A TOOLKIT FOR THE DESIGN OF AMBISONIC DECODERS

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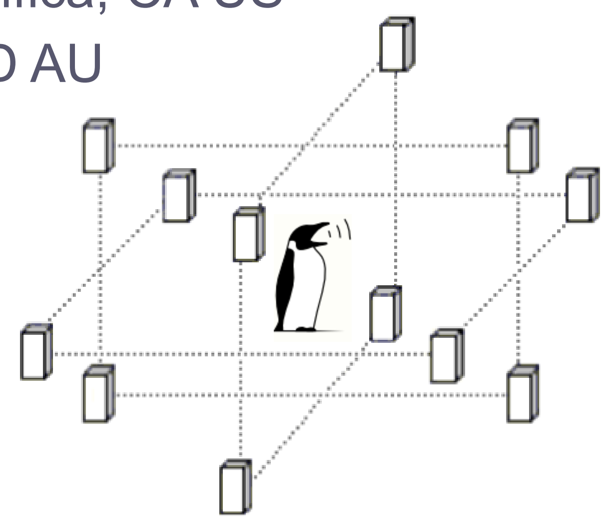


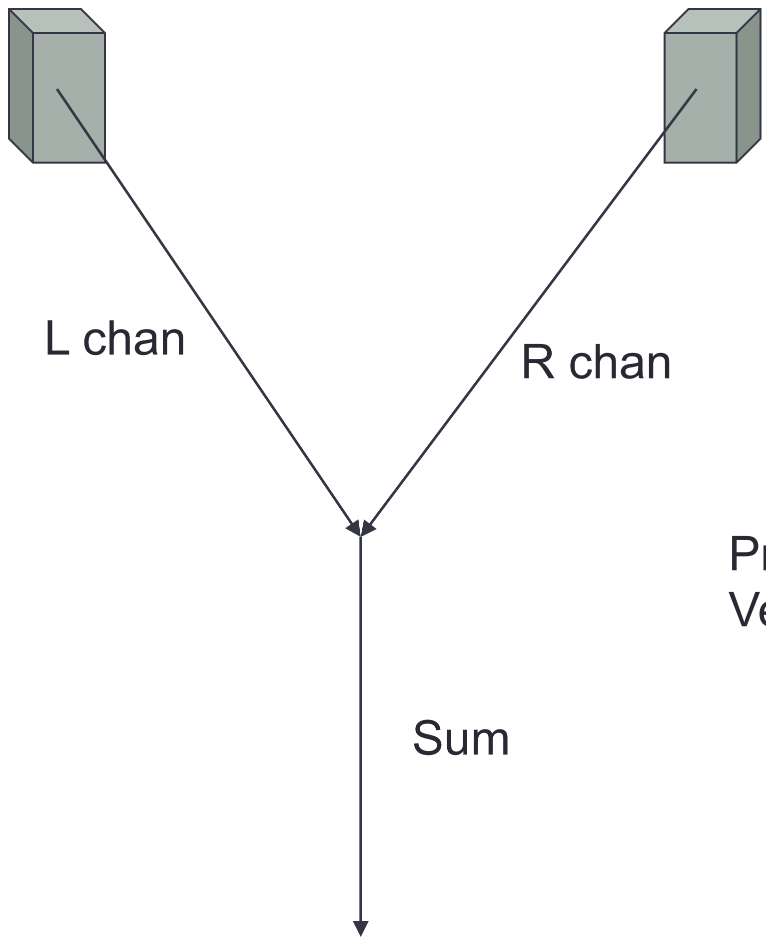
What is Ambisonics

- 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

Extensible?

- Ambisonics was originally implemented as first order, although always conceived as a hierarchical system
- More recently, various system have worked with as high as 5th order.
- CCRMA Listening Room works with signals up to 3rd order

2-channel stereo



Pressure = L + R

Velocity = $\vec{\mathbf{L}} + \vec{\mathbf{R}}$

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.

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.

What is a 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
  - E.g., Ambdec

Goals for decoder design

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

Frequency-dependent decoding

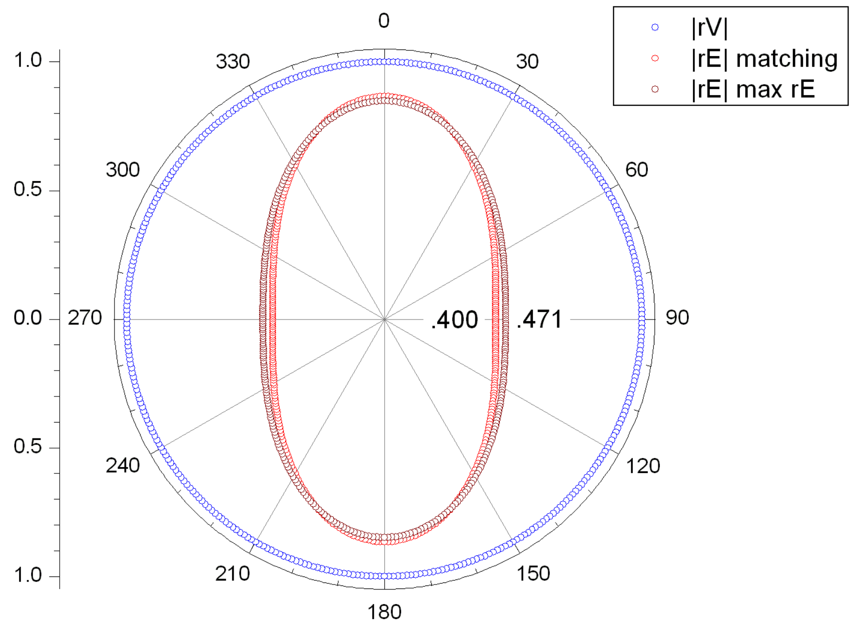
- Different localization cues are used at high and low frequencies
- Different decoders are needed for each frequency regime
- Solution is a dual-band decoder
  - Very few good ones (in 2008)
    - Ambdec
    - Offline decoder in toolkit

Max r_E Decoders

- Pseudoinverse of speaker projections gives low frequency solution
- For regular polygons and polyhedra per-order gains can be calculated that maximize $\mathbf{r}_E$
  - See paper for tables and formulas
- For irregular arrays, these provide a good starting point for the optimization process.

Simple example

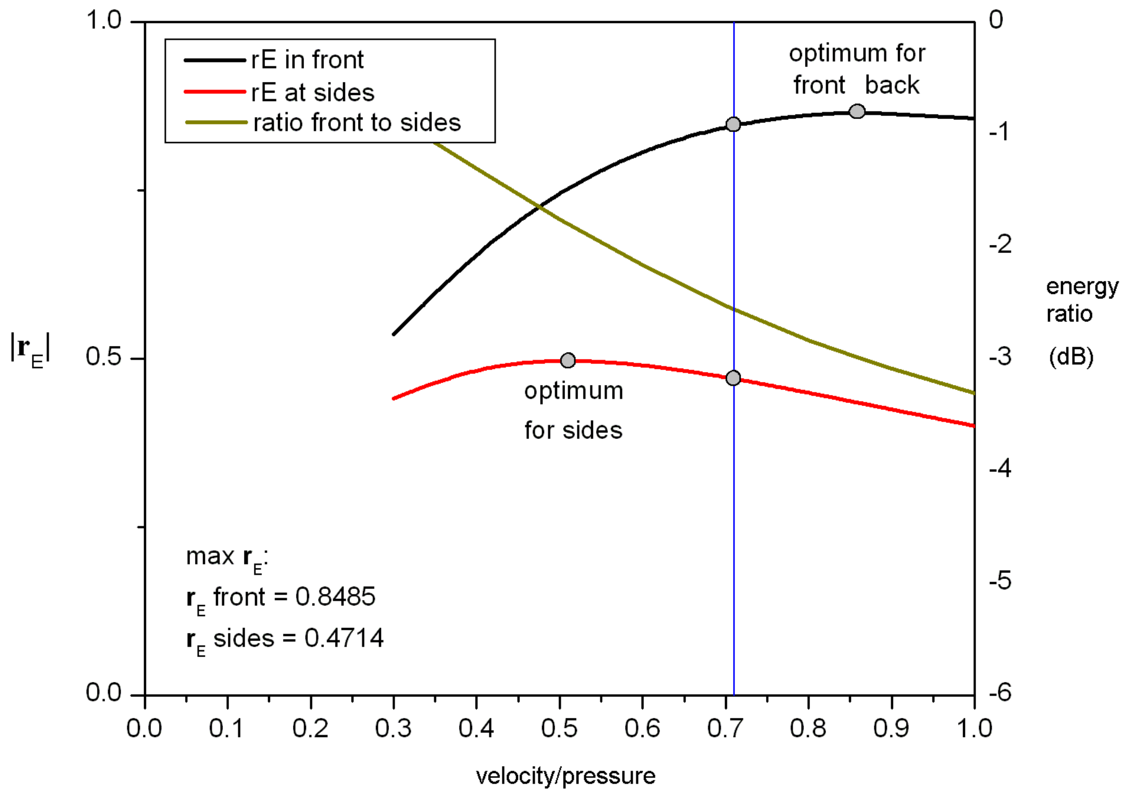
- A rectangle with aspect ratio √3:1 has higher values of r_E in the direction of the narrow sides.



rV and rE vs. direction for 'matching' and 'maxrE' decoders

Maximizing r_E depends on direction

- What maximizes r_E depends on which directions are important to you



Optimization

- With irregular arrays, simply scaling the LF and HF matrices does not result in r_v and r_E pointing in the same direction
- Key psychoacoustic criteria for good reproduction are non-linear functions of speaker locations, so we need to use numerical optimization techniques.
- We use the NLOpt library for nonlinear optimization
  - Free and open source
  - Provides a common API to a number of algorithms
  - Supports a number of local and global “derivative free” optimization algorithms.

Optimization Criteria

- For each test direction, we compute
  - Amplitude gain, *P*
  - Energy gain, *E*
  - Velocity localization vector, r_V
  - Energy localization vector, r_E
- Summarize
  - Deviation of amplitude gain from 1 along the X-axis
  - Minimum, maximum, and RMS values of
    - Amplitude gain
    - Energy gain
    - Magnitude of r_V
    - Magnitude of r_E
    - Pairwise angular deviations of r_V, r_E, and source direction
- Weighted sum to compute single figure of merit, which is minimized
  - Directional weighting possible
  - Soft limits

Test Directions

- Each candidate set of parameters is evaluated from a number of directions
  - 2D, 180 or 360 evenly spaced directions
  - 3D, no more than 20 points can be distributed uniformly on a sphere
- Lebedev-Laikov quadrature
  - Defines sets of points and weights that provide exact results for integration of spherical harmonics
  - Current implementation uses 2702 points, roughly 3° spacing.
- Toolkit also provides grids sampled in uniform azimuth and elevation increments – useful for visualization.

Optimization Behavior

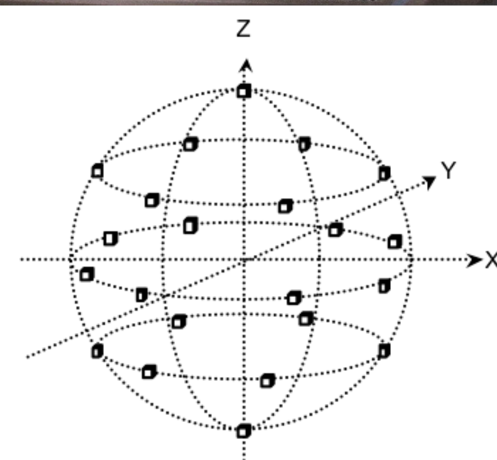
- User supplied stopping criteria
- Small 2-D arrays (12 to 24 parameters) < 1 minute
  - Use global optimizer (Controlled Random Search)
  - 40k to 1.5M configurations considered
- Large high-order arrays (200 to 400+) parameters < 20 minutes
  - Use local optimizer (Principal Axis)
  - ~20M configurations considered.

Initial Solution

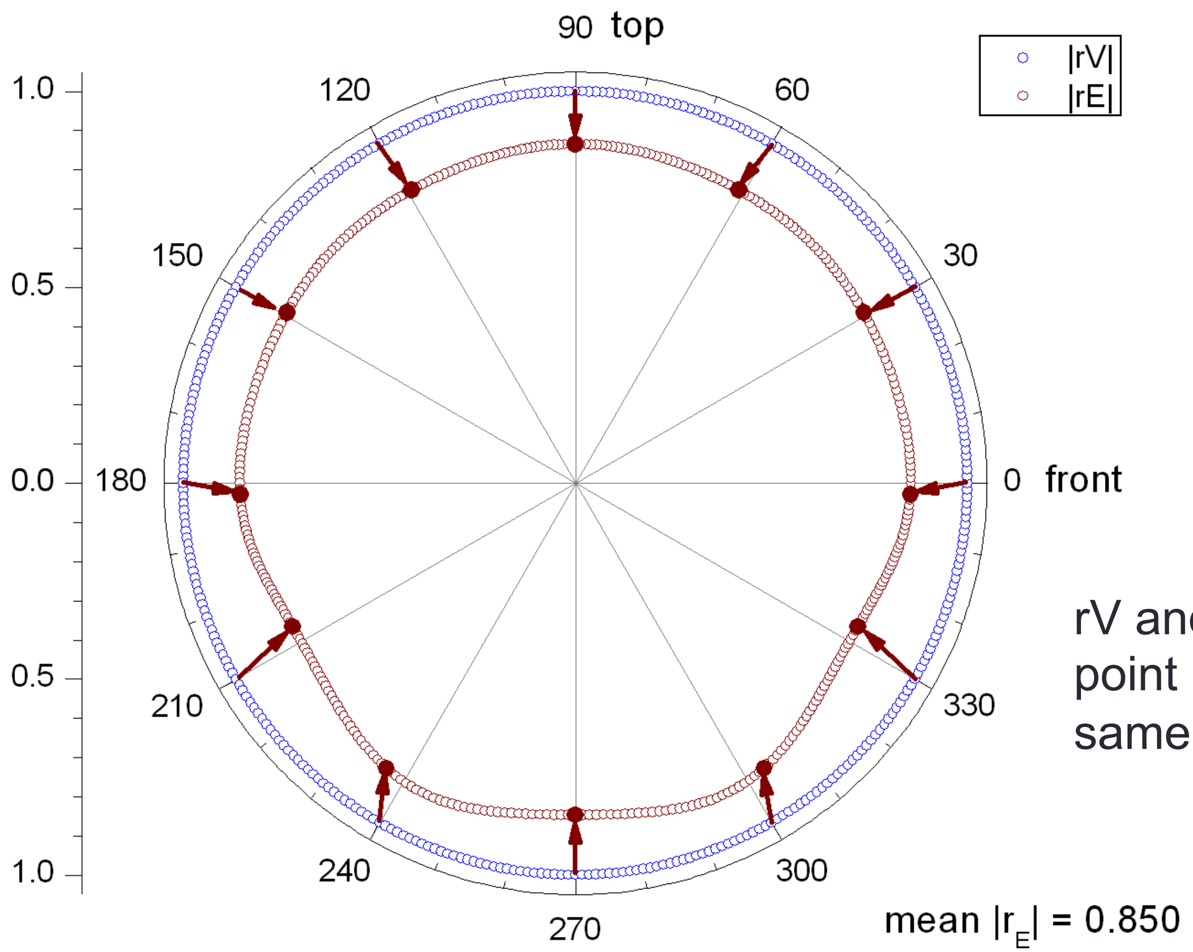
- For large arrays, need to start near optimum.
- Possible strategies
  - Use LF solution, modified with per-order gains to provide max-r_E solution.
  - Musil: insert additional “virtual” speakers into array to make the spacing more uniform
  - Hierarchical approach, optimize the solution for each order consecutively, allowing an overall gain adjustment for lower orders.

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

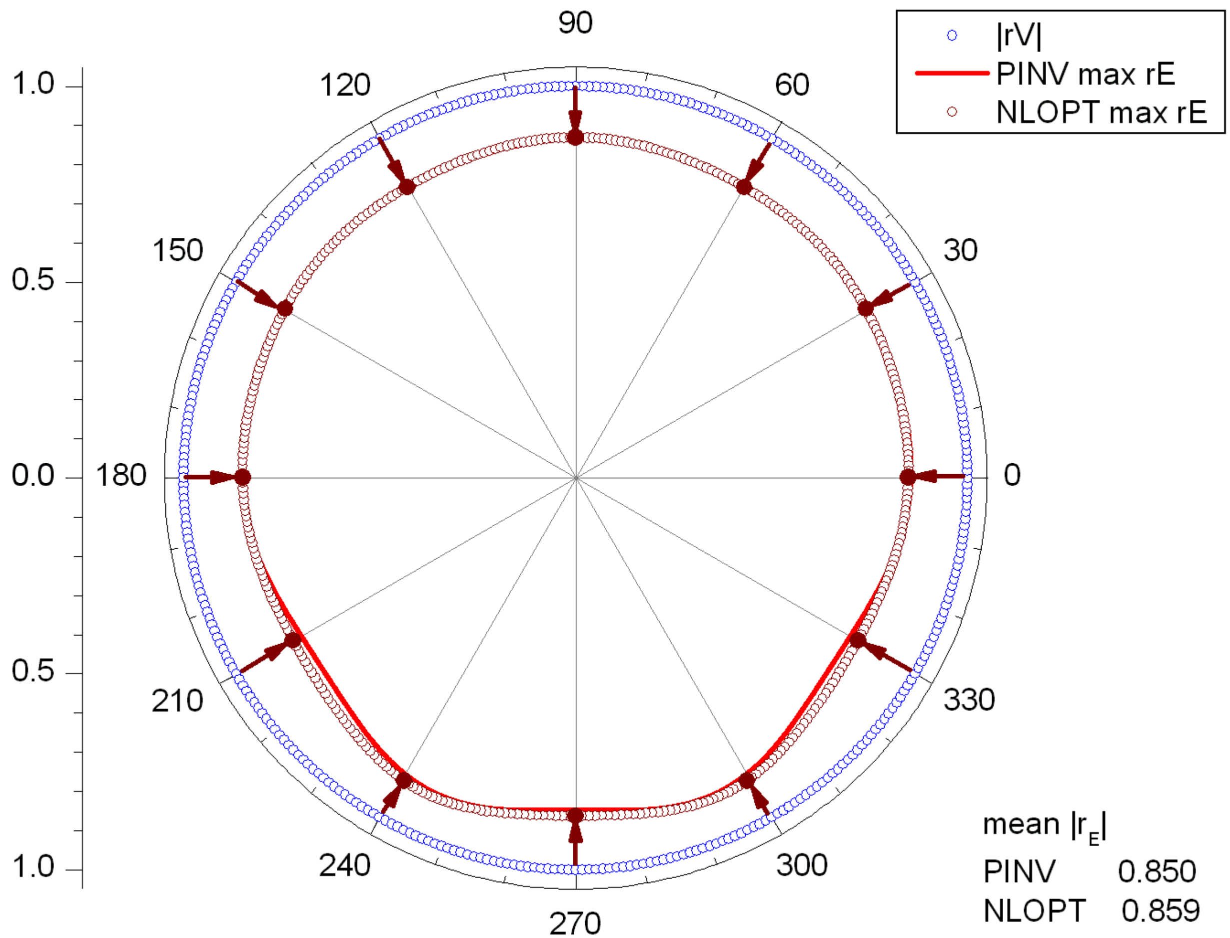


Before optimize; vertical r_V and r_E



rV and rE don't point in the same direction

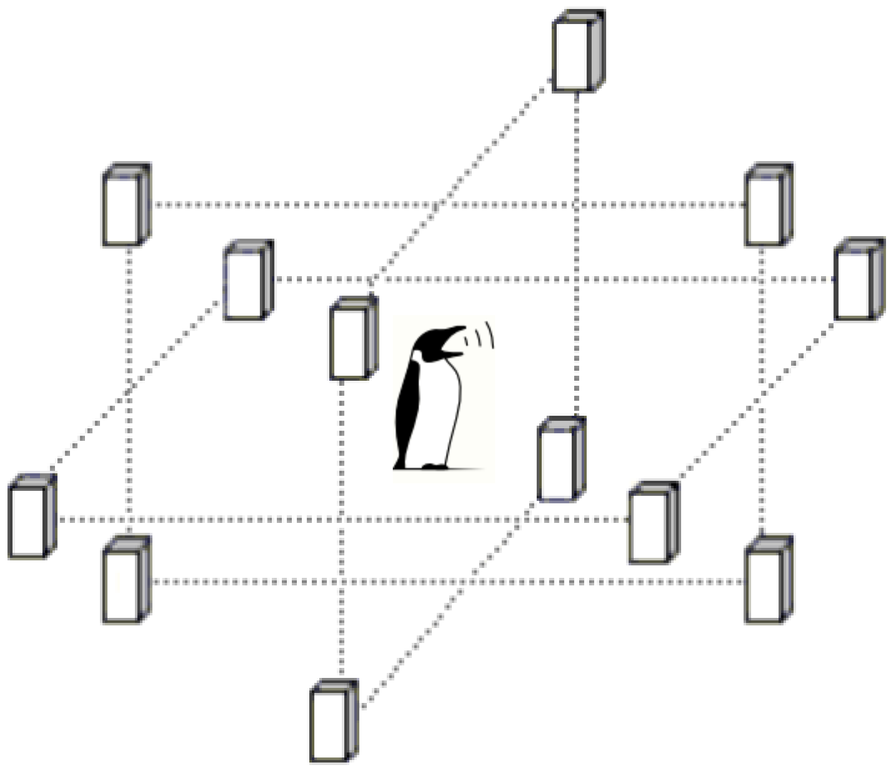
After Optimization



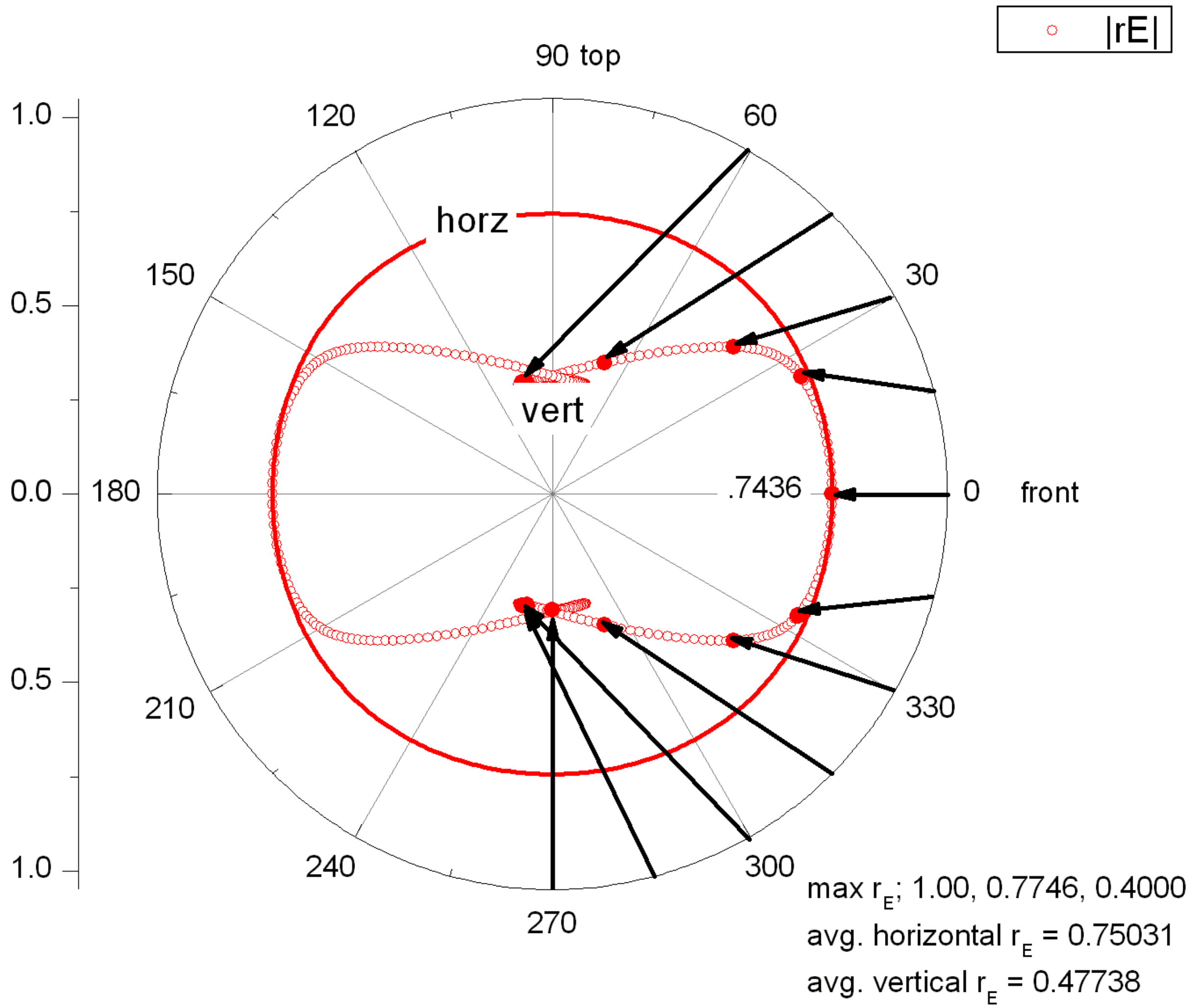
Slight improvement, especially in matching directions of rV and rE

Tri-rectangle

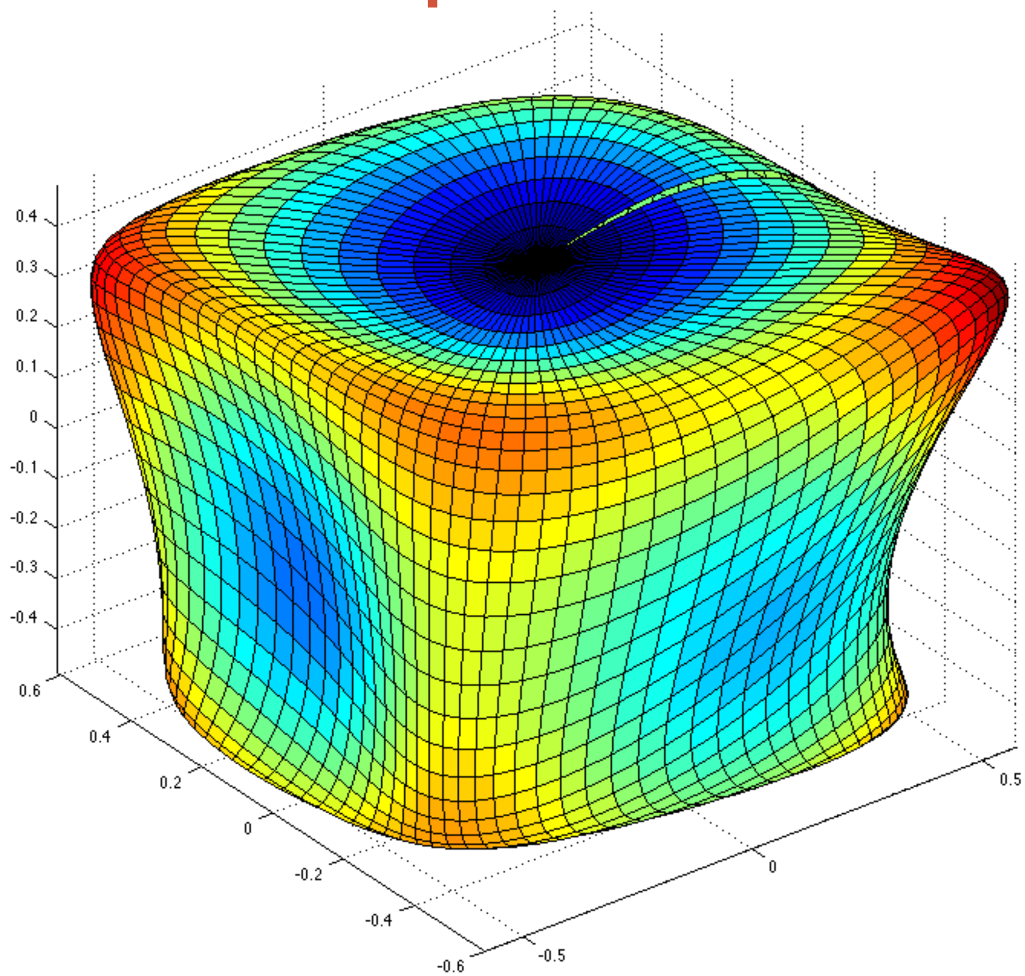
- Designed to fit in a room with an average ceiling height
- 12 loudspeakers, 3 rectangles



2^{nd} order solution by pseudoinverse

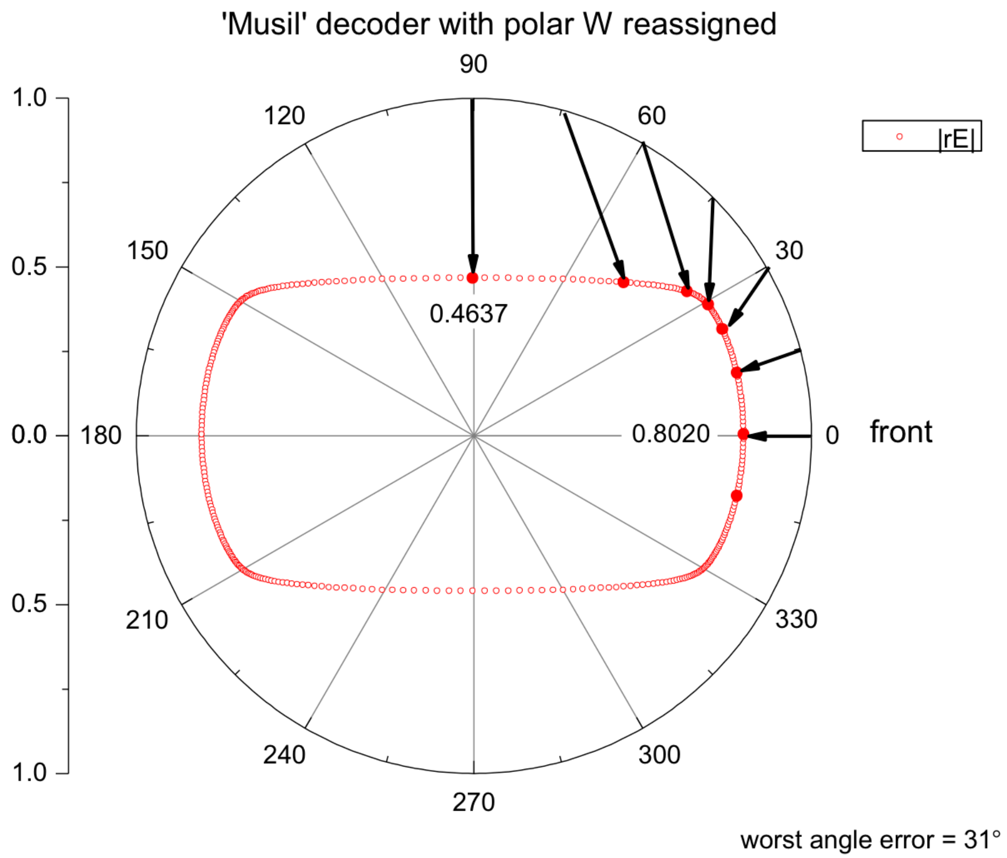


Unconstrained Optimization



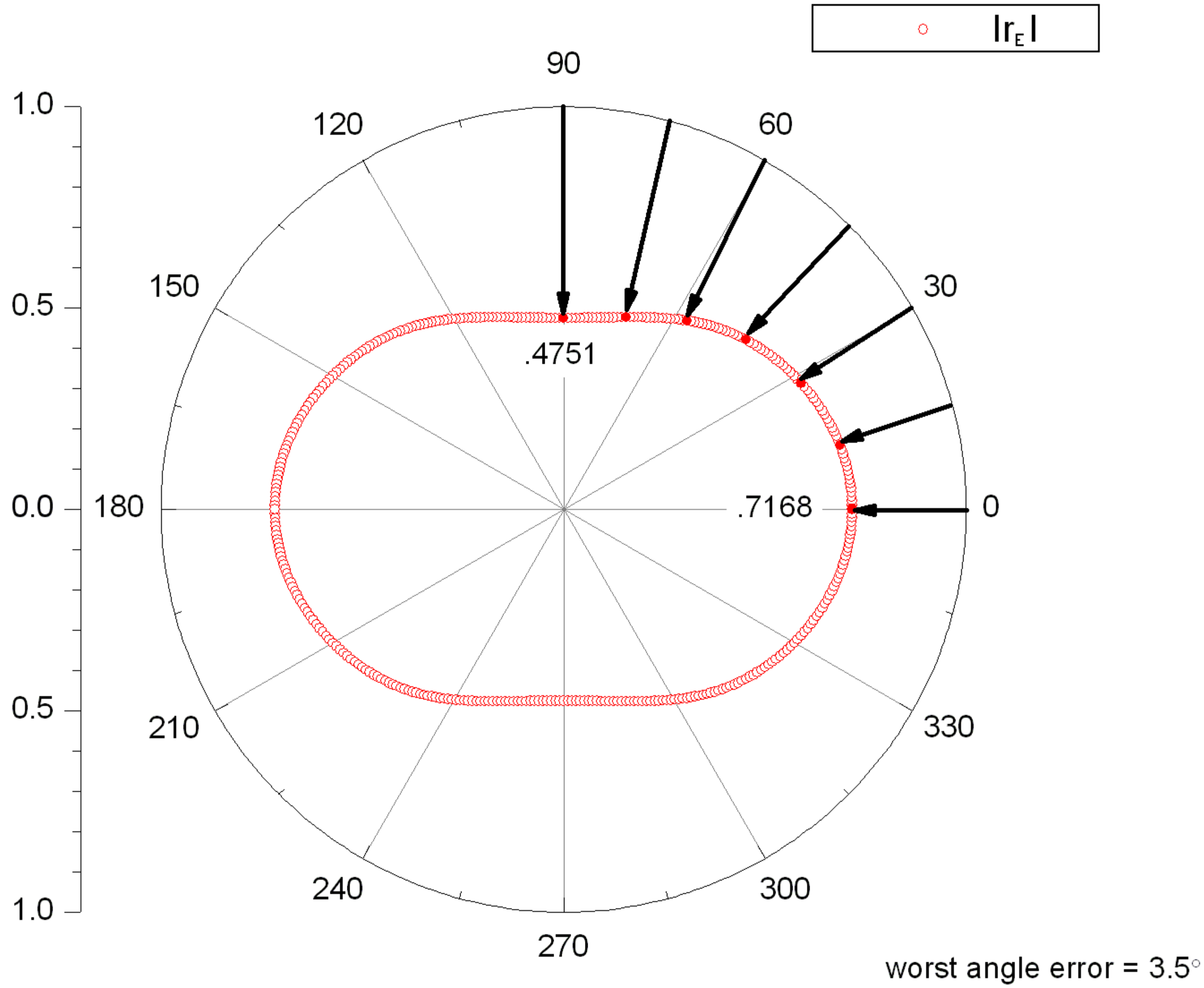
Not very well behaved!

Musil technique



Much better behaved, but large angular distortion for sources above 30º

Hierarchical decoder



Implementation

- Toolkit is implemented in Gnu Octave
  - Runs in MATLAB too. (about 2x faster)
  - Older 2-D version in C++, but performance almost as fast.
  - Most of computation is matrix multiplication
    - CUDA version possible
- Used to design current decoder for CCRMA Listening Room
- Includes
  - Tools for regular arrays
  - Nonlinear optimizer
  - Reference offline decoder
  - Output functions for Ambdec config files
- Beta release in early May.

Summary

- Toolkit for design of HOA decoders for irregular arrays
  - Implements multiple strategies
- Good results
  - Need good initial solution for large arrays
- Open problems
  - LF/HF matching
  - Automated evaluation of initial conditions and result

Thanks!

- Fernando for giving us the challenge of designing a new decoder for the Listening Room.
- LAC 2012 organizers
- CCRMA
- Linux community