# POSSUM Polarisation Characterisation Tests for BETA and ASKAP (POSSUM Report #66)


The POSSUM Commissioning Group:
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**Abstract**

In this report we define the tests necessary to characterise the polarisation performance of ASKAP prior to conducting science. The results of these tests will allow the ASKAP and POSSUM teams to agree on an operational polarisation calibration pipeline.


## 1 Scope and Background

In this document we define the instrumental polarisation effects and system variables which we would like characterised during the BETA and ASKAP commissioning process. We set out in detail the tests necessary to measure the magnitude of each effect. The results of the tests will inform the creation of the operational calibration pipeline and allow the ASKAP and POSSUM teams to specify a minimum set of corrections to meet the polarisation requirements. Additional tests for quality control are also described.

In Section 2 we summarise the specifications required by the POSSUM survey, either full ASKAP or ASKAP-12+. Section 3 outlines each of the effects to be measured and their likely priority. We describe in detail in Section 4 the tests required to fully characterise each effect. It also includes verification tests to assess the accuracy of source detection with different stages of calibration applied.

## 2 Requirement Specifications

The following are the requirements as for the POSSUM proposal:

- Band to cover: 700-1800 MHz.
  N.B.: This is not actually a POSSUM requirement, but we believe a polarisation calibration of the entire ASKAP band should be carried out during commissioning. It is also the band proposed for the early science with ASKAP-12+.

- Frequency resolution: 1 MHz.
- Polarisation Purity (after calibration): 25 dB (30 dB desirable)
- Polarisation Angle Accuracy (after calibration): unspecified ($1^\circ$ desirable)
- Absolute Flux Accuracy: 5% (3% desirable)
- dynamic range: $10^4$ (ASKAP-36)

# 3 Variables and Effects to be Measured

Below we describe in turn each of the effects which are required to be characterised in commissioning before finalising the ASKAP polarisation calibration pipeline.

## 3.1 On-axis Instrumental Polarisation

The Jones matrix formalism ($\vec{v} = \mathbf{J}\vec{e}$) describes the transformation of the true Stokes parameters, $\vec{e} = (I, Q, U, V)^T$, into the observed visibilities, $\vec{v}$. For linear feeds, the Jones matrix is formed by the matrix product

$$\mathbf{J} = \mathbf{G} * \mathbf{D} * \mathbf{C} * \mathbf{P} * \mathbf{S} \tag{1}$$

where $\mathbf{G}$ represents the effect of antenna gain, $\mathbf{D}$ is the leakage of the two feed polarisations into one another, $\mathbf{C}$ is the rotation of the feed relative to the mount, $\mathbf{P}$ is the rotation of the feed relative to the sky (the parallactic angle), and $\mathbf{S}$ transforms the Stokes vector into the $xy$ coordinate system.

Considering a feed composed of orthogonal linear receivers ($x$ and $y$), then ideally the feed would be represented by a unit matrix (where the coordinate axes are defined such that they coincide with the two polarisations of the incident radiation). In reality, there is some <u>leakage</u> of the opposite polarisation into either receptor such that the feed matrix for antenna $A$ is

$$\begin{pmatrix} D'_{Ax} & d'_{Ay} \\ -d'_{Ax} & D'_{Ay} \end{pmatrix} = \begin{pmatrix} D'_{Ax} & 0 \\ 0 & D'_{Ay} \end{pmatrix} \begin{pmatrix} 1 & d_{Ax} \\ -d_{Ay} & 1 \end{pmatrix} = \mathbf{G}'\mathbf{D}$$

The feed-error matrix $\mathbf{D}$ represents the deviations of the true feed from its design, where $d_{Ax}$ represents the spurious sensitivity of the $x$ receptor to the $y$ polarisation and vice versa. $\mathbf{G}'$ represents a gain factor that can be absorbed into the gain matrix $\mathbf{G}$, which is represented by the diagonal matrix

$$\mathbf{G} = \begin{pmatrix} g_{Ax} & 0 \\ 0 & g_{Ay} \end{pmatrix}$$

Both the gain and leakage are complex valued describing both amplitude and phase. As a first-order approximation, one can think of the real and imaginary parts of $d$ as being caused by feed alignment errors and feed deformation errors, respectively.

Ignoring products of $Q$, $U$ and $V$ with leakages, as well as non-linear terms in the leakages, we can expand Eqn. 1 for a single baseline (antennas $A$ and $B$) to give

$$\begin{pmatrix} v_{xx} \\ v_{xy} \\ v_{yx} \\ v_{yy} \end{pmatrix} \simeq \frac{1}{2} \begin{pmatrix} g_{Ax}g^*_{Bx} & g_{Ax}g^*_{Bx} & 0 & 0 \\ g_{Ax}g^*_{By}(d_{Ax} - d^*_{By}) & 0 & g_{Ax}g^*_{By} & ig_{Ax}g^*_{By} \\ -g_{Ay}g^*_{Bx}(d_{Ay} - d^*_{Bx}) & 0 & g_{Ay}g^*_{Bx} & -ig_{Ay}g^*_{Bx} \\ g_{Ay}g^*_{Bx} & -g_{Ay}g^*_{Bx} & 0 & 0 \end{pmatrix} \begin{pmatrix} I_r \\ Q_r \\ U_r \\ V_r \end{pmatrix} \tag{2}$$

where we have included the rotation terms into the Stokes vector. This shows that there is a degeneracy between some gain and leakage parameters. Also since the leakages appear in pairs, we cannot immediately solve for the complex-valued offset to the leakages from an observation of an unpolarised source. This prevents us from measuring all the system parameters with a single set of visibilities from a source with a known set of Stokes parameters. Three sets of linearly-independent Stokes vectors are required to make this system of linear equations non-singular. In practise, long observations of a linearly polarised source suffices for three distinct observations.

There are seven degrees of freedom in the instrumental parameter estimates that can lead to errors in the deduced Stokes parameters, described by the Stokes error vector $\Delta\vec{e}$.

$$\Delta\vec{e} = -\frac{1}{2}\begin{pmatrix} \gamma_{++} & \gamma_{+-} & \delta_{+-} & -i\delta_{-+} \\ \gamma_{+-} & \gamma_{++} & \delta_{++} & -i\delta_{--} \\ \delta_{+-} & -\delta_{++} & \gamma_{++} & i\gamma_{--} \\ -i\delta_{-+} & i\delta_{--} & -i\gamma_{--} & \gamma_{++} \end{pmatrix}\vec{e} \tag{3}$$

with

$$\begin{aligned}
\gamma_{++} &= (\Delta g_{Ax} + \Delta g_{Ay}) + (\Delta g^*_{Bx} + \Delta g^*_{By}) \\
\gamma_{+-} &= (\Delta g_{Ax} - \Delta g_{Ay}) + (\Delta g^*_{Bx} - \Delta g^*_{By}) \\
\gamma_{--} &= (\Delta g_{Ax} - \Delta g_{Ay}) - (\Delta g^*_{Bx} - \Delta g^*_{By}) \\
\delta_{++} &= (d_{Ax} + d_{Ay}) + (d^*_{Bx} + d^*_{By}) \\
\delta_{+-} &= (d_{Ax} - d_{Ay}) + (d^*_{Bx} - d^*_{By}) \\
\delta_{-+} &= (d_{Ax} + d_{Ay}) - (d^*_{Bx} + d^*_{By}) \\
\delta_{--} &= (d_{Ax} - d_{Ay}) - (d^*_{Bx} - d^*_{By})
\end{aligned}$$

where $\Delta g$ can be defined as the deviation of the gains from a normalised value of 1. If we assume that the linear polarisation of the calibrator source is unknown, then after solving the equations, the only remaining unsolved degree of freedom is $\delta^{++}$ (the absolute alignment between the antenna and sky rotation frames). See the Polarisation angle section for details on determining this parameter. In principle, the full, coupled, non-linear equations should be solved. In practice, this depends on implementation of efficient algorithms to avoid a large computation penalty. Generally, this whole process relies on the assumption that the instrumental parameters are constant with time; with ASKAP we should spin the dish to obtain the required parallactic angle coverage quasi-simultaneously, in order to determine the timescales on which the instrumental parameters vary. In order to account for any frequency dependence of leakage parameters, the equations should be independently solved in 1 MHz frequency intervals.

A suite of suitable polarised and unpolarised calibrator sources should be used to perform multiple tests of the on-axis leakage properties for each formed beam at various different dish elevation angles.

### 3.2 Off-axis Instrumental Polarisation

The optical properties of an antenna are described by the field co-polar $g(\theta, \varphi)$ and cross-polar $\chi(\theta, \varphi)$ patterns, one each polarisation : $g_x$, $g_y$, $\chi_x$, $\chi_y$. The co-polar pattern $g$ describes how the optics collect the desired polarisation as a function of the direction in the sky. The cross–polarisation $\chi$ measures how the other (unwanted) polarisation is collected, introducing a contamination.

The polarisation purity is measured in terms of instrumental polarisation, defined as the polarised signal generated by the device in presence of an unpolarised signal. In other words it is the response in terms of the Stokes parameters $Q$, $U$ and $V$ to an unpolarised source. This is described by a three instrumental polarisation patterns $\Pi_Q$, $\Pi_U$ and $\Pi_V$ given by (for details see e.g. Carretti et al., 2004, A&A 420, 437).

$$\Pi_Q = \frac{|g_x|^2 + |\chi_x|^2 - |g_y|^2 - |\chi_y|^2}{2}, \tag{4}$$

$$\Pi_U = \mathrm{Re}\,(g_x \chi_y^* + g_y^* \chi_x), \tag{5}$$

$$\Pi_V = \mathrm{Im}\,(g_x \chi_y^* + g_y^* \chi_x). \tag{6}$$

An example of mapping out the polarisation instrumental response over the field of view of a single pixel telescope is shown in Reid et al 2008 (Radio Science, Vol 43, issue 2, April 2008, DOI: 10.1029/2007RS003709). A similar mapping needs to be done for the individual PAF beams of the focal plane array.

The key point here is that the instrumental polarisation depends on the direction $(\theta, \phi)$. In Jones matrix glossary, they are part of the $E$-Jones terms. That way, the corrupting effect on each celestial source is different and depends on its position compared to the beam bore-sight. It is thus essential to map these polarisation patterns for each beam of the PAF system to estimate the effect and, in turn, to what extent it requires to be calibrated and corrected.

### 3.3 Phase Array Feeds and Beam Weights

Phase Array Feeds form the beams as weighted combinations of the PAF elements. From the same PAF it is therefore possible to obtain beams with different Stokes I and polarisation patterns depending on the beam weights used to form the beams.

Beam weight schemes can be optimised for different goals. In our case, the two most extreme cases are: (1) to optimise for sensitivity regardless of the cleanliness of the beam shapes; (2) to have beams as much uniform as possible to minimise the amount of off-axis instrumental polarisation. The former possesses excellent sensitivity, but "dirty" beams at the expense of polarisation purity and dynamic range. The latter is optimised for minimising systematic effects at the expense of higher stochastic noise.

Example of polarisation beams formed with two different weighting schemes are shown in Figures 1 and 2. The beams formed with conjugate field matching (CFM) weights (optimised for sensitivity) and Gaussian beam fitting (optimised for clean beam shape) are shown. The patterns of individual PAF elements of an early stage simulation of the ASKAP Mk I PAF is used here just for example purposes. The comparison of these two cases clearly shows the broad range of polarisation purity performance that can be obtained using different weighting schemes.

It is thus essential to test different weighting schemes to assess the best trade-off between stochastic noise and systematic effects.

Motivated by this, it is necessary to map Stokes I and instrumental polarisation patterns for:

- each individual PAF element;
- the formed beams for each beam weighting scheme to test the final product.

Mapping the individual PAF elements will allow us to combine them off-line with different beam weighting schemes to find the best solution. The comparison between expected (from simulations) and formed beams will test their effectiveness.

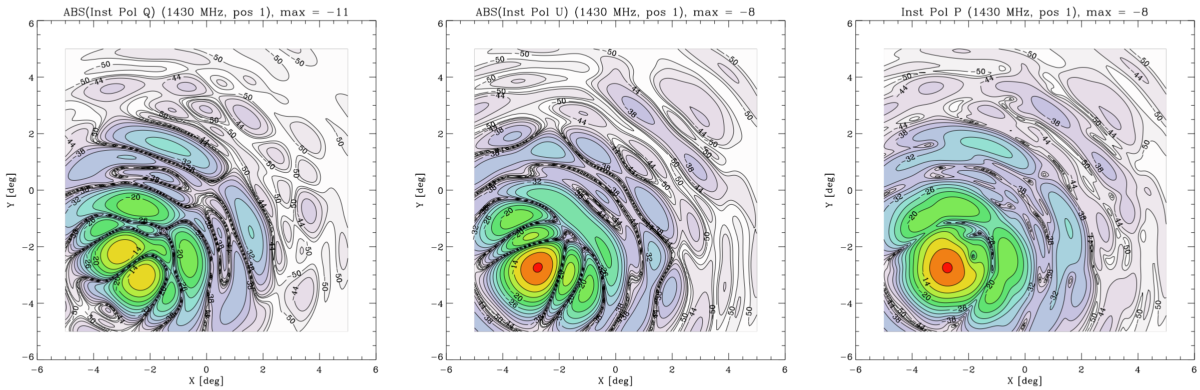


Figure 1: Instrumental polarisation beams at 1430 MHz of one of the early simulations of the ASKAP Mk I PAF is used for illustrative purpose. The beams have been formed from simulations of the patterns of individual PAF elements. A conjugate field matching weighting scheme is used. The beam shown here is the one of the corner beams of the ASKAP field-of-view. The beams of Stokes $Q$ (left), Stokes $U$ (centre) and polarised intensity $P = \sqrt{Q^2 + U^2}$ (right) are shown. The contour levels are dB referred to the peak of the co-polar pattern (not shown here). The maximum instrumental polarisation is -8 dB.

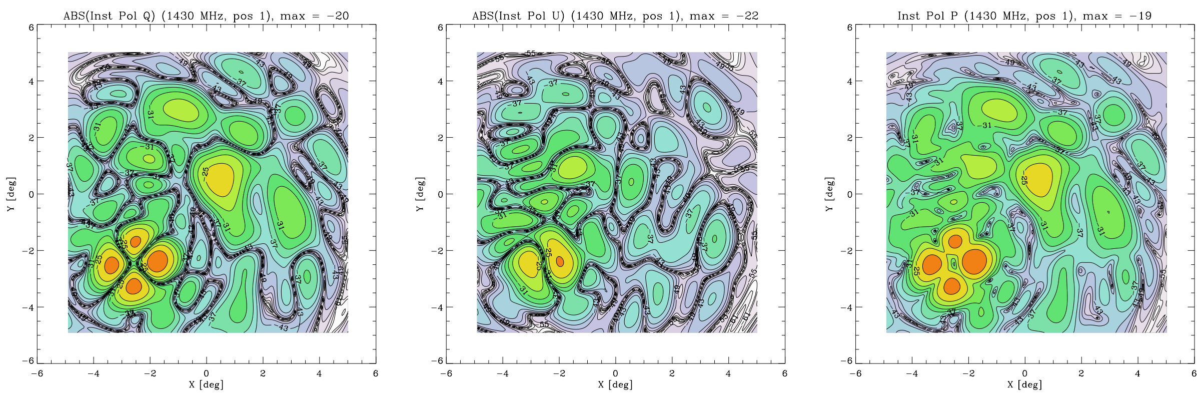


Figure 2: As for Figure 1 except the weighting scheme used here is a Gaussian fitting. The maximum instrumental polarisation is -19 dB. The comparison with the previous case illustrates the broad the range of polarisation purity performance than can be obtained with different weighting schemes.

Mapping the beam formed by the PAF hardware will allow end-to-end tests and assess the performance of different weighting schemes with the actual final products.

### 3.4 Polarisation Angle

For linearly polarised synchrotron emission, the electric vector polarisation angle of the plane of polarisation is given by

$$\phi = 0.5 \arctan\left(\frac{U}{Q}\right). \tag{7}$$

The orientation of this polarisation angle is related to the orientation of the intrinsic magnetic field at the source. Furthermore, the variation of the polarisation angle as a function of $\lambda^2$ provides a measure of Faraday rotation and corresponding information on the component of the magnetic field strength that is parallel to the line of sight as given by

$$\phi(\lambda) = \phi_{\rm inf} + {\rm RM}\,\lambda^2, \tag{8}$$

where $\phi_{\rm inf}$ is the polarisation angle at infinite frequency, and RM is the rotation measure. Polarisation angles therefore constitute a primary data product of the POSSUM survey.

Nevertheless, a number of factors can result in the corruption of linear polarisation angles for a linear-feed configuration such as that used by ASKAP, i.e. with four cross-correlations $XX$, $YY$, $XY$, and $YX$. This corruption can arise in a number of the pre-calibration steps, as any effect that corrupts Stokes $Q$ or $U$ will lead to incorrect polarisation angle measurements. For example:

1. If $Q$ or $V$ is incorrectly determined for a calibrator source
   - leads to mixing between $I$ and $Q$.

2. If $U$ or $Q$ is incorrectly determined for a calibrator source
   - leads to mixing between $I$ and $U$.

3. If the absolute $XY$ phase is incorrectly determined
   - leads to mixing between $U$ and $V$.

4. If the complex polarisation leakage is incorrectly determined:
   - if the real part is offset, leads to direct corruption of the polarisation angle.
   - if the imaginary part is offset, leads to mixing between $Q$ and $V$.

As extensions of these points, there are yet further effects that arise due to time-instability (both instrumental and ionospheric) and off-axis leakage. Furthermore, any frequency-dependent effects inhibit measurement of the polarisation angle versus $\lambda^2$, leading to stringent additional requirements on the bandpass and instrumental polarisation calibration. Measurements of the polarisation angle therefore constitute a critical final test of almost the entire pre-calibration process. Moreover, the polarisation angle is affected even further by the instrumental response of each PAF element, e.g. the complex polarisation leakage per antenna, becomes a consideration of the leakage per beam per antenna.

During commissioning, we therefore require to characterise the accuracy of the polarisation angle, after all of the pre-calibration steps have been undertaken. Furthermore, we seek to measure the stability of the measured polarisation angles as a function of position in each beam.

### 3.5 Time Stability

The stability of the system over time needs to be assessed for bandpass amplitude, phase, formed beam shape and calibration parameters. This will inform on how often the calibration parameters have to be measured for each individual effect to ensure the required polarisation performance are matched.

## 4 Characterisation Tests

Here we describe the tests to be conducted during ASKAP commissioning. The results will inform about the magnitude of such effects and allow the ASKAP and POSSUM teams to decide which effects should be corrected for in the production calibration pipeline and which can be omitted.

### 4.1 Universal Assumptions

- *Everything* can be measured as function of frequency (at 1 MHz resolution for continuum observations).

- *Everything* can be measured as function of position within the formed beams of each PAF.
- Beam forming weights can be specified arbitrarily.
- Artificial signals may be injected at each antenna during observations at whatever cadence needed to track antenna-based gain fluctuations.
- The ionosphere will be characterised and corrected for in 'real' time (POSSUM WG6 task).
- Suitable polarised calibrator standards will be identified in the southern sky.
- The BETA beam-former and correlator supply a bandwidth of 150 MHz and 9 simultaneous beams.
- The parallactic angle can be set using dish-rotation and measured to a sufficiently accurate degree.

### 4.2 On-axis Leakage and Mixing

The tests to determing the on-axis leakage and mixing (i.e., D-Jones terms) are a subset of those to characterise the E-Jones terms. However, because the E-Jones terms described below incorporate the D-Jones terms, separate tests are necessary to fully separate the off and on-axis contributions.

A suite of suitable polarised and unpolarised calibrator sources should be used to perform multiple tests of the on-axis leakage properties for each formed beam at various different dish elevation angles. Any elevation dependence or variation due to the third-axis rotation in the amount of on-axis leakage should be documented for all antennas. To measure the effect on the on-axis leakage from rotation about the third axis, a polarised calibrator source should be fixed at a sensitive spot on the dish (e.g. along an edge of a feed leg) and monitored over time. All tests should be repeated on day, week and month timescales the determine (and document) the stability of the on-axis leakage parameters.

Sources like Virgo A and B1934-638 (unpolarised) or 3C 286 (polarised) would be suitable. In order to accurately solve for the XY-phase, the observations should cover a wide range of parallactic angles. The ASKAP antennas are unique in their ability to rotate the whole dish to an arbitrary parallactic angle making such observations possible in a relatively short space of time. It is also perfectly acceptable to observe the calibrator using a standard *interleaved* scheme, whereby the calibrator is sandwiched between science targets over the course of a 12-hour track. We anticipate that data from the most of the early-science and commissioning observations will be suitable for calculating the D-Jones terms.

We will need to calculate the leakage as a function of frequency, so the test described here will be repeated for all 8 bands covering 700-1800 MHz.

Analysis software to solve for the on-axis XY-gains and leakages is present in most modern radio-interferometry analysis packages (e.g., MIRIAD, AIPS, CASA). We assume that suitable ASKAPSoft tasks or recipies will be available to the science commissioning team. Alternatively, we could select the subset of the *uv*-data along the central formed beam and export it to a measurement-set for analysis in CASA.

In summary, we propose to:

- Observe a strong unpolarised calibrator at the centre of each of the primary beams.
- Observe a strongly polarised calibrator at the centre of the primary beam.

- Vary the parallactic angle via dish rotation or by tracking the source in alt-az mode over 12 hours.
- Solve for the D-Jones terms using ASKAPSoft or CASA as appropriate.
- These effects account for (among the others):
  - differences in gain calibration between the two polarisations,
  - instrumental cross-product phase shift (Stokes U and V mixing).

### 4.3 Voltage patterns for each PAF element

Beams formed by a phased array feed (PAF) system have a shape which is dependent on the weights applied to the underlying individual elements of the PAF. The weights may be derived in many ways - e.g. conjugate field matching (CFM), eigenvector solutions, maximum sensitivity, gaussian beam fitting. These weights are usually derived from measurements of parallel hand XX,YY signals from individual elements, and the resulting cross-hand XY, YX phased up responses must be obtained by measurements rather than theoretical means.

In order to obtain a proper estimate of how different weighting schemes affect both parallel hand and cross hand responses of the a phased up PAF, we must make detailed measurements of the individual underlying PAF element beam responses. In Measurement Equation terminology this means measuring the E-Jones response of each PAF element. The phased up response is then just a weighted summation of individual E-Jones responses. Note that in this case we am assuming the E-Jones as described in Section 5.6 of Aips++ Note 185 (J. Noordam, 1996 available from http://www-astro.physics.ox.ac.uk/∼ianh/SSSC/aips++_note185.pdf), and that this E-Jones effectively includes the D-Jones terms.

The basic procedure involved is similar to holography - use one antenna as an on-boresight reference antenna, point the remaining telescopes of the array at a grid of L,M positions on the sky, and record the covariance XX, XY, YX and YY responses of each PAF element at each grid position. Since we are not doing holography we do not need to record the data at the high resolution required there but we do need to record the data at a sufficiently high resolution that we map out the position variable polarisation responses. The nominal on-axis instrumental response is a clover-leaf pattern which will require us to sample at a rate of 1/5 of the FWHM response at the highest frequency in the band. So if e.g. we are observing in the 150 MHz subband between 700 to 850 MHz we need to sample based on the FWHM at 850 MHz.

We should sample out to at least the first sidelobe response. This is perhaps not so important for polarisation, but the final ASKAP will be sufficiently sensitive that we are going to see numerous sources in the first sidelobe and an understanding of sidelobe behaviour will be important for subtraction of sources detected in the sidelobes. The sidelobes extend out farthest the low frequency beams, so our observing strategy has to be to sample on the basis of the FWHM at the high frequency end of the band, but extend the sampling grid out to the the end of the first sidelobes of the PAF elements at the outer edges of the PAF array. Exactly how long we want the telescope to integrate at each sample position is a function of system temperature and how accurately we want to measure the cross-hand response. This has to be assessed. However, since we assume that we are measuring the responses of all the PAF elements in parallel, the integration time needs to be based on the fact that in most of the PAF elements at any one time the target source signal will be significantly attenuated by the beam gains of the individual PAF elements. We assume that we would want to sample in frequency space at a 1 MHz channel width.

The parallactification of the third axis is required to avoid beam rotation while mapping. Orthogonal scans will have to be conducted in RA and Dec.

The patterns should be measured at different elevation, to understand the dependence on that axis.

The procedure outlined above has to be done for each of the eight 150 MHz bands required to cover the ASKAP 700 to 1800 MHz range. Nominally the procedure requires use of an unpolarised source. As candidates we suggest:

- to start with Virgo A, possibly the strongest source in the sky visible from ASKAP (some 220 Jy at 1.4 GHz). This will allow an easier initial characterisation of the beams.
- after that, PKS 1934-638 is an excellent candidate to characterise the beams at different elevations.

Our understanding is that the full covariance matrix can be recorded, so delivering the required information on all the individual PAF elements in one go. If not possible we would presumably have to measure the response of each PAF element separately and sequentially by giving that PAF element a weight of unity and everything else zero. This however would be time-consuming, since only 9 out of 188 elements can be measured at once.

It is also our understanding that this mode will be accessible only during commissioning of BETA (ASKAP-12 as well?) and individual PAF elements will be not measurable in normal operations.

For post–processing of this data we would like to get the output converted into some kind of standard visibility file format such as UVFITS or probably best, CASA Measurement Set format. Although the L,M sampling interval described above would be different for each subband, the goal should be a description of the E-Jones over the entire range of frequency. This can be done by interpolation of the lower frequency measurements onto the 2-D grid defined by the highest frequency observations.

In summary, this test consist of:

- to use an holography observing mode
- to point a reference antenna to a strong unpolarised source
- to scan the field around the source with the other antennas
- to set a scan spacing of 1/5 of FWHM at the highest frequency of the band observed
- to map at least out to the first lobe of Stokes I of the lowest frequency of the band
- to perform orthogonal scans in RA and Dec
- to parallactify with the third axis while scanning
- to use time resolution sufficient to move the telescope for less than 1/5 FWHM
- to observe frequency bands of 150 MHz with 1 MHz resolution
- to record the entire PAF noise covariance matrix (all elements)
- to repeat the mapping for 8 bands to cover the entire frequency range 700-1800 MHz
- to repeat the mapping at different elevations
- to observe Virgo A ($\sim$220 Jy at 1.4 GHz) for high signal

- to have the possibility to process the data off-line. Visibility data should be made available in some standard FITS format, like UVFITS or CASA Measurement format.

### 4.4 Formed Beams

The formed beams coming out of the beam former will be weighted according to some scheme. We need to check that the formed beam characteristics are consistent with what is predicted on the basis of weighting our individual PAF measurements. So the above analysis needs to be repeated on the PAF phased up beams.

Our understanding is that the BETA beamformer+correlator can deliver up to 9 beams. For this test the 9 beams should be those of one of the 4 quadrants the 36 PAF beams are arranged. For example, the bottom-left quadrant. The 27 formed beams in the other three quadrants 'should' have a reflection of mirror symmetry with respect to a given quadrant. Since BETA will not be used for astrophysics observations, characterisations of those 9 beams only might be sufficient. However, this obviously needs to be checked by measurement of beams in every quadrant. Although off-axis effects should be symmetrical (based on optical geometry), it is entirely possible that the responses of individual PAF elements could be affected by mutual coupling, and this could well vary in different ways across the PAF.

ASKAP-12+ will require characterisation of all beams, but at that stage the hardware will deliver all 36 beams at once.

The detailed measurement of the formed beams will also allow us to check on the 'symmetry' of a beam's Stokes I response as a function of the distance from the centre of the formed beam. This behaviour must be known in order to properly weight mosaics.

The procedure outlined above is best done with an unpolarised source as then the ionosphere will not affect the observed source polarisation characteristics, especially at the lower frequencies.

The procedure also assumes that the reference antenna will be using an on-boresight phased-up PAF beam. We assume that the D-Jones matrix for the phased up PAF has been derived and can be applied to the observation so that there are no leakage terms being contributed to the correlated visibilities between the reference antenna and the other elements in the array. However we do not think one needs to measure D-Jones for the off-boresight phased up beams. The measured E-Jones matrices intrinsically include the D-Jones leakage terms. And, in general, once we have E-Jones as described above, we do not need D-Jones at all. An independent characterisation of the D-Jones terms is however necessary to separate the two contributions and fully understand the PAFs polarisation performance.

The discussion here also assumes that we are using a strong unpolarised source which has no significant background sources within the ASKAP field of view. This might be true for Virgo A, but unlikely for other sources, even B1934-638. Regardless, background sources add rumble to the observed visibilities. It is desirable to be able to apply a sky model to subtract off the effects of background sources. The current ATCA calibration schemes should make use of background sky models so maybe we can get one from the ATCA. The effects of background sources become increasingly significant as we go to lower frequencies.

Once the polarised formed beams are measured we will apply our method to estimates the E-Jones terms and set up a calibration procedure to correct for them. This will be done offline.

Finally, observations of well calibrated polarised sources such as 3C 286 and 3C 138 will be conducted to test that we can correct for such effects and with what accuracy.

We have the same requests as for the previous test for data availability and their format.

In summary, this test consists of:

- same setup as test of Section 4.3, except:

- beamformer set up to deliver 9 beams of one of the four PAF quadrants
- if not yet available in ASKAPsoft, to use our own software to estimate E-Jones terms from the measured polarised beams
- if not yet available in ASKAPsoft, to use our own software to calibrate data for E-Jones terms (off-line)
- to conduct test observations of polarised sources such as 3C 286 and 3C 138 to test the effectiveness of the E-Jones term calibration.

### 4.5 Beam Weights

Different beam weighting schemes will need to be tested to assess the relevance of the off-axis instrumental polarisation effects and the need of their correction.

The test set up is as for Section 4.4. Those tests will have to be repeated for each one of the beam weighting schemes to be tested (e.g. conjugate field matching (CFM), eigenvector solutions, maximum sensitivity, gaussian beam fitting).

### 4.6 Polarisation Angle

We intend to observe a standard calibrator source for all of our polarisation angle characterisation tests. A source such as 3C286, or an equivalent, is desirable as it has been previously measured to have both a time-stable polarisation angle over long periods ($\phi_{\rm inf} = 33^\circ$) and a small known RM ($-1.2$ rad m$^{-2}$). A known, or well-measured, RM is important, as it provides a way to check if the polarisation angle is as expected at a given frequency – allowing checks on the calibration procedure, and the effects of ionospheric Faraday rotation. Choosing a calibrator with a small RM is useful in order to minimise the magnitude of the required polarisation angle corrections.

We note that assuming that the calibrator has an RM of exactly zero is not sufficient during either the calibration or characterisation stage, and would introduce a substantial systematic error into the broadband Faraday spectra of all measured sources. To simplify the characterisation, the ideal calibrator source will not have any broadband RM variation as a function of wavelength i.e. RM($\lambda$) = constant.

Using the standard calibrator, we will perform raster scan observations i.e. short snapshot observations of the same source at a number of different spatial offsets across the formed beams. Most importantly, we will require access to both the $Q$ and $U$ data as a function of frequency. Using equation 7, we will be able to reconstruct the polarisation angle as a function of $\lambda^2$ and retrieve both the RM and $\phi_{\rm inf}$. We will do this for each raster scan of the calibrator, and ensure that the measured quantities are consistent with those in the literature for the specific calibrator source. We will also check that the polarisation angles remain self-consistent across the formed beams. We intend to do this just once.

In the future, during ASKAP production operations, the same type of observations can be used as sanity check to inform on when it is time to remeasure the entire set of calibration parameters. The same calibrator can be used and regularly observed on-axis only, i.e. at the phase-centre of a given beam. The polarisation angle should remain constant as a function of time. If the angle changes beyond a pre-defined limit, remapping the whole beam/PAF field will be necessary.

### 4.7 Time Stability

The time stability of the system versus each of the effects described above needs to be estimated. This will inform us how often the calibration of each effect needs to be repeated to ensure the desired polarisation performance are obtained.

- Perform the tests described in the previous sections observing known stable calibrators on an optimally varying cadence and monitor changes of the polarisation performance (bandpass, phase delay, formed beams, ...) over time. The measurements should be repeated after an hour (if possible), a day, a week, a month.

### 4.8 Source Detection Tests

Sanity check tests are required to be performed at the three possible stages of polarisation calibration: (1) no calibration; (2) on-axis instrumental polarisation calibration applied only; (3) on- and off-axis instrumental polarisation calibration applied. The calibrations will be applied offline either using ASKAPSoft (if the functionalities required are available) or our own calibration software run under packages like CASA or Miriad.

The performance of ASKAP and the imaging pipeline for polarisation will be tested by a careful analysis of real sources in image cubes taken during commissioning. An adequate number of previously observed reference sources with known polarisation will be required for some of these tests. We will also perform statistical tests on source parameters in each field, and verify the quality of bandpass calibration in Q, U, and V. Test fields at high Galactic latitude are preferred because structure in the diffuse Galactic foreground will interfere with these tests. Tests for completeness as a function of flux density as part of pre-survey commissioning will require injection of artificial sources into the visibility data.

In order to perform tests for polarisation quality, we expect to have access to relevant meta data. Three significant areas of interest specific to ASKAP commissioning are:

1. The jiggling track on the sky as a function of time, in order to calculate a minimum and maximum distance from the field centre per beam for each source. It is assumed that antennas with severe pointing errors are removed before imaging. We will use this information to test beam-specific calibration and direction-dependent polarisation calibration.

2. For each source we need to know whether it was part of a sky model subtracted before imaging, and we need access to the details and version of the sky model, as it will be updated regularly during commissioning. In particular, we need to know if any polarised component was part of the sky model.

3. The timing and nature of changes to the ASKAP system (hardware or software) during commissioning must be communicated because they may impact the test results.

Tests on individual ASKAP mosaics:

- General polarisation quality: A detailed comparison of previously observed bright polarised sources will be made by matching Q, U, and V spectra from ASKAP with existing data.

- Instrumental polarisation: Obtain median $Q/I$ and median $U/I$ per channel for sources with Stokes I brighter than 200 times the band-average noise level, and test against the hypothesis that each is consistent with noise as derived from Stokes V images.

- Instrumental polarisation: Look for persistent RM components associated with all sources, especially around RM=0, as this can be an indication of instrumental polarisation.
- Bandpass calibration: Check for small-scale variations in the spectrum of $p = \sqrt{Q^2 + U^2}$ and look for correlation with the Stokes I spectrum. Apply a smoothness test, assuming that the signal for most sources does not vary rapidly with frequency.
- Check source parameters as a function of position in the field. Verify mosaic edges (outer rows of beams) compared with the inner mosaic. Look for problems related to specific beams. Knowing the jiggling pattern is important here.
- Time permitting, we will apply a spatial high-pass filter to the data to investigate polarisation quality for longer baselines.
- Visual inspection of Stokes Q, U, and V images for problems specific to polarisation, for example limited dynamic range near bright polarised sources.

Tests on multiple ASKAP mosaics as they become available:

- Make a histogram of polarisation angles (1 per source) and verify it is consistent with a uniform distribution.
- Verify consistency of the number of polarised sources, and the distribution of $P/I$ between ASKAP fields.