UCAM Albius Work

Summary

The objective of this element of the Albius work plan was to investigate the problem of wide-field polarization calibration in interferometry. This problem is intrinsic to the calibration of interferometer arrays and significant work appeared in the literature during the course of this work programme. The outputs of the work are summarised as follows:

1. After formulating the problem in the now established language of the measurement equation two key objectives were identified as (a) produce an example implementation of solving the full polarisation calibration problem for the case of observations of a polarization calibrator on axis of a tracking antenna-based interferometer and (b) development of the formalism of wide-field polarimetric calibration.
2. A Python-model was developed within CASA for the solution of the non-linear polarisation calibration problem (1a). This module provides enhancements over the standard CASA routines to deal with cases of severe polarization leakage. The module was tested on both artificial test data and data from the GMRT. A standard first-order parameterisation of the instrumental response in terms of elliptical voltage beams was used.
3. The wide-field calibration problem can be most succinctly stated as the need to solve for the two instrumental voltage patterns representing the instrumental response to two independent incoming polarization modes. The general problem must allow for these two voltage beams to be direction dependent, allow for the time varying coupling between sky and antenna as the sky rotates and can make no assumption of orthogonality of the two modes in the wide-field case. While simply stated, the practical implementation of any calibration scheme demands that a finite number of unknown quantities are introduced and then solved for. The lack of an orthogonality constraint demands a complete position-dependent Mueller-matrix representation of the sky to instrument coupling. To make any progress a compact representation in a small finite number of parameters of the antenna voltage beams is essential. Such a compact representation was therefore developed using Fourier-Bessel and Zernike polynomial representations.
4. Two additional output of the work, not foreseen at the time of writing the project plan, were (i) the development within the CyberSKA user portal of a test implementation of GMRT database query tool and (ii) techniques for the Bayesian analysis of polarization data in the very low signal-to-noise regime for the construction of wide-field rotation-measure maps.

Interferometric response to an incoming polarized signal

The theory of the response of an interferometer to an incoming polarised signal is well established and in recent years the use of the measurement equation in radio astronomy has become widely adopted. The work presented here is done within this context.

The measurement equation provides an excellent formalism for describing the response of an interferometer to an incoming polarised wave via the sequential application of Mueller matrices describing for example propagation effects, transformation from sky to antenna coordinates and instrumental effects such as gain variations.

To understand the complexity of the problem it is worth considering initially the response of an antenna in the simplest case when the radiation is incident on the axis of the antenna. Even in this case the description involves significant complexity. The source field is described in terms of a coordinate system on the sky which in turns defines the Stokes vector for the incident field. To determine the response this must be transformed to the coordinate system of the antenna; this transformation will in general change with time as the sky rotates relative to the antenna coordinate system. The antenna system defines two polarization responses and in general these will not have symmetric radiation patterns therefore with time the voltage received in each of the two receiver chains corresponding to the two polarization states of the antenna vary with time even if the gains are stable. The standard polarization procedure implemented in AIPS and CASA aims to calibrate the parameters of this simplest case. In an interferometer all the possible cross correlations are measured which provide a means of reconstructing the incoming Stokes vector for the on-axis case. The Mueller matrix in this simplest case in non-trivial and involves liner and quadratic terms in the calibration parameters – the standard routine in CASA uses a further linearisation approximation (valid for small polarization leakage terms) to solve this case.

For wide-field imaging the problem is considerably more complex. First since the sky is curved there is no single transformation from sky coordinates to antenna coordinates – in other words the Mueller transformation matrices are position dependent (albeit in a predictable analytical form). A more serious complication is that the total field at the antenna is three-dimensional since it is the combination of the multiple planar waves from a variety of directions on the sky. This results in a 9-element correlation matrix. All current feeds however only measure two polarization components and therefore some information about the polarization state of the net electric field due to the sky radiation is lost intrinsically. The response of the antenna to radiation from a particular direction on the sky is determined by transforming the incoming plane wave into the coordinate system of the antenna and working out the antenna response by using the appropriate component of the vector radiation pattern of each polarization state of the receiver. These are most simply characterised by voltage beams for each polarization state. The intrinsic polarization state of radiation from a particular sky direction can be inferred if the voltage beams are perfectly known provided the two polarization states are not degenerate. With some antenna designs and in the wide-field case, such degeneracies do exist and the polarization state of the incoming radiation cannot be completely recovered.

Polarization calibration in the wide-field limit can be regarded as solving for the properties / shapes of these voltage beams. Without constraints this is an insoluble problem. The on-axis polarization calibration can be regarded in these terms. For example in CASA the on-axis problem is characterised for a circular feed by assuming an elliptical response for each circular polarization together with a position-angle of the ellipse: these are the parameters (together with the gain for each channel) which are solved for during the calibration procedure making the additional assumption that there is no changes in the ellipticity of position angle of the response with time and therefore observations at multiple paralactic angle (i.e. the effective rotation between sky and antenna coordinate systems) are used to solve for the polarization characteristics.

Task 1: Improved on-axis calibration in CASA

The restriction in CASA (task polcal) to the case of low polarization leakage is numerically convenient, but not required for a solution and limits the application of CASA to the calibration of certain instruments. Making use of the Python-scripting capabilities of CASA we have implemented a python module to provide improved polarisation calibration solving the full non-linear problem for the on-axis case. During this implementation several bugs were discovered in CASA and in the python interface – these were fed back into the CASA development team.

The Python implementation has efficient access to the CSA measurement set. Observations of a source of known (or assumed) polariztion known are used as a model of the leakage on a channel by channel basis whilst making the standard assumption that this is non-time varying.

The procedure has been tested and evauated on simulated data and has been applied to data at 610 MHz from the Giant Metrewave Radio Telescope (GMRT). The calibration returned gives a similar scatter to that obtained via CASA's. An improved method of solving the full instrumental Muller matrix has been implemented, returning the full Muller matrix for each spectral channel; the final step is applying the inverse to the observational data. Results for GMRT data are Shown in Figure 1.

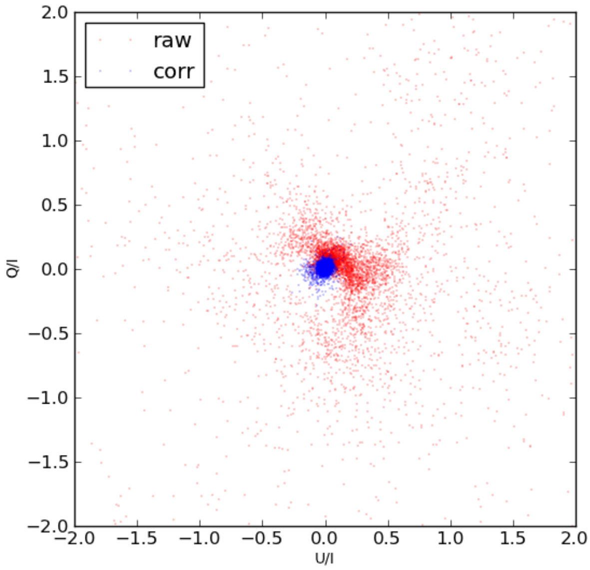


Figure 1. GMRT visibility data before (red) and after (blue) polarization calibration. The source is intrinsically unpolarized, but the raw data show large amounts of polarization leakage which is corrected by the CASA python module calibration procedure described above.

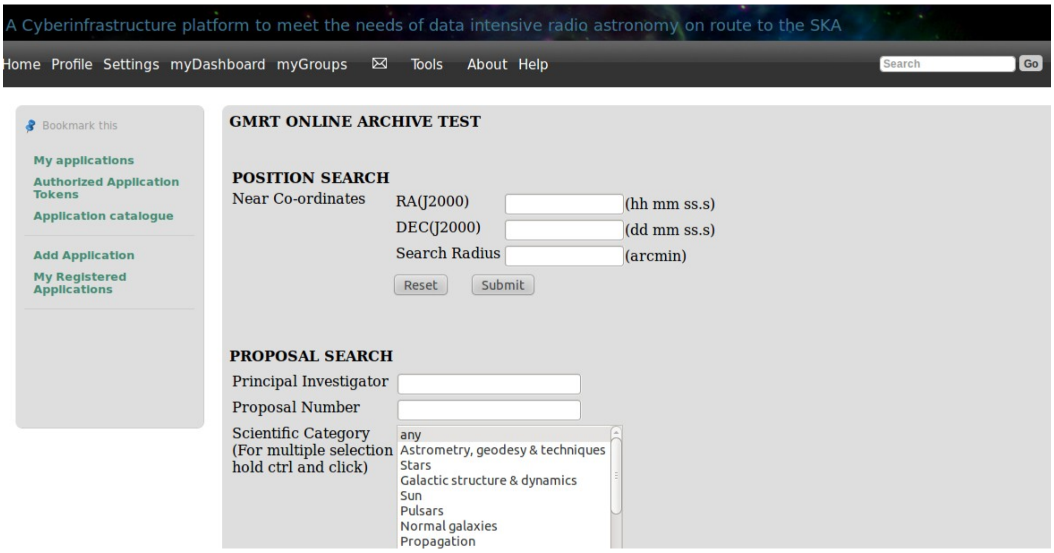
Task 2 Wide field polarization calibration

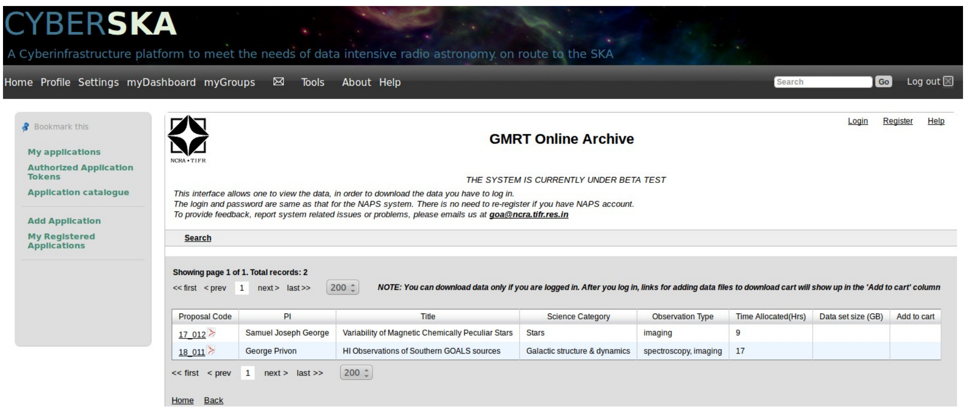
A significant theoretical and algorithmic advance was made in 2008 by Bhatnagar, Cornwell and co-workers, now called AW-projection. This technique uses a gridding kernel which uses the aperture illumination function of the antenna and can be combined with an image-plane deconvolution procedure to estimate position-dependent calibration effects (e.g. Bhatnagar et al. A&A 487, 419, 2008). The formulation is in terms of the full polarised measurement equations and the formalism in principle forms the basis for estimating the voltage beams of the polarised response as discussed above. However for this to be practical the vector antenna response must be characterised in a compact form via a small number of parameters: these can then be adopted as the calibration parameters. The key missing element of such an approach is an appropriate compact representation and therefore this was the aspect of the problem that became the focus of this task.

The approach was to review possible parameterisations and to find those which were effective in representing the voltage beams of antennas in a full vector wave representation. We show that three representations are possible, two of which are obtained from either Fourier-Bessel or Zernike polynomial representations of the radial behaviour of each azimuthal harmonic of the aperture fields. The aperture is taken at the level of an equivalence plane located just above the reflector. Good representations of both tracking parabaloid-like antennas and non-tracking phased arrays are possible with the number of coefficients of the representation ranging up to ~10 paramaters for a good representation of antenna responses including the first few main sidelobes.

Additional outputs

During this work two additional outputs were produced. The first is a web-based interface to the GMRT archive implemented in the CyberSKA framework. This output was produced to provide convenient way to access the GMRT archive, but may have broader applicability. Two screen shots are shown in Figure 2. Cyber-SKA is a web-based collaborative portal for radio astronomy being developed in Canada. The aim is to provide an interface which reflects the modern tools required for collaborative research which can be found within social networking environment.





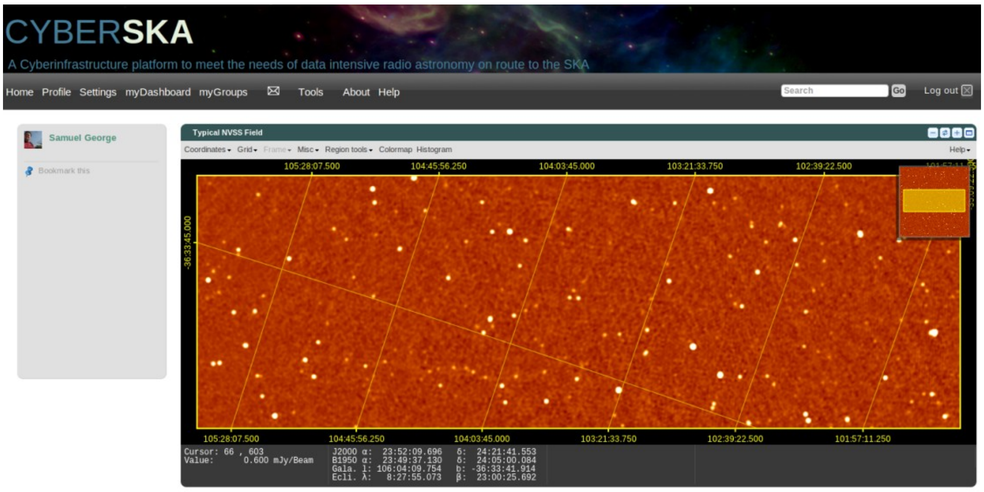


Figure 2: Three screen shots of the Cyber-SKA based web interface to the GMRT archive. The top panel shows the query form, the middle the results of the query and the bottom a visualisation of the image data retrieved.

The final output is a new approach to the Bayesian analysis of rotation measure data in the low signal-to-noise regime. The approach is described in http://aspbooks.org/custom/publications/paper/438-0292.html