Initial characterisation of BETA polarimetric response

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Introduction

BETA is an engineering array used to test aspects of the ASKAP system. In particular, it is a radio interferometer array of six antennas, with each antenna equipped with a phased array feed (PAF). Each PAF consists of 188 elements: half of the elements are sensitive to "X" linear polarisation, and the other half sensitive to "Y". The X and Y elements are not coincident, but rather offset from each other in a so-called checkerboard pattern. For astronomy work, up to 18 beams can be formed on each antenna by digitally combining the outputs from the different PAF elements. Normally there will be nine X and nine Y beams. Currently the beam forming is done so as to maximise the sensitivity of a formed beam at a particular point on the sky. The beams are formed in X and Y pairs so as to be sensitive to both polarisations at the same position. Currently the formed beams are not optimised to make the X and Y beams have similar beam responses: the optimisation is purely driven by sensitivity at a point.

The X and Y pairs of formed beams are correlated between antennas to give four polarisation products per channel per baseline. BETA simultaneously observes over 300 MHz, with channel resolution of 18.5 kHz. For the tests described here, the data have always been averaged down to 1 MHz resolution. These tests use the observing band of 700 – 1000 MHz.

Currently there is no calibration signal injected into the system, and so gain variations of PAF elements or phase variation between PAF elements are not measured or calibrated in real time. There is a reliance on their stability over the course of an observation. There is no direct method to measure XY phase.

While the antennas are naturally an alt-az design, there is a third drivable axis – the roll axis – which normally deparallactifies the antenna dish and PAF (i.e. make it so that the PAF does not rotate relative to the astronomical source over the course of an observation). Thus, when deparallactification is enabled, in terms of main beam properties, BETA antennas are more akin to equatorial mounts than alt-az. The tests described here use the system both with and without deparallactification enabled. The standard deparallactification mode results in the X and Y feeds being at $\pm 45^\circ$ to the vertical axis at transit ($\chi = 45^\circ$ in the convention of Thompson, Moran & Swenson), which means that Stokes $U = XX - YY$ and Stokes $Q = -(XY + YX)$.

Test 1: Observations of 1934-638 and 3C138 at field centre

A pair of observations were performed on 1934-638 and 3C138. The observation placed the source at the pointing centre of the antenna, and a single beam was formed at the pointing centre. The roll axis was fixed (i.e. deparallactification was disabled). Confusing sources are sufficiently weak relative to the main source that they can be ignored to first order. Thus these are simple observations: they can be thought of as observations of a single point source at the field centre using alt-az antennas. 1934-638 has insignificant polarised emission for the purposes of this test, and a total intensity flux density of 13.9 Jy at 850 MHz. 3C138 is strongly polarised. An indicative model is

$$(I, Q, U, V) = (11.6, 0.67, -0.31, 0) \text{ Jy}$$

at 850 MHz. The intrinsic rotation measure of 3C138 is "low": Cotton (A&A, 1997) states $RM = -2.1 \pm 0.7$ rad/m^2.

The observation of 1934-638 and 3C138 were for 13 and 7.25 hours respectively. 1934-638 was done at night, whereas 3C138 was a daytime source. The observation of 3C138 was affected by solar interference, particularly on the shortest baseline. Antenna gains and phases were affected by poor preliminary pointing and phase models of the array.

The calibration approach was reasonably standard: the calibration model was for a time-independent antenna bandpass plus time-varying antenna gains. Polarisation response was modelled by time-independent but spectrally-varying polarisation leakages. For a source with linear polarised emission, such as 3C138 and for the frequency range of interest, ionospheric Faraday rotation must be accounted for. It is assumed that all BETA antennas see the same patch of the ionosphere. The approach taken here was to use model ionospheric rotation measure values derived from global contemporaneous GPS ionospheric soundings. We have tried two packages for these: ionFR (Sotomayor-Beltran et al., A&A, 2013) and Albus (Willis et al., in prep.). These both download ionospheric soundings from global databases, develop a model of the ionosphere during the course of the observation and generate ionospheric rotation measure values for the given observing parameters. These model rotation measures were 2.0 to 3.5 rad/m^2 during the observation of 3C138. The two modelling packages differed at the level of $\sim$0.3 rad/m^2, which was within the errors quoted for the accuracy of the model. We processed our observations using both sets of ionospheric rotation measures, but the differences in the results were not material. The memo will focus on the reduction using the ionFR values.

The calibration process derived bandpasses and antenna gains from 1934-638 and 3C138 individually. The bandpass of the XY phase offset of the system was derived from 3C138 alone (it is generally not possible to derive this from an unpolarised source such as 1934-638). Polarisation leakages as a function of frequency were then determined for 1934-638 and 3C138 individually. In the case of 3C138, source polarisation was solved for at the same time, assuming the ionospheric rotation measures predicted by ionFR. Decoupling instrumental leakage and source polarisation is possible because of the rotation of the astronomical signal caused by parallactic rotation (recall deparallactification was disabled) and the time-varying ionospheric rotation measure.

Figures 1 and 2 give the polarisation leakages as a function of frequency for the six BETA antennas. The frequency resolution is better for 1934-638 than for

3C138: note the 3C138 data had the poorer daytime observing conditions (e.g. solar interference), a shorter total integration time and a somewhat weaker flux density. The leakages are uniformly low and reasonably constant with frequency. There is good agreement between the solutions for the two sources. There is a clear positive/negative symmetry between the real parts of the X and Y feeds on some antennas, with it most pronounced on ak15 and ak08. This is a indication of a rotational misalignment of the PAF on an antenna. For ak15, the PAF appears to be misaligned by about 0.035 radians, or about 2°.

Figure 3 gives the polarisation position angle of 3C138 as a function of frequency. The implied intrinsic polarisation angle and rotation measure from this spectrum is -9° and -2.4 rad/m^2 respectively, which is consistent with published data. The error in these values is dominated by the uncertainties in the ionospheric rotation measure. Figures 4 and 5 give I,Q,U,V images of 1934-638 and 3C138. The polarimetric dynamic range is about 1:7000 in the polarised images of the 1934-638 field. The errors in the Stokes I image is dominated by the poor preliminary phase model of BETA. These are multi-frequency synthesis images formed from the full 300 MHz bandwidth. It is probable that some background sources have been Faraday depolarized away in the Stokes Q and U images.

Test 2: 1934-638 on- and off-centre with deparallactification

This test was performed six weeks after the first test, with much improved antenna pointing model and system phase model. Again a single formed beam at the antenna pointing centre was investigated. Two pointings were done: one with 1934-638 at the field centre and a second with 1934-638 offset by 42 arcminutes from the field centre (roughly the 65% point in the formed beam gain response). Standard deparallactification with the roll axis was enabled. Total observing time for 1934-638 and the offset field were 0.5 and 12 hours respectively. No polarised source was observed, and so ionospheric rotation had no effect. To determine the XY phase offset of the system, the roll axis of one antenna was intentionally misaligned by 5°. This misalignment puts sufficient signal into the XY correlations that an XY phase can be determined. This way of determining the XY phase is analogous to the "crossed dipoles" approach that has sometimes be used at the WSRT (Weiler A&A, 1973).

Figure 6 gives the leakage solutions for the on-centre observation of 1934-638 (after the 5° rotation of one of the PAFs had been corrected for). This should be compared with Fig. 1, which was taken six weeks previous. Note that this solution contains $\frac{1}{2}$ hour of data – much less than the solutions of Fig. 1. Hence the solutions are noisier. Despite this, they again show low values which are quite constant with frequency. There is little obvious change in the solutions over the six weeks. There is a change in the real part of antenna ak03. This was the one where the PAF was intentionally misaligned by 5°. It appears the correction made for this misalignment prior to calibration was not perfect: we do not believe this is important.

Figure 7 gives the residual leakage solutions from the off-centre observation after these data had been corrected with the leakages from Fig. 6. These residual leakages are close to zero although there is a deviation of the real part of X and Y on ak03 and ak15 to a level of $\sim$1% at 1 GHz. With the exception of the XY phase offset (which was determined purely from the on-centre observations), independent gain solutions were determined for the off-centre run. Figure 8 gives Stokes I,Q,U,V images of the 1934-638 field using the off-centre observation. These images are at the same saturation levels as Fig. 4. Although there are some artifacts in the Stokes V image, the image quality is generally better than in Fig. 4. This is mainly because of improvements in system pointing and phase model between the observations. Detailed comparisons between Fig. 4 and Fig. 8 must consider some caveats. Because of the formed beam gain response, the relative intensities in Stokes I of the background sources will differ between them. Also because no ionospheric rotation correction has been applied to these data (and this correction is likely quite substantial), one should not expect any agreement between the two epochs in the Stokes Q and U of the background sources.

For discussion below, Fig. 9 shows the ratio of the amplitudes of the antenna gains for the X and Y feeds on the six BETA systems as a function of time for the off-centre 1934-638 observation. This is after the off-centre observation had been corrected with the on-centre observation. This figure shows that the X gains are generally systematically 1–3% lower than the Y gains.

Discussion

The tests above show that it is possible to make good quality polarimetric images with the BETA system. The polarimetric leakages are low, are near constant or vary smoothly with frequency, and appear to have varied little over six weeks between tests.

It needs to be recognised, however, that the tests were not mimicking calibration processes that are likely to be possible with real survey observations. It is useful to step back and consider how "conventional" arrays, such as the ATCA or WSRT, are able to make high quality *relatively* widefield (by the standards of their day) polarimetric images. For high quality polarimetric telescopes which use linear feeds and which are interested in linearly polarised emission, an important issue is the gain stability (or at least predictability) between the X and Y feeds across the field of view. The ATCA achieves this by an injected noise calibration system, regular calibrator observations and primary beams which are very similar in X and Y (at least at the bands of the ATCA useful for polarimetry). For long observations the ATCA calibration scheme can solve for the linearly-polarised emission of the calibrator and so eliminate this 'unknown' polarisation as a contaminant of the calibration process. The WSRT relies on relative stability of the X and Y amplifiers. Being an equatorial array, handling differences in the primary beam response of X and Y systems is much simpler than for an alt-az array (such as the ATCA), so the requirements for similar primary beam responses in X and Y is significantly less important than for the ATCA. X and Y primary beam responses can be corrected more readily in the data processing – provided it is known.

The good quality of the images in Fig. 8 is not representative of what could be achieved with surveys with "simple" or "realistic" calibration approaches. As Fig. 9 shows, there is a 1–3% systematic difference in the gain response between X and Y feeds. If the off-centre observation calibration had not constrained 1934-638 to be unpolarised, this systematic difference in gain responses would have resulted in a source with Stokes U ($= XX - YY$, assuming standard BETA deparallactification) of $\sim$4%. Preliminary tests suggest that the difference in gain response between X and Y become fractionally larger further out in the formed beam response. The gain difference changes slowly over time. The origin of this change is not understood – in might be pointing-related or receiver gain drifts, for example.

That the formed X and Y beams have different gain responses away from their centre should not be surprising. As noted above, currently BETA formed beams are optimised to give maximum sensitivity at a point on the sky. There is no constraint on the beam formation optimisation to make the X and Y beams similar in shape, or indeed for the gain to peak at the same point on the sky. For widefield polarimetry similarity (or at least predictability) of beamshapes for X and Y is as important as low leakages. To produce a widefield system with good polarimetric purity, either the beam optimisation needs to make the X and Y beams more similar, and/or there needs to be a way of predicting the difference between them spatially and temporally.

It is interesting to consider what polarimetric self-calibration can add (i.e. polarimetric calibration which looks for calibration solutions consistent with real source behaviour). With a many-beam system, ASKAP depends significantly on self-calibration in its calibration strategy. Unfortunately polarimetric self-calibration approaches do not constrain plausible source polarisation as much as one might hope (e.g. Sault & Perley, EVLA Memo 177). For equatorial antennas or antennas that are deparallactified, there are even less ways to separate plausible calibration solutions and source polarisation. It is interesting to note that time-varying ionospheric Faraday rotation, if it is accurately known independently of the astronomical measurements, can help to separate out instrumental and source characteristics.

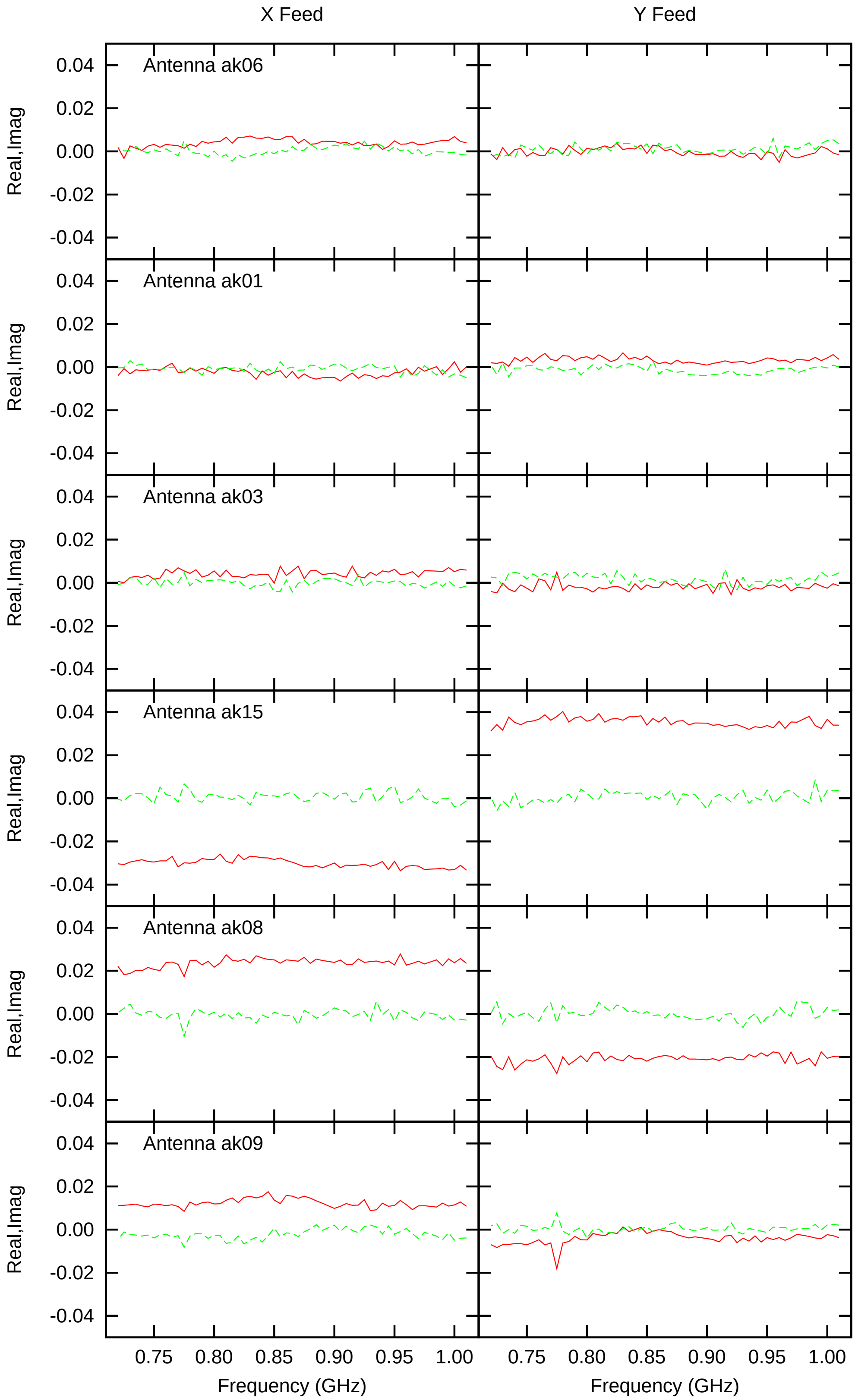

Figure 1: Polarisation leakage solutions for the six BETA antennas derived from 1934-638. Left and right columns are the X and Y feed solutions respectively. The real part is in red and imaginary in green.

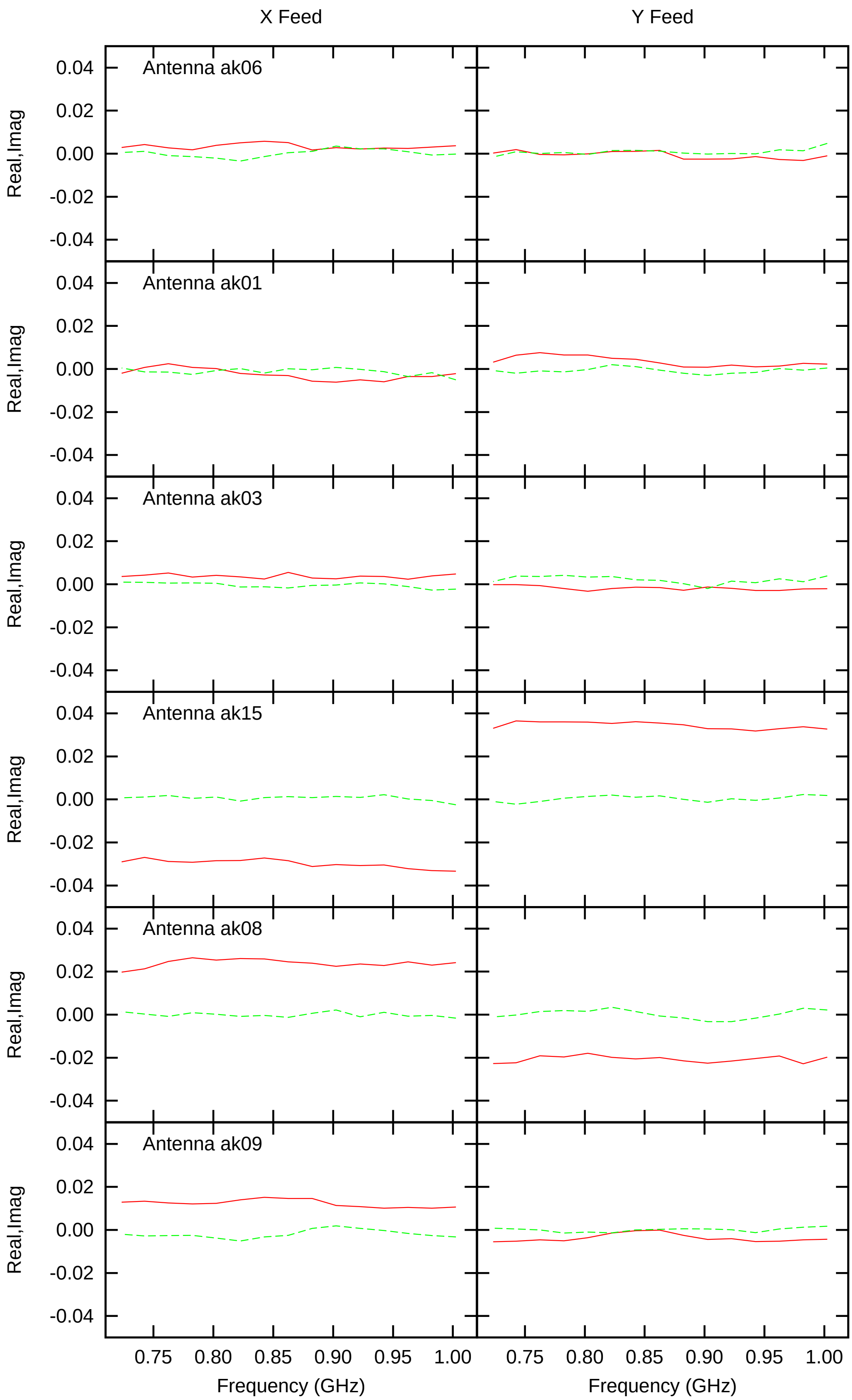

Figure 2: Polarisation leakage solutions as for Figure 1, but derived from 3C138. The poorer sensitivity of the observation led to coarser frequency resolution and noisier solutions.

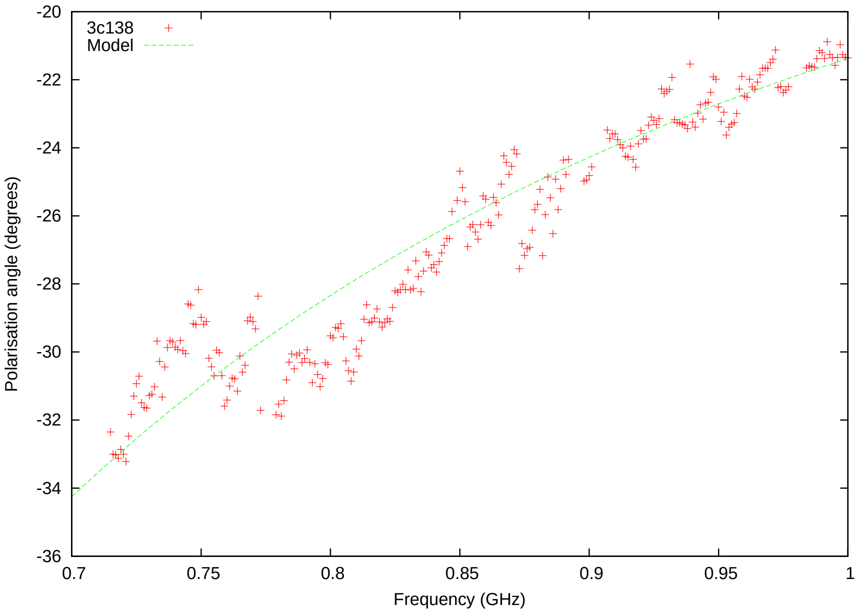

Figure 3: The measured polarisation angle of 3C138 as a function of frequency. The line gives the expected angle for a source with intrinsic polarisation angle of -9° and $RM = -2.4$ rad/m^2.

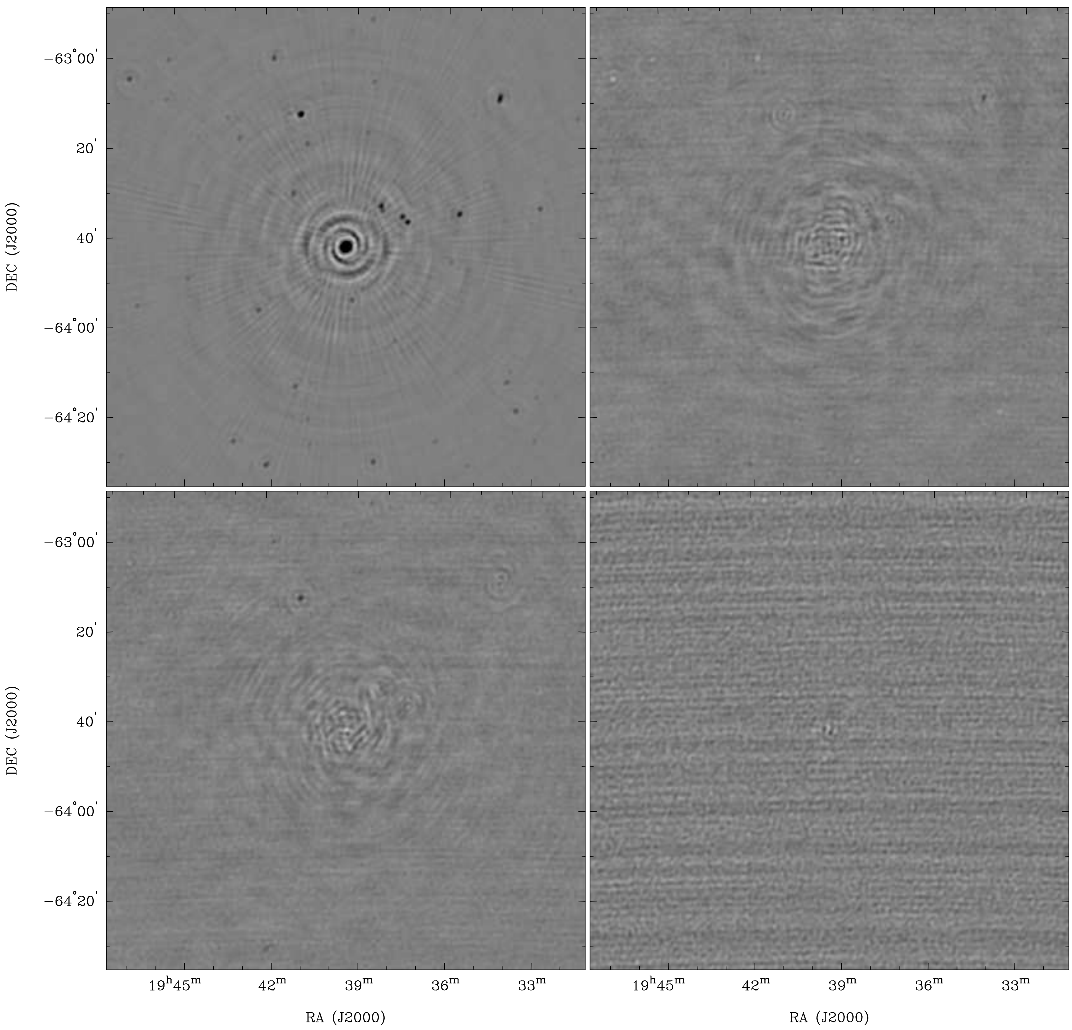

Figure 4: Images of the 1934-638 field. The four images are Stokes I, Q, U and V (top left, top right, bottom left and bottom right respectively). The greyscale is saturated at ±100 mJy/beam (Stokes I), ±5 mJy/beam (Stokes Q and U) and ±2 mJy/beam (Stokes V).

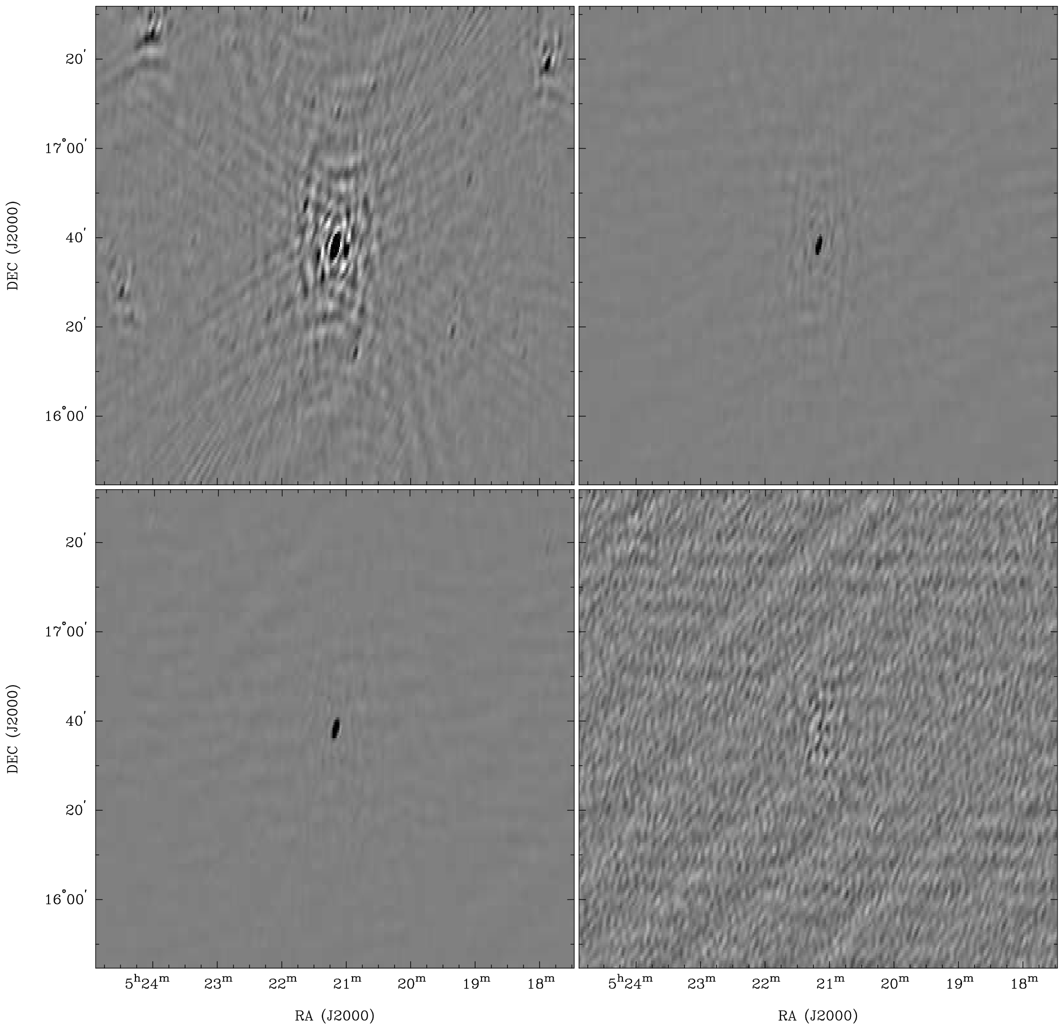

Figure 5: Images of the 3C138 field. The images are as in Fig. 4. The greyscale is saturated at ±100 mJy/beam (Stokes I), ±50 mJy/beam (Stokes Q and U) and ±2 mJy/beam (Stokes V).

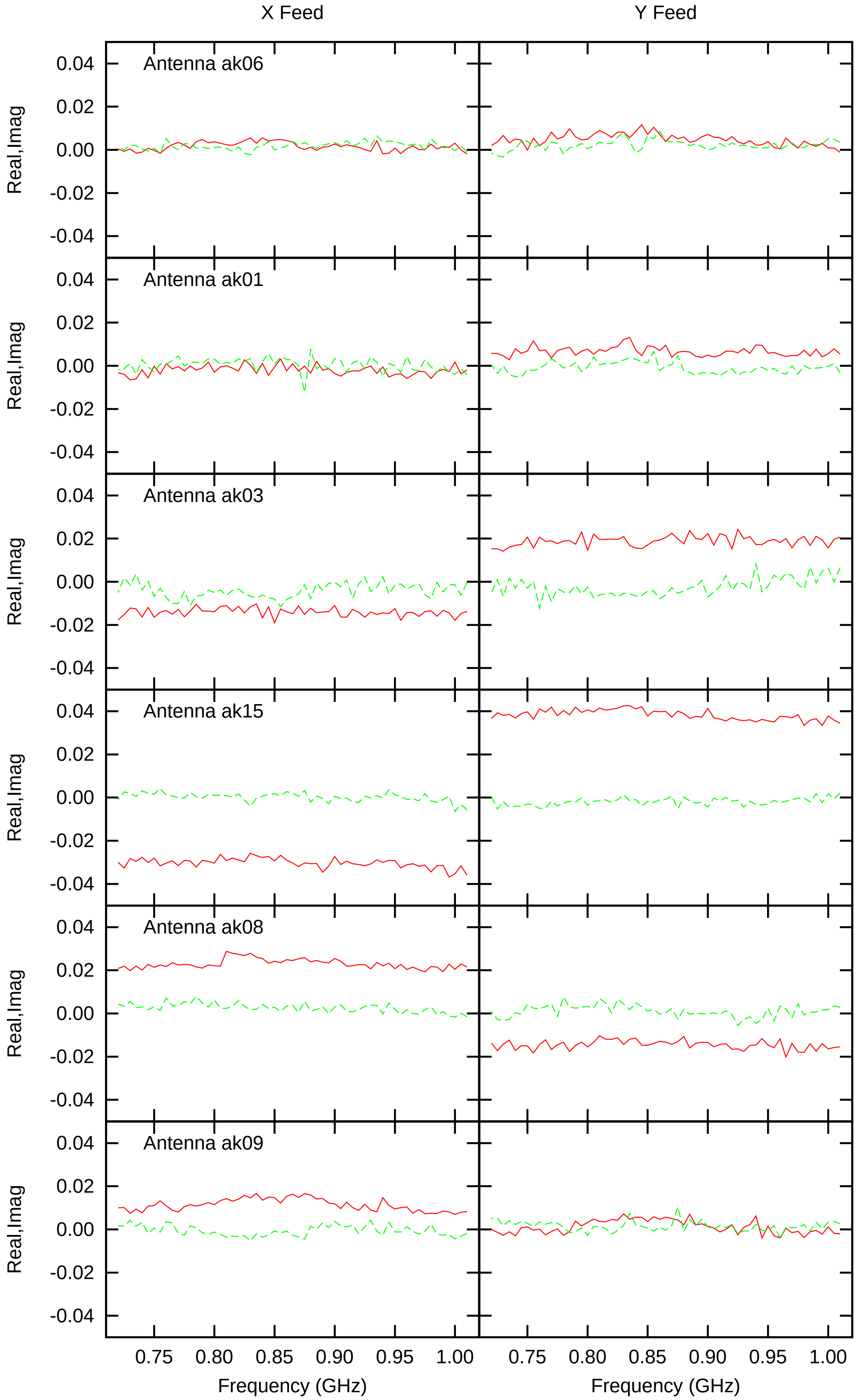

Figure 6: Polarisation leakage solutions from 1934-638 as for Figure 1, but six weeks later and from 0.5 hour of observing.

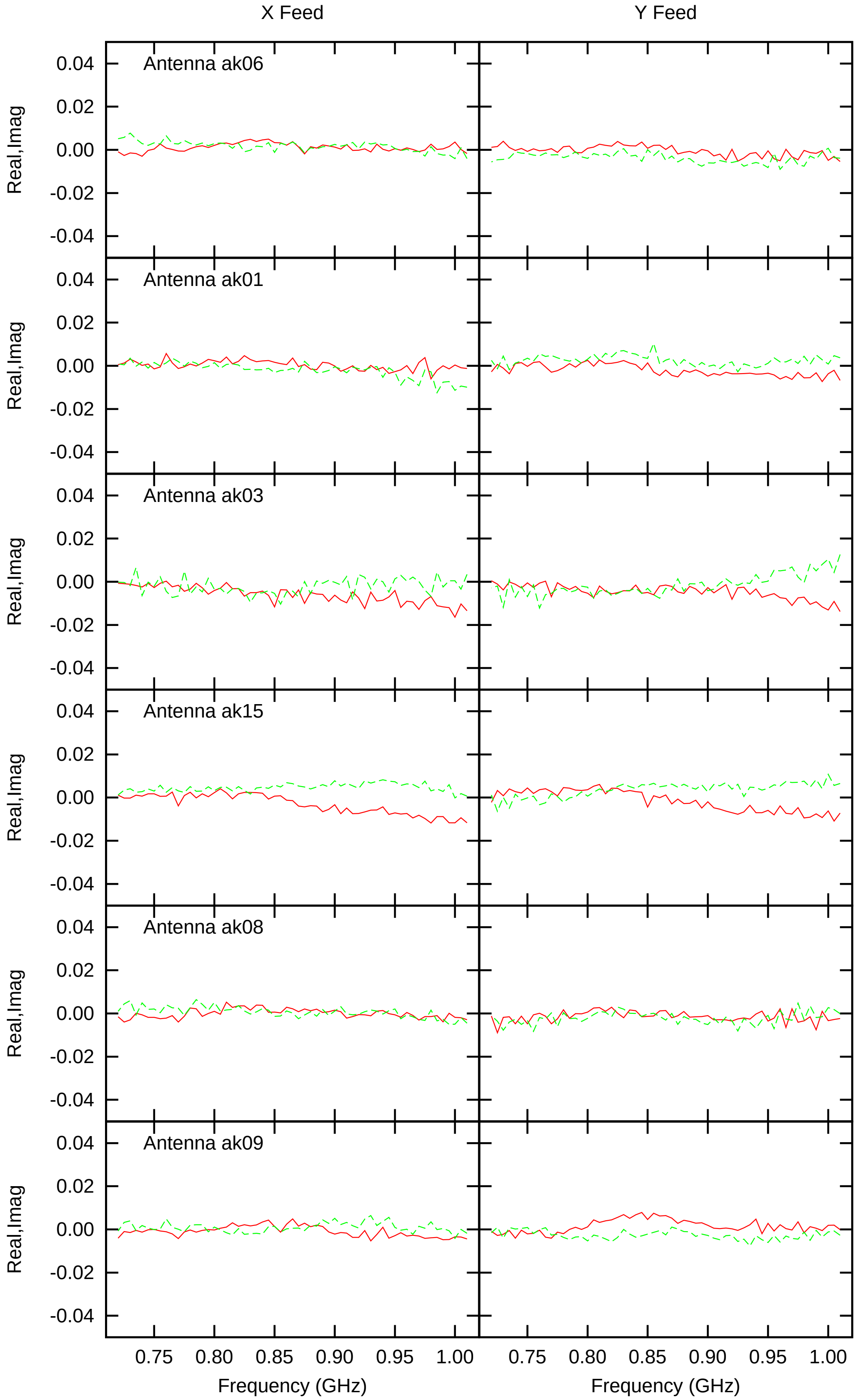

Figure 7: Polarisation leakage solutions from 1934-638 as for Figure 1. 1934-638 was offset 42 arcmin from the pointing and formed-beam centre.

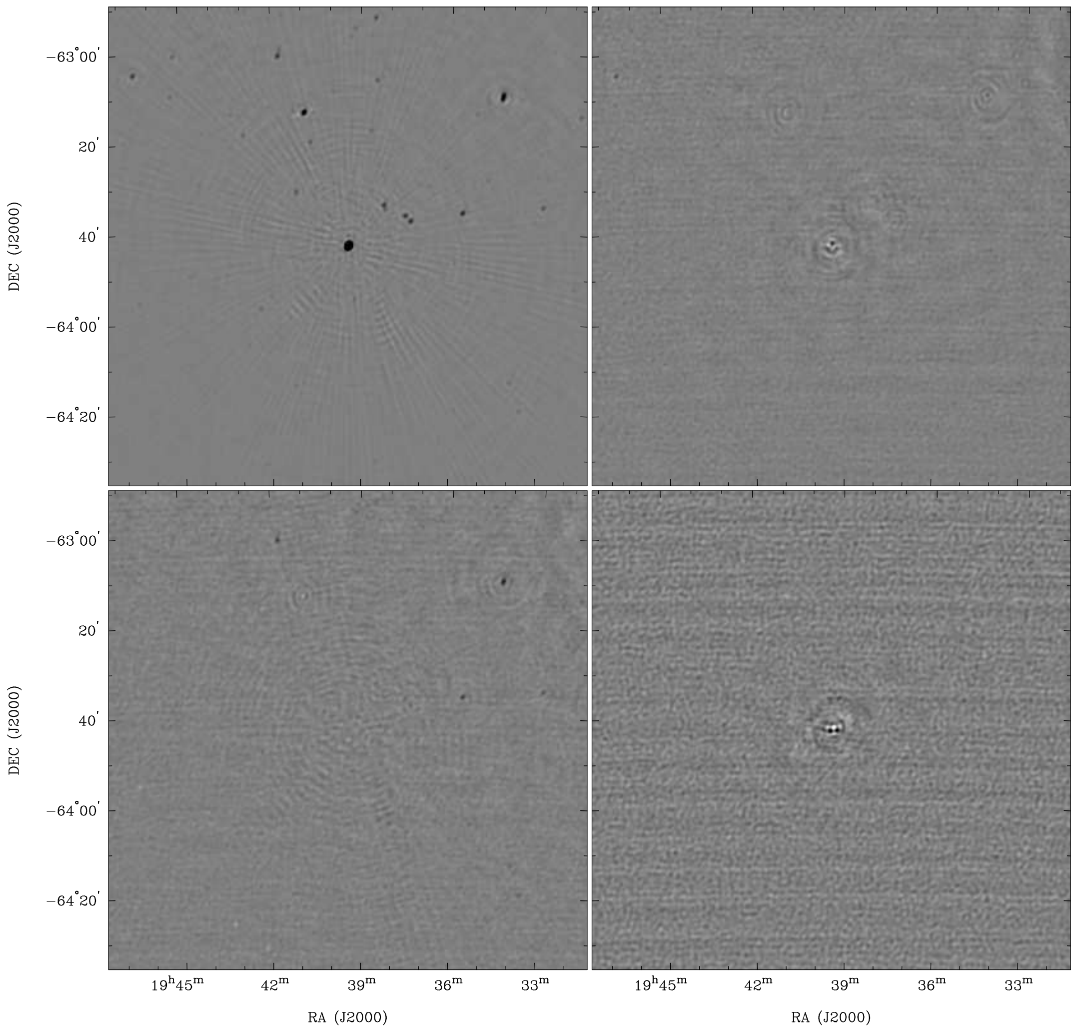

Figure 8: Images of the 1934-638 field from an observation with pointing offset by 42 arcmin from the source. The images and greyscale saturation levels are as in Fig. 4.

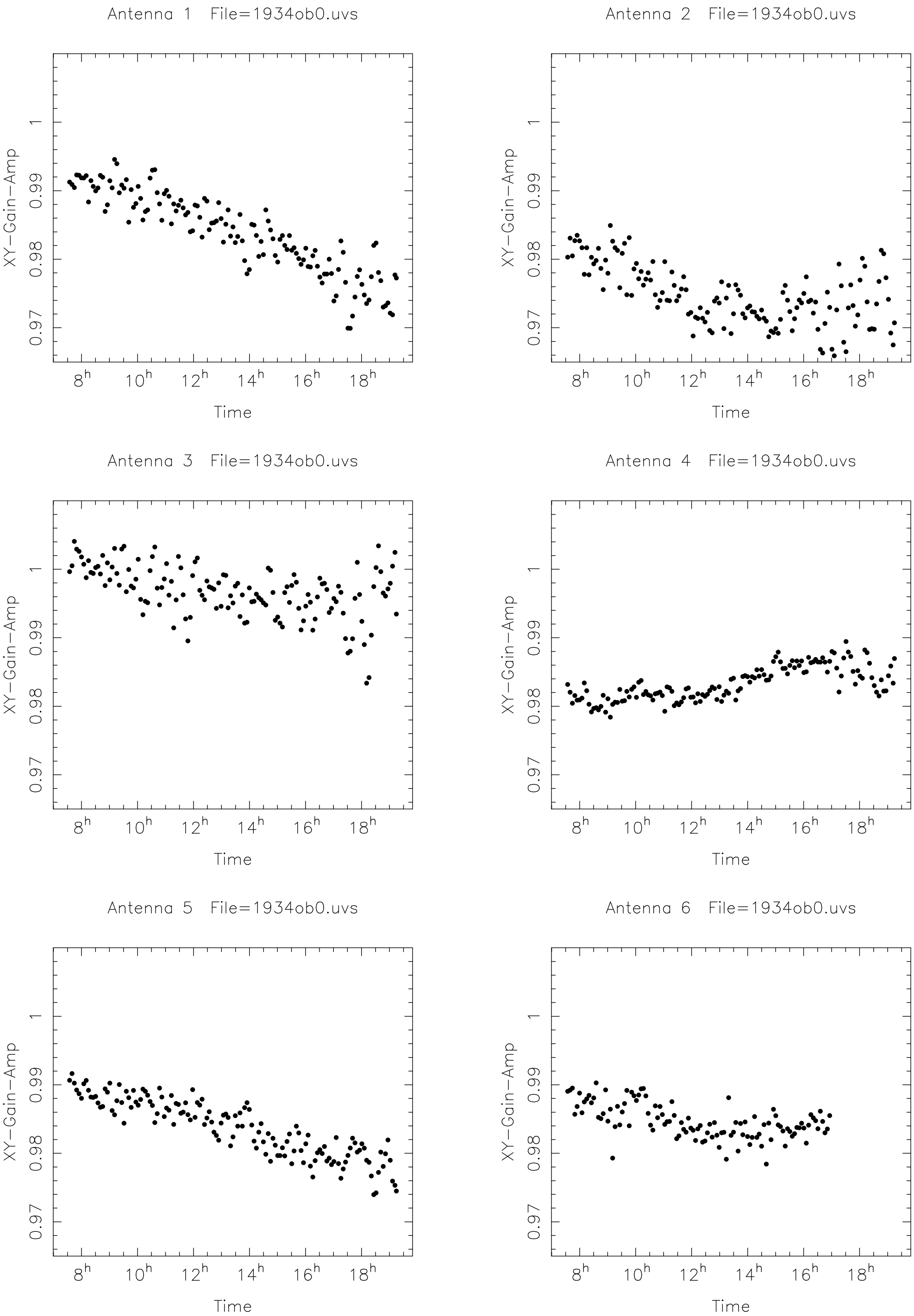

Figure 9: Ratio of antenna X and Y gain amplitudes as a function of time for the off-centre 1934-638 observation.