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Observing the Future: SKA Simulations with MeqTrees

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Abstract. Future radio telescopes such as the Square Kilometer Array (SKA) present us with a number of challenges in the areas of imaging and data processing. To select a design that will be able to achieve the SKA requirements, we need good models of the instrument and the observed sky. This makes detailed SKA simulations a vital part of any design effort. The Measurement Equation (ME) that grew out of aips++ development provides a succinct mathematical framework in which a radio telescope and the observed sky may be described. The MeqTrees software package can implement MEs of arbitrary structure and complexity, and solve for arbitrary subsets of their parameters. This paper demonstrates how MeqTrees can be applied to SKA simulations. We simulate an SKA pathfinder consisting of small dishes with phased-array focal plane arrays mounted at the prime focus, show some of the instrumental effects expected, and discuss their impact on observations.

1. MeqTrees and the SKA

MeqTrees (Smirnov & Noordam 2003) is a telescope calibration and simulation package being developed at ASTRON with outside collaboration from this author. The crucial difference between MeqTrees and other radio telescope data processing packages is that completely arbitrary Measurement Equations may be rapidly implemented. Source and instrumental models of any structure and level of complexity (at least in theory!) may be constructed, so the package is a uniquely useful tool for simulations of future radio telescopes such as the SKA(see e.g. Ekers, 2003 for a description of the proposed telescope).

One of the currently fashionable SKA pathfinder designs is that of a collection of small, approximately 10m diameter dishes, each of which has a phased-array focal plane array (FPA) mounted at the focus point. We form a beam pointing at a given direction in the sky with a phased-array FPA by assigning weights to the individual beam elements of the array according to some optimization criterion, and then combining the weighted beams together. By obtaining data simultaneously from multiple phased-up primary beams, we can greatly increase the instantaneous field of view of such an aperture-synthesis array.

We have ‘simulated’ a SKA pathfinder dish with a phased array feed that has the following properties:

- 90 dipole elements in each of X and Y directions
- Frequency = 1500 MHz; Spacing = lambda / 2
- Dish diameter = 10m; Focal length = 4.5m

- No coupling between elements; No feed struts in simulation
- Voltage radiation patterns for each of the X and Y dipoles are calculated with the commercial GRASP antenna design package.
    - We get both co-polarization and cross-polarization leakage (instrumental polarization) terms
- This phased-array FPA is not meant as a 'realistic' final FPA design, but is a good testbed for various aspects of software development and data processing

2. Simulated Observations

The phased-up primary beams are created by combining the individual beams of the array by a device called a beamformer. The beamformer combines the different beams together by assigning different complex weights to each beam. Different weighting schemes can be used to produce primary beams with differing properties. The optimal weighting schemes to be used will be both a function of the telescope's design and the type of observation to be done. Here we show some of the primary beam characteristics that are obtained with different weighting schemes. A typical simulation consists of something like the following:

- MeqTrees reads in individual dipole radiation patterns.
- Phase up X and Y radiation patterns from weighted combinations that depend on optimization criteria, to get voltage beams (fully complex) of individual antennas for a specified observing direction. A phased-up voltage pattern directly corresponds to an E-Jones matrix in ME terminology.
- Simulate observations of the 'visible' sky via the usual radio interferometry equations. These simulations are used to study how phased array FPAs will impact on the quality of the data produced by the system.

3. Equatorial or Azimuth-Elevation Telescope Mounts?

The big advantage of a telescope with an equatorial mount over one with an Az-El mount is that, with the exception of pointing errors, the phased-up beams should retain a constant shape over time as we only need a single set of weights for a particular beam. This should greatly simplify the amount of post-observation data processing required to obtain a decent image, compared to the problems associated with an Az-El mounted dish, as we now show.

We can track a given point in on the sky with our focal plane array mounted on an Az-El mounted telescope by continually adjusting the beam-former weights required to phase up the beams pointing to the requested position in sky coordinates. For the simulation shown here, we use the method of phase conjugate weighting (Veidt, 2006) to phase up a beam at a specific sky position. Figure 1 shows the changing phased-up primary beam required to track a point located 137 arcmin (approximately 2 x FWHM) from the FPA bore-sight during a 8 hour synthesis observation centred at 28 degrees declination. It is clear from Figure 3 that while the central part of a primary beam formed by this weighting scheme will be fairly constant as a function of time, the sidelobe structures

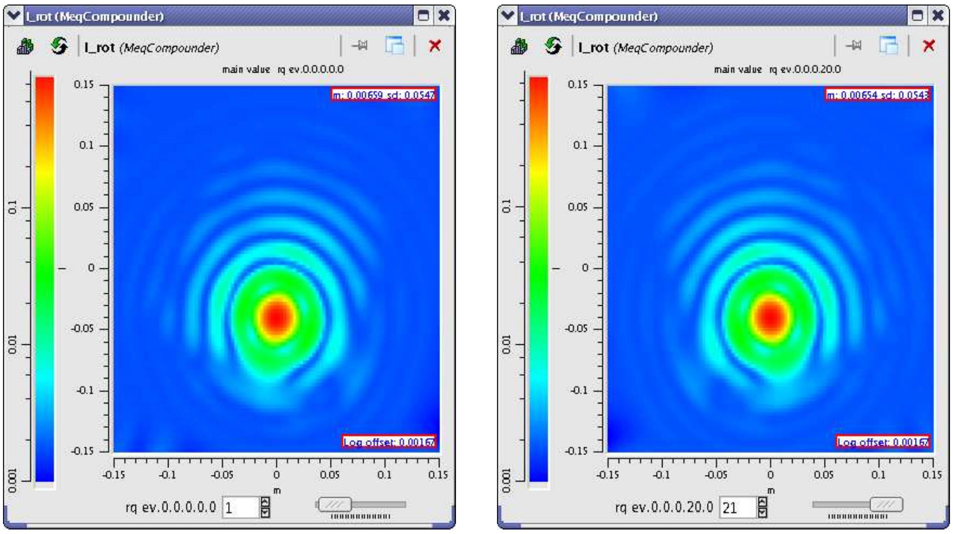

Figure 1. Phased-array primary beam at the beginning (left) and end (right) of an 8 hour observation made at declination 28 degrees with dishes having Az-El mounts. The plots show the beam in the reference frame of the sky. By constantly adjusting the weights used to combine the actual beams of the phased array together we can track an individual Ra,Dec coordinate on the sky. However note the variations in the beam sidelobes. The coordinates in the plot have units of radians.

change positions and gain responses as a function of time. This will make the removal of effects due to sources in the sidelobes problematic.

In theory we can correct for at least some of the effects associated with an Az-El telescope by either having a mechanical feed rotator counteract the rotation of the sky, or by breaking up the observation into a sequence of short observations for separate calibration. At a minimum, a feed rotator seems essential, or there will be an enormous post-observation data-processing problem (Cornwell, 2006).

The weighting scheme used can also have a significant impact on the observed instrumental polarization associated with a phased-up beam.

It is clear from Figure 1 that especially the sidelobes of an off axis phased beam formed with phase conjugate weighting may have a significantly asymmetric shape. Therefore we used the phase conjugate weights as starting values for MeqTrees solutions in which we attempted to optimize the weights to form a well-shaped, perfect Gaussian total intensity beam. This equates to the Stokes I response of the beam. Such a beam is the product of an E-Jones matrix with its complex conjugate. The weights derived from this procedure also had the interesting side-effect of lowering the instrumental polarization associated with the phased up beam. In the case of X and Y dipole arrays oriented at 90 degrees to each other the instrumental polarization will appear dominantly in Stokes Q.

In Figure 2 we compare the total intensity beam shape derived from phase conjugate weighting at a distance of 2.5 x FWHM from boresight with the corresponding phased up beam obtained when we use weights obtained by fitting to the Gaussian beam. The improvement is obvious, both in the lowering of the

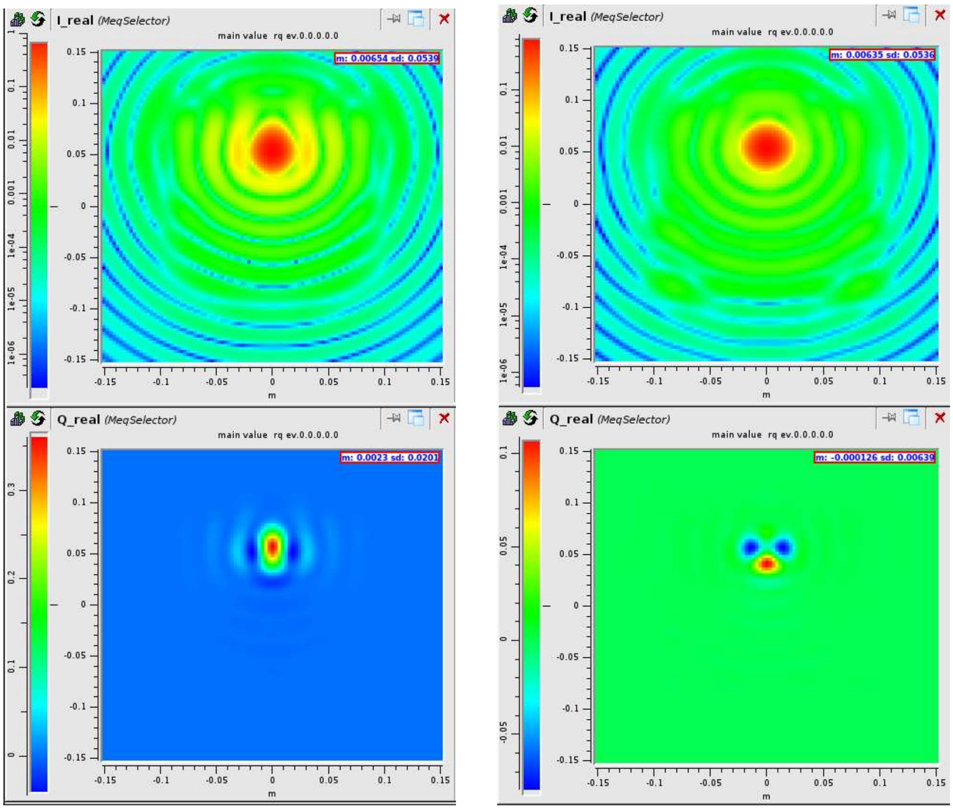

Figure 2. A comparison of different weighting schemes. The left column displays I (upper) and Q (lower) images at distances of 2.5 x FWHM from boresight obtained with phase conjugate weighting. The right column shows the corresponding results for a well-shaped gaussian I beam. The total intensity I beams are normalized to have a peak response of unity. Note the significant drop in instrumental Q polarization obtained when we fit to a Gaussian beam.

near-in sidelobe response in the total intensity beam and in the lowering of the Stokes instrumental Q signal.

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References

Cornwell, T. 2006, `http://ftp.kat.ac.za/pub/calim2006/06-01_Cornwell.pdf`

Ekers, R. D. 2003, in ASP Conf. Ser. 295, ADASS XII, ed. H. E. Payne, R. I. Jedrzejewski, & R. N. Hook (San Francisco: ASP), 125

Smirnov, O. M., & Noordam, J. E. 2003, in ASP Conf. Ser. 314, ADASS XIII, ed. F. Ochsenbein, M. Allen, & D. Egret (San Francisco: ASP), 18

Veidt, B. 2006, `http://www.skatelescope.org/PDF/memos/71_Veidt.pdf`