Measuring 3D Directivity of Microphones and Radiated Sound in Headsets and Hearables

Workshop
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Abstract

This workshop discusses practical approaches for automated measurement of three-dimensional audio directivity information in product development of modern head-worn personal audio devices. It focuses on the primary acoustic data, such as microphone response, that is crucial input data for effective DSP algorithms. In addition to measuring directivity patterns of individual microphones integrated in distributed microphone arrays, this workshop also addresses smart approaches for testing and evaluating near-field sound radiation like acoustic leakage.

Modern digital headsets such as true wireless earphones or so-called hearables, the bridging devices between consumer products and hearing aids, are much more than just miniature speakers with a microphone attached to them. In addition to simply playing music and providing hands-free telephony, such devices are more and more becoming personal assistants for an augmented reality experience.

Acoustically relevant components are especially critical because sophisticated DSP algorithms (active noise control (ANC), ambient awareness, speech enhancement, voice service interaction, etc.) rely on meaningful acoustic input data to capture both the user as well as the constantly changing three-dimensional environment in order to provide optimal overall performance and user experience.

Multiple miniature microphones (e.g. MEMS) may be accommodated in a small audio device or even distributed over various interacting wearable devices (e.g. smart glasses) in order to provide the required distributed primary acoustic data for high-level algorithms that exploit directivity information (e.g. time of arrival for beam steering).

For the R&D engineer, this is a complex challenge, and therefore it is crucial to focus on the mechano-acoustical design problems before integrating and tuning multi-channel DSP algorithms.

Outline

- Motivation
- Part 1: Sound Radiation & Acoustic Leakage
  - Conventional methods for directivity measurement of sound sources
  - limitations for head-worn personal audio devices
  - Near-field scanning using holographic methods
  - Example: Radiated sound pressure of semi-open back headphone
- Part 2: Sound Reception (Microphones)
  - Conventional methods for microphone directivity scanning
  - 3D scanning approach of head-worn device microphone response
  - Interpolation using spherical harmonics
  - Example: MEMS microphone for in-ear and over-ear headphones
- Conclusions

Directivity in Head-Worn Audio Devices

Sound Radiation and Acoustical Leakage

Root Causes of Radiated Sound

- Undesired leakage
  - Leakage through ear cushion or ear piece
  - Insufficient attenuation of enclosure
- Leakage by design
  - (Semi)-open back electrodynamic headphones
  - electrostatic headphones
- Intentional radiation in personal near-field audio devices
  - Smart glasses with integrated speakers
  - Off-ear headphones
  - Neck-worn personal audio speakers

Why quantifying directive SPL output?

- Privacy of content and communication
- Disturbance in calm environment like work space
- Undesired feedback to microphones in duplex mode (echo)
- Impairment of microphone input based DSP algorithms

JBL Soundgear

Valve Index®

STAX Lambda

Directivity in Head-Worn Audio Devices

Sound Reception: Microphone Directivity

Miniature microphones and arrays are applied for

- Personal voice capture
  - Voice service control
  - Communication/Telephony
- Ambient sound-based DSP algorithms such as
  - Active noise cancelation
  - Source separation, beam steering
  - Augmented reality
  - Ambient awareness
  - Speech enhancement
  - Echo cancelation

→ precise measurement of raw 3D directivity of the individual microphones integrated in the device is required for optimal tuning of DSP algorithms

Magic Leap 1

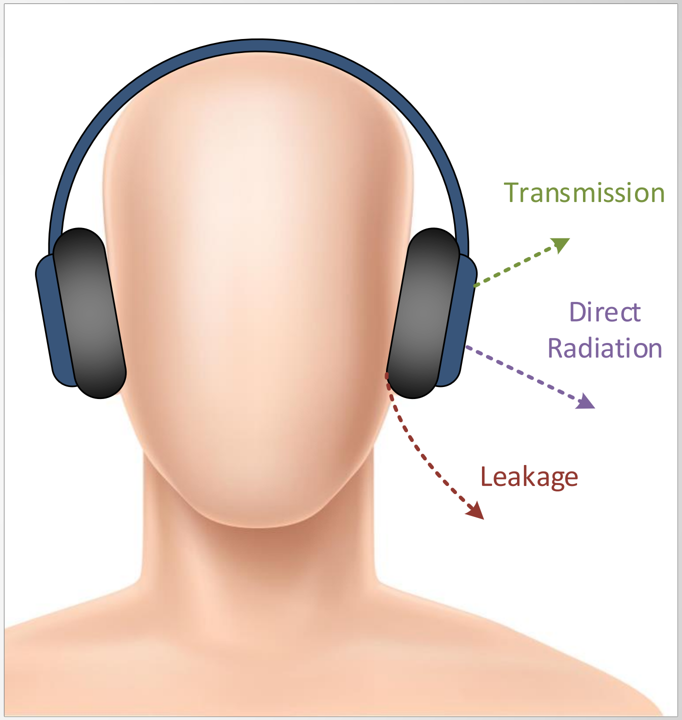
Bose Headphone 700

Part 1: Sound Radiation

Radiated Sound of Head-Worn Devices

Important Questions

- How is the sound pressure distributed in direct proximity of the device?
- How does the SPL change with distance?
- How directive is the SPL output?
- Which frequencies are radiated?
- Where is the sound radiated?



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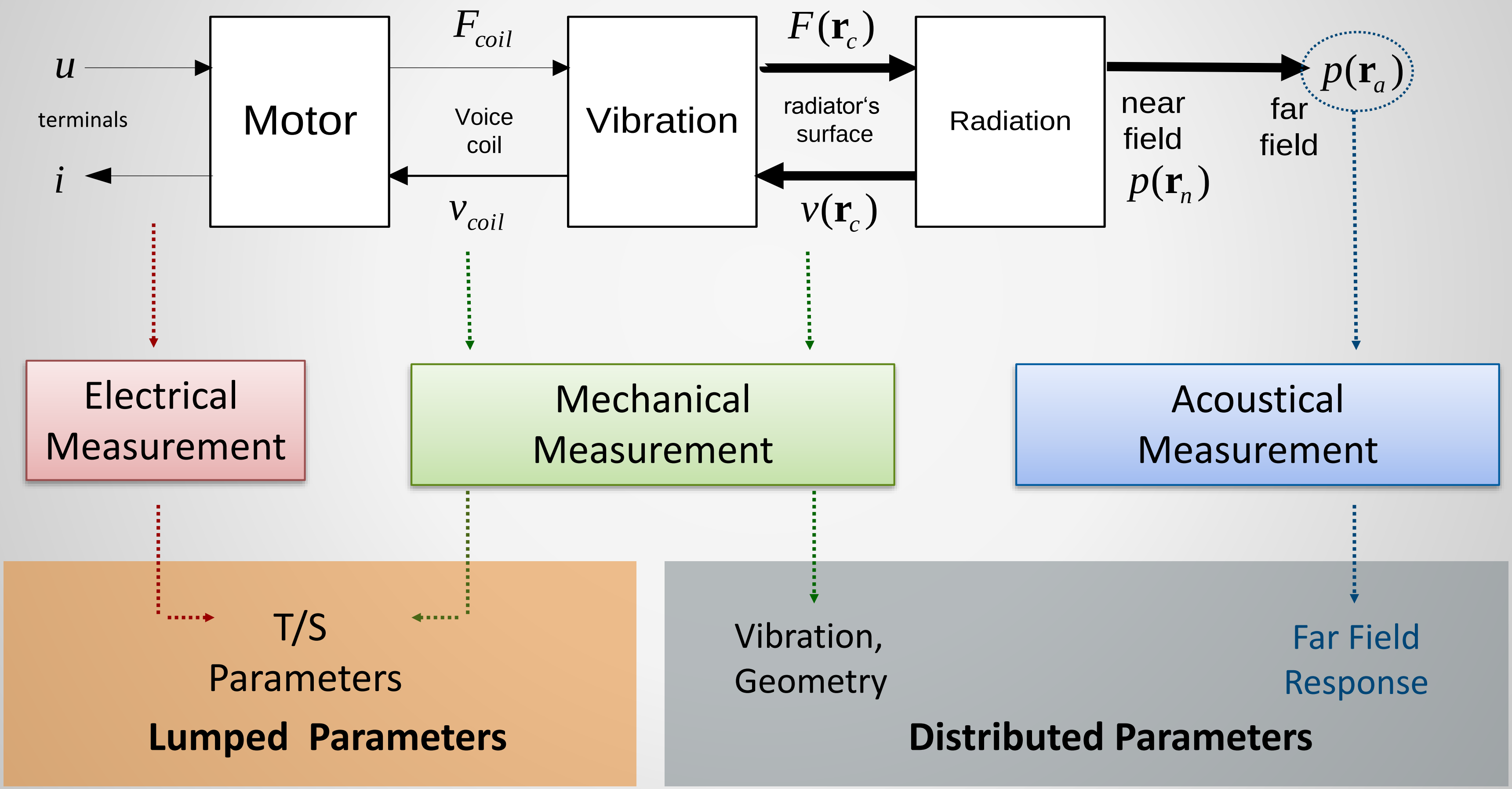
Audio System Measurements

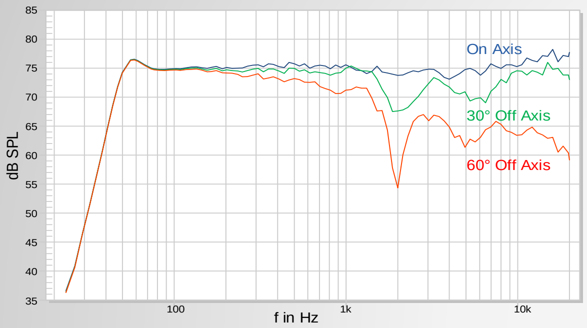
Assessing Small Signal Performance



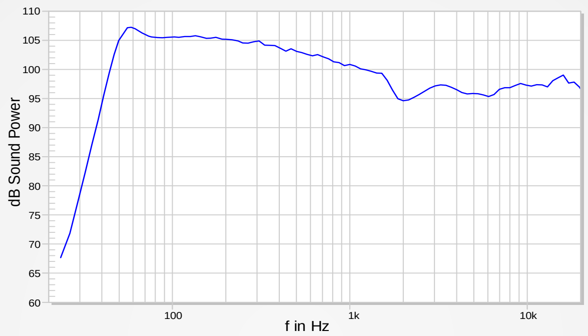
Sound Radiation

Far Field Characteristics

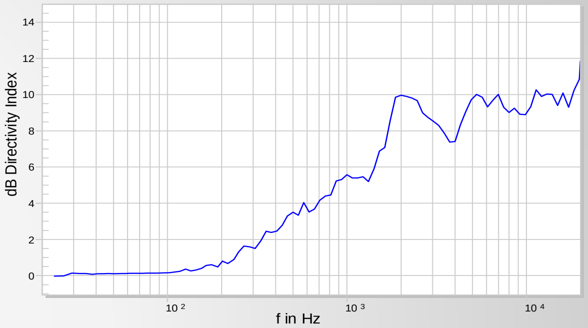
Frequency Response

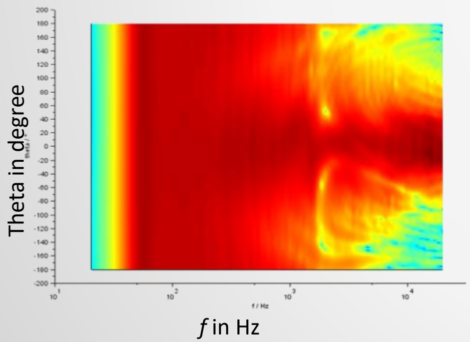


Sound Power

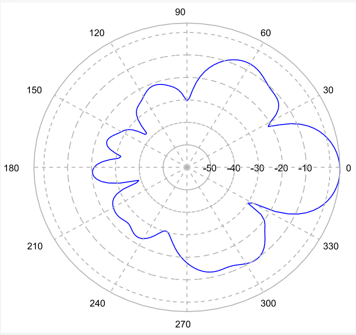


Directivity Index

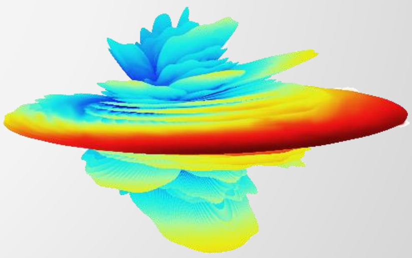




Contour Plot

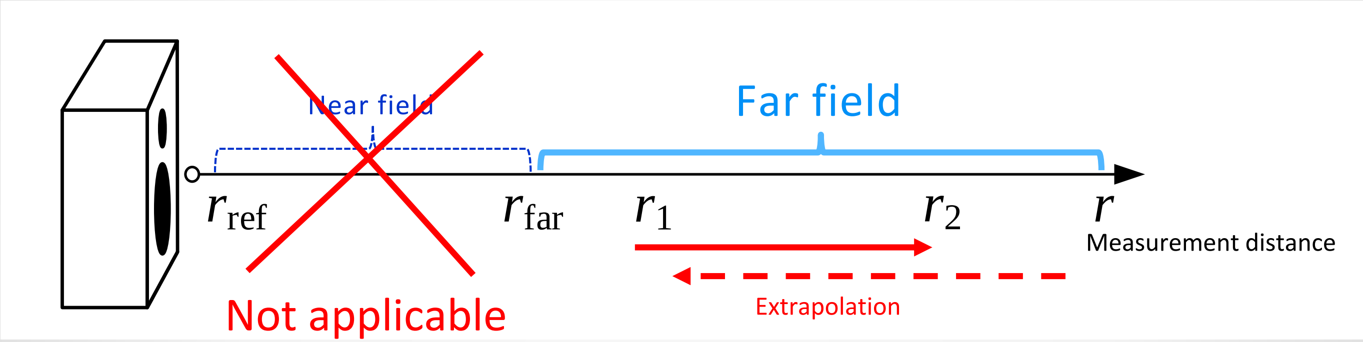


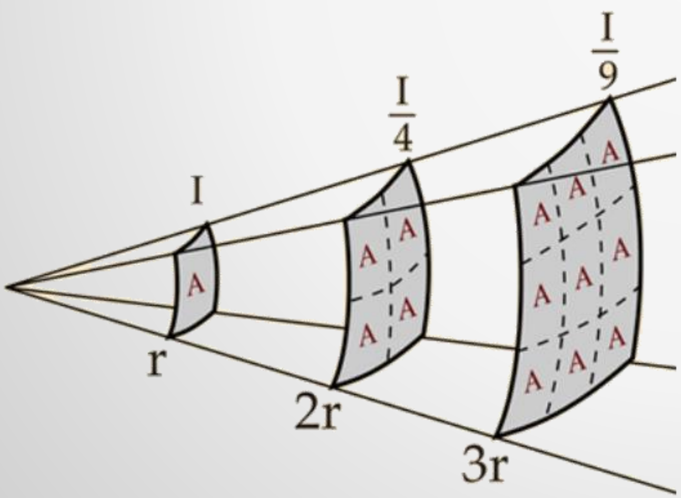
Polar Plot



Directivity Balloon

Extrapolation of Far Field Data





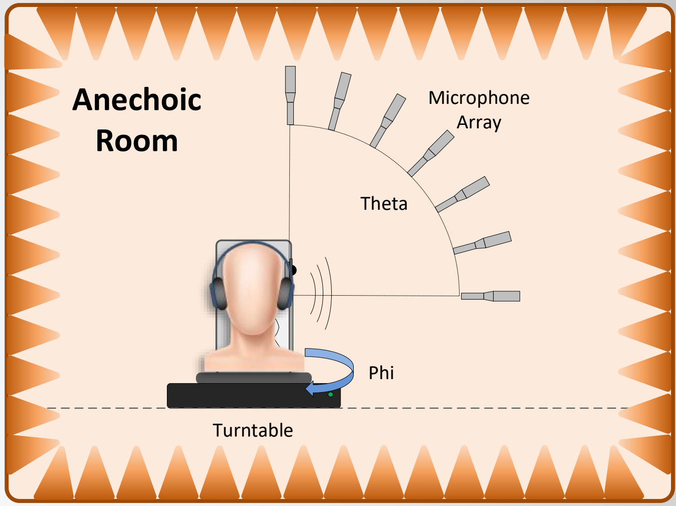
$$\boxed{\underline{H}(f, r_2, \theta, \phi) = \underline{H}(f, r_1, \theta, \phi)\frac{r_1}{r_2}e^{-jk(r_2 - r_1)}}$$

Requirements:

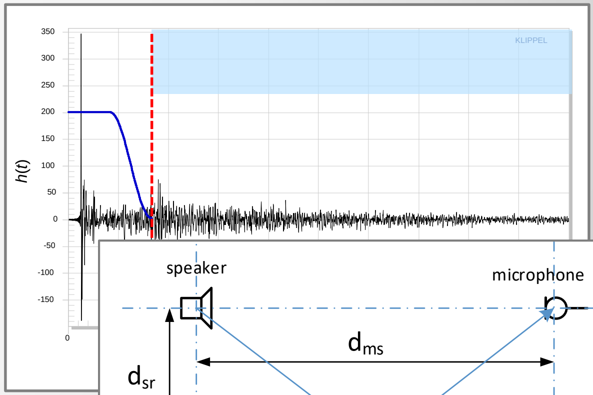
- free field condition (direct sound)
- *far field condition*
- same direction ($\phi_2 = \phi_1$, $\theta_2 = \theta_1$)

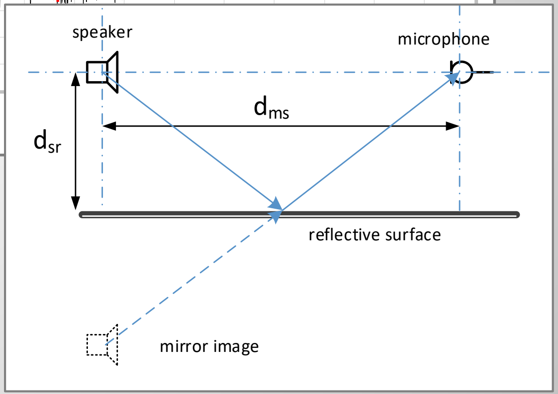
Conventional Far-Field Measurements

- In anechoic chambers
  (1930's, Beranek and Sleeper 1946)
  - Realized as a half or full space
  - Good absorption of room reflections (> 100 Hz)
  - High ambient noise isolation
  - Controlled climate conditions and avoids wind effects



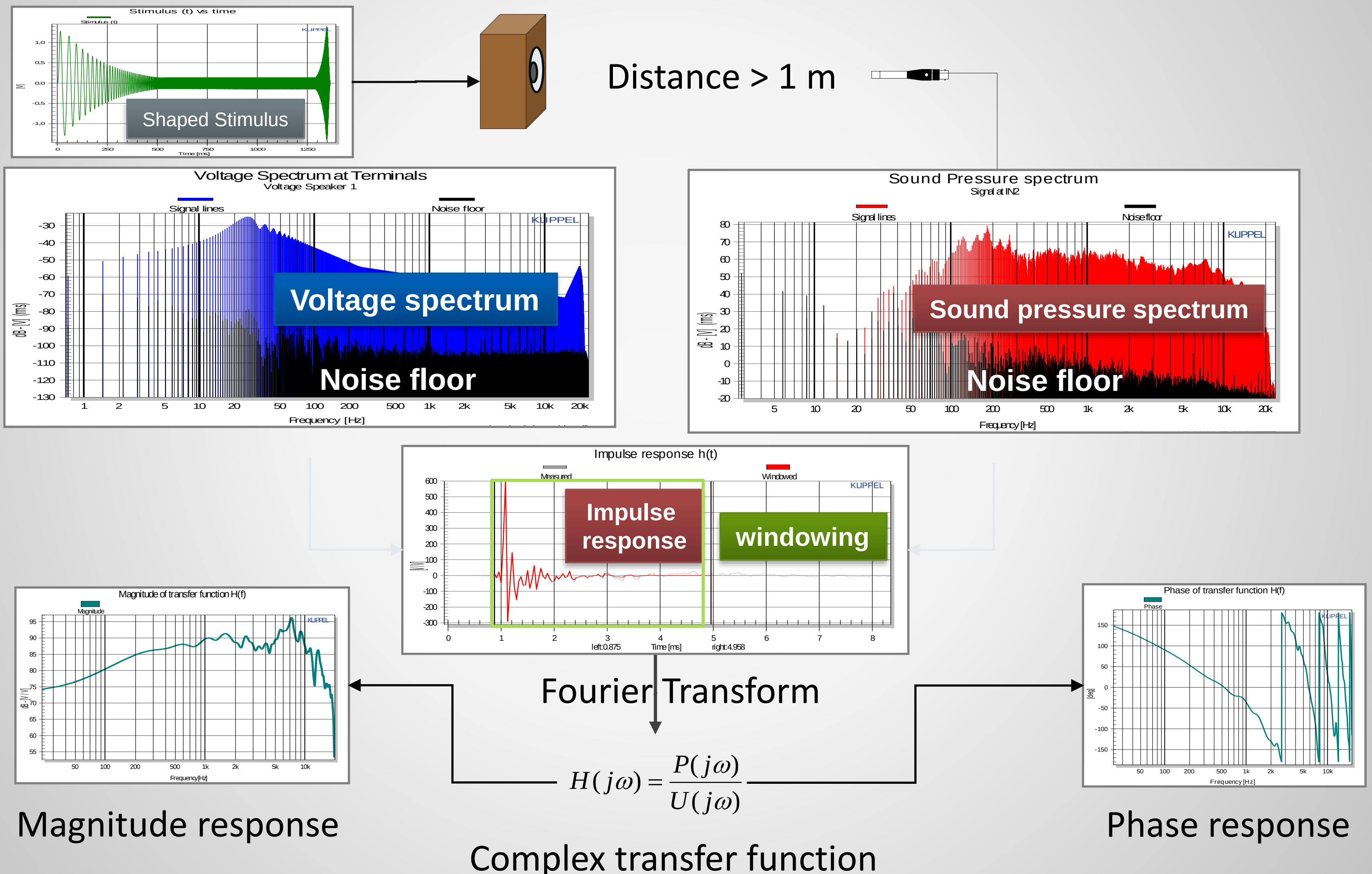
- Under simulated free-field conditions by gating or windowing the impulse response
  (Heyser 1967-69, Berman and Fincham 1973)
  - Good suppression of room reflections at higher frequencies
  - Higher SNR due to ambient noise separation
  - Limited low frequency resolution (depends on time difference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





Are those methods applicable for indirect radiation of personal audio devices?

Measurement of Far Field Response



Conventional Far Field Methods

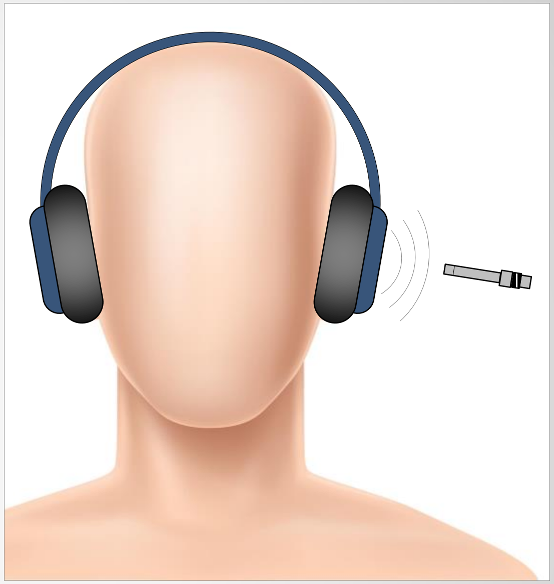
Drawbacks for Personal Audio Devices and Headphones

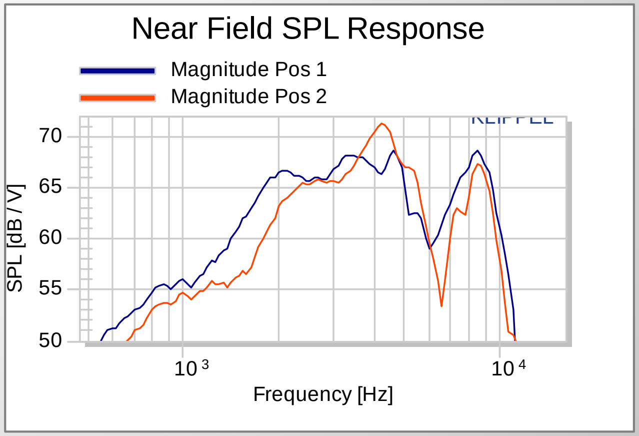
- Anechoic room required (time windowing possible for higher frequencies)
- Angular resolution directly related to measured grid and thus time (e.g. sphere with 1° resolution → 64800 points – not practical)
- Accuracy of measurement depends on:
  - tolerance of microphone placement (both θ and r)
  - DUT positioning while maintaining the acoustic center
  - Sound reflections from turntable
  - Room absorption irregularities
  - temperature deviations and air movement
- Signal-to-noise ratio in far-field is too low for sources with low SPL output due to
  - Sound attenuation of air and inverse square law
  - Superposition of ambient noise disturbance (e.g. fan noise)
- Far-field data is not really of interest, but near-field SPL distribution closer to the device

Near Field Measurement

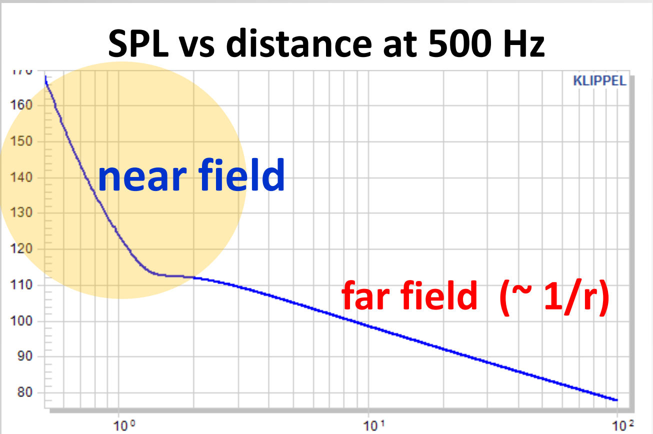
Conventional Method IEC 60268-7 (Unwanted Sound)

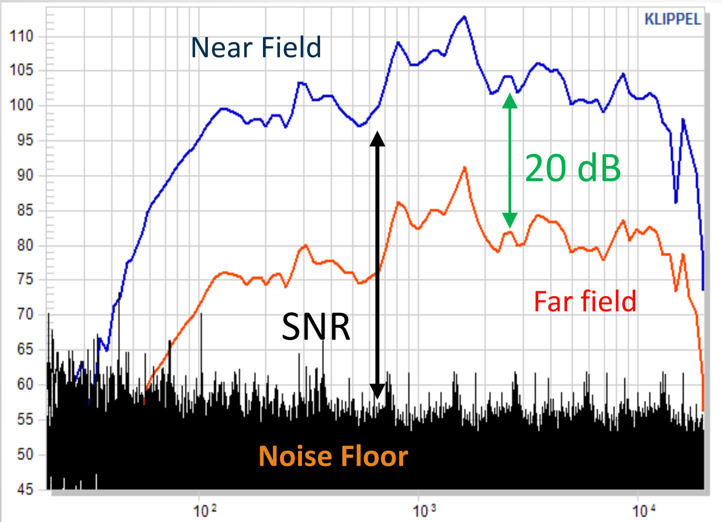
- SPL frequency response in free field at 0.1 m from the headphone on the axis in a direction opposite to that of the normal acoustic exit
- Good SNR due to low distance
- Problems:
  - Positioning is not sufficiently defined – strong dependency of frequency response on mic position (complex near field)
  - Beaming and directivity is neglected
  - No evaluation of SPL at realistic distance (second listener)
  - No sound power evaluation
  - There may be more critical test positions





Measurements in the Near Field





Advantages:

- Better SNR
- Amplitude of direct sound much greater than room reflections → good conditions for simulated free field
- Minimal influence of air properties (air convection, temperature deviations)
- Better positioning accuracy

Disadvantages:

- Not a plane wave
- Velocity and sound pressure are out of phase
- 1/r law does not apply → no sound pressure extrapolation into the far-field

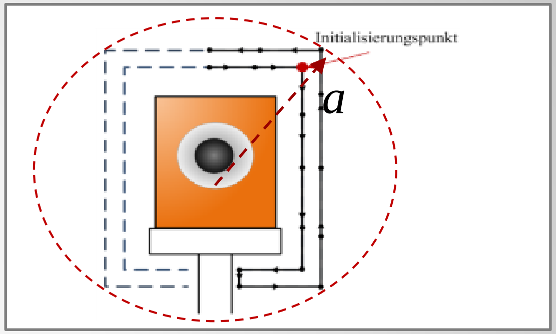
Solution → Holographic Postprocessing

Holographic Measurement

Using Spherical Waves and Hankel Functions as Basic Functions

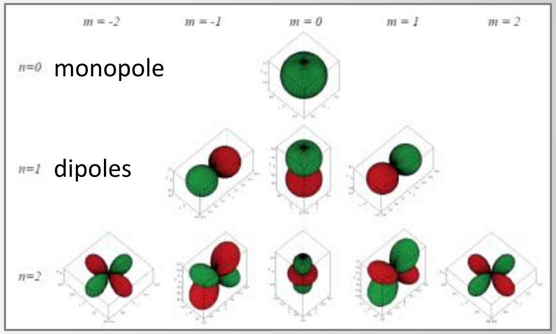
1st Step: Measurement

- Scanning the sound pressure in the near field of the source at a single or multiple surfaces



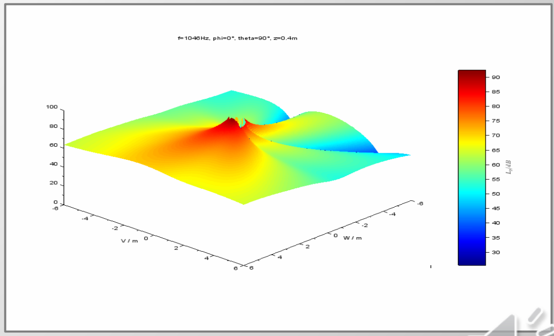
2nd Step: Holographic Data Processing

- Expansion into spherical waves using Legendre and Hankel functions
- Optimal estimation (LMS) of the free parameters of the expansion (order N(f) and coefficients C(f))

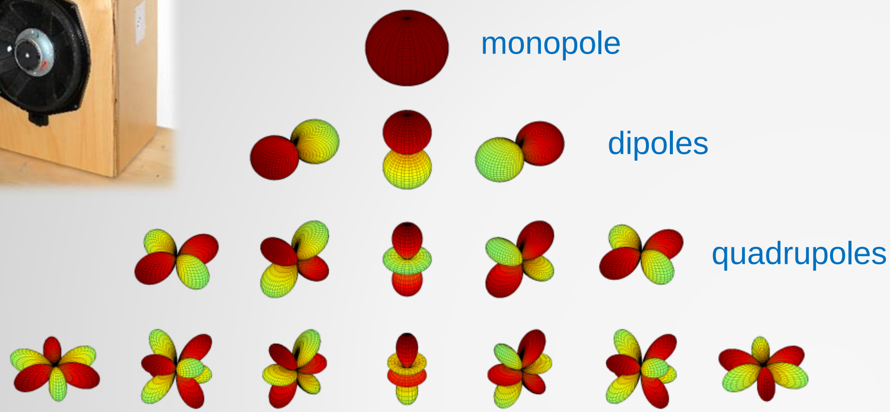


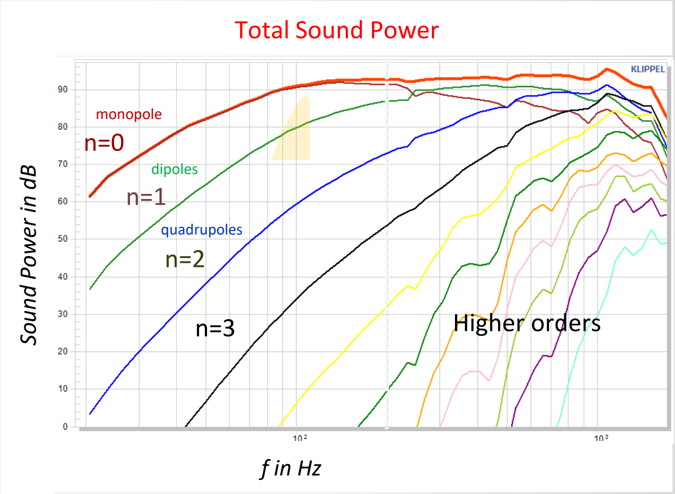
3rd Step: Extrapolation

- Calculation of the transfer function H(r,f) between input u and sound pressure p(r) at an arbitrary point r in the 3D space outside the scanning surface
- Calculation of derived characteristics (directivity, beam pattern, sound power)

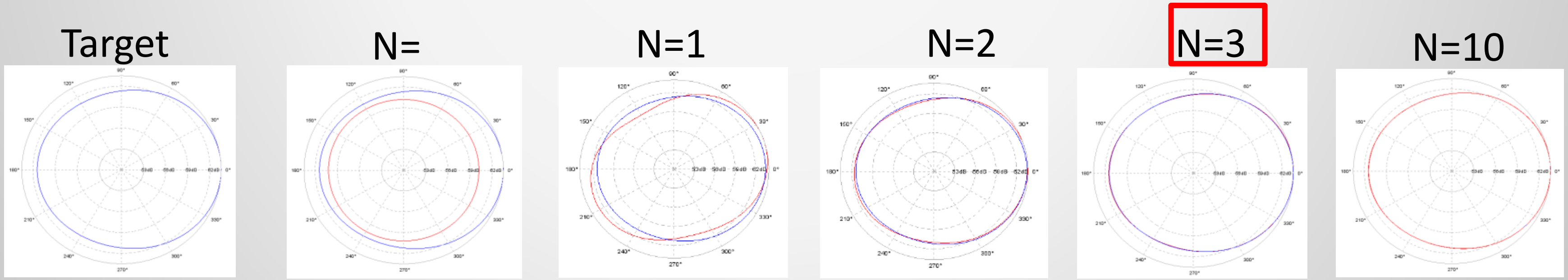


Wave Expansion of a Woofer in a Closed Box





Directivity patterns at 200 Hz:

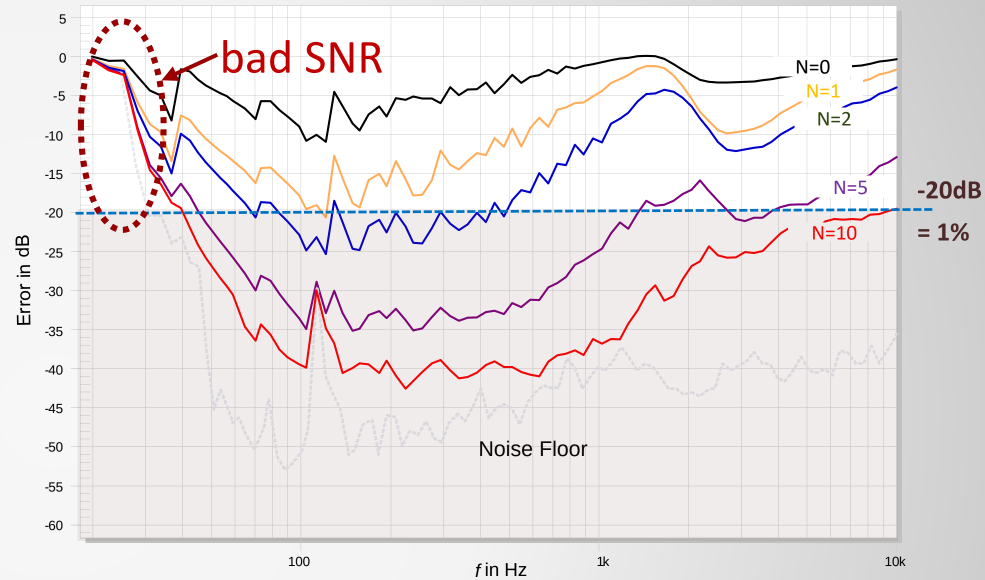


sound field is completely described by order N=3 (16 coefficients)

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

How to Find the Maximum Order N ?

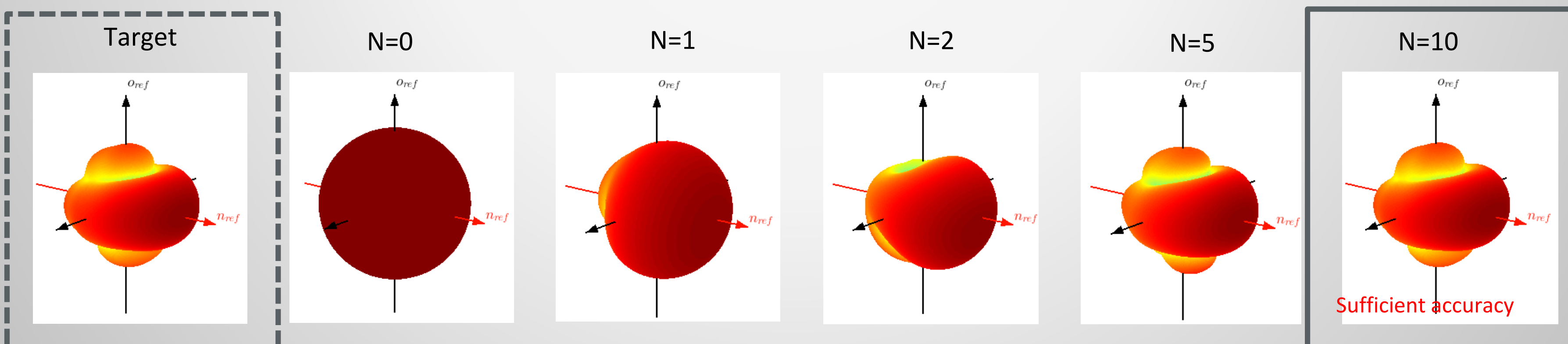
Fitting error versus maximum order N



The measurement system determines:

- optimum order N of the wave expansion
- total number of the measurement points

Directivity at 2kHz:



How Many Points Need to be Measured ?

Number of points	Application
1	*On-axis response*
	Sound power
100	
	Directivity
	Professional
1000	

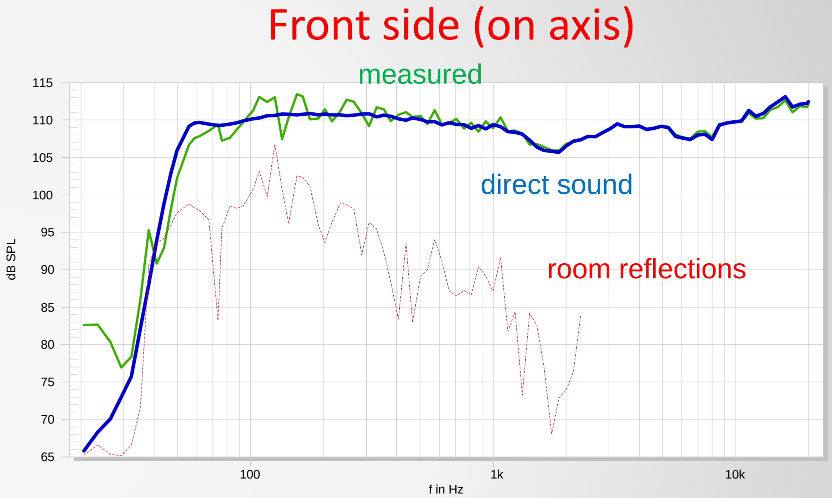
Benefit of using a Spherical Wave Expansion:
Number of measurements points M required is **much lower** than the final angular resolution of the calculated directivity pattern !

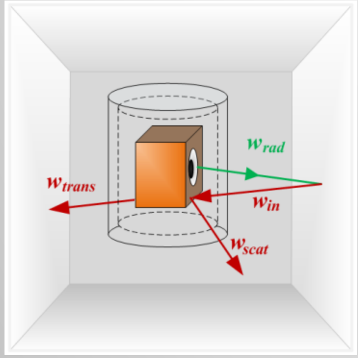
Number of points M depends on:

- Total number of **coefficients** J in the expansion (M>1.5J)
- Maximum **order** 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 separation (non-anechoic conditions)

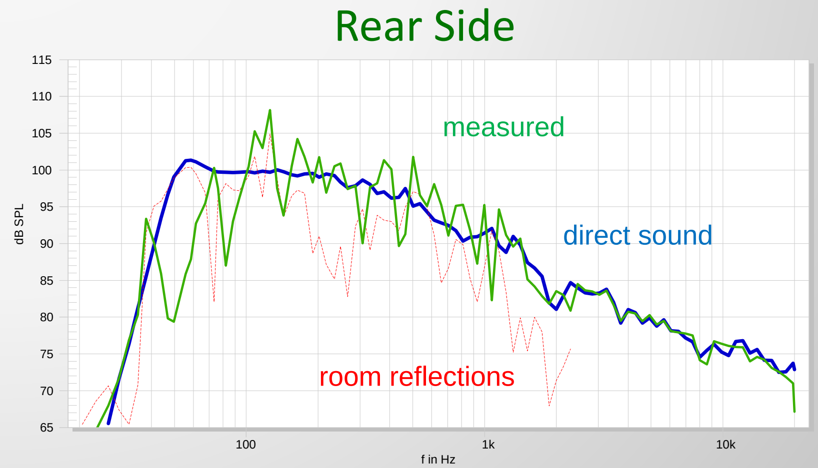
Sound Pressure Response

Measured in a Normal Office





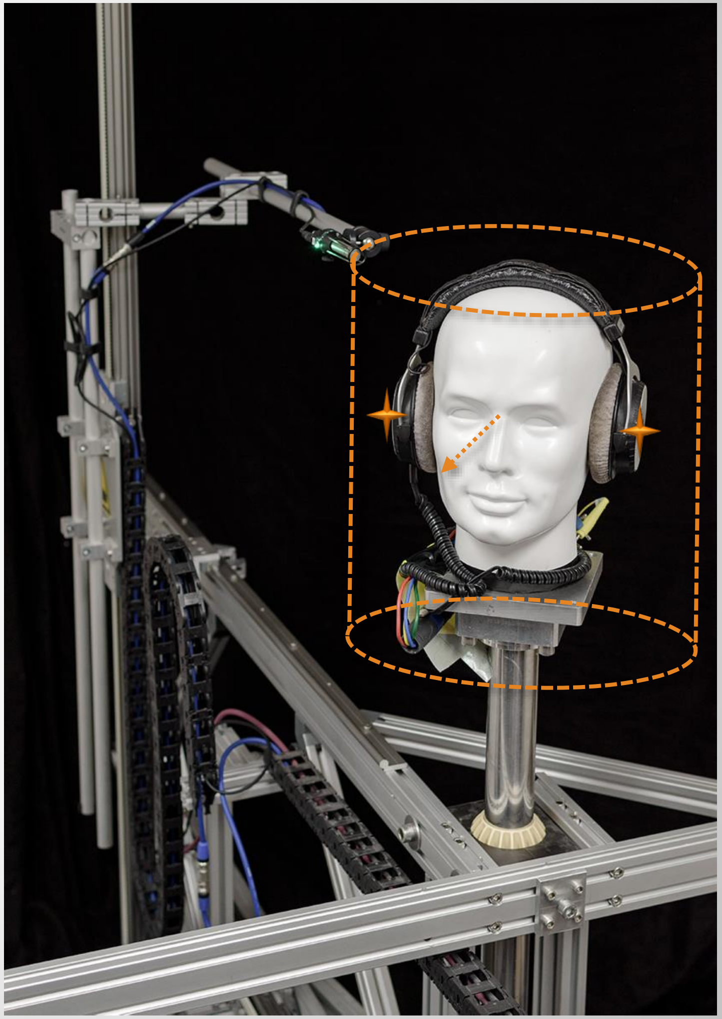
Double layer scanning + holographic processing allows to separate the direct sound from room reflections



Headphone Near Field Radiation Scan

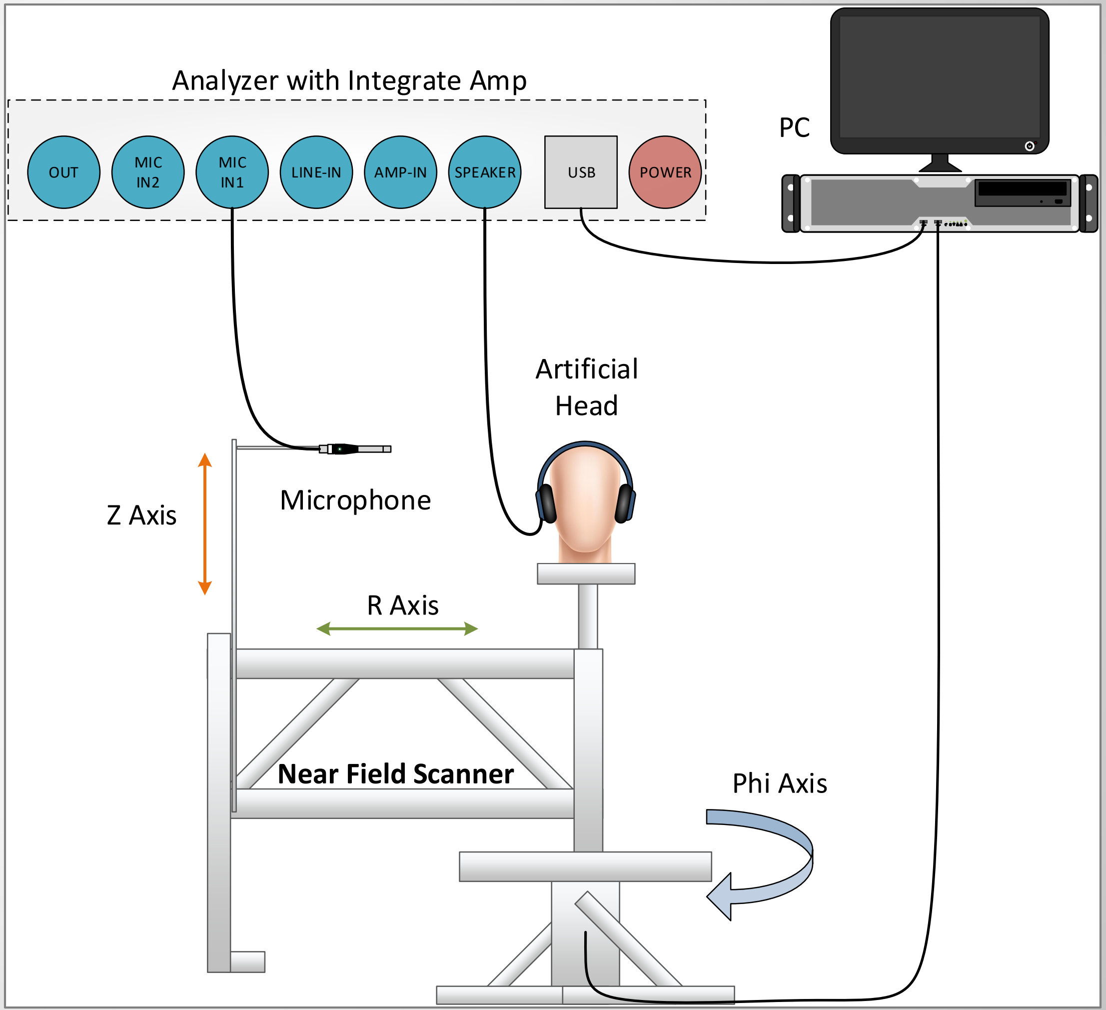
Example: Semi-open HiFi Headphone (DT 880)

- Near field scanning in normal office room
  - IR gating > 2kHz
  - field separation < 2kHz
- Headphone mounted on simple artificial head (alternatively use HATS)
- Separate scanning of left and right channel (superposition)
- Development points at ear pieces; reference vector above nose, between eyes
- Scanning radius (cylinder): ~ 40 cm
- Number of points: 500 (x2 for 2^{nd} layer)
- Scan duration: ~ 1 h (2 h)
- Spherical development order: <20
- Sweep time: 340 ms
- Averaging per point (SNR): 8x



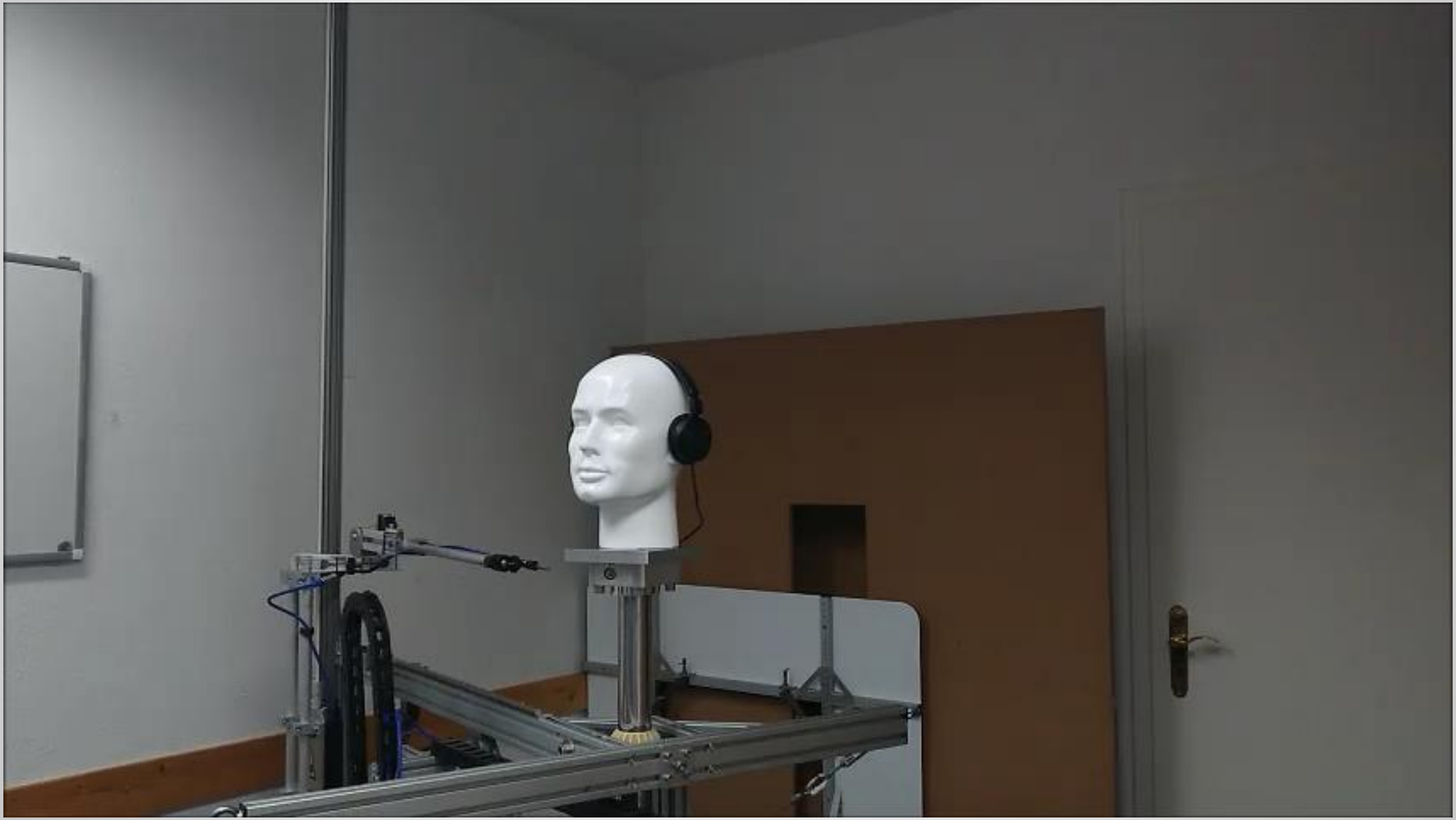
Headphone Radiation Directivity Scanning

Hardware Setup

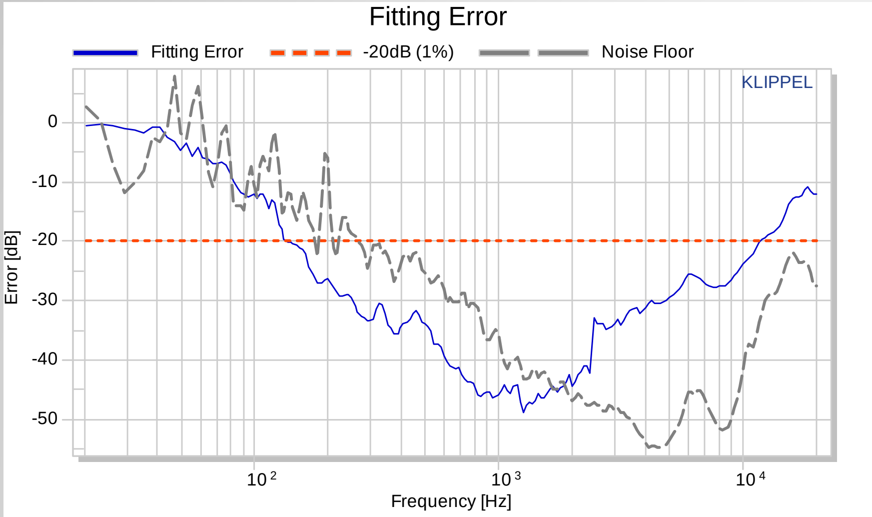


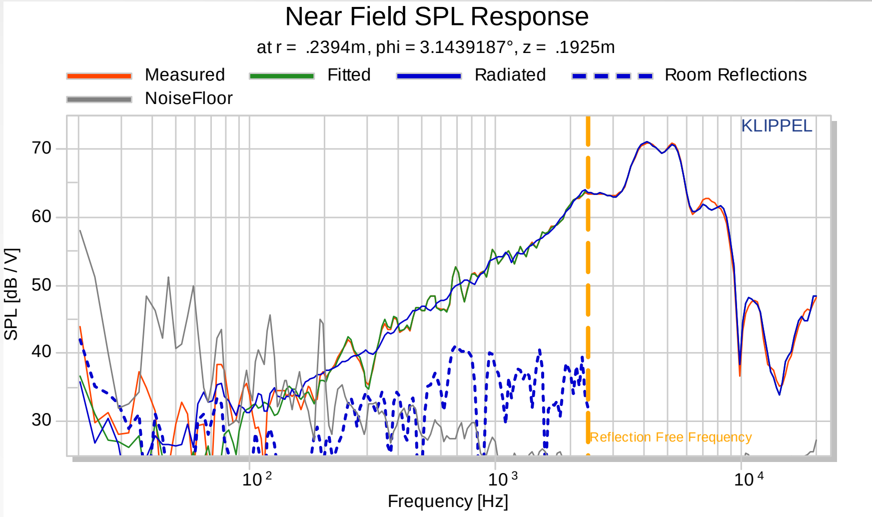
Headphone Radiation Directivity Scanning

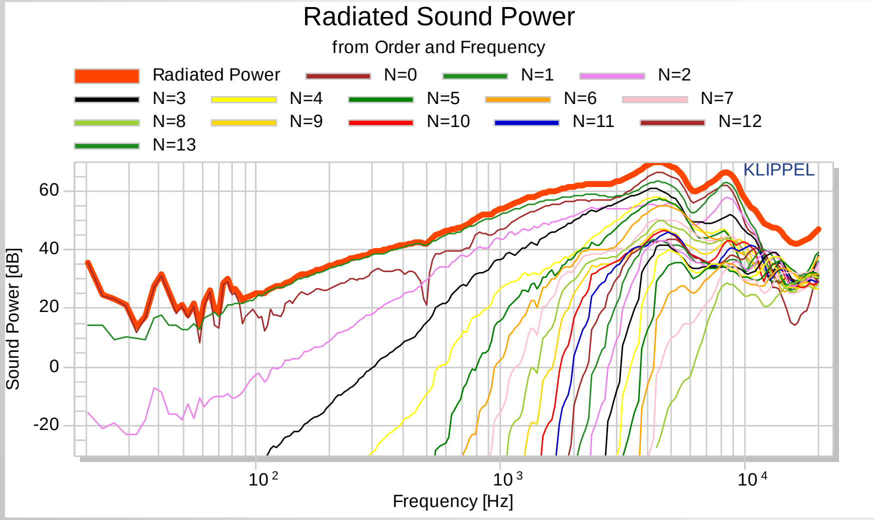
NFS Timelapse (Different Headphone Model)

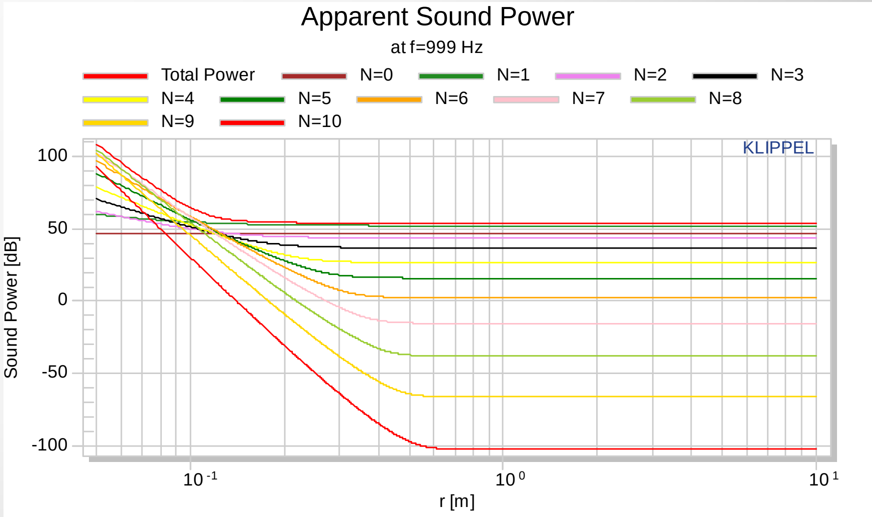


Field Identification Metrics



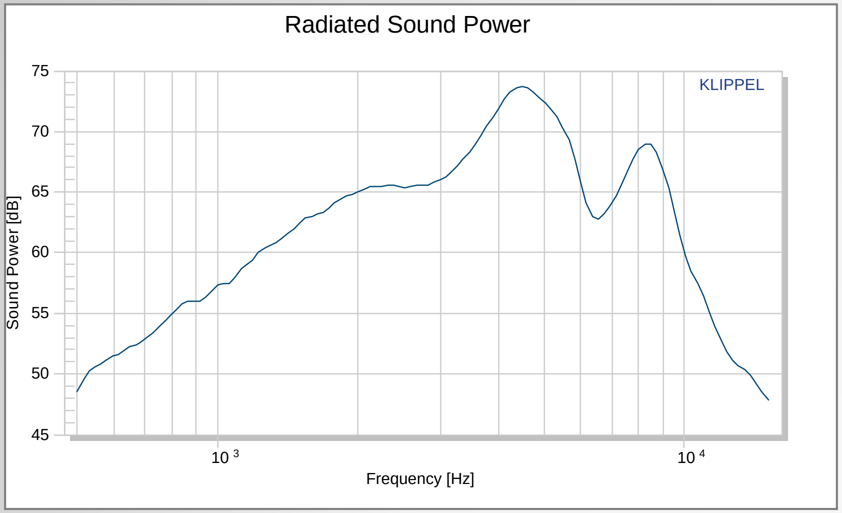


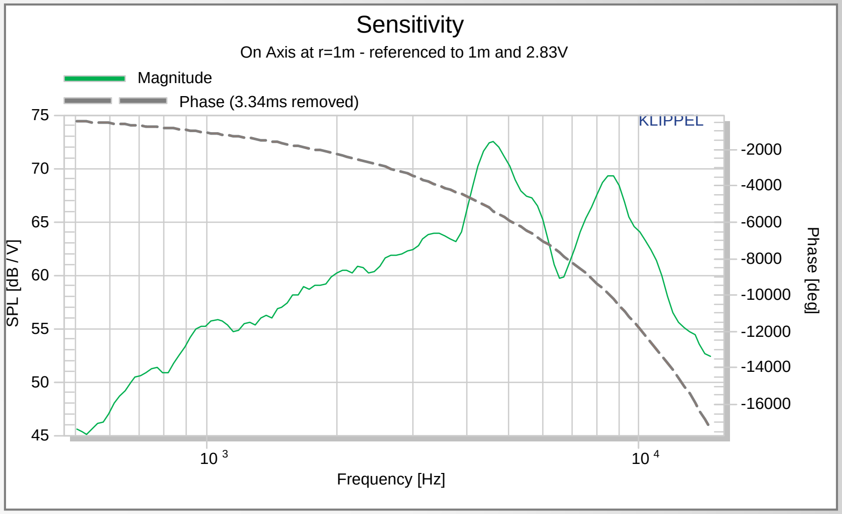


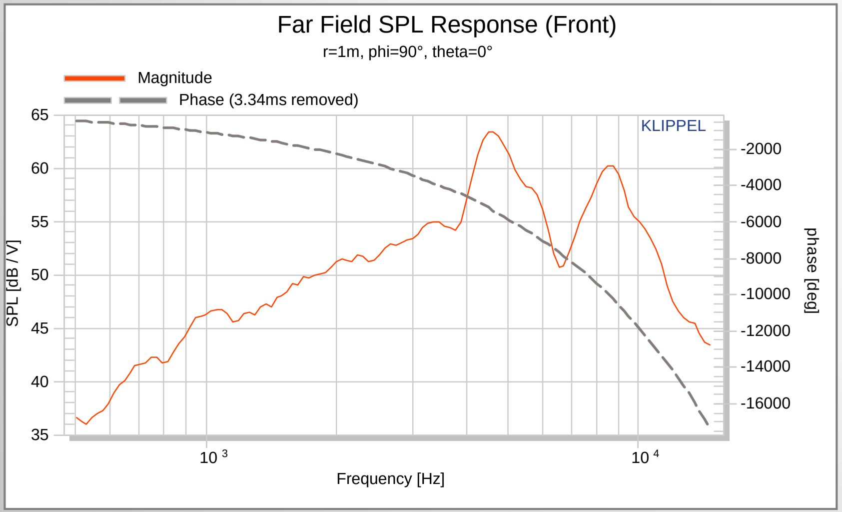


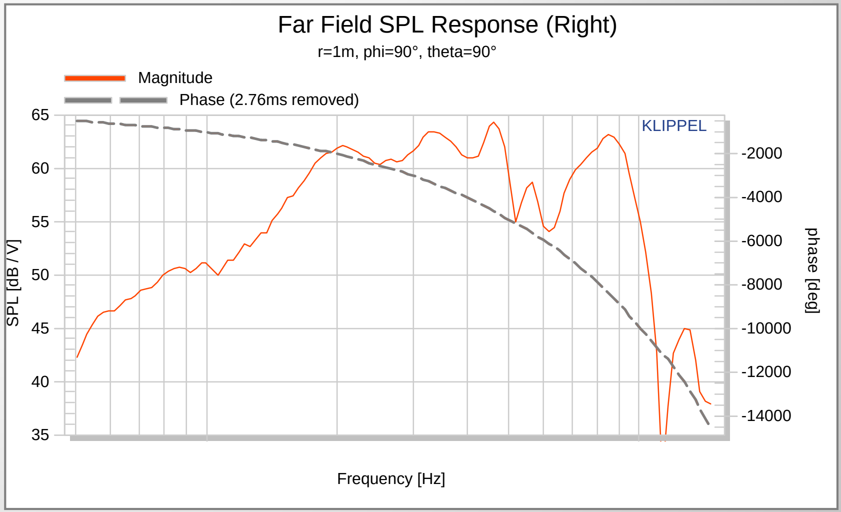
Far Field Data

Sound Power, Sensitivity



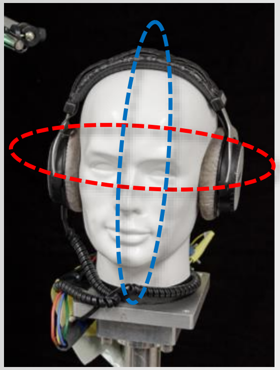


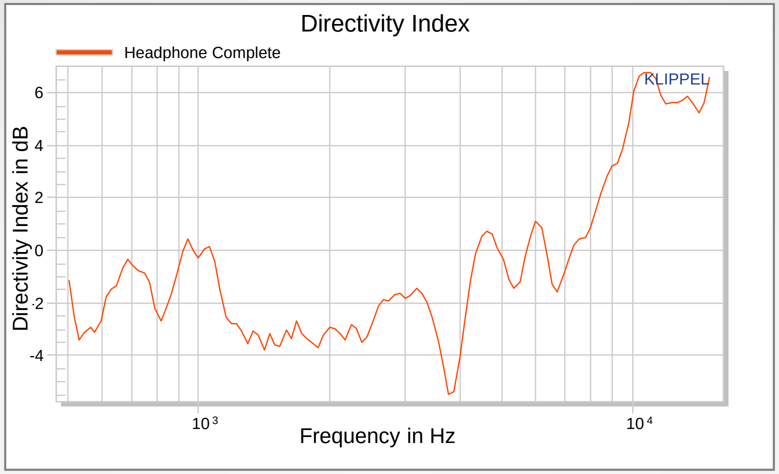


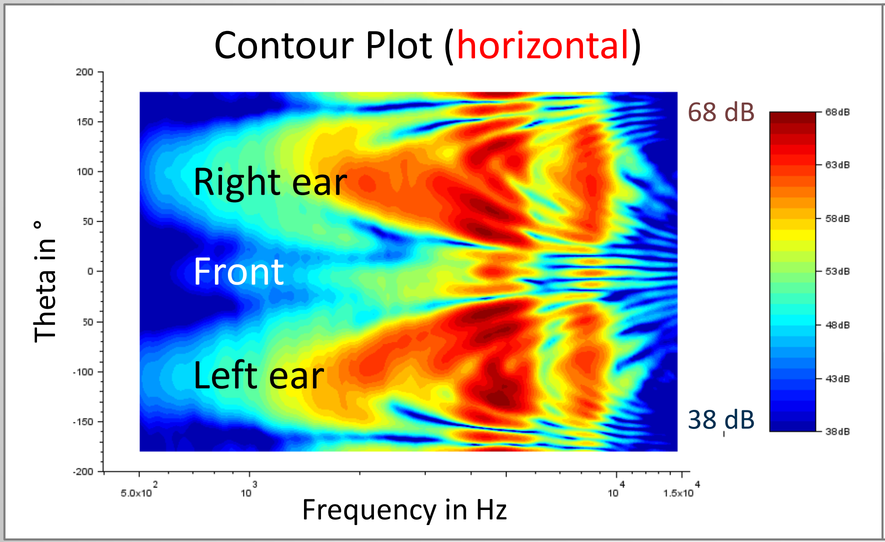


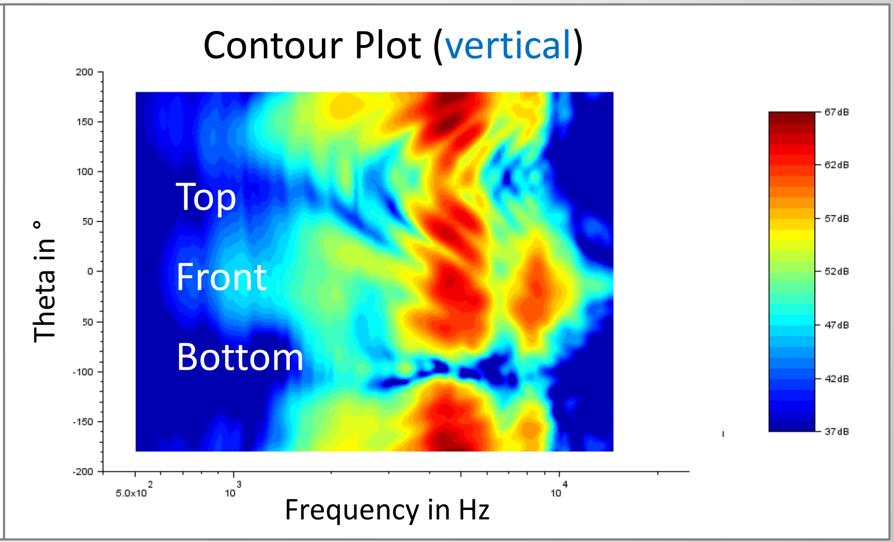
Far Field Data

Directivity Index, Contour Plots (1 m)





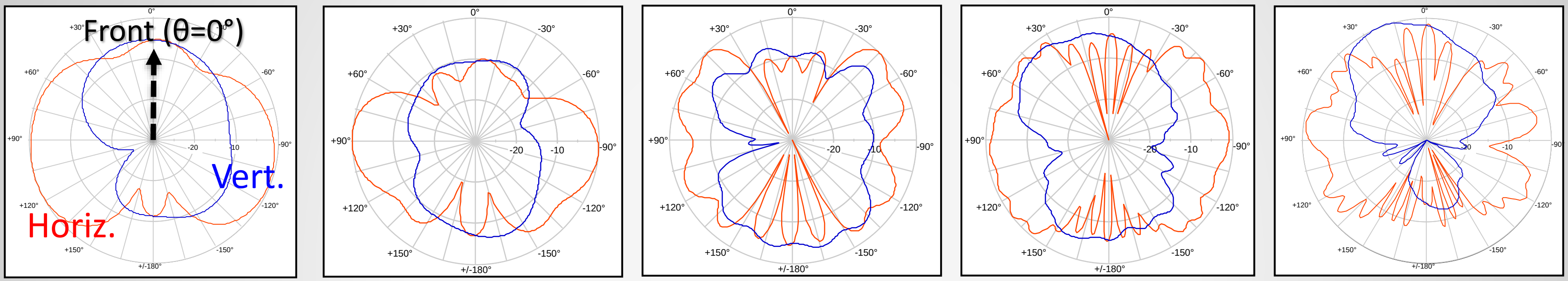


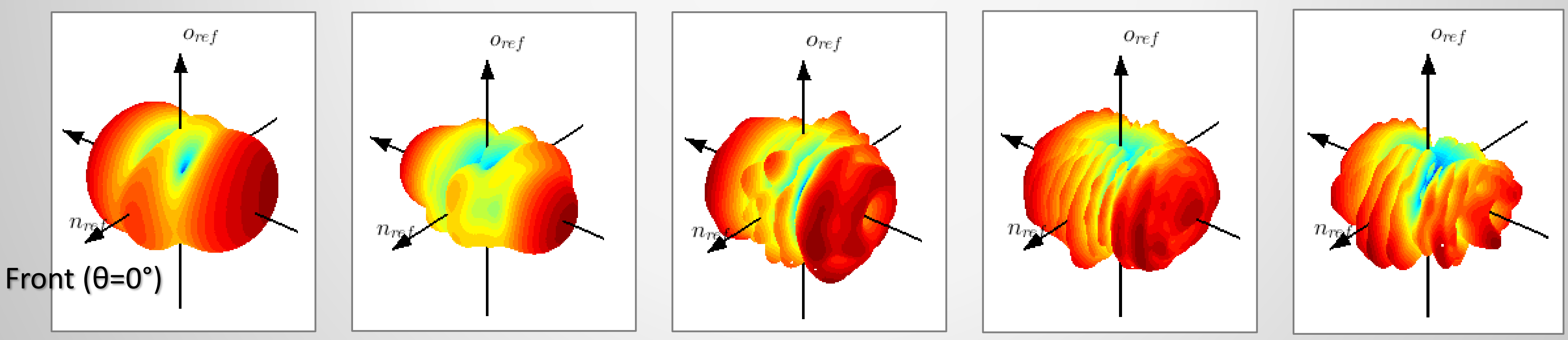


Far Field Data

Polar and Balloon Plots vs Frequency (1 m)

1 kHz | 2 kHz | 4 kHz | 8 kHz | 10 kHz

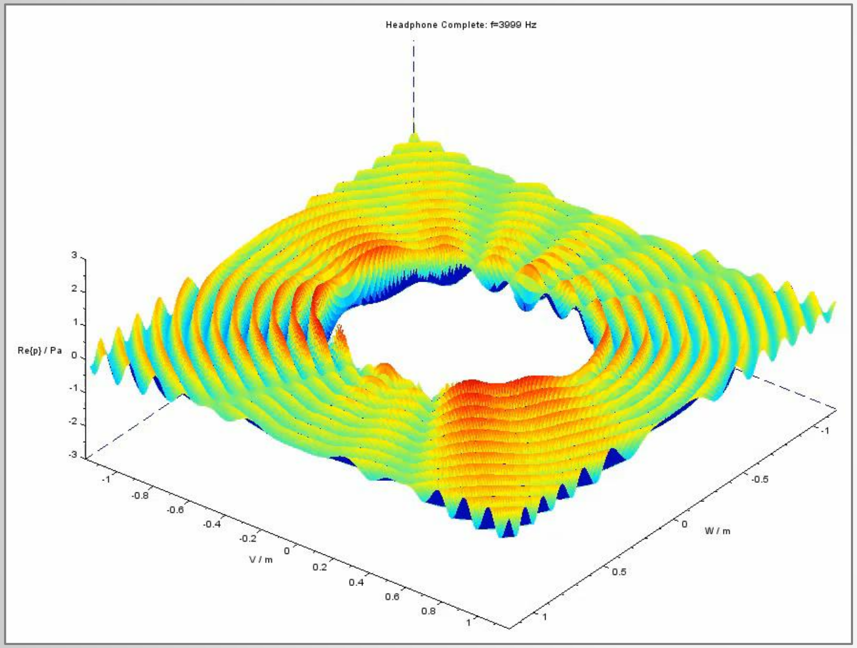




3D Near Field Data

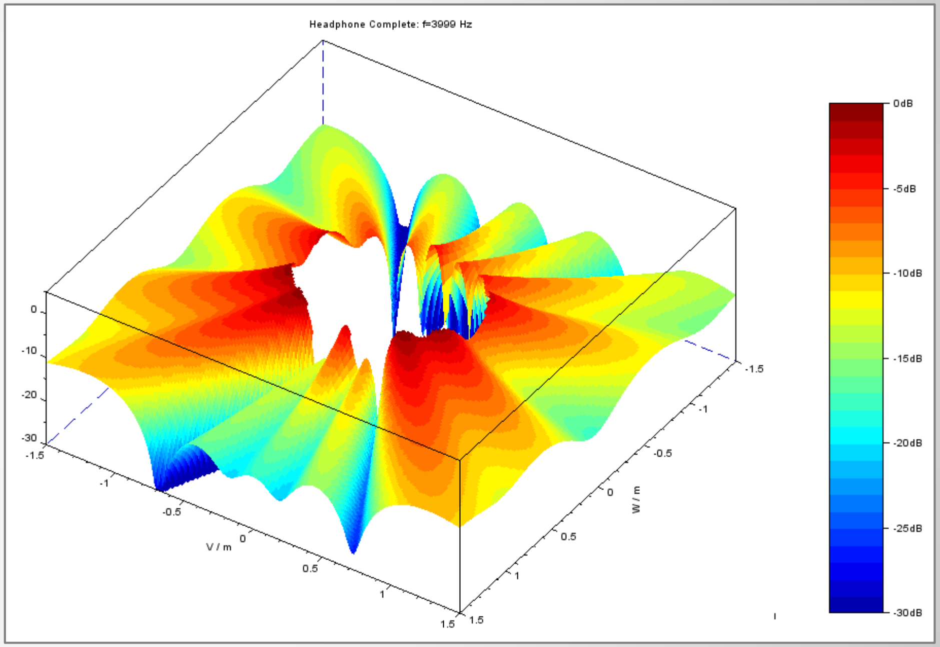
Horizontal Plane (Top View) @ 4 kHz

Wave Propagation



1 m x 1 m

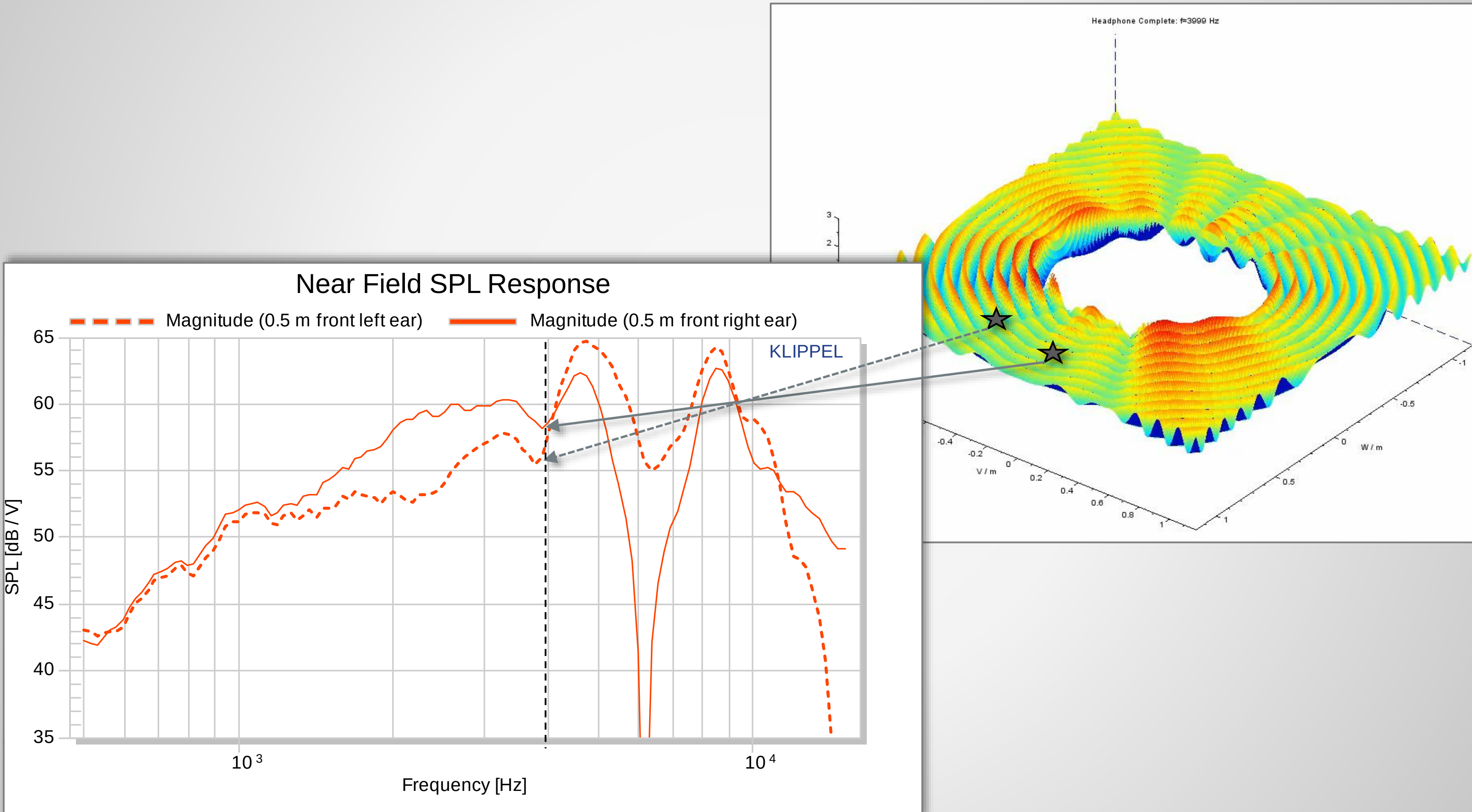
SPL Distribution



1.5 m x 1.5 m

3D Near Field Data

SPL Magnitude/Phase Response at Any Distance and Angle



Part 2: Sound Reception

Capturing Sound with Wearable Devices

Important Questions

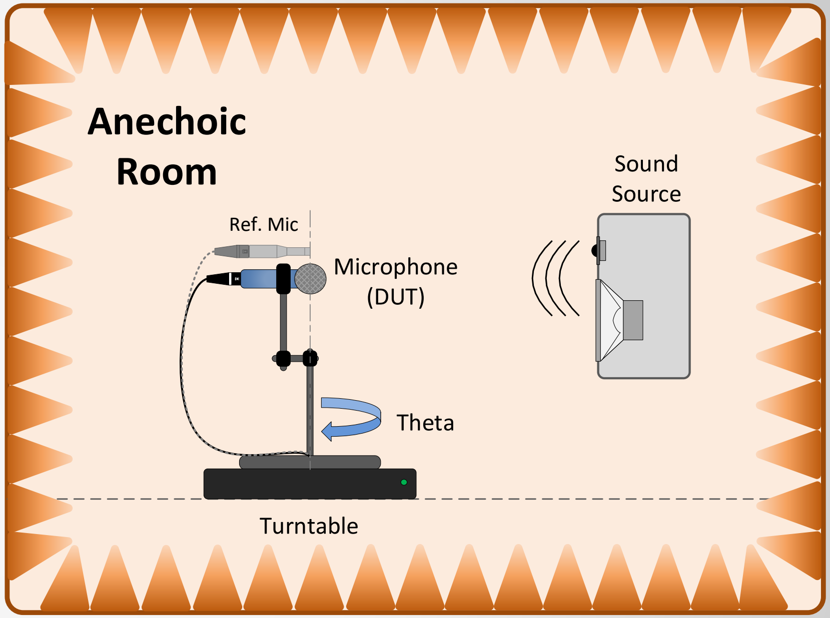
How is directivity and frequency/phase response of the individual microphone(s) affected by

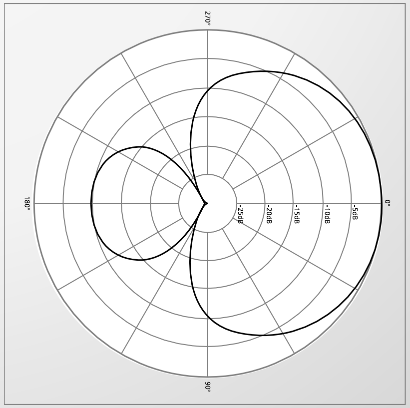
- Placement on the device?
- Human ear/head?
- Housings, cover grids or membranes?
- Parasitic acoustical or mechanical resonances?

Conventional Methods

For Microphone Directivity Scanning

- Anechoic room or gated impulse response
- DUT mounted on turntable for (single rotation axis)
- Sound source: reference full-band speaker at fixed position in far field
- Reference microphone to calibrate speaker response at test position (substitution method)
- Drawbacks:
  - Rotational symmetry assumed (φ) → actual 3D directivity neglected
  - Angular result parameter resolution defined scanning grid (number of points)

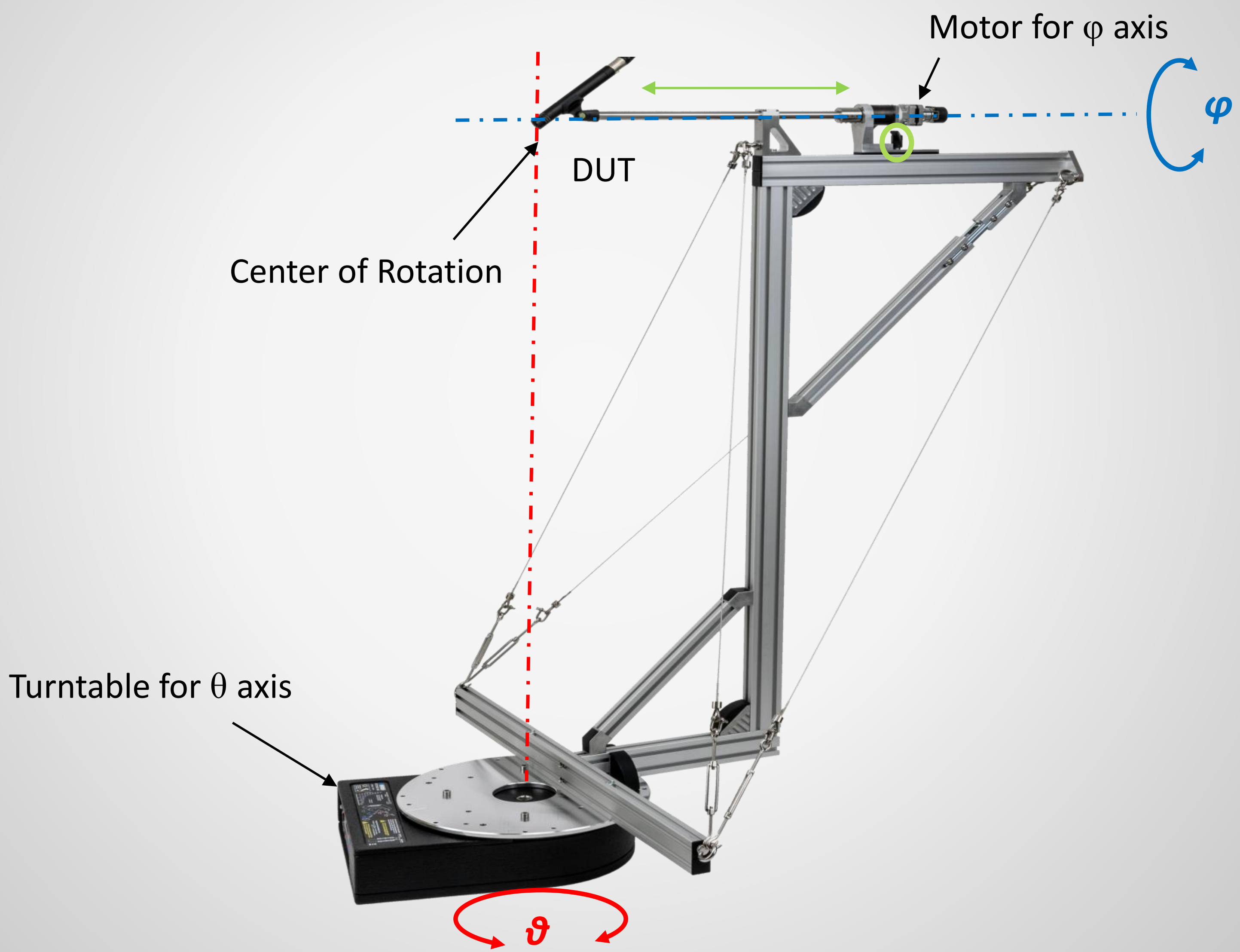




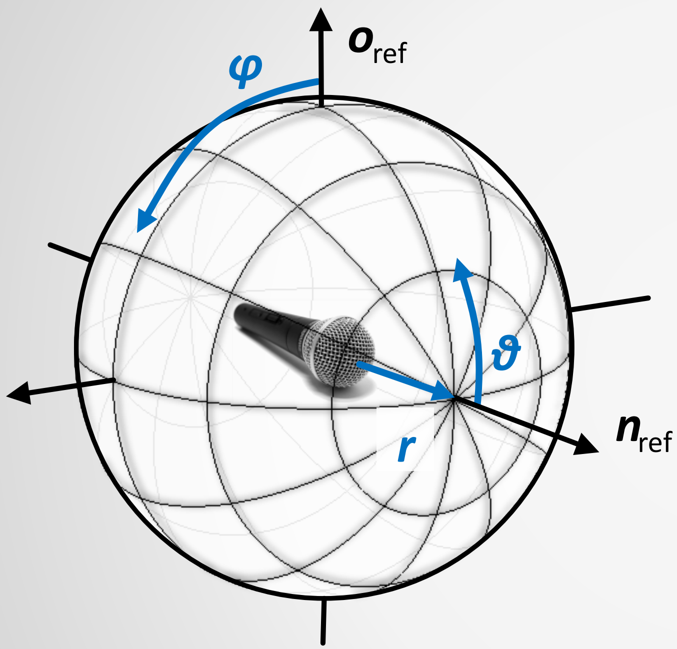
2D Polar plot

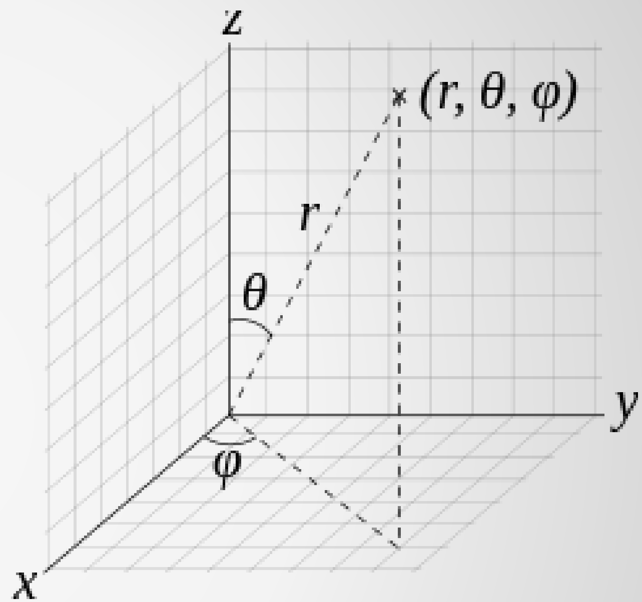
3D Microphone Scanning

Using Two Rotational Axes



Coordinate System

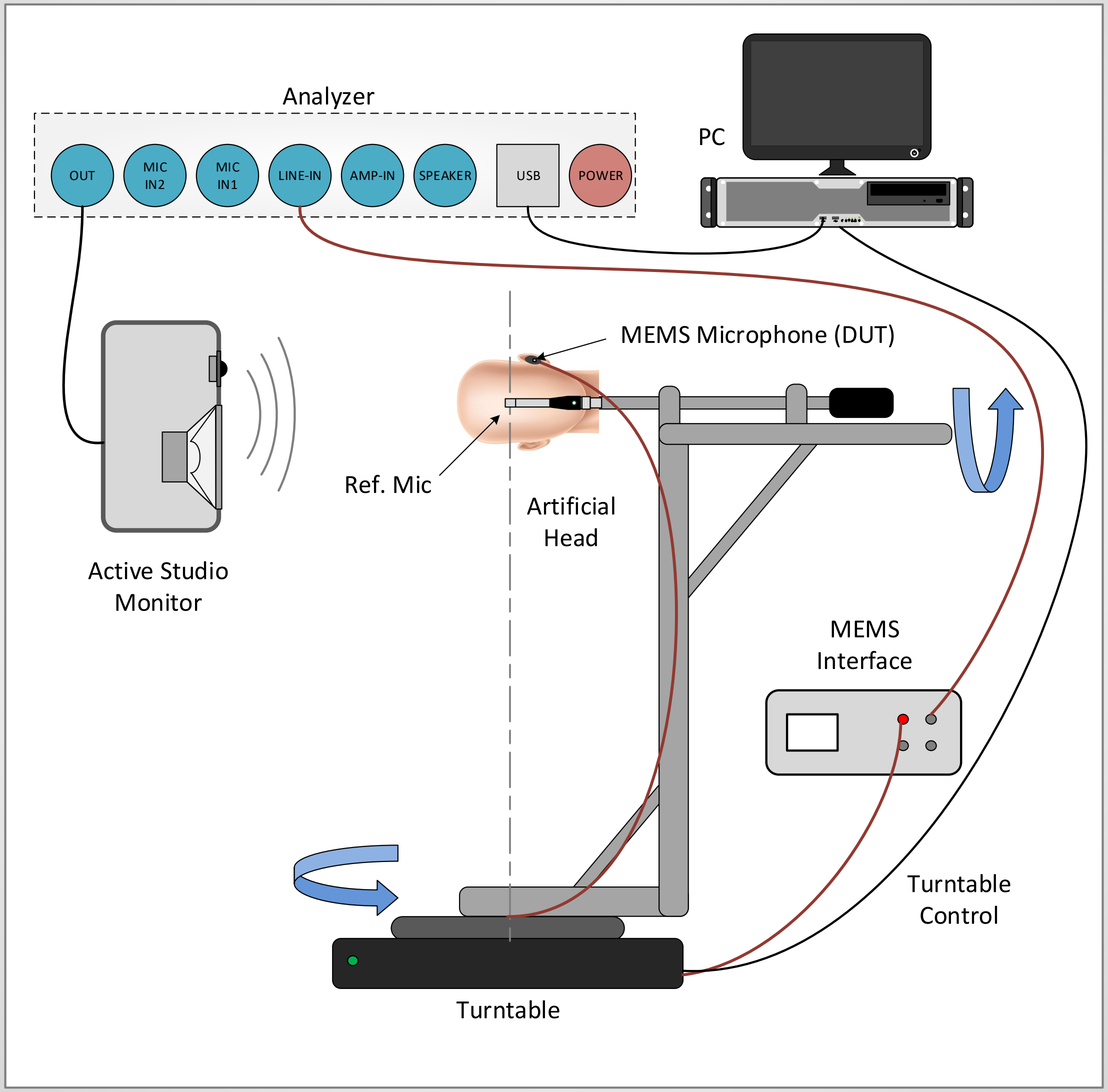




nRef – Normal vector to define On-axis reference
oRef - Orientation vector to define the orientation reference

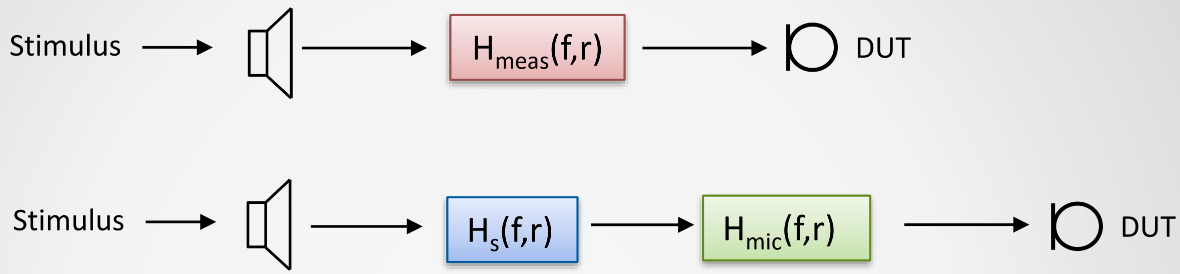
- Spherical coordinate system (r, θ, φ)
- Alignment with center of rotation (Offset compensation)
- Alignment with acoustic center of source - Needs *nRef* and *oRef* position

Hardware Setup



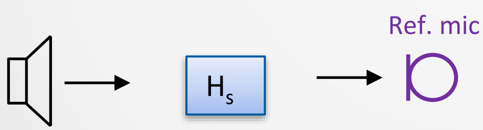
Frequency Response Calibration

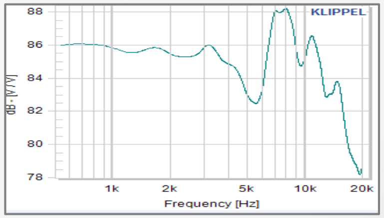
Insertion Method



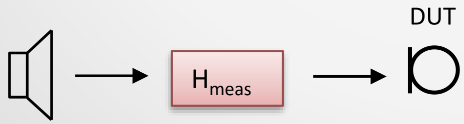
$$H_{mic}(f,r_m) = \frac{H_{meas}(f,r_m)}{H_s(f,r_m)}$$

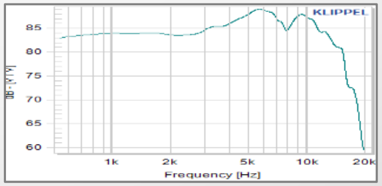
$$H_s(f,r_m) = \frac{P_{ref}(f,r_m)}{U_{stim}(f)}$$

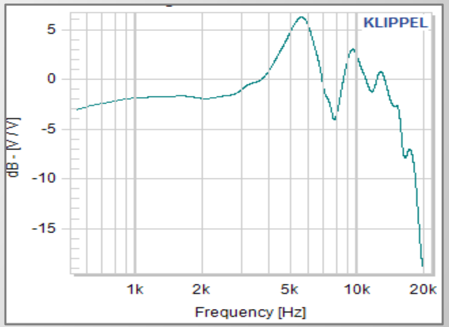




$$H_{meas}(f,r_m) = \frac{P_{DUT}(f,r_m)}{U_{stim}(f)}$$



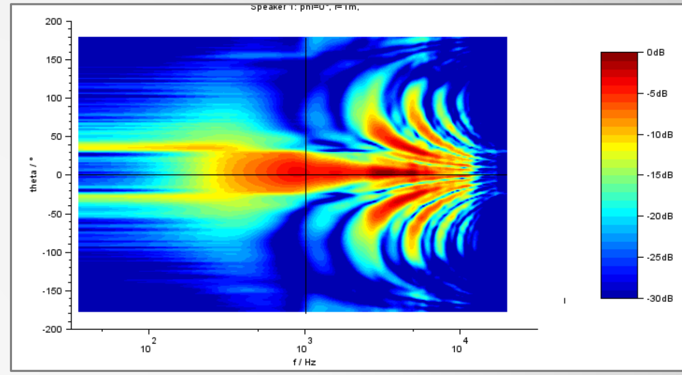




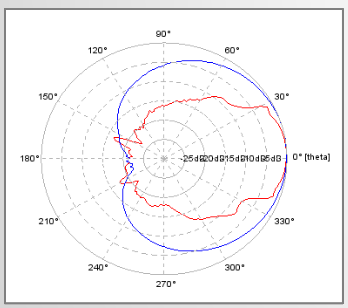
Example

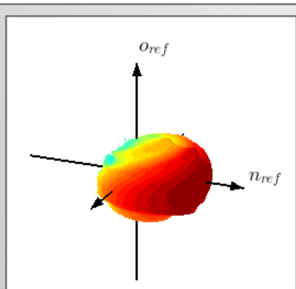
Dynamic Microphone Array (Plain Sum)

Contour plot (horiz.)

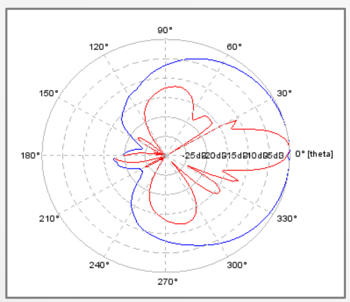


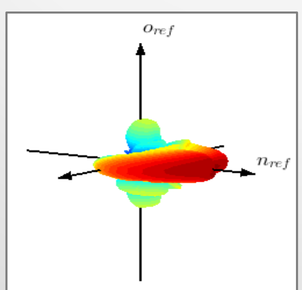
500 Hz



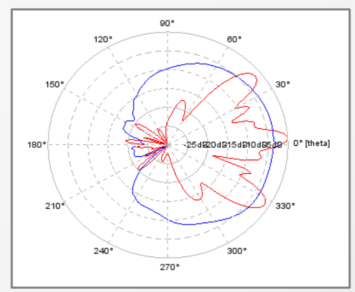


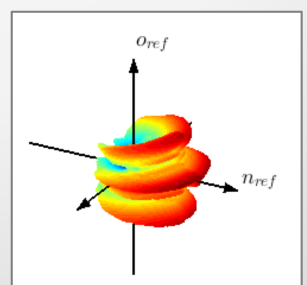
2 kHz



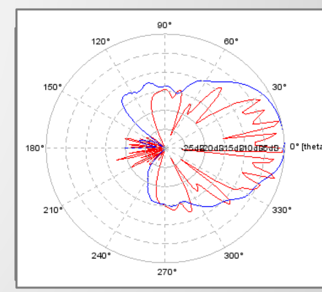


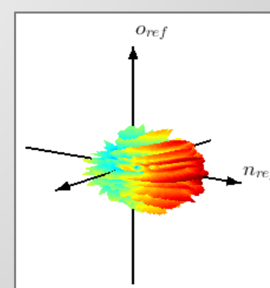
4 kHz





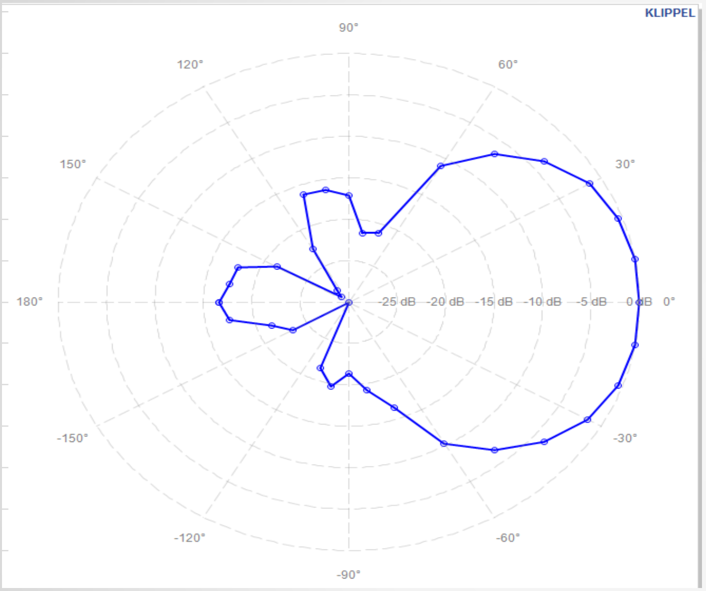
10 kHz



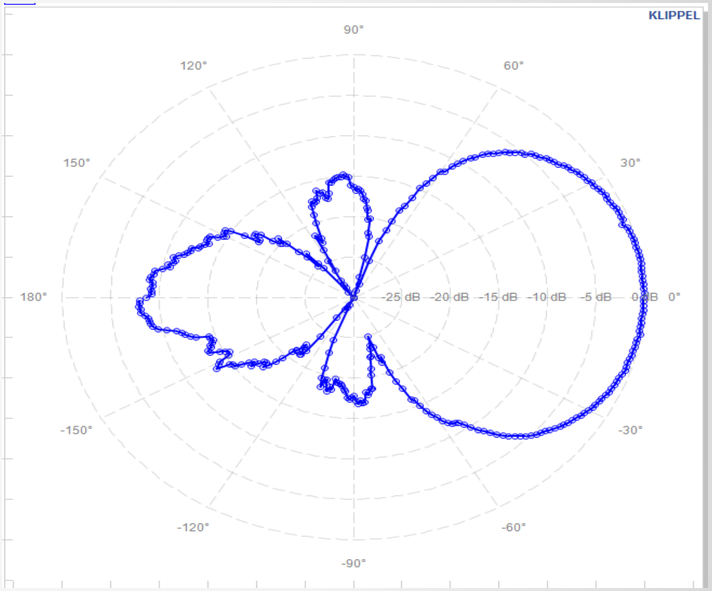


Angular Resolution

Defined by Measurement Grid



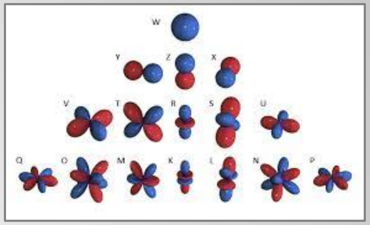
10 kHz @ 10° resolution → 648 pts (full sphere)



10 kHz @ 1° resolution → 64800 pts (full sphere)

Spherical Harmonics Interpolation

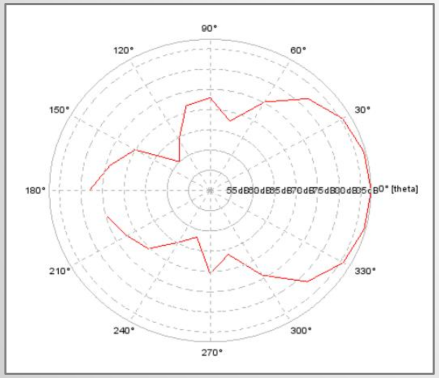
$$p(r,\theta,\varphi,\omega) = \sum_{n=0}^{\infty} \cdot \sum_{m=-n}^{n} \cdot C_{m,n}(\omega) \cdot hn(kr) \cdot Y_n^m(\theta,\varphi) \cdot e^{j\omega t}$$



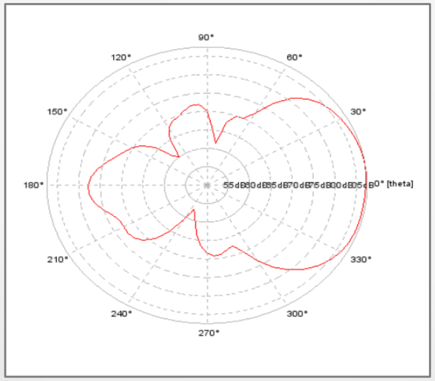
With the use of spherical harmonics interpolation (SHI) we can reduce number of measured points while getting a higher output data resoution.

$J = (N+1)^2$ number of coefficients for the expansion
$M = 2 \cdot (N+1)^2$ total number of measured points needed

10° Resolution @ 10kHz

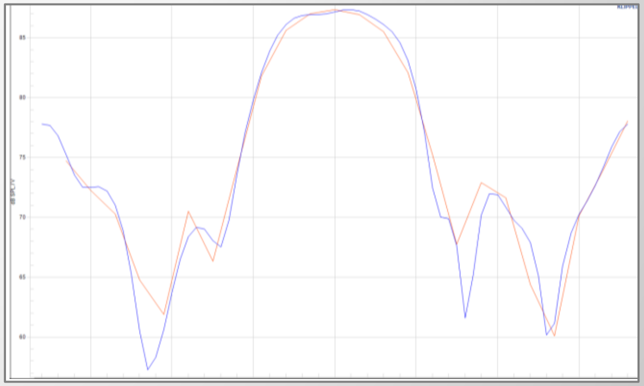


SHI @ 10kHz



N=10

Polar Plot Unwrapped (meas vs SHI)

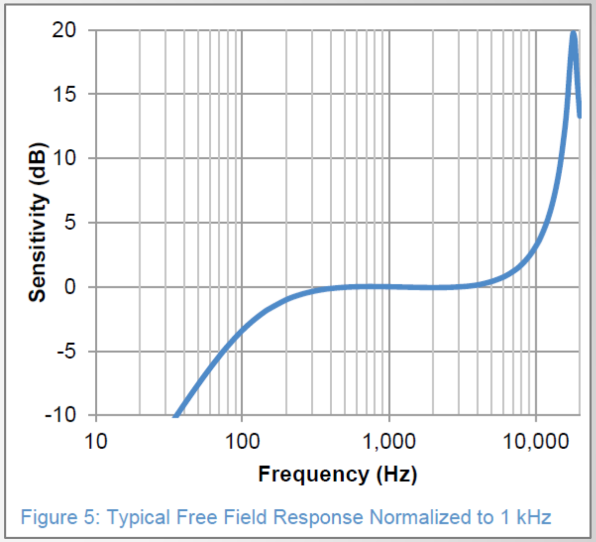


SHI
Measured

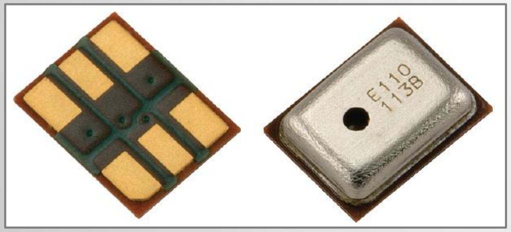
MEMS Microphone

For Mobile Audio Applications

- Package size: 3.5 mm x 2.65 mm
- Top-Ported
- Omnidirectional
- Sensitivity: 94 dB SPL → -20 dBFS @ 1 kHz



Spec Sheet Free Field Response

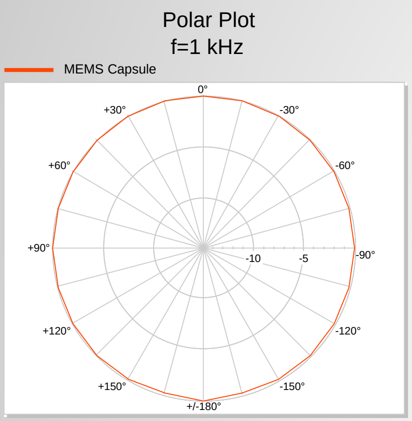


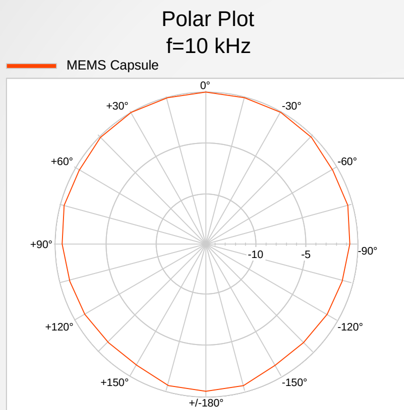
Knowles SPH0644HM4H-1

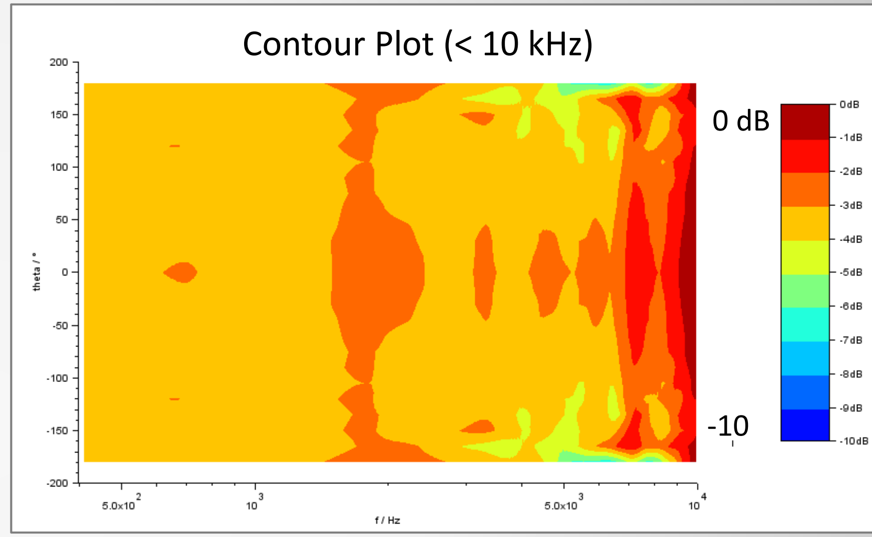
Scan Results

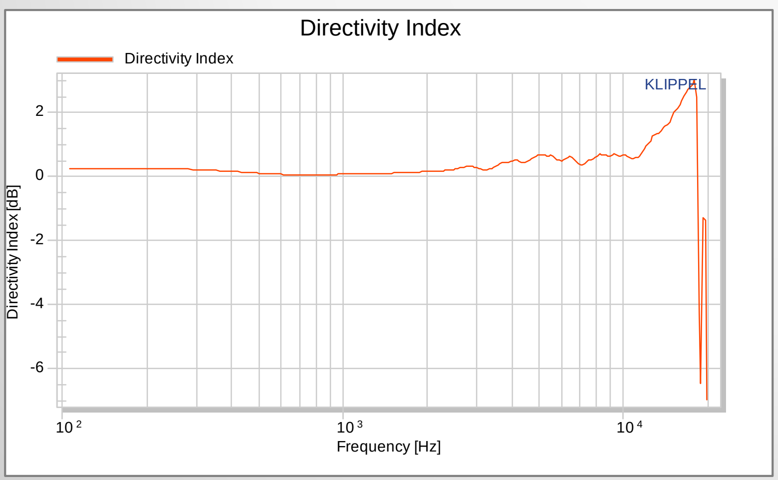
MEMS Microphone Directly Mounted on Scanner

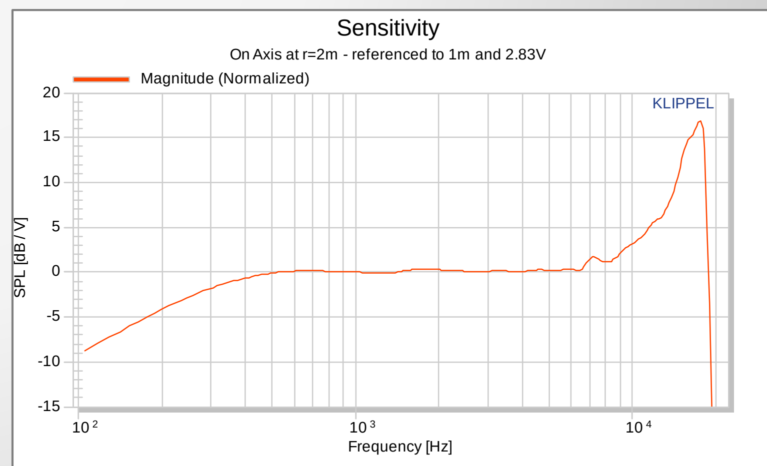
Nearly omnidirectional pattern below 10 kHz





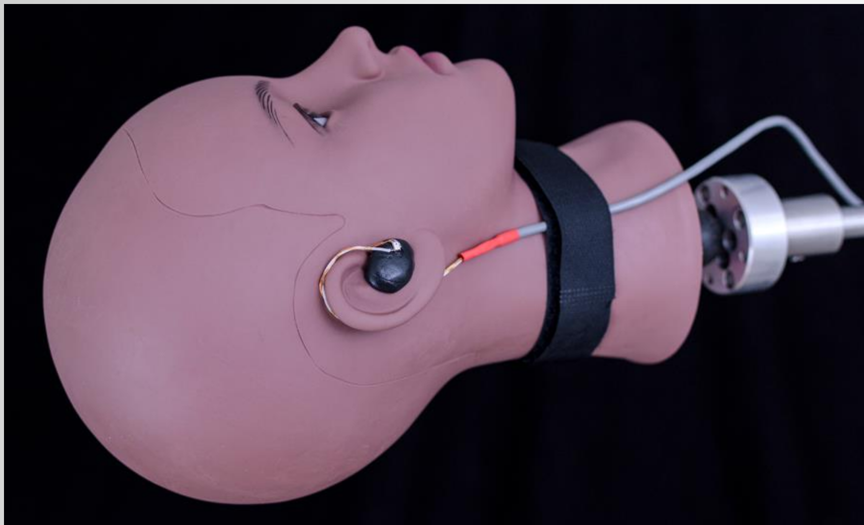




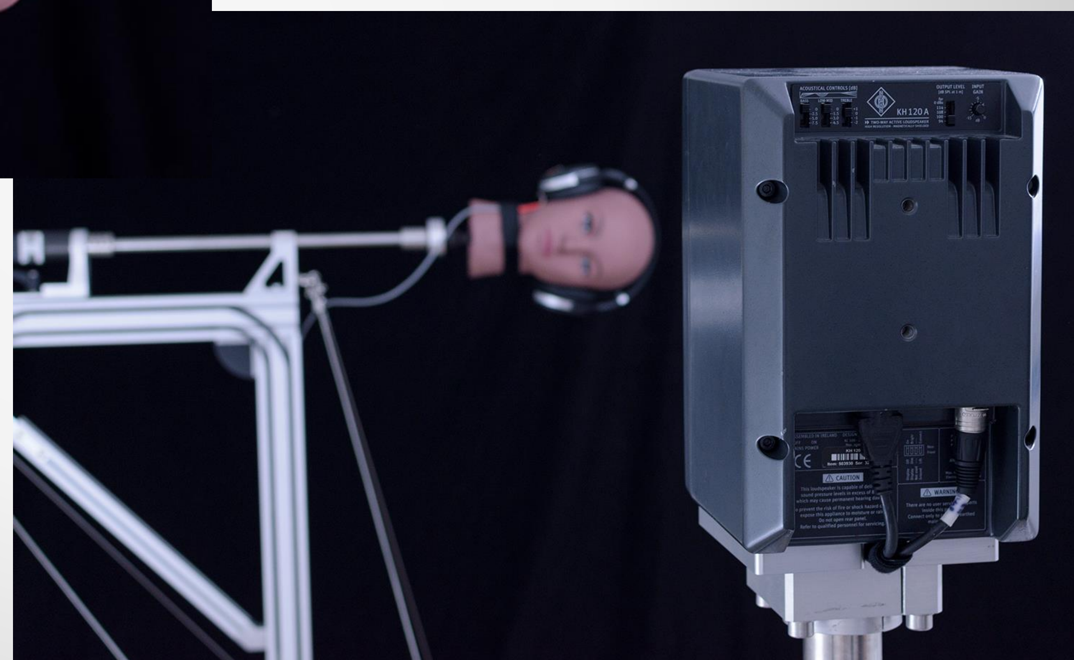


3D Directivity Scan

MEMS Microphone Mounted on In-Ear Device



- Mannequin head (soft PE)
- Resolution: 10° (648 pts)
- Total scan time: 90 min
- Sweep time: 2 x 340 ms



- Small room – IR window length = 5 ms → $F_{min} \approx 300$ Hz)
- Reference axis: front (between eyes)
- Coordinate transformation used

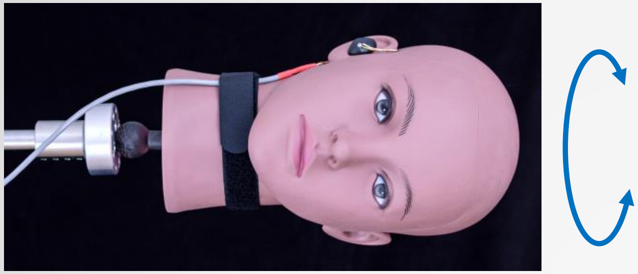
3D Directivity Scan

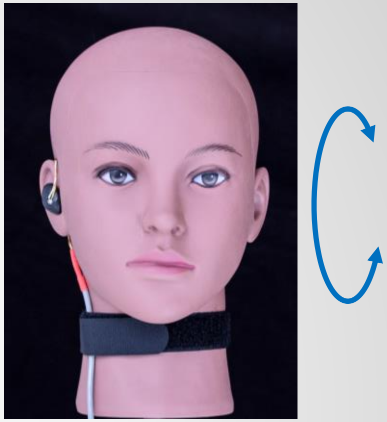
Time Lapse (Speaker View with Alt. Grid)

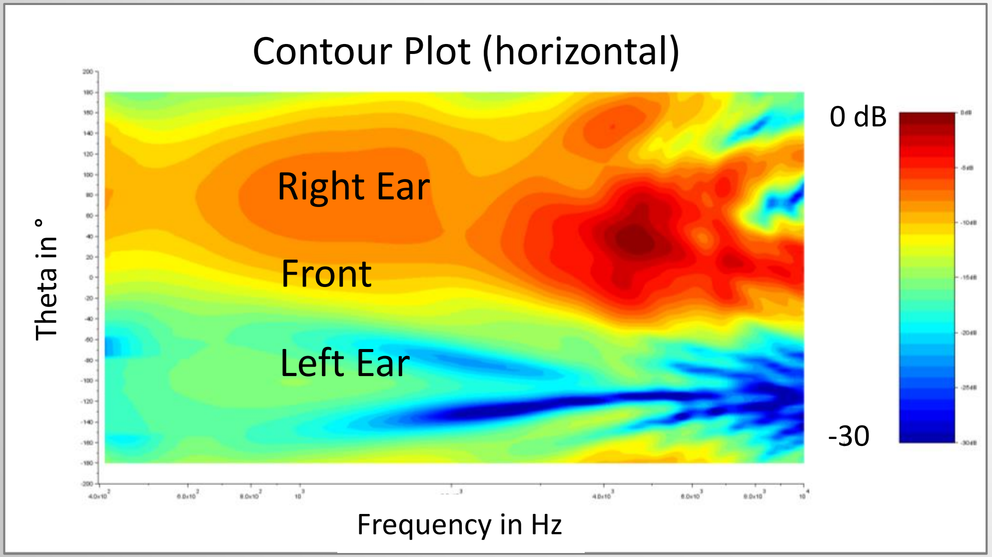
- Mic Scanner Timelapse

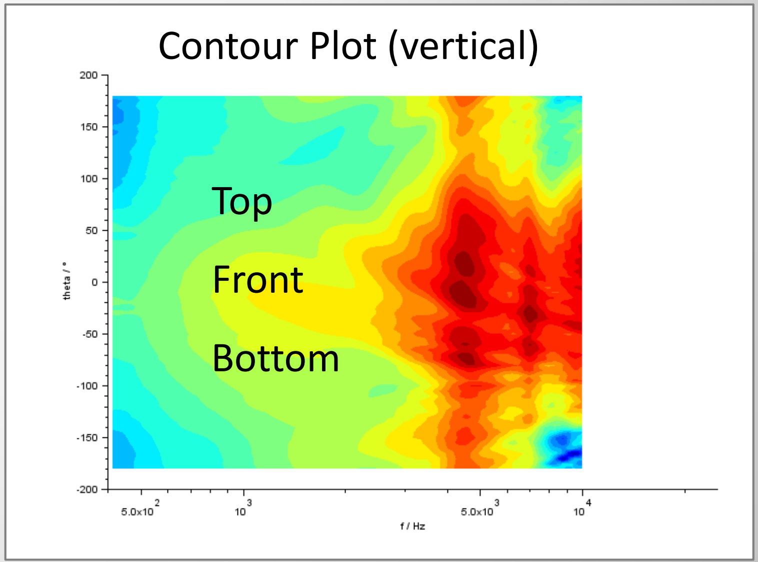
Scan Results

Contour Plots (f < 10 kHz)



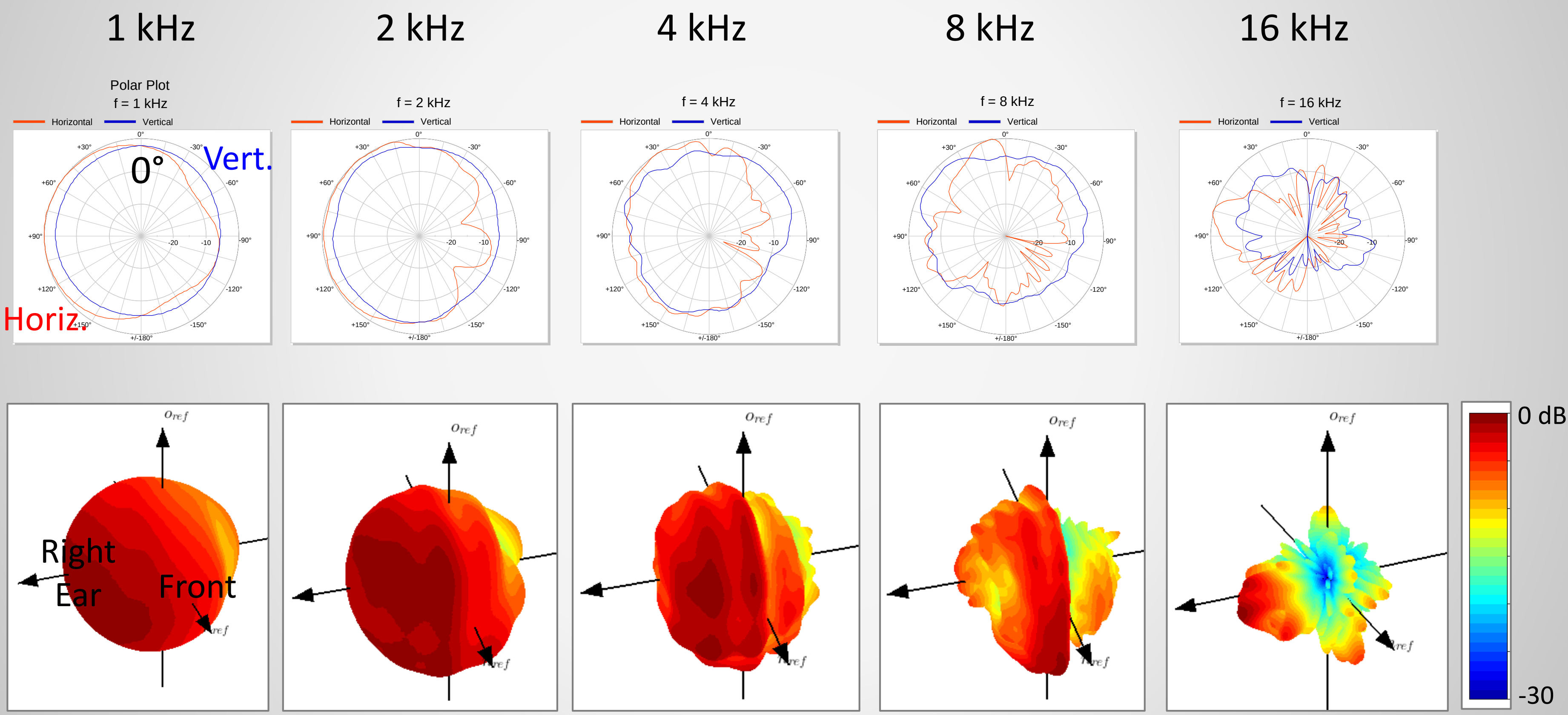






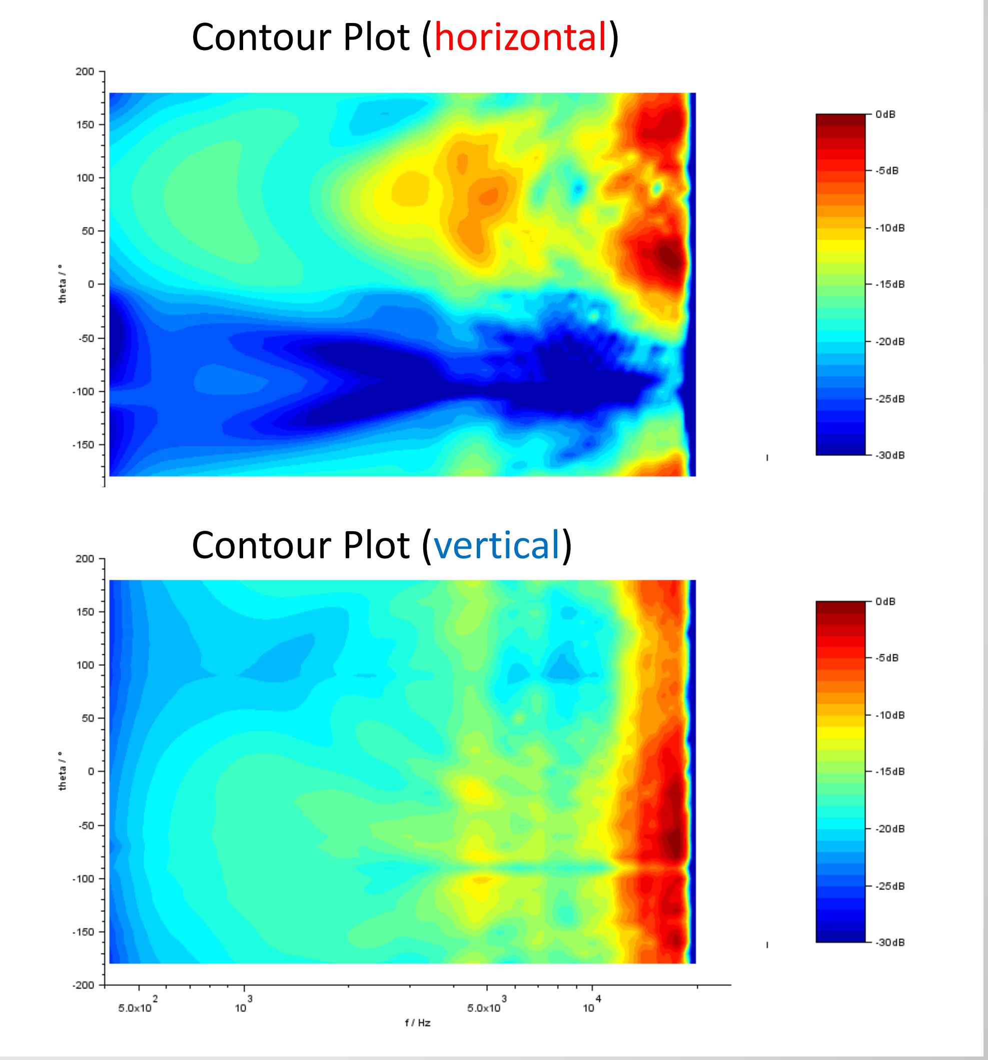
Scan Results

Polar and Balloon Plots (In-Ear)



3D Directivity Scan Results (2)

MEMS Microphone on Over-Ear Headphone



Conclusion

- 3D directivity information of both radiated and received sound gain importance in modern DSP-enhanced personal audio devices equipped with multiple acoustical transducers
- Conventional methods for far-field directivity measurement of loudspeakers are not suitable
- 2D microphone polar scanning is insufficient to evaluate full space directivity → add second rotating axis
- Spherical wave expansion and interpolation methods are beneficial for
  - reducing measurement time (points)
  - obtaining better result data resolution
  - separating direct sound from room reflections (only radiation)
  - overcoming SNR problems (through near field scanning)
  - analyzing sound radiation at any point and distance including device near field
  - Describing the 3d sound field with only a few coefficients

Related Documents

- Standards
  - IEC 60268 Sound system equipment
    - Part 1: General
    - Part 4: Microphones - Directional Characteristics
    - Part 7: Headphones and earphones - Unwanted Sound
    - Part 21 (new): Acoustical (output based) measurements - Directional Characteristics
- Books
  - Fourier Acoustics: Sound Radiation and Nearfield Acoustical Holography, Earl G. Williams
- KLIPPEL Application Notes
  - AN54 Directivity Measurement with Turntables
  - AN69 Far Field Measurement using Microphone Arrays
- KLIPPEL Specifications
  - C8 NFS Near Field Scanner
  - S41 POL Polar Turntable Measurements