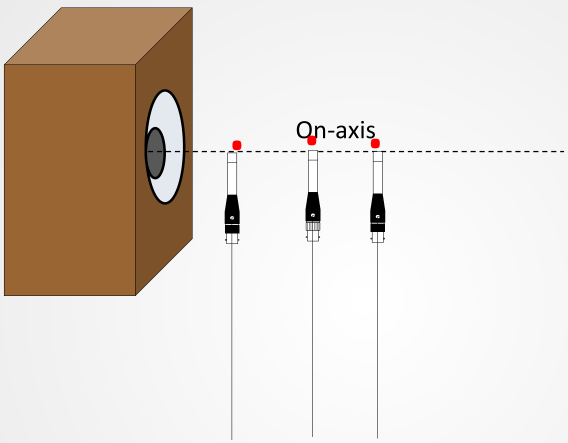
Short History on Near-Field Measurements

Single-point measurement close to the source



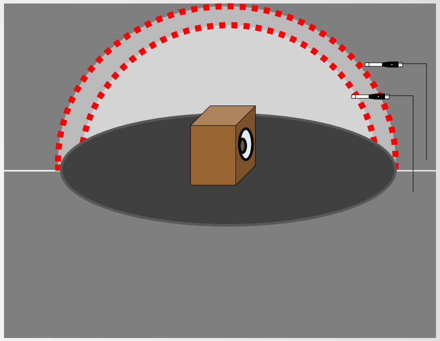
Don Keele 1974

Multiple-point measurement on a defined axis



Ronald Aarts (2008)

Scanning the sound field on a surface around the source



Weinreich (1980), Evert Start (2000)
Melon, Langrenne, Garcia (2009)
Bi (2012)

Robotics required

Postprocessing of the scanned data required

Near Field Scanner

US 20140198921A1

(19) **United States**
(12) **Patent Application Publication**
Klippel et al.

(10) **Pub. No.: US 2014/0198921 A1**
(43) **Pub. Date: Jul. 17, 2014**

(54) **ARRANGEMENT AND METHOD FOR MEASURING THE DIRECT SOUND RADIATED BY ACOUSTICAL SOURCES**

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(73) Assignee: **Klippel GmbH**, Dresden (DE)

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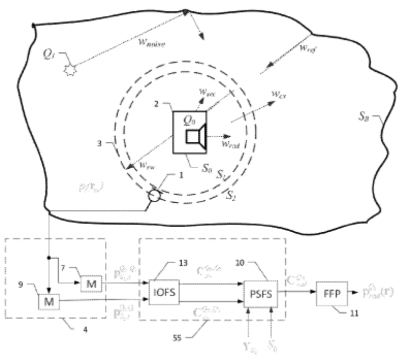
H04R 29/00 (2006.01)

(52) **U.S. Cl.**
CPC ***H04R 29/001*** (2013.01)
USPC **381/59**

(57) **ABSTRACT**

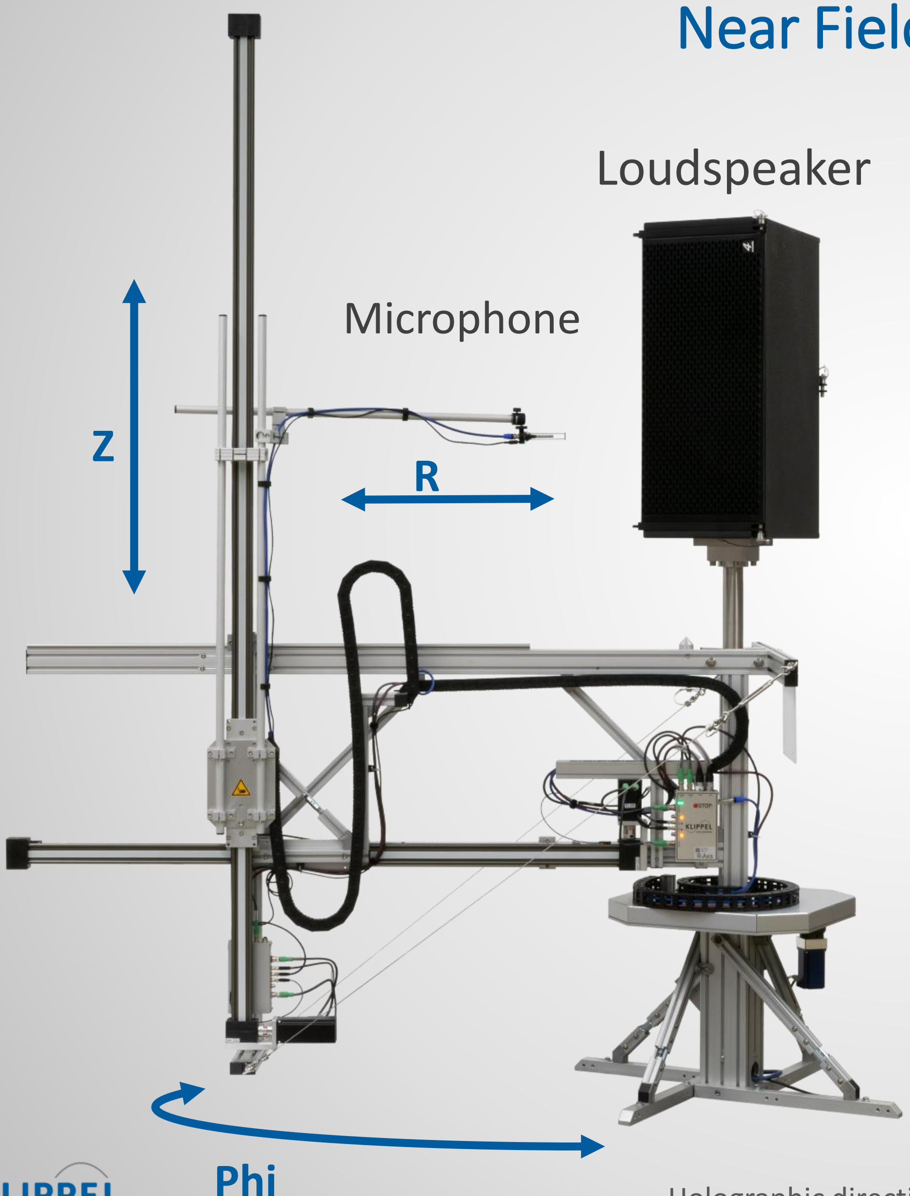
The invention provides an arrangement and a method for measuring the direct sound w_{rad} radiated by an acoustical source under test (e.g. loudspeakers) under the influence of acoustic ambient noise sources Q_1 and reflections at acoustical boundaries (e.g. room walls). An acquisition device measures a state variable $p_j(r_m)$ of the sound field at a plurality of measurement points r_m in a scanning range G_m by a sensor and generates a scanned data set $P_{G_m,t}^{Q_0Q_1}$. Based on this data set an analyzer determines the coefficients $C_{rad}^{Q_0}$ associated with expansion functions which are solutions of the wave equation. An identifier uses the scanned data set $p_{G_m,t}^{Q_0,Q_1}$ for generating parameter information P for the analyzer which are the basis for separating the direct sound w_{rad} from room reflections W_{ref} and other waves w_{sc} scattered at the surface of the source under test. An extrapolator predicts the state variable $p_{rad}^{Q_0}$ of the direct sound w_{rad} at any point outside the scanning range G_m by using the coefficients $C_{rad}^{Q_0}$ of the wave expansion.



ARRANGEMENT AND METHOD FOR MEASURING THE DIRECT SOUND RADATED BY ACOUSTICAL SOURCES
Klippel 2014

Measurement Setup

Near Field Scanner

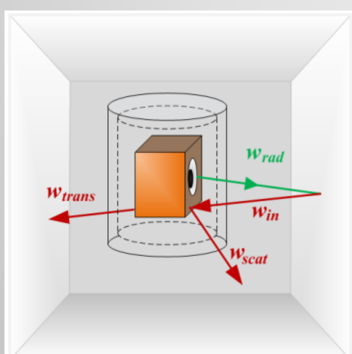


Moving the microphone has the following advantages:

- Constant DUT interaction in the room during the scan (required in a non-anechoic environment)
- Accurate positioning of Mic
- Facilitate heavy loudspeakers (hanging on a crane)
- Minimum gear within the scanning surface (only a platform and a pole)

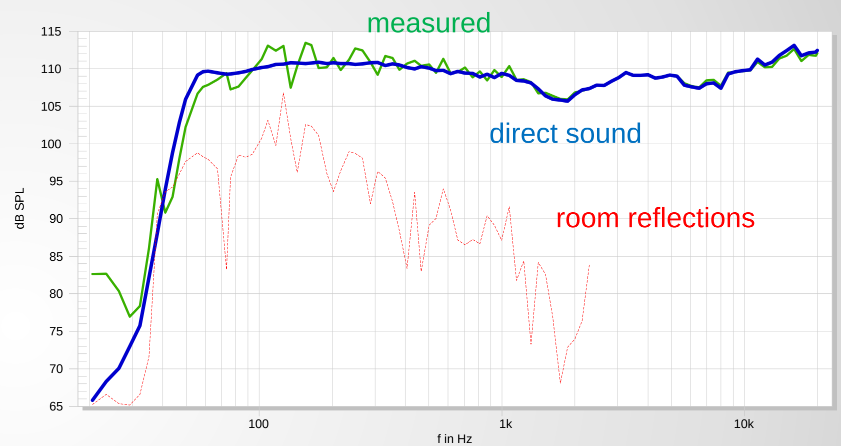
Sound Pressure Response

measured in a normal office

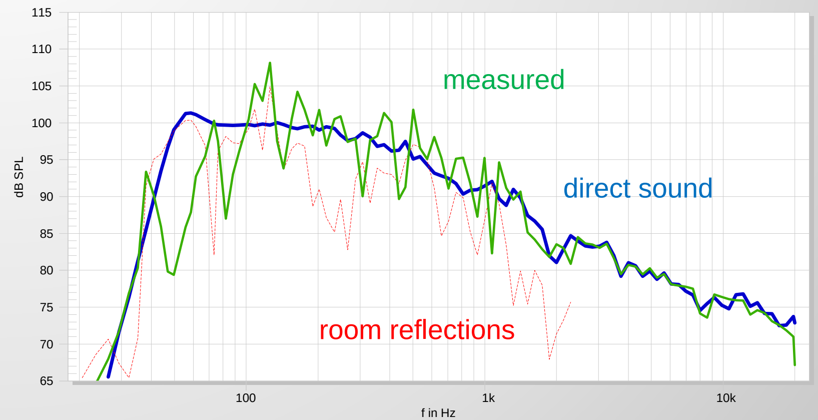


Double layer scanning + holografic processing allows to separate the direct sound from room reflections

Front side (on axis)



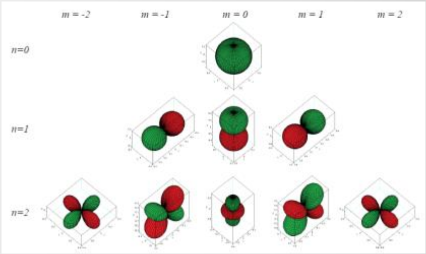
Rear Side



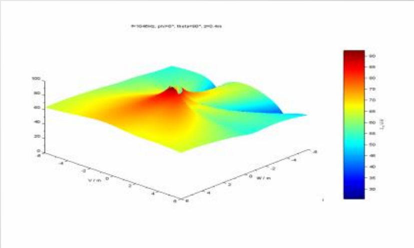
Holographic Measurement Process

1st step: Near-field Scanning

2nd step: Holografic Data Processing



3rd step: Extrapolation



2nd Step: Holographic Wave Expansion

SCANNING DATA

$\underline{H}(f,\mathbf{r})$

+

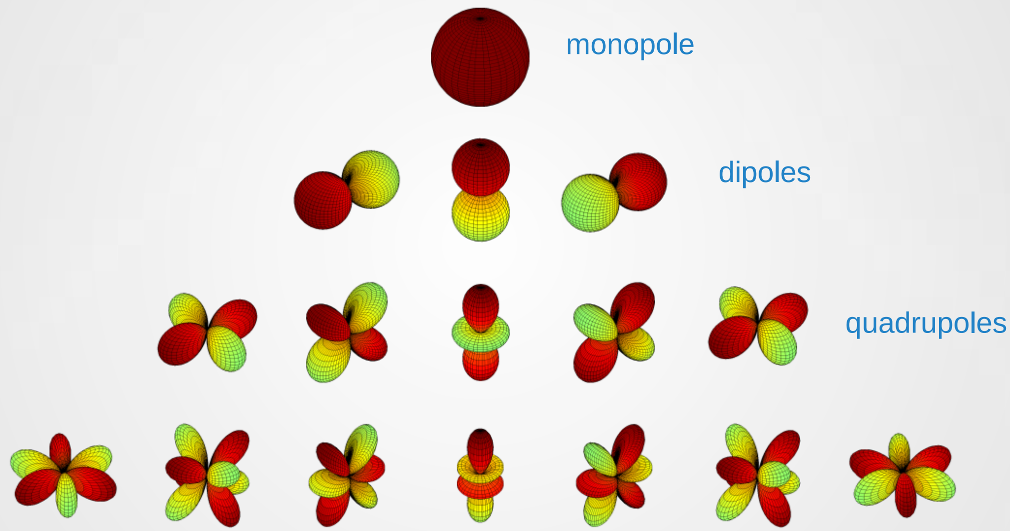
BASIC FUNCTIONS

$\mathbf{B}(f,\mathbf{r})$

→

COEFFICIENTS

$\mathbf{C}(f)$



Results

General solutions of the wave equation are used as basic functions in the expansion

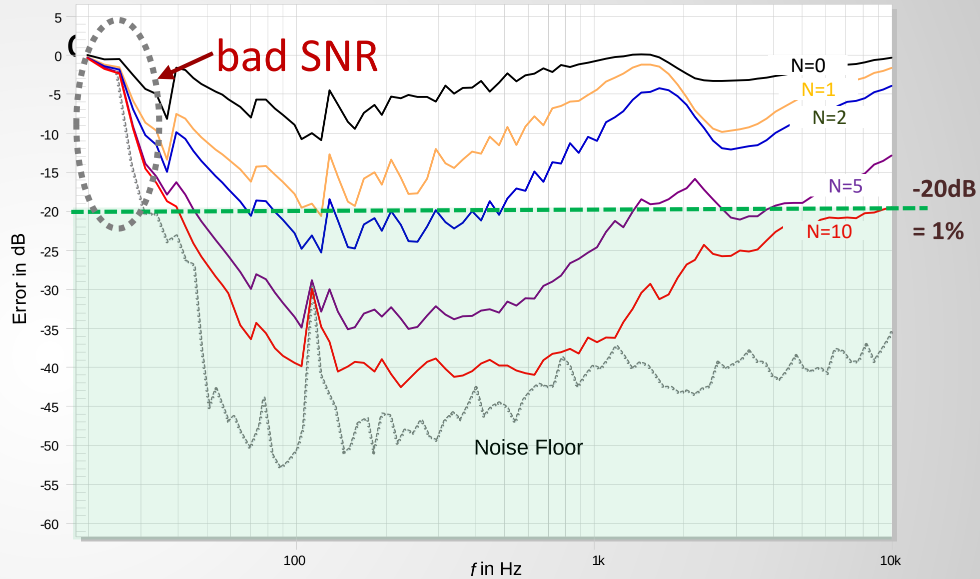
Total number of coefficients = $(N+1)^2$

3rd Step: Wave Extrapolation

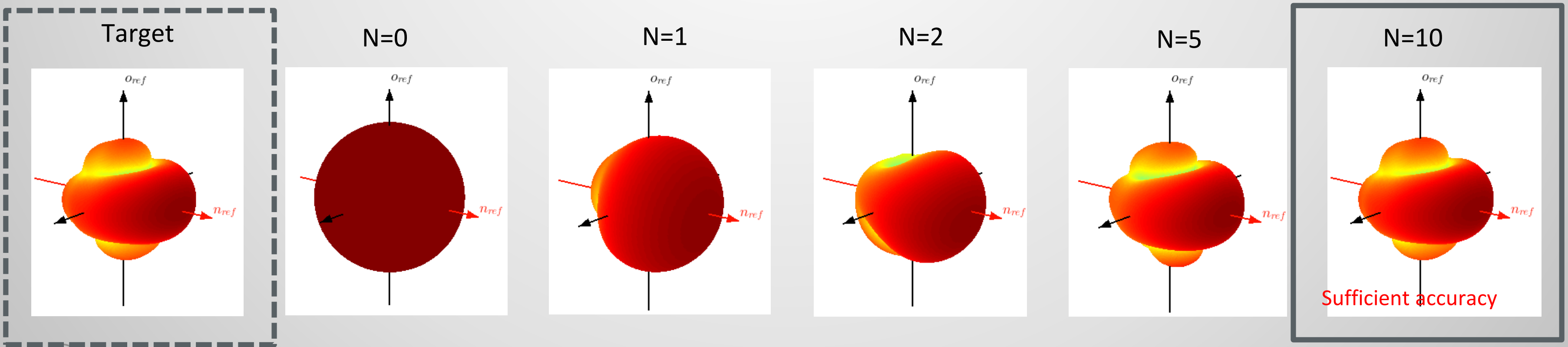
How to Find the Maximum Order N ?

The measurement system determines automatically:
→ optimum order N of the wave expansion
→ total number of the measurement points
→ measurement time

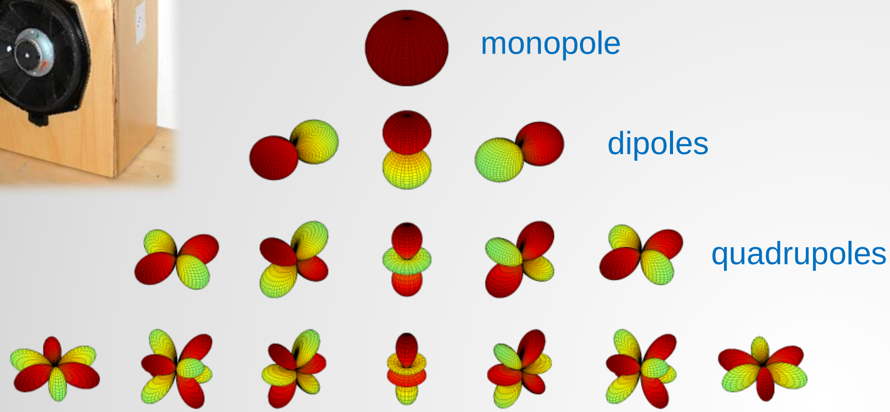
Fitting error as a function of the maximum

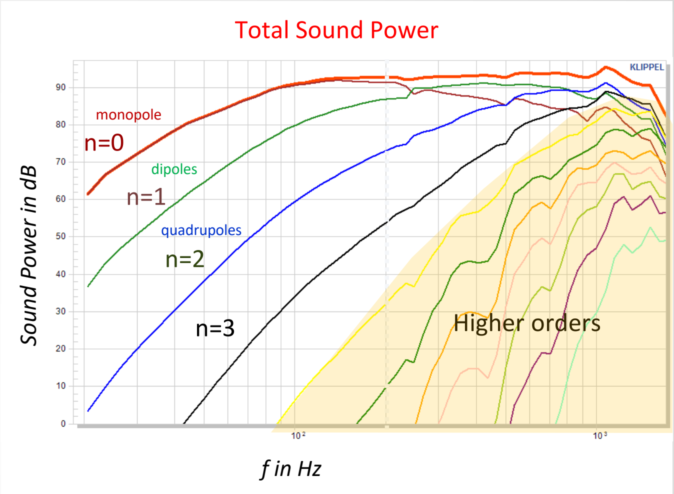


Directivity at 2kHz:

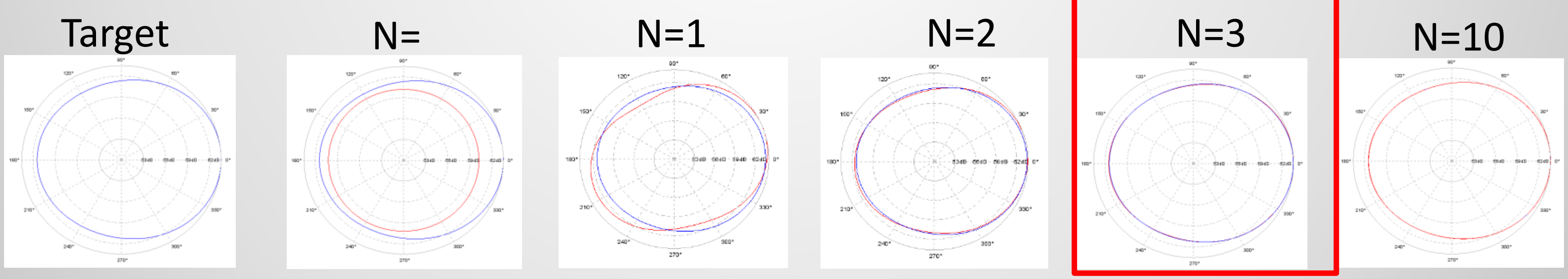


Wave Expansion of a Woofer





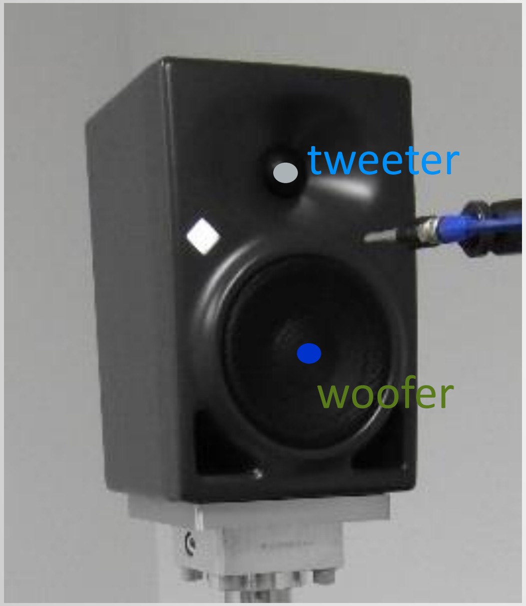
Directivity patterns at 200 Hz:

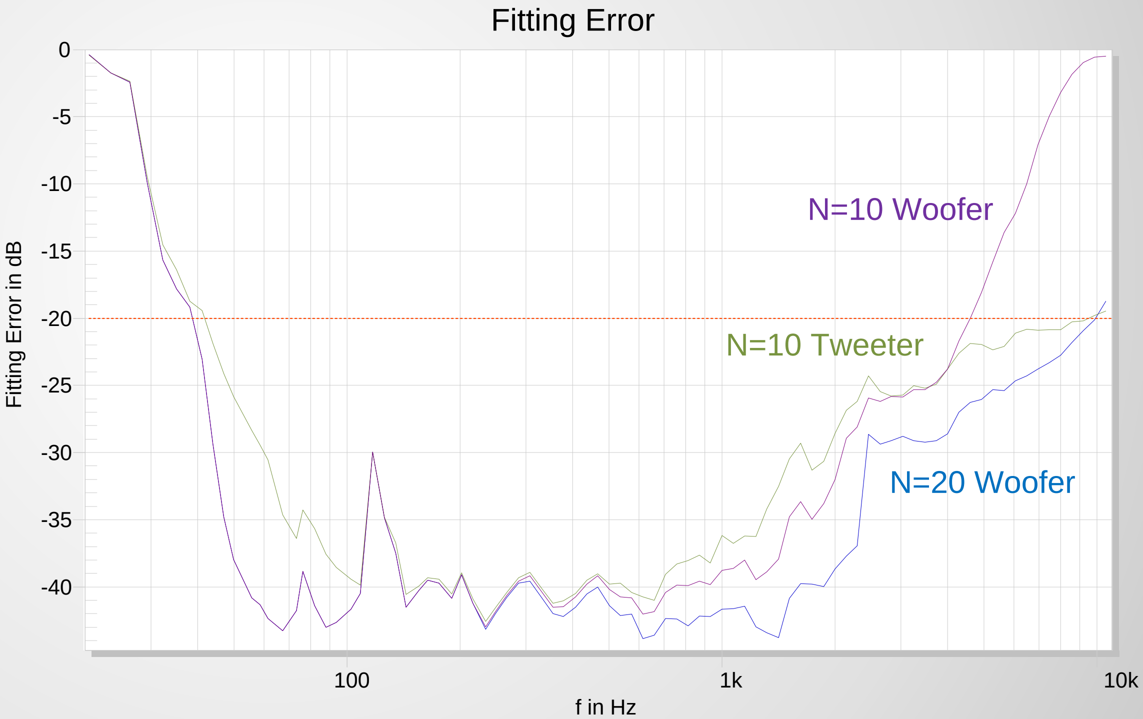


sound field is completely described by order N=3 (16 Coefficients)

can be estimated by a few measurement Points (M > 16)

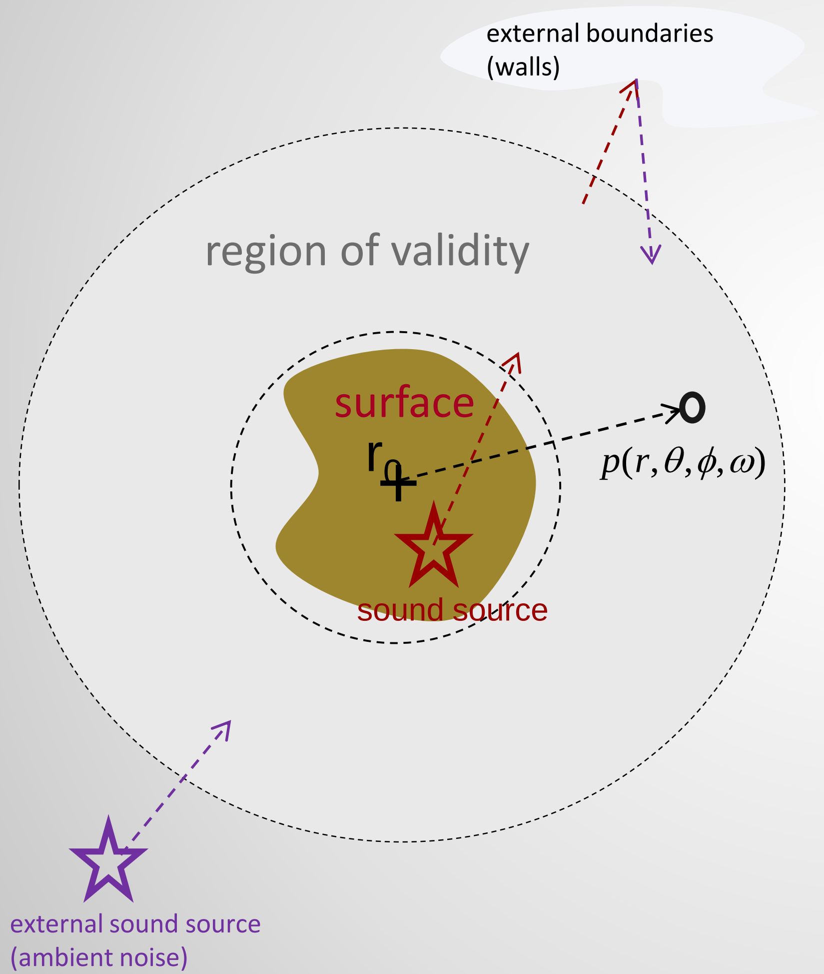
Optimal Choice of the Expansion Point





Setting the expansion point to the center of the tweeter reduces the number of measurement points to 25%.

Expansion into Spherical Waves



general solution of the wave equation in spherical coordinates

$$p(r,\theta,\phi,\omega) = p_{out}(r,\theta,\phi,\omega) + p_{in}(r,\theta,\phi,\omega)$$

outgoing wave — incoming wave

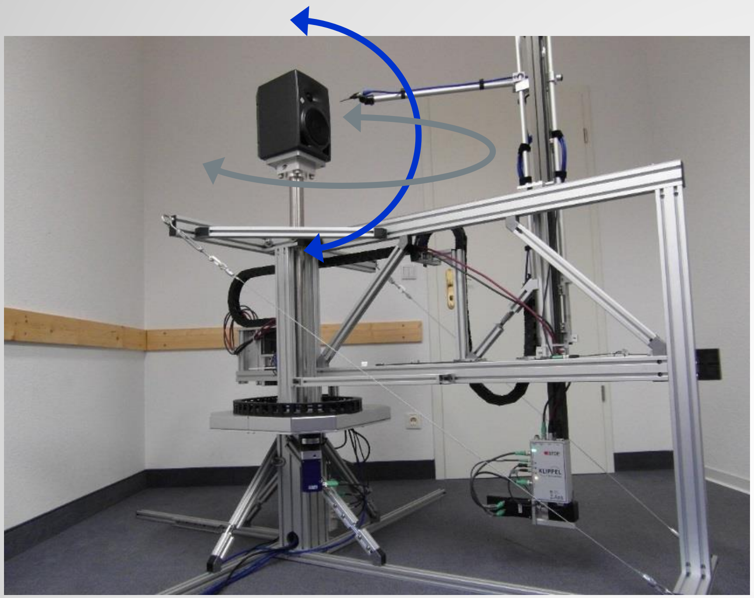
Coefficients outgoing wave — Hankel function of the second kind — Spherical Harmonics

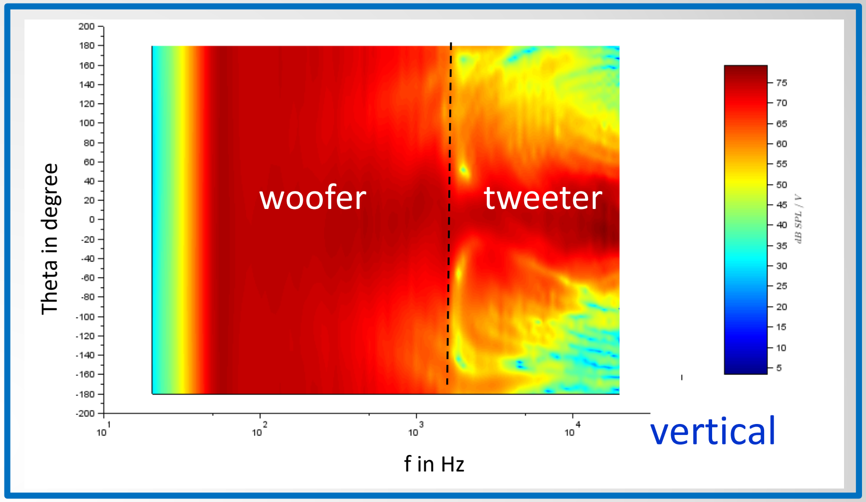
$$p(r,\theta,\phi,\omega) = \sum_{n=0}^{N}\sum_{m=-n}^{n} c_{n,m}^{out}(\omega) h_n^{(2)}(kr) Y_n^m(\theta,\phi) e^{j\omega t} + \sum_{n=0}^{N}\sum_{m=-n}^{n} c_{n,m}^{in}(\omega) h_n^{(1)}(kr) Y_n^m(\theta,\phi) e^{j\omega t}$$

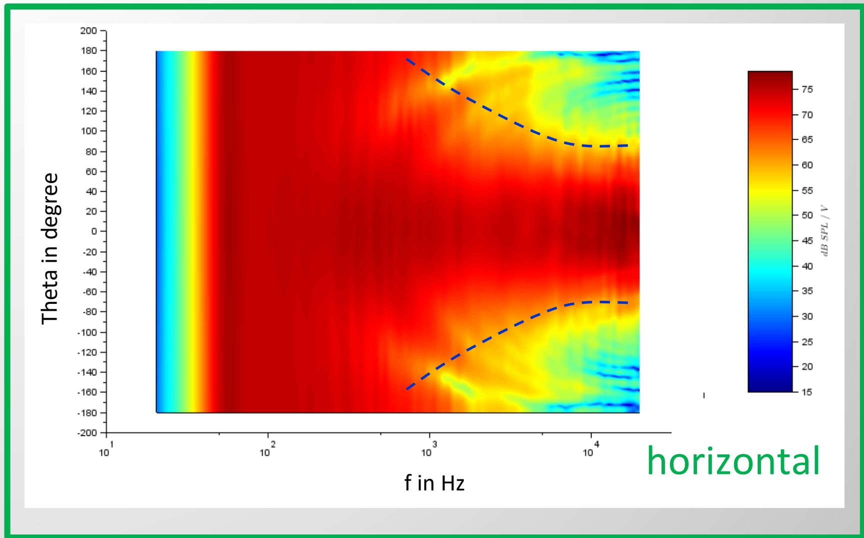
Coefficients incoming wave — Hankel function of the first kind — Spherical Harmonics

depending on frequency ω — depending on distance r — depending on angular direction

Example: Studio Monitor







- Near-field scanning in an ordinary office room
- 500 points
- Order of expansion N=20

Far Field – where does it start ?

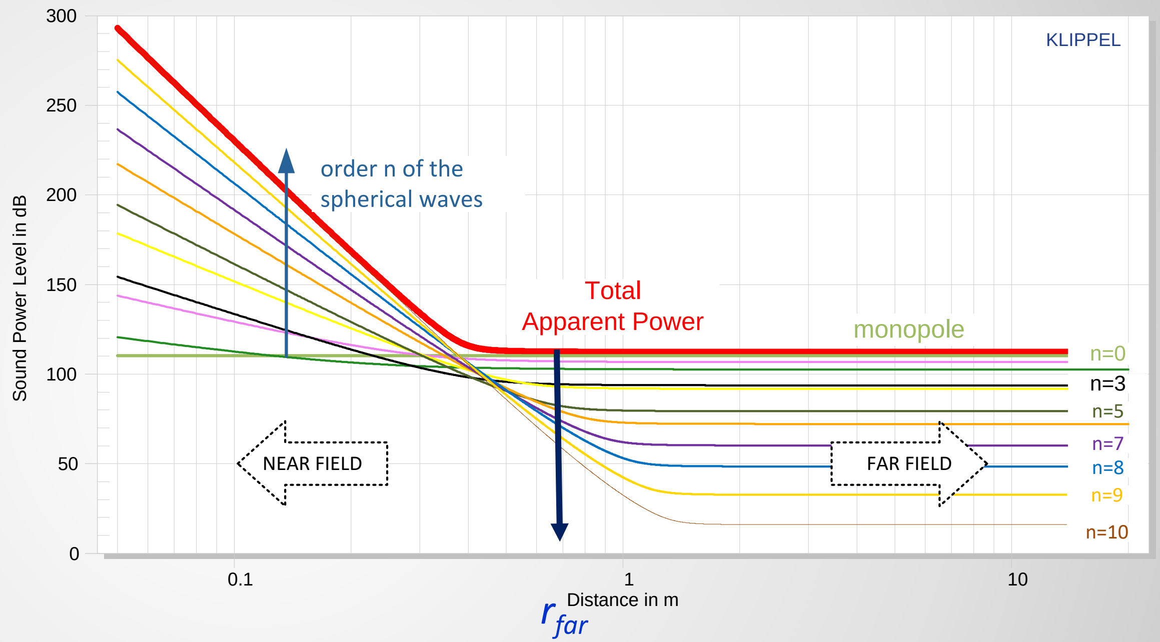
A useful characteristic for investigation the radial dependency of the sound pressure output is the **apparent power**

$$\Pi_A(f,r)) = \frac{1}{2}\int_S |P(f)||V(f)|dS$$
$$= \sum_{n=0}^{N'(f)} \Pi_{A,n}(f,r)$$

with the nth-order wave components

$$\Pi_{A,n}(f,r) = \frac{|U|^2(f)r^2}{2\rho_0 c}\sum_{m=-n}^{n}|C'_{nm}(f)|^2$$
$$|h_n^{(2)}(kr)||h_{n-1}^{(2)}(kr) - \frac{n+1}{kr}h_n^{(2)}(kr)|$$

which neglects the phase relationship between particle velocity and sound pressure.



The critical distance ($r > r_{far}$) where the far field conditions are approximately are fulfilled can be calculated by

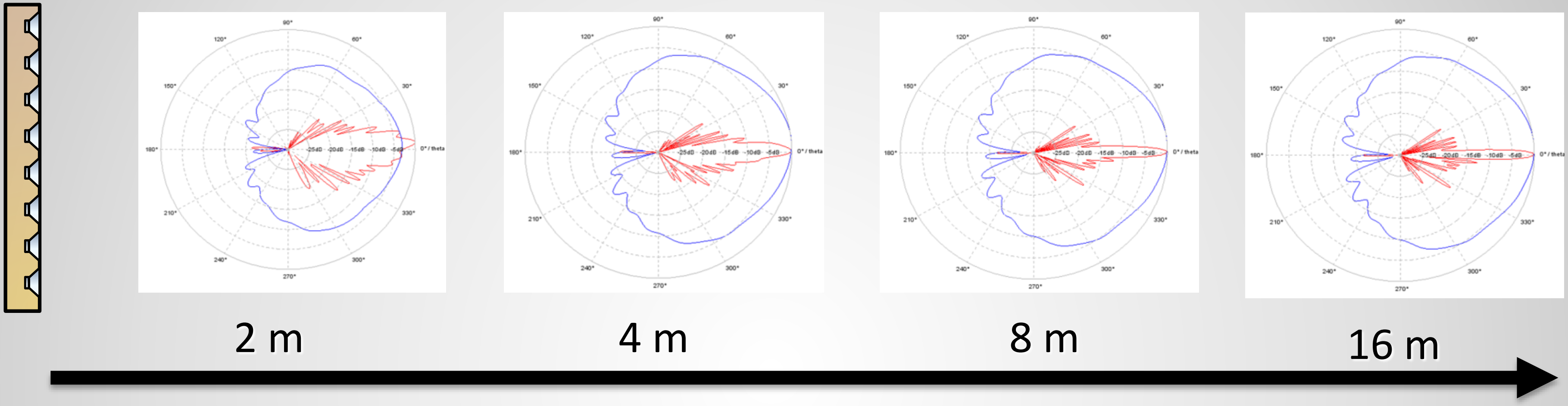
apparent power

$$10\log\left(\frac{\Pi_A(f, r_{far}(f))}{\Pi(f)}\right)dB \overset{!}{=} 0.5dB$$

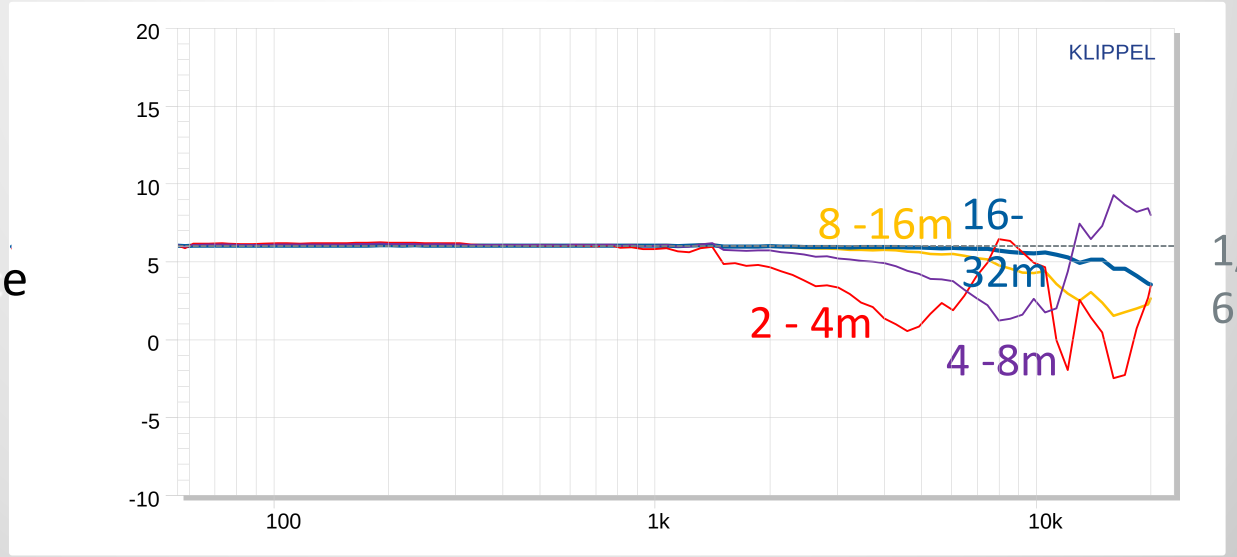
real power

Radiation into far field

Radiation Pattern at 5kHz

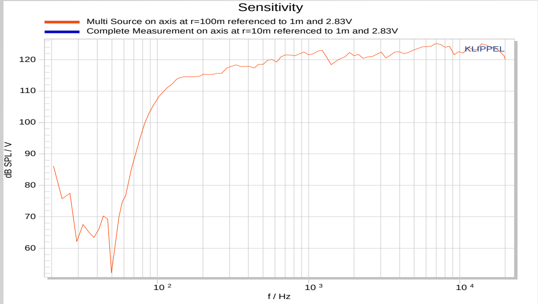


SPL decrease by doubling the distance

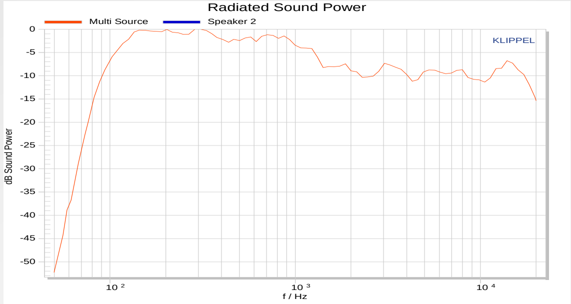


Far field characteristics

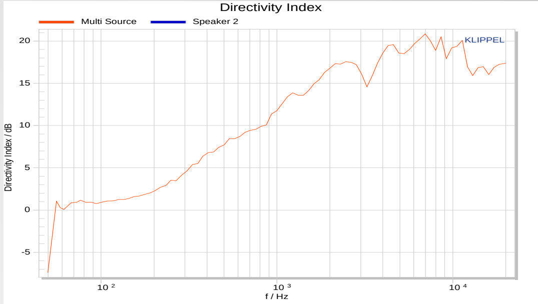
Sensitivity



Sound Power

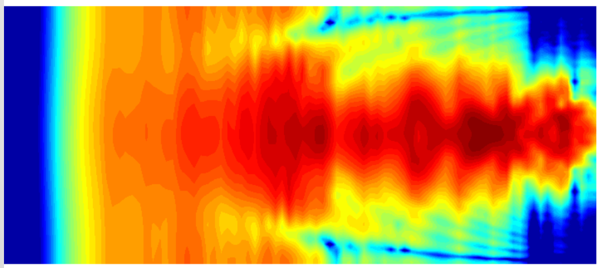


Directivity Index

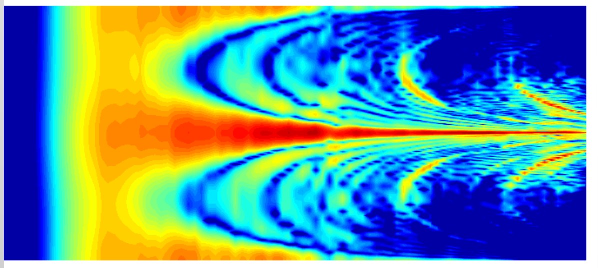


Contour

horizontal

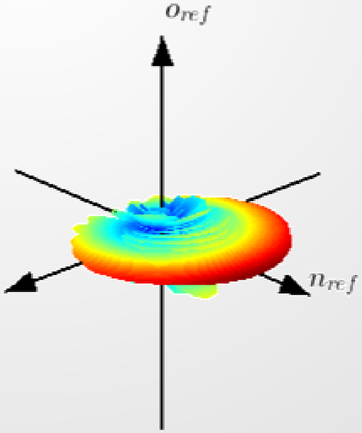


vertical

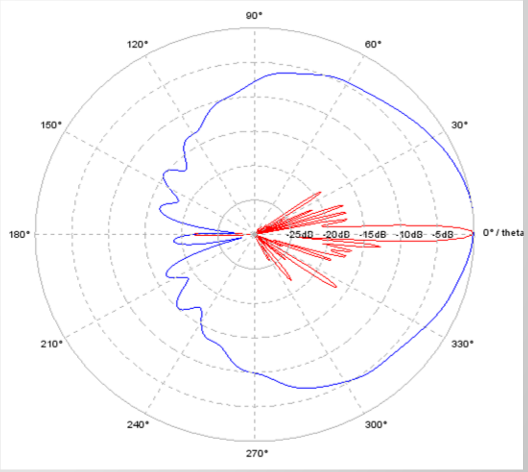


Directivity Pattern at 5kHz

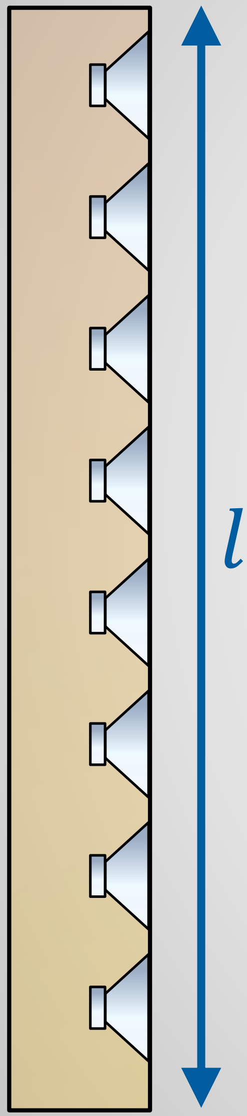
Balloon



Polar



Line Sources



Particularities:

- Large dimensions
- multiple tweeter
- Wide spreaded near field (r>>l)

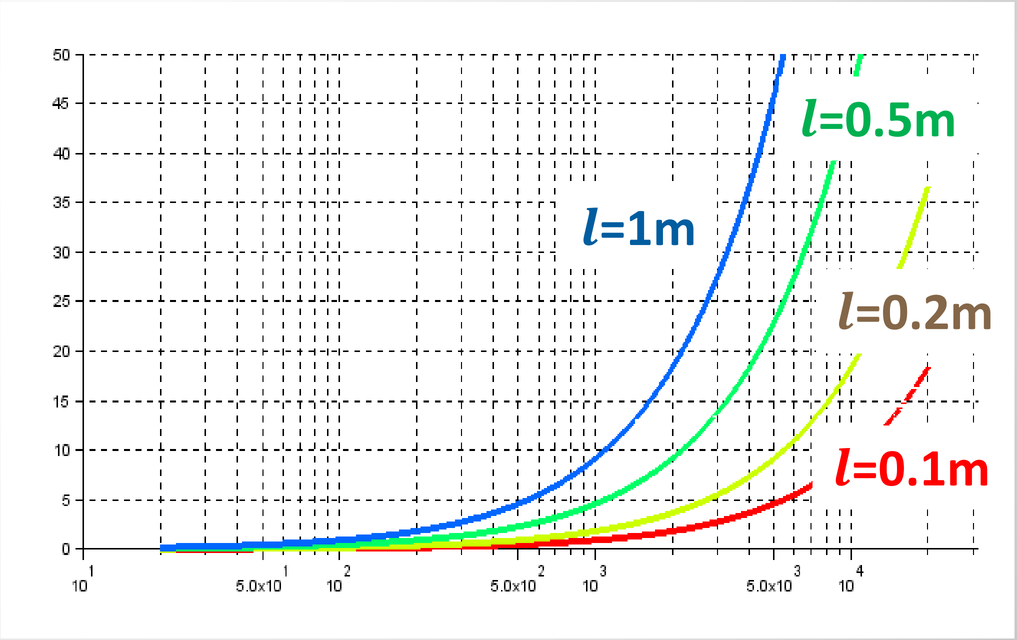
Problems:

- sound field has high complexity
- Fitting for high Frequencies (>5kHz) requires high order N>50
- **Many measurement points M, long measurement time**

Rule of Thumb

$$N \approx \frac{l}{2} \cdot \frac{2\pi f}{c}$$

$$M > (N+1)^2$$



Single Plane Symmetry (1PS)

symmetry axis aligned to the coordinate system $\phi_s = 0$

Simple coupling of the coefficients on the left side (m < 0) on the right side (m > 0)

$$C_{mn}(f) = C_{-mn}(f)(-1)^m \quad \text{with} \quad \begin{array}{c} 0 \le m \\ 0 \le n \le N \end{array}$$

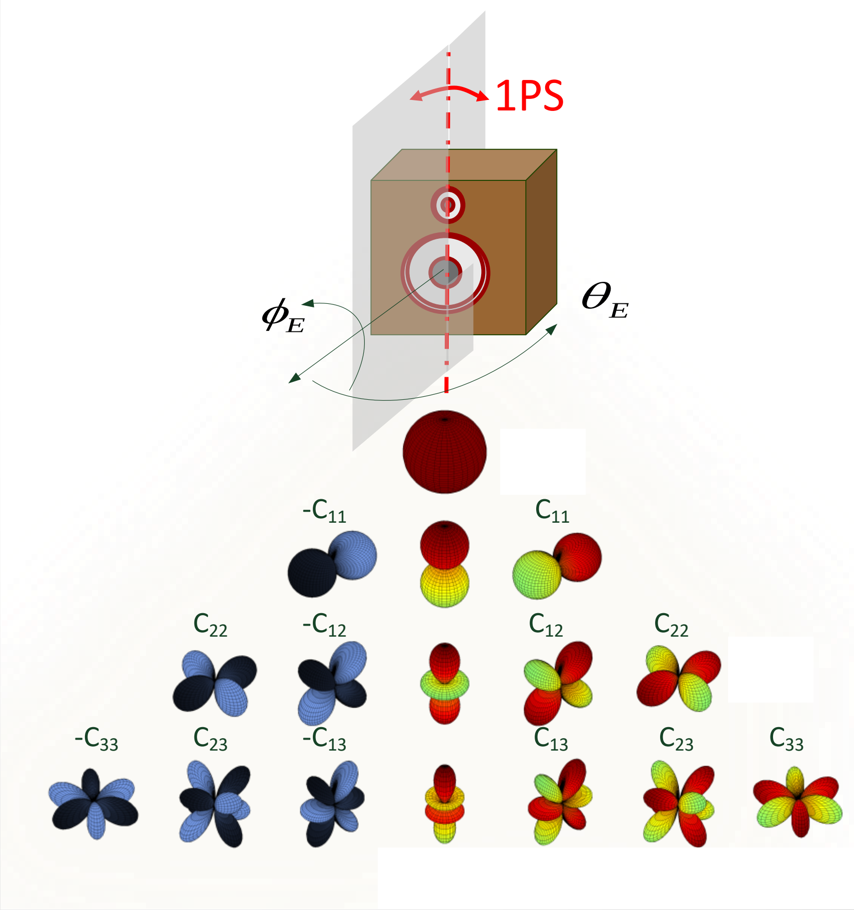
Reduced Number of Coefficients:

$$J = \frac{(N+1)(N+2)}{2}$$

Evaluating the single plane symmetry (1PS) by the metric

$$S_{1PS} = 1 - \frac{\sum_{n=1}^{N}\sum_{m=1}^{n}\left|(-1)^m(f)C_{-mn} - C_{mn}\right|^2}{\sum_{n=0}^{N}\sum_{m=-n}^{n} C_{mn}^2}$$

and predefined limit value (e.g. $S_{1PS} > 0.95$)



KLIPPEL

Dual Plane Symmetry (2PS)

symmetry axes ϕ_s=0 and $\phi_s = 90°$ aligned to the coordinate system

Simple coupling of the coefficients on the left side (m < 0) on the right side (m > 0)

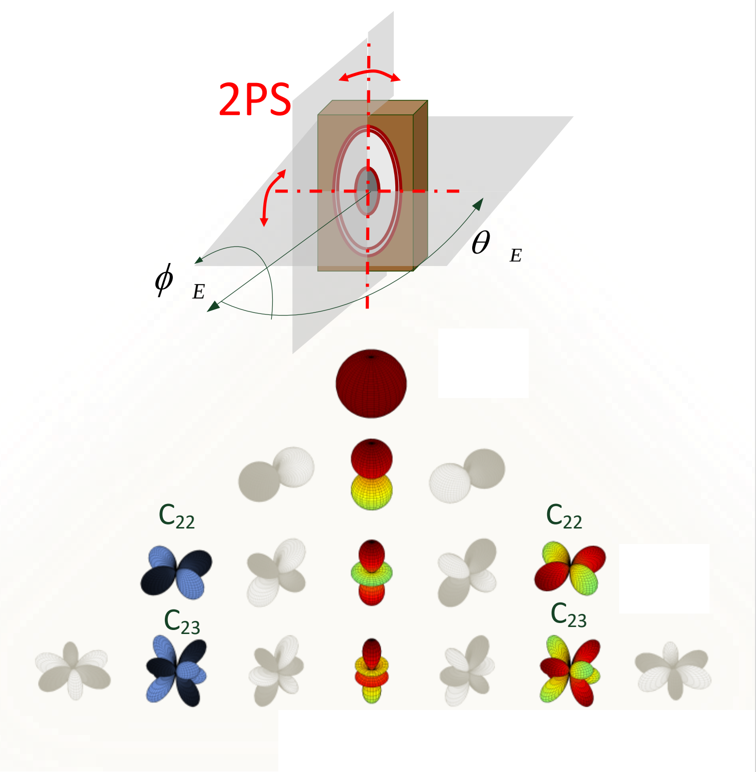
$$\left.\begin{aligned} C_{-(m-1)n}(f) &= 0 \\ C_{(m-1)n}(f) &= 0 \\ C_{mn}(f) &= C_{-mn}(f)(-1)^m \end{aligned}\right\} m = 2s, s = 1,2,3$$

Reduced Number of Coefficients:

$$J = \begin{cases} \left(\frac{N}{2}+1\right)^2 & N = 0,2,4,\ldots \\ \left(\frac{N}{2}+1\right)^2 + \frac{1}{4} & N = 1,3,5,\ldots \end{cases}$$

Evaluating the dual plane symmetry (2PS) by the metric

$$S_{2PS} = 1 - \frac{\sum_{n=2}^{N}\sum_{s=1}^{n/2}\left|(-1)^{2s} C_{2s,n} - C_{2s,n}\right|^2 + \sum_{n=1}^{N}\sum_{s=0}^{n/2}\left|C_{2s+1,n}\right|^2}{\sum_{n=0}^{N}\sum_{m=-n}^{n} C_{mn}^2}$$



and predefined limit value (e.g. $S_{2PS} > 0.95$)

KLIPPEL

Rotational Symmetry (RS)

no phi dependency

Condition for used Spherical harmonics:

$$C_{mn} = 0 \qquad m \neq 0$$

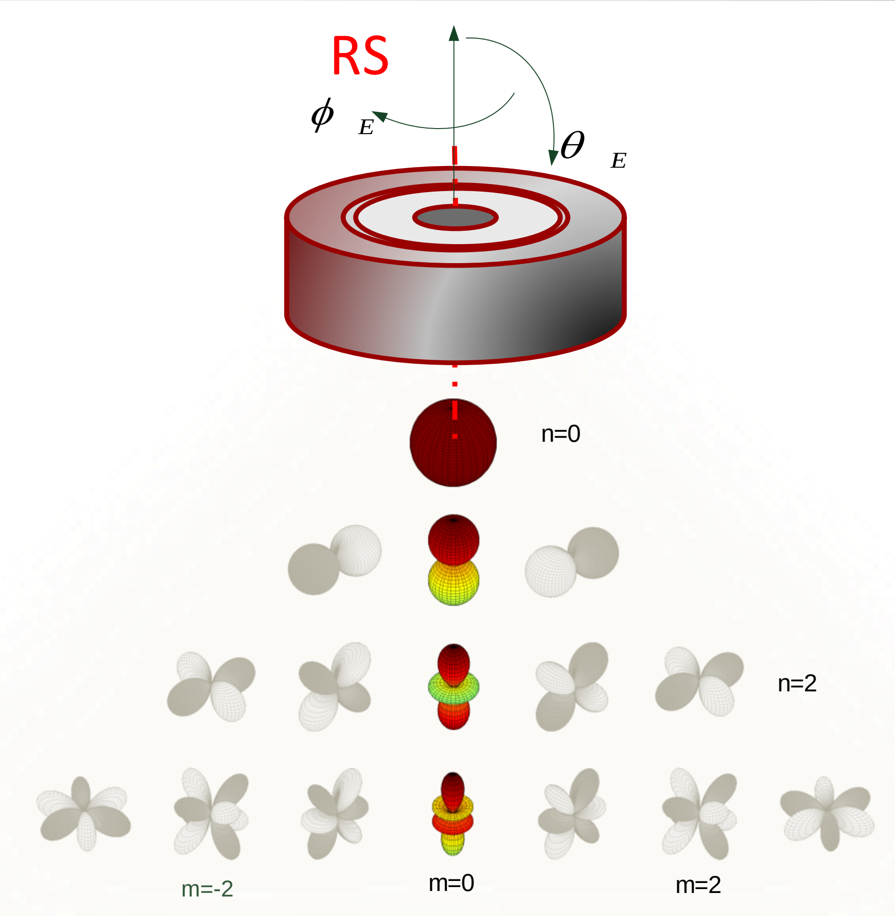
Reduced Number of Coefficients:

$$J = N + 1$$

Evaluating the rotational symmetry (RS) by the metric

$$S_{RS} = 1 - \frac{\sum_{n=1}^{N} \sum_{s=1}^{n} \left| C_{sn} \right|^2}{\sum_{n=0}^{N} \sum_{m=-n}^{n} C_{mn}^2}$$

and predefined limit value (e.g. $S_{RS} > 0.95$)



Reduction of Scanning Effort (System)

Example: wave expansion with maximum order N=30

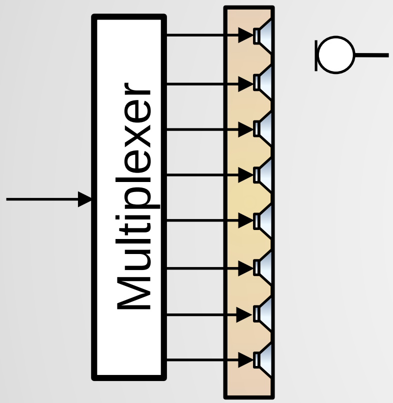
Symmetry	Number of Coefficients	Reduction of measurement samples
No Symmetry	961	0 %
Single plane symmetry	496	48 %
Dual plane symmetry	256	73 %
Rotational symmetry	31	97 %

Knowing the **symmetry properties** (a priori user input or automatic detection) can reduce the number of **measurement points** significantly.

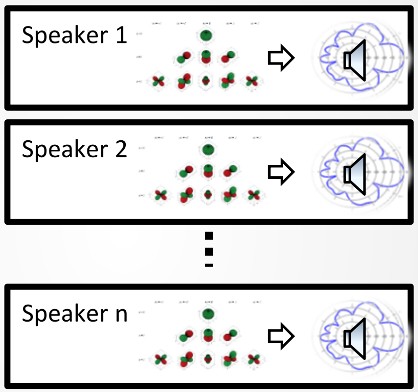
Line Source

individual measurement of transducers

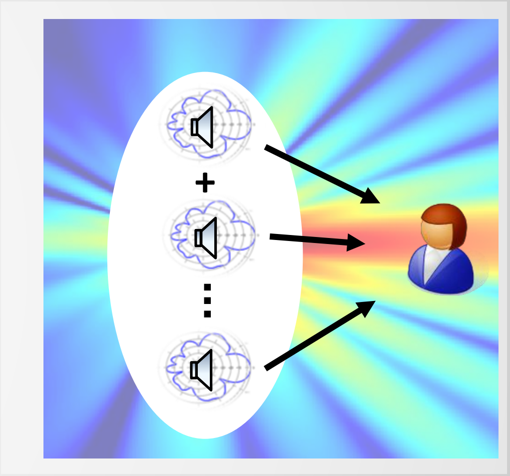
1) Measure each loudspeaker separately by using a multiplexer



2) Wave expansion of each loudspeaker



3) Super positioning of the multipoles

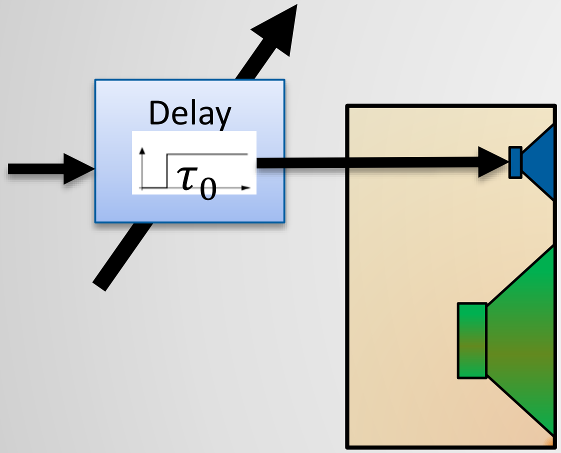


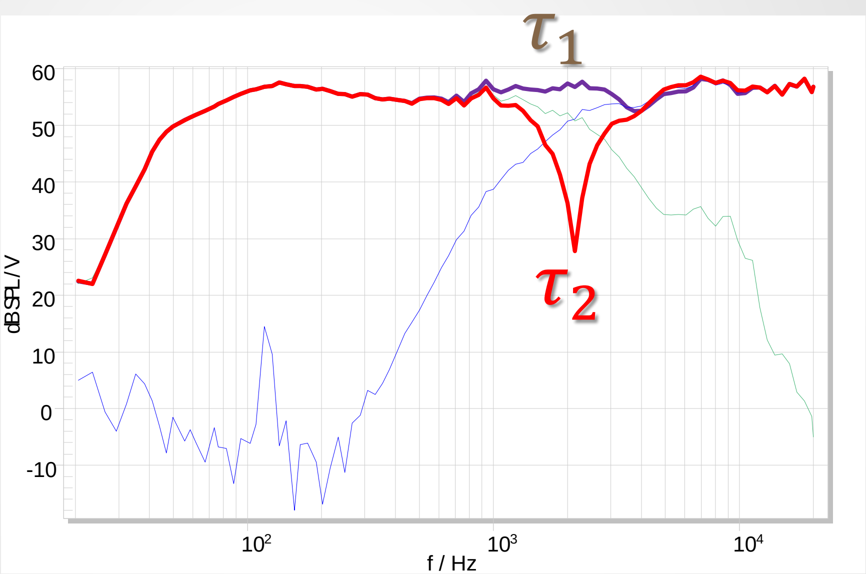
Benefits

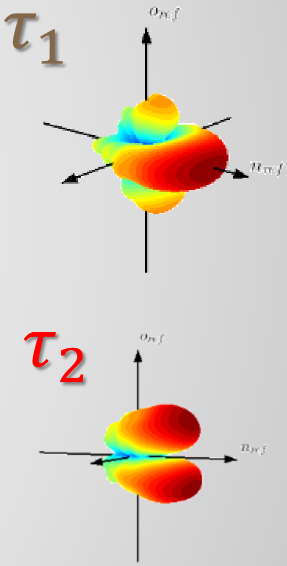
- Directivity of individual transducers is less complex
- Automatic measurement, accurate positioning
- Accurate phase data
- sound pressure at any point

2 Multiplexing of Transducers

Simple Example: 2 Way Loudspeaker



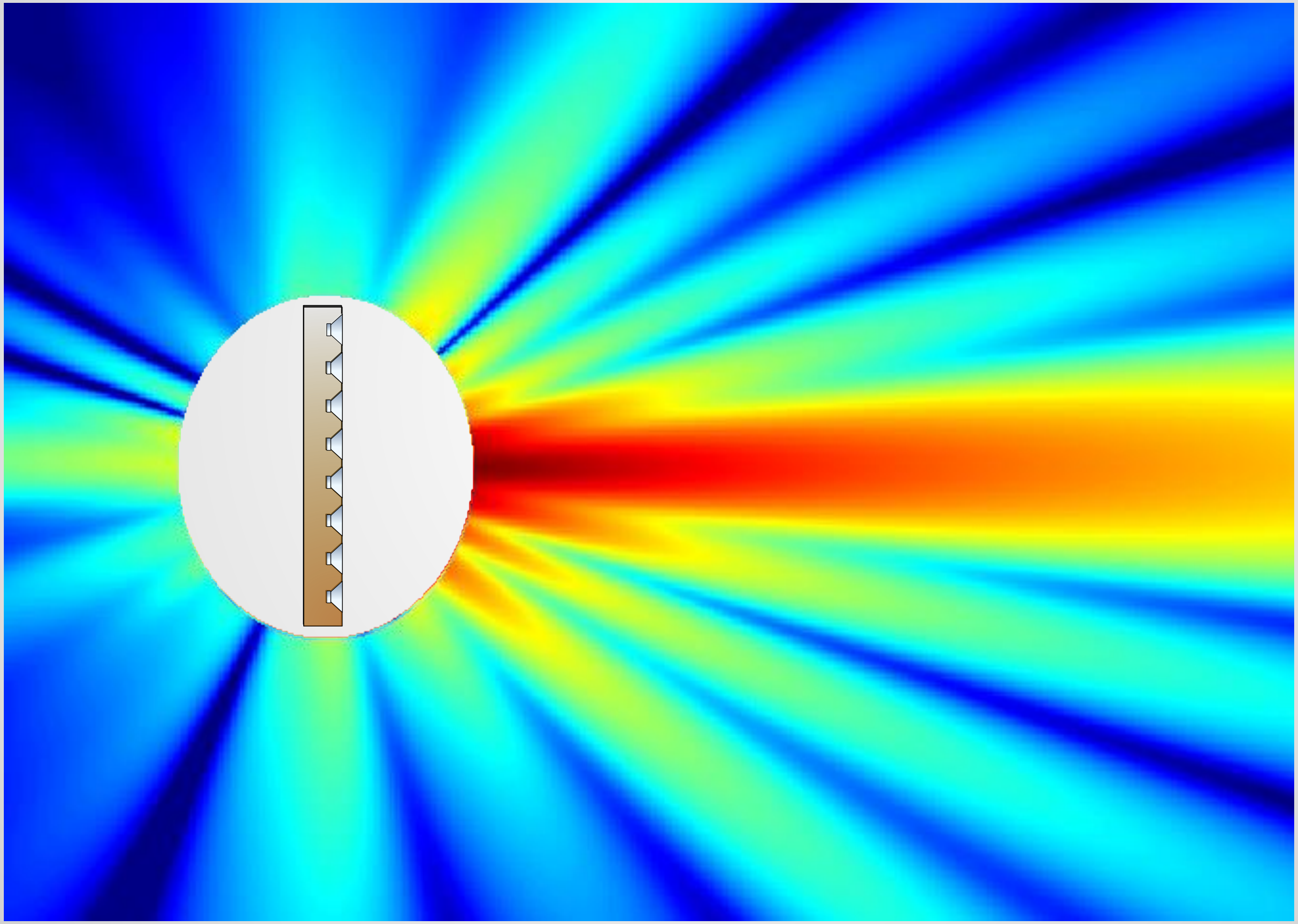




Measurement Results

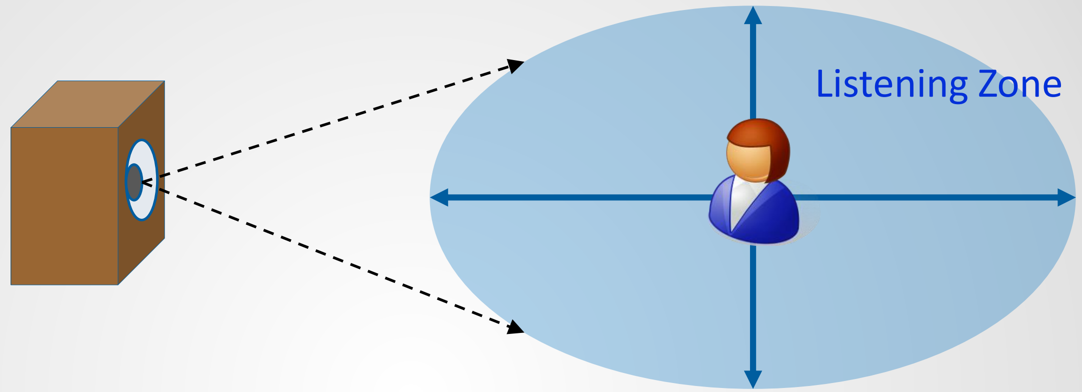
Superposition of individual measurements

2kHz

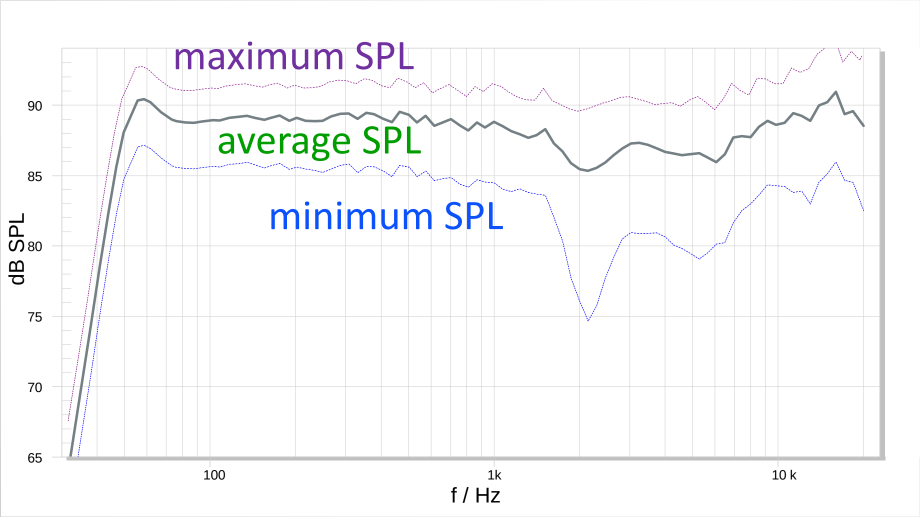


User defined Listening Zone

Step 1: Define a target listening area



Step 2: Extract representative curves

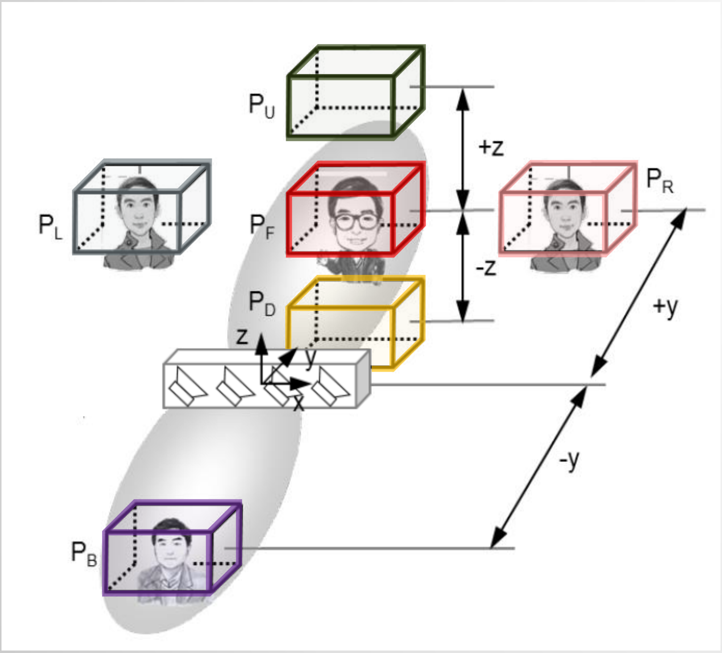


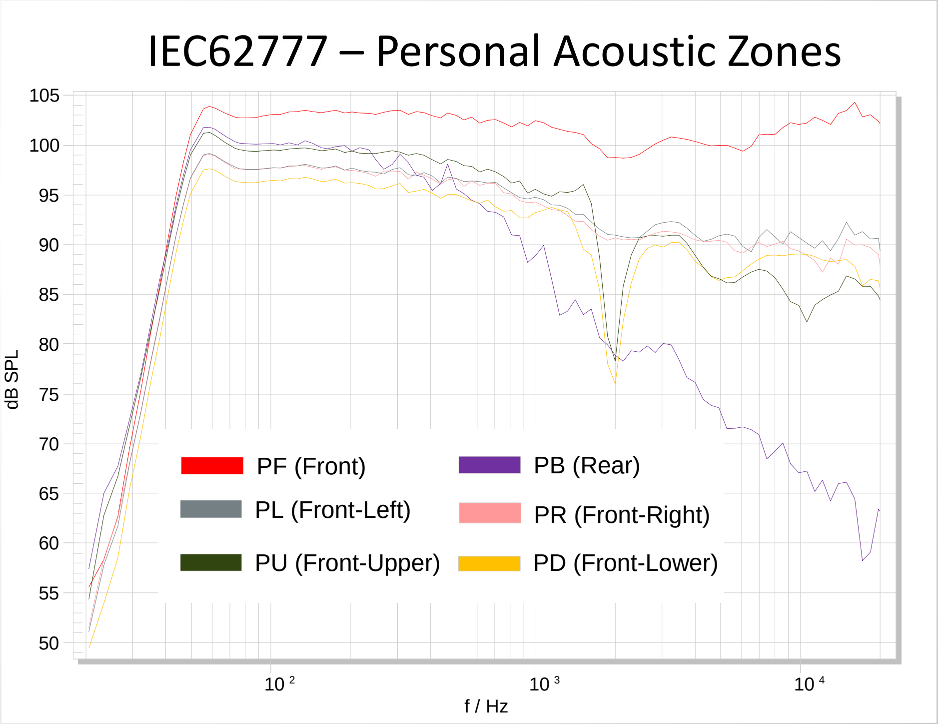
Summary Window collects most significant curves

e.g. spatial average + devitation of sound pressure level

IEC 62777 Standard
using Listening Zone

Application: Personal audio devices, Laptops, Tablets, etc.

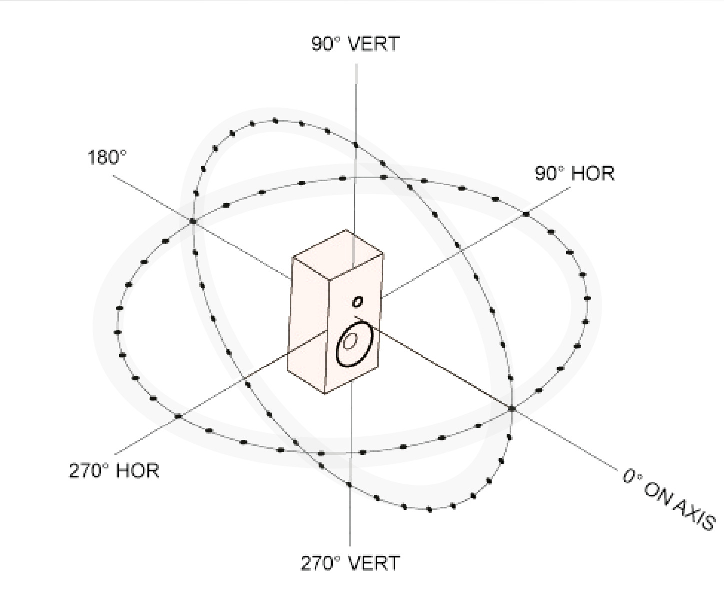


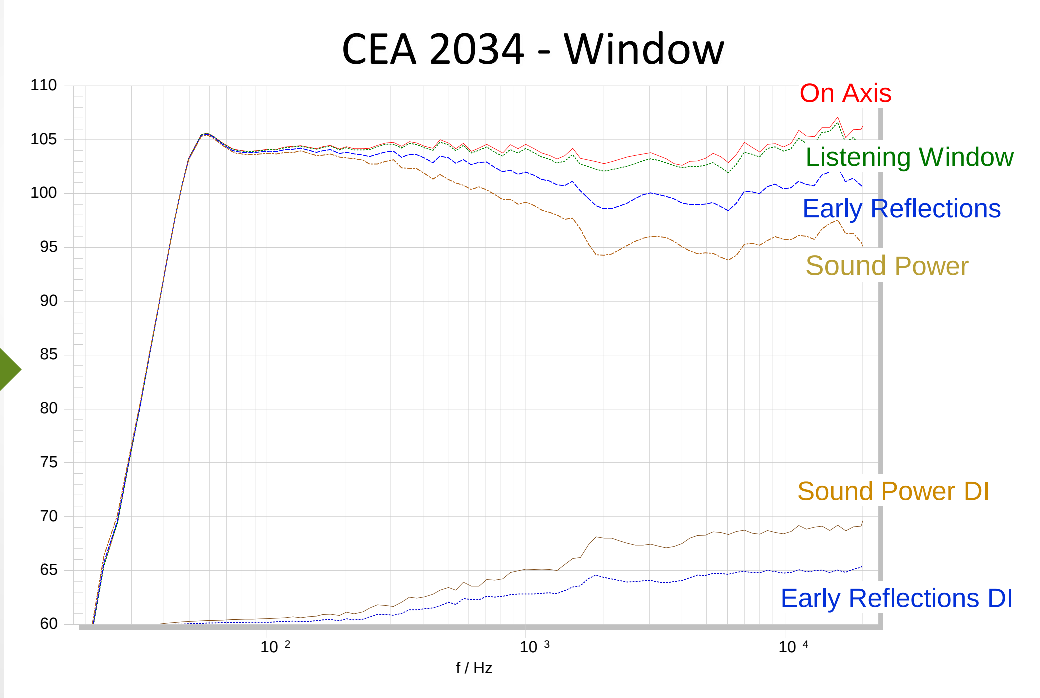


CEA2034 Standard

using Listening Zone

Application : Home audio devices, Hifi-Loudspeaker





Conclusion

Measurement Targets:

- ✓ Directional characteristics
- ✓ Including boundary effects from the cabinet
- ✓ Far field (Pro Audio Line Arrays)
- ✓ Near Field (e.g. sound bars, studio monitor)
- ✓ Accurate Phase information
- ✓ Reasonable Time

Conclusion

Holographic measurement of line sources

- Comprehensive assessment of direct sound in 3D space (near + far field)
- High signal to noise ratio
- Suppression of room reflections (simulated far field conditions)
- Minimal influence air properties (air convection, temperature field)
- Automatic measurement minimizing positioning errors
- Low redundancy in the generated data set
- Directivity individual transducer by multiplexing or interleaved sweeping
- Accurate and comprehensive data set for simulation
- Spatial resolution can be controlled by order N(f) of the expansion
- Spatial interpolation is based on acoustical model

Thank you!