EVLA Memo 170
Determining full EVLA polarization leakage terms at C and X bands

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Introduction

Polarimetric calibration of an interferometer array involves determining the polarization leakages – these describe the imperfections of the polarimetric response of the system. Jones matrix formalism is a popular approach to expressing these leakages. In this memo we will restrict consideration to polarimetric response at the field center: widefield issues are not considered. Also, while we consider the polarimetric response across a broad set of frequencies, our approach is to treat each frequency channel individually: polarimetric solutions have not been coupled together between frequency channels in any way. Consequently in the discussion on the principles of polarization calibration, we will assume characterization at the field center at a single frequency.

In general, calibration of an interferometer array does not completely solve for the leakage Jones matrix. Sault, Hamaker & Bregman (A&A 1996) consider this in some detail. This memo uses a number of results from that paper. From a single observation of a point source with unknown polarization, the polarimetric response of an interferometer array can be solved down to seven unknown (real-valued) parameters. From a single observation of a point source with known polarization (which may be unpolarized, weakly or strongly polarized), the number of unknown (real-valued) parameters in the polarimetric response can be reduced to three. Polarimetric calibration of an interferometer array is usually much more involved than a single observation of a known source. For EVLA observations, polarimetric calibration will often use some combination of a flux density calibrator, an RL phase calibrator, and a secondary calibrator. The latter may be observed with significant parallactic angle rotation. However, depending on the details of the calibration approach, two (or sometimes three) parameters in the full polarimetric calibration will generally remain unknown or poorly known (see Sault, Hamaker & Bregman for more details).

That a few parameters remain undetermined in the polarimetric characterization is not generally a serious issue. These is both because

- the polarimetric properties of the antennas is generally good (i.e. the leakage times the fractional polarization is not significant), and
- the few unknown parameters relate to leakage between linearly and circularly polarized components (i.e. they do not relate to Stokes I leaking into the polarized measures).

That the signatures of these unknown parameters are difficult to measure is a sign that in general they do not have a significant effect on observations and may be unimportant. Generally polarimetric dynamic ranges (i.e.

ratio of Stokes I to artifact in Stokes Q, U and V) of 10^3 can be achieved without having a full polarimetric characterization. Generally, also, lacking a full polarimetric characterization will not limit the dynamic range of a Stokes I image. However, assuming source polarizations of several percent and leakages of a few percent, a full polarimetric calibration may be needed for polarimetric dynamic ranges of more than 10^3 or perhaps 10^4.

Usually the two parameters that remain undetermined is a complex-valued offset, β, to the antenna leakages (see eq. 21 and 22 in Sault, Hamaker & Bregman). As noted in Sault, Hamaker & Bregman, it is often possible to add an offset to the R leakage, and the conjugate of the offset to the L leakage of the leakage solutions without significantly changing the quality of a calibration, i.e.[1].

$$\begin{aligned} d'_{\rm R} &\leftarrow d_{\rm R} + \beta, \\ d'_{\rm L} &\leftarrow d_{\rm L} + \beta^*. \end{aligned}$$

For the EVLA, this offset will be important for observations which have both significant linearly- and circularly-polarized emission (e.g. some maser science). The aim of this memo is to determine the absolute leakages (i.e. the leakages without an unknown offset) for the EVLA antennas at C and X bands. The rationale for this is to gain a better understanding of when full polarization characterization may be needed to meet polarimetric dynamic range requirements.

We have used two approaches to measuring the absolute leakages:

- the "two source" approach using observations of one weakly and one strongly polarized source over good parallactic angle coverage; and
- the "receiver rotation" approach which physically rotates a receiver package between two observing runs.

The two approaches should give essentially the same results. Consistency and agreement will give us confidence in our conclusions.

This memo is one of three relating to EVLA polarization. A second memo will consider the long term stability of the polarimetric characteristics, whereas the third will consider the polarimetric characterization needed to achieve different dynamic ranges.

The two source approach

Sault, Hamaker & Bregman's analysis shows that to determine full polarimetric characterization it is sufficient to observation of a source with known strong linear polarization at three (or more) well-spaced parallactic angles. What is not apparent from this statement is an assumption that the antenna gains do not change during the course of the observation. If the antenna gains are solved for with time, part of the antenna leakages can be subsumed into the gain solution. To avoid this, we also observe a second source which is nominally unpolarized. This source acts as a calibrator for the time-varying gains: we use the gain amplitude solutions from this source to avoid the need to solve for gains on the linearly polarized source.

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[1] It is not truly an offset, but strictly a Jones matrix in θ and ϕ:

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \cos\phi & i\sin\phi \\ i\sin\phi & \cos\phi \end{pmatrix}. \qquad (1)$$

For small angles θ and ϕ, this approximates to a leakage offset of $\beta = \theta + i\phi$.

Broadly speaking, this approach is able to determine the full characterization through the signature of the linear polarization leaking through into the parallel hand correlations. This will change with parallactic angle rotation. By allowing gain solutions with time, it becomes ambiguous whether a fluctuation in the parallel hands is a gain change or a polarimetric signature. This ambiguity can be avoided by using a gain calibrator which is nominally unpolarized.

Our approach is to observe 3C286 and 3C287 for three hours near their transit. These sources are separated by about 5° on the sky, and have a declination near 30°. As a consequence, they transit near the zenith at the EVLA, and so the parallactic angle goes through a sweep of -70 to 70° during the course of our observation. 3C286 is strongly linearly polarized with a fractional polarization of 11-12% over the observing frequencies used. We have used 3C286 to determine the RL phase. 3C287 is weakly polarized. To determine the antenna gains from 3C287, we have done a fairly standard polarimetric calibration on this source. Being only weakly polarized, and having solved for its polarization using parallactic rotation, the antenna gains are to very good approximation unaffected by the leakages, source polarization etc.

We observed 16 128-MHz subbands across the two WIDAR bands with 64 2-MHz channels in each subband. We time-shared between C and X bands with a duty cycle of 4 minutes. Our observations spanned 4.3 to 11.5 GHz. These settings mean that the frequency coverage is not complete across C and X bands. The observations were on 18 March 2013.

Calibration and data reduction were performed in Miriad. This uses the full quadratic approach to polarimetric calibration (not linearized) as well as modelling leakage between all Stokes parameters (i.e. a "weakly polarized" approximation is *not* used). Polarization characterization was performed at each of the 2 MHz channels. As noted above, 3C287 was used as a gain calibrator (as well as its own polarization and an initial relative leakage solution), whereas 3C286 was used to determine the absolute leakages and the RL phase offset.

The receiver rotation approach

The receiver rotation approach uses the fact that if a receiver is rotated by 90°, and all else being equal, then the (absolute) leakage attributed to that receiver will be negated. It is thus possible to determine any leakage offset by doing two observations which only solve for the relative leakages. The first observation is a standard one whereas the second has receivers on some (at least one but not all!) antennas rotated by 90°. From the changes in the relative leakage solutions of the rotated antennas, the leakage offset can be determined and so absolute leakages can be deduced on all antennas. Apart from the engineering effort to rotate receiver packages, a drawback of this approach is that it assumes that the leakage is purely from the receiver package: it neglects the contribution of the antenna optics to the polarimetric response. For the off-axis optics of the EVLA antennas this is an assumption which is not immediately obvious to be a good one. However EVLA Memo 58 suggests the antenna effect at the field center should not be substantial. Comparison of the two polarimetric calibration approaches is a useful test of this. Given the engineering work required, in practise the observations need to be spaced over a couple of days, and there is some question whether the rotating of the receiver on an antenna may change an antenna's response more than simply negating it.

The receiver rotation approach has been used in prior characterization of EVLA polarization characteristics (see EVLA Memos 131 and 151 by Perley and Hayward). Unlike the "two source" approach, this technique broadly relies on the cross-hand correlations to determine the offset (the "two receiver" approach looked for signatures in the parallel-hand correlations). This memo used a reduction approach that compared relative leakages to determine an offset. Memos 131 and 151 used a more direct way which involves simply combining RL and LR correlations. For a linearly unpolarized source, such as 3C84, the two ways of handling the data should be equivalent.

Observations using this approach were carried out on 23 and 24 July 2013. All of X and C bands were observed giving complete frequency coverage between 4 and 12 GHz. The observation cycled between four frequency setups to acquire data at the high and low ends X and C bands at 2 MHz channel resolution (observations were also performed at S and L bands, but these are not considered here). The observations were performed four times. On the first day an observation was done with receivers in the standard state and then two sets of observations with the receiver on antenna 26 rotated. On the second day there was a final observation with the receiver on antenna 26 returned to normal. Each observation lasted 40 minutes.

Each observation consisted of two cuts of 3C84 and 3C138. This did not provide any useful parallactic angle rotation. 3C84 was assumed be linearly unpolarized and was used for standard (relative) leakage calibration. 3C84 may have some circularly-polarized emission (Homan & Wardle 2004). Although this would affect the antenna gains, this circular polarization would not affect the leakages in our calibration. 3C138 was used for RL phase offset calibration: it is approximately 10% linearly polarized at the frequencies of this observation.

These data were again reduced using Miriad. The data were also reduced in AIPS using the task TRUEP (a task specifically intended for "receiver rotation" observations). The AIPS and Miriad results were consistent with each other.

Comparisons

Figures 1 and 2 show absolute leakages (real and imaginary parts for the R and L channels respectively) for a representative antenna - antenna 24. The agreement is typical of most of the antennas (see the exceptions noted below). The plots shows the 4 observations using the "receiver rotation" approach of July 2013 as well as the "two source" approach of March 2013. Results in general show good agreement. This gives us confidence that the two approaches are indeed measuring the absolute leakages. Given that the sets of observations for the two approaches are four months apart, this also indicates good temporal stability of the polarimetric response.

Some antennas which showed atypical behavior are worth noting:

- antenna 1, at C band in the R channel only, and only in the March 2013, showed significant and rapidly frequency-varying leakage. The poor response is most pronounced at the low C-band frequencies, but is still somewhat apparent at the top end as well. The L channel does not show similar poor response. Between March and July the receiver was repaired and upgraded to use a "new-style" polarizer.
- antenna 14 showed significant change at X band. The response was very poor in March – it was "broken" in some way and apparently was "fixed".
- antennas 26 and 28 showed appreciable change at C band. Absolute leakage calibration of these antennas had been done in March 2011 (see EVLA Memo 151). The March 2011 and March 2013 determinations showed good agreement. We believe there was a change in the response of these antennas between March and July 2013. Figures 3 and 4 show the absolute leakages for antenna 28. We note, without explanation, that the change is in the imaginary part only. This is not the only instance of a change in leakage that has affected the imaginary part only. This must be a clue to the origin of the change.

A useful quantity to come from these observation is an estimate of the average leakage (eq. 29 in Sault, Hamaker

& Bregman)[2]

$$\frac{1}{2N}\sum_{i}^{N} d_{i\mathrm{R}} + d^{*}_{i\mathrm{L}}.$$

Given that this quantity is summed over many antennas, it could be expected to remain more stable with time than other measures of absolute leakage. It is also a more robust measure if antennas are present/absent from particular observations. Given the expectation of what the average leakage should be, then an absolute leakage calibration estimate could be made by adding offsets to a relative solution to get the desired average leakage.

Figure 5 plots this average leakage measure from the data observed in July 2013. Note the broad similarity of this and the leakages of antenna 24 (Figures 1 and 2). Indeed most antennas broadly have this form.

Conclusions

Agreement between the two approaches for determining absolute leakage is good. The degree of agreement shows that there is good stability of the polarization characteristics in the four months between the two observing runs. The agreement also shows that the leakages at the field center are dominated by the receiver package rather than the antenna optics.

In general X band receivers have better polarimetric performance than C band. As, for example, Fig. 5 shows, the average leakage at X band is centered around 0. At C band, however, there is an offset from 0 of the average leakage. Performance degrades further at the low end of C band. Both of these are expected to be addressed by the new-style polarizers.

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[2] The sign convention used for leakages by Miriad, by Sault, Hamaker & Bregman and by AIPS differ. For the d_{L} leakage (but not d_{R}), Sault, Hamaker & Bregman use the negative of the convention used by Miriad. Throughout this memo (both equations and plots of results) we use the sign convention of Sault, Hamaker & Bregman. Miriad and AIPS use the same convention for leakages, but they use different conventions for visibilities! The result is that leakage solutions of Miriad and AIPS are the conjugate of each other.

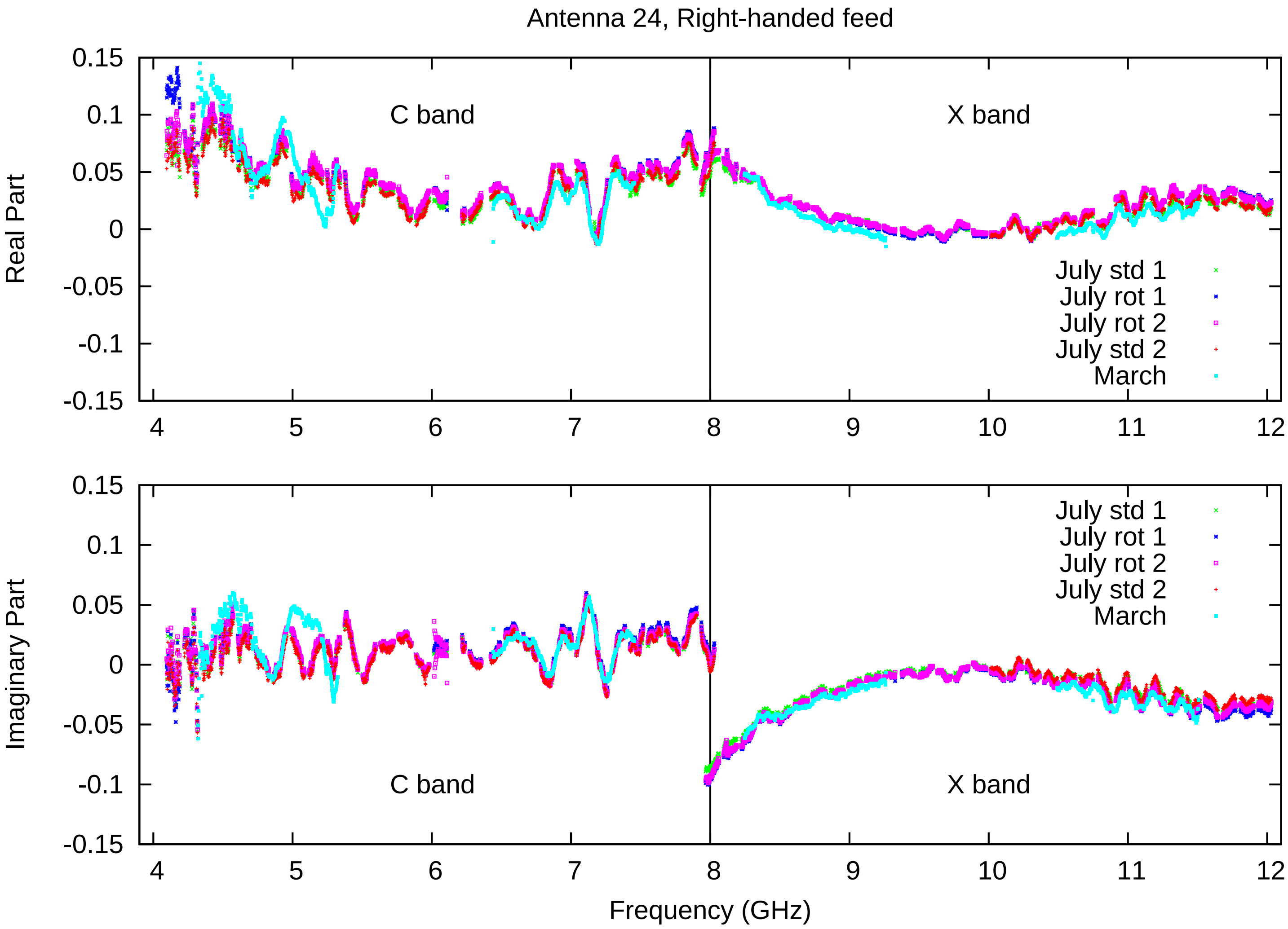

Figure 1: The absolute leakages for the right-handed feed for antenna 24.

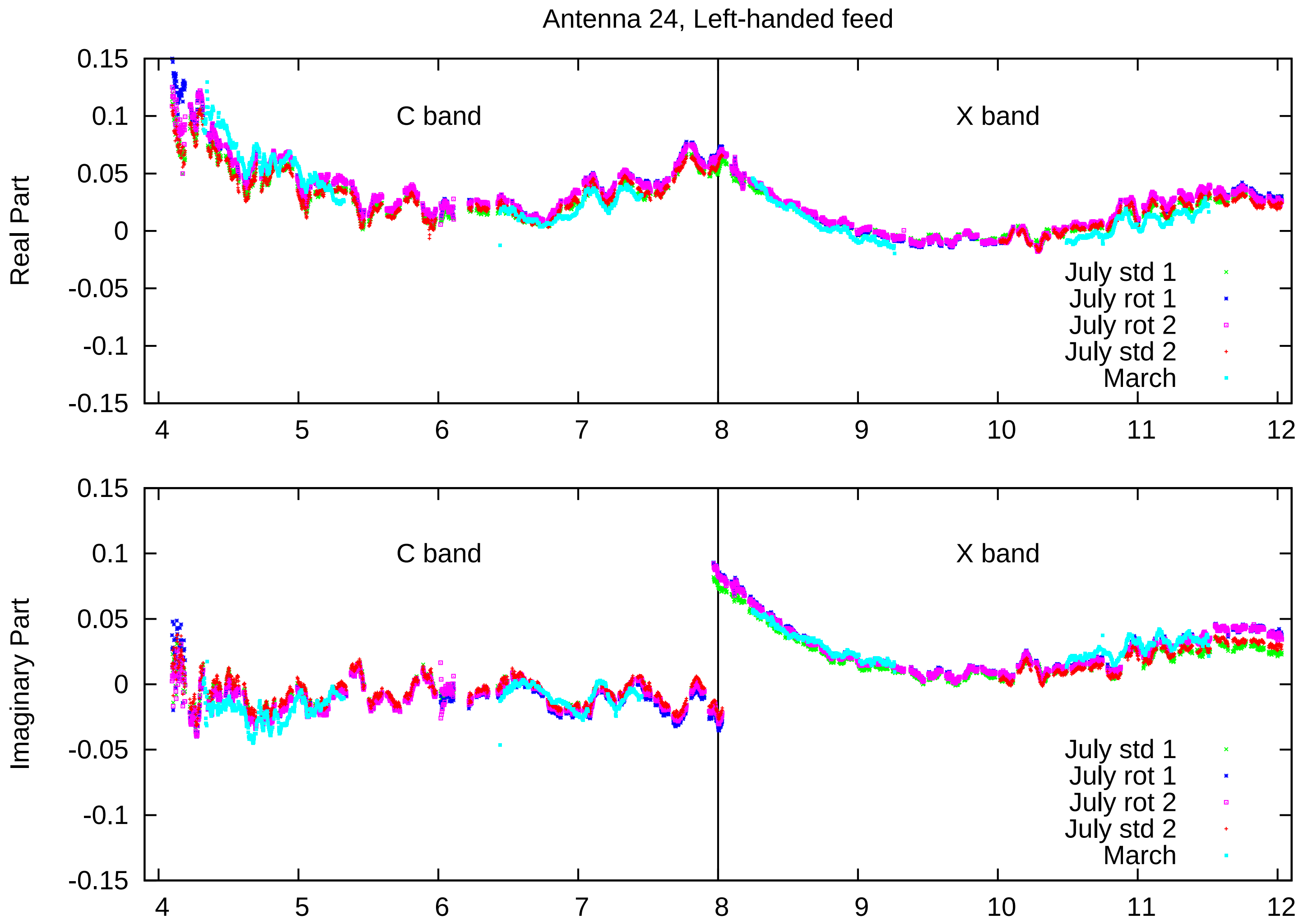

Figure 2: The absolute leakages for the left-handed feed for antenna 24. The left and right halves of the plots correspond to C and X band. These are physically separate receiver packages with different polarimetric designs. Continuity of the plot of the real part is purely coincidental. The blue-colored dots correspond to the March ("two source") observation. Note the similarity of the real parts, and conjugate symmetry of the imaginary parts of the right and left feeds. Equal real parts and conjugate imaginary parts is expected when the two feeds are orthogonal (but not purely circular).

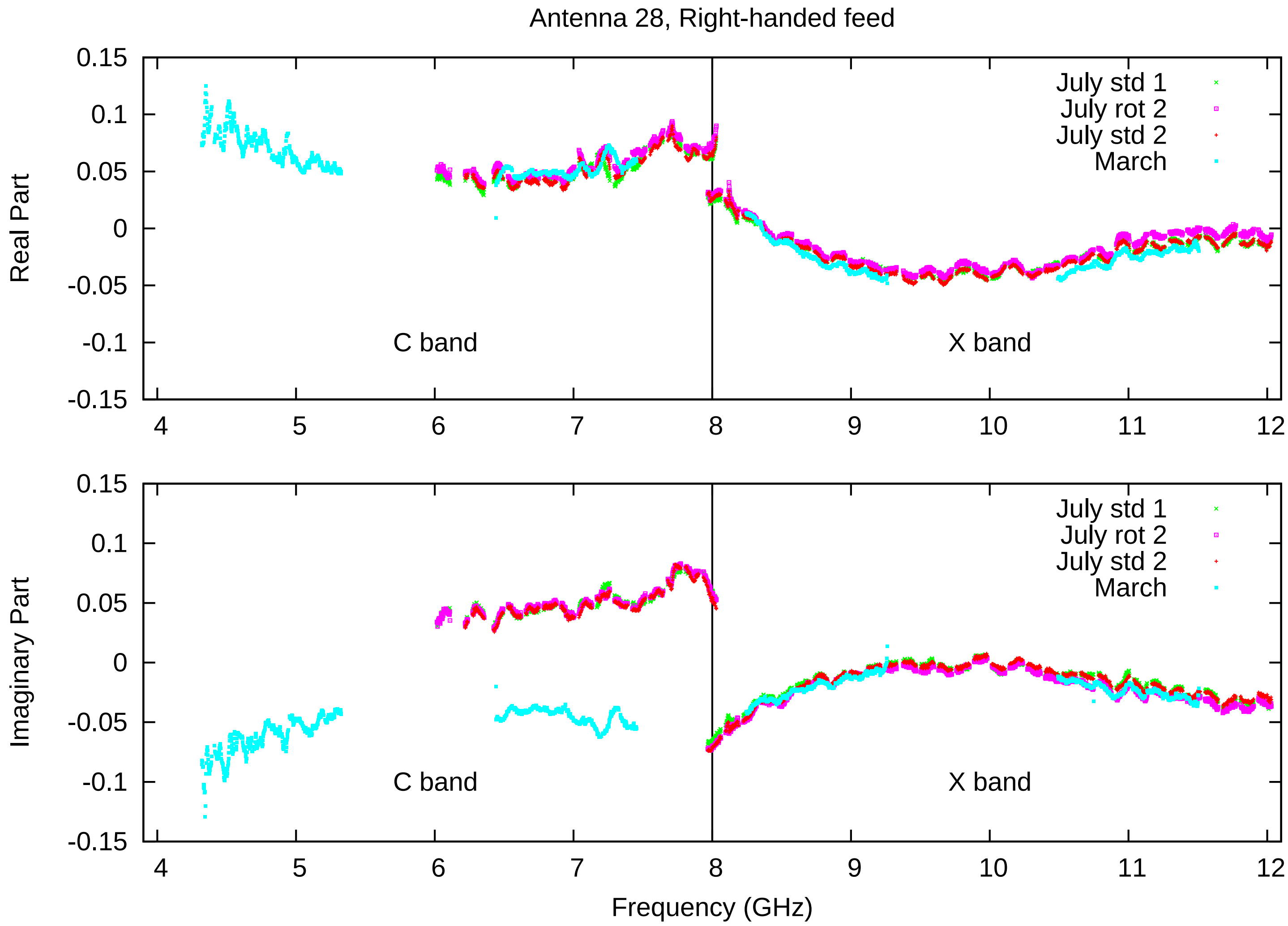

Figure 3: The absolute leakages for the right-handed feed for antenna 28.

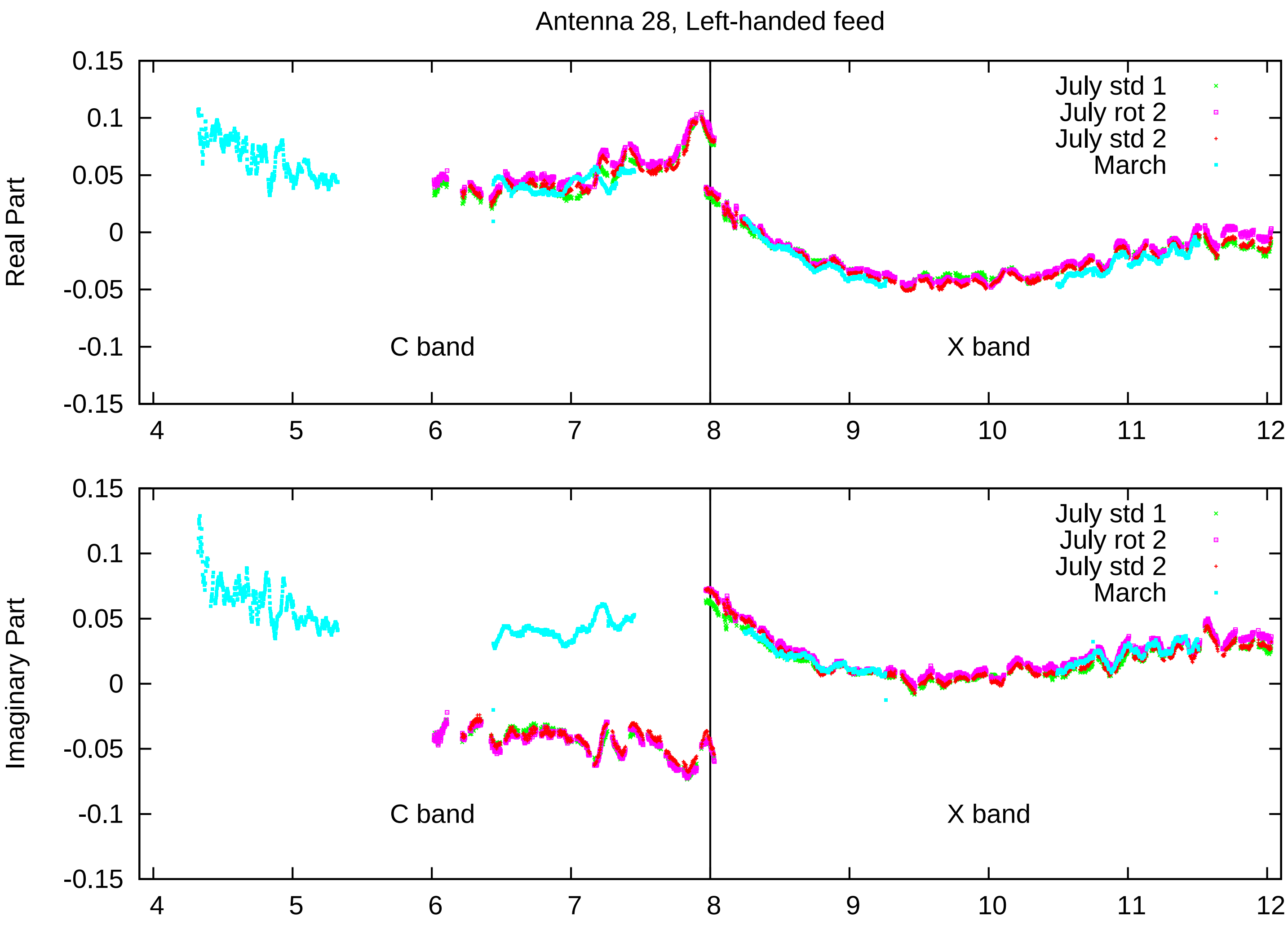

Figure 4: The absolute leakages for the left-handed feed for antenna 28. The response at C band has changed between the March and July observing runs.

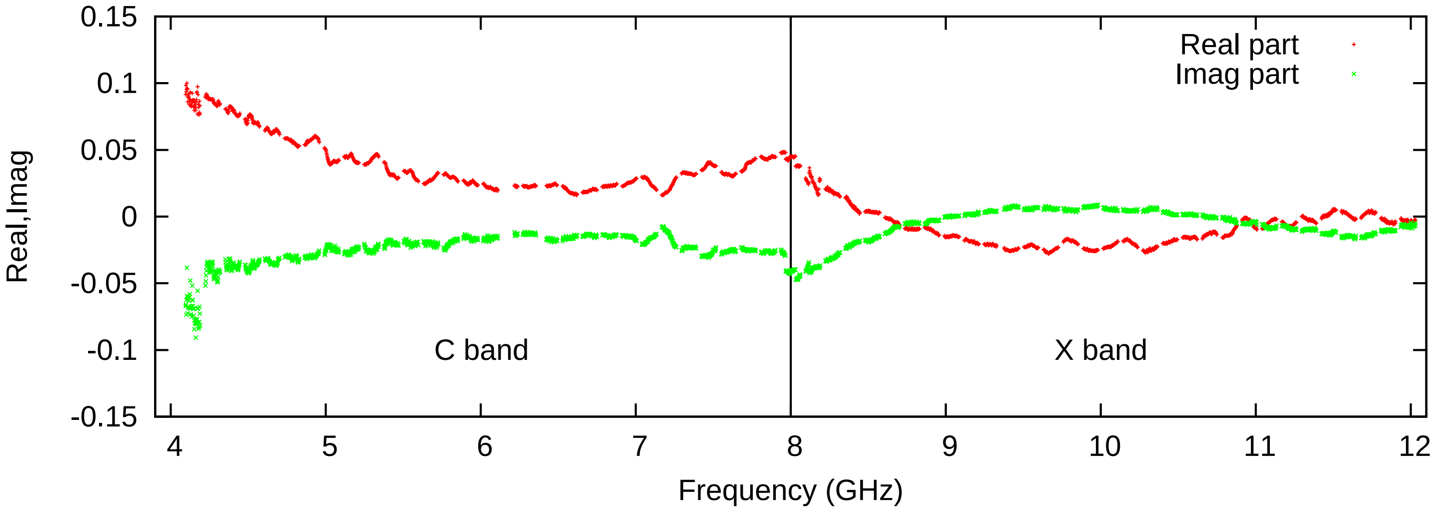

Figure 5: The average leakage offset, β. These were determined by averaging together the absolute leakages found using the receiver rotation approach. Note the broad similarity of the plots to Figures 1 and 2.