OSKAR-2: Simulating data from the SKA

AACal 2012, Amsterdam, 13th July 2012

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Overview

- OSKAR-2: Interferometer and beamforming simulator package.
- Intended for simulations of SKA_1 aperture arrays.
- Based on full-sky Measurement Equation formalism.
  - “Brute force,” 3D, direct evaluation approach.
- Takes advantage of large computational power offered by modern GPUs via NVIDIA’s CUDA API.
  - Scale up to large aperture array interferometer simulation.

Measurement Equation

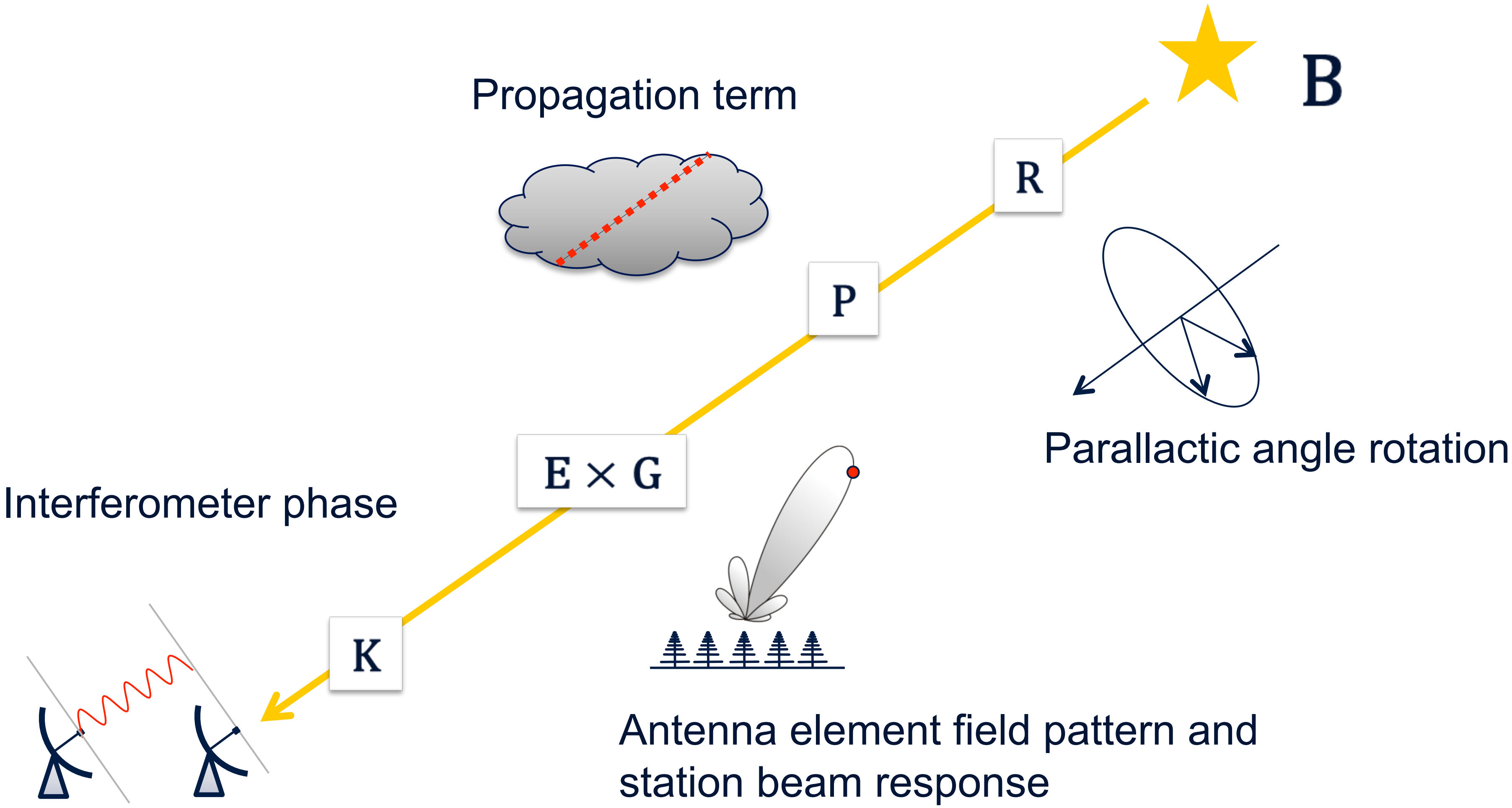
- The ME as implemented by OSKAR-2

$$\langle \mathrm{V}_{p,q} \rangle = \sum_{s} \mathrm{K}_{p,s} \mathrm{E}_{p,s} \mathrm{G}_{p,s} \mathrm{P}_{p,s} \mathrm{R}_{p,s} \langle \mathrm{B}_s \rangle \mathrm{R}^{H}_{q,s} \mathrm{P}^{H}_{q,s} \mathrm{G}^{H}_{q,s} \mathrm{E}^{H}_{q,s} \mathrm{K}^{H}_{q,s}$$

- Baseline *p, q* for all visible sources, *s*.
- **B** – Source brightness.
- **R** – Parallactic angle rotation.
- **P** – Propagation term.
- **G** – Antenna element field pattern.
- **E** – Station beam.
- **K** – Interferometer phase.
- **V** – Complex visibility.

... and any others required!

Measurement Equation

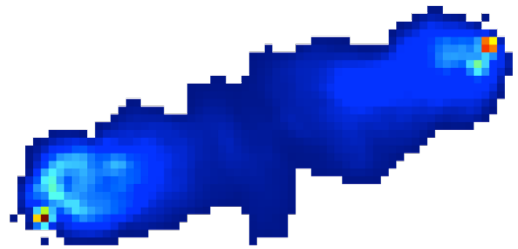


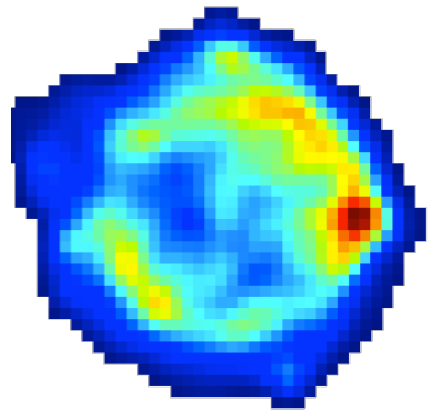
New (since December 2011)

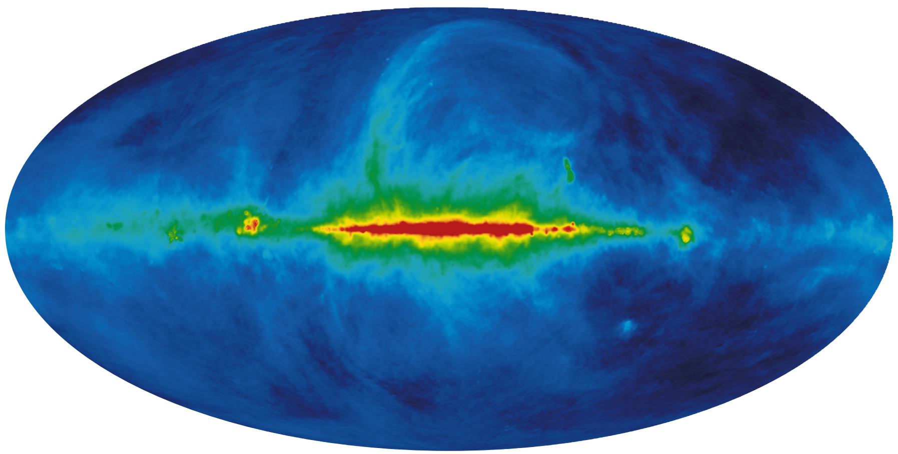
- Usability improvements:
  - Simple GUI and scriptable simulation applications.
- Extended sources.
- Element pattern evaluation now implemented on GPU.
- (Ideal) dipole rotation allowed within station.
- Can use FITS images directly as sky models.
- Addition of visibility noise (currently in testing).
- Planned:
  - Ionospheric model.
  - Multiple antenna types per station.
  - Hierarchical stations.

Sky Model

- Equatorial point source model.
- Extended objects modelled as large collections of pixels.
- "Large" could easily be ~ 10^6 sources across whole sky!





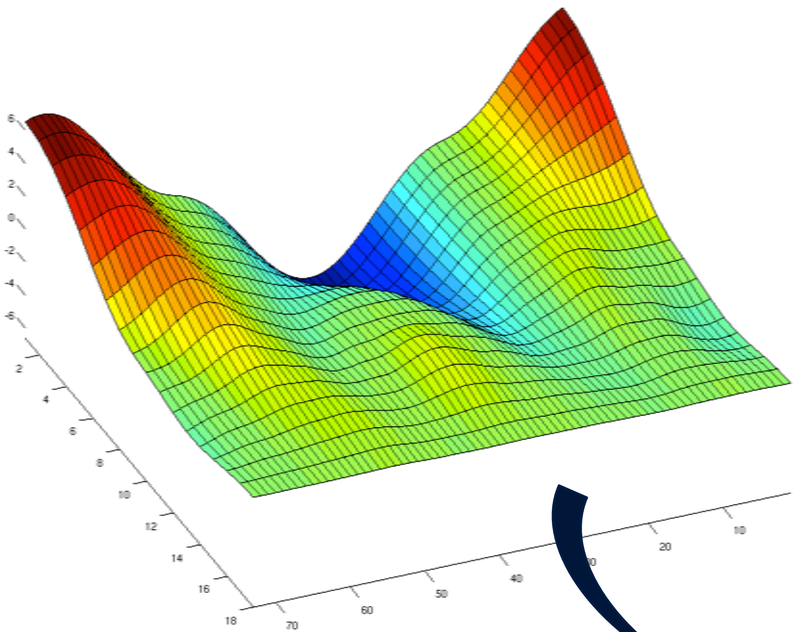


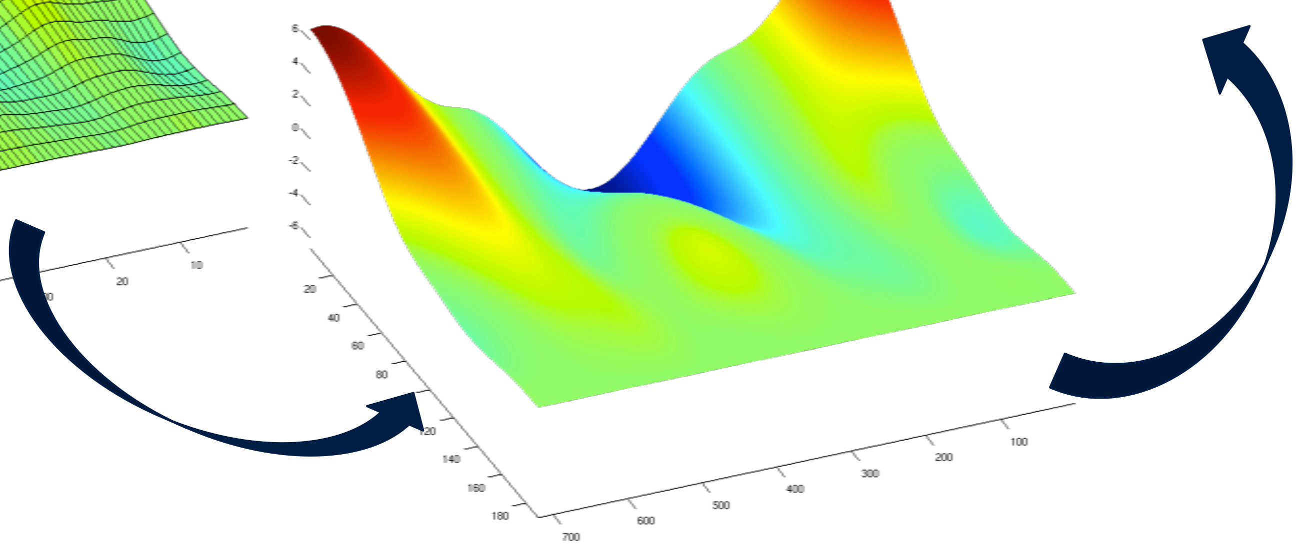
$$\langle \mathbf{B} \rangle = \begin{bmatrix} I + Q & U + iV \\ U - iV & I - Q \end{bmatrix}$$

Antenna Field Pattern (G-matrix)

- The average embedded element pattern for antennas within a station
- Antenna data given in tabular form:
  - Fit bicubic B-splines to nodal points to construct surface with continuous derivatives.
  - Evaluate spline coefficients to get antenna response at each source position.

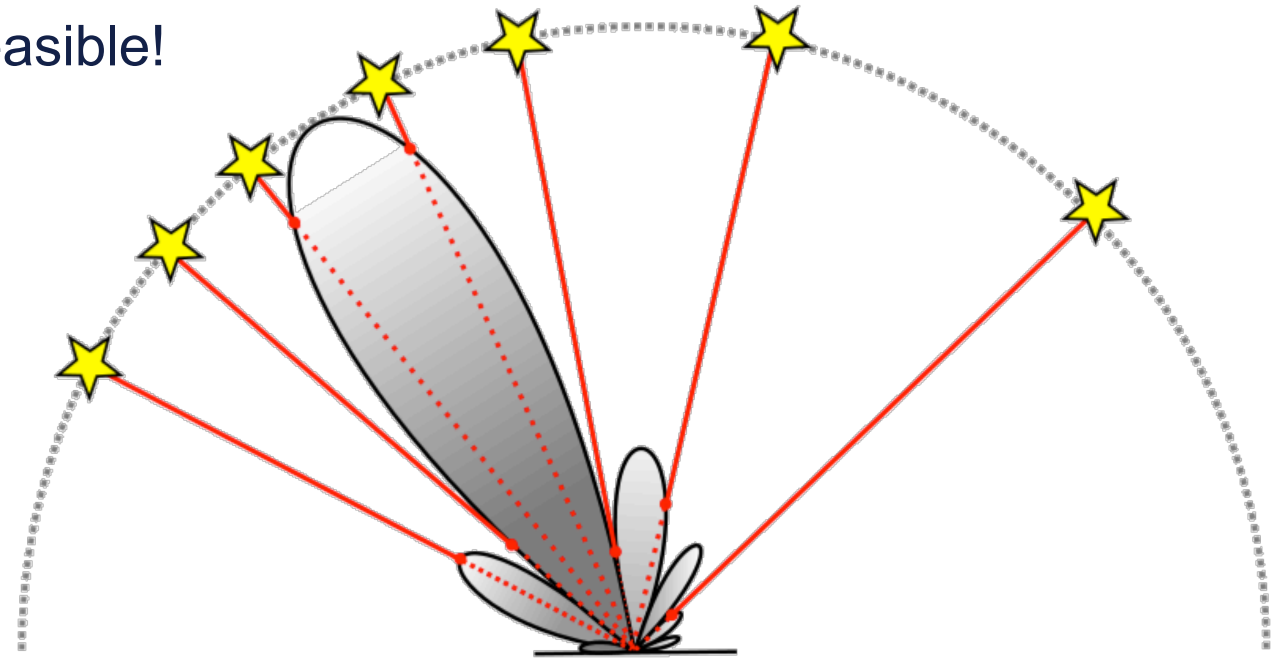
$$\mathbf{G} = \begin{bmatrix} g_\theta^X & g_\phi^X \\ g_\theta^Y & g_\phi^Y \end{bmatrix}$$





Station Beams (E-matrix)

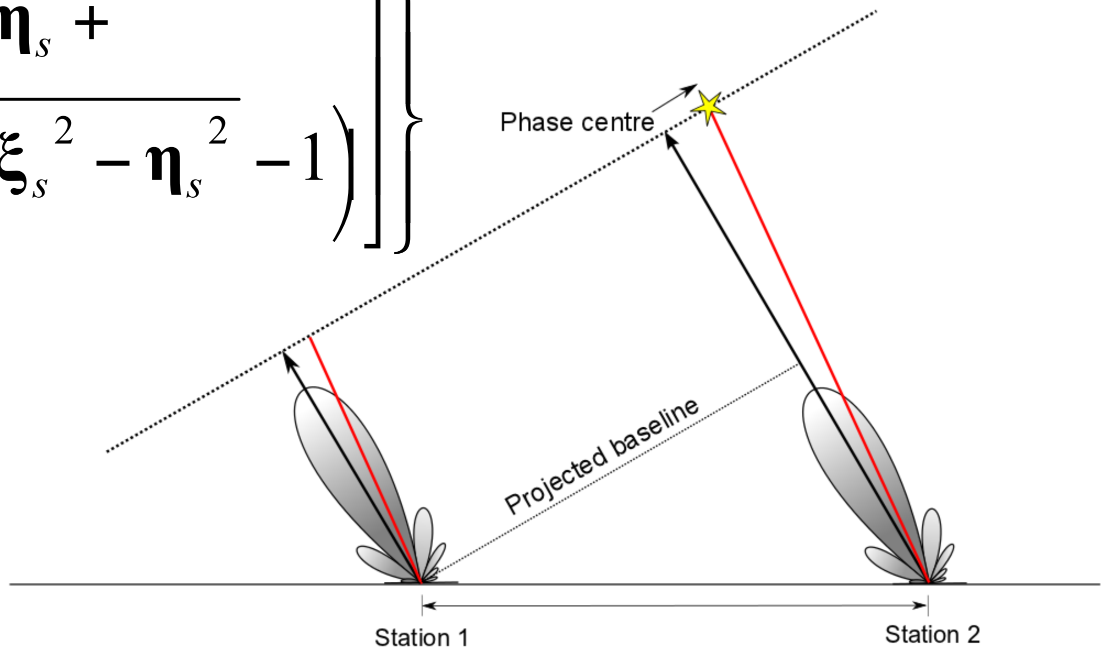
- OSKAR-2 evaluates every station beam (i.e. for every aperture array) at every source position.
- This incorporates all effects at the station level, e.g. phase and gain errors, different beamforming schemes, antenna patterns...
- GPUs make this feasible!



Station Phases (K-matrix)

- K-matrix effectively “phases-up” the array of stations.
- Compute phase of each source *s* at every station *a*.
  - Determine station (u,v,w) coordinates by rotating (x,y,z) onto a plane perpendicular to direction of phase centre.

$$\mathbf{K}_{s,i} = \exp\left\{-2\pi i k \left[\mathbf{u}_i \boldsymbol{\xi}_s + \mathbf{v}_i \boldsymbol{\eta}_s + \mathbf{w}_i \left(\sqrt{1 - \boldsymbol{\xi}_s^{\,2} - \boldsymbol{\eta}_s^{\,2}} - 1\right)\right]\right\}$$



"Correlator"

- Multiplies Jones matrices with the source brightness to obtain a complex visibility per source and per baseline.

$$\mathbf{V}_{i,j} = \sum_{s} \mathbf{J}_{s,i} \mathbf{B}_{s} \mathbf{J}^{*}_{s,j}$$

- Time-average smearing: each visibility point can be averaged over time.
  - K is recomputed to include motion of baseline during integration period.
  - E is allowed to vary throughout the integration at a slower rate than K.
- Bandwidth smearing: multiply each visibility by $f_{s,i,j}$ before collapsing the source dimension.

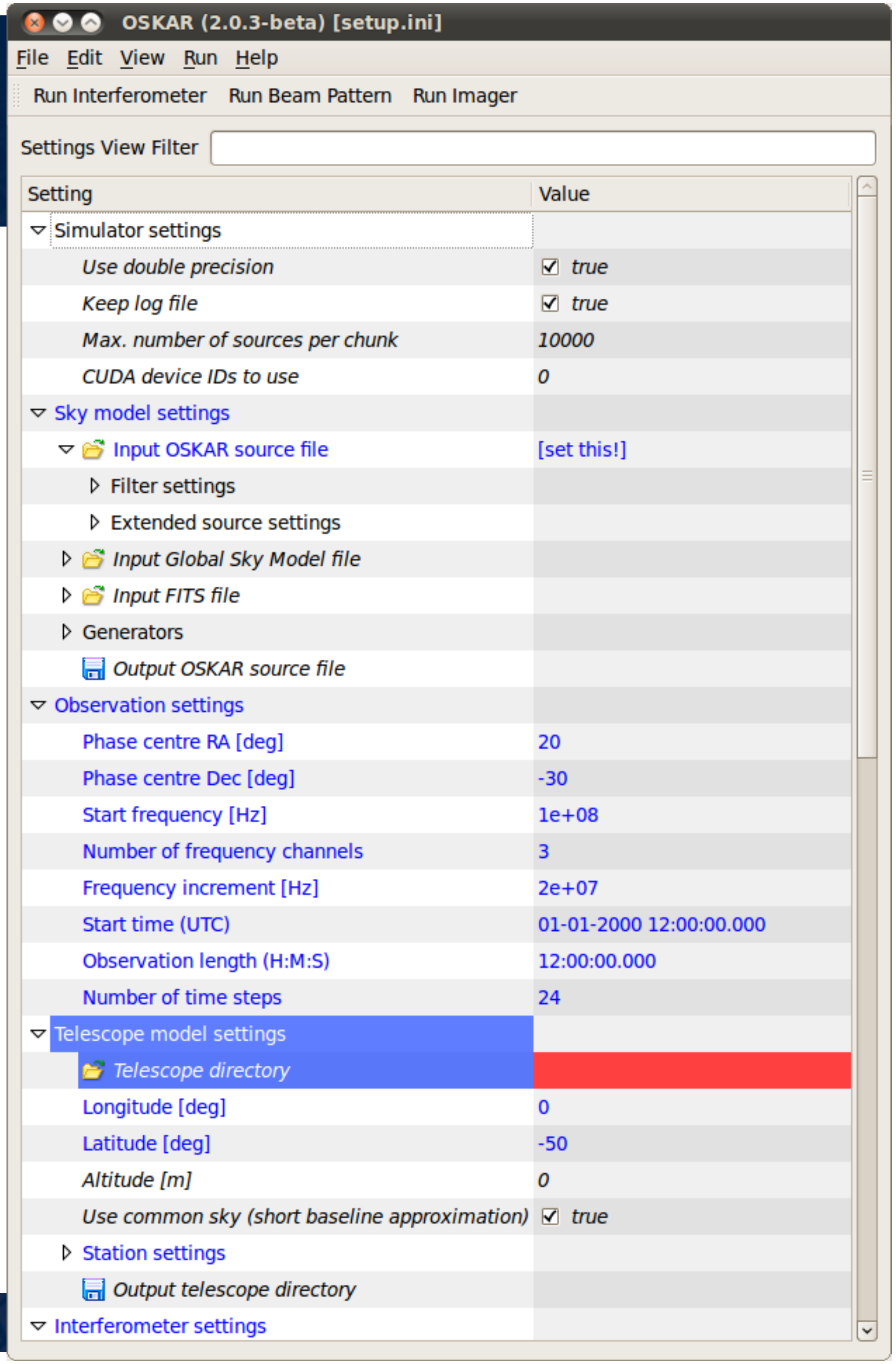
$$f_{s,i,j} = \frac{\sin(\pi D_{i,j} \xi_s \Delta\nu / c)}{\pi D_{i,j} \xi_s \Delta\nu / c}$$

The OSKAR Package

- OSKAR-2 consists of a library and some simulation applications:
  - oskar_sim_interferometer
  - oskar_sim_beam_pattern
  - oskar_imager
  - oskar (simple GUI to edit settings files)
  - … and some command-line utilities to allow easy scripting of simulations.
- All computationally intensive functions carried out using NVIDIA CUDA.
- Can be used with multiple GPUs for very large simulations.
- Output can be written to measurement set.

OSKAR-2 Settings

- Plain-text settings file (INI format) can be edited by hand.
  - Consists of key, value pairs.
- All parameters can be set using simple GUI.
  - Can easily hide settings not of interest.
  - Highlights required parameters, and those not at default values.



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Sky Model

- Text files contain columns describing, for each source:
  - Apparent Right Ascension
  - Apparent Declination
  - Stokes I
  - Stokes Q *
  - Stokes U *
  - Stokes V *
  - Reference Frequency *
  - Spectral Index *
  - Gaussian FWHM (major axis) *
  - Gaussian FWHM (minor axis) *
  - Gaussian Position Angle *

```
# Example sky model
220.0, 50.0, 0.1
220.1, 50.1, 0.5, 0.5, 0.0, 0.0, 0.0, 0.0, 80, 30, 25
219.9, 49.9, 0.1, 0.0, 0.1
```

* optional

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Telescope Model

- Directory structure containing text files describing layout at each level of the telescope:
- my_telescope_model/
  - station001/
    - config.txt [describes configuration of station 1]
  - station002/
    - config.txt [describes configuration of station 2]
  - station003/
    - config.txt [describes configuration of station 3]
  - … [other station directories]
  - config.txt [describes layout of stations in interferometer]
- Each station directory may also contain (different) embedded element pattern data files.

Telescope & Station Configuration

- Text files (‘config.txt’) contain columns describing:
  - x (East) coordinate.
  - y (North) coordinate.
  - z (up) coordinate. *
- Station files may also contain:
  - Element x position error. *
  - Element y position error. *
  - Element z position error. *
  - Systematic gain factor. *
  - Time-variable gain factor standard deviation. *
  - Phase offset. *
  - Time-variable gain standard deviation. *
  - Element complex multiplicative beamforming weight. *
  - X dipole axis azimuth angle. *
  - Y dipole axis azimuth angle. *

* optional

Some Example Simulations

Some Example Simulations

- Telescope model consisting of:
  - 50 stations
  - in a log-spiral, 3-arm configuration
  - with maximum baseline 100 km,
  - each a 180-m diameter aperture array,
  - containing 10000 randomly placed antennas.
- Observation parameters:
  - Observing at 100 MHz,
  - for 8 hours on 1 Jan 2000,
  - for a telescope at latitude 50 degrees (0 degrees longitude),
  - (720 visibility dumps 40 seconds apart),
  - updating fringe every 0.2 seconds for time-average smearing,
  - and bandwidth smearing for 150 kHz channel.

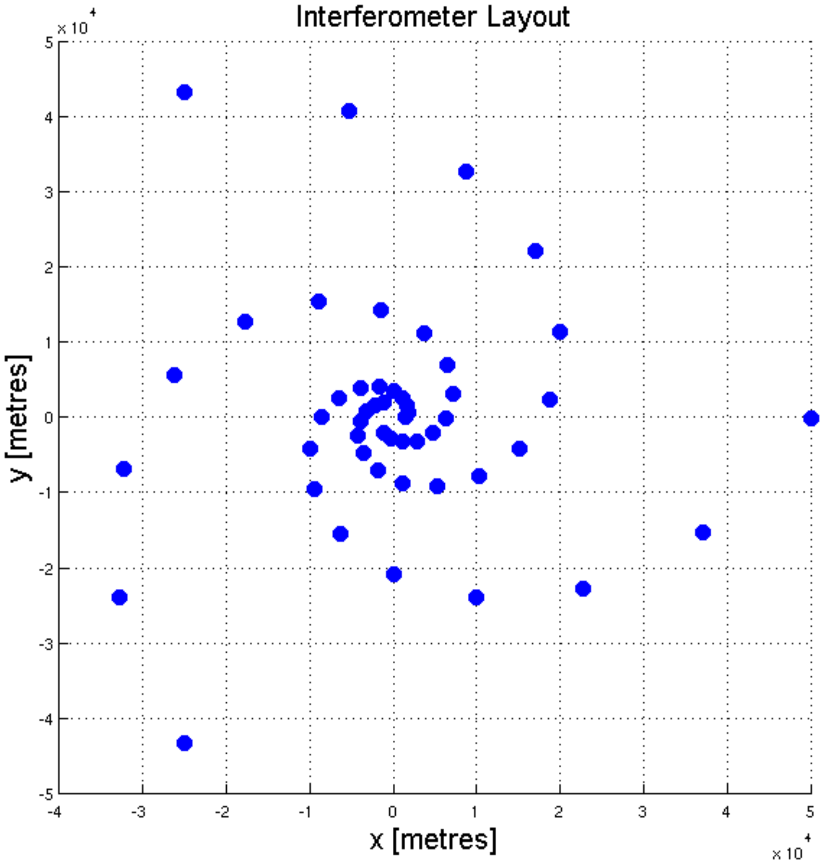
Some Example Simulations

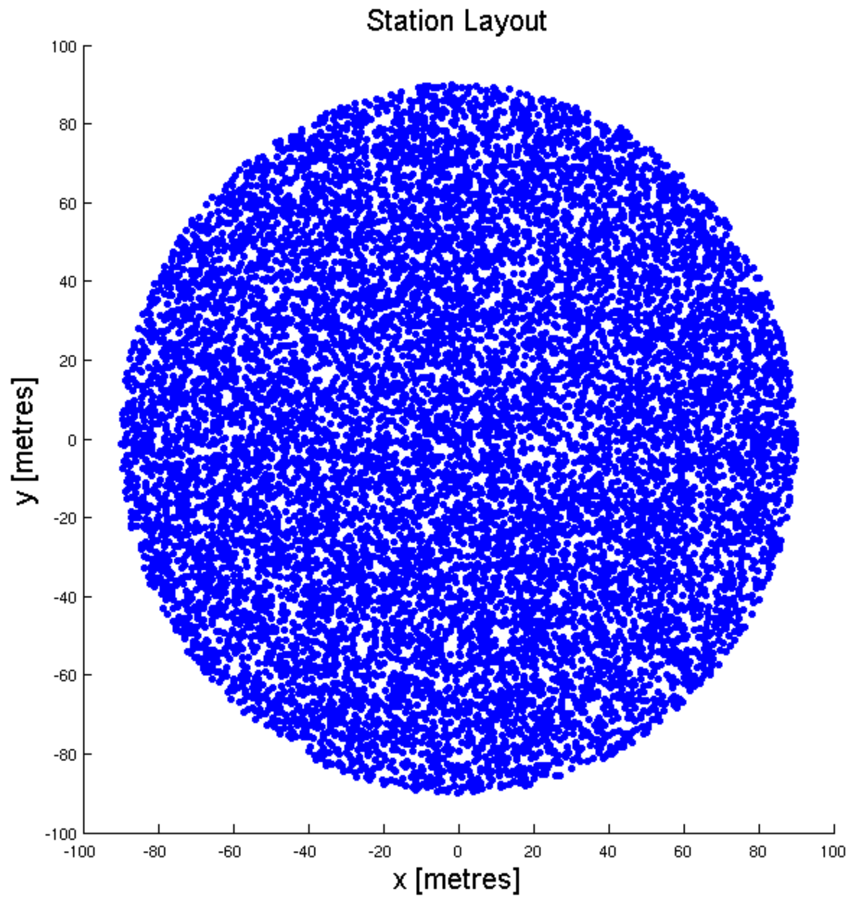
1. Canonical sky model (17 3C sources), looking at a 100 mJy source a long way from any other.

2. Canonical sky model (17 3C sources), looking at a 100 mJy source with Cas A in the first sidelobe.

3. Fictitious sky model containing some polarised and extended sources.

Layouts

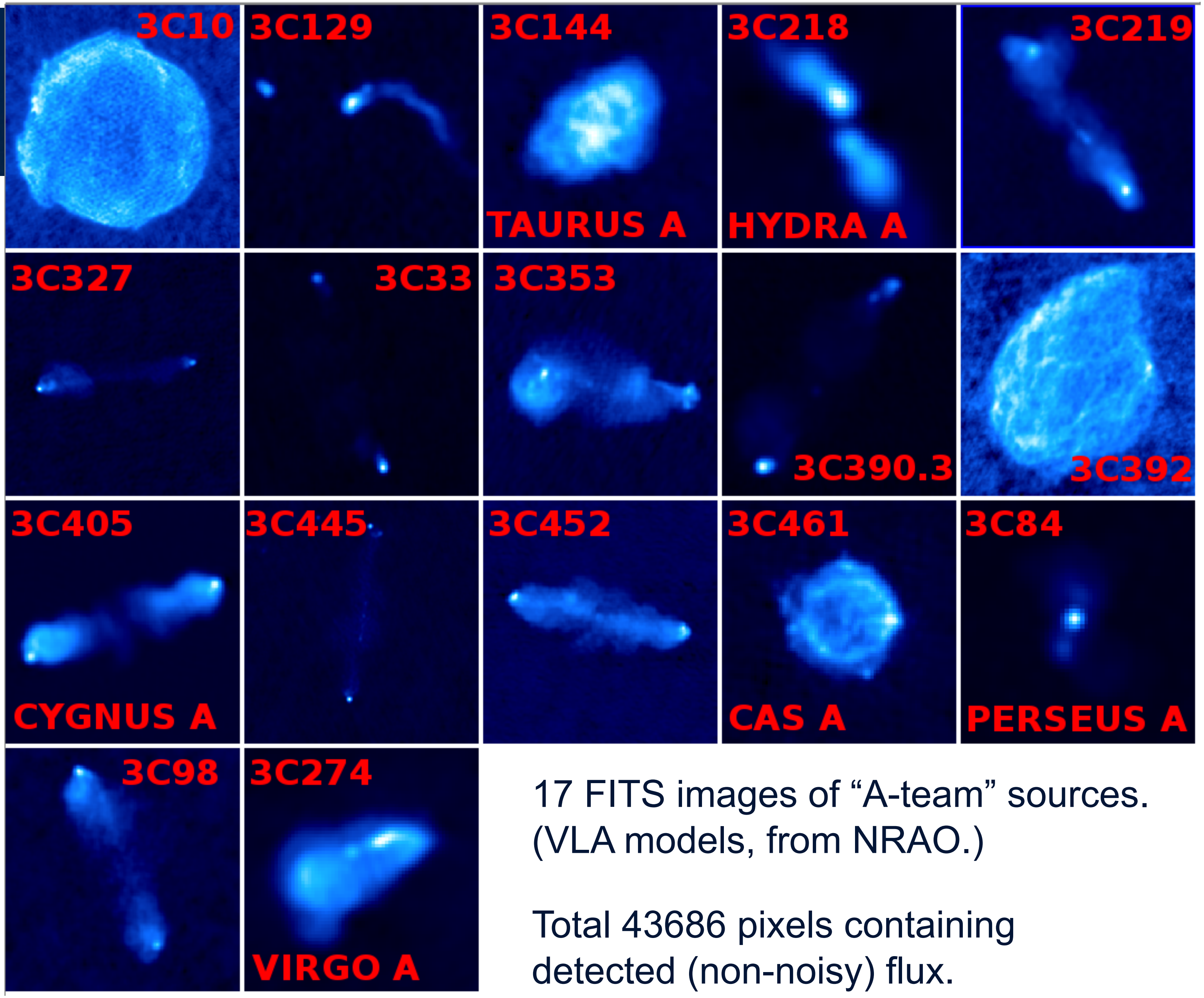




50 stations (max baseline ~ 100 km).

10000 elements, 180 m diameter.

Sky Model

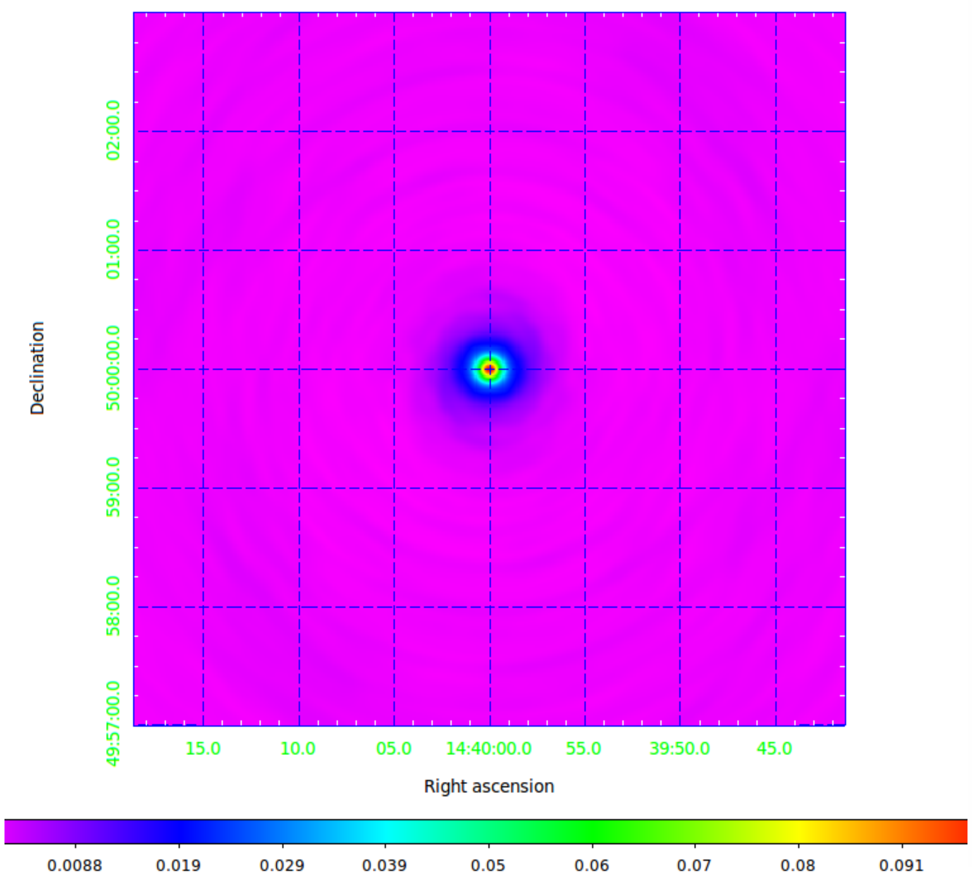


17 FITS images of “A-team” sources. (VLA models, from NRAO.)

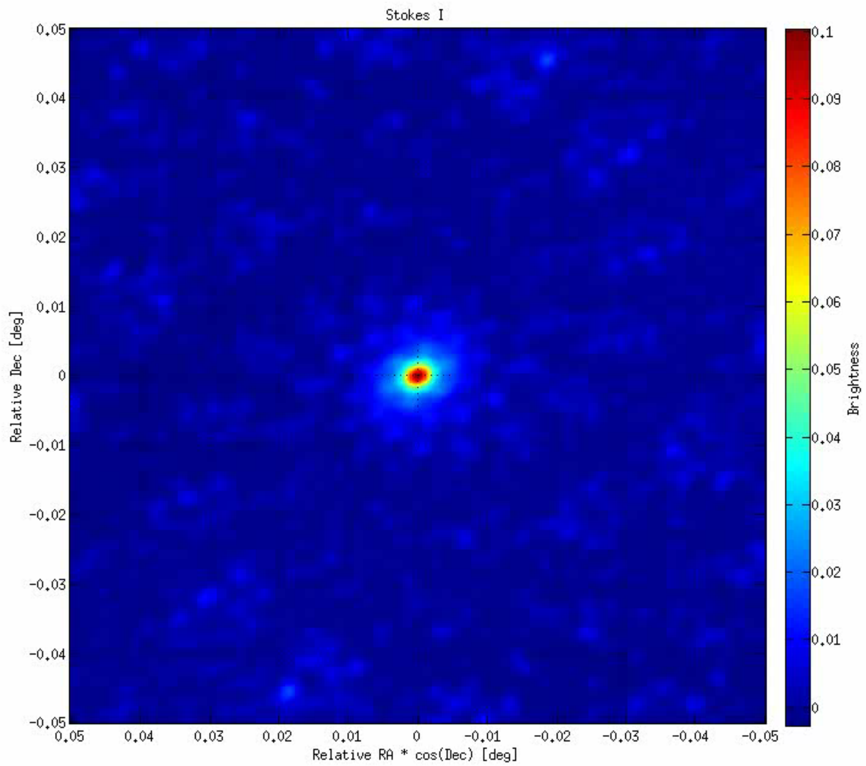
Total 43686 pixels containing detected (non-noisy) flux.

Example 1: 100 mJy source in quiet part of sky

Time synthesis



Time snapshots



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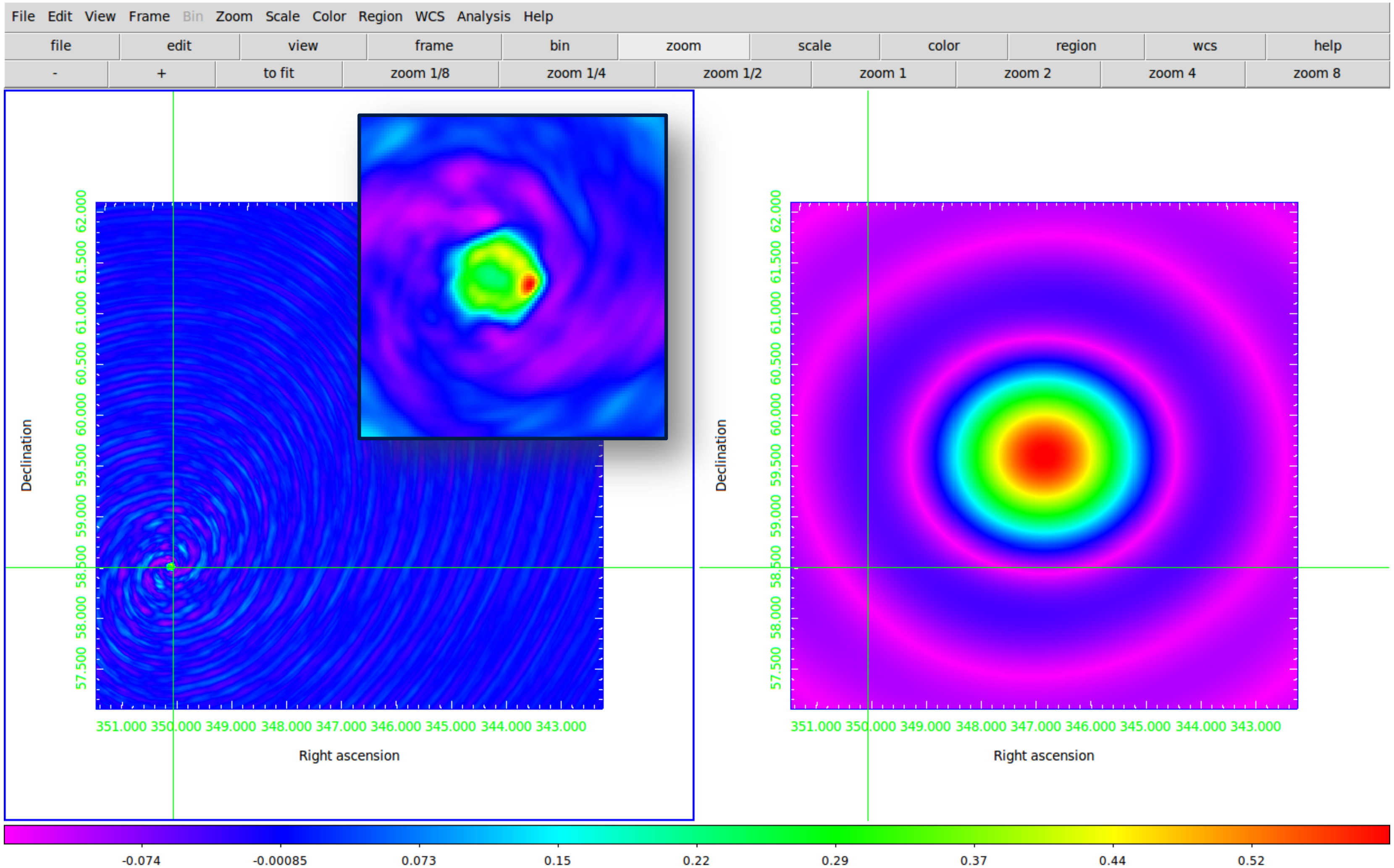
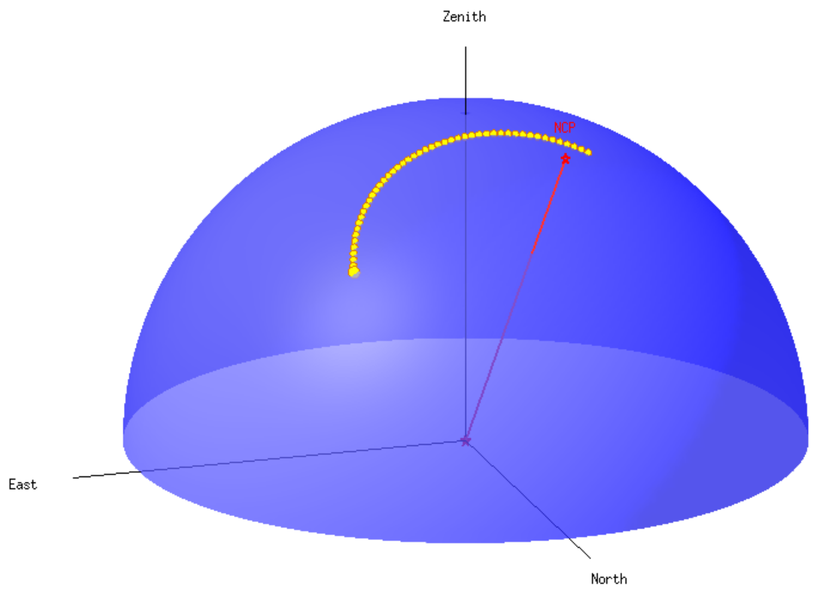
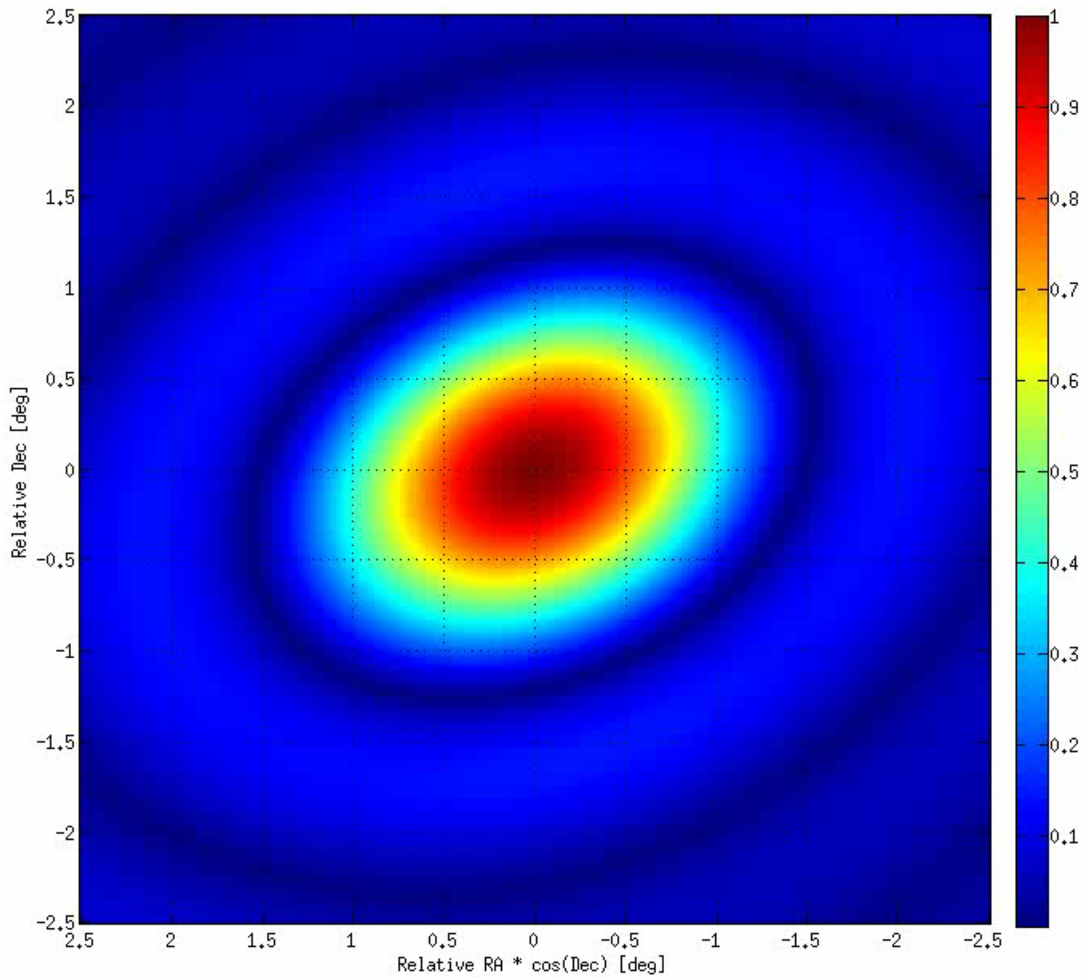
Example 2: 100 mJy source with Cas A in first sidelobe



Example 2: 100 mJy source with Cas A in first sidelobe (beam)





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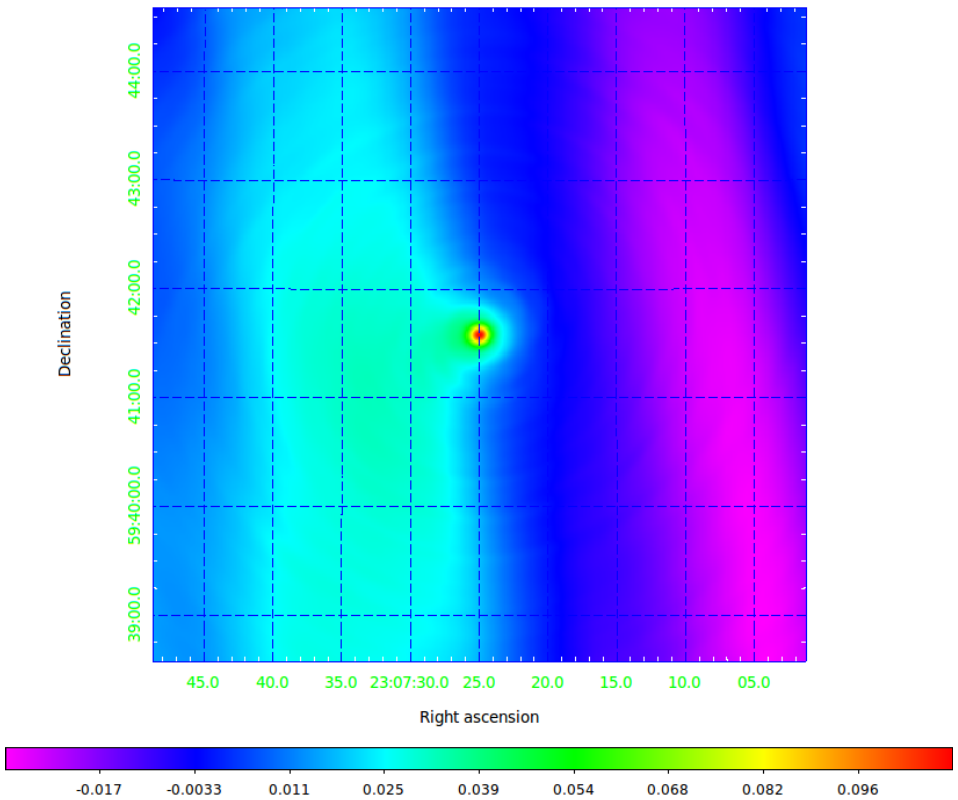
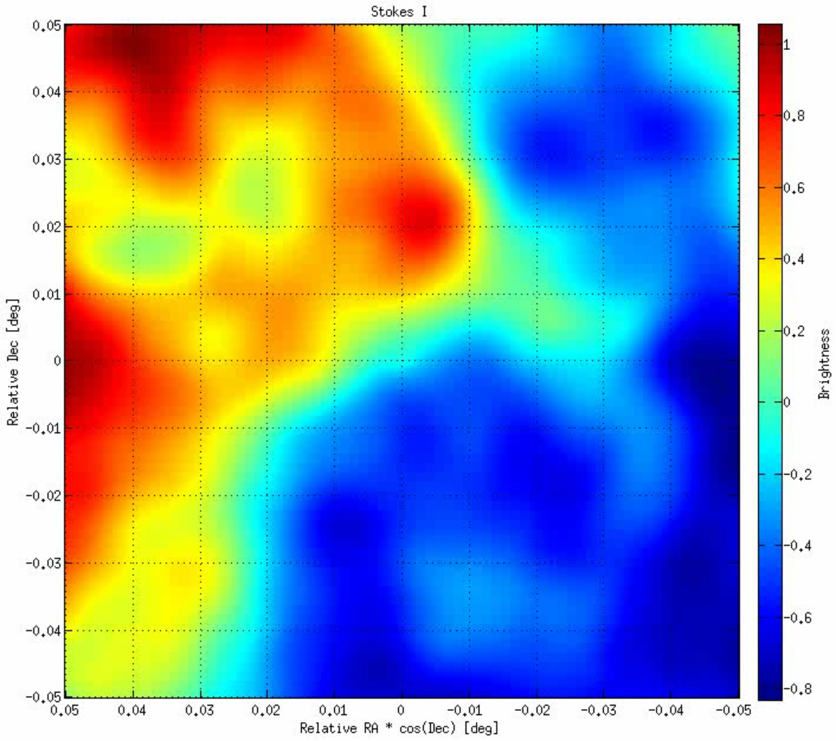
Example 2: 100 mJy source with Cas A in first sidelobe (Stokes I)

Time synthesis

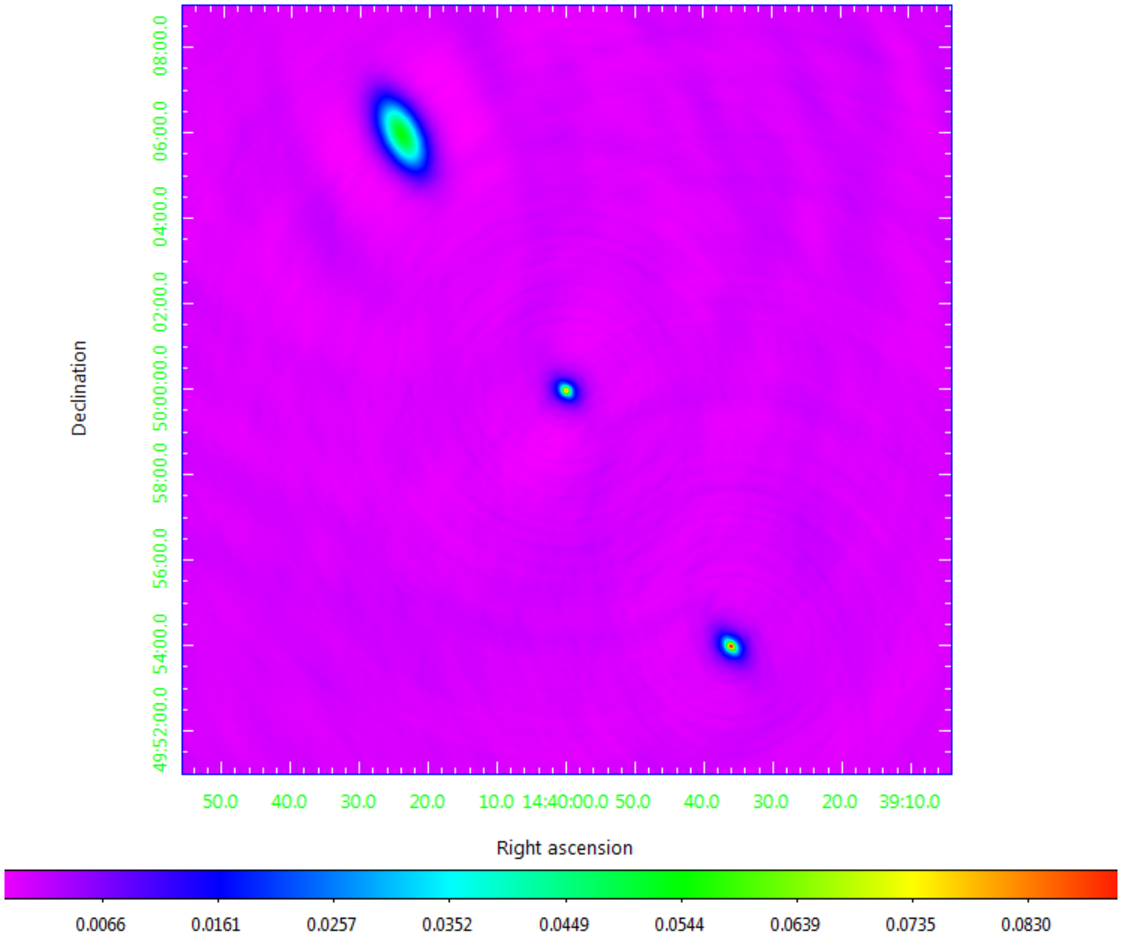


Time snapshots



Example 3: Fictitious sky model (Stokes I)

Time synthesis



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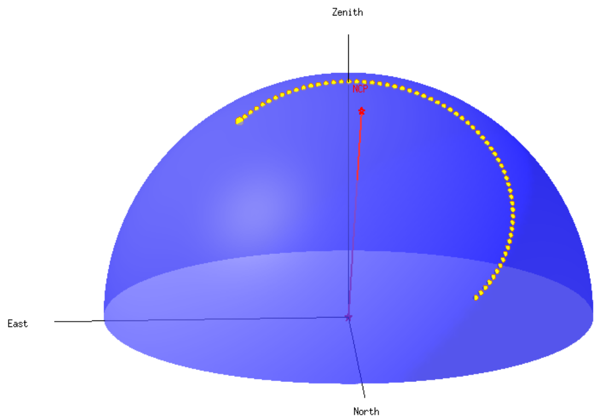
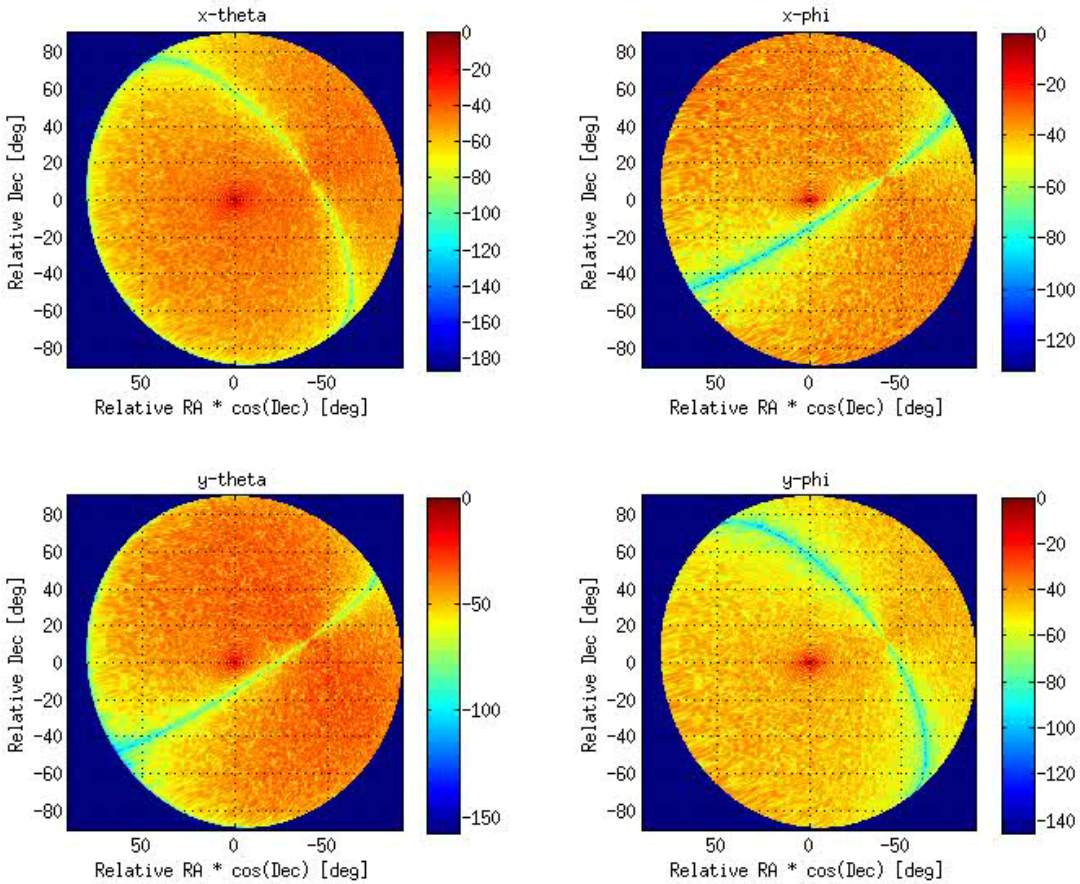
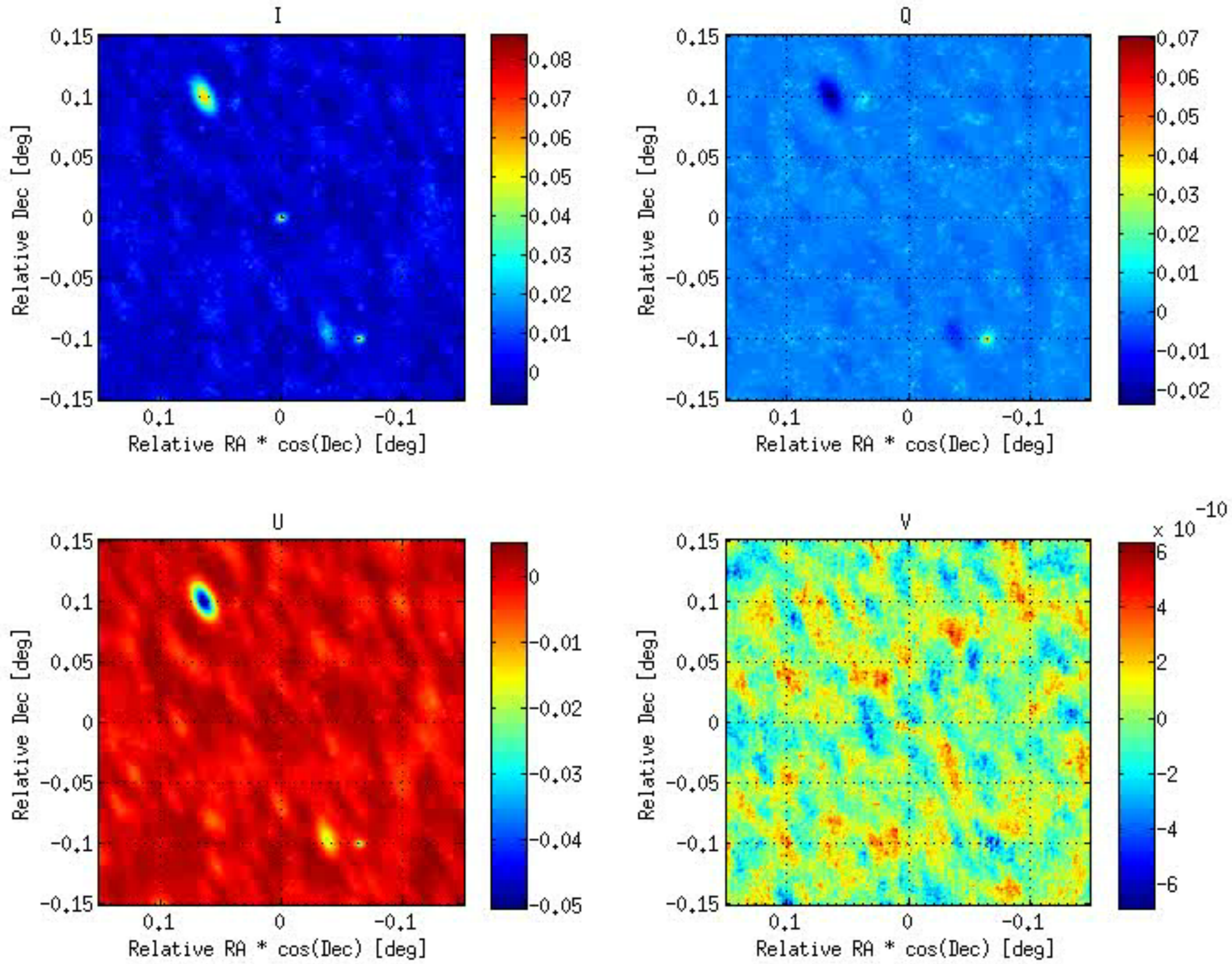
Example 3: Beam patterns





Example 3: Images



Next Steps

- New features (on-going work)
  - Ionosphere model
  - Element patterns per antenna type
  - Hierarchical station model
  - Simulations using dishes
  - Integration with MeqTrees
- Using OSKAR
  - SKA AA phase 1 design studies (single, dual band?)
  - Simulating existing instruments → LOFAR
  - Open questions
    - Choice of configurations for comparison?
    - Ability to calibrate and image simulated data?
    - Performance metrics?
- OSKAR release
  - Currently in pre-release (2.0.3-beta)
    - Source code only
    - Documentation and examples available
  - Suggestions? Contact Us!

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