OSKAR-2: Simulating data from the SKA

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Fred Dulwich, Ben Mort, Stef Salvini
Overview

- **OSKAR-2**: Interferometer and beamforming simulator package.
- Intended for simulations of SKA₁ 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.
The ME as implemented by OSKAR-2

\[ \langle V_{p,q} \rangle = \sum_{s} K_{p,s} E_{p,s} G_{p,s} P_{p,s} R_{p,s} \langle B_s \rangle R_{q,s}^H P_{q,s}^H G_{q,s}^H E_{q,s}^H K_{q,s}^H \]

- 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

- **Interferometer phase**
- **Propagation term**
- **Parallactic angle rotation**
- **Antenna element field pattern and station beam response**
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 $\sim 10^6$ sources across whole sky!

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

\[
G = \begin{bmatrix}
    g^X_{\theta} & g^X_{\phi} \\
    g^Y_{\theta} & g^Y_{\phi}
\end{bmatrix}
\]
• 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.

$$K_{s,i} = \exp \left\{ -2\pi ik \left[ u_i \xi_s + v_i \eta_s + w_i \left( \sqrt{1 - \xi_s^2 - \eta_s^2} - 1 \right) \right] \right\}$$
“Correlator”

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

\[ V_{i,j} = \sum_s \mathbf{J}_{s,i} \mathbf{B}_s \mathbf{J}_{s,j}^* \]

- 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 \( f_{s,ij} \) 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.
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 *

* optional
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.
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
Example 2: 100 mJy source with Cas A in first sidelobe
Example 2: 100 mJy source with Cas A in first sidelobe (beam)
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
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!

oskar@oerc.ox.ac.uk