Direction Dependent Beam Calibration for the MWA-LFD

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Outline

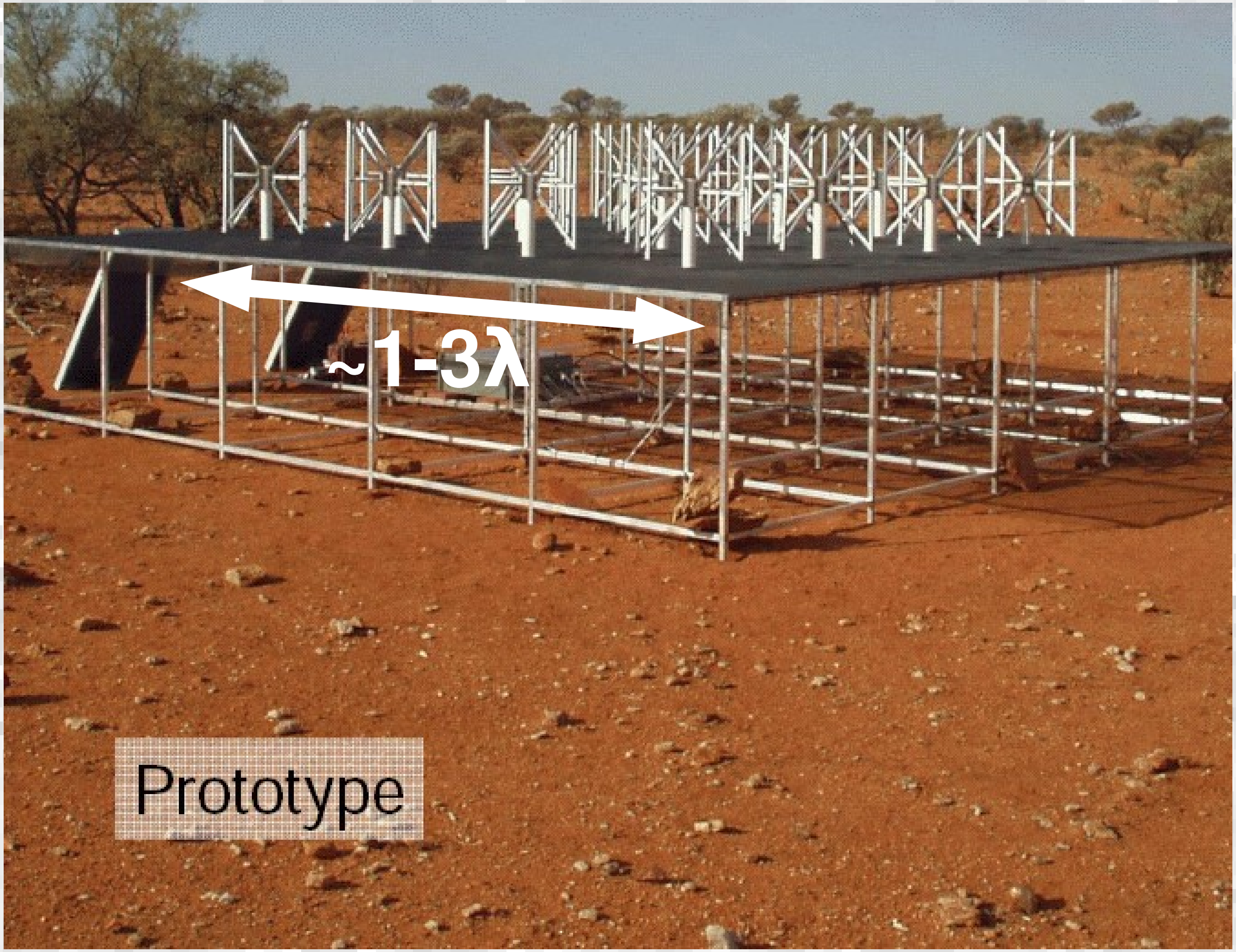
- Real-time software calibration pipeline
  - ➔ Sequential ionospheric and instrumental calibration
  - ➔ Sequential source confusion subtraction (peeling)

- Tile response parameterisation
  - ➔ Examples of the tile beam with dipole errors
  - ➔ Examples of dipole parameter convergence

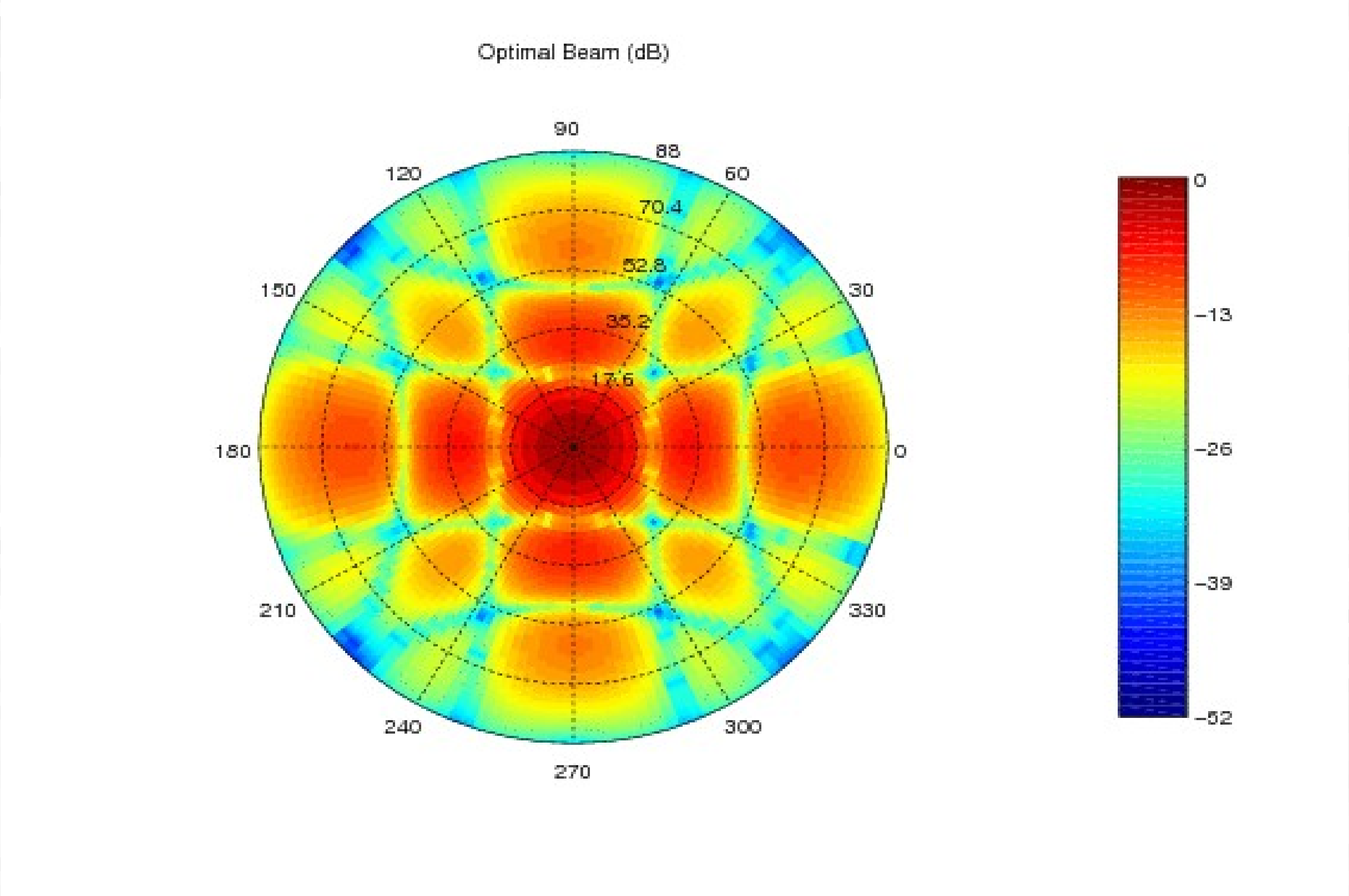
Challenges

- Characterisation of tile beam pattern
  - Moving discretely in az/el => changing on the sky
- Ionospheric noise (refractive & FR)
- Global sky model: calibrator uncertainty and sidelobe confusion
- Processing constraints

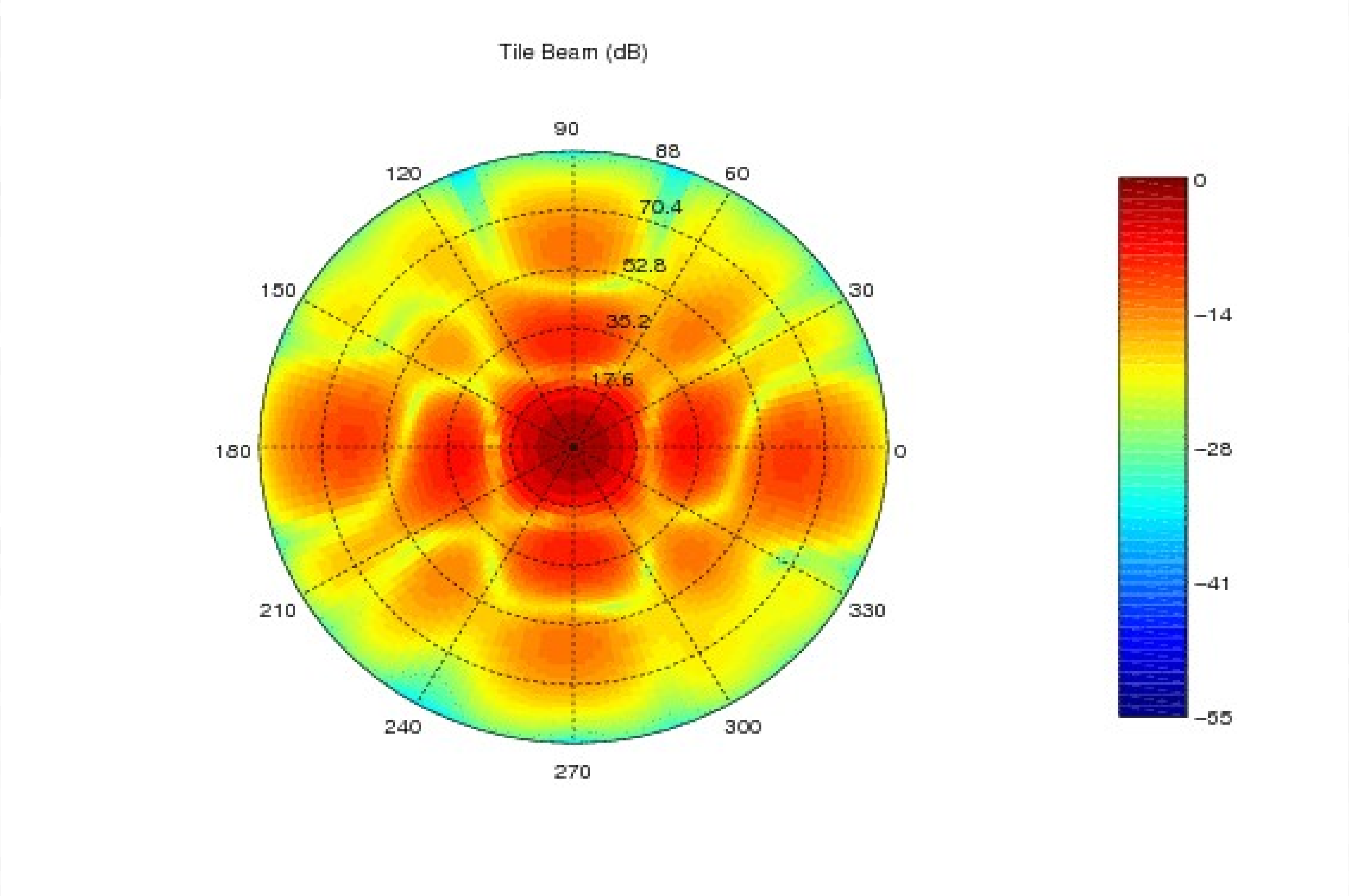
Prototype Tile



Simulated Tile Beam (190 MHz)



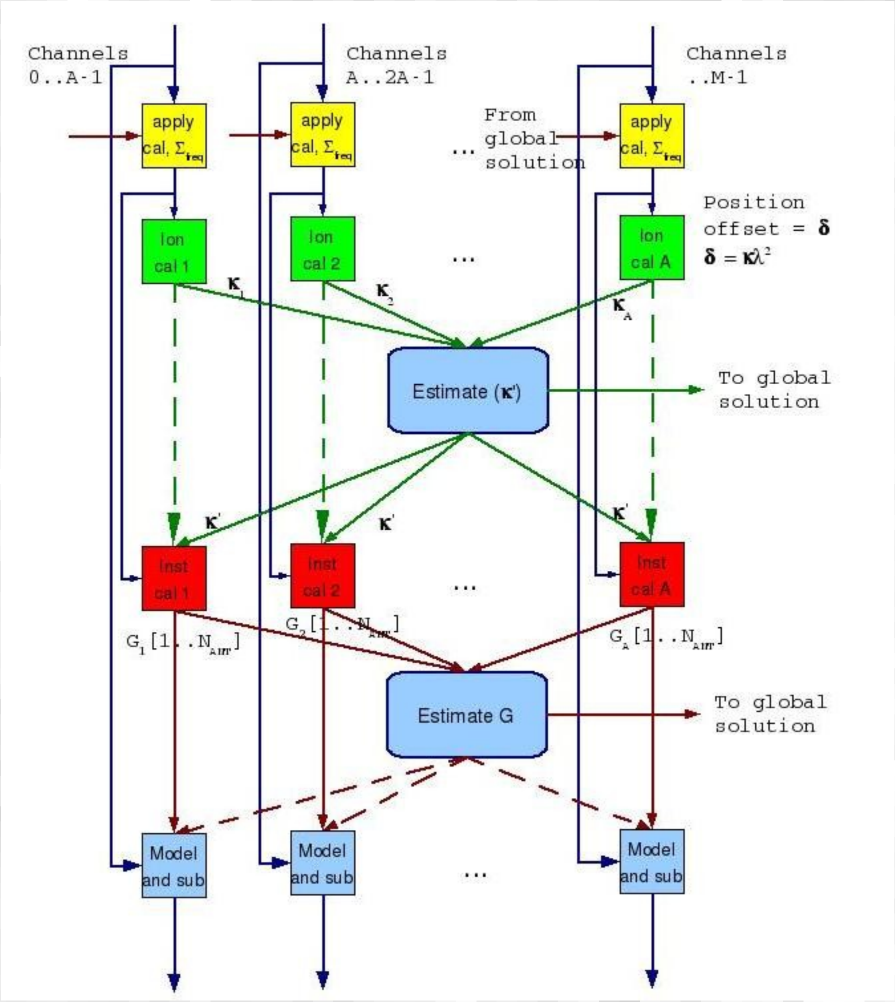
Tile Beam Amplitude Variability



Real-time Calibration Pipeline

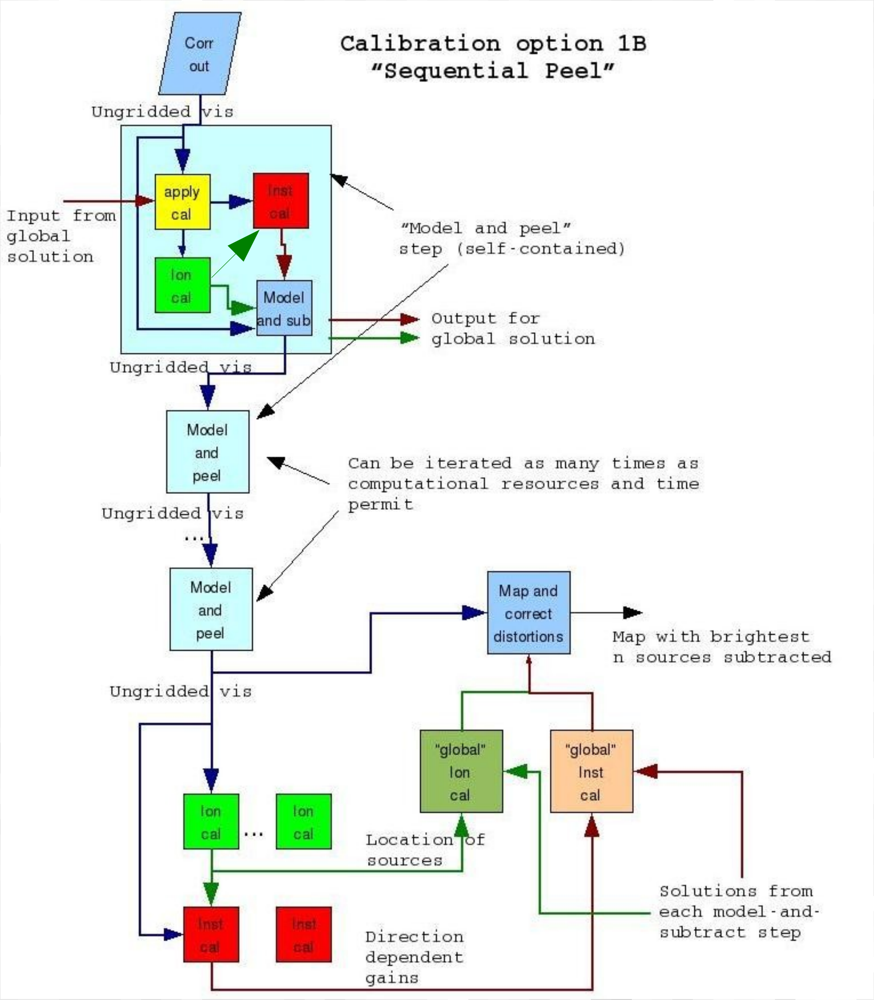
- The correlator feeds data directly to a ~Tflop cluster which handles calibration and (to some extent) imaging.
- Parallelized processing across frequency, which is loosely coupled in most respects.
- At the CfA we will test and develop the real-time system on a smaller cluster that has recently been purchased part of the Harvard Initiative in Innovative Computing (IIC).
  - ~ 60 cores, each with 4GB RAM
  - Can test many components of the system, and have some software ready for the software for the 32-tile system.
  - Generate complicated and realistic skies (MAPS).

Parallel Frequency Blocks



- Iteratively measure instrumental response towards each calibrator source
- *M* frequency channels in A sub-bands of *M/A* channels
- Need to find the right trade-off between larger *A* (less processing) and smaller *A* (less smearing, etc.)

Sequentially peeling sources



Similar to other efforts (Noordam, Jeffs, etc.)

1. Choose the source contributing the most variability to the visibilities.
2. Beam towards source
3. Estimate the incoherent contribution from weaker sources, then update derivative matrices of the global solver.
4. Peel source contribution from the visibilities. Go back to 1.

Tile Response Parameterisation

- Off-line foreground subtraction for EoR means we need to store the calibration for the full beam, not just peel.
- Unsure about the optimal parameterisation scheme until we have tile measurements. May not know conclusively until the full array is complete.
- Leading candidate: Assuming the tile response is accurately described by a simple superposition of dipole signals, use dipole complex gains, leakages, etc. to model each tiles response.
- What tests can be carried out with a single tile and the 32-tile system, and what are their limitations?

Day-to-day calibration

- SUMPLE algorithm essentially finds the least-squares solution for a tile's complex gain in a single direction, minimising over baselines.
- We can extend the idea to find the least-squares solution for the complex gains of a tile's dipoles, minimising over baseline and calibrator (direction).
- Main limitations: possibly an inadequate model; sidelobe confusion; errors in fixed dipole parameters; processing constraints.

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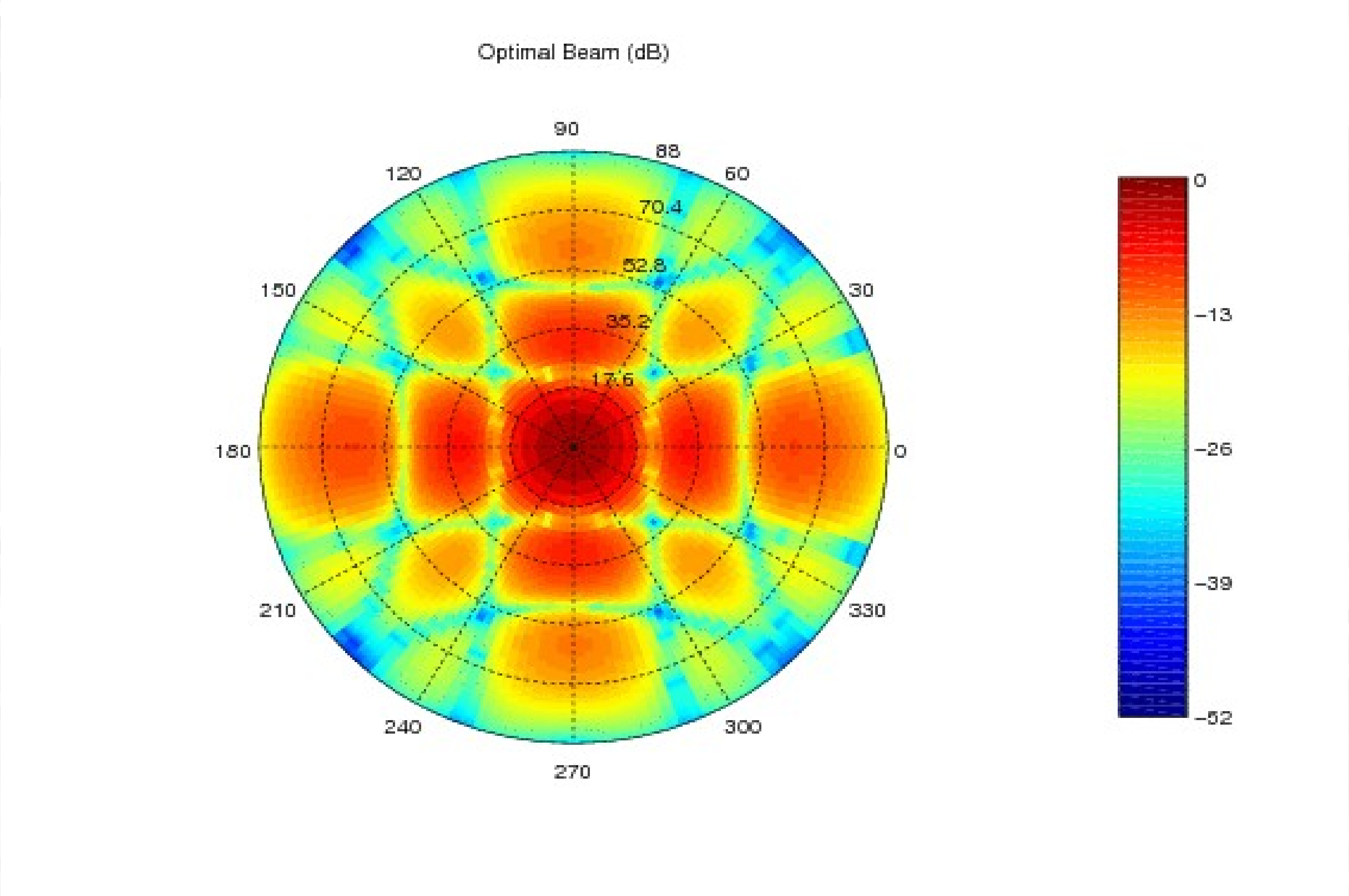

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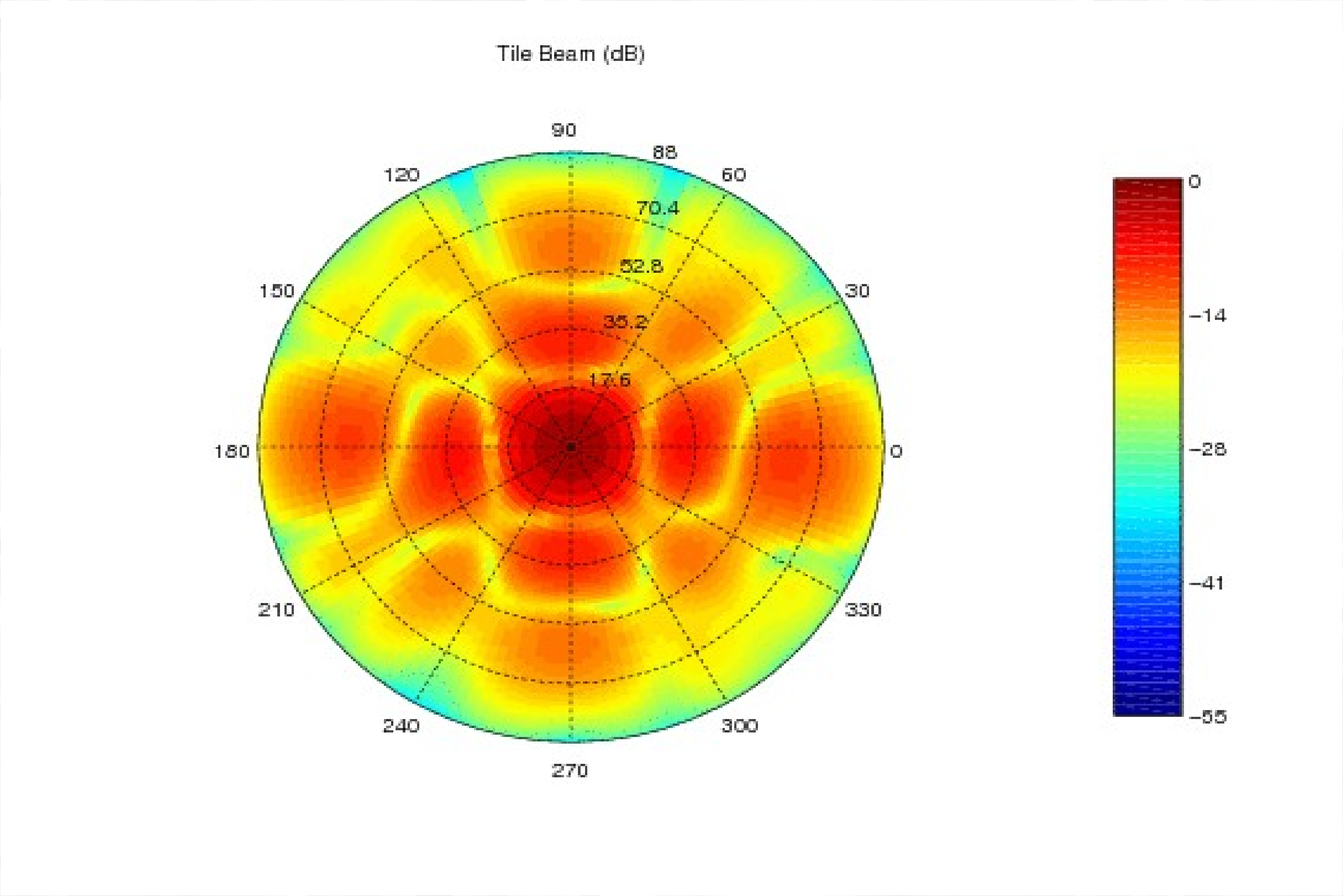
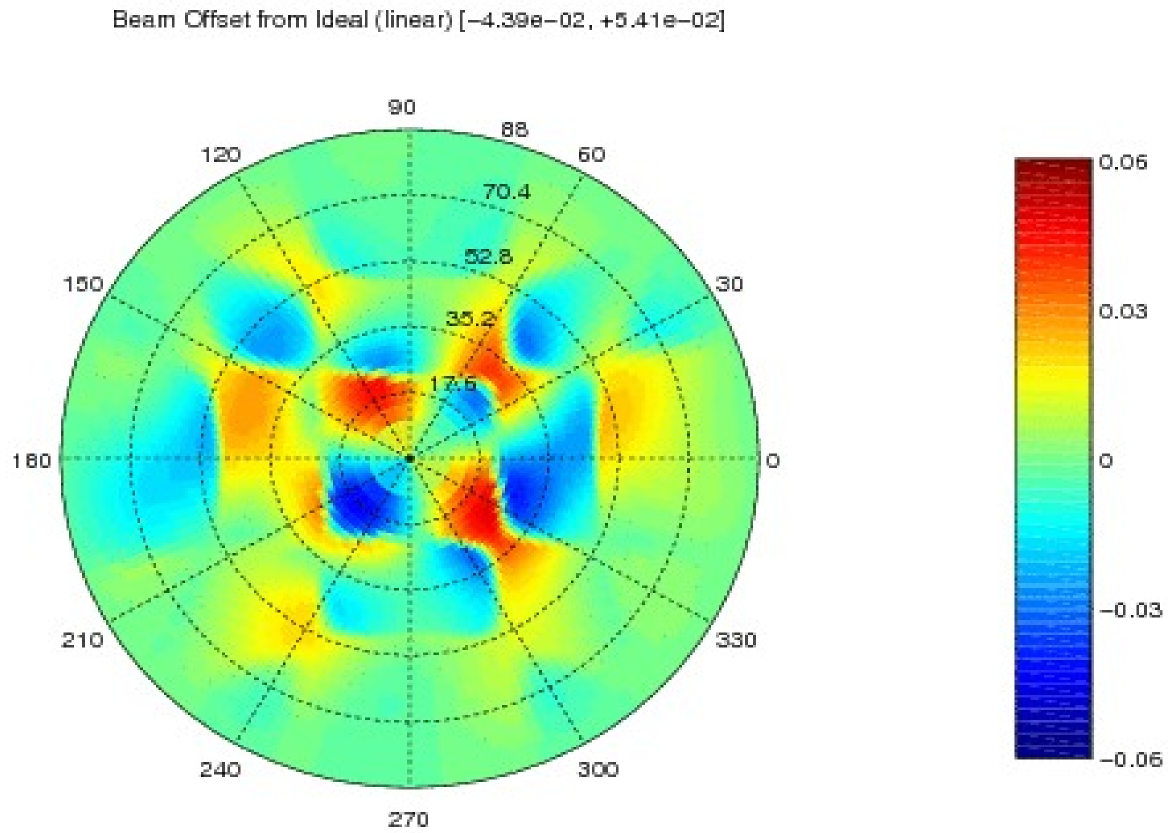
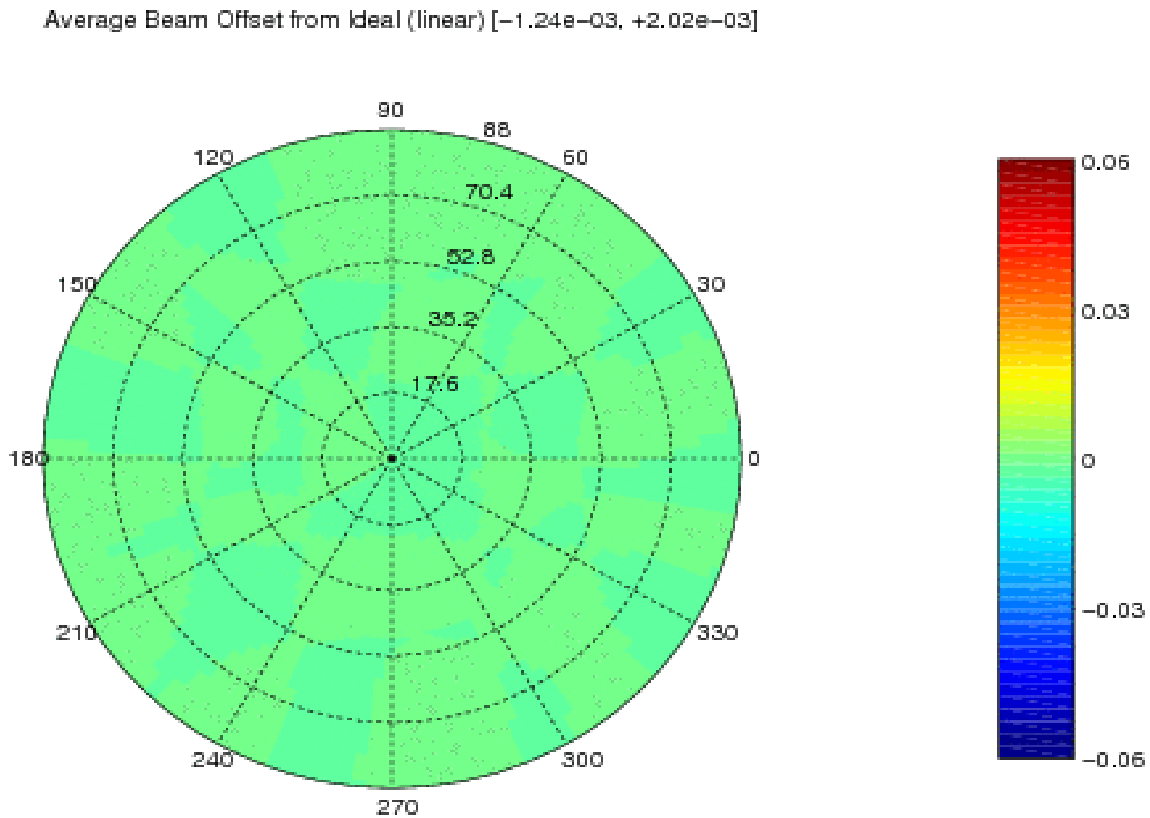


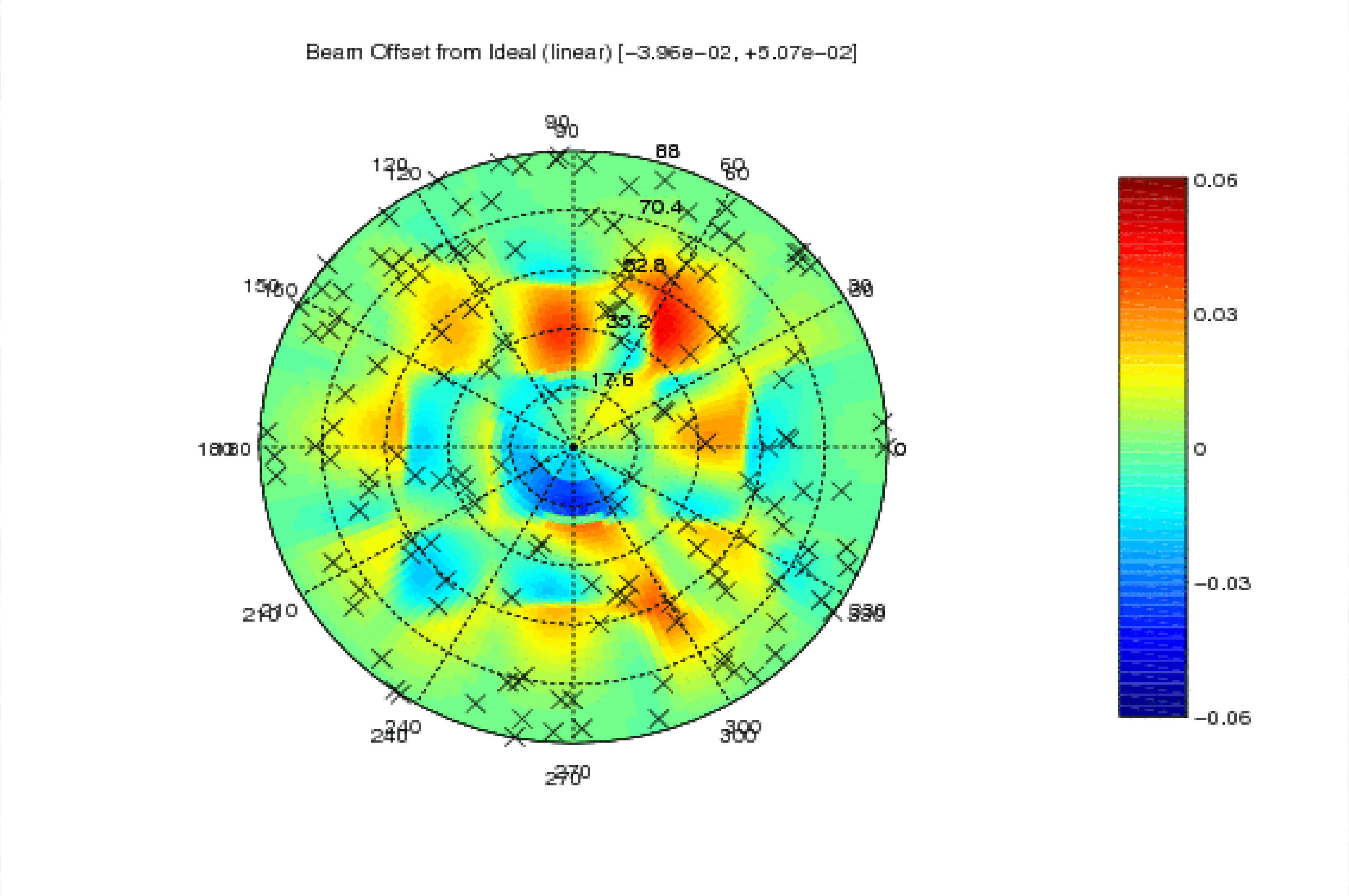
Tile Beam Amplitude Errors



Average Beam Errors

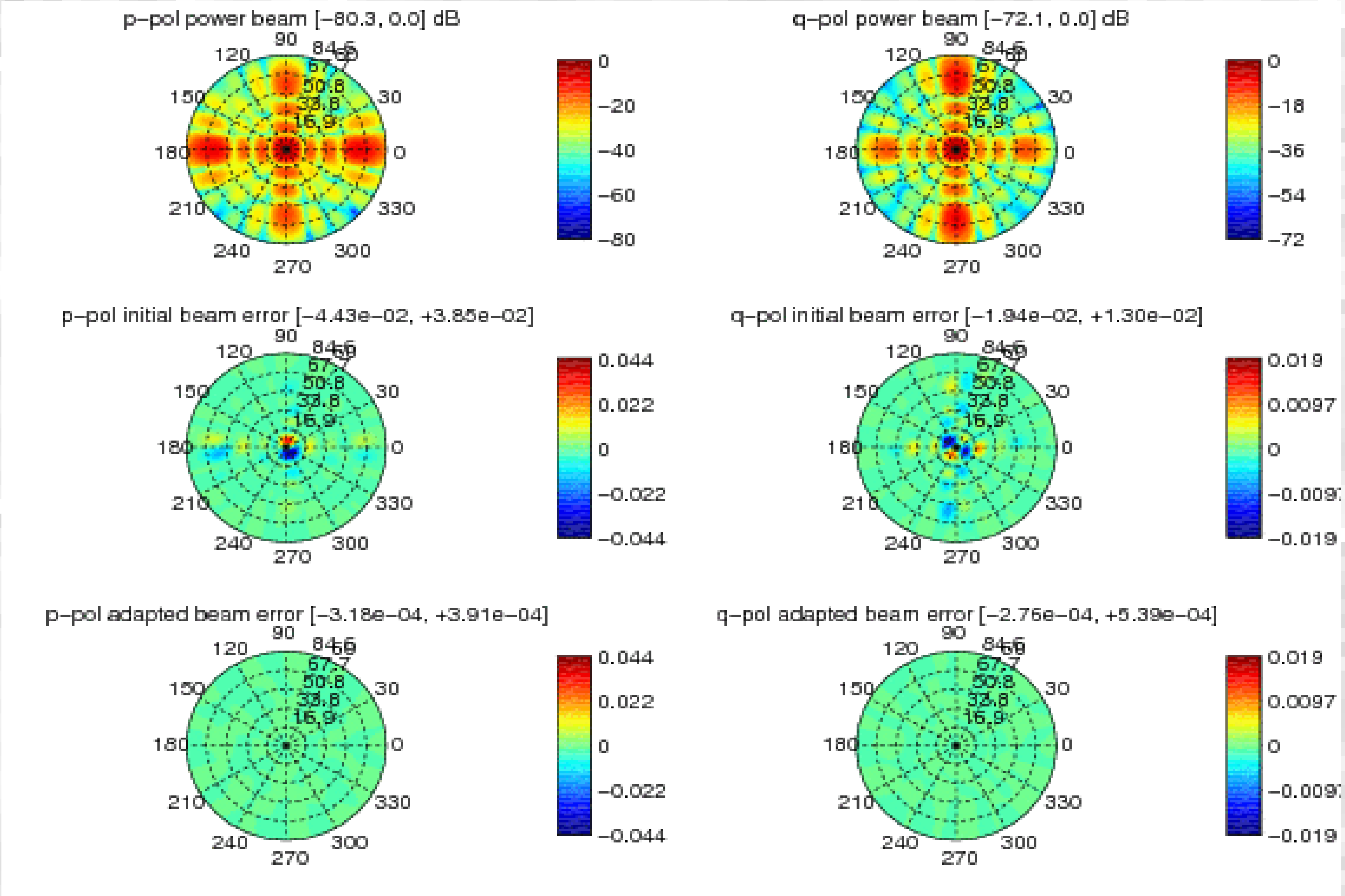


Beam Sampling



Before and After (perfect peel)

$N_{sources} = 100, N_{tiles} = 128$



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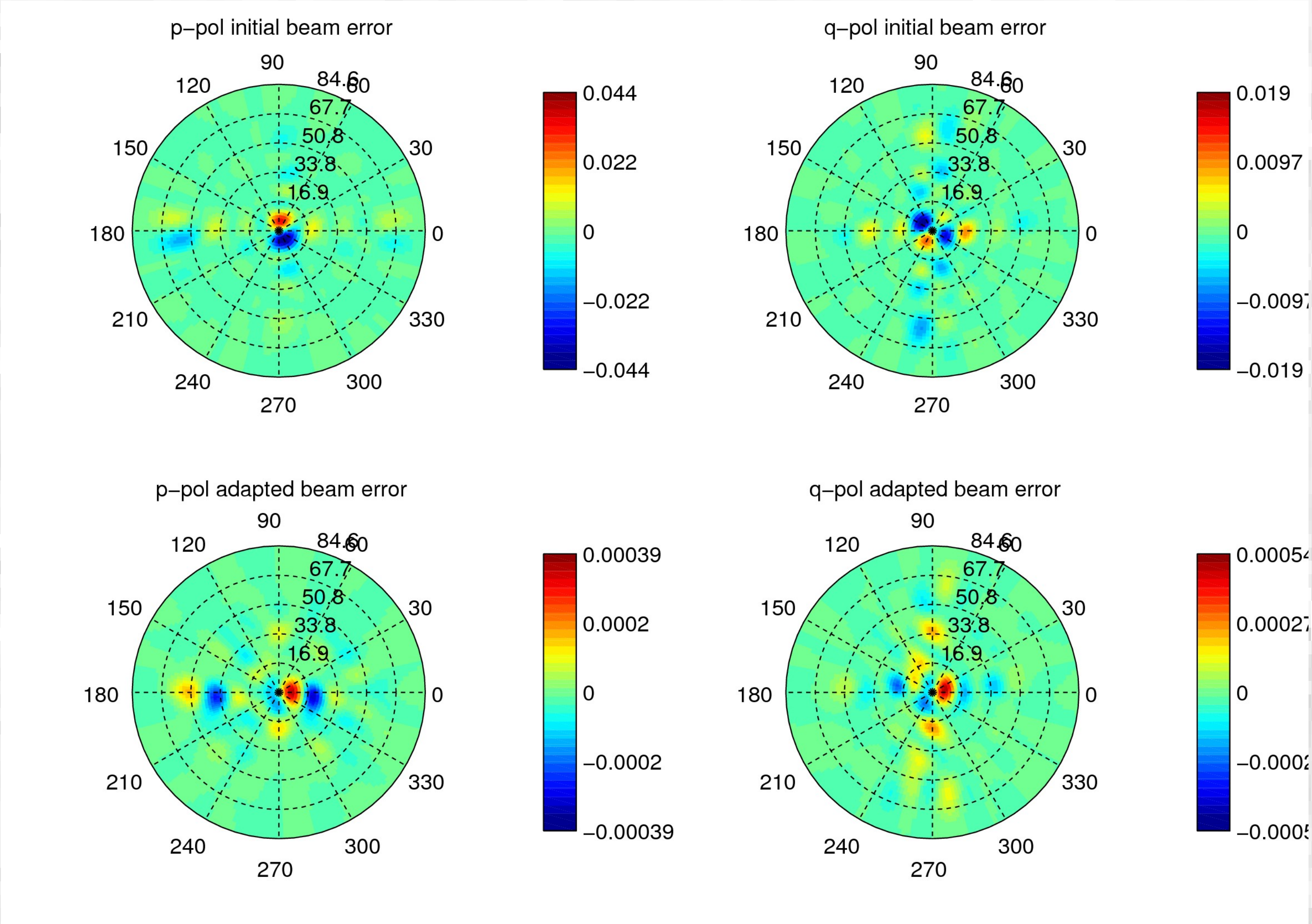
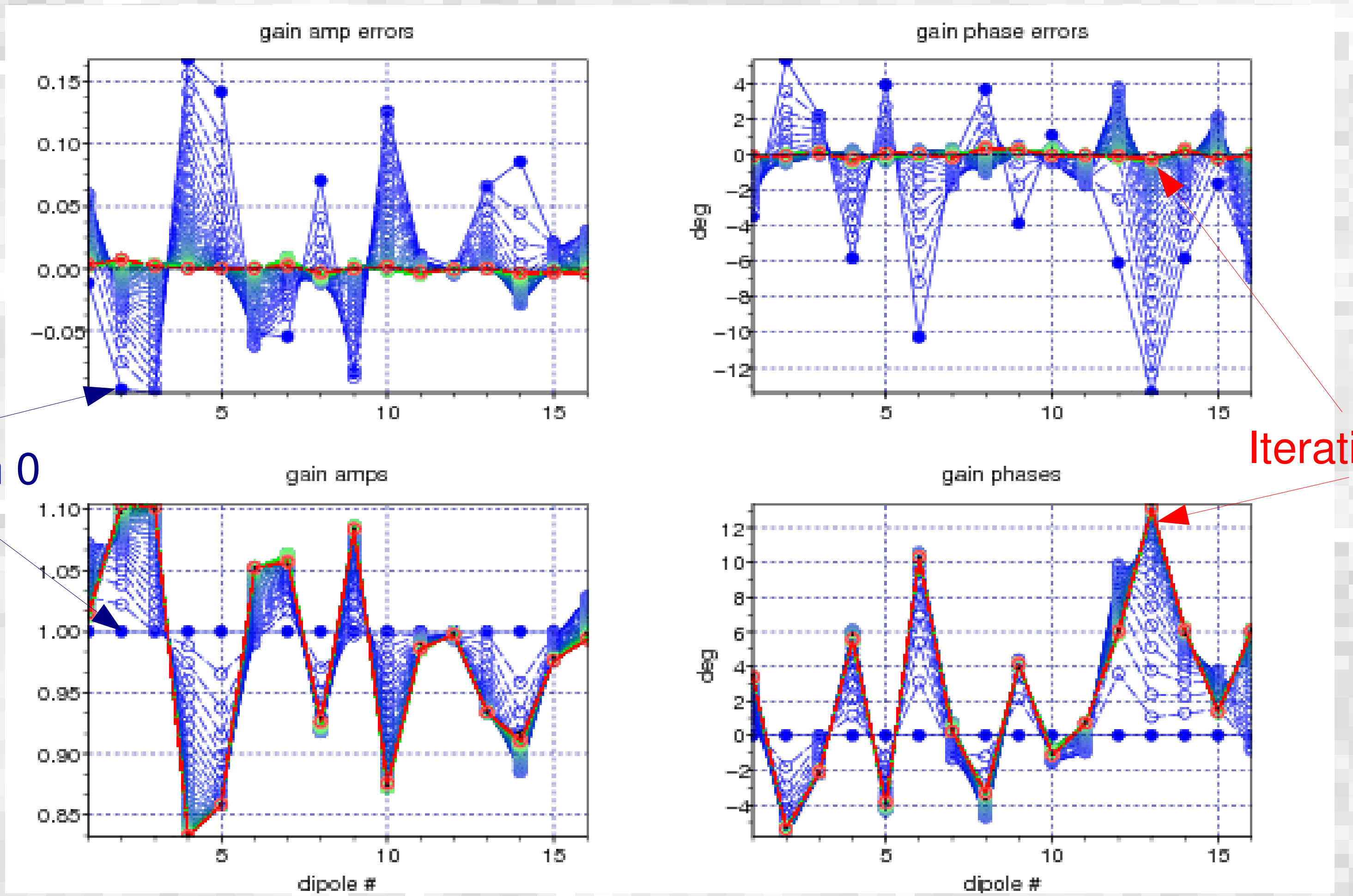


Adapting gains (perfect peel)

$N_{sources} = 100, N_{tiles} = 128, \mu = 0.2$



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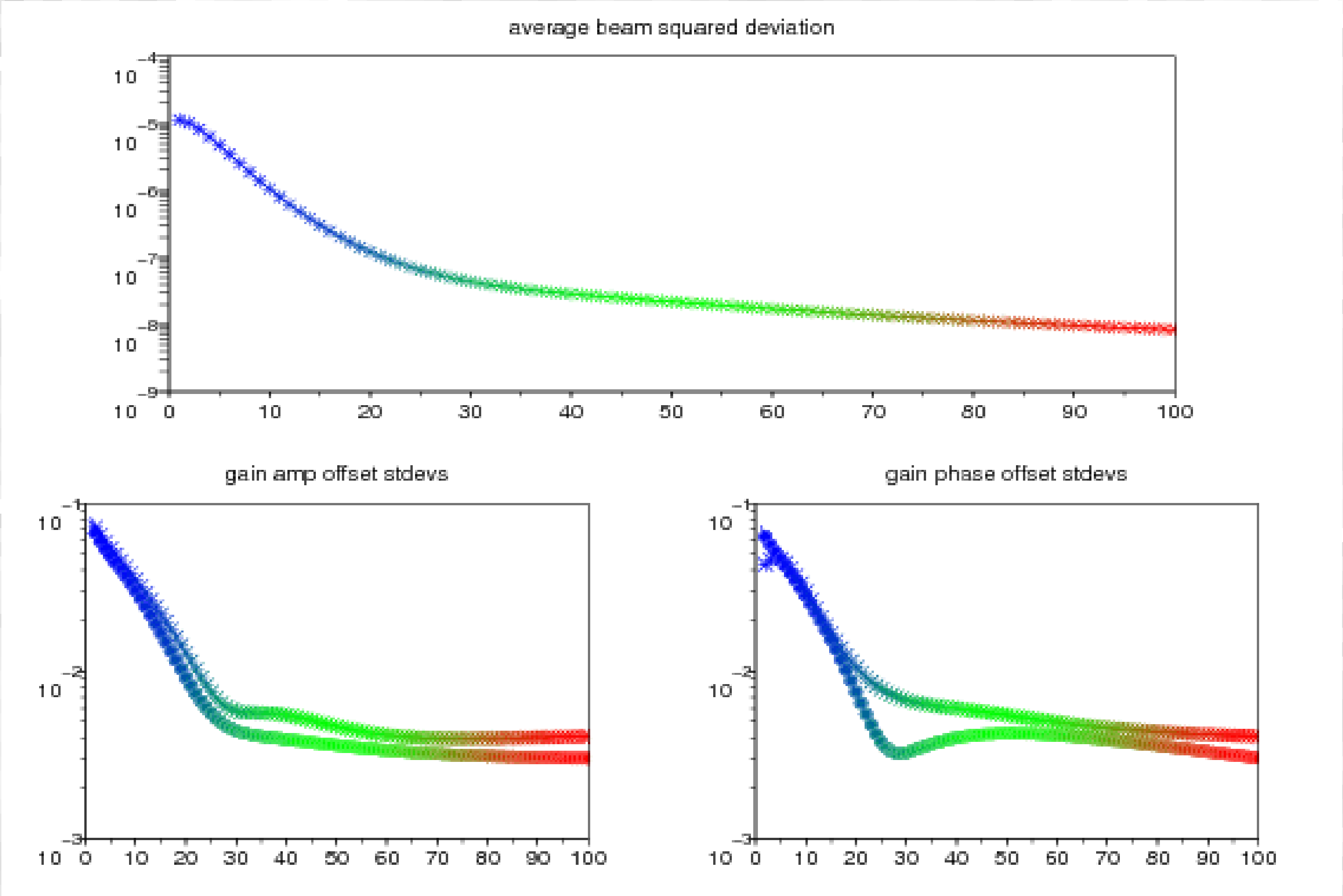

Tile Response Parameterization

- Two different modes being considered:
- **Day-to-day gain and leakage calibration**
  - Currently analyzing different frequencies separately.
  - Have not yet implemented full polarisation.
  - Sidelobe confusion problems.
- **Initial dipole position and pointing calibration**
  - Need to combine all frequencies and polarisations.
  - Many more parameters in solver.

Position and Pointing Calibration

- Initially/periodically the array will need to undergo a setup calibration to determine all of the stationary dipole offsets.
- The obvious parameters are the 3 dipole positions, the 3 dipole rotations, and complex gain constants, but there may be more.
- The beamformer delay setting does not appear to pose a problem and will probably not need to be included.
- Convergence can be confused by errors in all of the other parameters, so it is important to include frequency and polarisation information in a single fit (per tile).
- Numerical derivatives may prove to be more robust.

Summary

- **Real-time software calibration pipeline**
  - ➔ Currently ramping up the building and testing of the pipeline.
- **Tile response parameterisation**
  - ➔ Empirical versus physical. Make the pipeline robust enough to be able to change as the accuracy of response pattern measurements are improved.

32 Tile Priorities

- **Critical**
  - beam shape (stability in time/freq/temp/pol, parameterisability)
  - peeling (dealing with and estimating sidelobe confusion)
- **Important**
  - calibration sources (polarised & unpolarised GSM)
  - calibration source properties (including ionospheric effects)
- **Useful**
  - M&C (error / failure recognition, etc.)
  - calibration using satellites (orbcomm, FR)