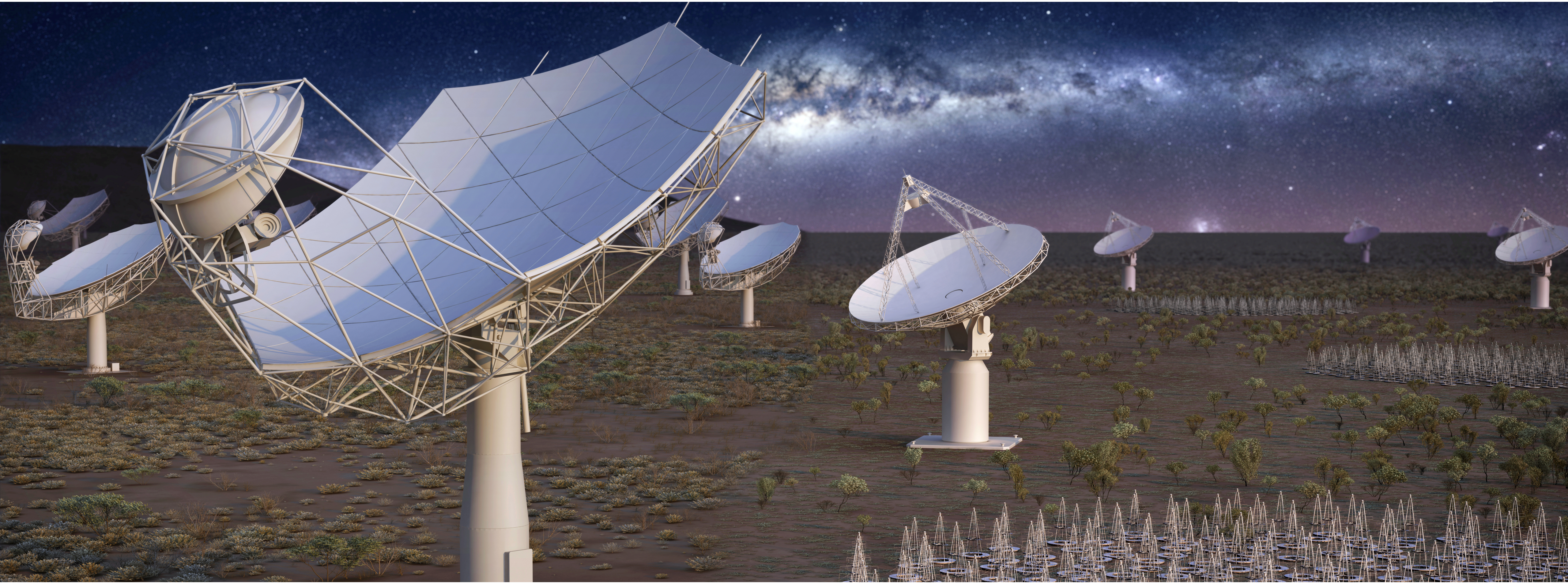
Calibration and Systematic Effects



SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

Robert Laing

2019 November 26

Outline

- Summarise the SKA1 Calibration Plan
- Present the work of the SIM Team on simulation of the effects of systematic errors on SKA1 imaging

SKA Calibration Plan

CALIBRATION PLAN

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1. What are the required calibrations?
2. Is the proposed set of calibrations complete?
3. What cadence and duration is needed for each calibration?
4. Which parts of the SKA system are responsible for executing the calibration?

Calibration for the SKA has two key parts:

1. implementation of the conversion between measured and perfect interferometric visibilities and
2. adjustment of the system before and during observations to enable and optimise observations.

”Perfect" visibilities are precisely related to the sky brightness distribution by the standard Fourier transform relation whereas "measured" visibilities are corrupted by atmospheric and instrumental effects.

Basic Principles

- Calibration formalism is Hamaker-Bregman-Sault measurement equation
  - Accounts for coupling between polarizations
  - Good method for assessing completeness of calibration
- Key issue for SKA1
  - Direction-dependent effects (beams, ionosphere) are critical for both MID and LOW
- Most calibration is off-line (SDP; ICAL pipeline)
- Closed-loop calibration is required for beam-forming and reference pointing (RCAL pipeline)

Array Element Calibrations

- Dish/station positions and cable delays
- Dish pointing model
  - All-sky calibrator grid; 5-point/cross-scan
- Gain-elevation models
- Verify voltage pattern models using interferometric holography
  - Full polarization
  - Dish
    - Scan subset of antennas; others as reference
    - Satellites and astronomical sources
  - LOW station beam
    - Multiple beams observed simultaneously
- LOW station calibration (interferometric/holographic or purely electronic)

Applied a priori

- Assume flagging for non-operational equipment, antenna not on source, shadowing done in advance by TM
- Pre-correlation flagging according to mask and clipping recipe (CSP)
- Ionospheric Faraday rotation (total electron content from GPS)
- Noise diode calibration to monitor gain
- Gain-elevation

Standard on-line calibration

- Residual delay offset (parallel and cross-hand)
- Bandpass (same observation as delay, usually)
- Polarization leakage
- Absolute flux scale
- Antenna/station complex gain as function of time
- Autocorrelation spectra using cross-correlations
- Iteration to solve fully for D terms in XY basis
  - Second-order D terms important for high dynamic range I
- RFI flagging during calibration
  - Baseline AOFlagger
  - Iterative (Flag → calibrate → flag deeper → restart calibration from scratch → ….)

Heuristics based on current pipelines.

Real-time Calibration

- Requires analysis by SDP and return of results to TM
- MID reference pointing
- MID and LOW: complex gain solutions for beam-forming
  - Assume 30s timescale
  - Applied by CSP
- Direction-dependent corrections for beam-forming
  - Ionosphere (measure and apply in ~30s closed loop): LEAP technique
  - Application of P Jones corrections (calculated in advance and applied in real time – open loop)

Self-calibration and DDEs

- Direction-independent, phase and amplitude
  - Straightforward; automated in current pipelines
- Direction-dependent
  - Facet calibration or equivalent to correct for ionosphere (baseline is Factor pipeline for LOFAR)
  - Alternatives to be explored (LEAP)
  - Additional peeling of bright sources at very large distances from the pointing centre
- Pointing self-calibration?
  - See later for simulations of pointing errors

Strategy

- Common framework for MID and LOW
  - Conceptually similar
- Major unresolved question: how well do we know our dish and station beams?
- Research Topics (evolving rapidly and directly relevant to SKA)
  - Measurement of and correction for dish voltage patterns (VLA, MeerKAT)
  - Correction for ionosphere + station beams (LOFAR, MWA, LWA): DDFacet, LEAP, …

Simulations of SKA1 Image Formation

SAFe SIM Team

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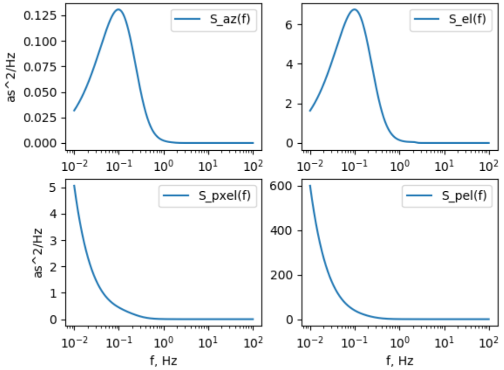
Long-term aim: evaluate the potential performance of the MID and LOW arrays in the presence of realistic sources of error and (direction-dependent) calibration strategies:

- Troposphere
- Ionosphere
- MID dish errors
- LOW station errors
- Low-level RFI

Road Map for Simulations

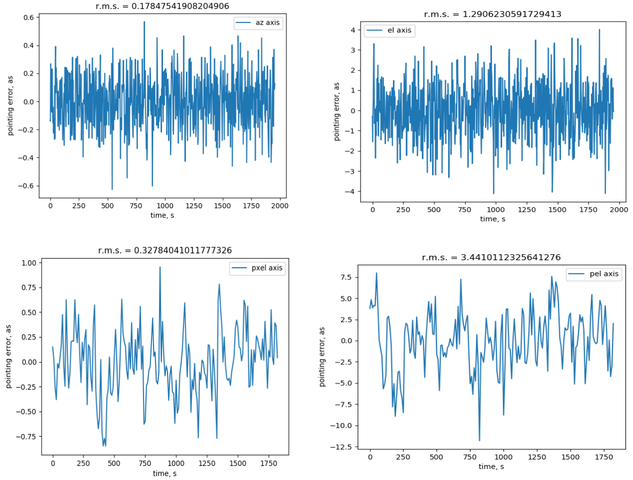
- Start with effects directly related to hardware design
  - Dish pointing and deflections
  - Heterogeneous array imaging
  - LOW station-beam miscalibration
  - Use design models initially; then as-built data
- Add atmospheric effects
- Model direction-dependent calibration

SKA1-MID Dynamic Pointing Errors



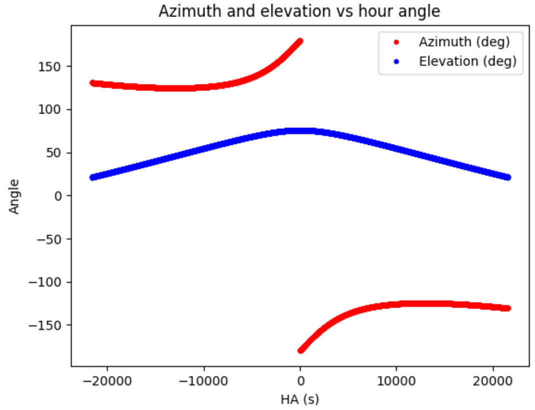
Servo

Structure

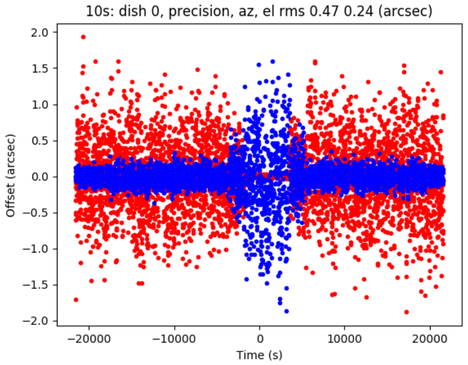


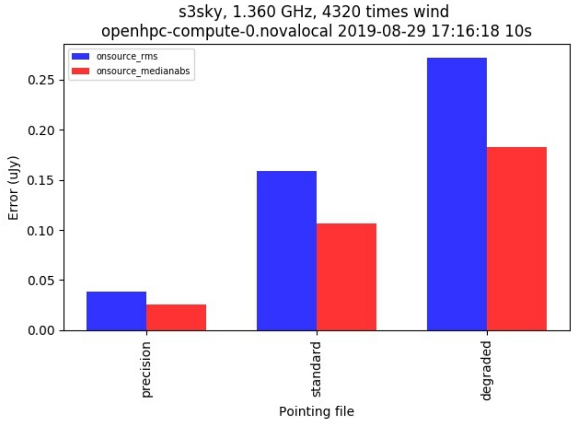
Servo

Structure



Source at -45 deg Declination
Constant wind direction
1366 MHz





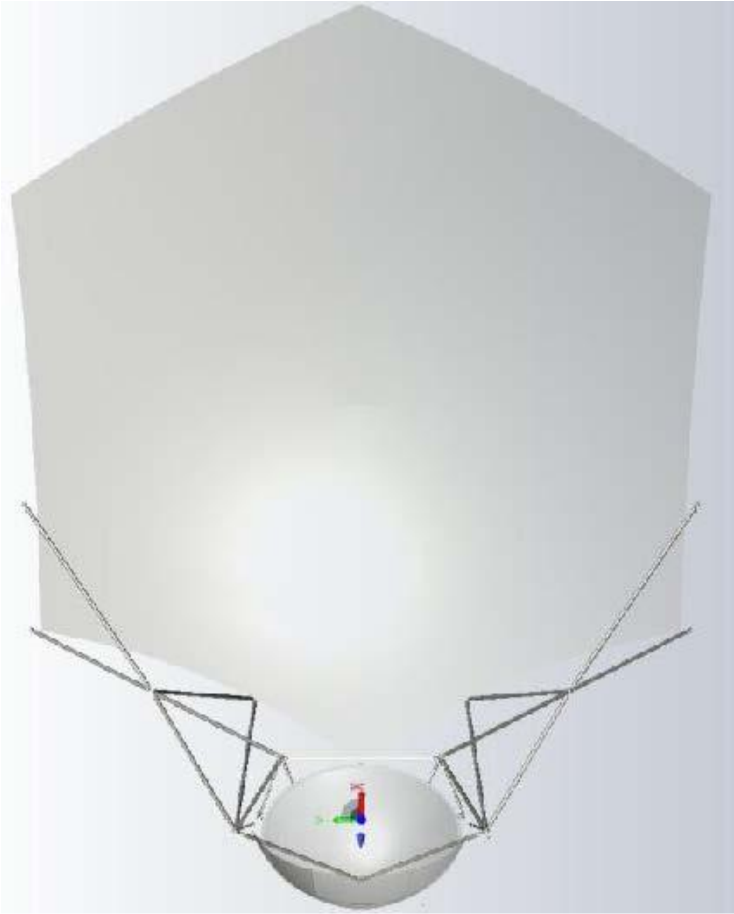
Model power spectra from MTM
Generate realisations

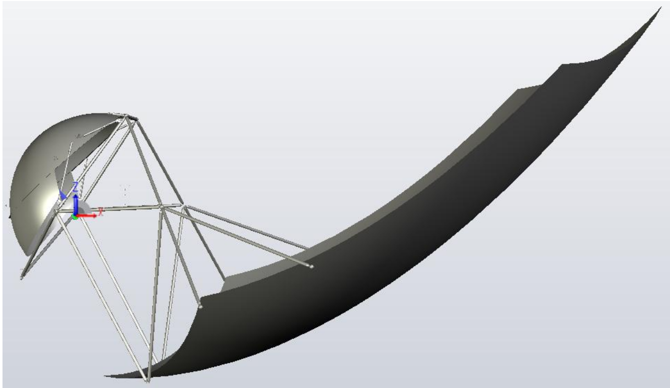
Elevation
Cross-elevation

RMS error in image
3 wind categories

Long track for an array of 197 SKA1 dishes (no MeerKAT) with fixed beams from EM simulation
Typical model sky distribution

SKA1-MID Dish Deformation

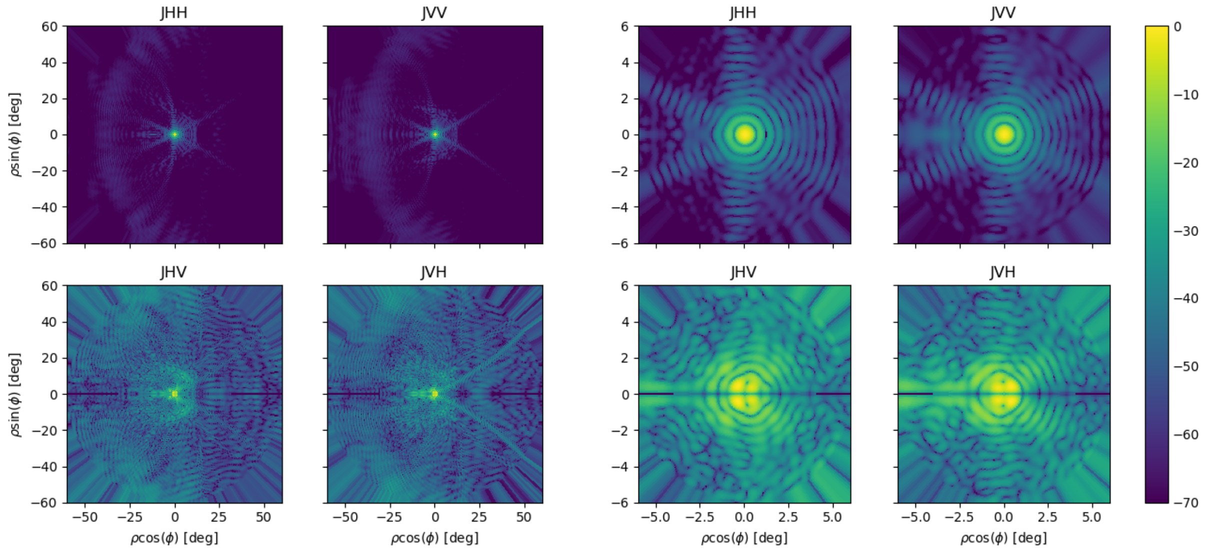


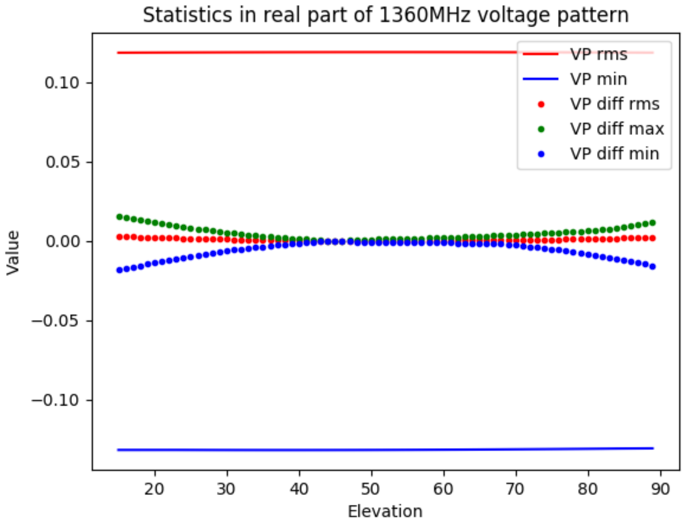


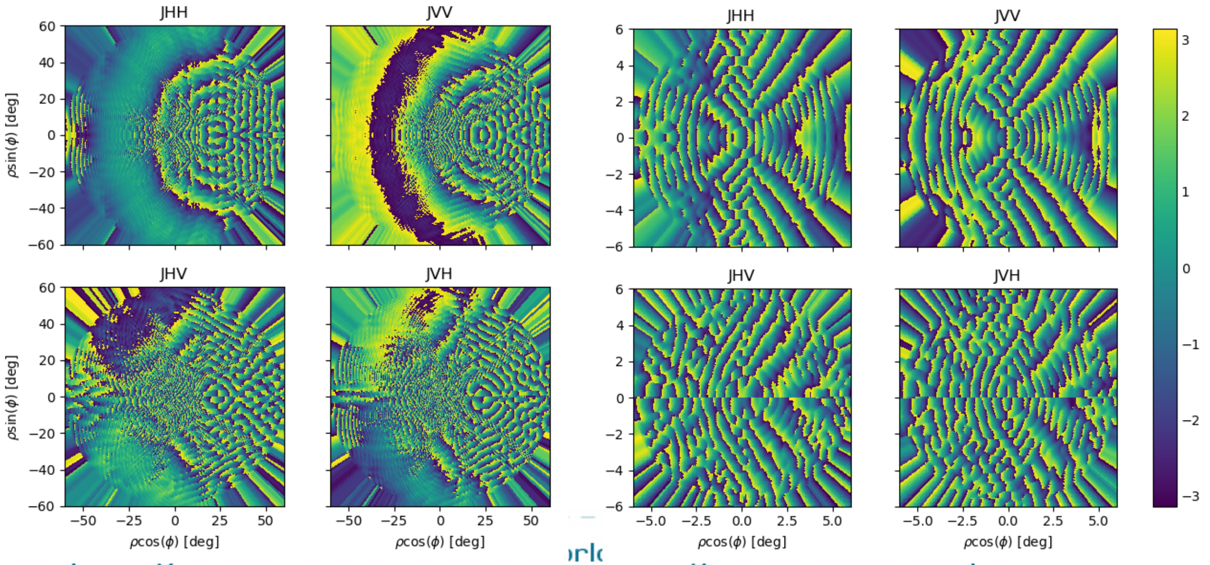
Finite-Element Model
Beams generated by EMSS using FEKO
Gravity (elevation-dependent) effects only

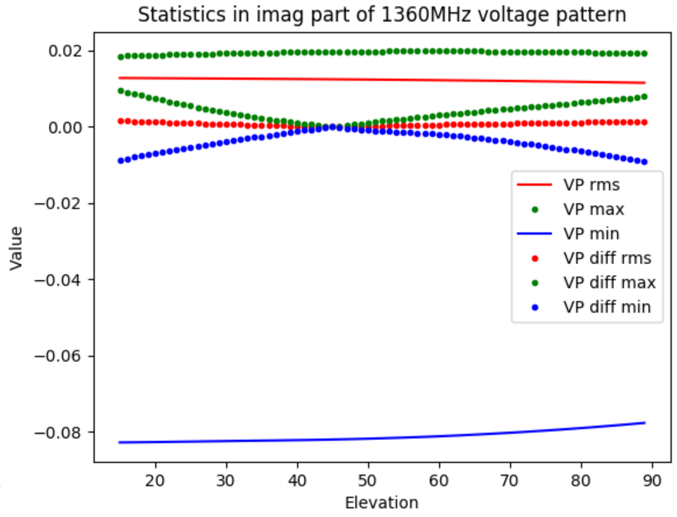
Interpolate beams to finer elevation grid
Assume a typical model sky
Calculate visibilities for elevation-dependent and nominal (45 deg) voltage patterns
Image the difference visibilities

1360-MHz beams

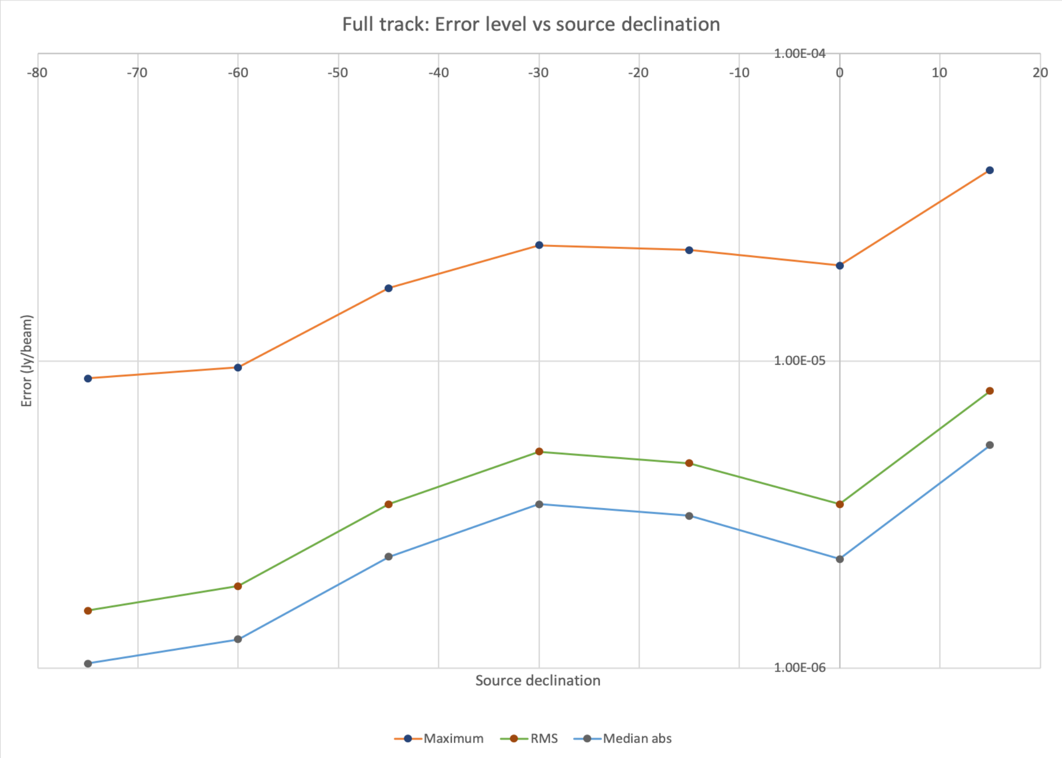


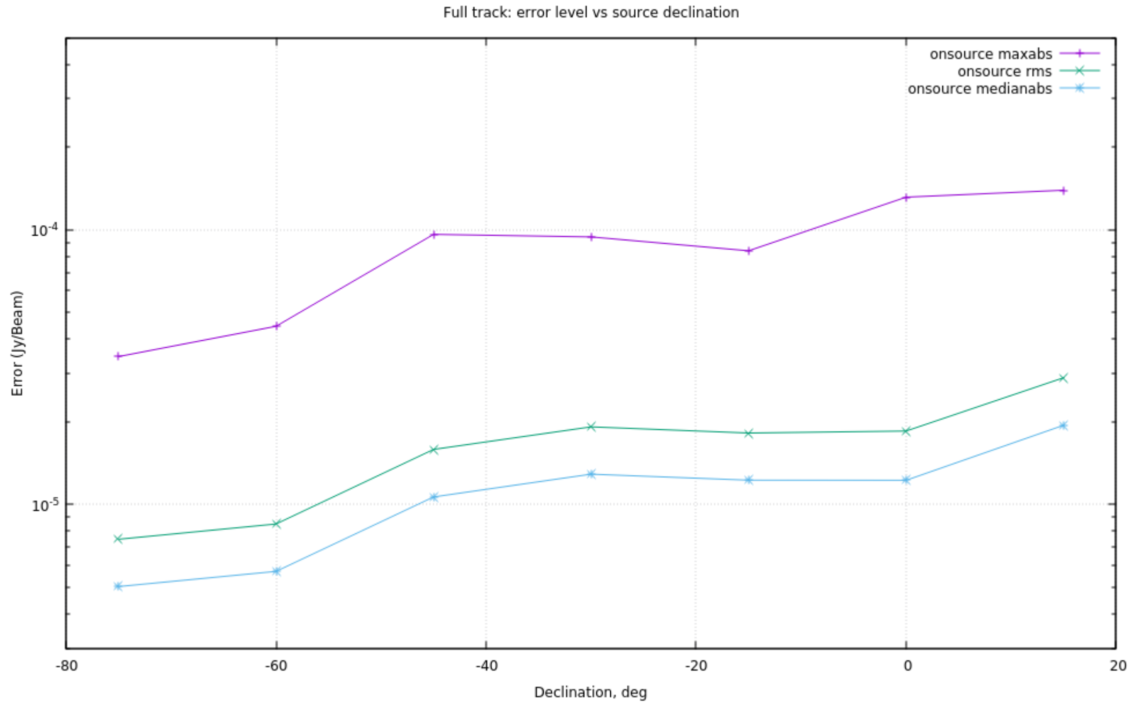






Error Levels: 1360 and 565 MHz





1360 MHz
Brightest source in the field ~1 Jy
Dynamic range of 10^6:1 requires rms ~1 μJy

565 MHz

To meet dynamic range requirement, will need an elevation-dependent beam model

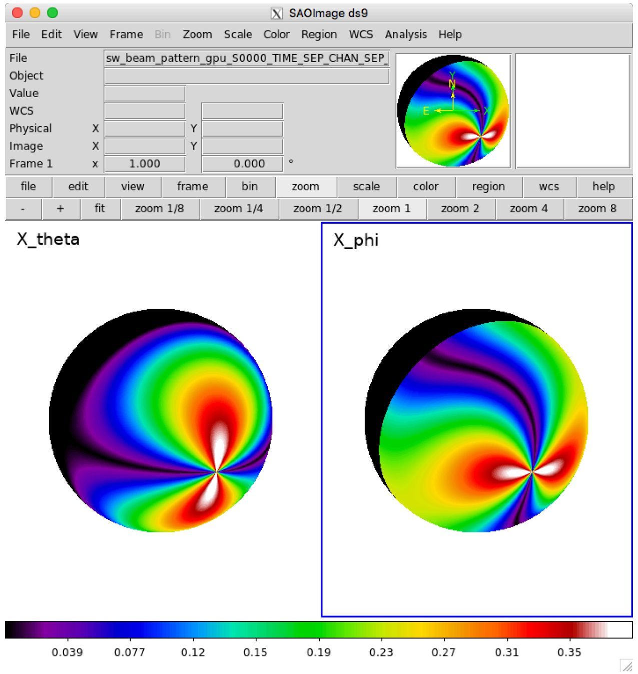
Summary of results for SKA1-MID

- Assuming the current FE models, the typical image error in Band 2 due to dynamic, wind-induced pointing errors is 0.05 - 0.25 μJy/beam, corresponding to a dynamic range of 4 x 10^6 – 2 x 10^7:1.
  - Meets requirements even in degraded conditions
  - Assumes errors are uncorrelated between antennas and rapidly varying
  - "Average" sky model; far too optimistic if source fills the primary beam
- Image error scales as 0.25 : 0.10 : 0.005 Band 1 : Band 2 : Band 5.
- A randomly-distributed but static distribution of pointing errors causes larger effects on the image: pointing rms = 17 arcsec rms corresponds to a noise level of 1 μJy/beam/DR 10^6:1 in Band 2, for the assumed model sky.
- Image errors from uncorrected elevation-dependent dish deflections are more important than pointing errors:
  - 3 μJy/beam in Band 2; 12 μJy/beam in Band 1
  - More significant than pointing because errors are perfectly correlated between antennas
  - Need elevation-dependent beam models for imaging, but these should be the same for all dishes to a first approximation

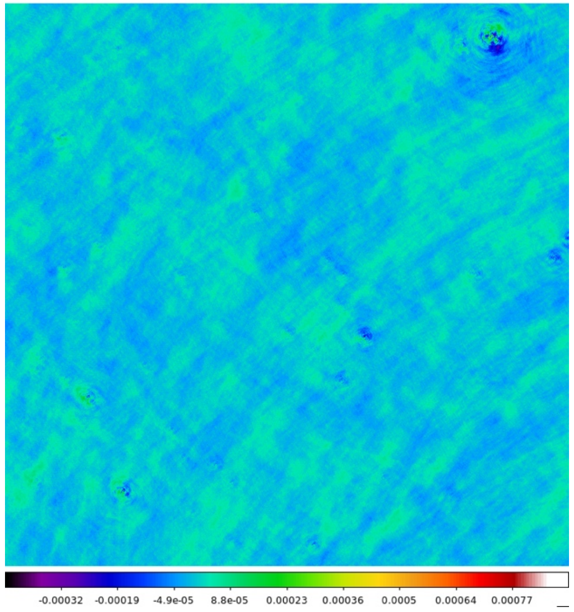
SKA1-LOW Station Beam Errors

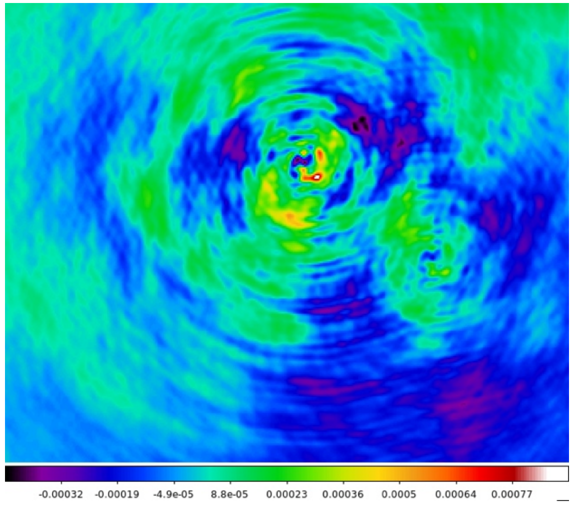
- Base telescope model
  - Station coordinates from latest revision
  - 512 38m diameter stations; different randomised layouts; identical EEPs
- Sky model
  - Based on GLEAM catalogue + 10 “A-team” source
  - MWA EoR field
- Station beam errors
  - Modify beamforming weights and phases
  - Individual errors for each element (rms from L3 requirements and measurements)
- Imaging
  - Full 3D model
  - w-projection imaging

Results



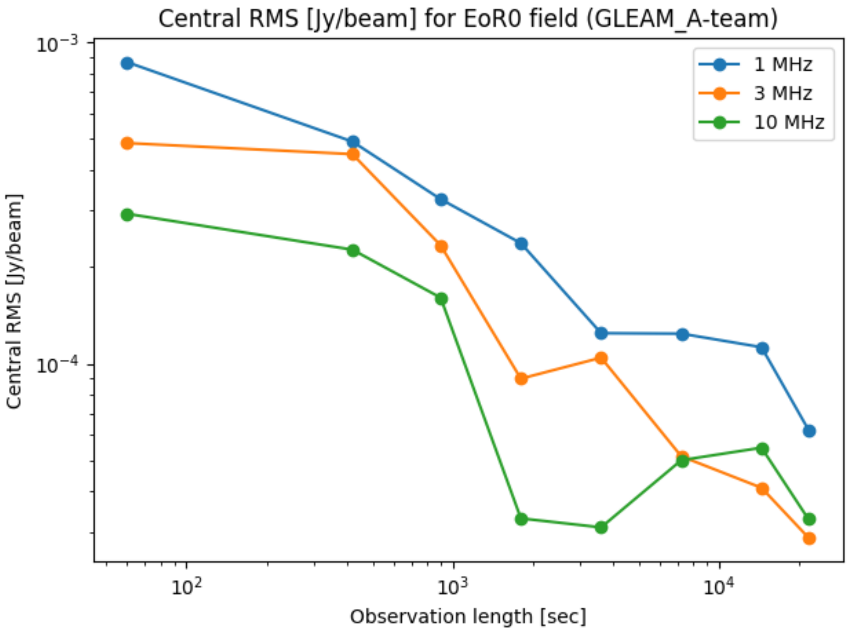
Spherical wave representation of SKALA-4 element beam ingested into OSKAR



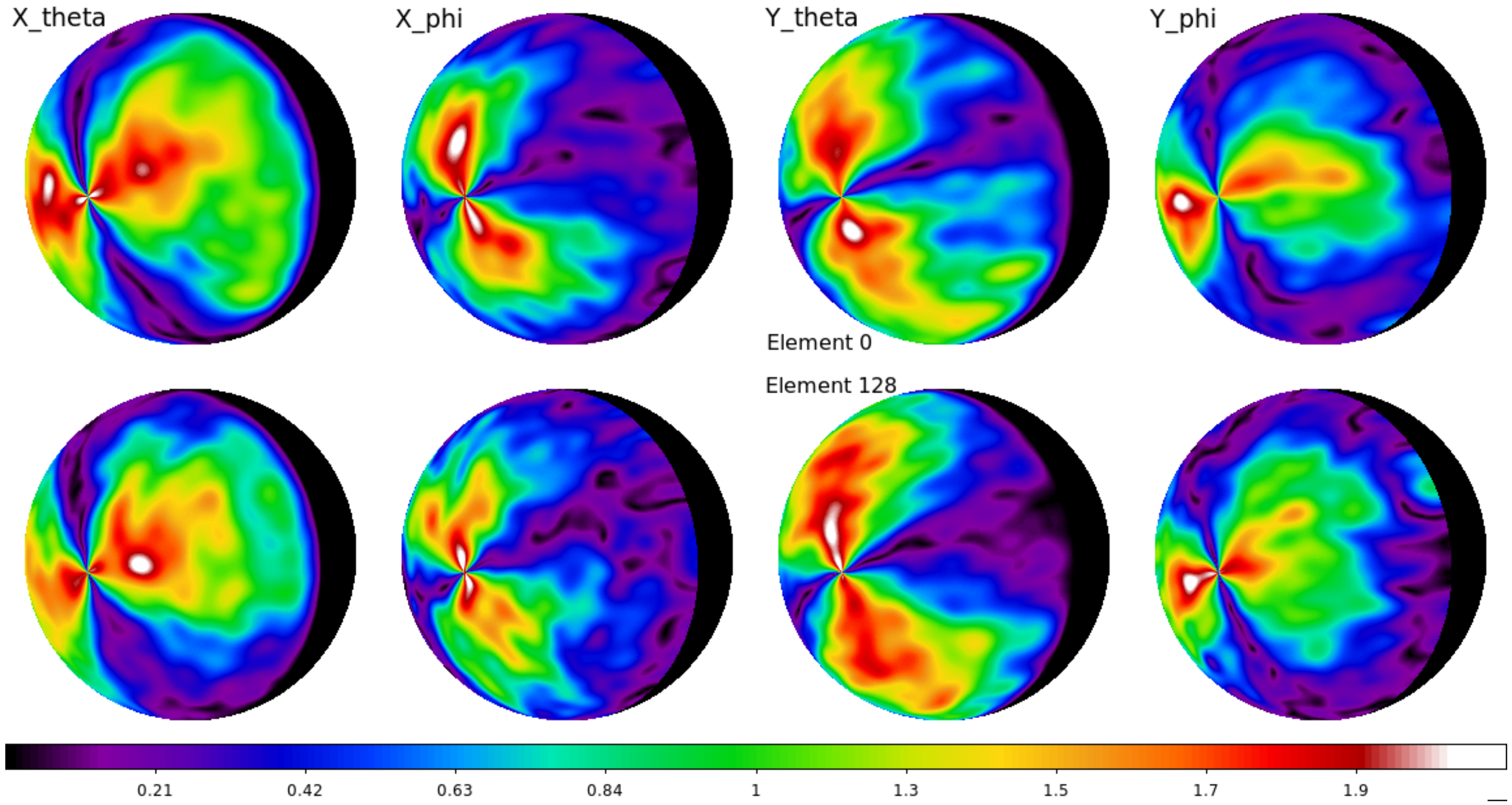


Residual image with random station beam errors (weights and phases)

Noise is dominated by A-team sources far from the phase centre (consistent with LOFAR experience)

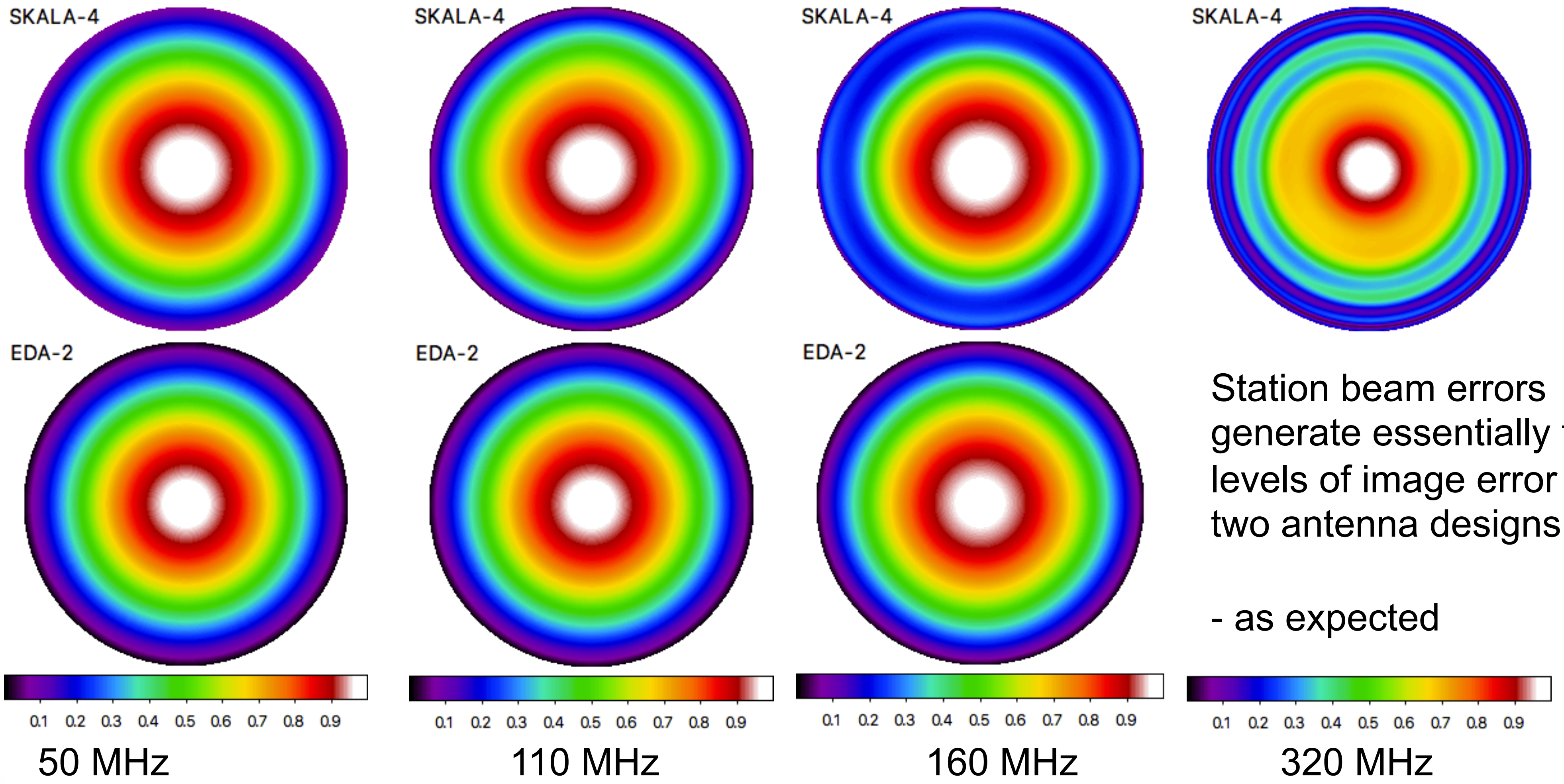


SKALA-4 Station Beams with Mutual Coupling



Can be used in simulations, but not yet computationally feasible to investigate randomised station layouts

Comparison of station-beam errors for EDA-2 and SKALA-4 antennas



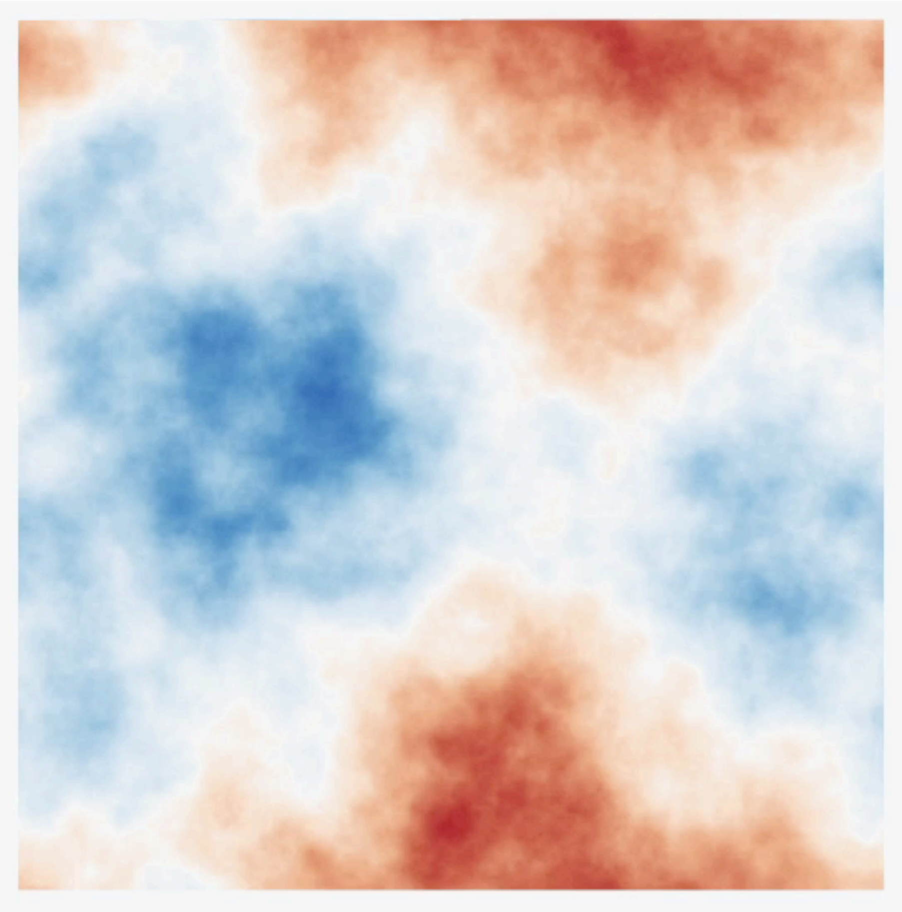
Station beam errors generate essentially the same levels of image error for the two antenna designs

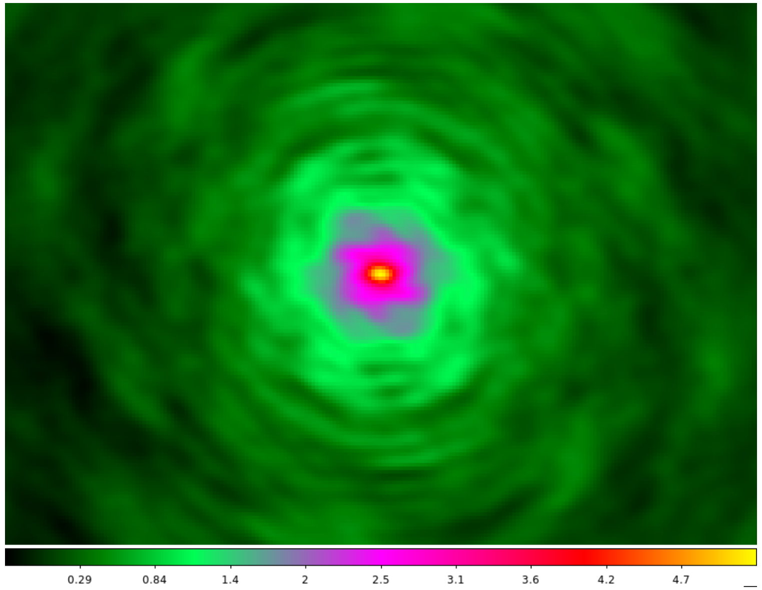
- as expected

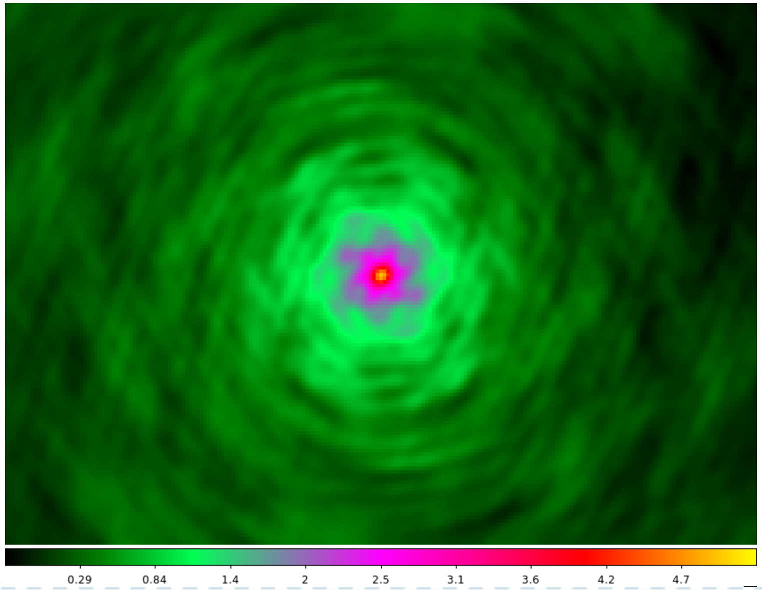
SKA1-LOW Ionospheric Errors

- Phase screen generated externally using ARL auto-regressive atmosphere generator package and loaded into OSKAR
  - allows the screen to evolve over time.
- Screen properties:
  - 200 km by 200 km
  - two layers: 150 km/h at 300 km altitude, 75 km/h at 310 km altitude
  - resolution 100 m per pixel
  - 40 deg FOV
  - TEC converted to delay
- Simulations:
  - 50, 70, 110, 137, 160, 230 and 320 MHz
  - 4 hours duration, sampled every 60s

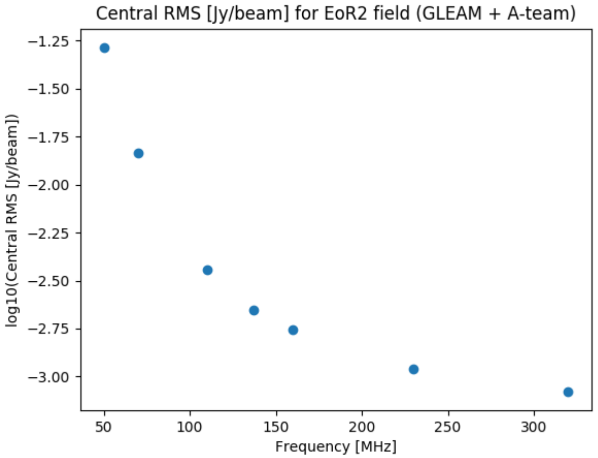
Results







Clear evidence of anisoplanatism, as expected.



Summary of Results for SKA-LOW

- Can perform realistic simulations for station beams with mutual coupling treated correctly
- Analysis of the effects of station-beam errors:
  - Very similar for EDA-2 and SKALA-4
  - Dominated by A-team sources in far sidelobes
  - Mitigate by demixing/peeling
- Ionosphere now included
- RFI propagation modelling currently being tested with AAVS data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