Holographic Nearfield Measurement of Loudspeaker Directivity

Wolfgang Klippel, Christian Bellmann

Klippel GmbH, Technical University Dresden

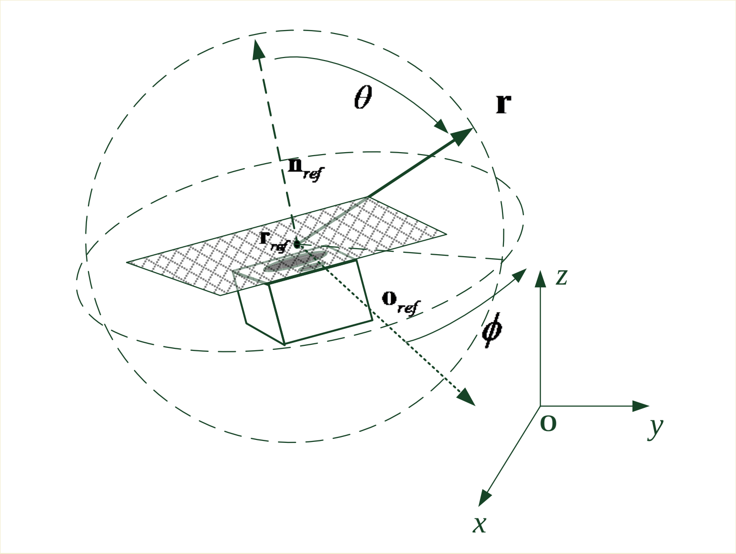
AUDIO ES 141ST AES CONVENTION

Agenda

1. Motivation
   – Drawbacks of Traditional Far Field Measurement
2. Basic theory of holographic nearfield measurement
   – Spherical Wave Expansion
   – Angular resolution and scanning grid
3. Minimization of Scanning Effort
   – Optimal choice of the expansion point
   – Exploiting the symmetry of the sound field
   – Partial fitting with non-uniform sampling
4. Practical Application

Standard Coordinate System

for Far Field Properties of Loudspeaker Systems



IEC 60268-5
IEC 60268-21

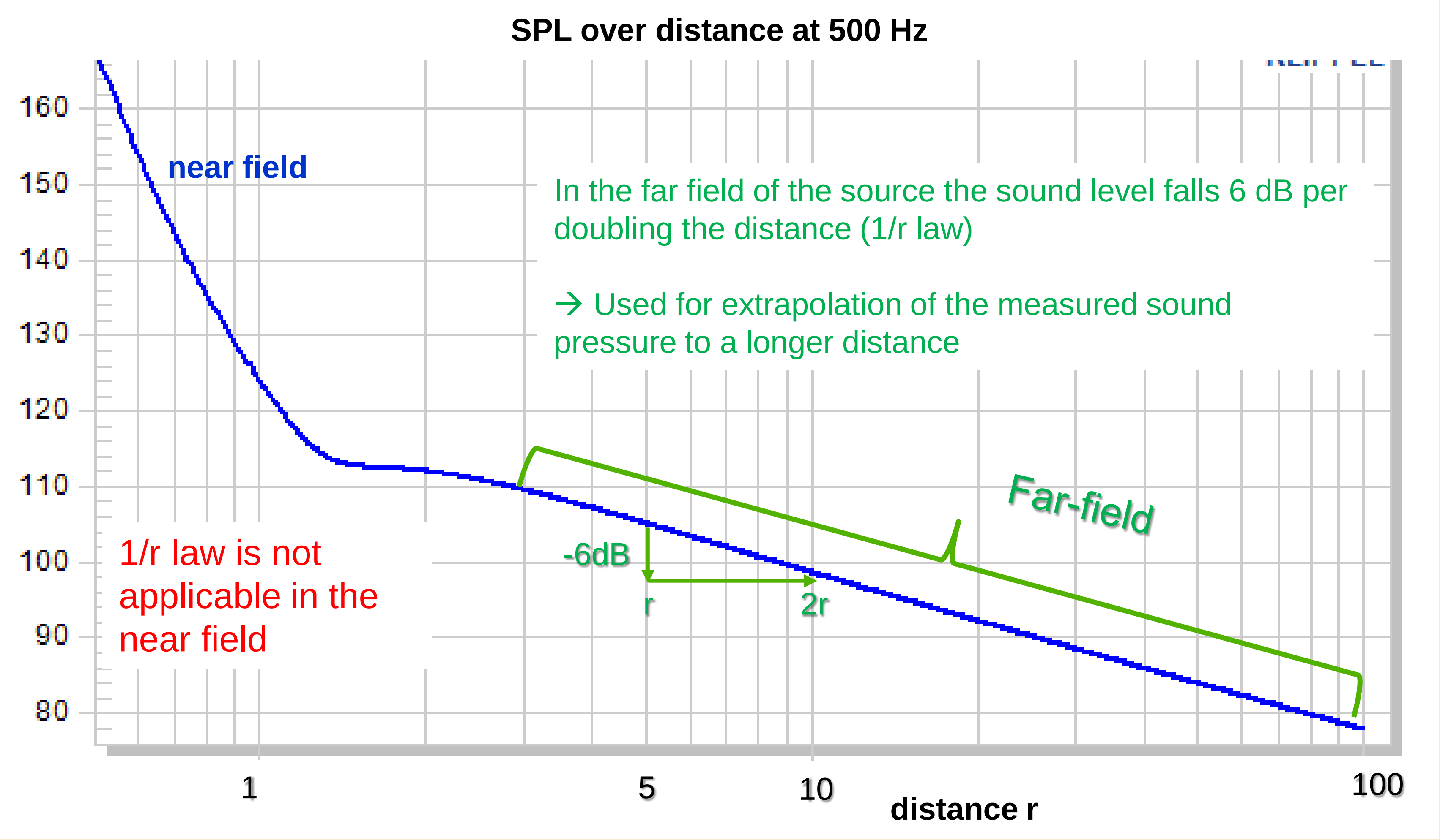
$$\mathbf{r} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \mathbf{r}_{ref} + r \begin{pmatrix} \cos(\phi)\sin(\theta) \\ \sin(\phi)\sin(\theta) \\ \cos(\phi) \end{pmatrix}$$

orientation vector $\mathbf{o}_{\mathbf{r}\mathrm{ef}}$

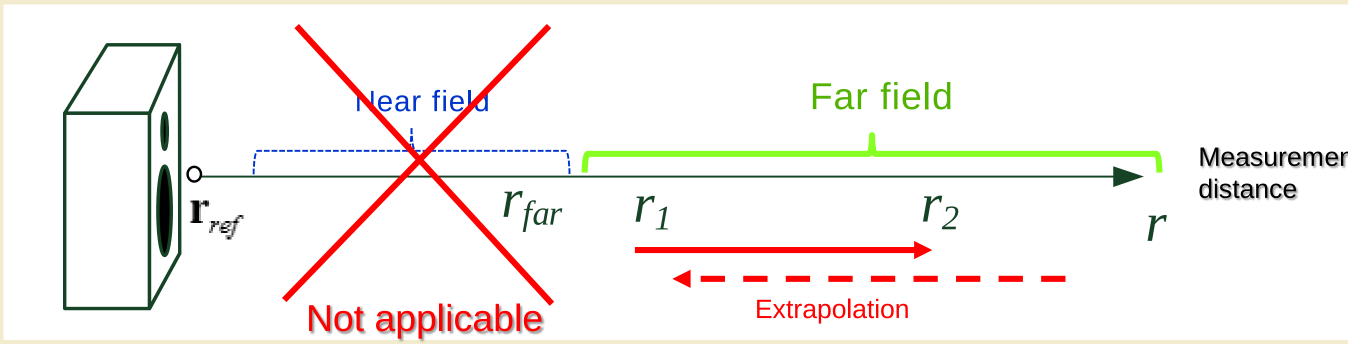
normal vector $\mathbf{n}_{\mathbf{r}\mathrm{ef}}$

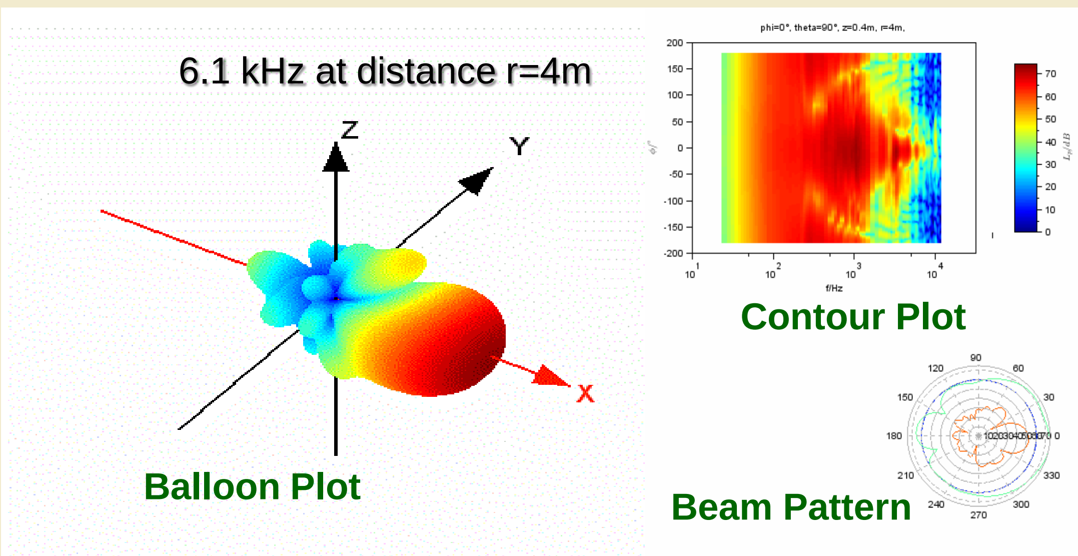
- origin is placed at the reference point $\mathbf{r}_{\mathrm{ref}}$ defined at a convenient place on the surface of radiator, grill or enclosure close to the supposed acoustical center

Why are Far-Field Conditions Used ?



Extrapolation of Far Field data





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

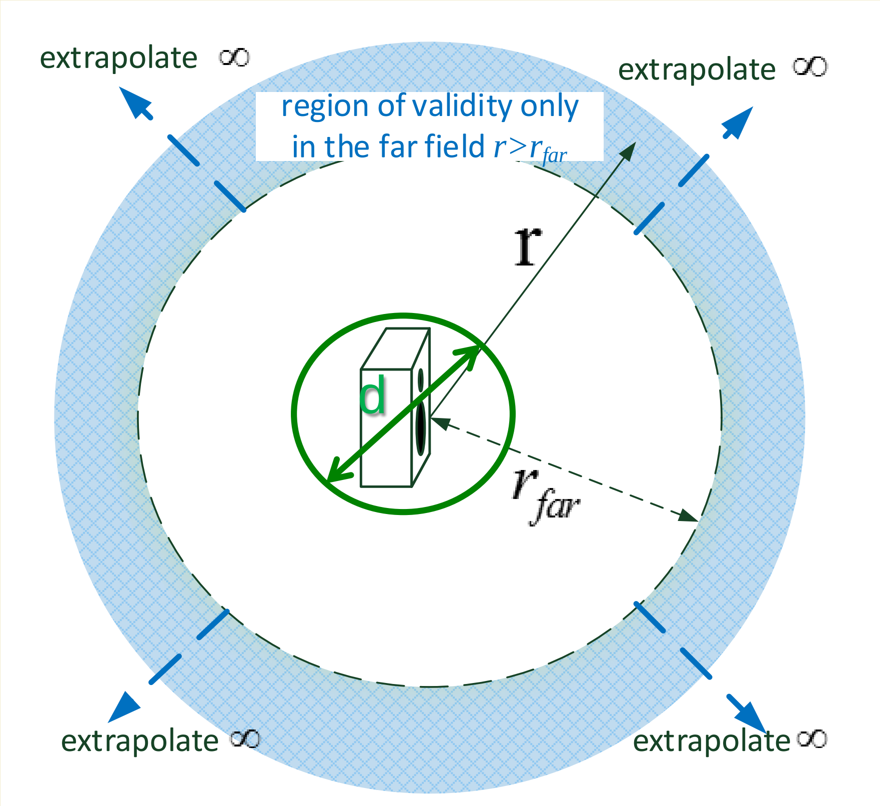
Requirements:

- 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)

Problems and Drawbacks

of conventional far-field measurements

- Angular resolution limited by number of measurement points
- Low frequency measurements (accuracy, resolution) limited by acoustical environment
- 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

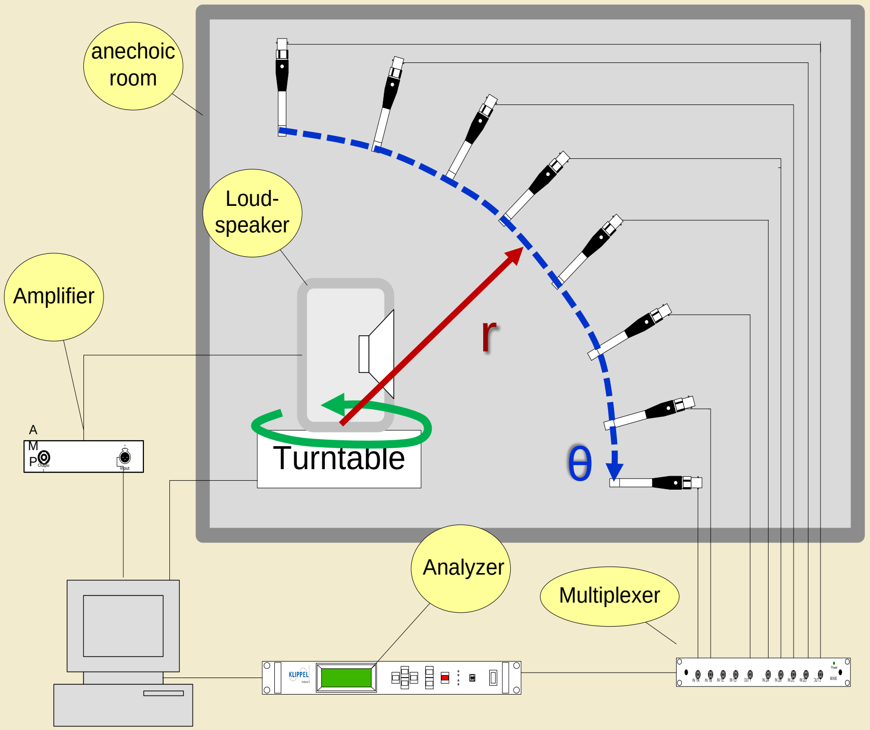
Angular Resolution limited by Sampling

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

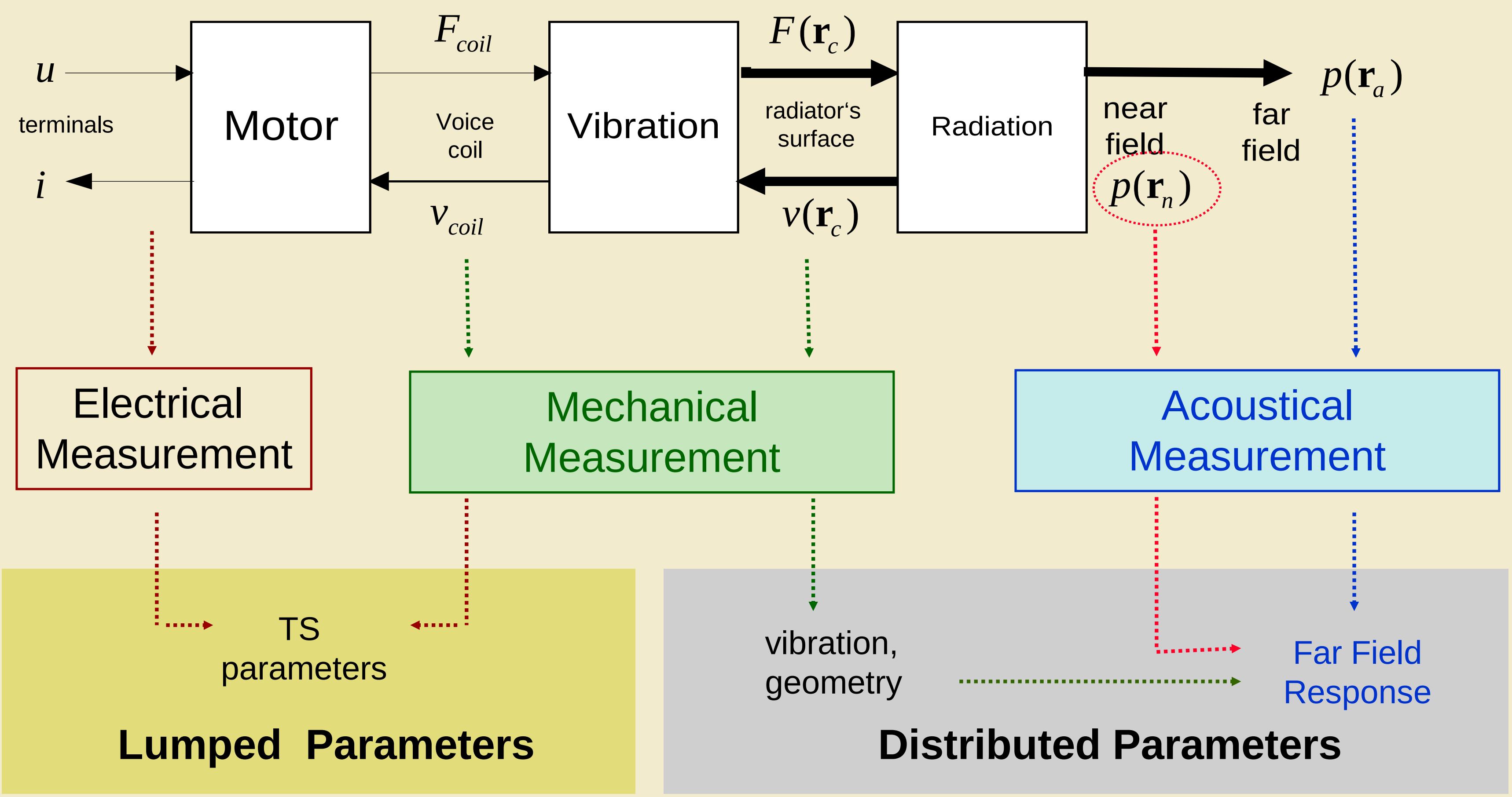


Accuracy of measurement depends on:

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

Loudspeaker Measurements

for assessing small signal performance



Measurements in the Near Field

Sound Pressure Field at 10 kHz

baffle

Surround

cone

Dust cap

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)

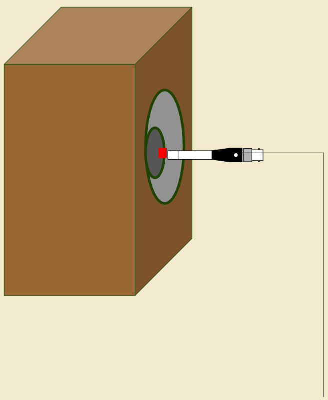
Disadvantages:

- 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

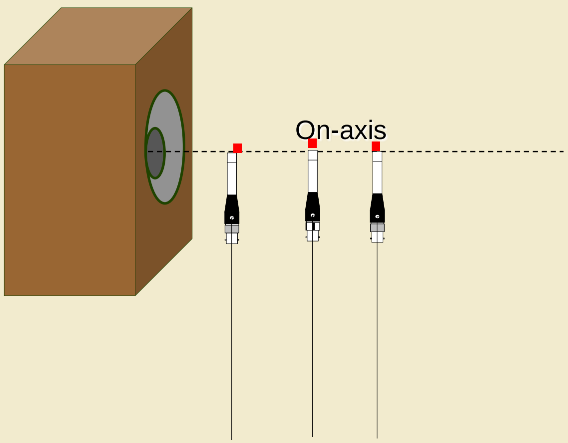
Short History on Near-Field Measurements

Single-point measurement close to the source



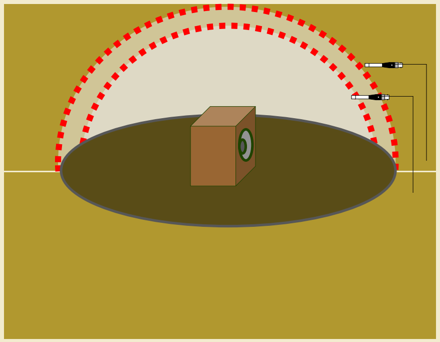
Don Keele 1974

Multiple-point measurement on a defined axis



Ronald Aarts (2008)

Scanning the sound field on a surface around the source

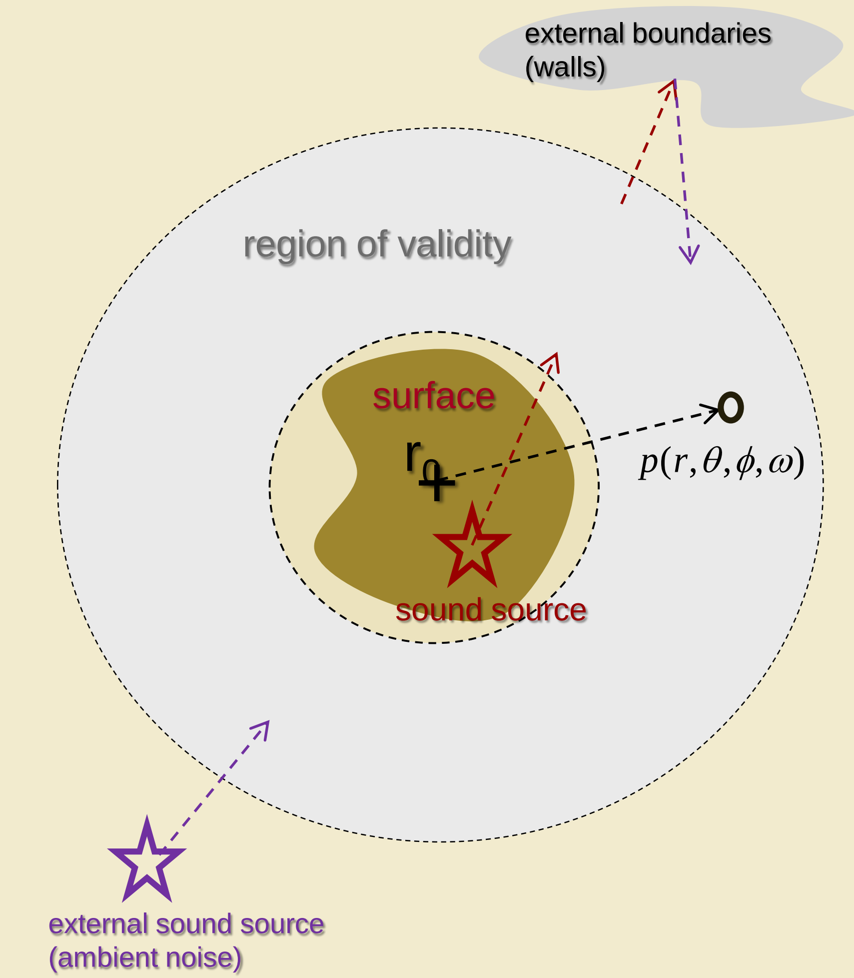


Weinreich (1980), Evert Start (2000)
Melon, Langrenne, Garcia (2009)
Bi (2012)

Robotics required

Postprocessing of the scanned data required

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

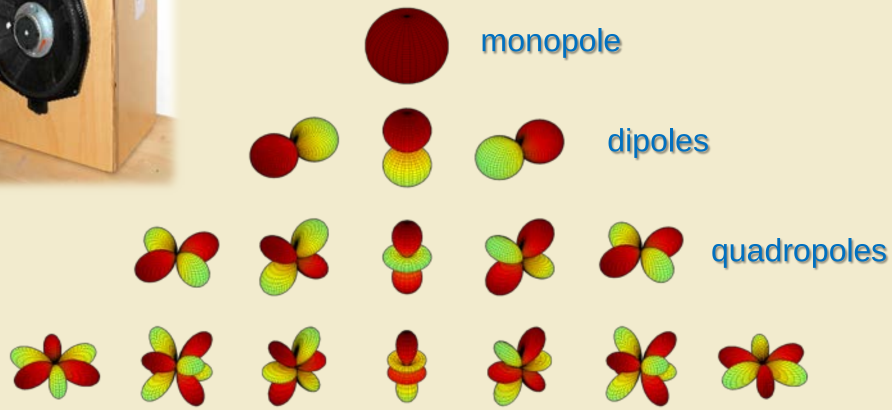
Coefficients outgoing wave — Hankel function of the second kind — Spherical Harmonics

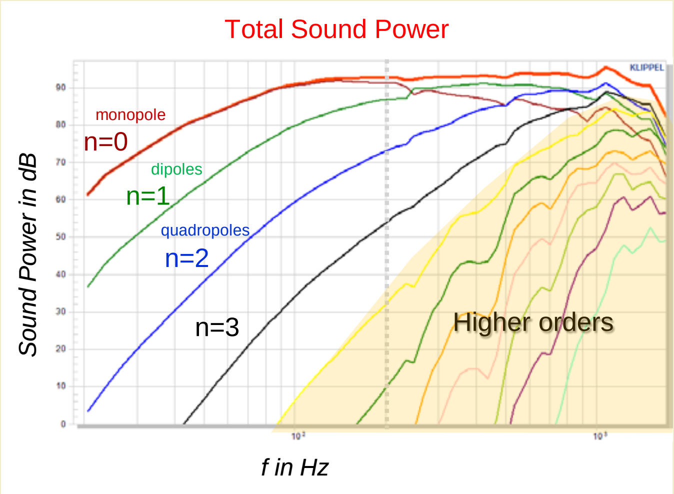
$$p(r,\theta,\phi,\omega) = \sum_{n=0}^{N}\sum_{m=-n}^{n} c_{n,m}^{out}(\omega) h_n^{(2)}(kr) Y_n^m(\theta,\phi) e^{j\omega t} + \sum_{n=0}^{N}\sum_{m=-n}^{n} c_{n,m}^{in}(\omega) h_n^{(1)}(kr) Y_n^m(\theta,\phi) e^{j\omega t}$$

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

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

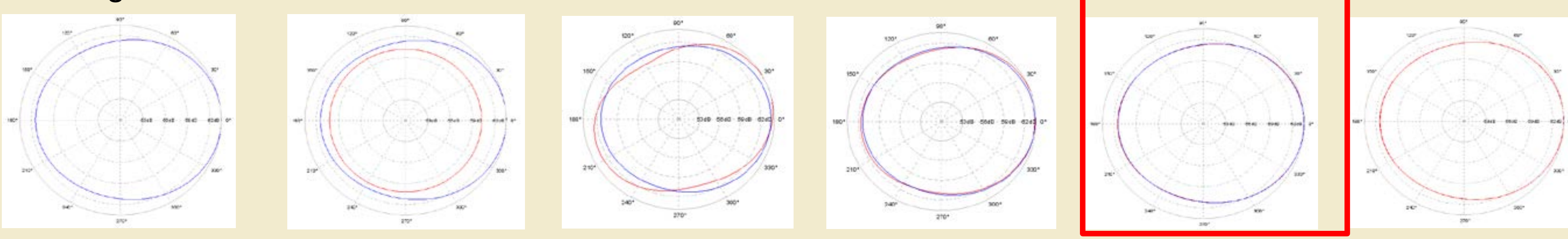
Wave Expansion of a Woofer





Directivity patterns at 200 Hz:

Target N=0 N=1 N=2 N=3 N=10

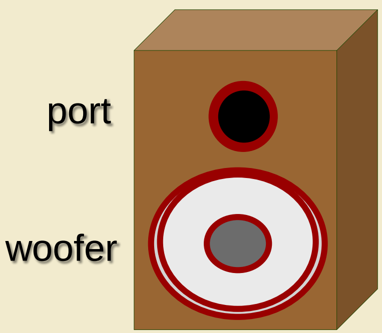


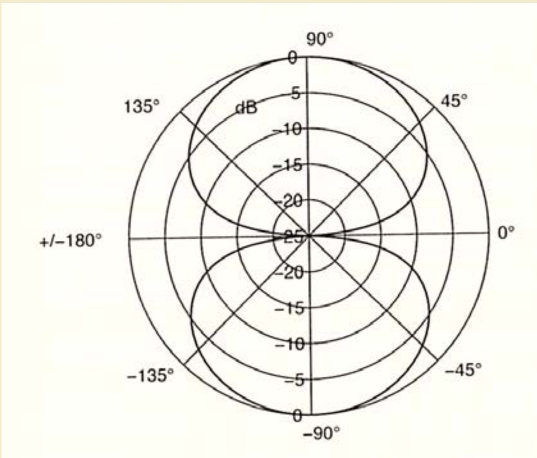
sound field is completely described by order N=3 (16 Coefficients)

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

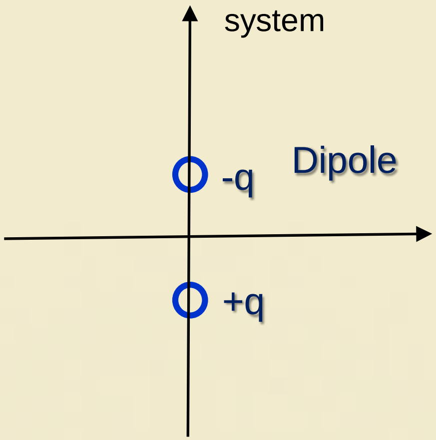
Order of the Expansion Depends on the Loudspeaker Properties

Example: Woofer in a Vented Box far below port resoance



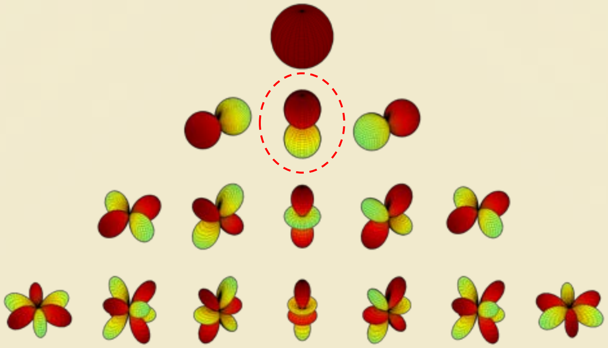


internal coordinate system



The directivity can be modeled by a few coefficients (in theory one) if

- the expansion point (origin of the internal coordinate system) is in the acoustical center
- the dipole axis is aligned with the coordinate system

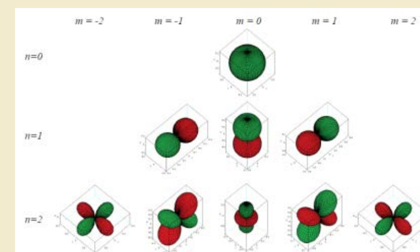


→ a single measurement point is required to identify the directivity

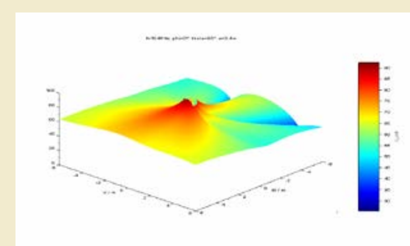
Holographic Measurement sound output in 3D space

1st step: Near-field Scanning

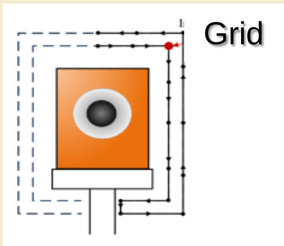
2nd step: Holografic Data Processing



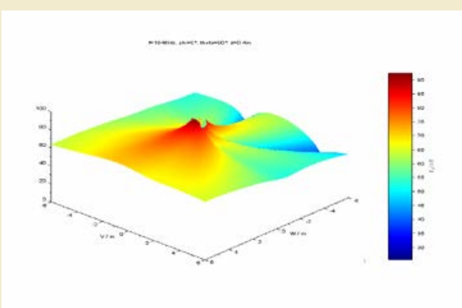
3rd step: Extrapolation



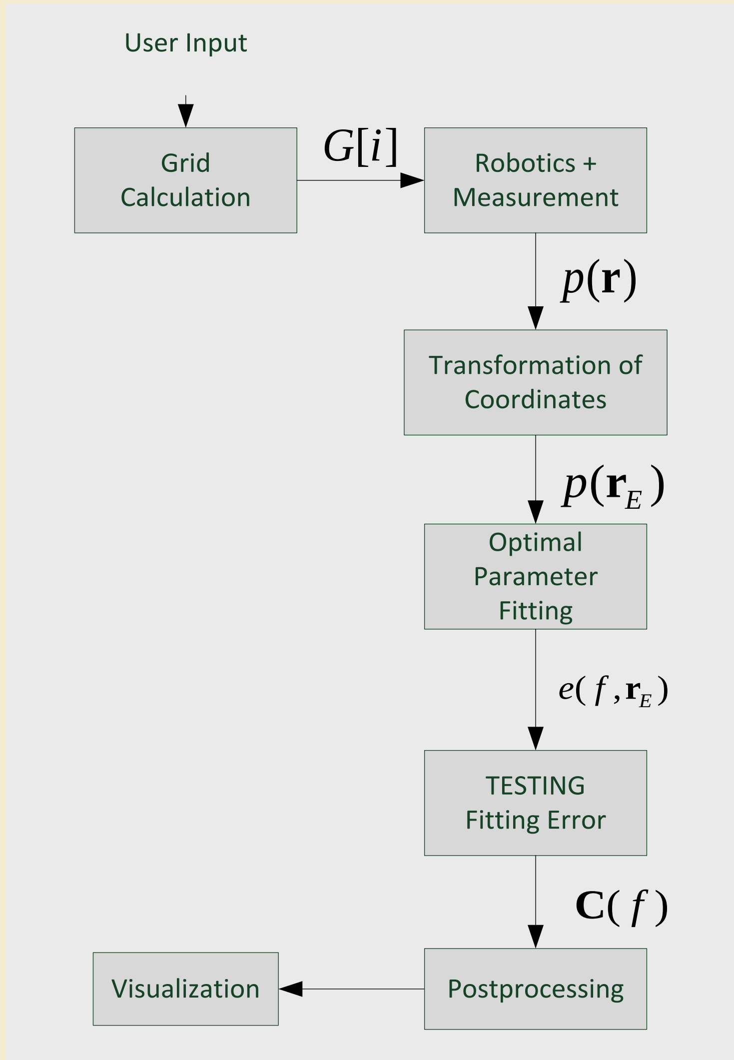
Holografic Near-Field Measurement



Iterative development of the scanning grid and optimization of the wave expansion



sound pressure field



$$\mathbf{r}_E(f) = \mathbf{Q}(f)\mathbf{r} + \mathbf{r}_{EP}(f) - \mathbf{r}_{ref}$$

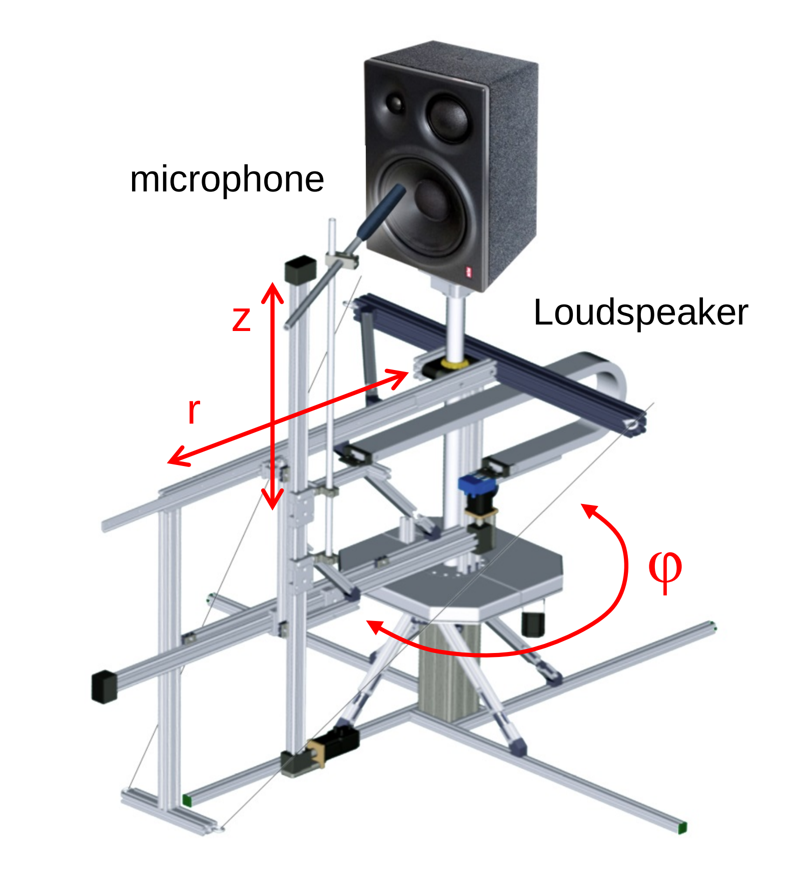
$$\mathbf{c}(f) = \arg\min_{\mathbf{c}(f)} \left(\sum_{\forall \mathbf{r}_E \in G} \left| e(f,\mathbf{r}_E) \right|^2 \right)$$

$$e(f,\mathbf{r}_E) = H_m(f,\mathbf{r}_E) - H(f,\mathbf{r}_E))$$

modelled measured

Results: Coefficients $\mathbf{C}(f)$ of the wave expansion

Requirements of the Robotics



1. **Acoustical properties**
   - transparent,
   - low noises
2. **Flexible scanning grid**
   - any scanning surface
   - scanning close to the source
   - accurate positioning on multiple layers
   - 2 π half-space (driver in baffle)
   - 4π full-space (compact sources)
3. **High-Speed measurement**
   - simultanous positioning in 3 coordinates
   - multiple channel aquisition (mic array)
4. **Wide range of application**
   - from smart phone to line array
   - heavy systems (> 500 kg)
   - slim system (> 4 m)
   - cost effective, portable

Optimal Estimation

of the coefficients in the spherical wave expansion

There are two approaches:

1. Correlation with the basic function (Fourier)
   - Exploiting orthonormal properties of the basic function
   - Scanning surface should be a sphere
   - Fixed position of the expansion point in the center of the sphere
2. Least Mean Squares (→ Matrix Inversion)
   - can be applied to any scanning surface enclosing the sound source
   - Expansion point can be adjusted to the acoustical center of the sound source

beneficial for loudspeakers

Verification of the Measurement

Nearfield scanning process provides sufficient redundancy in the data which is used to

- perform an automatic self-test of the measurement results
- provide two error metrics TFE(f) and MLE(f) for objective assessment of the validity
- reveal the root cause of the error (sampling, expansion, noise, ...)
- increase the order N of wave expansion
- increase the sampling density and to adjust the scanning grid to the loudspeaker

Error Measures for Verification

$$e(f,\mathbf{r}_E) = H_m(f,\mathbf{r}_E) - H(f,\mathbf{r}_E))$$

modelled measured

Total fitting error (TFE)

$$TFE(f) = 10\log\left(\frac{\sum_{\mathbf{r}_E \in G} |e(f,\mathbf{r}_E)|^2}{\sum_{\mathbf{r}_E \in G} |H(f,\mathbf{r}_E)|^2}\right)$$

checks agreement between measured and modelled transfer response on all points on the grid error {L_1 L_2, L_3}

Multi layer error (MLE)

$$MLE(f) = 10\log\left(\frac{\sum_{\mathbf{r}_E \in G_1} |e(f,\mathbf{r}_E) - e'(f,\mathbf{r}_E)|^2}{\sum_{\mathbf{r}_E \in G_1} |H(f,\mathbf{r}_E)|^2 + |H(f,\mathbf{r}'_E)|^2}\right)$$

$$e'(f,\mathbf{r}_E) = \frac{H(f,\mathbf{r}_E)}{H(f,\mathbf{r}'_E)} e(f,\mathbf{r}'_E) \qquad \mathbf{r}'_E = \arg\max_{\forall \mathbf{r}'_E} \frac{\langle \mathbf{r}_E \mathbf{r}'_E \rangle}{\|\mathbf{r}_E\| \|\mathbf{r}'_E\|} \qquad \forall r_E \in L_1$$

checks agreement between error $e(f, \mathbf{r}_E)$ on a first point $\mathbf{r}_E$ on the outer layer L_1 and the error $e(f, \mathbf{r}'_E)$ at the closest point on the inner layers {L_2, L_3}

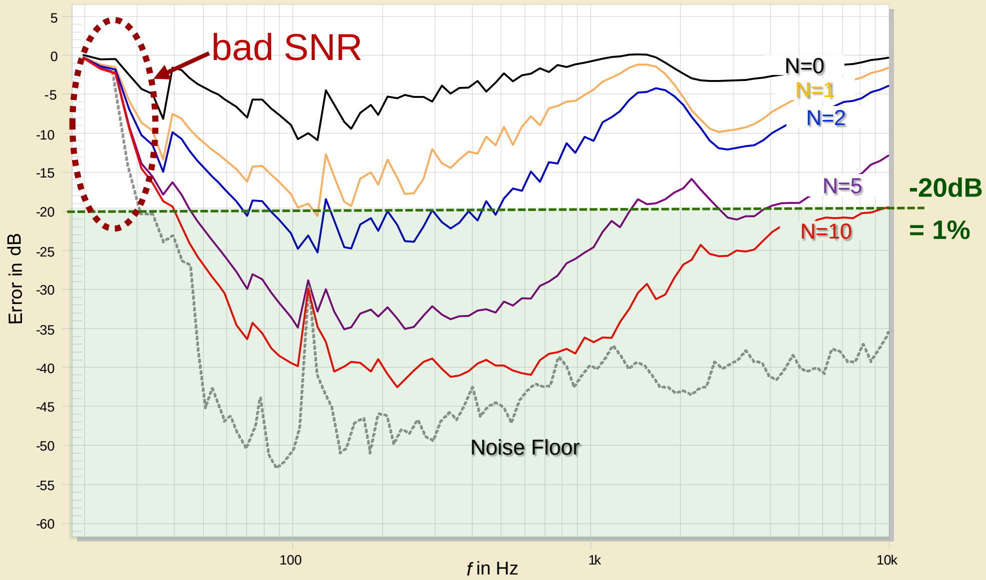
If the errors $TFE \approx MLE$, then the measurement is corrupted by noise, room reflections or positioning errors.

If the errors $TFE > MLE$, then the maximum order N of the expansion and the number of scanning points have to be increased.

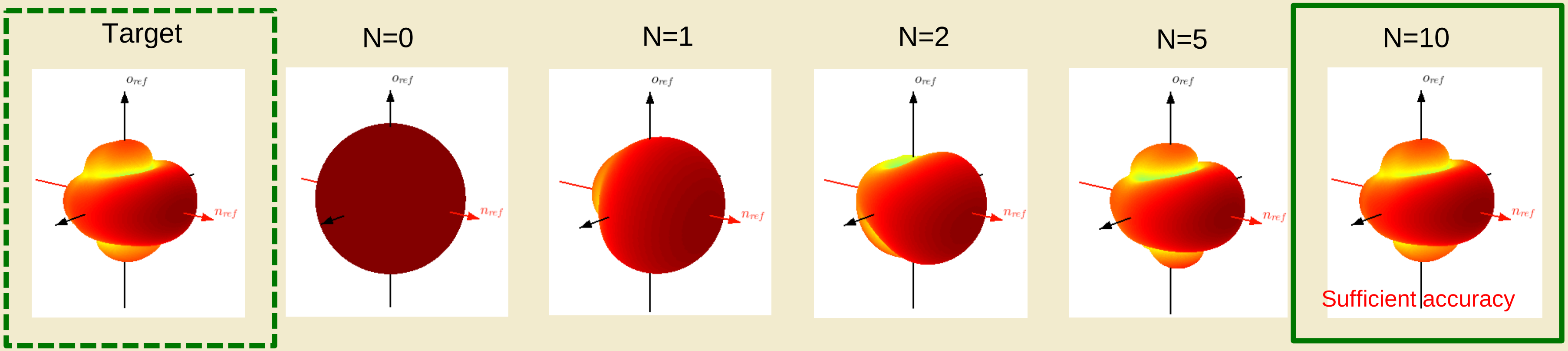
How to Find the Maximum Order N ?

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 order N

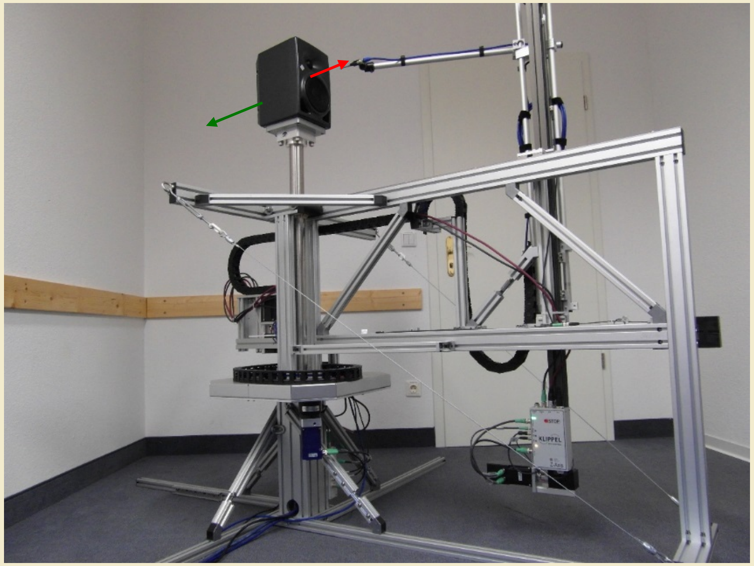


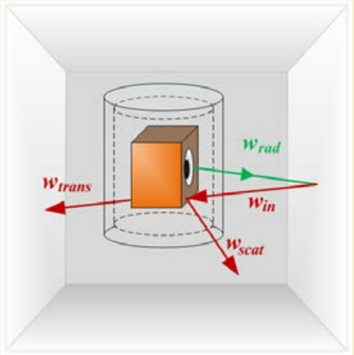
Directivity at 2kHz:



Sound Pressure Response

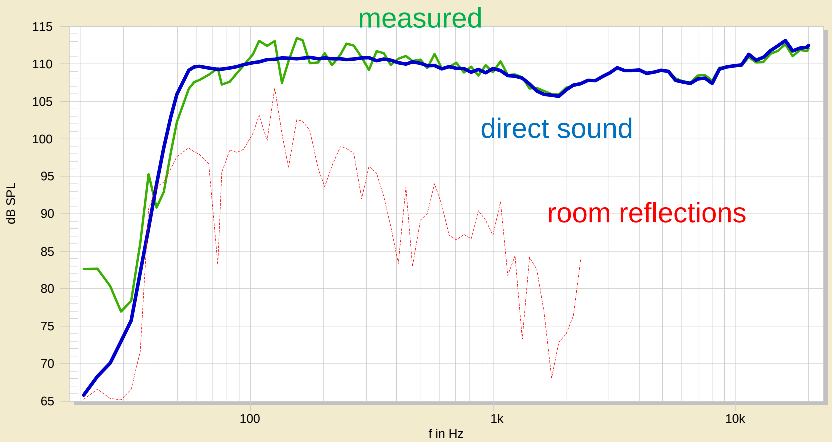
measured in a normal office



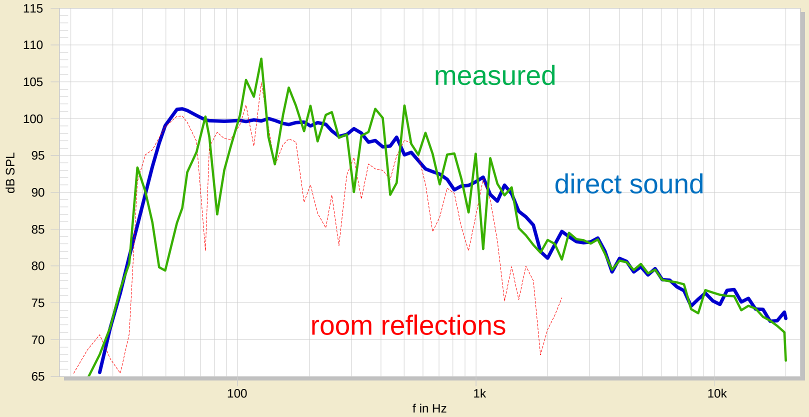


Double layer ´scanning + holografic processing allows to separate the direct sound from room reflections

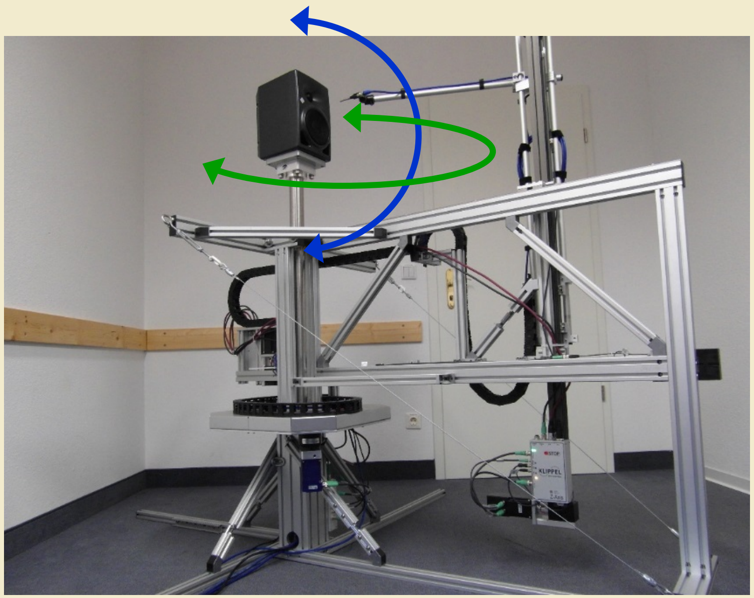
Front side (on axis)

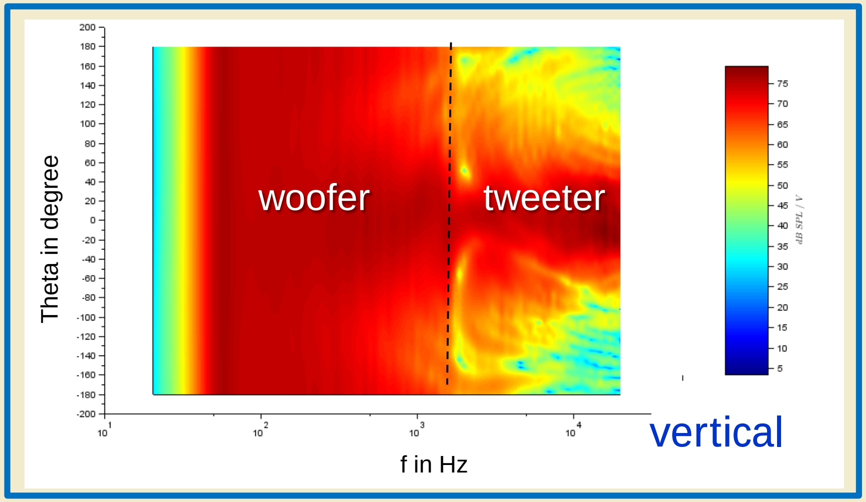


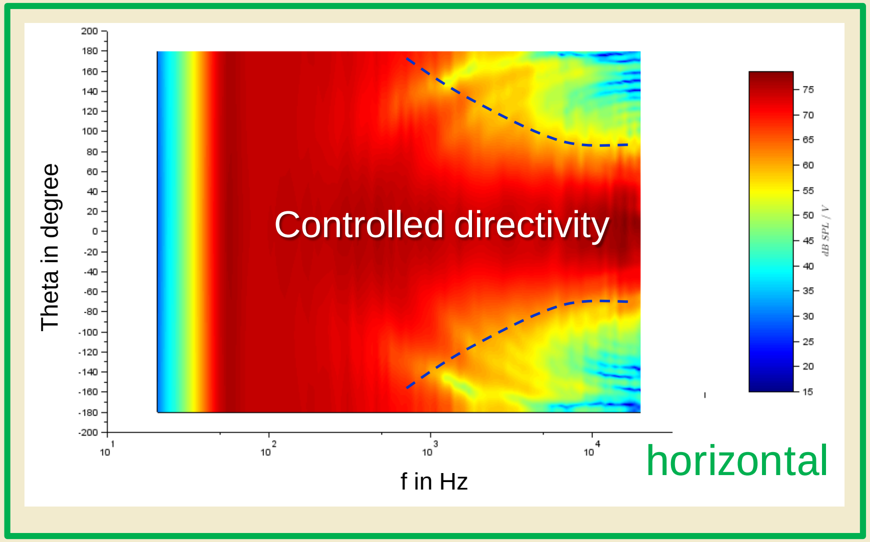
Rear Side



2nd Example: Studio Monitor

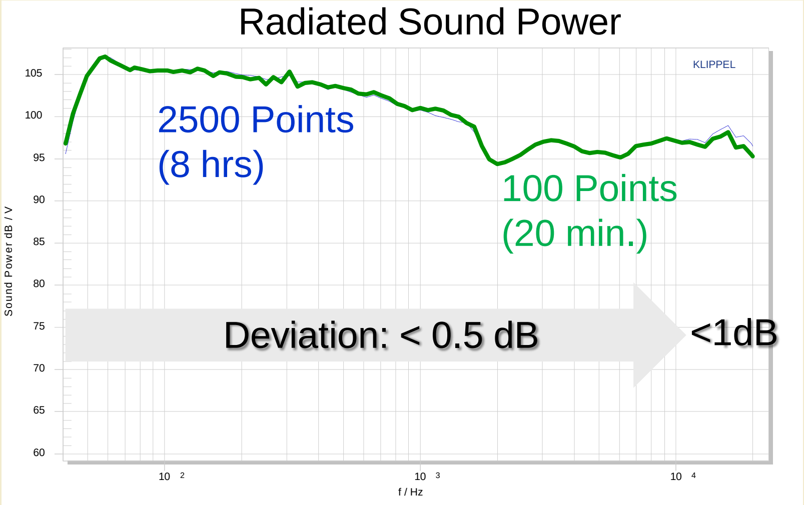


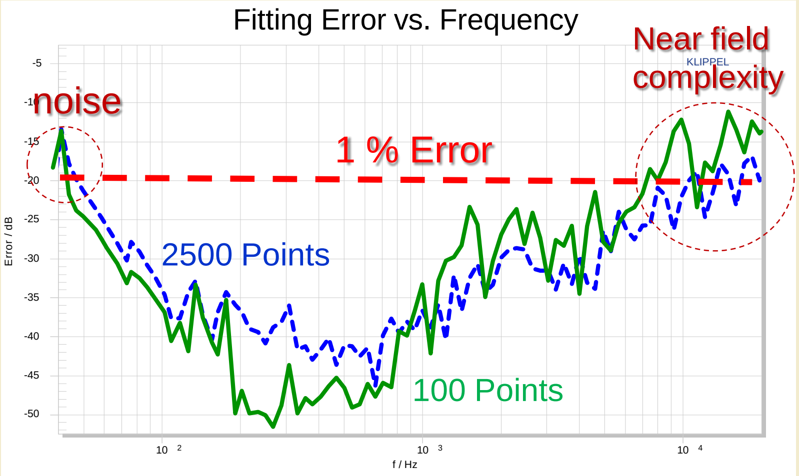




- Near-field scanning in an ordinary office room
- 500 points
- Order of expansion N=20

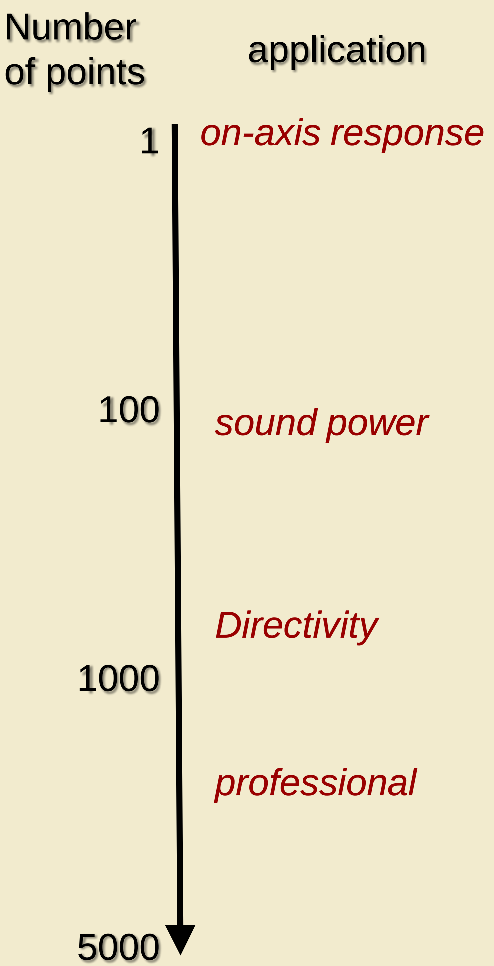
What is the Accuracy of a 20 min Scan to Determine Sound Power?





Fitting error provided by holographic post-processing shows the accuracy of the results !!

How Many Points Need to be Measured ?



Number of measurements points M required is much lower than the final angular resolution of the calculated directivity pattern !

Number of points M depends on:

- Total number of coefficients J in the expansion ($M>1.5J$)
- Maximum number N of the expansion $J=(N+1)^2$
- Loudspeaker type (size, number of transducers)
- Symmetry of the loudspeaker (axial symmetry)
- Application of the data (e.g. EASE data)
- Field seperation (non-anechoic conditions)

How to shorten the scanning time ?

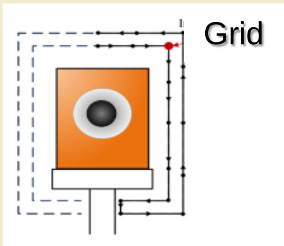
Idea:

- Optimal adjustment of the scanning grid to the partical application to provide sufficient angular resolution

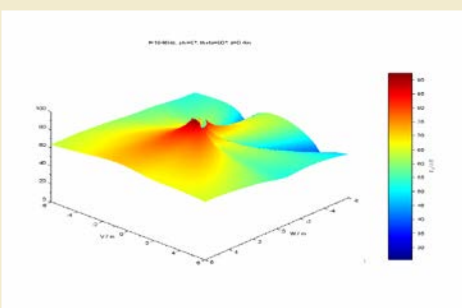
Consequences:

- Using identified loudspeaker properties (directional complexity, symmetry, acoustical center) to minimize order of expansion
- Checking the fitting error
- Coordinate transformation of the measured data (positioning of the expansion point, orientation)
- Adaptive (iterative) adjustment of the scanning grid
- non-uniform sampling → partial fitting

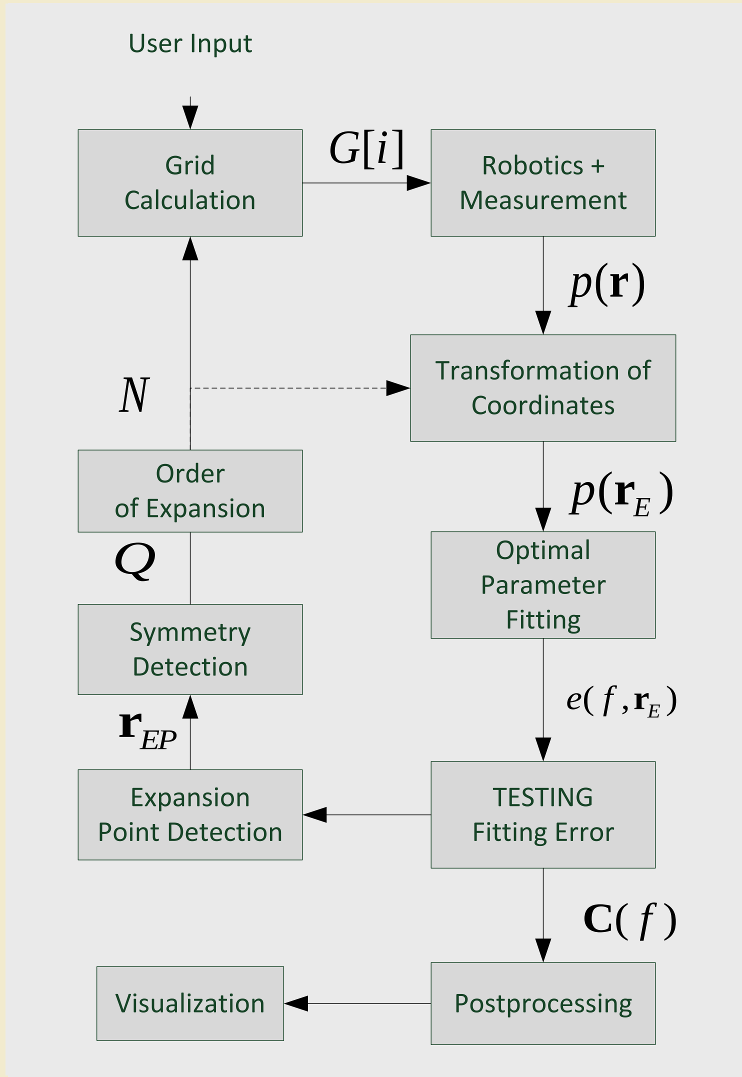
Iterative Near-Field Measurement



Iterative development of the scanning grid and optimization of the wave expansion



sound pressure field



$$\mathbf{r}_E(f) = \mathbf{Q}(f)\mathbf{r} + \mathbf{r}_{EP}(f) - \mathbf{r}_{ref}$$

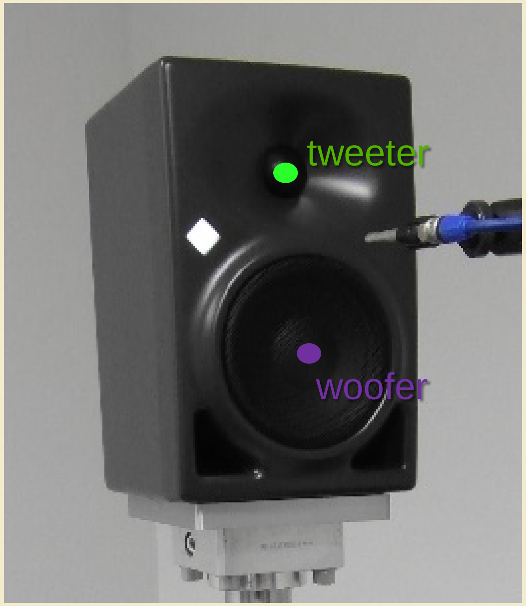
$$\mathbf{c}(f) = \arg\min_{\mathbf{c}(f)} \left(\sum_{\forall \mathbf{r}_E \in G} \left| e(f, \mathbf{r}_E) \right|^2 \right)$$

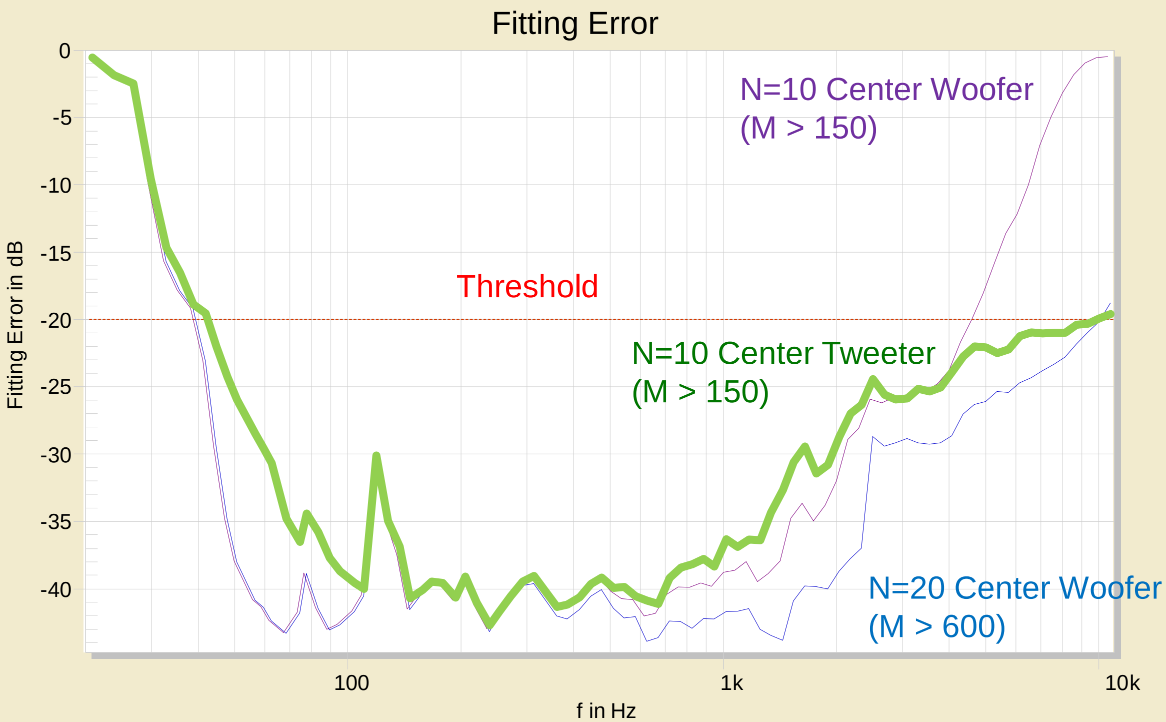
$$e(f, \mathbf{r}_E) = H_m(f, \mathbf{r}_E) - H(f, \mathbf{r}_E))$$

modelled measured

Results: Coefficients **C**(*f*) of the wave expansion

Optimal Choice of the Expansion Point

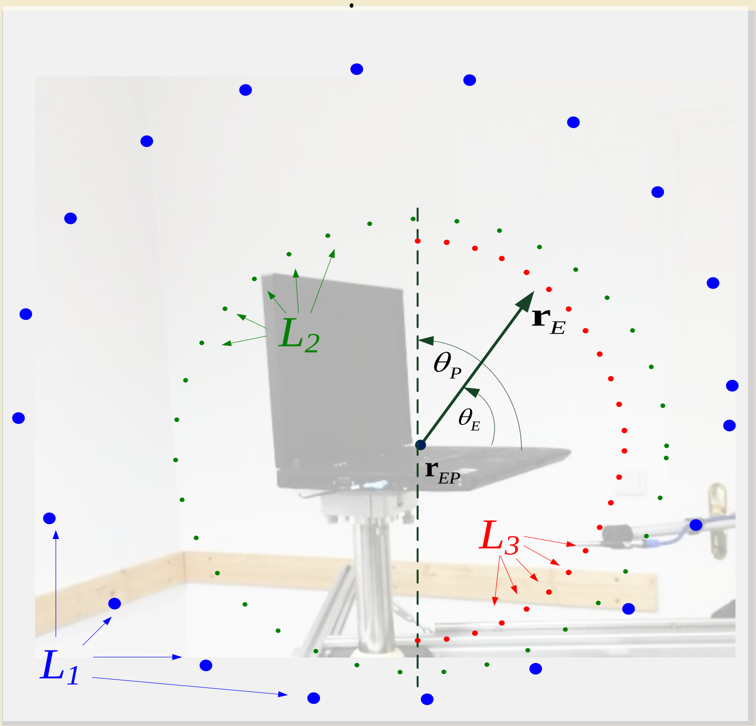




Setting the expansion point to the center of the tweeter reduces the number of measurement points M from 600 to 150.

Iterative Generation of the Scanning Grid

$$G[1] = L_1 = \{\mathbf{r}_1, \mathbf{r}_1, \ldots, \mathbf{r}_E, \ldots\}$$
$$G[2] = \{L_1 + L_2\}$$
$$G[3] = \{L_1 + L_2 + L_3\}$$
$$\vdots$$



Subset L_1 uses a sparse sampling to identify an optimum position of the expansion point $\mathbf{r}_{EP}(f)$ close to acoustical center at frequency and f the symmetry properties of the loudspeaker.

Subset L_2 comprising additional measurement points located at a shorter distance from the expansion point and spaced with sufficient angular resolution to satisfy the spatial sampling on the rear side of the loudspeaker.

Subset L_3 of points are placed on the front side of the loudspeaker to identify the coverage angle of the main lobe at higher accuracy.

Non-uniform Sampling and Partial Fitting

Problem: Horn loaded compression loudspeaker and other sound sources with high directivity need a much higher angular resolution at the front side than at the rear side to assess the coverage angle.

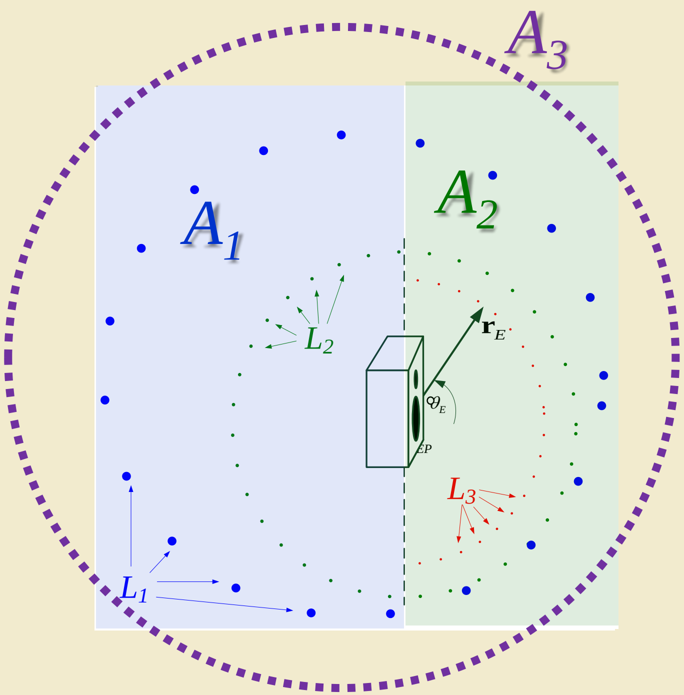
Scanning rear side with sparse grid A_1

$$H(f,\mathbf{r}_E) \quad \forall \mathbf{r}_E \in A_1$$

Wave expansion with order N_1

$$H_m(f,\mathbf{r}_E) = \mathbf{c}_1(f)\mathbf{b}(f,\mathbf{r}_E) \qquad \forall \mathbf{r}_E \in A_1$$

Extrapolation to a left hemisphere in the far field



Scanning front side with dense grid A_2

$$H(f,\mathbf{r}_E) \quad \forall \mathbf{r}_E \in A_1$$

Wave Expansion with order $N_2 > N_1$

$$H_m(f,\mathbf{r}_E) = \mathbf{c}_i(f)\mathbf{b}(f,\mathbf{r}_E) \qquad \forall \mathbf{r}_E \in A_2$$

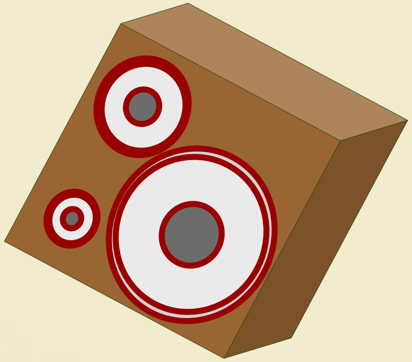
Extrapolation to a right hemisphere in the far field

Merging data to a complete sphere with dense grid A_3

Wave expansion with order N_3

$$H_m(f,\mathbf{r}_E) = \mathbf{c}_3(f)\mathbf{b}(f,\mathbf{r}_E) \qquad \forall \mathbf{r}_E \in A_3$$

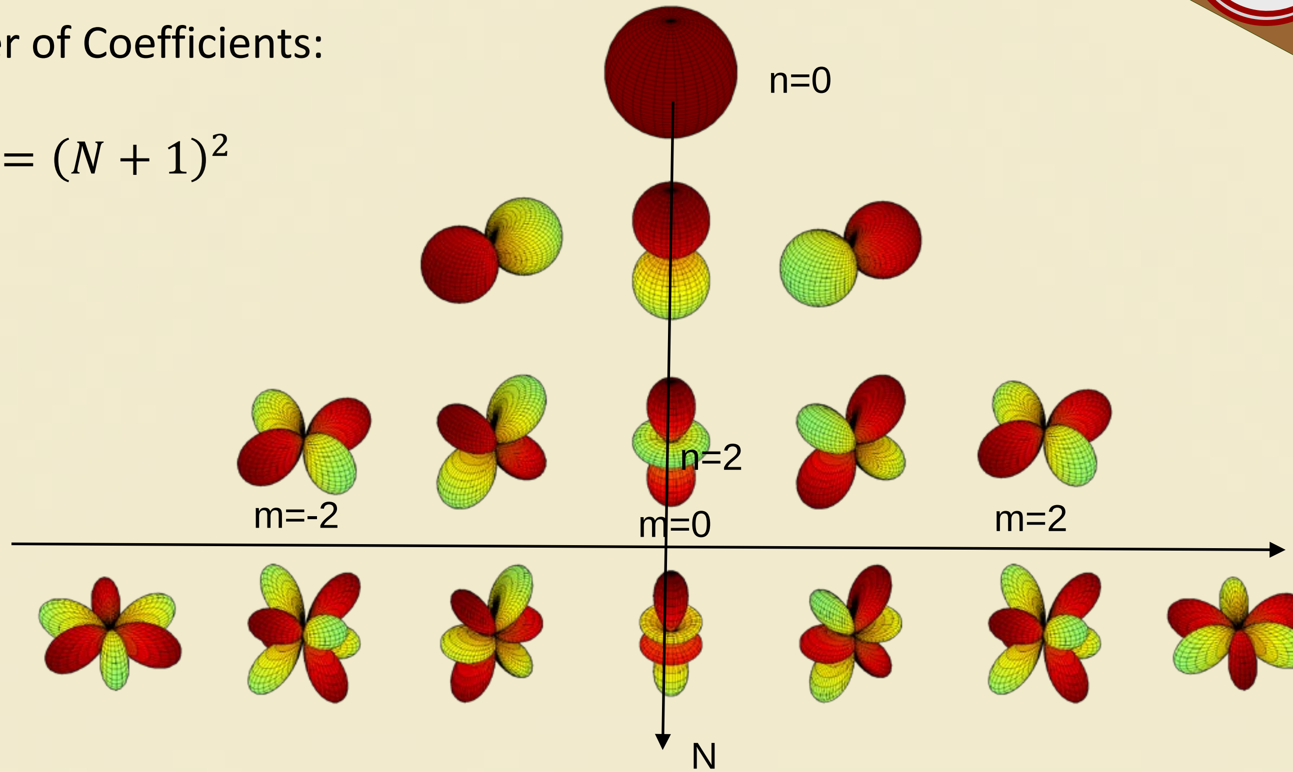
No Symmetry



Condition for used Spherical harmonics:
All orders used

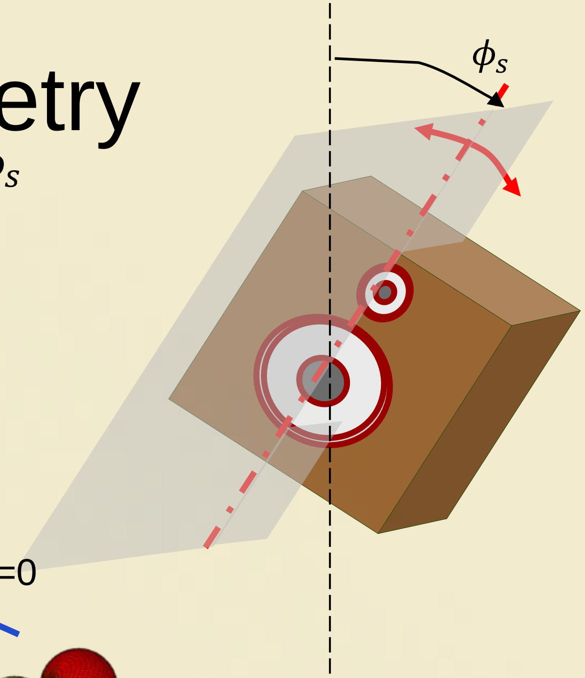
Number of Coefficients:

$$J = (N+1)^2$$



Single Plane Symmetry

symmetry axis at arbitrary angle ϕ_s



Condition for used Spherical harmonics:

$$m \geq 0$$

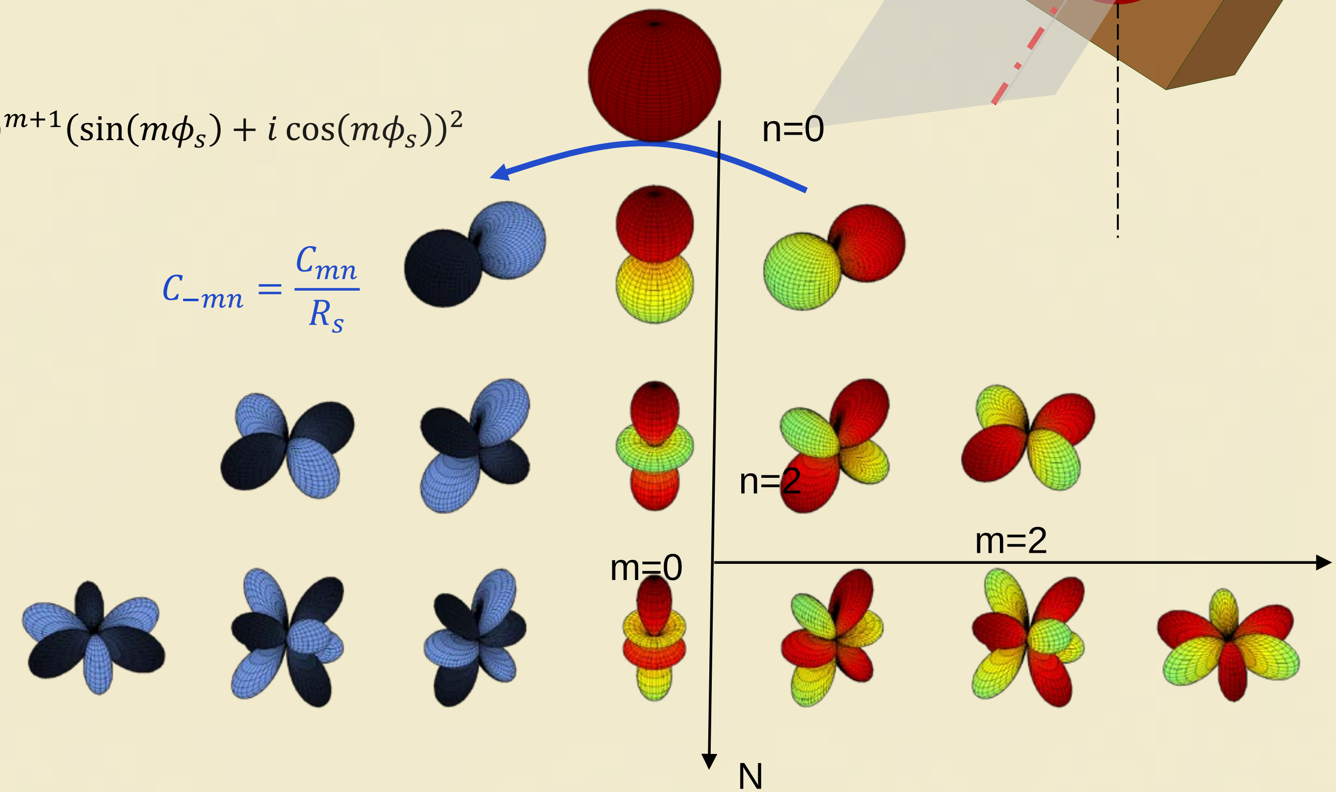
Coupling between coefficients with positive ($m > 0$) and negative index ($m < 0$)

$$R_m = \frac{C_{mn}}{C_{-mn}} = (-1)^{m+1}(\sin(m\phi_s) + i\cos(m\phi_s))^2$$

$$C_{-mn} = \frac{C_{mn}}{R_s}$$

Number of Coefficients:

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



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)

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

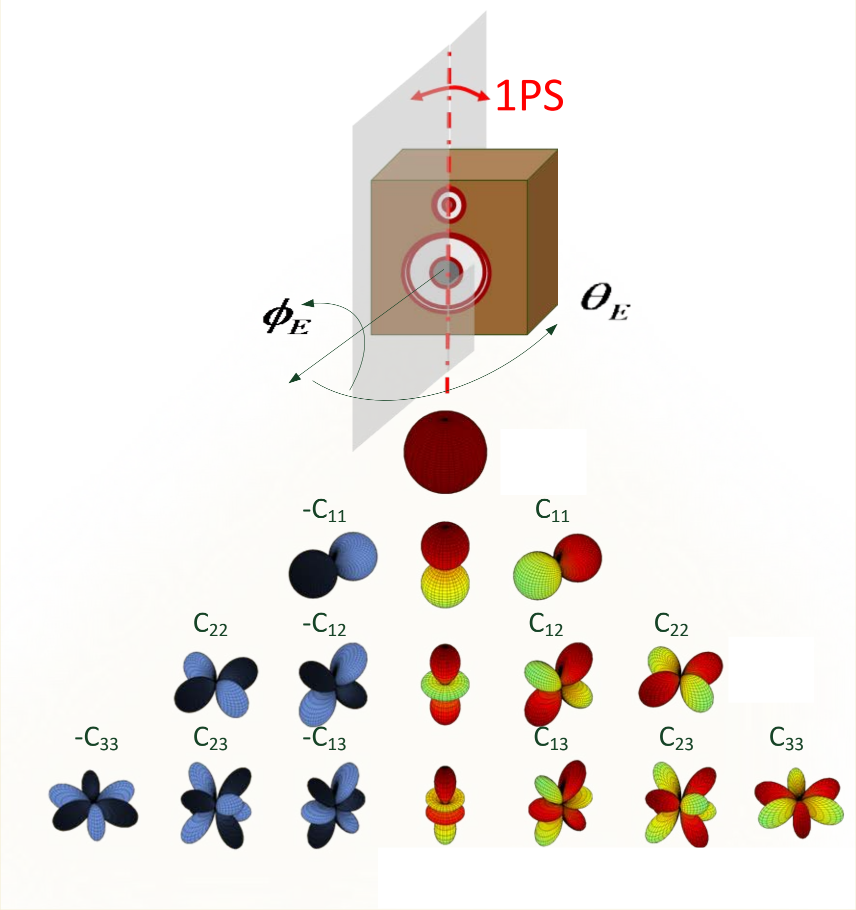
Reduced Number of Coefficients:

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

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

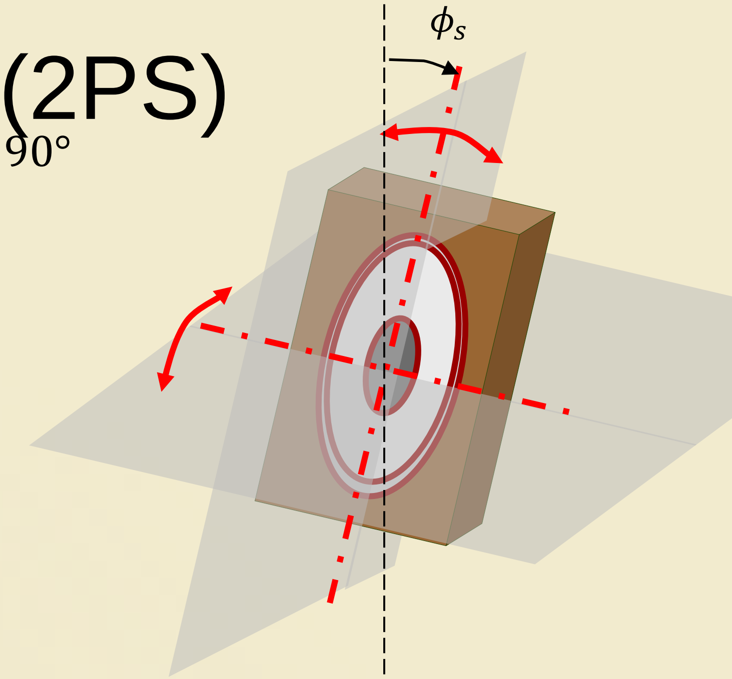
$$S_{1PS} = 1 - \frac{\sum_{n=1}^{N}\sum_{m=1}^{n}\left|(-1)^m(f)C_{-mn} - C_{mn}\right|^2}{\sum_{n=0}^{N}\sum_{m=-n}^{n}C_{mn}^2}$$

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



Dual Plane Symmetry (2PS)

arbitrary symmetry axes ϕ_s and $\phi_s + 90°$



Condition for used Spherical harmonics:

$m \geq 0$ and $m = 2s$, $s \in \mathbb{N}^+$

Coupling between the coefficients with positive ($m > 0$) and negative index ($m < 0$)

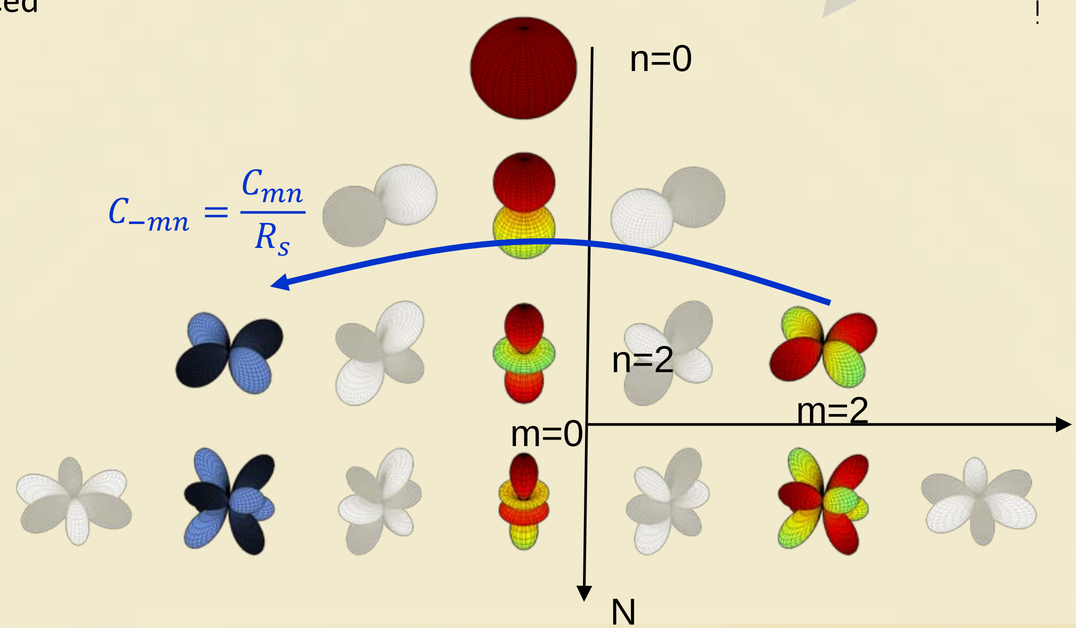
$$R_s = \frac{C_{mn}}{C_{-mn}} = (-1)^{m+1}(\sin(m\phi_s) + i\cos(m\phi_s))^2$$

Number of Coefficients is reduced for even orders $\mathrm{N} = 0,2,4,6, \ldots$

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

for uneven orders $N = 1,3,5, \ldots$

$$J = \left(\frac{N}{2} + 1\right)^2 - \frac{1}{4}$$



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)

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

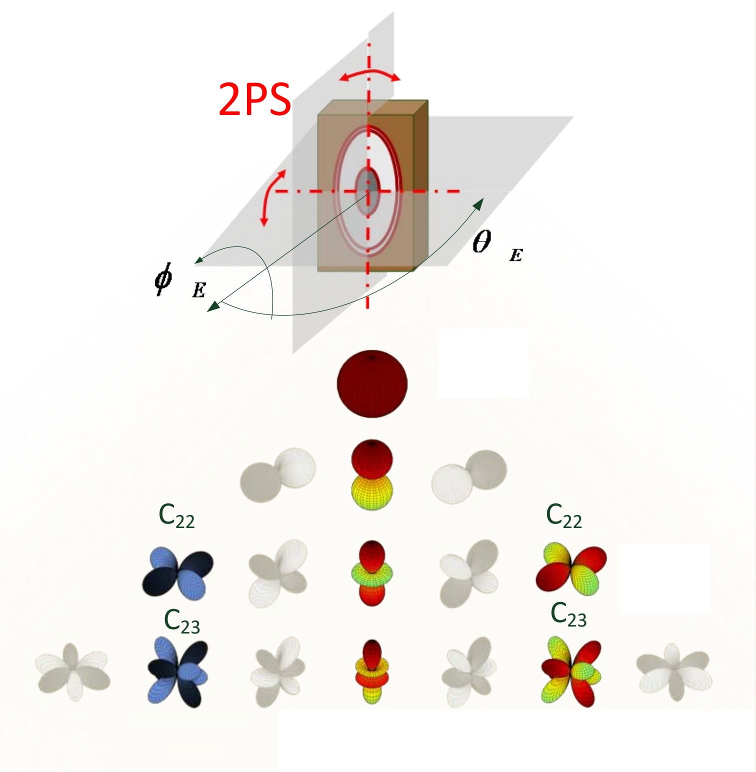
Reduced Number of Coefficients:

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

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. $S_{2PS} > 0.95$)



Rotational Symmetry (RS)
no phi dependency

Condition for used Spherical harmonics:

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

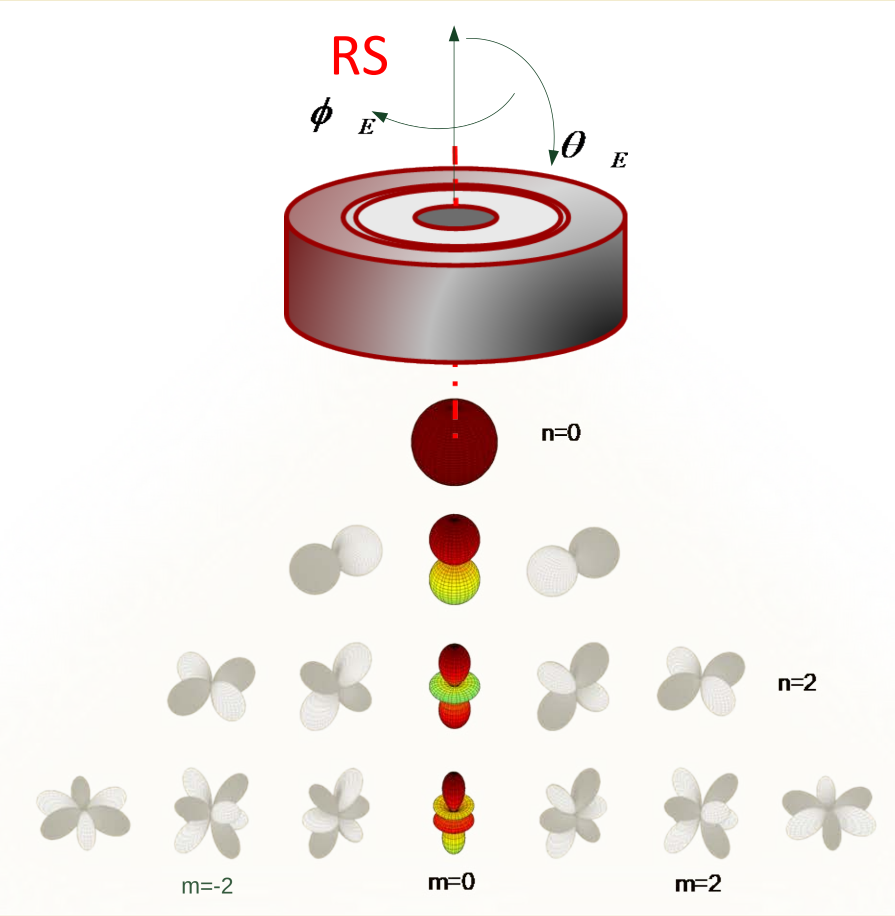
Reduced Number of Coefficients:

$$J = N + 1$$

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. $S_{RS} > 0.95$)



Baffle Symmetry (BS)

symmetry axis $\vartheta = 90°$

Condition for used Spherical harmonics:

$$C_{mn} = 0 \qquad n - m \neq 2s \mid s \in \mathbb{Z}$$

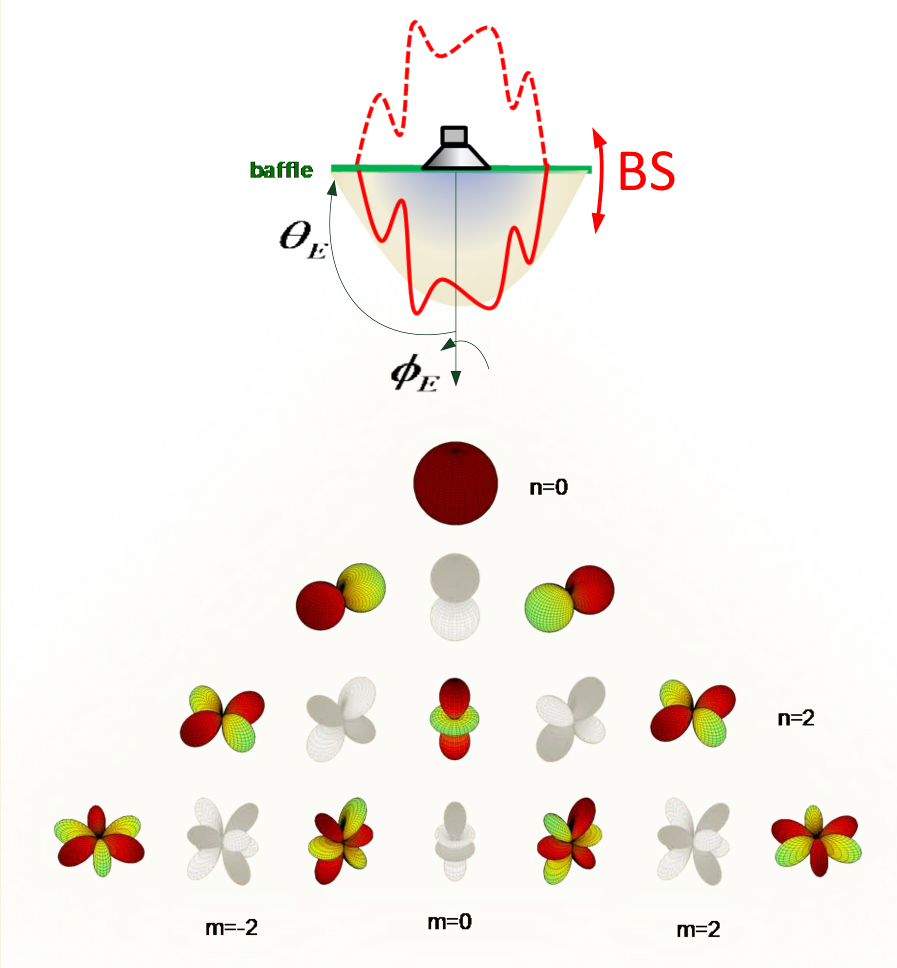
Reduced Number of Coefficients:

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

Evaluating the baffle symmetry (BS) by the metric

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

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



Single Plane + Baffle Symmetry

symmetry axis $\varphi = \varphi_s$ and $\vartheta = 90°$

Condition for used spherical harmonics:

$$m \geq 0 \text{ and } n - m \neq 2s \;|s \in \mathbb{Z}$$

Coupling between used coefficients ($m > 0$) and depending coefficients ($m < 0$)

$$R_s = \frac{C_{mn}}{C_{-mn}} = (-1)^{m+1}(\sin(m\varphi_s) + i\cos(m\varphi_s))^2$$

Number of Coefficients:

for even orders $\mathrm{N} = 0,2,4,6, \ldots$

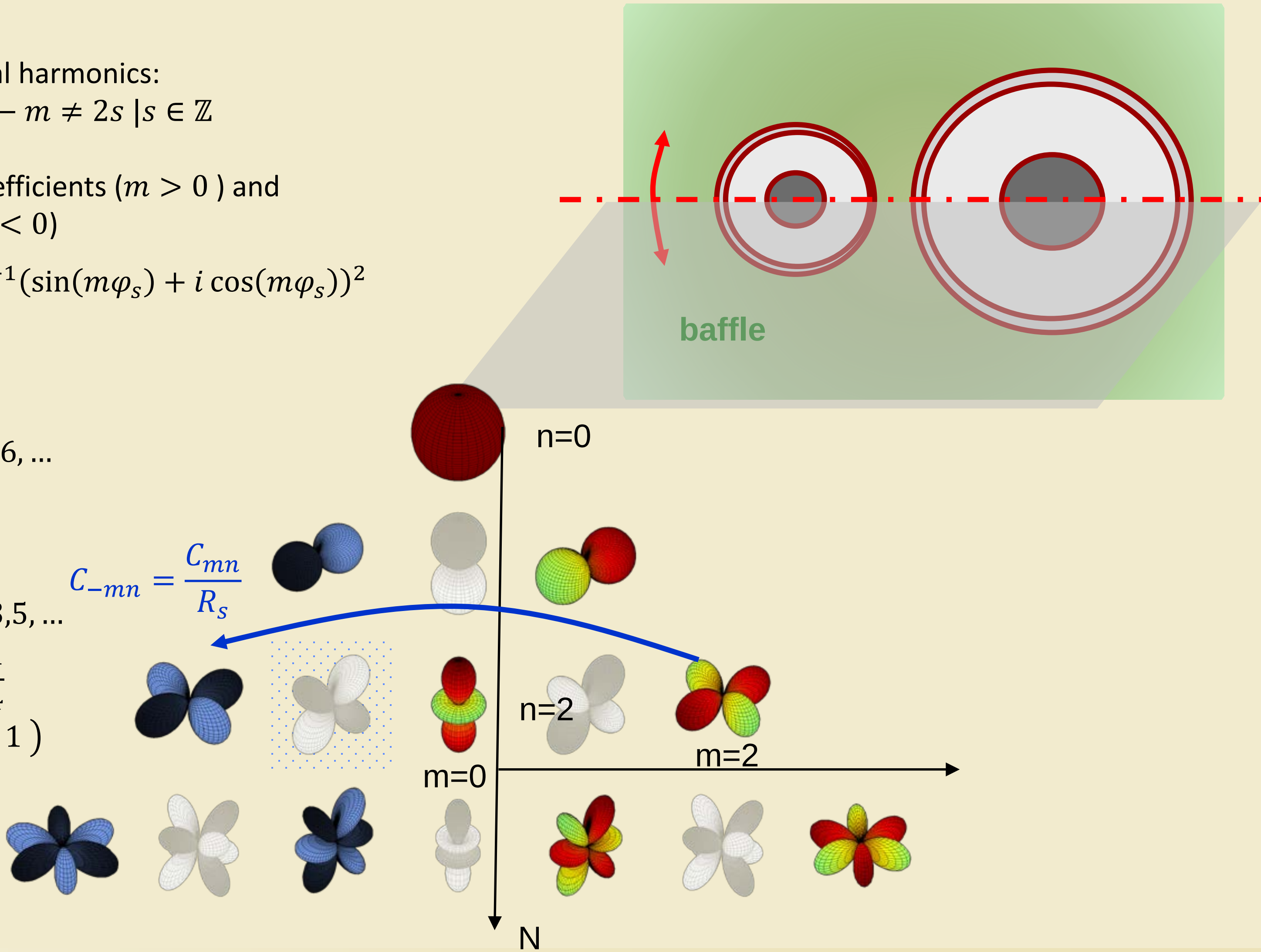
$$J = \left(\frac{N}{2} + 1\right)^2$$

$$N = 2\left(\sqrt{J} - 1\right)$$

for uneven orders $N = 1,3,5, \ldots$

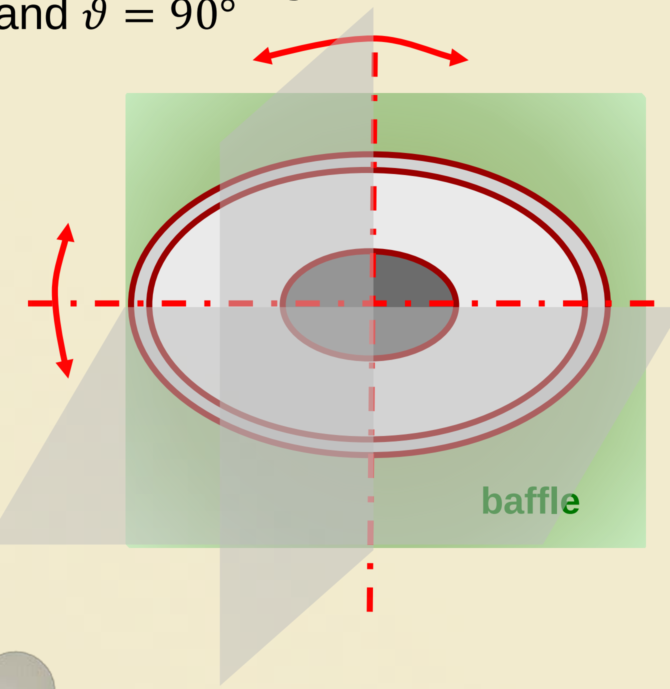
$$J = \left(\frac{N}{2} + 1\right)^2 - \frac{1}{4}$$

$$N = 2\left(\sqrt{J + 0.25} - 1\right)$$



Dual Plane + Baffle Symmetry

2 symmetry axis $\varphi = \varphi_s$, $\varphi = \varphi_s + 90°$ and $\vartheta = 90°$



Condition for used spherical harmonics:

$$m \geq 0$$
$$n - m \neq 2s$$
$$n = 2s \ \mid s \in \mathbb{Z}$$

Coupling between used coefficients ($m > 0$) and depending coefficients ($m < 0$)

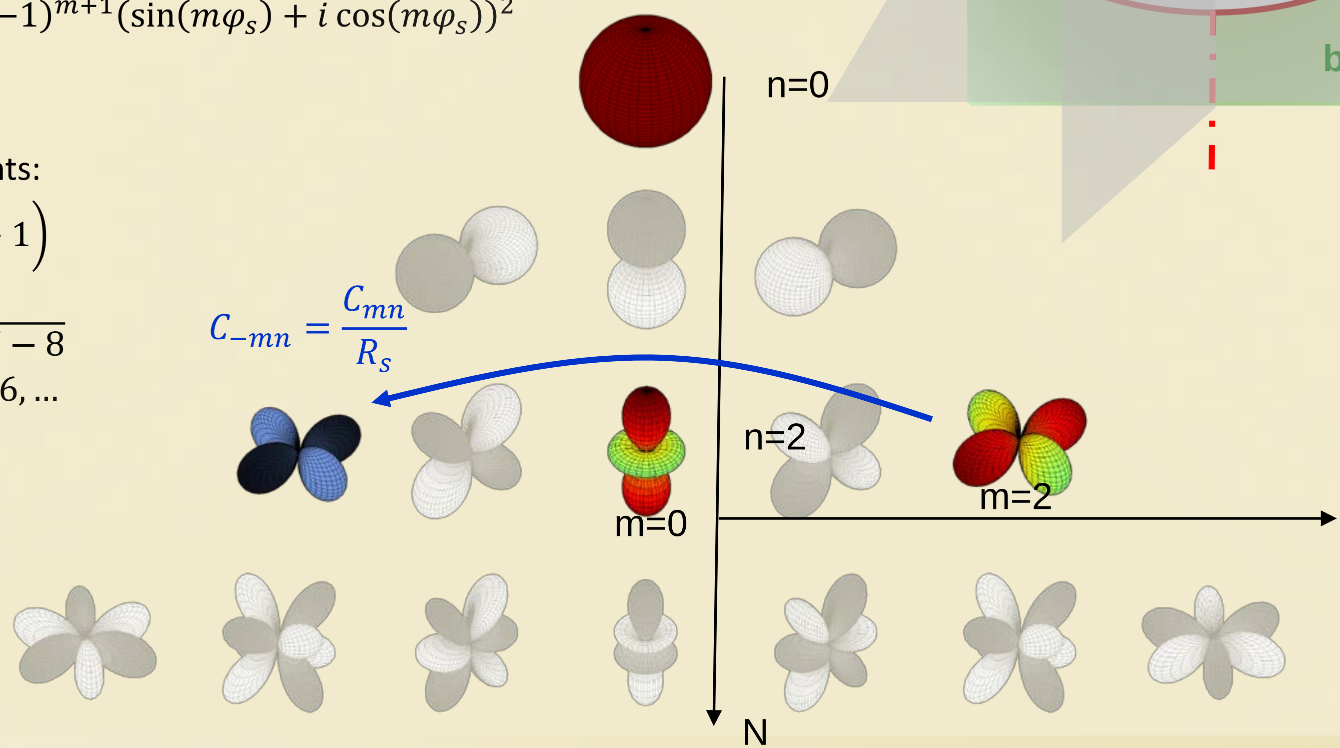
$$R_s = \frac{C_{mn}}{C_{-mn}} = (-1)^{m+1}(\sin(m\varphi_s) + i\cos(m\varphi_s))^2$$

Number of Coefficients:

$$J = \left(\frac{N}{2} + 1\right)\left(\frac{N}{4} + 1\right)$$

$$N = -3 + \sqrt{9 + 8J - 8}$$

only even $N = 0,2,4,6,\ldots$



Rotational + Baffle Symmetry

no phi dependency + sym. axis $\vartheta = 90°$

Condition for used spherical harmonics:

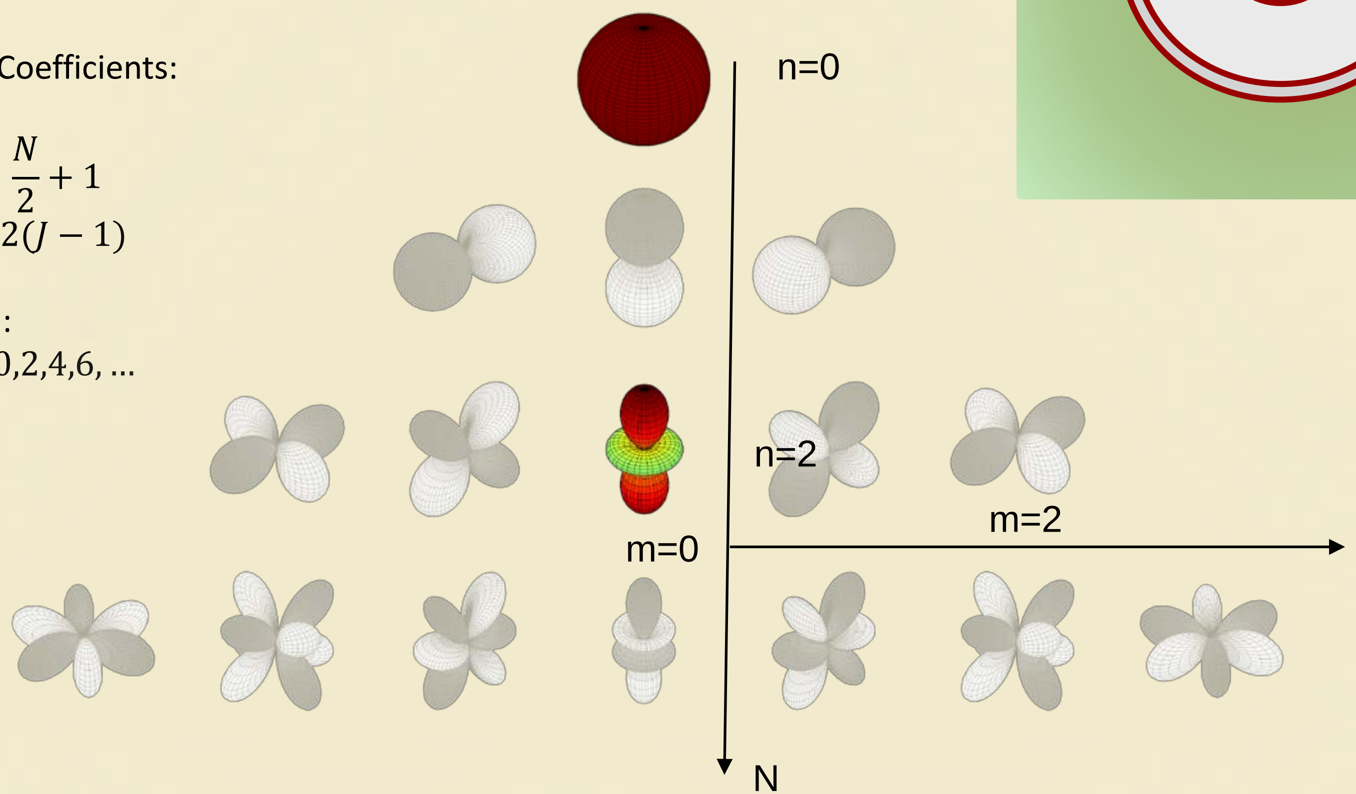
$$m = 0$$
$$n = 2s\,,\, s \in \mathbb{N}^{+}$$

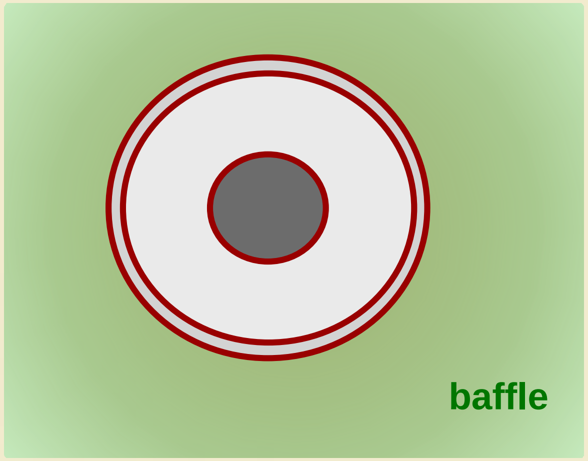
Number of Coefficients:

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

only even N:

$$N = 0,2,4,6, \ldots$$





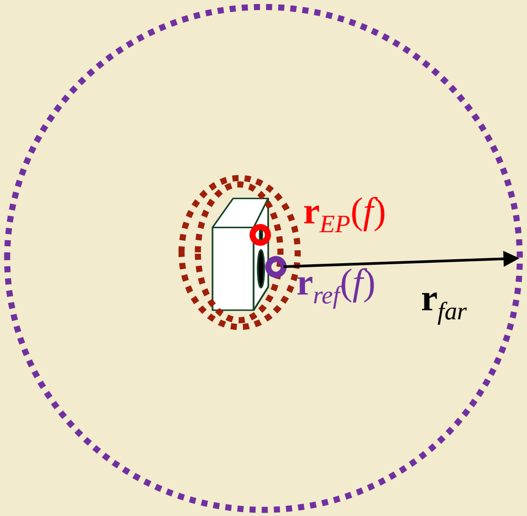
Reduction of Scanning Effort

Example: wave expansion with maximum order N=30

Symmetry	Number of Coefficients	Reduction of measurement samples
No Symmetry	961	0 %
Baffle Symmetry	496	48 %
Single plane symmetry	496	48 %
Dual plane symmetry	256	73 %
Rotational symmetry	31	97 %
Single plane symmetry + Baffle Symmetry	256	73 %
Dual plane symmetry + Baffle Symmetry	136	86 %
Rotational + Baffle	16	98 %

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

Processing of the Far-Field Data



rotation translation

$$\mathbf{r} = \mathbf{Q}(f)^{-1}\left(\mathbf{r}_E(f) + \mathbf{r}_{ref} - \mathbf{r}_{EP}(f)\right)$$

1. Initial Expansion using an Internal Coordinate System

$$H(f,\mathbf{r}_E) = \sum_{n=0}^{N(f)} \sum_{m=-n}^{n} C_{mn}(f) \cdot h_n^{(2)}(kr_E) Y_n^m(\theta_E, \phi_E)$$

- The internal coordinate system is frequency dependent
- The origin is the expansion point $\mathbf{r}_{EP}(f)$ close to the acoustical center
- The coordinate system is rotated by matrix $\mathbf{Q}(f)$ to exploit the symmetry properties

2. Extrapolation of far field data

3. Coordinate transformation $\mathbf{r}_E \rightarrow \mathbf{r}$

4. Far field expansion using the Standard Coordinate System

$$H(f,\mathbf{r}) = \sum_{n=0}^{N'(f)} \sum_{m=-n}^{n} C'_{mn}(f) \cdot h_n^{(2)}(kr) Y_n^m(\theta, \phi)$$

- The standard coordinate system is frequency independent
- The origin (reference point $\mathbf{r}_{ref}$) and the orientation of the coordinates can be defined according to the application

Benefit: Full angular resolution with less coefficients (N‘ < N)

Far Field – where does it start ?

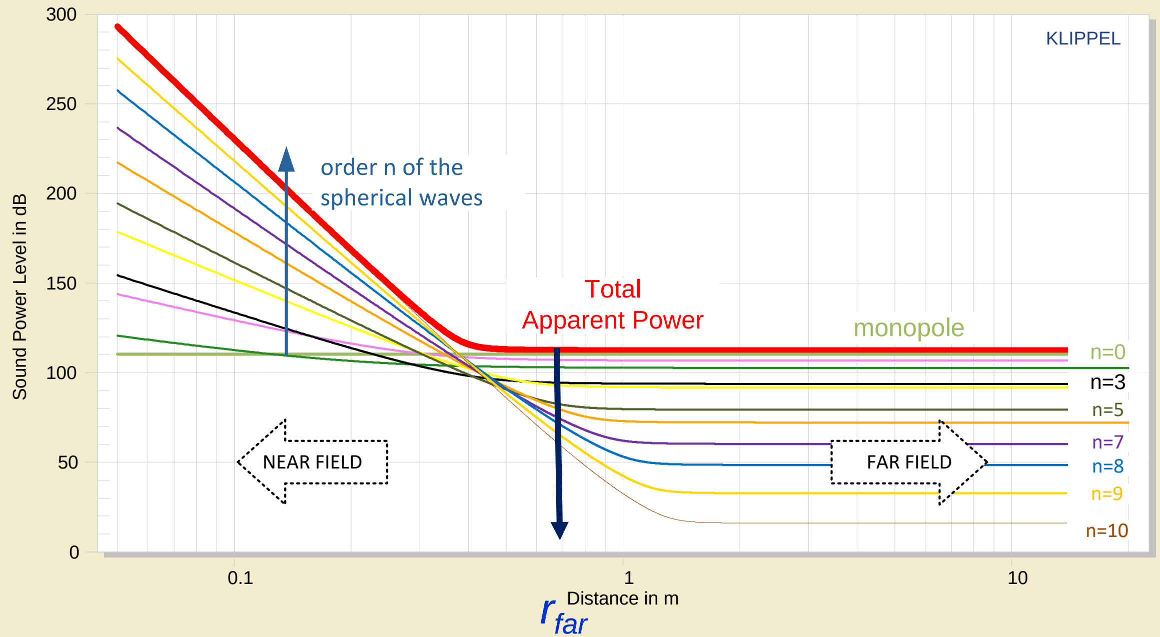
A useful characteristic for investigation the radial dependency of the sound pressure output is the **apparent power**

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

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

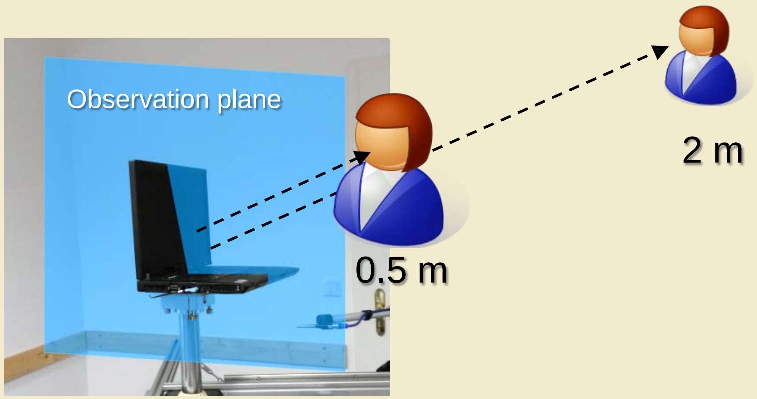
apparent power

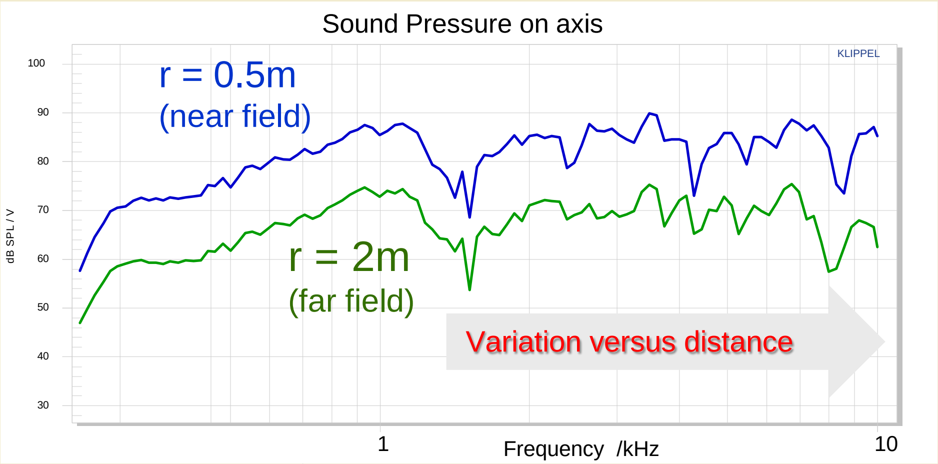
$$10\log\left(\frac{\Pi_A(f, r_{far}(f))}{\Pi(f)}\right)dB \overset{!}{=} 0.5dB$$

real power

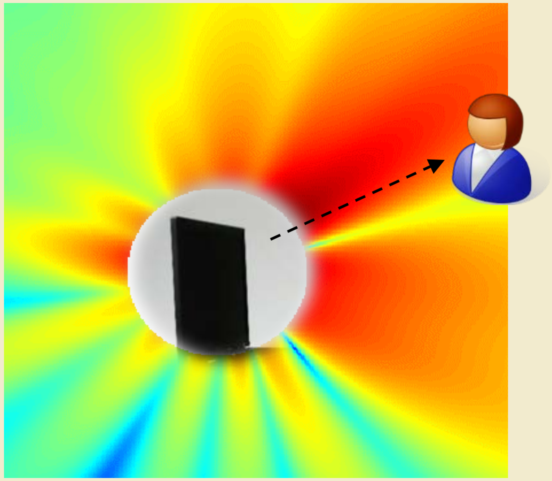
Near-field Information

is important for 3D sound effects





Sound pressure distribution (3kHz)



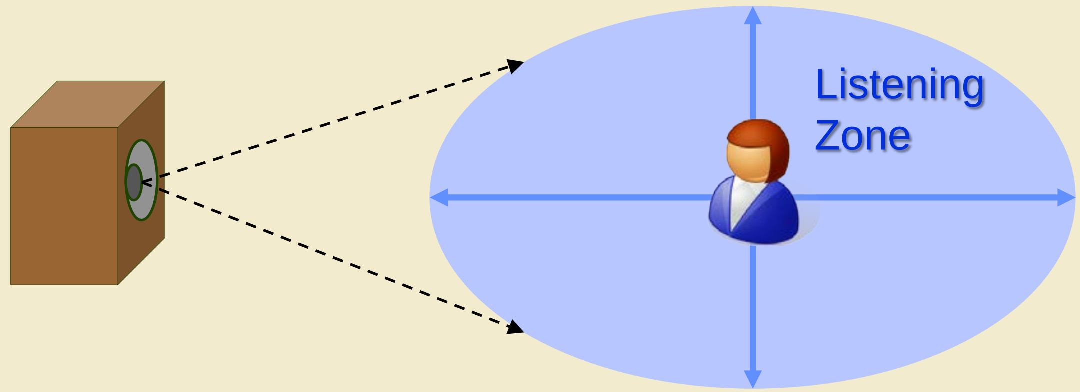
Comprehensive Information

(Amplitude) (Phase)

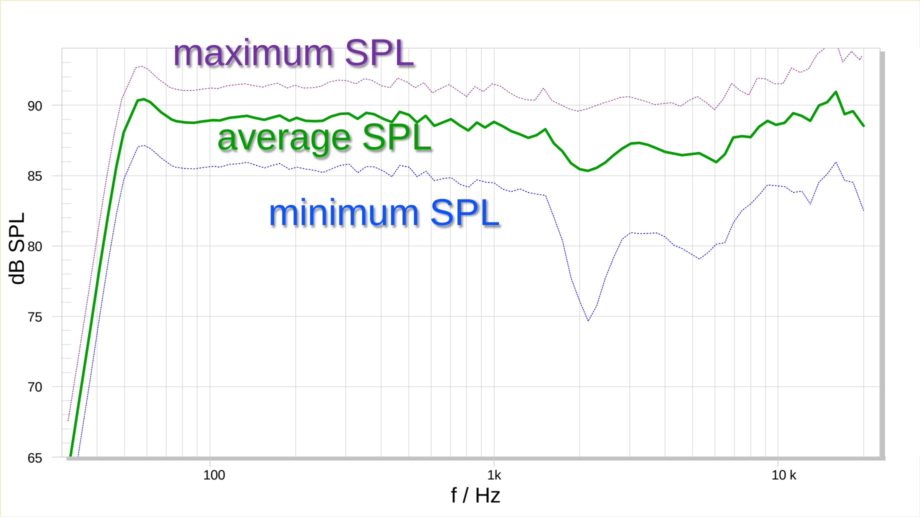
Wave front propagation (3kHz)

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

Summary

Near-field scanning + holografic wave expansion + Field separation provides the following benefits:

- More information about the acoustical output
- Sound pressure at any point outside scanning surface (complete 3D space)
- Improved accuracy compared to conventional far-field measruements (coping with room problems, gear reflections, positioning, air temperature, ...)
- Higher angular resolution with less measurement points
- Simplified handling (moving of heavy loudspeakers)
- Dispenses with an anechoic room
- Self-check by evaluating the fitting error
- Comprehensive data set with low redundancy