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Holographic Measurement of ASKAP Primary Beams

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Summary

In this document, an experimental method for measuring the complex-valued sensitivity pattern of an ASKAP phased array feed beam is described in detail. This method uses the principle of holography, in which the voltage amplitude and phase response of a beam are measured over a two-dimensional field by correlation with a reference signal. The antenna under test performs a raster scan around a bright astronomical source, while the received signal is correlated with a reference antenna that tracks the source continuously.

We use the radio galaxy M87 as our reference source and select the grid size and spacing such that a single complete measurement can be done while the source is above the horizon. Interpolation and smoothing are used to enhance our visualisation of the measured beam shape. Multiple ASKAP beams can be measured simultaneously using this method, up to the number supported by the real-time beamforming hardware. Some example results are presented, but more detailed analysis of beam characteristics can be found within other memos from this series (e.g. ACES Memo 010) and future journal publications.

1 Introduction

The Australian SKA Pathfinder (ASKAP) utilises Phased Array Feed (PAF) technology to form several simultaneous primary beams on each of its 36 antennas. This allows for rapid survey speeds and a great deal of flexibility, but also adds complexity to the system. In a traditional radio telescope, the primary beam shape is defined by a physical feed structure and (more importantly) is fixed by the manufactured characteristics of that feed. In contrast, the primary beams of an ASKAP antenna can be changed by altering the digital weights uploaded to the beamforming hardware, which forms a single beam by taking the weighted sum of up to 188 individual receptor elements on each PAF.

The beam weights are determined using one of a number of possible algorithms that are designed to optimise quantifiable aspects of the beam itself. To date, the most commonly used algorithm optimises the sensitivity or signal to noise ratio of a test source observed during the beamforming process. See Ivashina et al. (2011) and Jeffs et al. (2008) for more information.

While sensitivity is an important quantity for any radio telescope, there are other factors that limit image quality. Future large-area surveys are likely to be limited more by dynamic range, where imaging artefacts from strong sources in a field can swamp weaker sources that would otherwise still appear above the thermal noise limit. These imaging artefacts arise primarily due to assumptions in the deconvolution process designed to compensate for the limited number of baselines available. In particular, it is necessary for the imaging software to know the primary beam shape very well, in order to correctly deal with sources that appear in regions of reduced sensitivity away from the beam centre (or even in the side-lobes). It is also important for the primary beams to be consistent over an extended period of time and from one antenna to another, as such variations are not usually accounted for in the imaging process.

ASKAP's PAF technology offers the chance to optimise primary beam shapes for desirable characteristics such as symmetry and polarisation leakage, as well as sensitivity. However, such techniques are new to the field of radio astronomy and as such, it will be important to verify the level to which such optimisations can be made. Put another way, it is important to be able to experimentally determine the shape of a PAF beam in order to better understand and optimise the beamforming algorithms that we use. This notion prompted the development of the holographic technique described herein.

2 Overview

The method of holography has long been used to analyse the surface accuracy of radio telescope antennas. This technique makes use of the Fourier transform relationship between the aperture field distribution (illumination pattern) and its corresponding diffraction pattern (otherwise known as beam shape). The goal is typically to measure the beam pattern by scanning the antenna under test over an astronomical reference source or a microwave transmitter located closer to the telescope itself (either on a ground-based platform or a satellite orbiting the Earth), while correlating the received output with a copy of the reference signal obtained from a second antenna that maintains a fixed direction with respect to the source. With knowledge of the diffraction pattern, a Fourier transform can be taken to derive the illumination pattern (with spatial resolution limited by the size of the field scanned). The aperture field distribution is then used to describe the surface characteristics (typically the axial offsets of individual structural panels).

In our case, we are primarily interested in the diffraction pattern (beam shape) itself. We use a measurement process similar to that described by Scott & Ryle (1977), with the added complexity of multiple beams per antenna. The steps can be summarised as follows:

- Load several identical copies of a boresight beam into the reference antenna(s).
- Load the weights for the test beams into the test antennas.
- Command the reference antenna(s) to track the reference source.
- Command the test antennas to perform a raster scan about the reference source.
- Allow the array phase tracking machinery to compensate for geometric delays as usual.
- Record visibilities on baselines between the reference and test antennas.
- Place the averaged complex visibilities onto a square grid, then visualise or analyse.

It should be noted that this is a special mode of operation for ASKAP, amounting to a split array where two subsets of the antennas are driven in different ways. This requires a special observing procedure (known as a scheduling block template in the ASKAP software system) designed specifically for this mode, which we named HoloGrid. For simplicity, most tests have been done with a single reference antenna, but in order to efficiently test all the antennas in the array it might be beneficial to use multiple reference antennas (e.g. half the entire array) and swap roles only once.

3 Raster Scan

In addition to the parameters present in the standard observing procedure (known as Pointings in the BETA prototype system, see Hotan et al. (2014)), the following additional parameters should be specified when using HoloGrid:

```
holography.grid_size = 15
holography.grid_step = 0.6
holography.ref_antenna = ant1
```

The grid_size is the number of discrete steps on one side of the raster field. Therefore, the total number of pointings is grid_size squared. The grid_step parameter is the distance between raster grid points in degrees (the distance that the test antennas will slew in one axis when transitioning between adjacent points).

Drive commands are sent to the test antennas as offset positions from the celestial coordinates of the reference source. The drive control system interprets these offsets with respect to the antenna's azimuth and elevation, first correcting the azimuthal offset for the elevation of the source to ensure that the raster grid remains square with respect to the antenna. This system is sometimes known as cross-azimuth and elevation and is computed as follows:

$$\delta_{XAz} = \delta_{Az} \cos El \quad (3.1)$$

$$\delta_{XEl} = \delta_{El} \quad (3.2)$$

The default grid spacing of 0.6 degrees was chosen to be smaller than half the Full Width at Half Maximum (FWHM) of the primary beam within the standard observing band (covering 700–1000 MHz), in order to Nyquist sample the beam pattern. With this spacing, our standard 15×15 point raster covers an 8×8 degree square field.

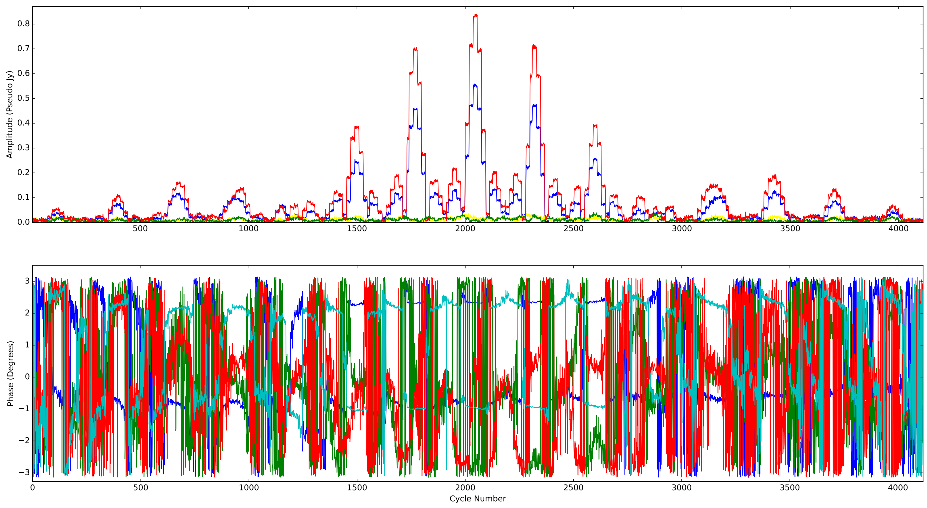

Figure 3.1: Example visibility time series for a single beam during a holography raster. The different colours represent different polarisation products.

4 Setup and Observation

We use the normal astronomy correlator system to capture data for holography, although only some of the baselines (those to the reference antennas) are useful. This has the benefit that delay and phase tracking are performed automatically by the observing system. In the case of BETA, this means that the phase centre of each beam is set to the coordinates of the reference source (even if the beam is offset from the antenna boresight).

The reference antenna tracks the source, so the choice of beam weights is not particularly important. In order to optimise signal-to-noise, we used standard boresight maximum sensitivity weighting, with identical copies of the boresight beam loaded into all of the available beamformer slots. This ensures that every beam under test is correlated with the same reference signal from the astronomical source.

In order to ensure the raster grid does not rotate on the sky during the course of the observation, we operate all antennas in pol_fixed mode, where the roll axis of the antenna is fixed at an angle of zero with respect to the horizon. This includes the reference antenna, so as to keep its polarisation aligned with the antennas under test.

The dwell time on each raster grid point is determined by the need to keep the total observing time within the period for which the reference source is above the horizon. In the case of Virgo A observed from the Murchison Radio Observatory (MRO), the upper limit is about 8 hours. We adopted a dwell time of 90 seconds per point, which, allowing for slew time and overheads, makes a 225 point raster complete in roughly 6 hours. This proved sufficient to easily detect the second side-lobe of the primary beam.

4.1 Reference Sources

The main selection criteria for the astronomical reference source are that it be bright at the frequencies observed, and also compact on all baselines used. We have successfully used two reference sources, the radio galaxy Virgo A (M87) and the quasar PKS 0407–658. In our typical BETA observing band of 700–1000 MHz, Virgo A has a flux density of roughly 300 Jy, while PKS 0407–658 is about a factor of 10 lower. For this reason we use M87 whenever possible.

5 Processing Pipeline

All data captured from the correlator during a holography experiment are stored in a CASA measurement set by the ASKAPsoft ingest pipeline. Each individual grid point is treated as a new scan in the measurement set, allowing the results to be gridded on the basis of scan ID.

Data are copied to a high-performance compute cluster called Galaxy, which resides within the Pawsey supercomputing centre in Western Australia [1]. During the early stages of commissioning we have been archiving the raw visibilities for offline processing.

5.1 Extracting Data From the Measurement Set

The first stage in the analysis process is to take the raw visibilities and perform some simple flagging (to reject narrow-band radio frequency interference) before averaging the 16416 narrow-band frequency channels down to 304×1 MHz channels.

```
> sbatch ~/ACES/holography/msavg.slurm [Filename]
```

Next, we use a casapy script to extract the visibilities corresponding to baselines with the reference antenna(s), for all beams that were defined. These intermediate data are split into different files on the basis of frequency channel, to facilitate parallel processing during the next stage.

[1] https://www.pawsey.org.au/our-systems/

```
> salloc -t 04:00:00
% casapy -c ~/ACES/holography/get_holo_from_ms.py [Filename] [RefAnt]
```

Due to the way casapy is configured on the cluster, this stage is usually run from an interactive terminal session on a single compute node (hence the use of salloc).

5.2 Gridding and Averaging

The extracted visibilities are processed using a python script that runs across multiple cores of the compute cluster using a very simply MPI arrangement wherein the rank of each job defines which frequency channel it works on. The script averages visibility data over all 5 second cycles within a single scan (one raster grid point), treating each of the polarisation products independently. It then constructs a set of seven arrays, each with a length equal to the number of raster grid points. The first three arrays hold the position of the antennas while observing the grid point (RA, Dec and PA) and the last four hold the time-averaged complex visibility for each of the polarisation products XX, XY, YX and YY.

```
> sbatch ~/ACES/holography/holography_mpi.slurm [AntennaID] [Nscan]
```

These data are written back to disk as a python pickle file for quick access. We write one small file per antenna, beam and frequency channel.

5.3 Display and Analysis

The pickle files created during the previous stage contain the complex beam voltage pattern. In order to display this pattern, we developed several python scripts that make use of the plotting and interpolation libraries included in the scipy package. The most commonly used script is plot_scans.py, which simply reshapes the array of Nscan complex numbers (independently for amplitude and phase) into a square grid and uses the scipy RectBivariateSpline routine to re-grid onto a finer mesh before displaying the resulting two-dimensional array using the pcolormesh routine.

```
> python plot_scans.py [SBID] [AntID] [BeamID] [PolID] [Nscan] [Pitch]
```

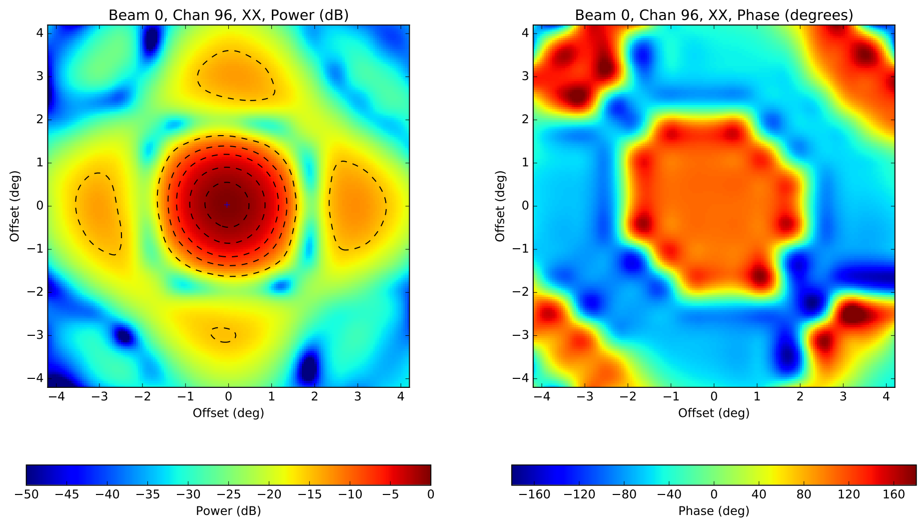

Figure 5.1: Example beam pattern from a single 1 MHz channel formed using the maximum sensitivity algorithm, using the Sun as a beamforming reference and M87 as the holography reference.

Variations on this plotting script have been created to mosaic a set of different beams onto a larger grid defined by the footprint used when beamforming (see ACES Memo 001) and to create animations over different frequency channels.

Aside from visualising the beam pattern, it is also useful to investigate its properties more quantitatively. We have developed scripts to estimate the location of the beam centre and its width using contour analysis, then plot those properties as a function of frequency. Observing trends in the small offsets from the expected beam location can highlight systematic errors in the beamforming process. This also allows more detailed studies of the variation in properties between individual beamforming solutions (given similar input constraints). Detailed analysis of these results is a topic for other documents (e.g. ACES Memo 010).

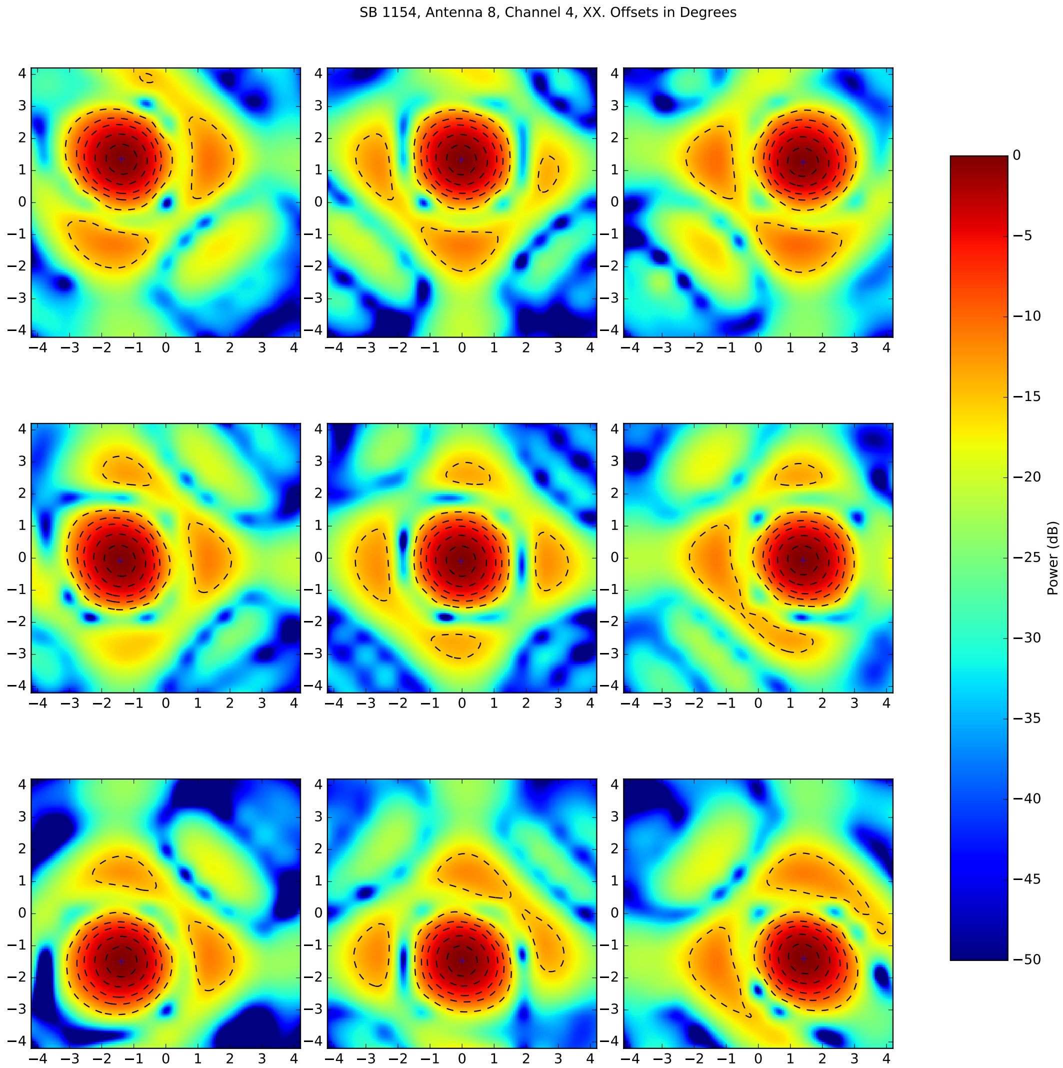

Figure 5.2: Example mosaic of 9 beam patterns (amplitude only) from a single 1 MHz channel formed using the maximum sensitivity algorithm in a square footprint, using the Sun as a beamforming reference and M87 as the holography reference.

6 Summary and Conclusions

The techniques described in this memo allow for routine measurement of the ASKAP beam patterns, which will be crucial to the refinement of beamforming algorithms in the coming years. Knowledge of the beam patterns of single PAF elements can also be obtained this way (by setting trivial beamformer weights), allowing comparison with simulations and providing input to methods of beamforming that optimise the desired pattern itself, instead of secondary metrics like sensitivity.

7 Appendix: Internal References

The development of this technique is described in more detail in various internal JIRA tickets, including:

https://jira.csiro.au/browse/ACES-29
https://jira.csiro.au/browse/ACES-38
https://jira.csiro.au/browse/ACES-83

Source code can be found in the ASKAPsoft repository:

https://svn.atnf.csiro.au/askap/ACES/holography/

The entire ACES Memo series can be found here:

http://www.atnf.csiro.au/projects/askap/ACES-memos

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