Application of Measured Directivity Patterns to Acoustic Array Processing

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My Background

- 2011-present: Postdoctoral Researcher, Researcher (2013), Audio and Acoustics Research Group, Microsoft Research, Redmond, USA.
    - Microphone arrays (linear, planar, cylindrical, spherical).
    - Echo cancellation, noise suppression.
    - Head-related transfer functions.
    - Loudspeaker arrays.

- http://research.microsoft.com

Microsoft® Research

My Background

- 2001-2002: Pre-University/Vacation Trainee, BBC Research & Development, Kingswood Warren, Tadworth, Surrey.
  - DAB data protocols, audio signal processing for HDTVs, TV spectrum planning, hardware for live TV streaming.

- 2002-2010: MEng/PhD in Electrical and Electronic Engineering, Imperial College London.
  - MEng Thesis, “A Novel Loudspeaker Equalizer.”
  - PhD Thesis, “Glottal-Synchronous Speech Processing.”

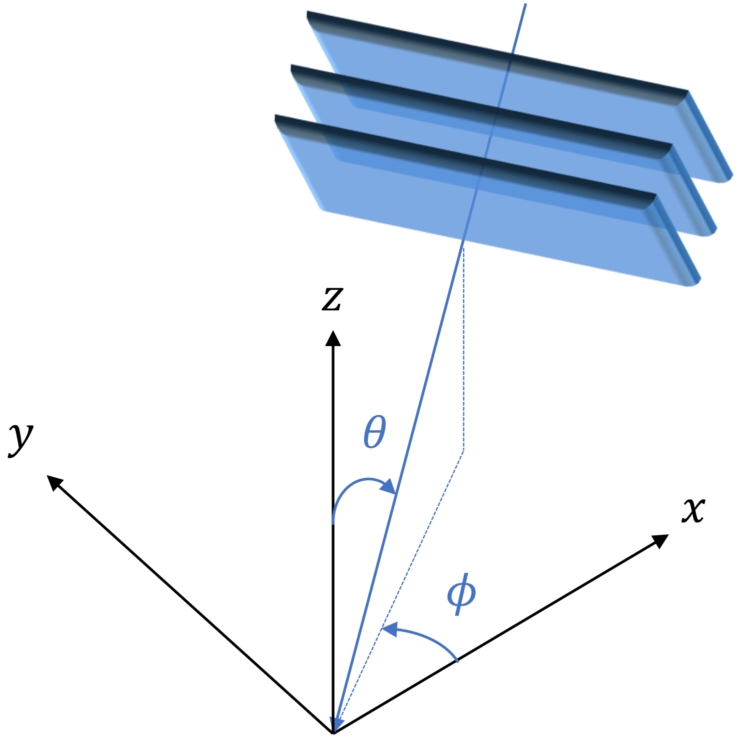
- 2010-2011: Research Associate, Imperial College London
  - EU FP7 project Self Configuring ENVironment-aware Intelligent aCoustic sensing (SCENIC)
  - Spherical microphone arrays, geometric inference, channel identification & equalization.

Directivity Patterns: Background

- Directivity pattern is the response to a **plane wave** emerging from a known direction relative to the device under test.
  - Function of azimuth ϕ
  - Function of elevation / colatitude θ
  - Function of frequency ω

- This is the ‘farfield’ response
  - Practically measured with a loudspeaker at a fixed distance of 1-2m.

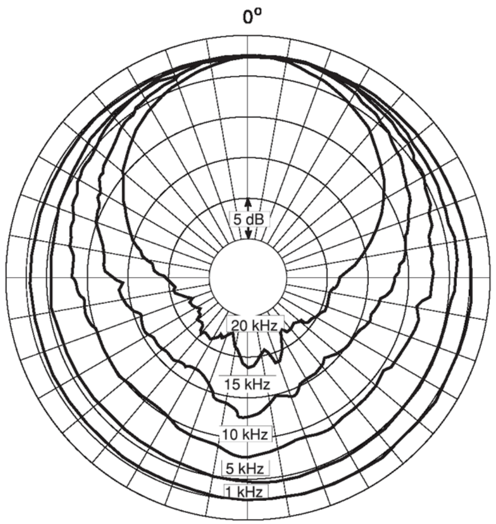
- Independent of reverberation



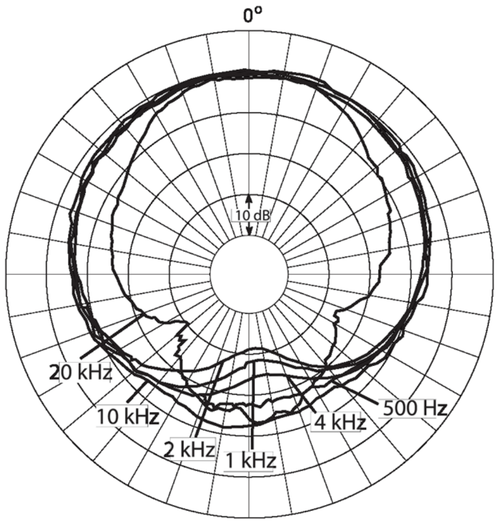
Directivity Patterns: Background

- All acoustic transducers exhibit some degree of directivity
  - Sometimes by design (e.g. cardioid microphone)
  - Sometimes parasitic (e.g. mounting hardware – example to come)

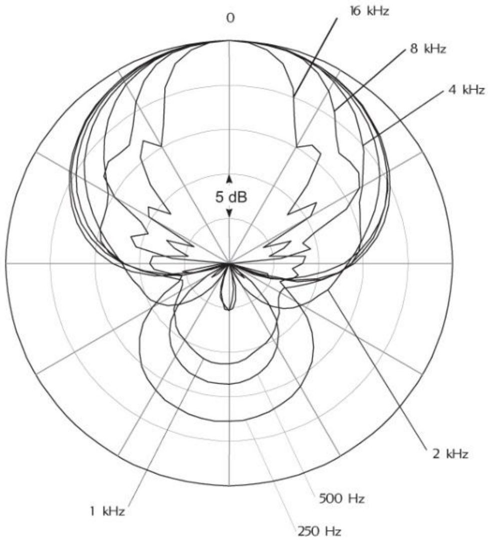
DPA 4006 Omni



DPA 4011 Cardioid



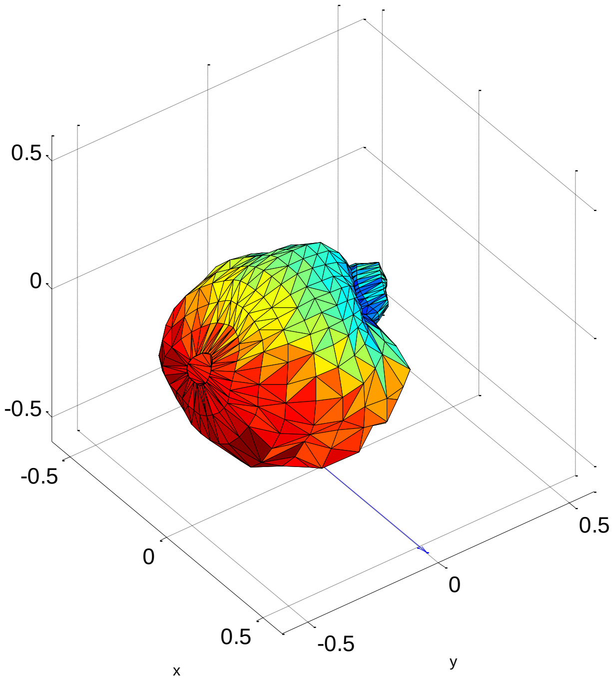
DPA 4017 Shotgun

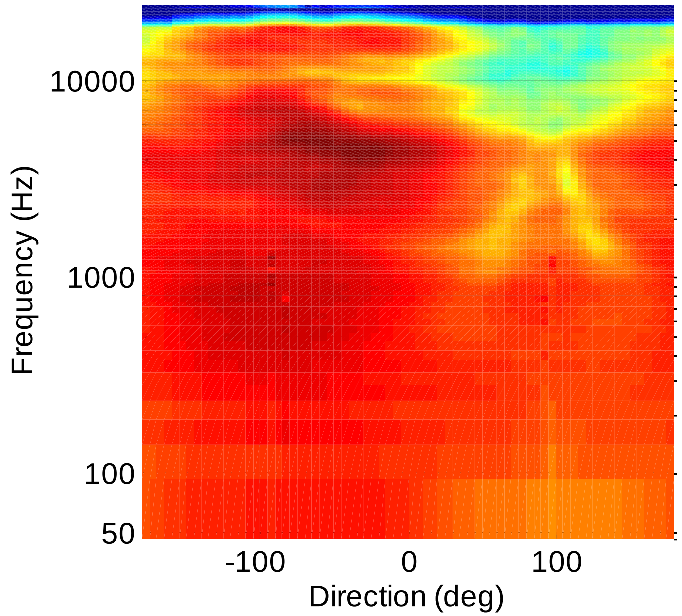


Images: http://www.dpamicrophones.com/

Other Examples of Directional Behaviour

- Head-Related Transfer Functions (HRTFs)

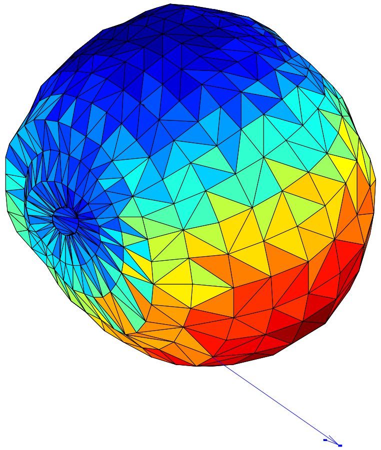




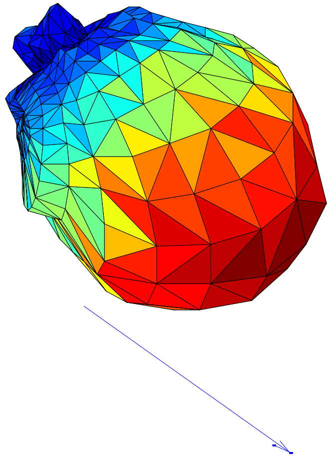
Other Examples of Directional Behaviour

- Loudspeakers

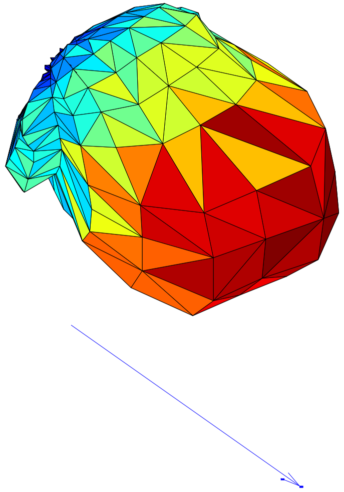
Loudspeaker Radiation Pattern at 200 Hz



Loudspeaker Radiation Pattern at 1 kHz



Loudspeaker Radiation Pattern at 10 kHz



Left image: http://www.m-audio.com

Contents

- Background on directivity patterns
- Part 1: Design of a measurement rig
  - Test signals
  - Loudspeaker placement
  - Extrapolation/interpolation of missing data
- Part 2: Practical Applications
  - Beamforming with Kinect for Xbox 360
  - Head-related Transfer Functions
- Conclusions

Design of a Measurement Rig: Requirements

1. Must be able to reliably measure the linear **impulse response** (transfer function) between a source signal and a test microphone.

2. Source signal must be **spectrally flat**.
   - Loudspeaker response may need compensating.

3. Sources must be able to be moved to a **precise location**.

4. Sources must be sufficiently far away to **avoid nearfield effects**.

5. Environment must be **anechoic** or sufficiently far away from acoustic reflectors.

Test Signals

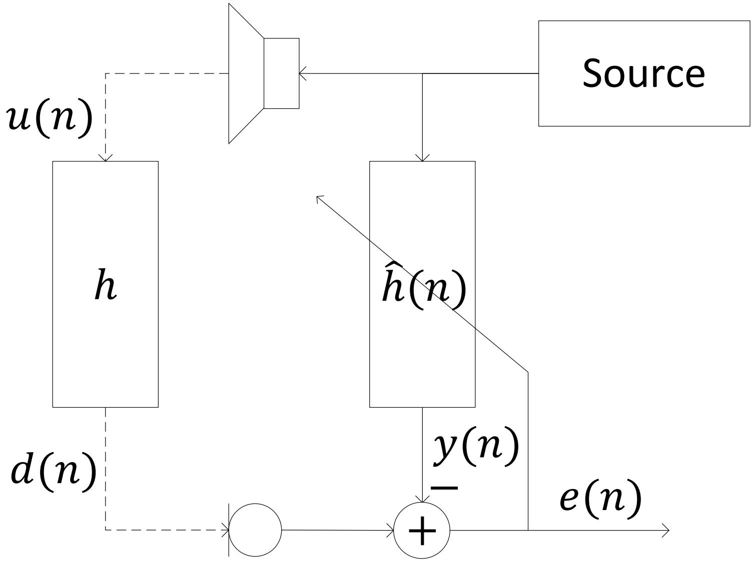
- Source is a known signal $u(n)$.
- Record signal $d(n)$
  - Has been filtered by unknown **finite impulse response** (FIR) system h.

- Estimate h by minimizing the difference between $y(n)$ and $d(n)$.

  - FIR system identification is a **convex problem**: always a **unique minimum**.

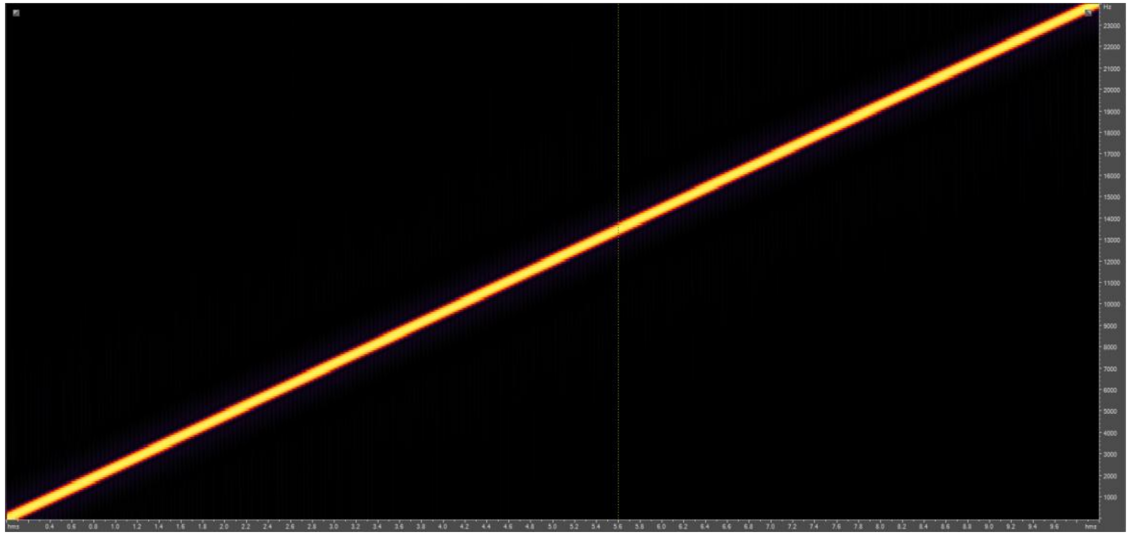
  - Most solutions are **closed form** (non-adaptive).

  - **Adaptive** solutions are useful for cases when h is constantly changing.



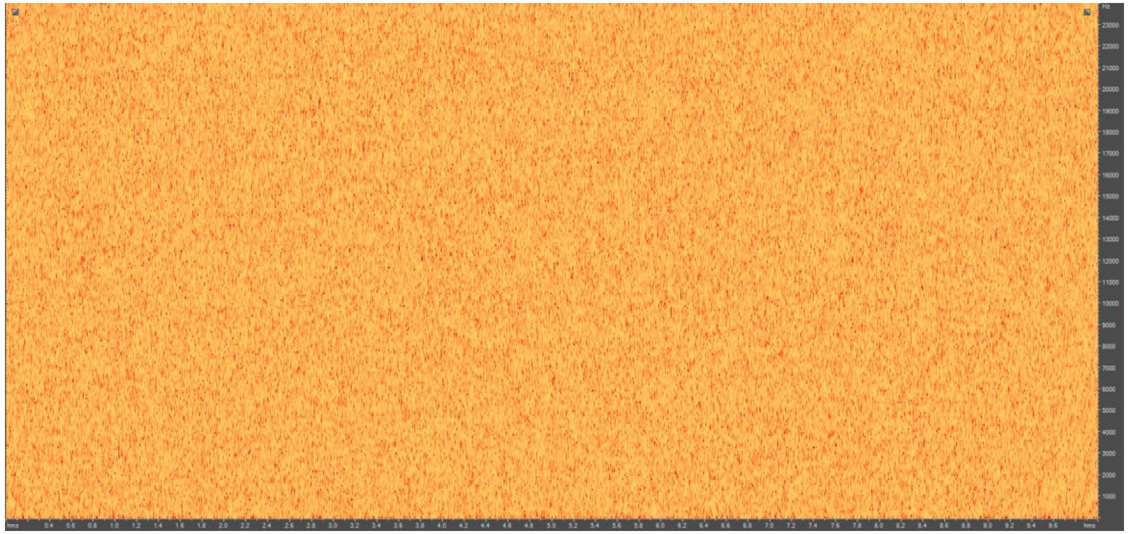
Choice of Test Signal: Chirp-Like

- Chirp-Like Signals
  - Linear chirp
    - \+ Easy to produce
    - \+ Intuitive
    - \- System ID requires generalized methods.
  - Time-stretched pulse (TSP)
    - \+ Pulse and its inverse are compact in support. Very low-complexity system ID.
    - \+ Robust to nonlinearities.



\- Energy is concentrated in a narrow band; possibility of standing waves in cone material producing nonlinearities.

Choice of Test Signal: Pseudorandom Noise

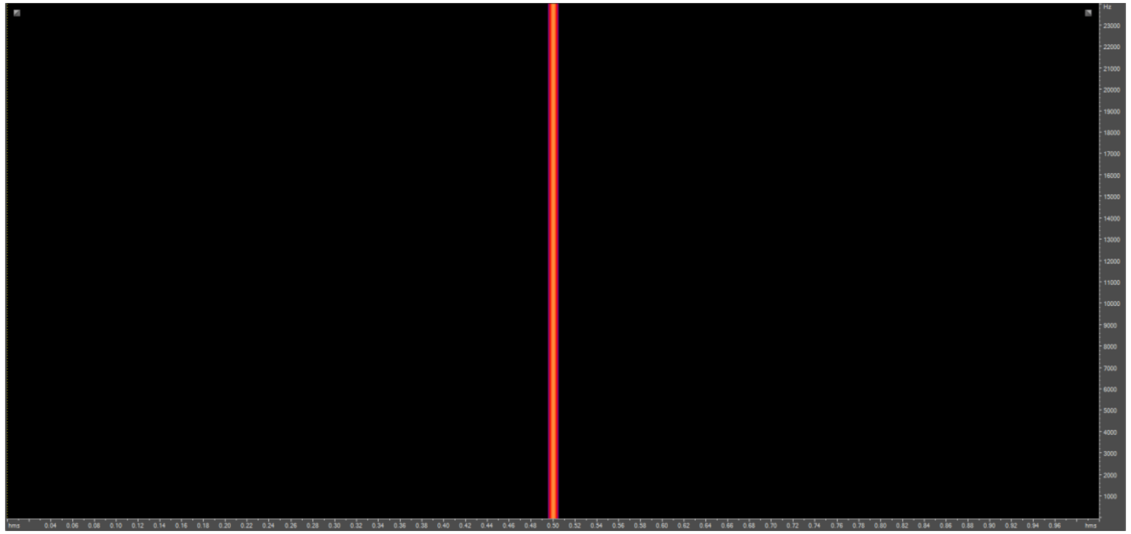


- Maximum-length sequences (MLS) / perfect sequences
  - \+ Autocorrelation is a perfect impulse.
  - \+ Fast system ID with modified Hadamard transforms.
  - \- Sensitive to nonlinearities.
- Gaussian Noise
  - \+ Easy to generate
  - \+ Autocorrelation theoretical impulse with sufficiently long data
  - \- Several solutions for system ID, some inexact and/or computationally expensive.

\+ Spectrally flat (energy not concentrated in a single spectral band).

Choice of Test Signal: Direct Impulse

+ Recorded signal is the system impulse response.
+ Straightforward to produce in the digital domain.
- In the analogue domain, gunshots, hammer blows and clickers have been used for room acoustics.



\- Requires high amplitudes in order to provides good signal-to noise ratio (risk of nonlinearity).

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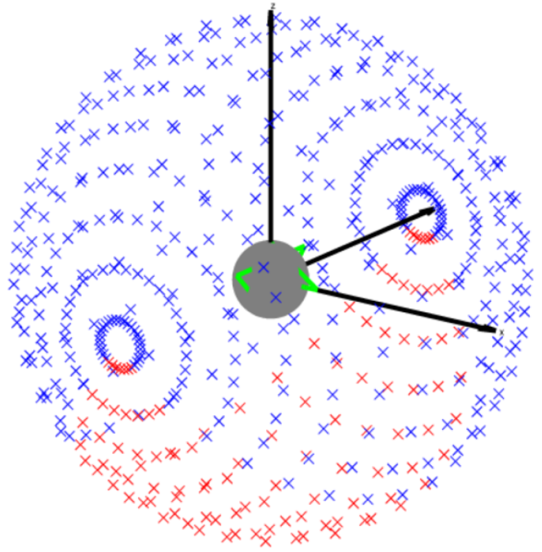
Equiangular Sampling

- Mount an array of loudspeakers on a semicircular arc and rotate about the device
  - Example: 16 loudspeakers spaced 11.25°, poles at the sides.
  + Practically continuous azimuth.
  - Colatitude angles fixed at discrete locations.
  - Missing spherical wedge underneath.
  - Mechanically complicated
  - Nonuniform sampling

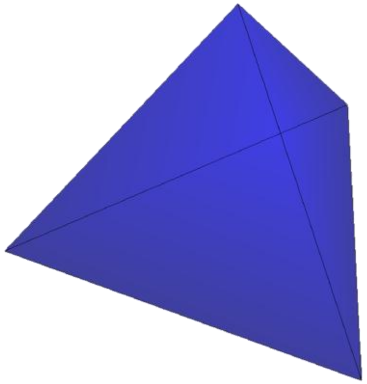


- Other variations on the theme
  - Rotate device relative to fixed loudspeaker.

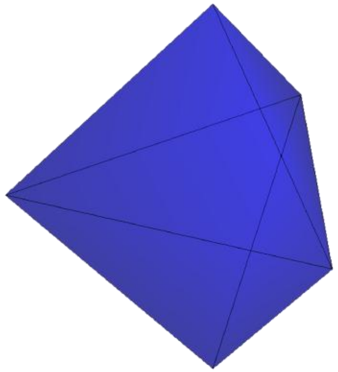
Uniform Sampling

- Place sources in **fixed locations** around the device under test
  - **Uniform distribution** of test points can be ensured.
  + No moving parts
  - Only 4 truly uniform solutions in 3D! The points lie on the vertices of 4 regular polyhedra.

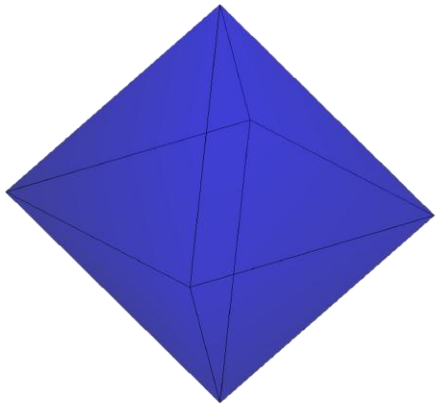
N=4: Tetrahedron



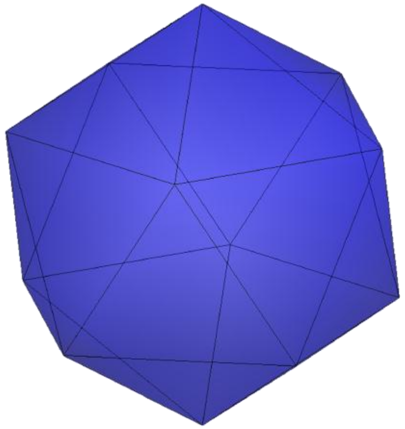
N=5: Triangular dipyramid



N=6: Regular octahedron



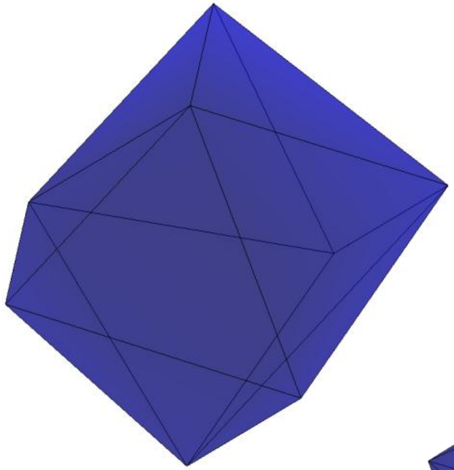
N=12: Regular icosahedron



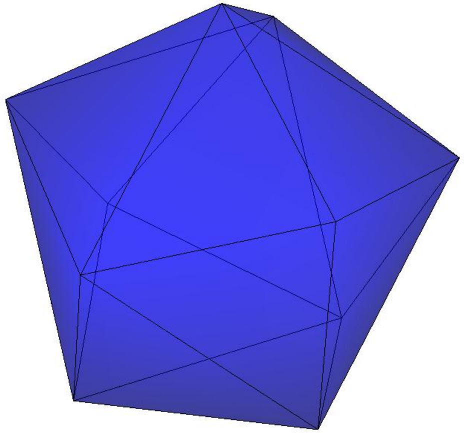
Near-Uniform Sampling: Geometric Solutions

- There a few geometric solutions to the **near-uniform sampling** case.

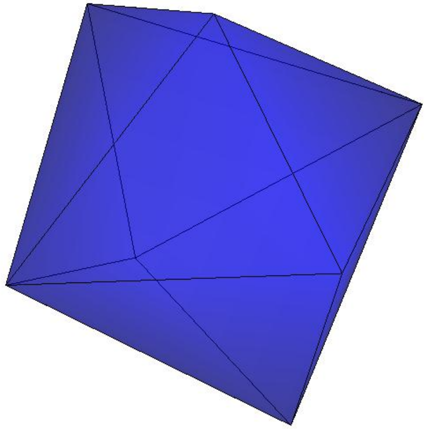
N=8: Square Antiprism



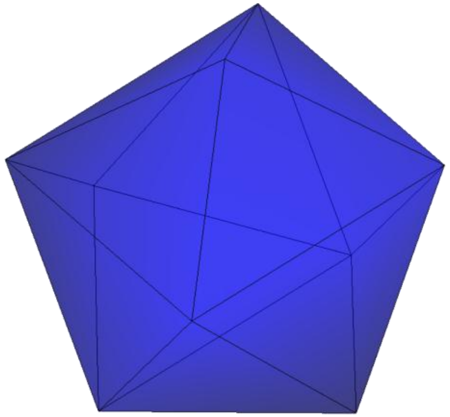
N=10: Gyroelongated square dipyramid



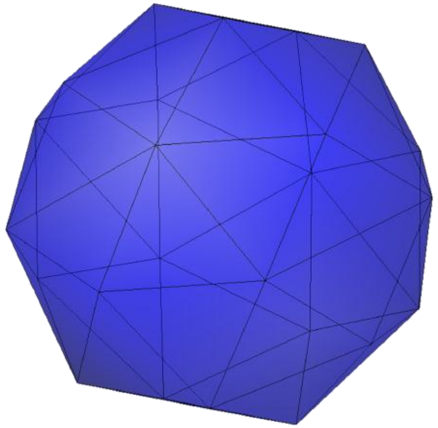
N=7: Pentagonal Dipyramid



N=9: Triaugmented Triangular Prism



N=24: snub cube



Near-Uniform Sampling: Numerical Solutions

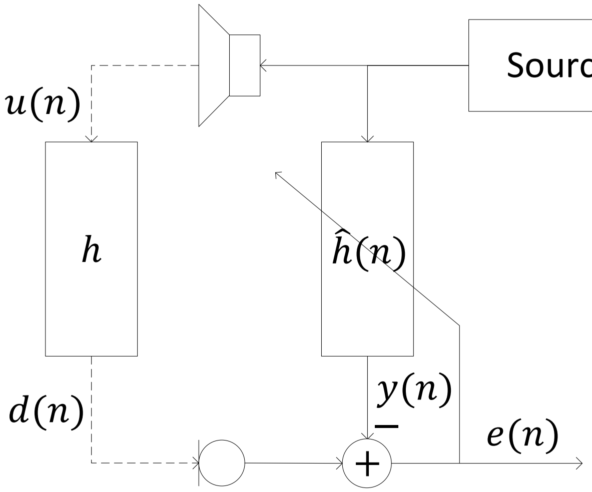
- For all other *N*, only **numerical solutions** exist
  - This is the **Thomson Problem**: determine the **minimum electrostatic potential** energy configuration of *N* electrons on the surface of a unit sphere.
  - I use the **Fliege** solution[1].

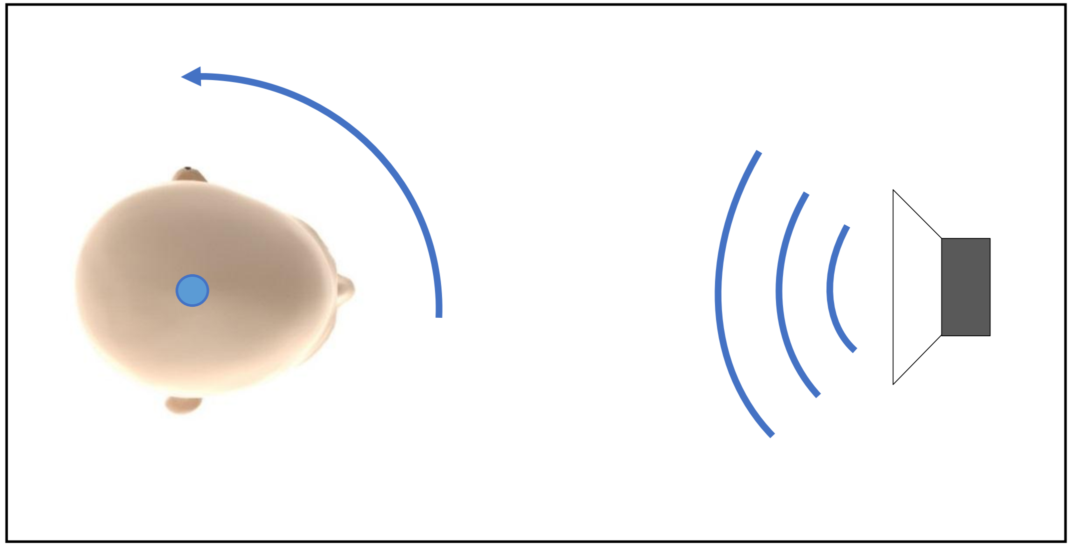
- Solutions have several other uses:
  - Spherical **microphone arrays**
  - **Geodesic domes**
  - Solutions in higher dimensions useful for **quantization** in coding schemes.

[1]J. Fliege, “The distribution of points on the sphere and corresponding cubature formulae,” *IMA J. Numer. Anal*. Vol. 19, no. 2, pp. 317-334, 1999.

Continuous Sampling

- Sound source is continuous Gaussian noise
- Device under test (in this case a human head) is **continuously rotated**.
- NLMS adaptive filter identifies **instantaneous** transfer function
  - Assumption: filter is **constantly converged** to correct solution.
  - Only suitable for horizontal plane.





G. Enzner, M. Krawczyk, F-M, Hoffmann, M. Weinert, "3D Reconstruction of HRTF-Fields from 1D Continuous Measurements," *WASPAA,* 2011.

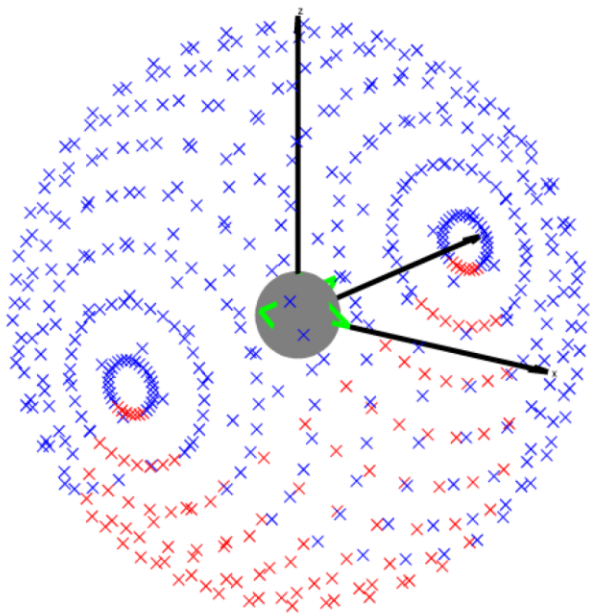
Contents

The Missing Data Problem

- A **spherical wedge** of data is missing beneath the test subject.

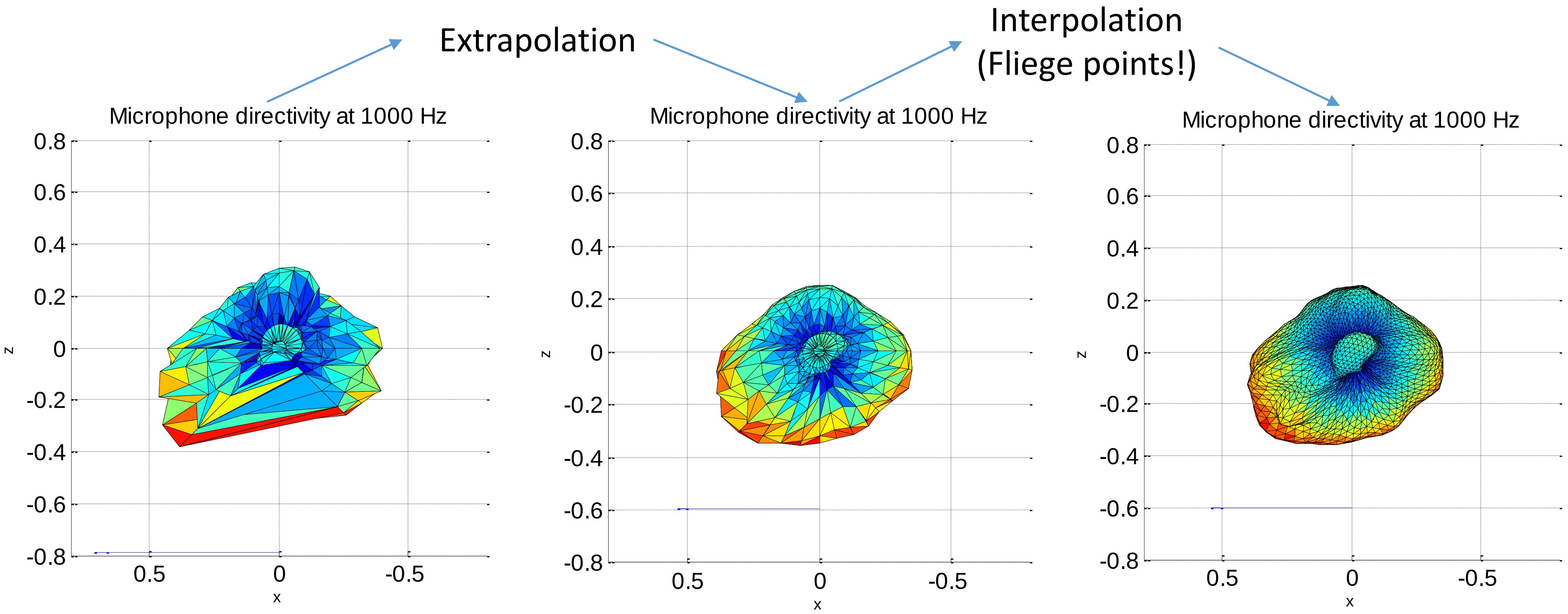
- Polynomial / spline interpolation do not work well
  - Do not exploit the **natural periodicity** of the data.
  - Do not account for **curvature** of the surface.
  - Solutions tend to be **numerically unstable**.

- Need an interpolation/extrapolation scheme better suited to data in spherical coordinates.



The Missing Data Problem

- Extrapolation: the missing spherical wedge underneath.
- Interpolation: the data between measurement points.



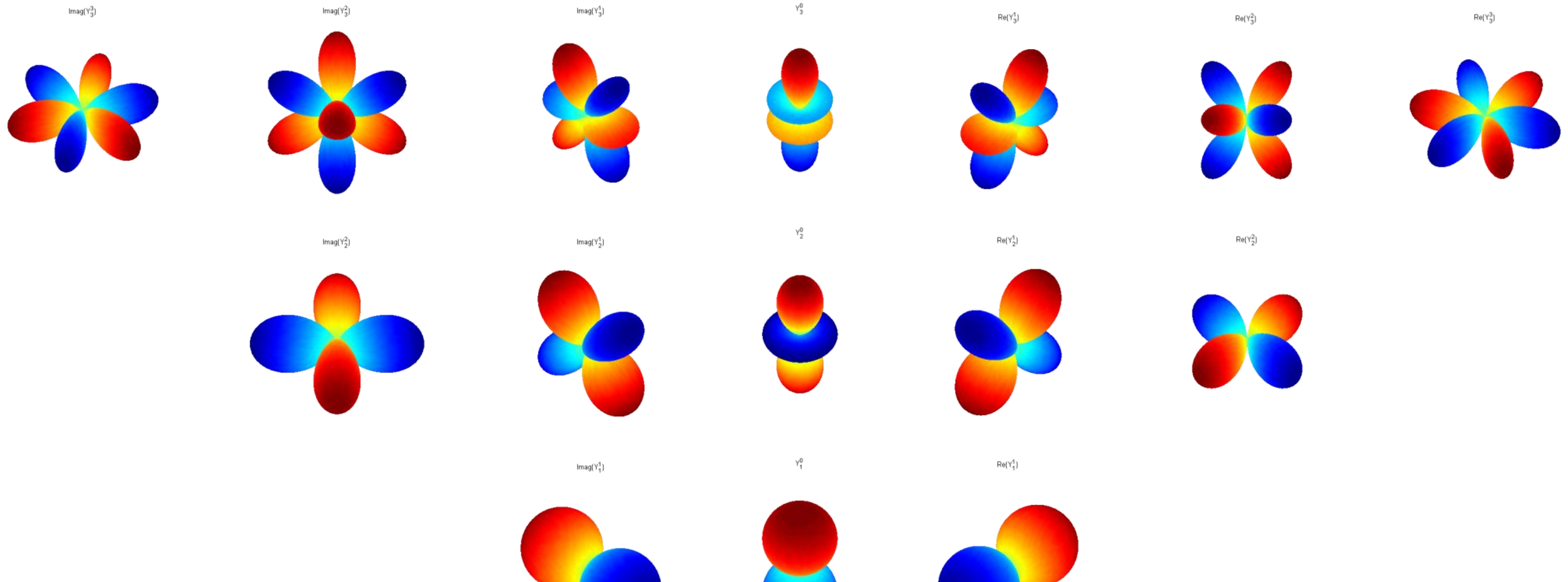
Spherical Harmonics

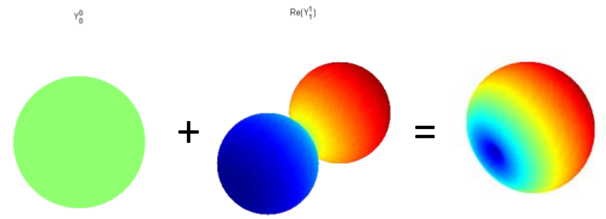
- Spherical harmonics are the **angular solutions** to the wave equation in spherical coordinates
  - They form an **orthogonal basis** for functions on the sphere.
  - Useful for analysis of orbital angular momentum of electrons.
  - Also useful for **wave field analysis** with spherical microphone arrays.

- They are to spherical space as the sine/cosine functions are to 1D space
  - They are the basis for a **spherical Fourier Transform**.
  - Think of it as a **spatial frequency domain**.

- Spherical harmonics have **discrete solutions** with degree n and order m.

Spherical Harmonics





Extrapolation with Spherical Harmonics

- If the sphere were complete, there would be **512 points** in total
  - 16 colatitude angles x 32 azimuth angles.
  - This permits a **15^{th} order** model.

- The actual number of measured points is **400**
  - 16 colatitude angles x 25 azimuth angles.
  - We cannot compute a 15^{th} order model in the unknown region.

- How do we perform a good fit?

J. Ahrens, M. R. P. Thomas, I. J. Tashev, "HRTF Magnitude Modeling Using a Non-Regularized Least-Squares Fit of Spherical Harmonic Coefficients on Incomplete Data," *APSIPA* 2012.

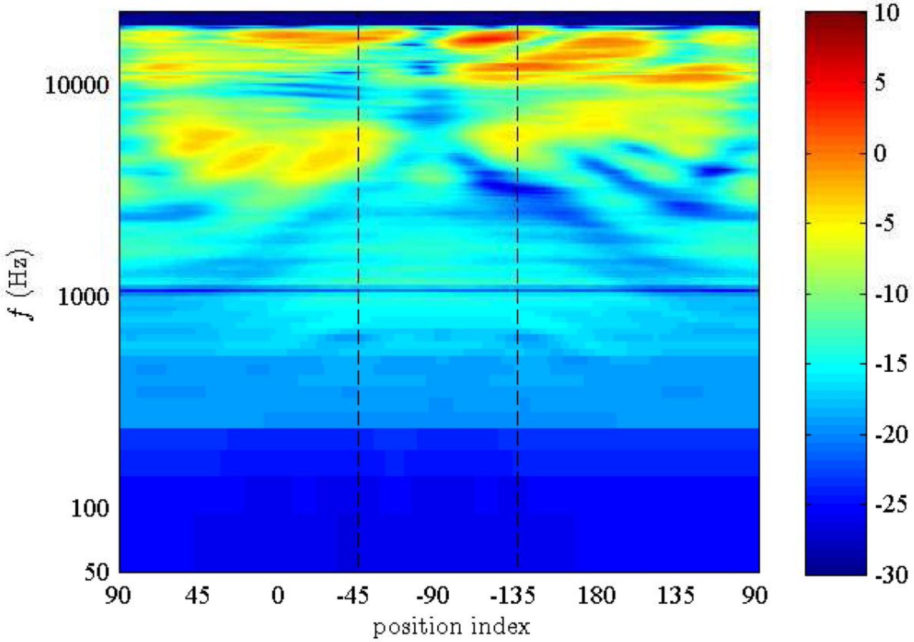
Test Subject: B&K Head and Torso Simulator

- B&K Head and Torso Simulator (HATS)
  - Simulates **anthropometry** of average human.
- Baseline measurements
  - Taken both right way up and upside down
  - Data combined to form complete sphere.

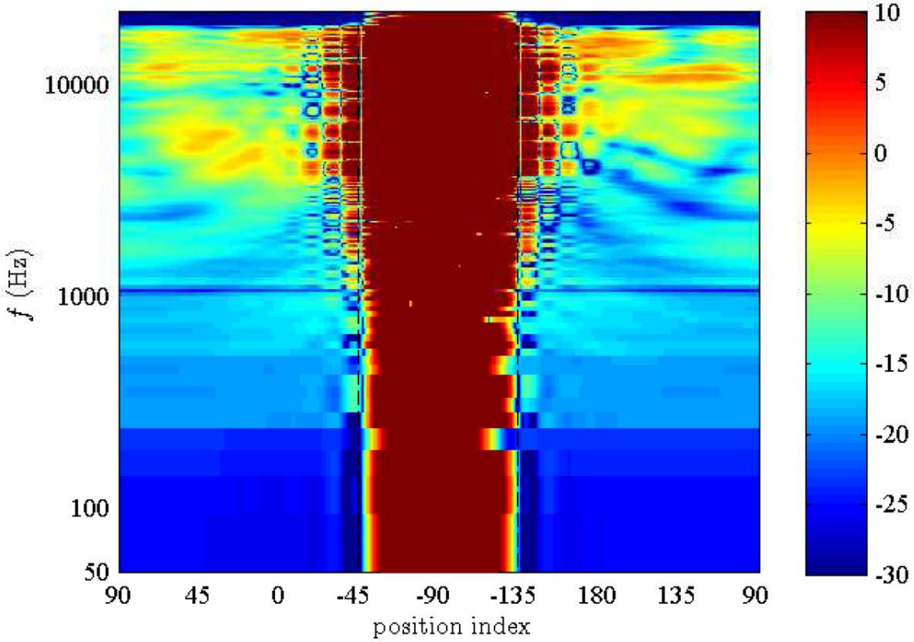
Fitting Problem

- Spherical harmonics aren't enough!
  - 15th order model is very poorly behaved when reconstructing missing region.

15th order model on complete data



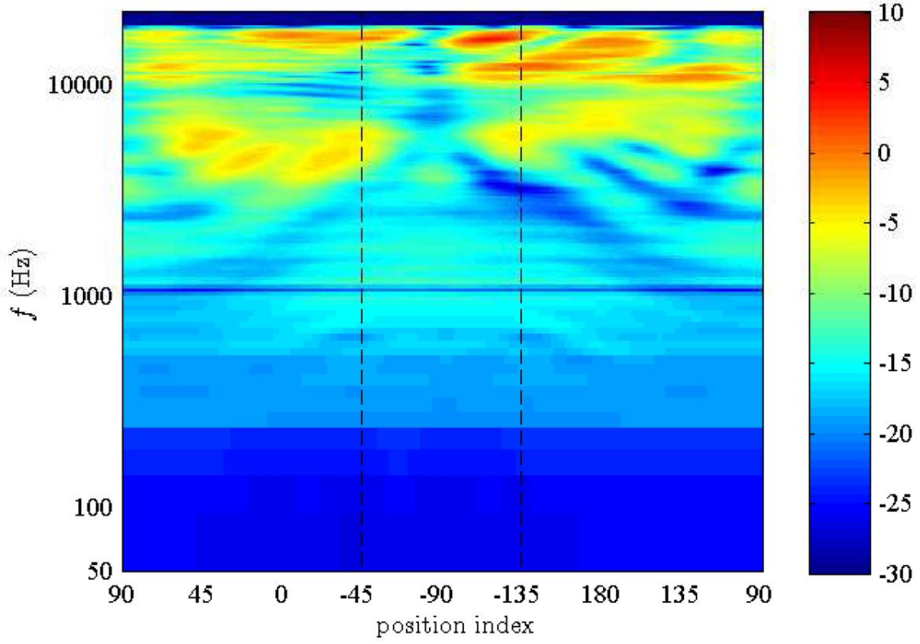
15th order model on incomplete data



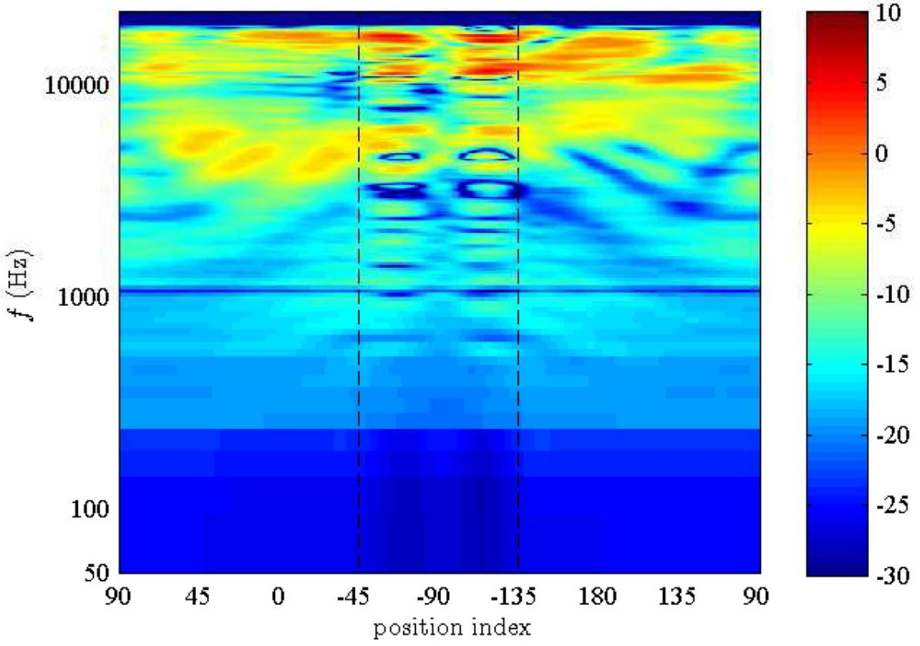
Regularization to the Rescue?

- Regularized least-squares fit can help prevent blow-up.
  - Regularization hurts the data we know to be correct.
  - Still a poor fit: artificial periodicity creeps in.

15th order model on complete data



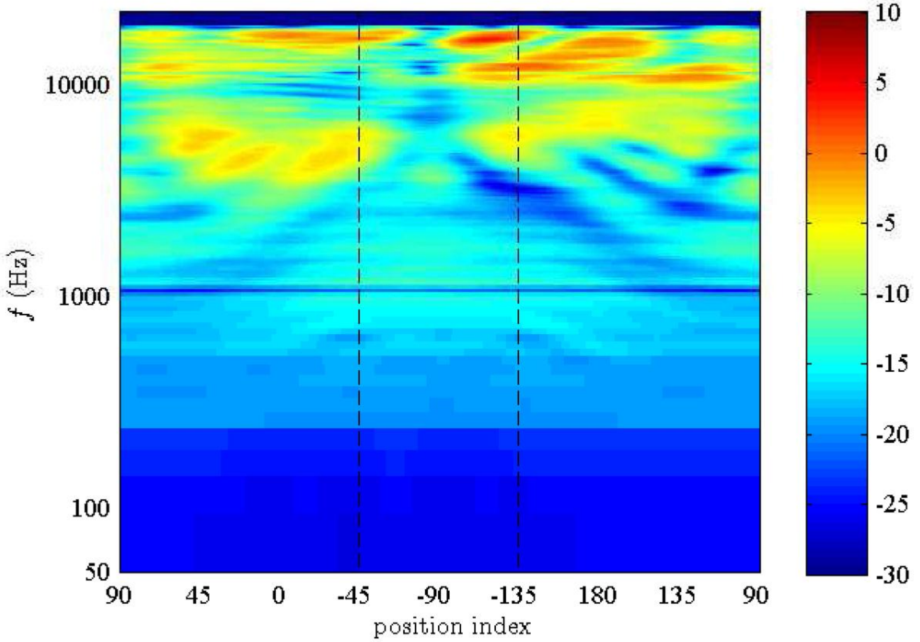
Regularized 15th order model on incomplete data



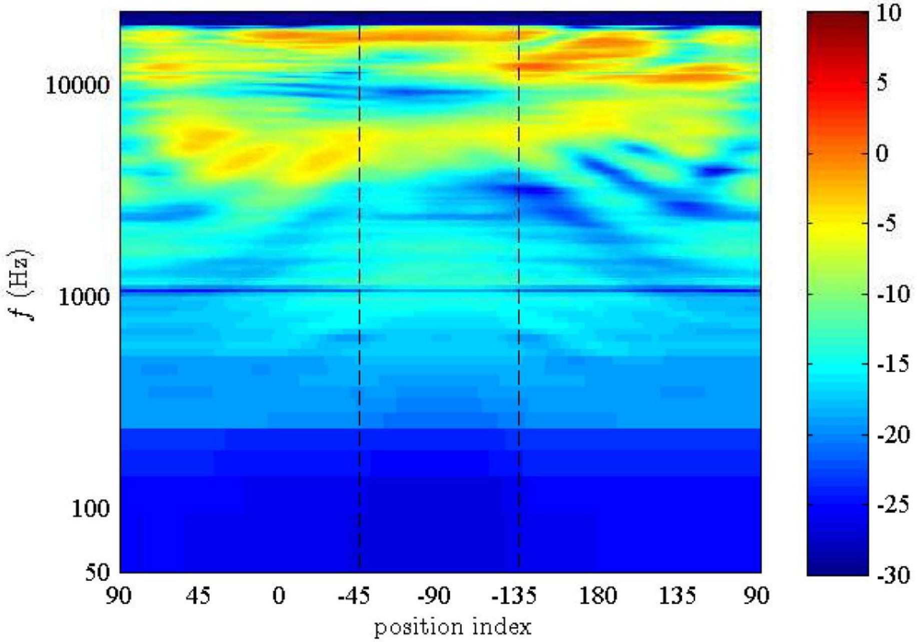
Non-Regularized Least-Squares Fit

- There is theoretically enough data for a 3rd order model.
    1. Extrapolate unknown data using a 3rd order model.
    2. Combine with the original data (leaves this unharmed).
    3. Perform 15th order non-regularized fit over the entire sphere.

15th order model on complete data



Proposed model on incomplete data



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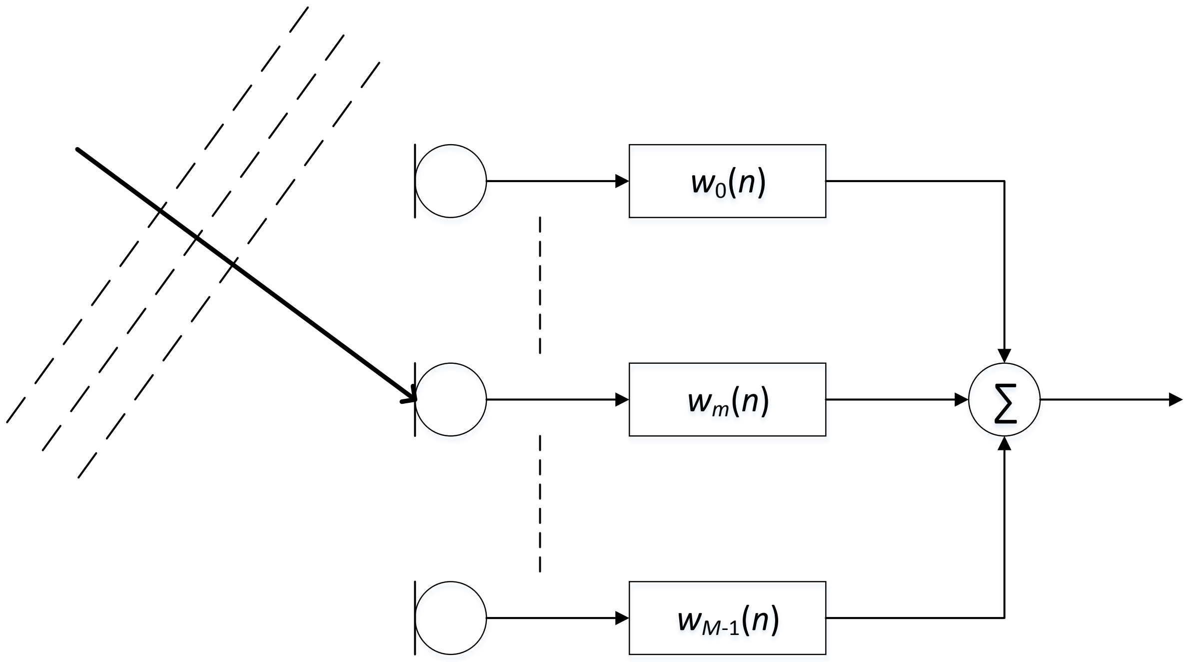
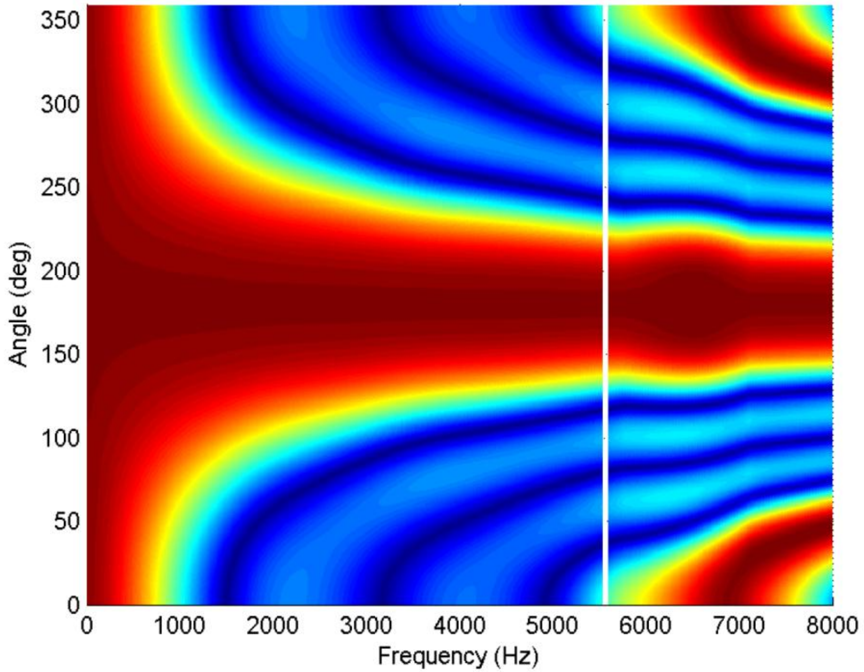
Delay and Sum Beamformer (DSB)

- DSB temporally **aligns wavefronts** so that they sum **coherently** in a given direction.

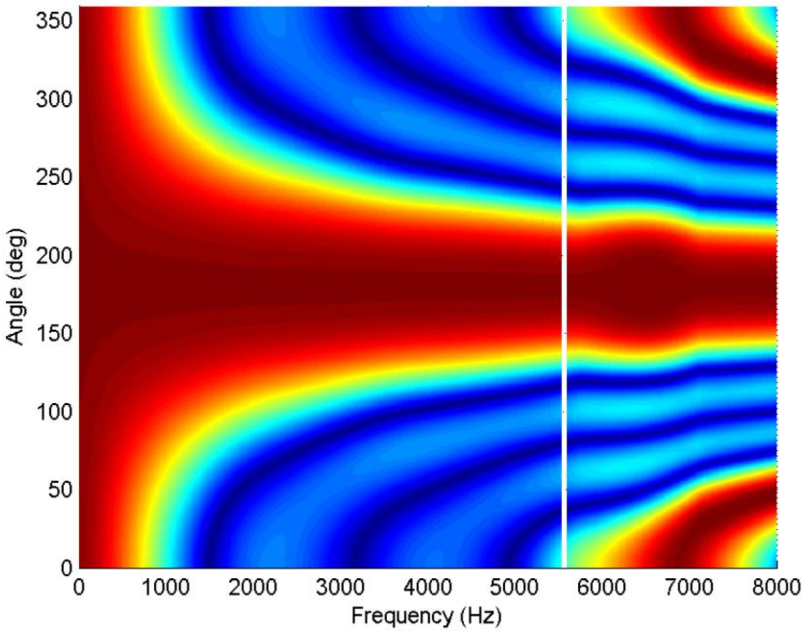




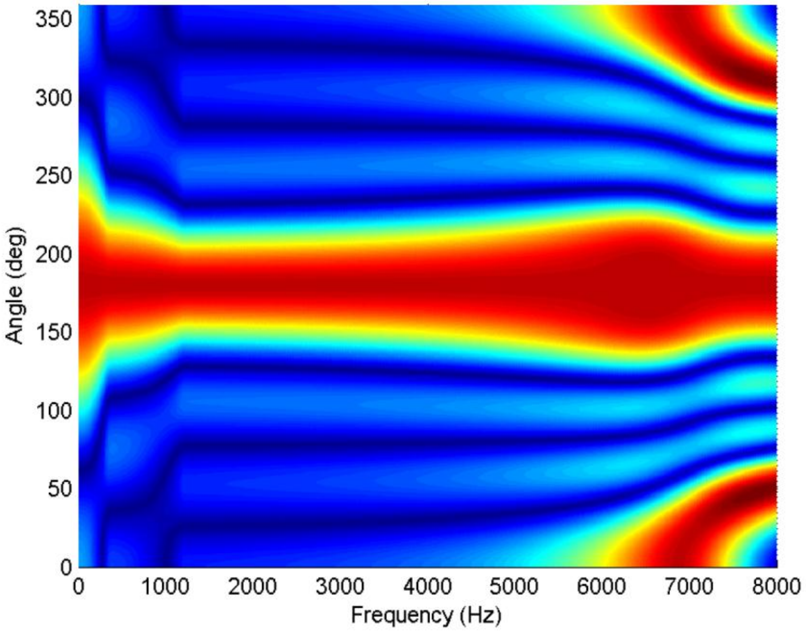
Optimal Superdirective Beamformer

- Calculate weights by **optimization** to synthesize a **frequency-independent** pattern.
  - Can exploit true directivity pattern.
  - Practical limitations with **white noise gain** at low frequencies.

Delay and Sum Beamformer



Superdirective Beamformer



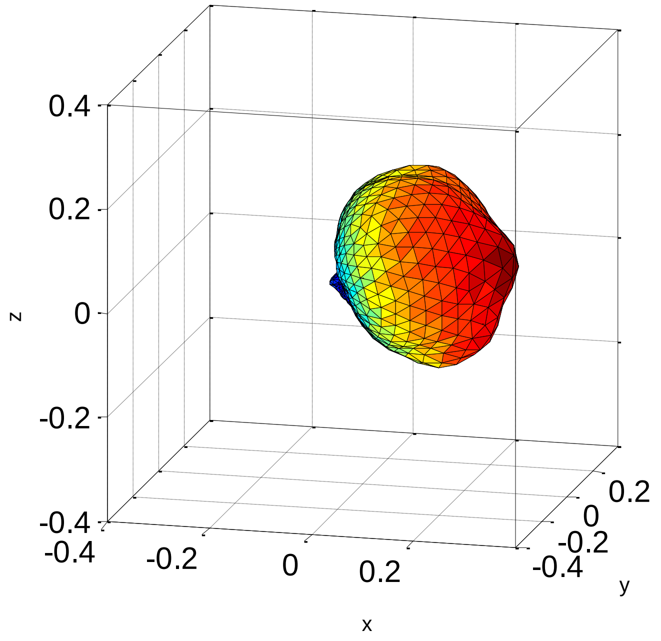
Kinect for Xbox 360

- RGB camera
- Depth camera
- Motorized tilt
- 4 cardioid microphones

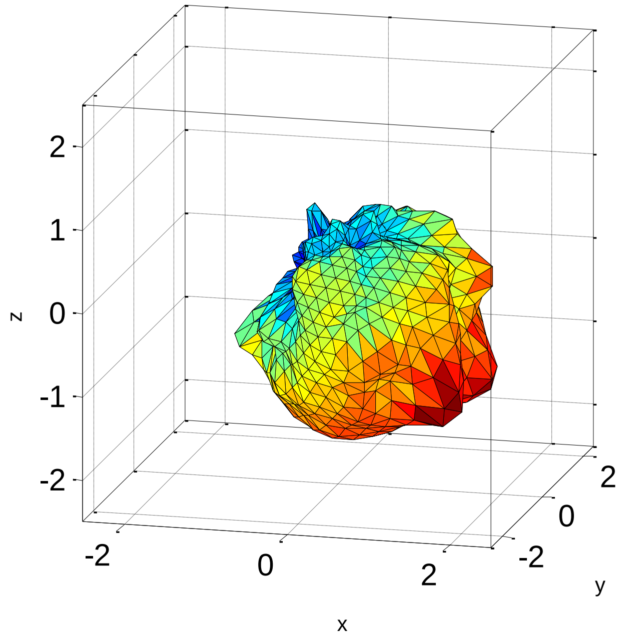
Kinect for Xbox 360

- Classic cardioid at 1 kHz, points to the floor at 5 kHz.
- Need to design with measured directivity patterns in mind.

Microphone Directivity at 1 kHz



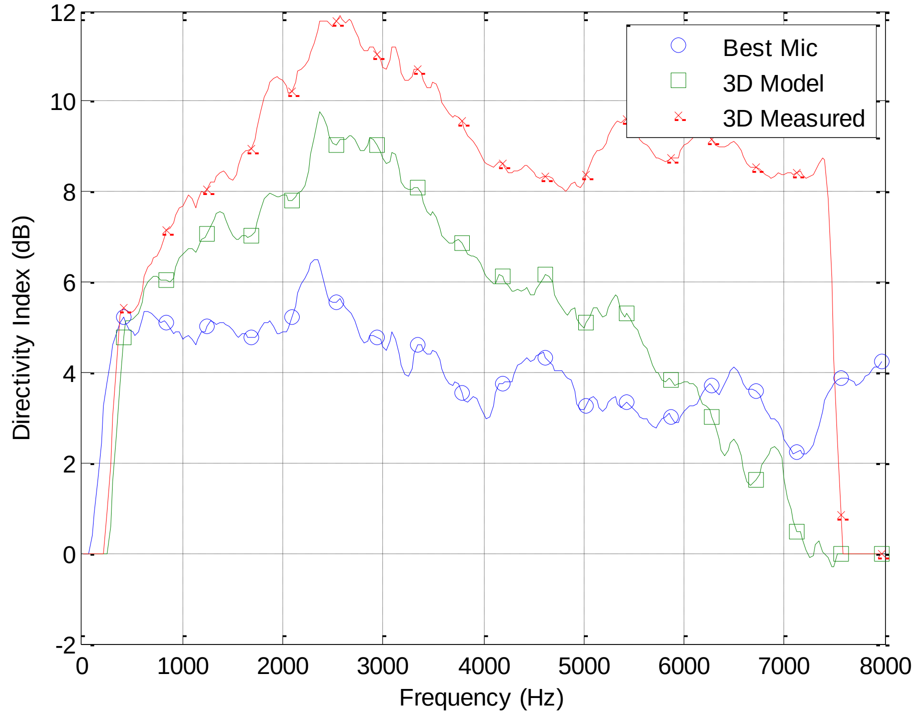
Microphone Directivity at 5 kHz



Performance Metrics

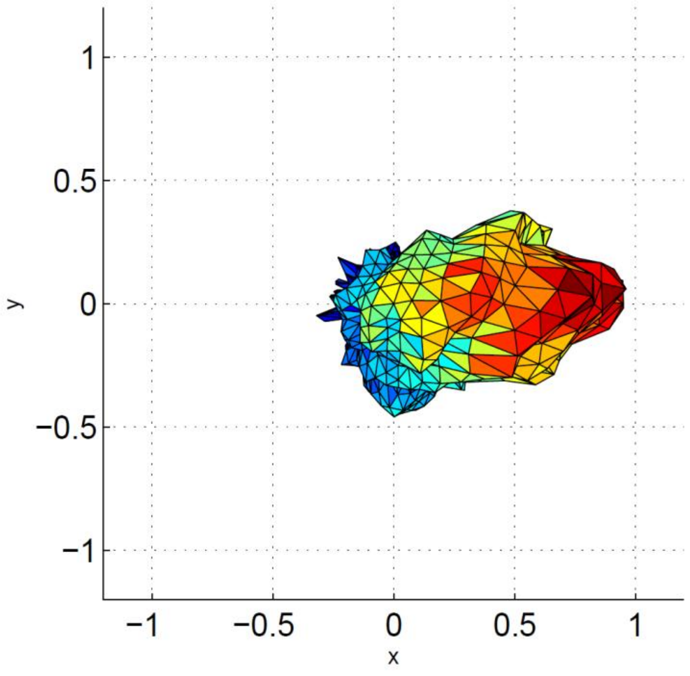
- Directivity index: log ratio of wanted signal to unwanted signals
  - Examples: Single cardioid: 4.8 dB, single omni: 0 dB.
  - **~4-6 dB improvement** over best microphone
  - Cardioid model OK up to ~3 kHz
  - Cardioid model suffers > 6 kHz
- Speech recognition task:
  - **50% relative** (5% absolute) in word error rate over 3D model.

	PESQ (1-4.5)	WER (%)	SER (%)
Best Mic	2.13	18.47	31.67
3D Model	2.64	9.79	15.00
3D Measured	2.66	4.92	9.17

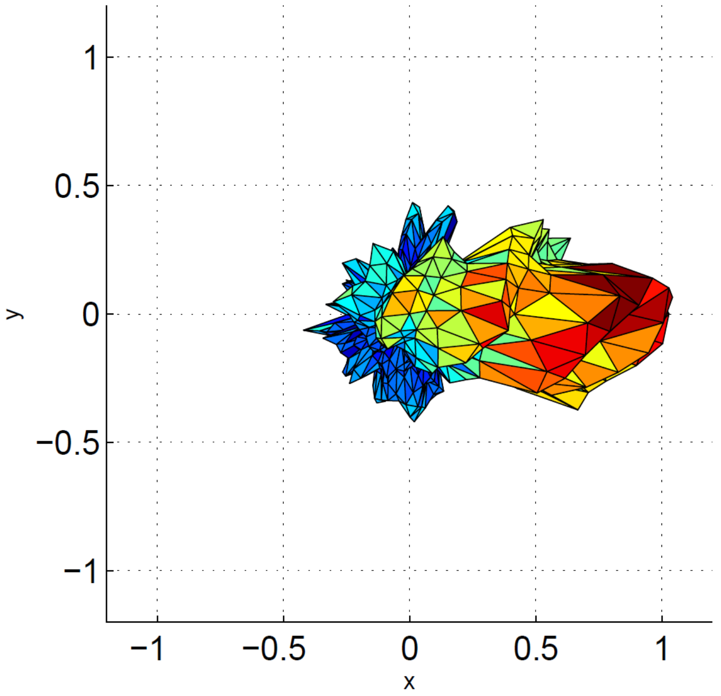


Optimal Beamforming with Kinect

Beamformer with 3D cardioid model at 1 kHz



Beamformer with 3D measurements at 1 kHz

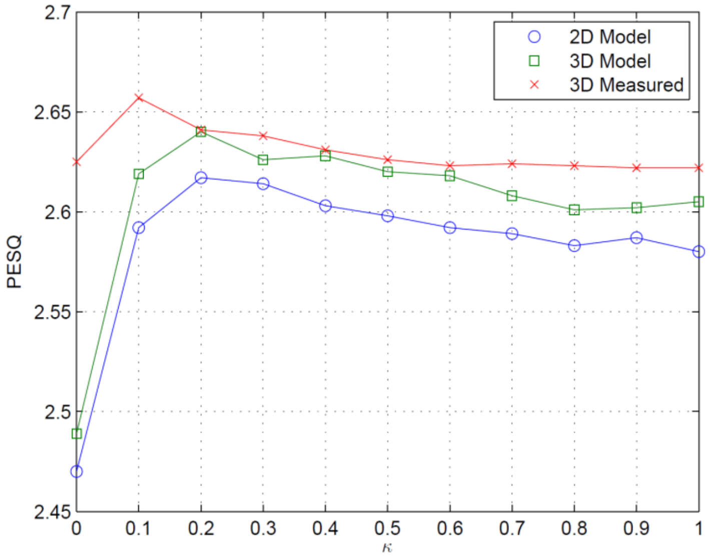


M. R. P. Thomas, J. Ahrens, I. J. Tashev, "Optimal 3D beamforming using measure microphone directivity patterns," *IWAENC* 2012.

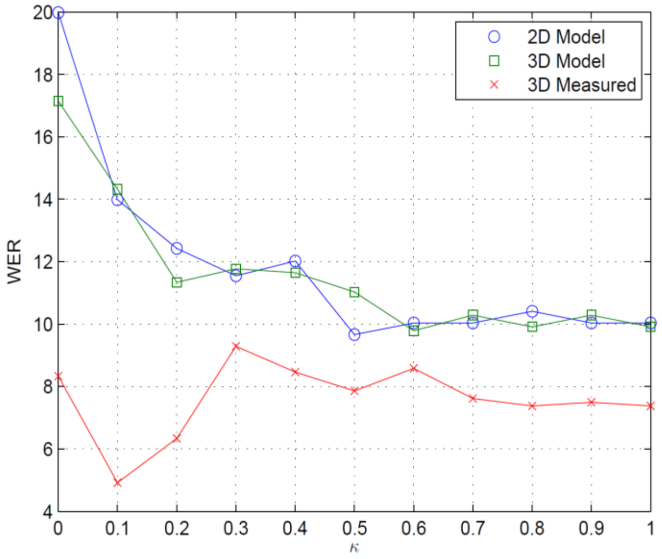
Beamforming with Kinect – Regularization

- Problem: danger of becoming **too device-specific**
  - Account for manufacturing variations by adding **regularization** – becomes closer to delay-and-sum (lower performance).
  - Solution: a) **calibrate** during manufacture (expensive), or b) determine necessary regularization.

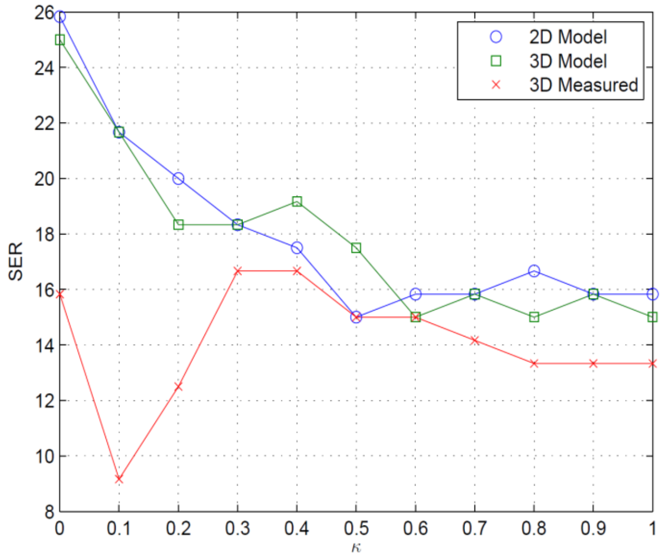
PESQ



Word Error Rate



Sentence Error Rate



M. R. P. Thomas, J. Ahrens, I. J. Tashev, “Beamformer design using measured directivity patterns: robustness to modelling error,” *APSIPA,* 2012.

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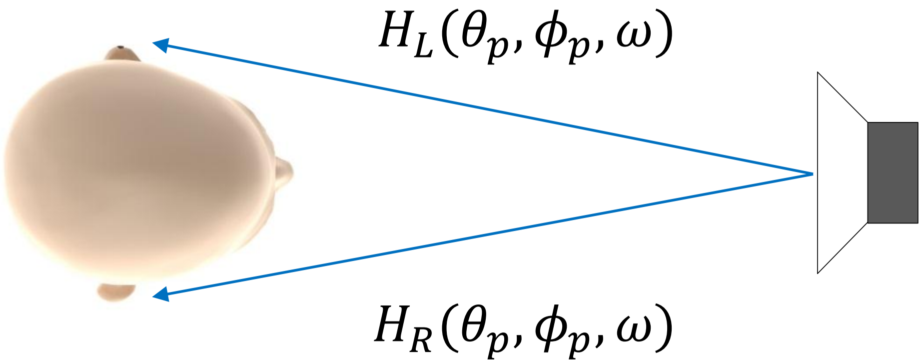
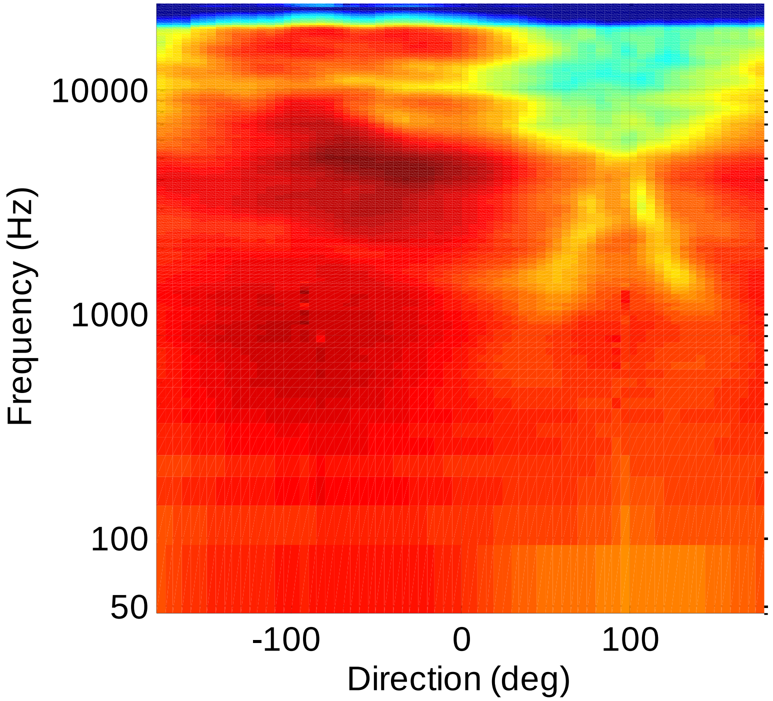
Head-Related Transfer Functions

- HRTFs capture acoustic properties of the head
  - Enables rendering of 3D audio over headphones





Personalizing HRTFs

- HRTFs are **highly personal**
  - Function of **anthropometric features** (head width, height, ear position, size etc.).

- HRTFs provide **temporal** and **spectral** cues for source localization
  - Inter-aural time differences (**ITD**)
  - Inter-aural level differences (**ILD**)
  - Pinna resonances
    - ITD and ILD insufficient: they help localize to within a **cone of confusion**.
    - Introduce subtle **spectral cues** to help resolve elevation and front/back.

- Should be used in conjunction with real-time **head tracking**
  - **Head rotations** provide additional information for source localization.

Measuring and Estimating HRTFs

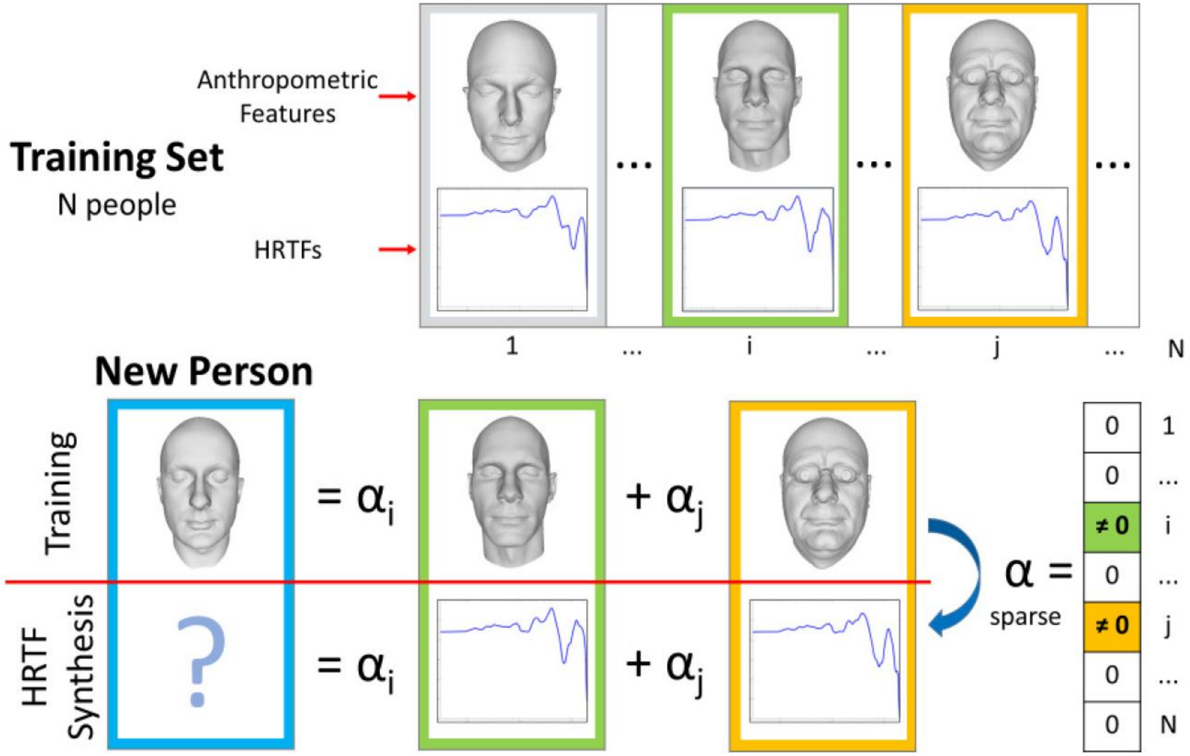
1. Anechoic chamber and measurement rig
   - Accurate
   - Expensive

2. Finite-element modelling
   - **Less accurate** than measurement
   - **Slow**: can take a single machine several days

3. Estimate from anthropometric data
   - **Less accurate** than measurement
   - Requires **no invasive measurements**

HRTF Magnitude Synthesis

1. Measure anthropometric features on a large database of people.
2. Represent a new candidate's anthropometric features as a **sparse combination** α of people in the database.
3. Combine HRTF magnitude spectra with **same weights** α to synthesize personalized HRTF.

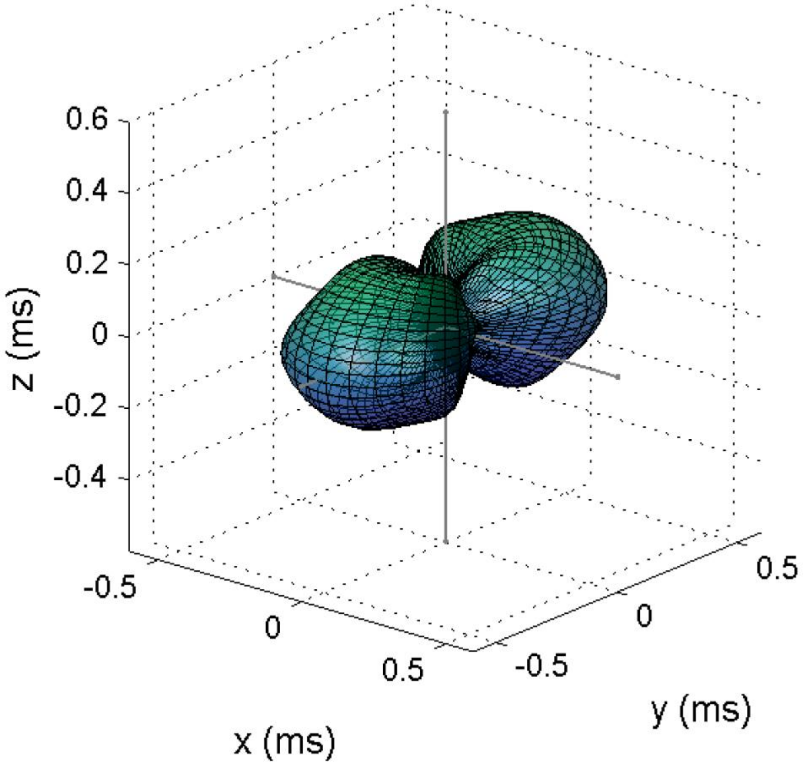


P. Bilinski, J. Ahrens, M. R. P. Thomas, I. J. Tashev, J. C. Platt, "HRTF magnitude synthesis via sparse representation of anthropometric features," *ICASSP,* 2014.

HRTF Phase Synthesis

- Most **ITD contours** have near figure-of-8 shape.
- Phase synthesis by scaling average ITD contour.
  - Also estimated with anthropometric features.
  - Appears to be perceptually sufficient with informal testing.

Average ITD Contour



I. J. Tashev, "HRTF phase synthesis via sparse representation of anthropometric features," *ITA Workshop,* 2014.

Objective Evaluation of HRTF Magnitude Synthesis

- Very difficult to evaluate **perceptual quality** of HRTFs
  - Many more **degrees of freedom**: both spatial localization and perceived quality.
    - Not necessarily correlated.
  - Risk of ‘**uncanny valley**’ effects: as realism increases, so too do the standards by which we judge the rendering quality.
- **Log spectral distance** used as an **objective measure** of magnitude response fit:

Direction	Frequency [Hz]	Best Classifier	Sparse Representation	HATS	Worst Classifier
Straight	50 – 8000	2.46	3.53	6.13	7.86
	0 – 20000	4.20	5.58	7.97	10.25
All	50 – 8000	4.32	4.49	7.35	7.85
	0 – 20000	9.48	9.88	13.77	14.93

HRTF Synthesis – Conclusions

- This is by no means a solved problem!

- First step is **reliable** and **consistent** measurement of HRTFs.

- Subjective testing for HRTFs is a big research problem
  - How is **perceived quality** linked to **localization accuracy**?
  - How soon does **listener fatigue** set in?
  - What is the nature of the **uncanny valley**?

- Objective measures equally in their infancy
  - Classic measures (PESQ, LCQA, LSD, MSE etc.) do not measure spatial component.

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Conclusions

- Directivity patterns are everywhere!

- Many practical methods for measurements with real devices including:
  - Microphone (arrays)
  - Loudspeakers
  - Head-related transfer functions

- Some degree of choice on source signal, loudspeaker configuration and interpolation / extrapolation of missing data.

- Practical uses in:
  - Beamformer design (improved weights synthesis adds no overhead at runtime).
  - Personalization of HRTFs.
  - Also loudspeaker enclosure design.

Thank you!

Questions?