THE AMBISONIC DECODER TOOLBOX: EXTENSIONS FOR PARTIAL COVERAGE LOUDSPEAKER ARRAYS

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What is Ambisonics?

- Extensible, hierarchical system for representing sound fields
  - Says how something should sound, rather than specific speaker signals.
- Capture or creation
  - Microphone arrays
    - 2-D or 3-D
    - Natural B-format, Tetrahedral, Spherical arrays
  - Ambisonic Panners
- Reproduction
  - 2-D, “horizontal” or 3-D “with height” loudspeaker arrays
  - “Any” size or shape array of loudspeakers

What is an Ambisonic Decoder?

- In Ambisonics, the program format is independent of the reproduction layout.

- The decoder's task is to create the best *perceptual impression* possible that the sound field is being reproduced accurately, given the resources available
  - Bandwidth, number of speakers, configuration of speakers …

- We use the term "decoder" to mean the configuration for a decoding engine that does the actual signal processing

Goals for decoder design

- Mimic conditions of natural hearing
  - Constant amplitude gain for all source directions (*P*)
  - Constant energy gain for all source directions (*E*)
  - At low frequencies, correct reproduced wavefront direction and velocity (r_V)
  - At high frequencies, maximum concentration of energy in the source direction (r_E)
  - Matching high- and low-frequency perceived directions

- Getting r_E correct is the most difficult aspect
- Recent work shows that it is also the most important!

Designing Decoders

- Decoders for regular polygon and polyhedra loudspeaker arrays are easy to design
  - Build the speaker encoding matrix, K, by sampling the spherical harmonics at the speaker directions
  - Use pseudoinverse to find the basic decoding matrix M
  - rE guaranteed to point in same direction as rV
- However…
  - Room geometry or visual considerations often limit speaker placement
  - 3-D HOA requires placing more speakers above and *below* the listener

How you'd like to do it

AuraLab, San Francisco

A useful compromise

The Bubble, San Francisco

Tradeoffs

- Once we deviate from regular geometry
  - we must trade off localization accuracy for uniform loudness
  - Directions of rE and rV are not the same
- Localization degrades outside the area with a high density of loudspeakers
- Gerzon used nonlinear optimization for this
  - Many implementations: Wiggins, Moore & Wakefield, Tsang, BLaH
- Works well for small arrays (e.g., ITU 5.1)
- Convergence is slow for large HOA arrays (hrs)

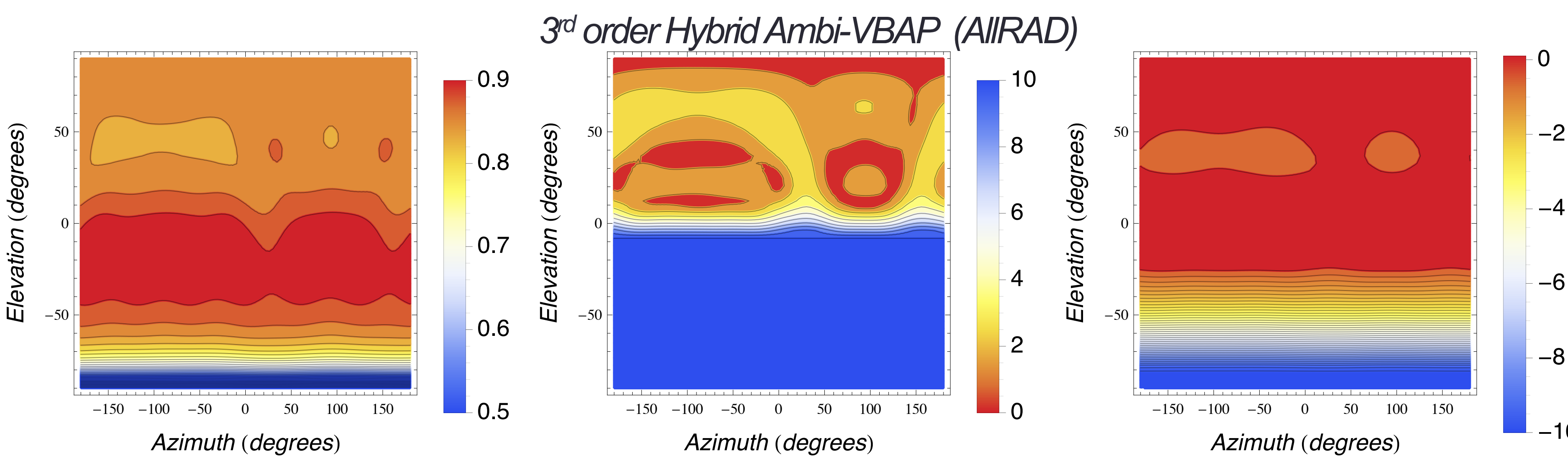
- IDHOA (Scaini and Arteaga) looks promising
  - Better objective function and zero out small coefficients

New Strategies in Toolbox

- Use an inversion technique suited to ill-conditioned matrices
  - Constant energy decoder
  - Truncated SVD
  - Energy limited
- Invert a well-behaved full-sphere virtual speaker array, map to a real array
  - Hybrid Ambisonic-VBAP
  - AllRAD (Zotter and Frank)
- Derive a new set of basis functions for which inversion is well behaved
  - Spherical Slepian Functions
  - EPAD (Zotter, Pomberger, Noisternig)

Are these decoders Ambisonic?

- Ambisonic theory specifies performance goals, not how to design a decoder
- We use the same criteria for these decoders
- But…
  - Apply them only to source directions in the covered part of the sphere
  - Require them be "well behaved" in other directions



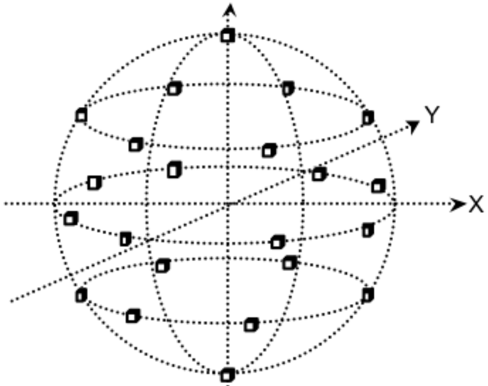
(a) r_E vs. Test Direction

(b) r_E Direction Error (degrees)

(c) Energy Gain (dB)

CCRMA Listening Room

- 22 identical loudspeakers in five rings
- Horizontal ring of 8 loudspeakers
- 2 rings of 6 loudspeakers, one 50° below horizontal and one 40° above
- 1 loudspeaker at each pole
- Array is almost regular
- Upper 15 used for hemispherical dome
- Full-sphere decoder described in our LAC2012 paper



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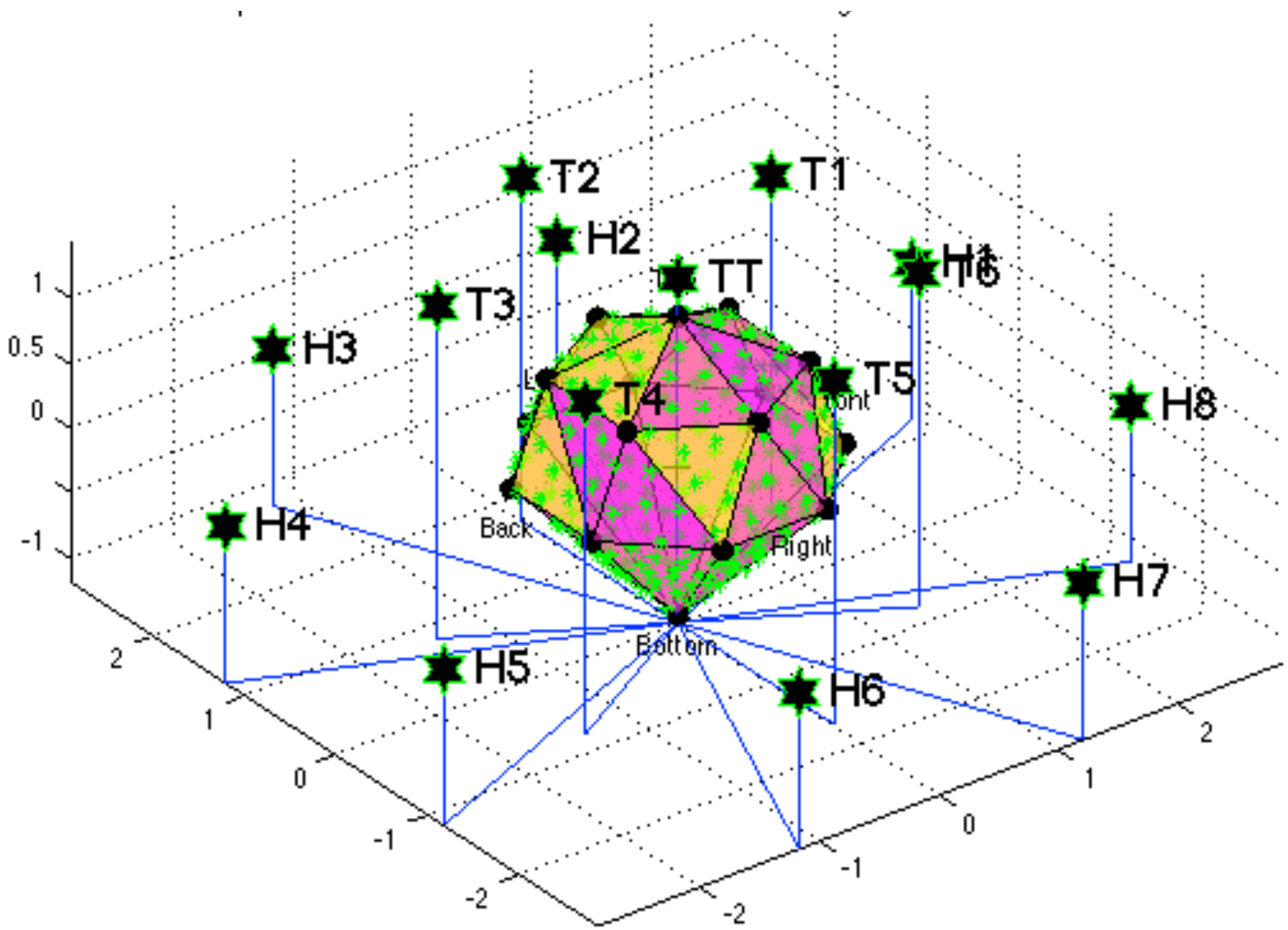
AllRAD – Hybrid Ambi-VBAP



- 240 point spherical design for virtual speaker array
- Dome of upper 15 loudspeakers of CCRMA Listening Room, 8-6-1
- Imaginary speaker at bottom
- Design procedure detailed in paper

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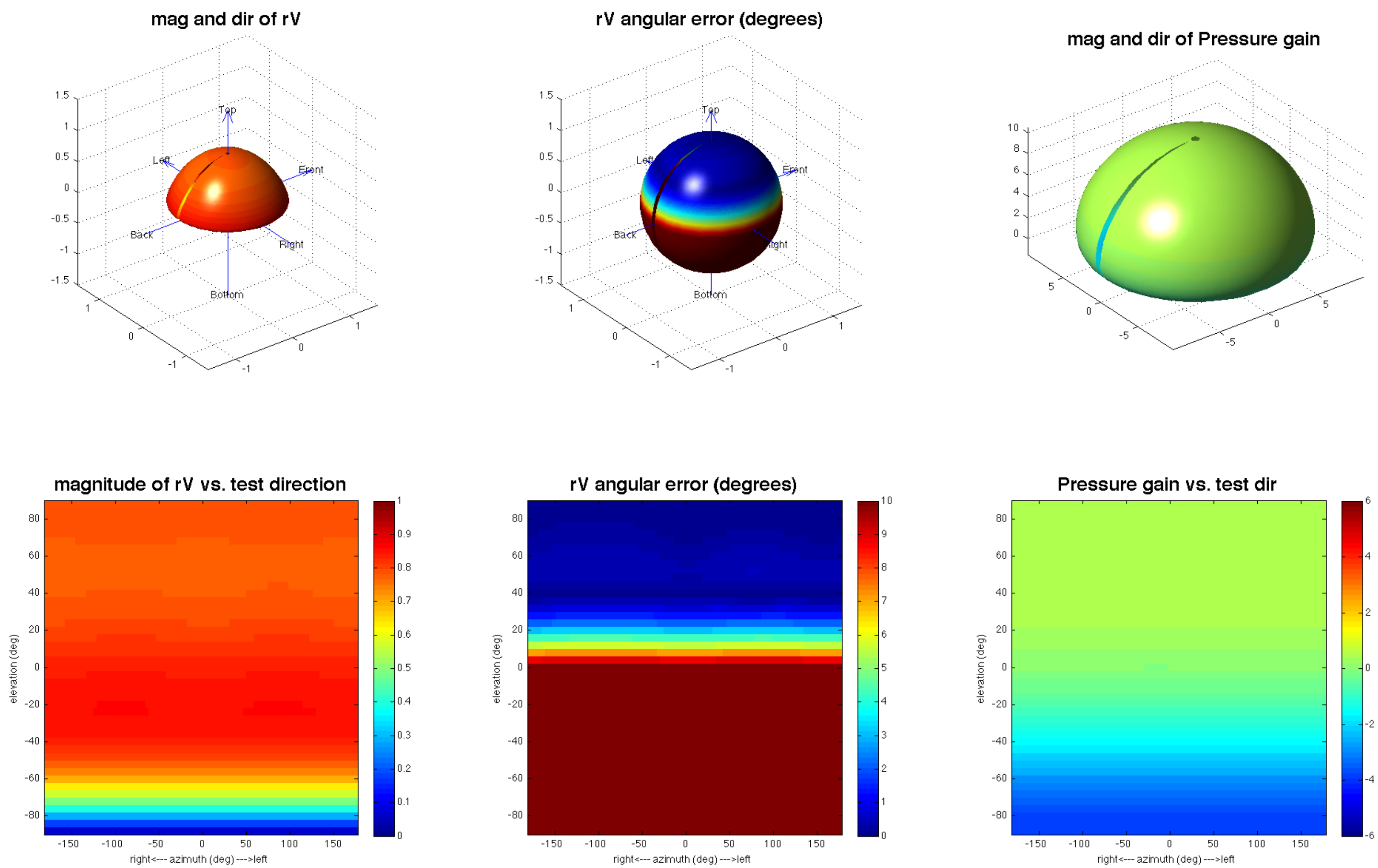
AllRAD performance r_V



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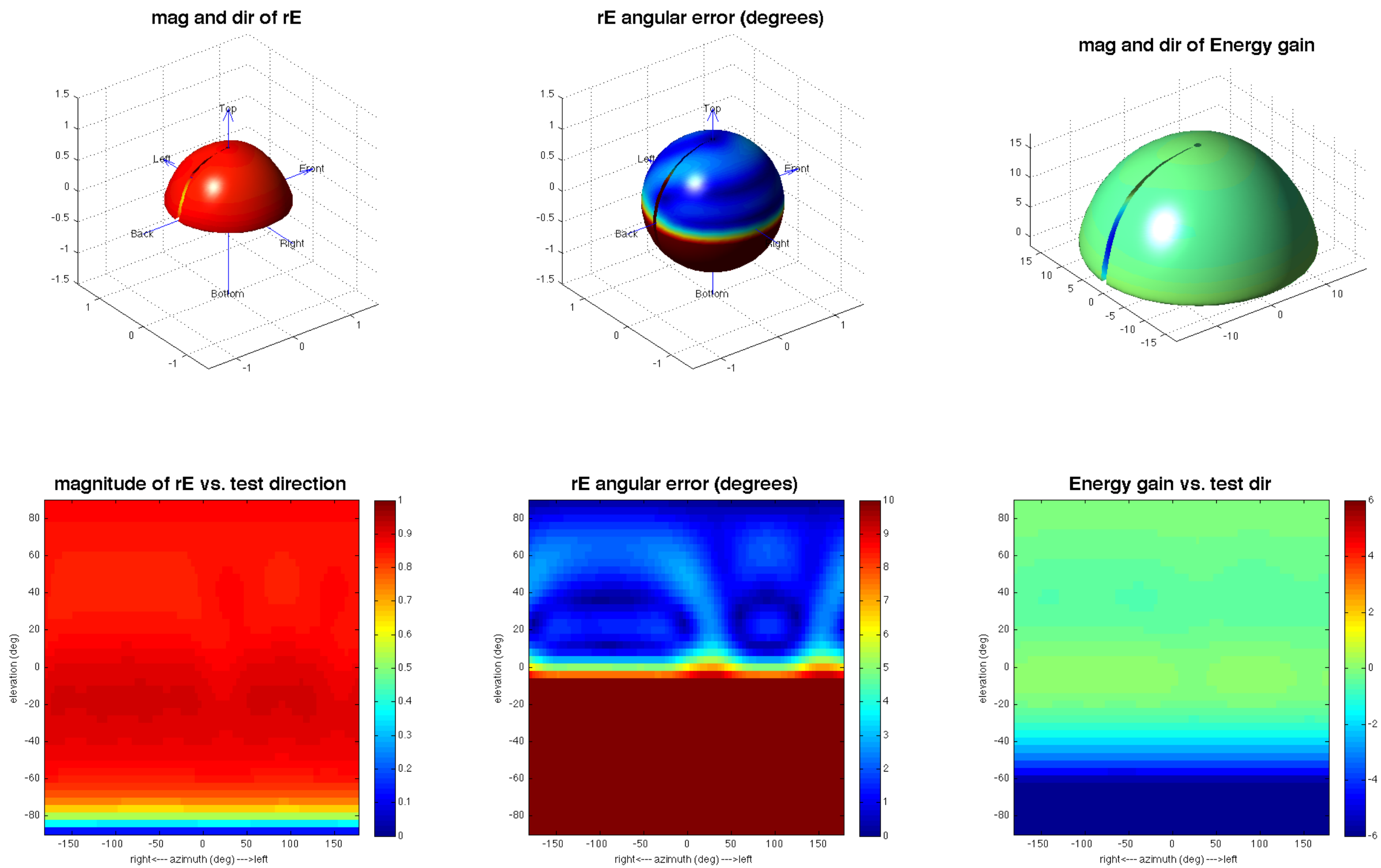
AllRAD performance r_E



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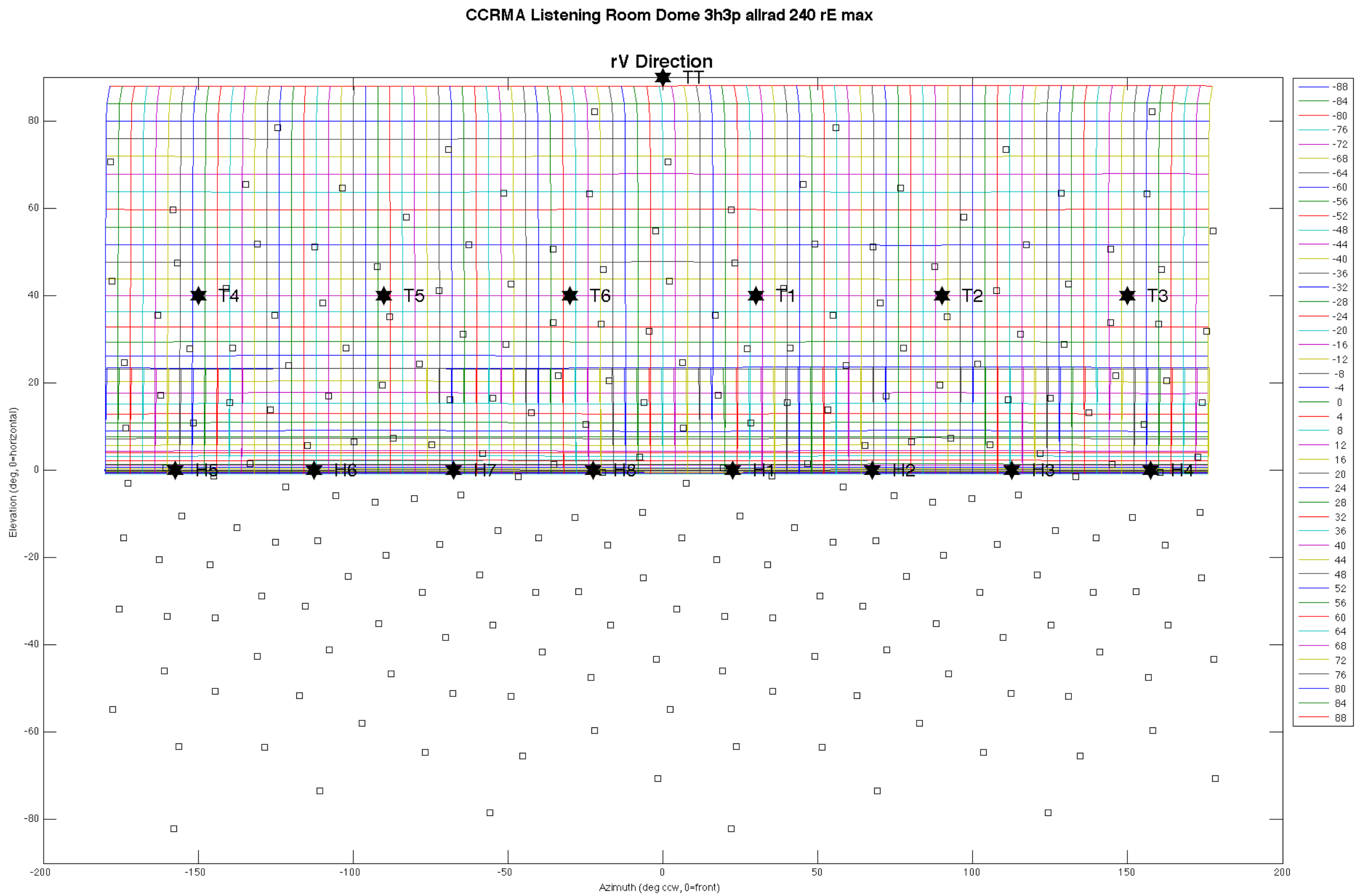
AllRAD r_V direction grid



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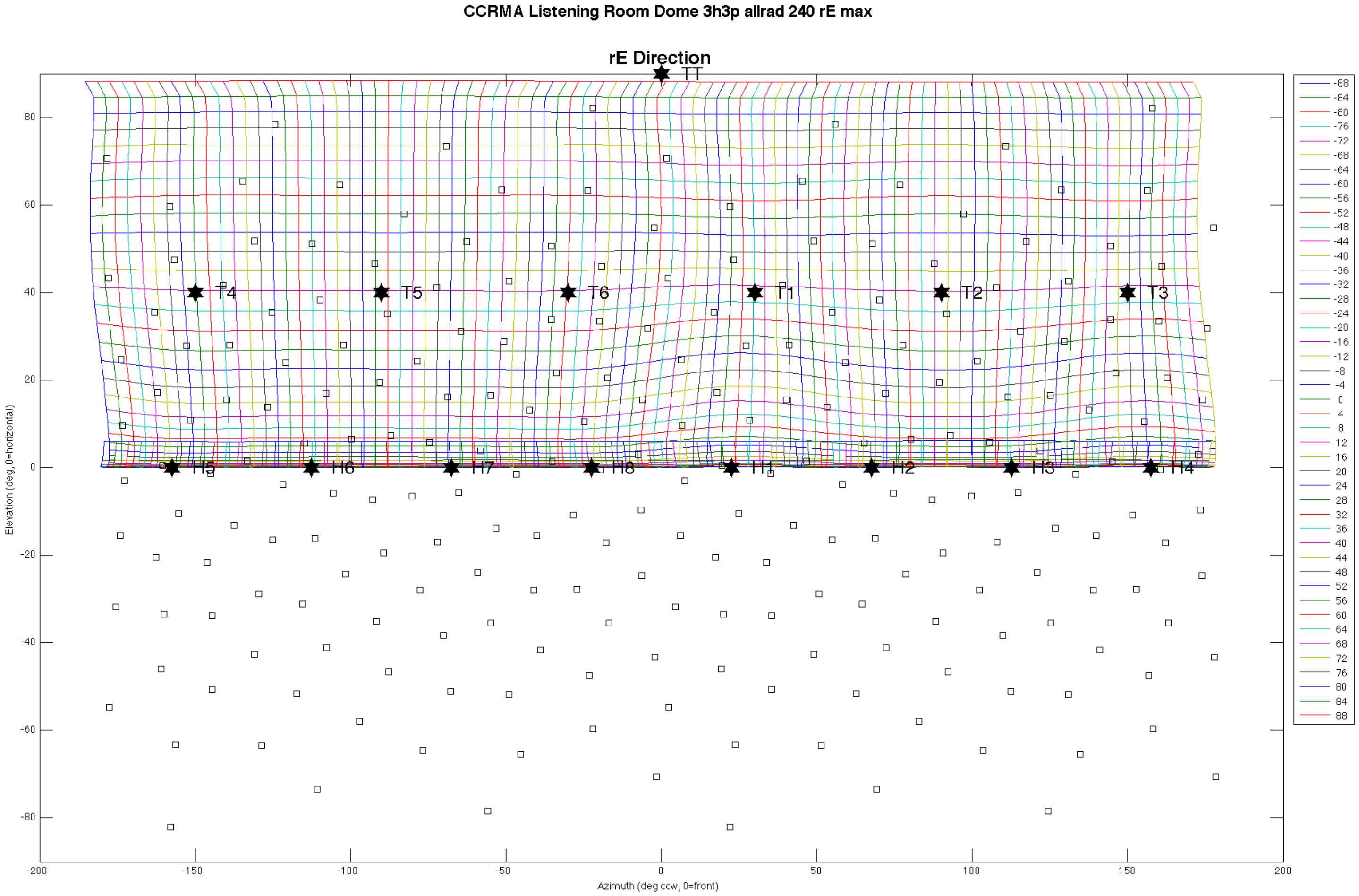
AllRAD r_E direction grid



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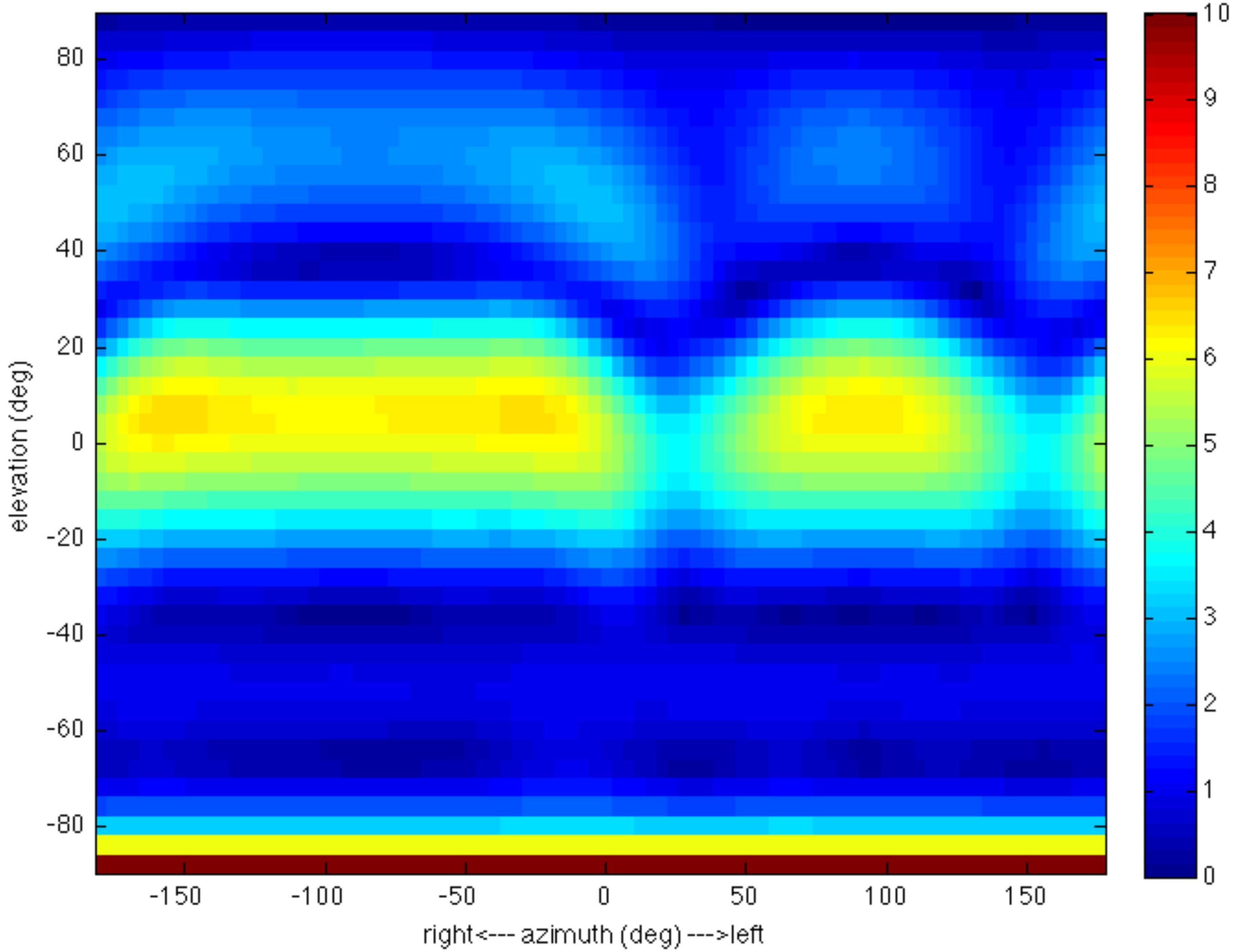
CCRMA Listening Room Dome 3h3p allrad 240 rE max
rV rE Direction Difference



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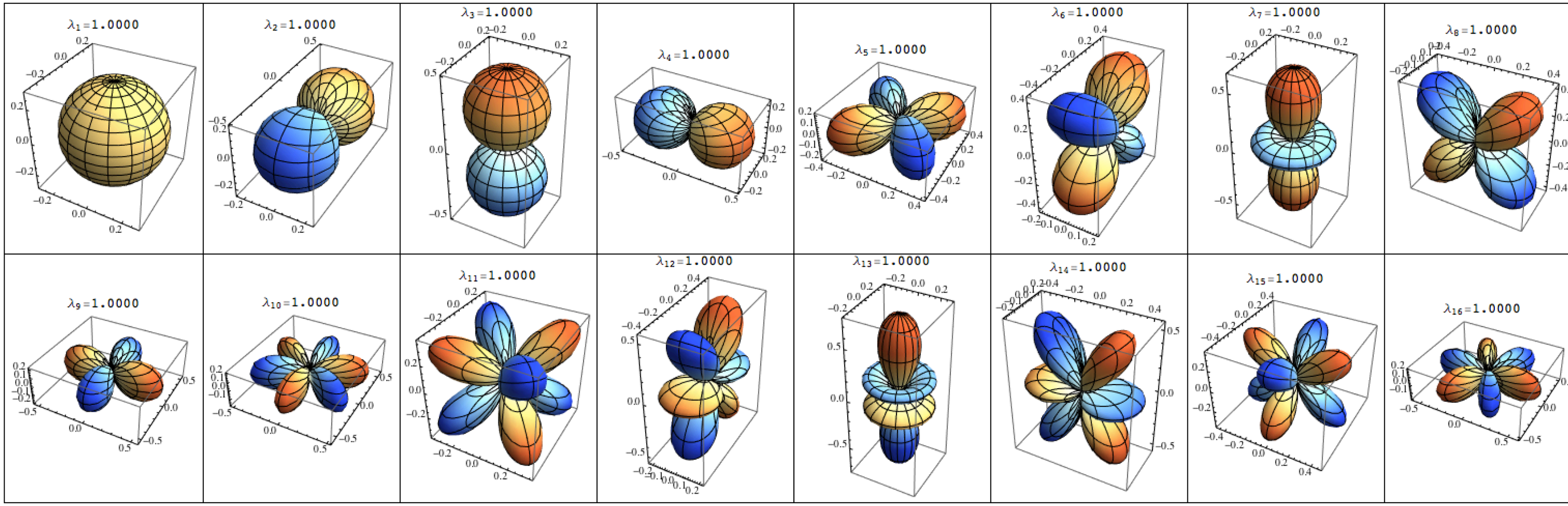
Spherical Slepian Functions

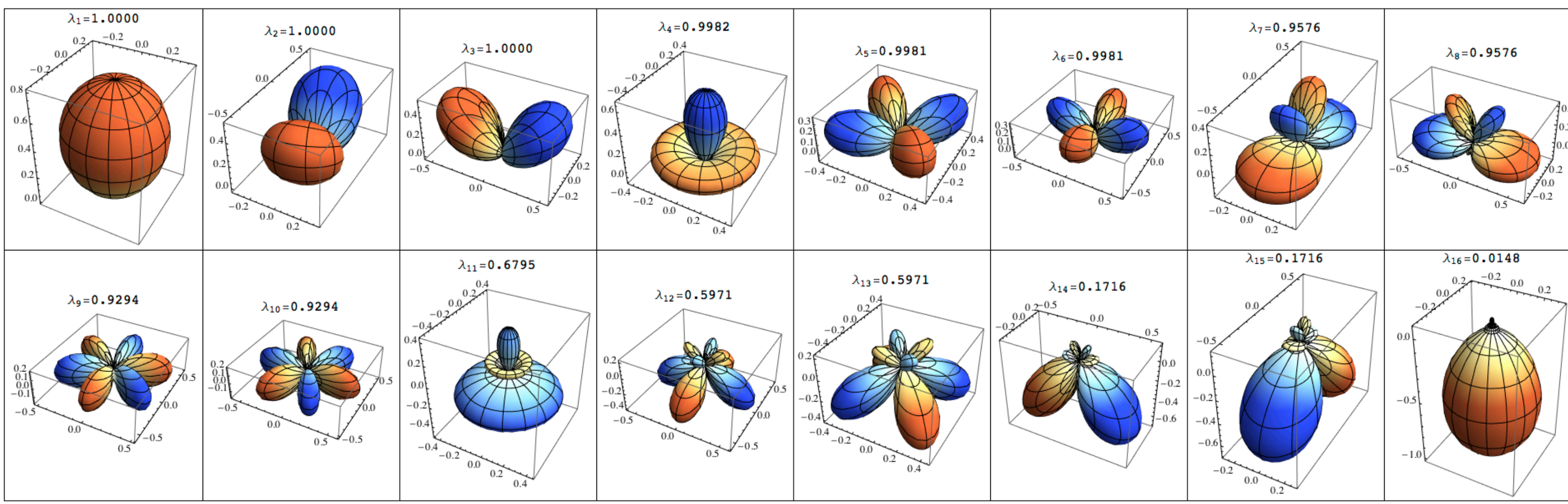
- Linear combinations of spherical harmonics
- Produce a new set of basis functions that are zero outside the region of interest on the sphere
- Remain orthogonal within the region
- Used in satellite geodesy to model earth's gravitational and magnetic fields from incomplete data

- In Ambisonic decoding, we can specify a region of the sphere, a dome or a ring, and derive a well behaved set of basis functions for that region.
- Design procedure detailed in paper

3rd order spherical harmonics (blue = inverted polarity)



3rd order spherical Slepian functions for +90° to -30° dome (first 13 used for decoder)



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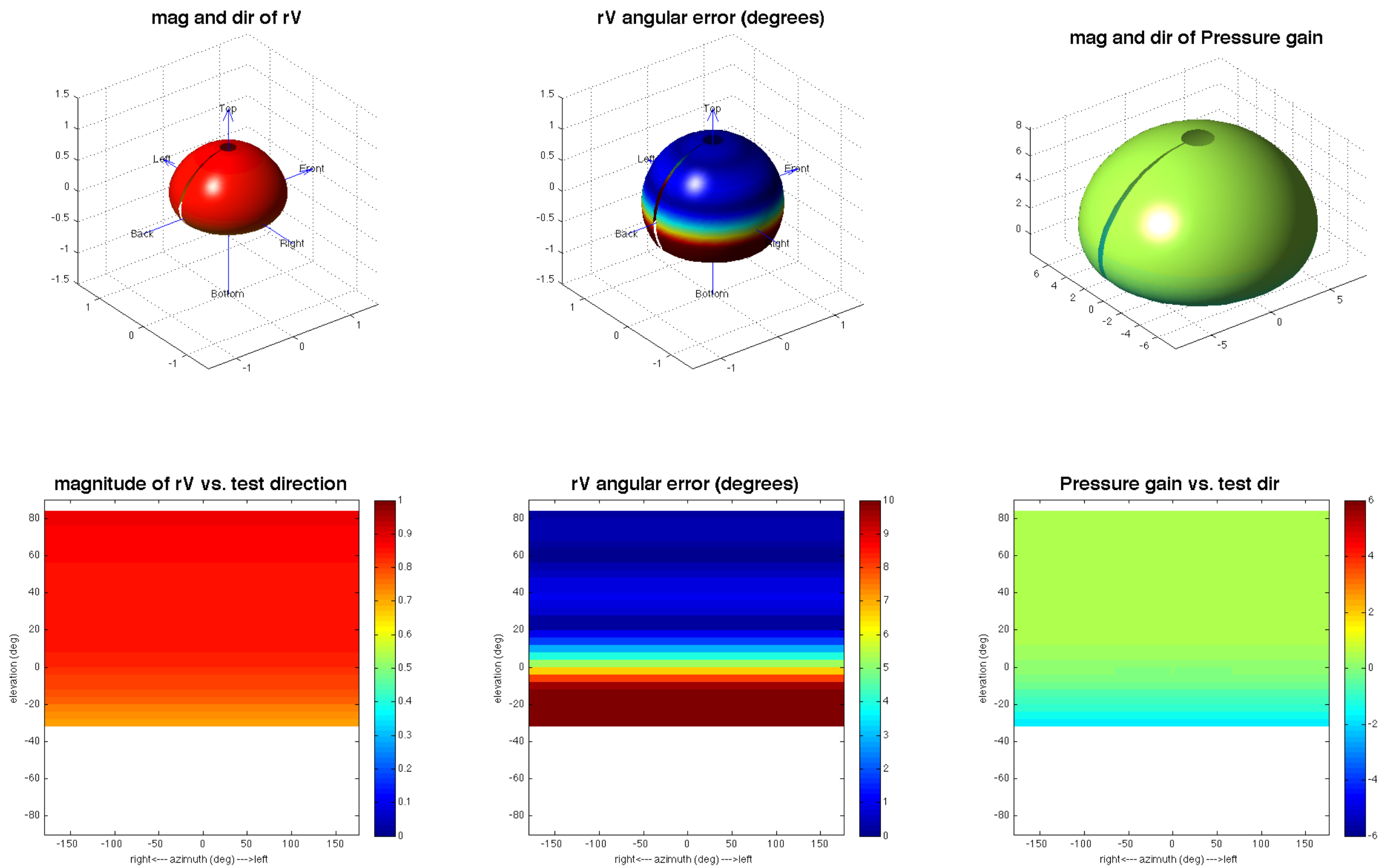
Spherical Slepian performance r_V



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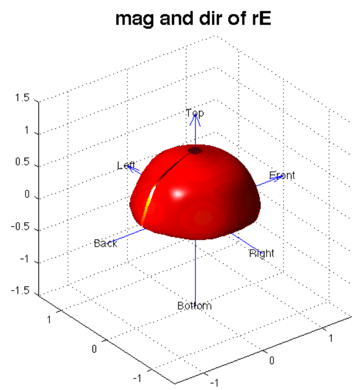
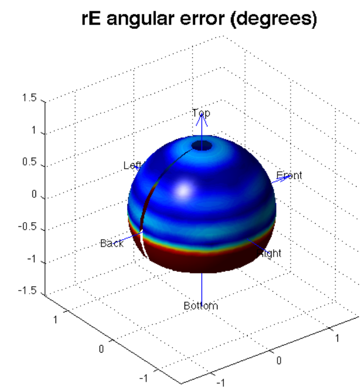
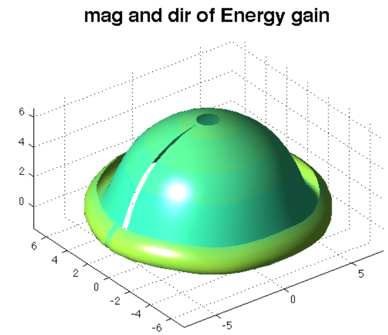
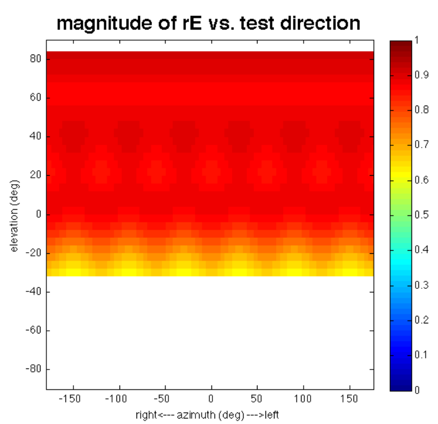
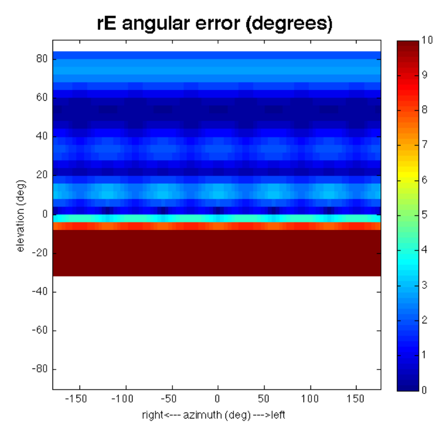
Spherical Slepian performance r_E

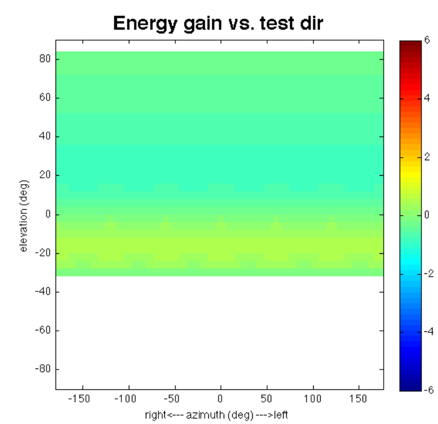












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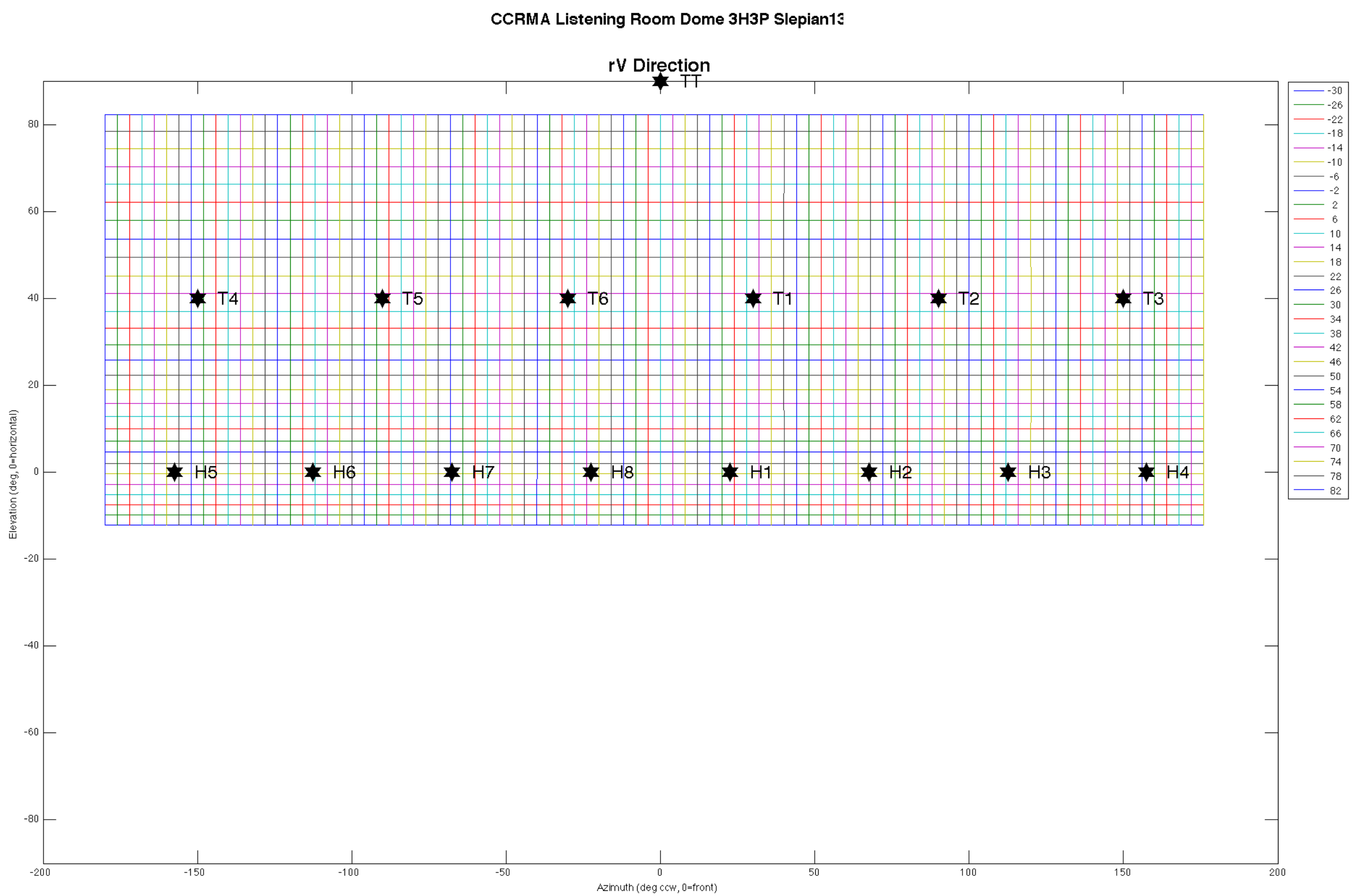
Spherical Slepian r_V direction grid



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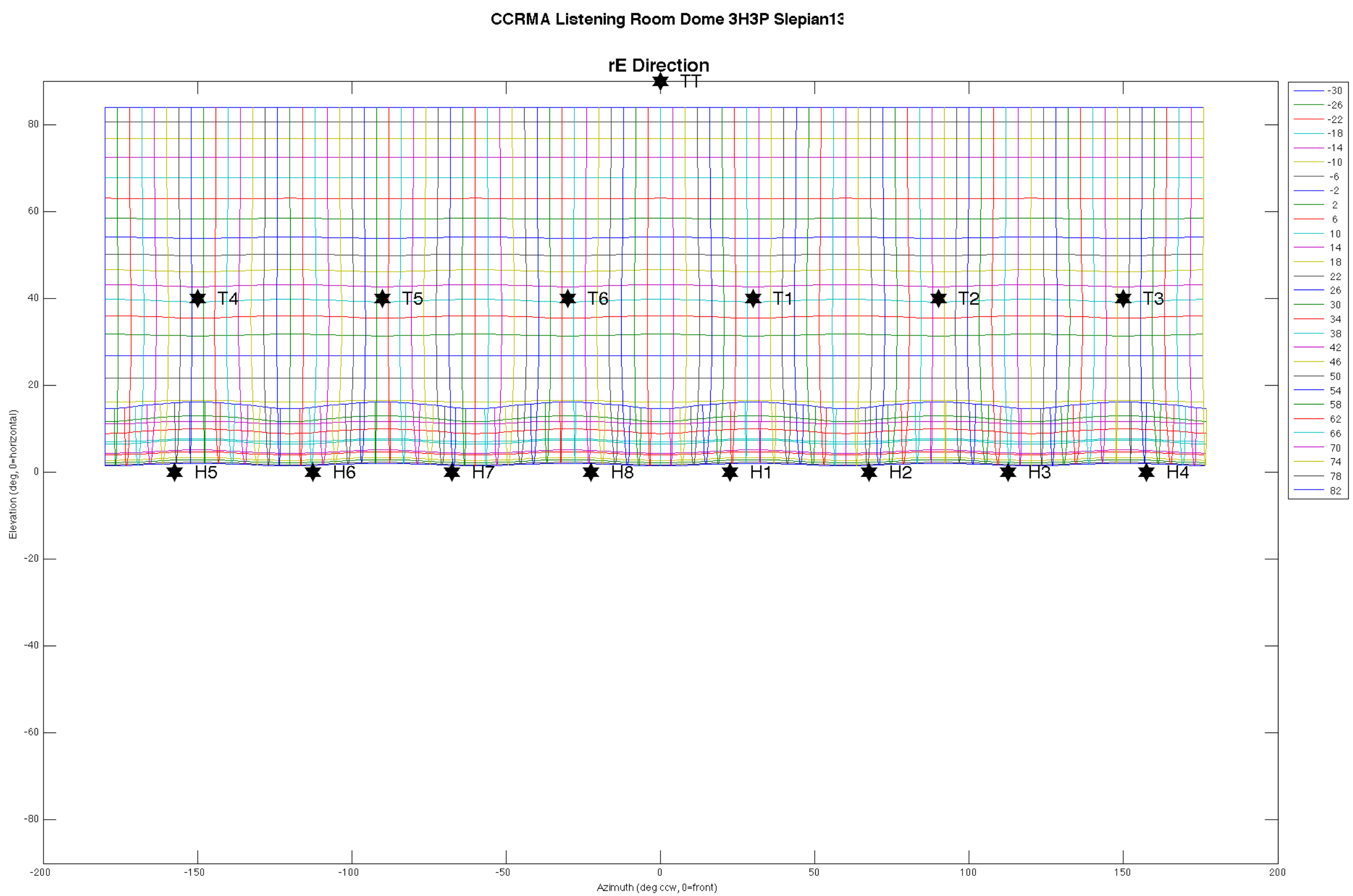

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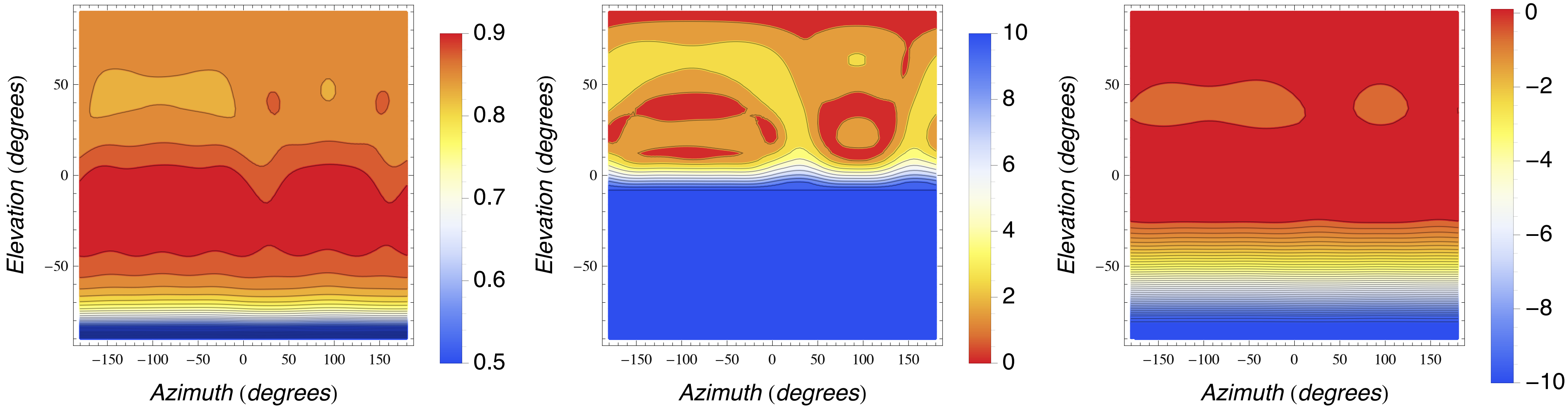
3rd order Hybrid Ambi-VBAP (AllRAD)

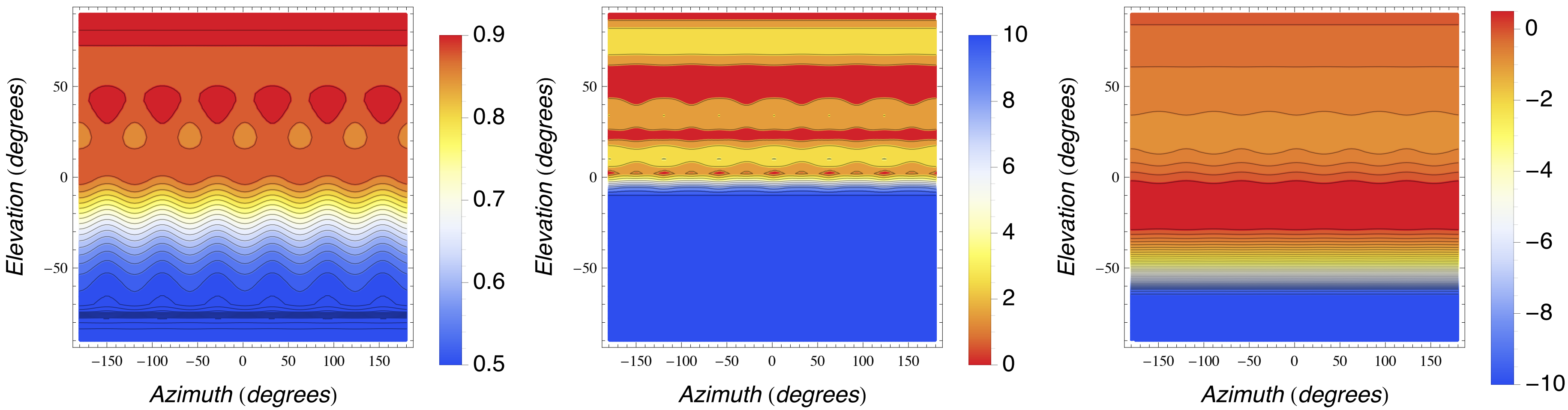


(a) r_E vs. Test Direction

(b) r_E Direction Error (degrees)

(c) Energy Gain (dB)

3rd order spherical Slepian function (EPAD)



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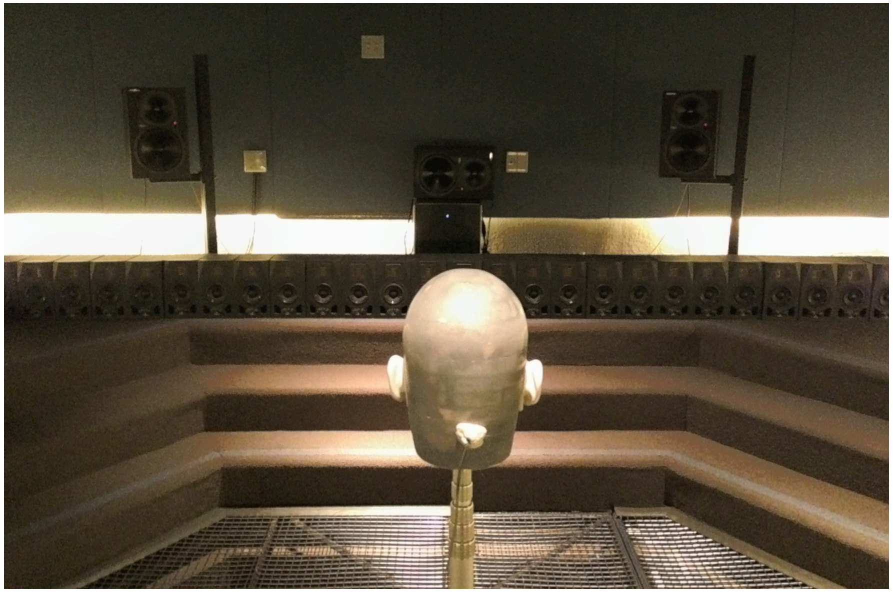
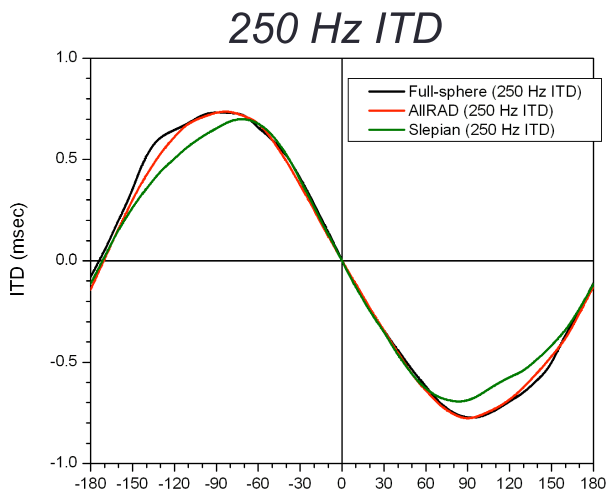
In situ performance measurements

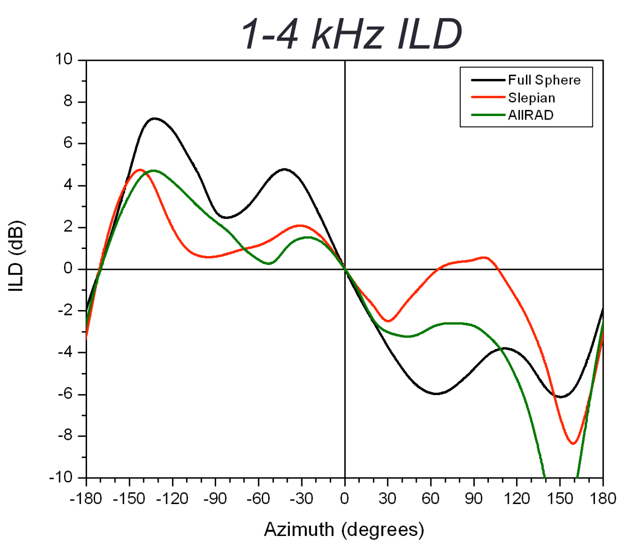


- Dummy head and reference omni
- Dome array using upper 15 speakers in CCRMA's listening room (8-6-1)

- Tested
  - AllRAD Dome
  - Spherical Slepian Dome
  - Full-sphere (from LAC2012)
- Collected
  - individual speaker IRs
  - Ambisonically panned IRs at 10° azimuth, 30° elevation intervals for each decoder
- Analyzed horizontal data
  - 250 Hz ITD (r_V)
  - 1 to 4 kHz ILD (r_E)

ITD and ILD measurements





Observations

- The measured ITDs were similar with the three decoders but ILDs were very different
- This supports the subjective observations that the three decoders sound different
- Detailed analysis is pending

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Informal listening tests

- 3rd-order test programs
  - Full-sphere mix of “Babel” by Allette Brooks (Jay Kadis)
  - *Chroma XII* by Rebecca Sanders (Jörn Nettingsmeier)
- Both dome decoders sounded good subjectively (but different!)
  - Compact and directionally accurate localization down to horizon
  - Faded below horizon
  - SSF decoder sounded brighter and more detailed than AllRAD
- Neither decoder sounded as good the full-sphere reference decoder
- 1st-order orchestral recording not reproduced well
  - Most of orchestra is below the horizon

Decoding Engine

- New decoding engine written in FAUST
  - No inherent limit on order
  - Dual band, NFC filters, distance compensation, …
- Toolbox writes out configuration section, appends implementation
- Compiles to LADSPA, LV2, Pd, Supercollider, VST, AU …
- Can be used independently of toolbox
- Drawback: Configuration “baked into” plugin

- Toolbox also writes out configuration files for
  - Kronlachner’s ambiX plugin suite
  - Adriaensen’s Ambdec

Implementation

- Toolbox runs in MATLAB and GNU Octave
  - Implements all known channel ordering and normalization conventions; both mixed-order conventions (HP and HV)
  - No inherent limit on Ambisonic order
  - Actively in use by a few beta testers
  - Mixed results for graphics output in Octave
  - Moving graphics output code to Python with MayaVi
  - Interface to IDHOA optimizer
- GNU Affero General Public License
- Faust decoder engine BSD 3-Clause License
- Git repo at https://bitbucket.org/ambidecodertoolbox/adt

Summary and Conclusions

- Extensions to Ambisonic Decoder Toolbox to handle speaker configurations that do not cover full sphere
- New decoder engine in written in Faust
- Ability to generate decoders quickly has proven valuable in performance settings

- Plans
  - Dual-band AllRAD and Slepian decoders
  - Optimizer to refine decoders

- Open question:
  - What to do when sources move into areas of poor coverage.
    - Current implantation fades them out.
    - Decorrelate and mix into other speakers?
    - Should transmission standards include “rendering hints”?

Thanks!

- Fernando Lopez-Lezcano for helping with the listening tests and in-situ measurements, and overall feedback and encouragement.
- Andrew Kimpel, Marc Lavallée, and Paul Power who are active users.
- Richard Lee, Jörn Nettingsmeier, and Bob Oldendorf who read early drafts and provided feedback.
- LAC 2014 reviewers and organizers

Human Auditory Localization

- At low frequencies (up to about 800 Hz) works by Interaural *Time* Differences (ITDs)
- At middle frequencies (800 Hz to 5 kHz) works by Interaural *Level* Differences (ILDs)
  - Transition is fairly sharp
  - due to the ITDs becoming ambiguous once the wavelength become smaller than ear spacing.
- 2-channel stereo doesn't get it right
  - ILD cues are such that the images tend to stick to nearest speaker
- Ambisonics was designed from the beginning to get this correct with modest resources.
  - Small number of program channels and loudspeakers

Gerzon's Theory of Auditory Localization

- Early workers in stereo did theoretical analysis showing how stereo did (or didn't) provide proper localization cues
- Gerzon's contribution was to integrate those theories and came up with a theory that defined
  - $\mathbf{r}_V$, the vector sum of the signals from the loudspeakers
  - $\mathbf{r}_E$, the vector sum of the squares of the signals from the loudspeakers.
- By providing a simple mathematical encapsulation, we can use these to
  - design decoders
  - prove theorems, e.g., polygonal decoder theorem
  - help understand what various spatial sound reproduction systems can and cannot do

Localization Vector Theory

- $\mathbf{r}_V$ predicts low-frequency localization almost perfectly.
  - If $\mathbf{r}_V$=1, then low-frequency sounds will be precisely located.
- $\mathbf{r}_E$ predicts mid-frequency localization moderately well.
  - If $\mathbf{r}_E$=1, then mid-frequency localization will be good
  - BUT… $\mathbf{r}_E$ is always less than1, unless the sound is coming from a single point source.
  - At best $\mathbf{r}_E = \cos(\theta/2)$, where θ is the angle between the loudspeakers, so for a square array $\mathbf{r}_E \leq 0.707$.
  - In general, $\mathbf{r}_E$ is low in directions with few loudspeakers
  - Best we can do is have it change smoothly in performance from dense areas to sparse areas.

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Energy Localization Vector

- Maximizing $\mathbf{r}_E$ *and* getting it to point in the right direction is the crux of the decoder design problem.
  - Easy with regular arrays
  - Irregular arrays always involve tradeoffs
  - Virtually all real world arrays are irregular!
    - Arrays need to fit in real rooms
    - ITU 5.1 is the dominant domestic standard, rear speakers 120° apart.
- Because it is a non-linear function of speaker position, we currently need to use numerical optimization methods.