EVLA Memo 178
Stability of EVLA Polarizers at L, S, C, and X Bands

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Abstract

The absolute cross-polarizations of the VLA antennas at L, S, C, and X bands have been determined from data taken in March 2011, March 2013, May 2013, and July 2013, using the methods described in EVLA Memo #131 and EVLA Memo #170. In general, the cross-polarization of the VLA's antennas at these four bands varies only slightly over the 2.4 year span of these measurements, with typical variations of ∼2% and 20 degrees. The stability at L and S bands appears to be better than at C and X bands. Variations over timescales of a few days are very small, typically 0.05% and 1 degree. These small variations mean that for most polarimetric observations, there is no need for independent measurement of the cross-polarizations. Use of tabulated values, determined approximately yearly, should be sufficient.

1 Introduction

Accurate polarimetry over the entire primary beam is one of the key goals of the VLA. Achieving this requires accurate characterization of the polarimetric responses of the VLA's antennnas – both as a function of frequency and offset from the antenna pointing center. In general, accurate measurement of the antennas' polarimetric response as a function of frequency and antenna offset is a lengthy observational undertaking, which becomes particularly onerous if the antenna polarizations change significantly over time, antenna elevation, and offset position within the antenna's main beam. However, if the antenna polarizations are stable over timescales of a month or more, we can consider a regimen of occasional measurement, which can then be applied to the data as a matter of course. The first step in instituting such a system is demonstration that the polarization responses at the beam center are sufficiently stable over a period of a year or more.

In this memo, we consider only the on-axis frequency dependence of the antenna polarization. Although the off-axis patterns, relative to the on-axis values, are expected to be stable (since they are set by the antenna optics), no measurements to prove this have been made. Additionally, as the antenna surface is known to deform as a function of elevation, changes in the off-axis patterns are to be expected at the higher frequencies. Again, this has not yet been demonstrated, and remains a task to be completed.

To determine the long and short-term stability of the on-axis polarizations, we have conducted three absolute-polarization experiments at L, S, C, and X bands in 2011 and 2013.

2 Relative and Absolute Cross-Polarization Determinations

We first briefly review the three methods of polarization calibration we have employed. In the following, the factor T describes the (complex) voltage transfer from one polarization channel to the other.

The traditional method for determining the VLA's antenna polarizations utilizes the change in cross-hand response for one or more sources over a period long enough for the parallactic angle to change significantly. Presuming the data are gain-calibrated, that the Stokes V value is zero, and that the two component antennas view the source with the same parallactic angle Ψ, the cross-hand responses can be written

$$R_{r_1 l_2} = \frac{1}{2}\{(T_{r1} + T^*_{l2})I + e^{2i\Psi}(Q - iU) + e^{-2i\Psi}(Q + iU)T_{r1}T^*_{l2}\} \tag{1}$$

with a similar expression for the 'LR' correlation. The first two terms on the RHS of these expressions are approximately of the same magnitude, while the third is typically two orders of magnitude smaller, and is generally ignored. The cross-hand response is thus the sum of a constant term, equal to the total intensity multiplied by the sum of the leakage terms arising from each antenna, and a term proportional to the polarized intensity, which rotates with parallactic angle. This rotation allows a separation of the source and antenna polarizaions. However, this relation is not sufficient to allow a unique determination of the 'T' terms – there are more unknowns than knowns, even if the source polarization is known in advance. In general, with N antennas, there always remains one more complex parameter to determine than there are unique visibilities. Hence, the leakage terms can only be determined relative to an assumed offset, corresponding to the cross-polarization of one polarization of one antenna or, perhaps better, the entire array. A small error results from this unknown offset, the effect of which is explored in EVLA Memo #177. Use of these 'relative' cross-polarizations is not ideal for a study of polarizer stability, as the stability of the reference (either an antenna, or the entire array) cannot be guaranteed. Hence, we have utilized two methods for determining the absolute cross-polarizations.

EVLA Memo #131 describes a simple method for determining the absolute cross-polarizations of the antennas in an interferometric array. In its simplest form, this method requires that an unresolved, unpolarized source be observed twice – once with all antennas in their normal orientations, and again with at least one antenna rotated by 90 degrees. For such a source, and assuming that all antennas view the source with the same parallactic angle, the cross-hand correlations can be written as:

$$R_{r_1 l_2} = \frac{1}{2}(T_{r1} \pm T^*_{l2})I \tag{2}$$

where the '+' corresponds to the reference antenna in the normal position, and the '$-$' applies when the reference antenna is in its rotated state. The absolute cross-polarizations are then determined from the sum and difference of the cross-hand visibilites on those baselines with the rotated antenna. This method has the advantage that the data are very easy to analyze, but has the disadvantage that for the VLA, the antennas cannot be rotated by 90 degrees – only the receivers at L, S, C, and X bands can – so that the cross-polarizations determined do not include any component arising prior to the receivers[1]. An additional, and significant complication is that the process of rotating the receivers is a very laborious one. Furthermore, the method can not be applied to the VLA's four high frequency receiver bands.

In EVLA Memo #170, we reported on another method, utilizing the parallel-hand visibilities of the strongly linearly polarized source 3C286 as it rotates through a large change in parallactic angle. To illustrate, again assume $V = 0$, and that the two antennas have the same parallactic angle. In this case, the parallel-hand visibilites are, for calibrated data

$$R_{r_1 r_2} = \frac{1}{2}\{(1 + T_{r1}T^*_{r2})I + e^{-2i\Psi_p}T^*_{r2}(Q + iU) + e^{2i\Psi_p}T_{r1}(Q - iU)\} \tag{3}$$

with a similar expression for the opposite pair. This expression shows that the parallel hand visibilities will show a small (~1%) offset in amplitude and phase as a function or parallactic angle due to the coupling of the linear polarization into the parallel hand correlations. Most importantly, as the variations have a known dependence on parallactic angle, the cross-polarization terms to be easily identified.

This method has the considerable advantages of not requiring any physical changes to the antenna, and can be applied to all the VLA's frequency bands. EVLA Memo#170 compares the results of this method to that of the unpolarized source method, with excellent agreement. Although the analysis is more complicated, (currently only possible within Miriad), the ease of observation, and the fact it measures the true total system polarization (i.e., including both the receiver and the antenna) makes it the favored method for the future.

3 Observations and Data Reduction

Observations of 3C147 were taken on March 9, 10, and 11, 2011 at L, S, C and X bands, while the array was in the 'B' configuration. The receivers in antenna 6 were rotated by 90 degrees for the observations on March 10. These observations did not include a polarization calibrator, so the phase of the leakage terms could not be determined. Since 3C147 is slightly polarized at C and X-bands ($\sim 1-2$ %), there will be a small bias in the results. As EVLA construction was ongoing at this time, not all antennas were outfitted with final design receivers.

With the completion of the receiver implementation in 2012, we ran a further polarization measurement campaign, utilizing the receiver-rotation method, on 23 July 2013, when the array was in the 'C' configuration.

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[1] From symmetry arguments, we believe this component is small in comparison to the receiver contribution.

This test provided results for all antennas at the four lowest frequency bands. These new observations utilized both 3C147 (for L and S bands) and 3C84 (for C and X bands) as the unpolarized source, and included the highly polarized source 3C138 to permit the phase of the leakage terms to be determined.

The 'strongly polarized source' method was utilized on 18 March 2013 for C and X bands, when the array was in the 'D' configuration, and on 20 May 2013 for S and L bands, when the array was in the 'DnC' configuration. For both observations, 3C286 was the highly polarized source, and the low-polarization source 3C287 was used for gain calibration. Observations extended over three hours, centered on meridian transit, over which the antenna parallactic angle changed by ~ 140 degrees.

Calibration of the data followed standard methods. The phase of the leakage terms for the 2013 observations was set by the known polarization angle of 3C138. Lacking a strongly polarized calibrator, the March 2011 data cannot determine the absolute phase of the leakage terms. We have thus adjusted the phases of solutions such that the median phases matches those determined in the 2013 observations.

No special efforts were made to remove RFI — the effect of this on the leakage term solutions is easy to identify, and clearly descrepant results have been purged. The March 2011 data are much less affected by RFI – this is clearly due to the additional phase winding provided by the longer spacings.

4 Results

Of interest are the typical variations in cross-polarization over various timescales. In the following two sections, we display the short-term (2-day) variabilities at L and S bands, then the long-term (4 months and 2.4 year) variations at all four bands.

4.1 Short-Term Variability

The March 2011 data were taken over three days – observations with the polarizer on the reference antenna (ea06) in the normal position on 09 and 11 March, and observations on 10 March with the polarizer rotated by 90 degrees. The two observations in the normal position provide us an opportunity to judge polarizer changes over two days. We show in Figure 1 the cross-polarization of ea12R at L-band, and ea06R at S-band, on 09 and 11 March. For each, the differences are typically 0.05% in amplitude, and 1 degree in phase. This result strongly supports the expectation that the polarizers are very stable over short time spans. Polarization calibration parameters determined on any given day can certainly be utilized over timescales of many days.

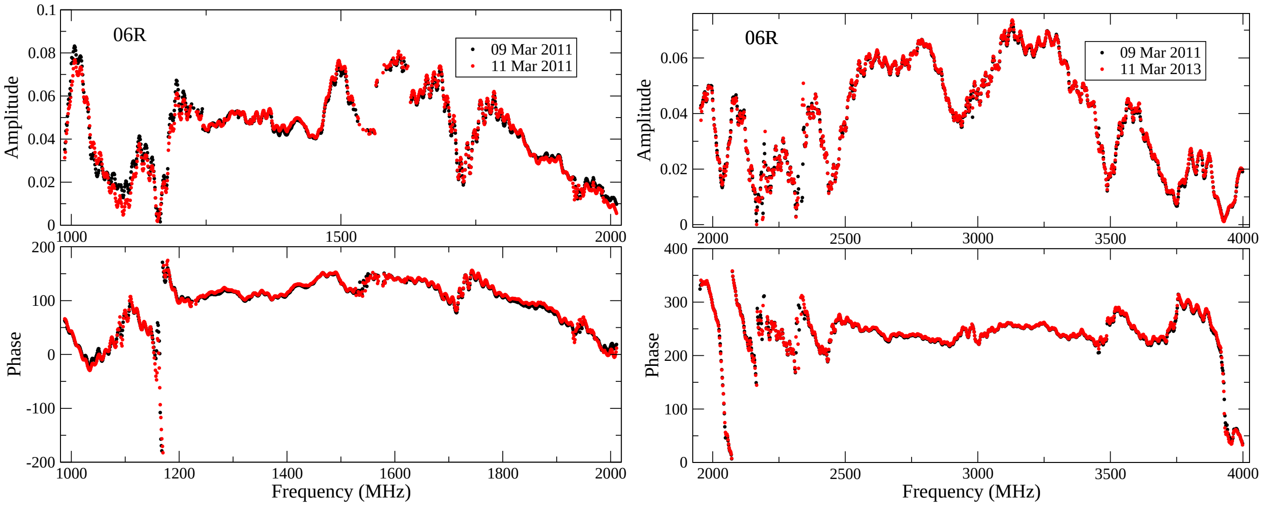

Figure 1: Amplitude and phase of the cross-polarization for ea06R at L-band (left) and at S-band (right). The differences are barely perceptible – at the 0.05% level in amplitude, and 1 degree in phase.

4.2 Stability over 4 Month and 2 Year Timescales

Of greater interest is the stability over longer timescales. We present below typical results at all four frequency bands for the March 2011 to July 2013 time span, and the March 2013 to July 2013 time span. All plots utilize the same color scheme: Black for the March 2011 observations utilizing the ‘unpolarized source’ method, red for the 2013 ’strong polarized source’ method (March and May, 2013), and blue for the July 2013 data, utilizing the ‘unpolarized source’ method. Note that some differences between the red plots and the others are expected due to the antenna polarization, as this will not be seen in the ’unpolarized source’ method data. From symmetry arguments, we expect the on-axis antenna polarization to be small – but it is unlikely to be zero. Furthermore, the phases of the March 2011 data (black traces) have been offset by an amount to align them with the 2013 data. Hence, no conclusions on phase offsets can be drawn from these data. However, variations of this phase with frequency are meaningful.

4.2.1 L-Band

We show in Fig. 2 typical results for two antennas – one with low polarization (ea12), and one with higher polarization (ea14), which was at the time outfitted with the prototype wideband polarizer. RFI is a significant problem in the analysis of these data. The most troubled frequency zones are from ∼ 1170 – 1280 MHz (GPS,

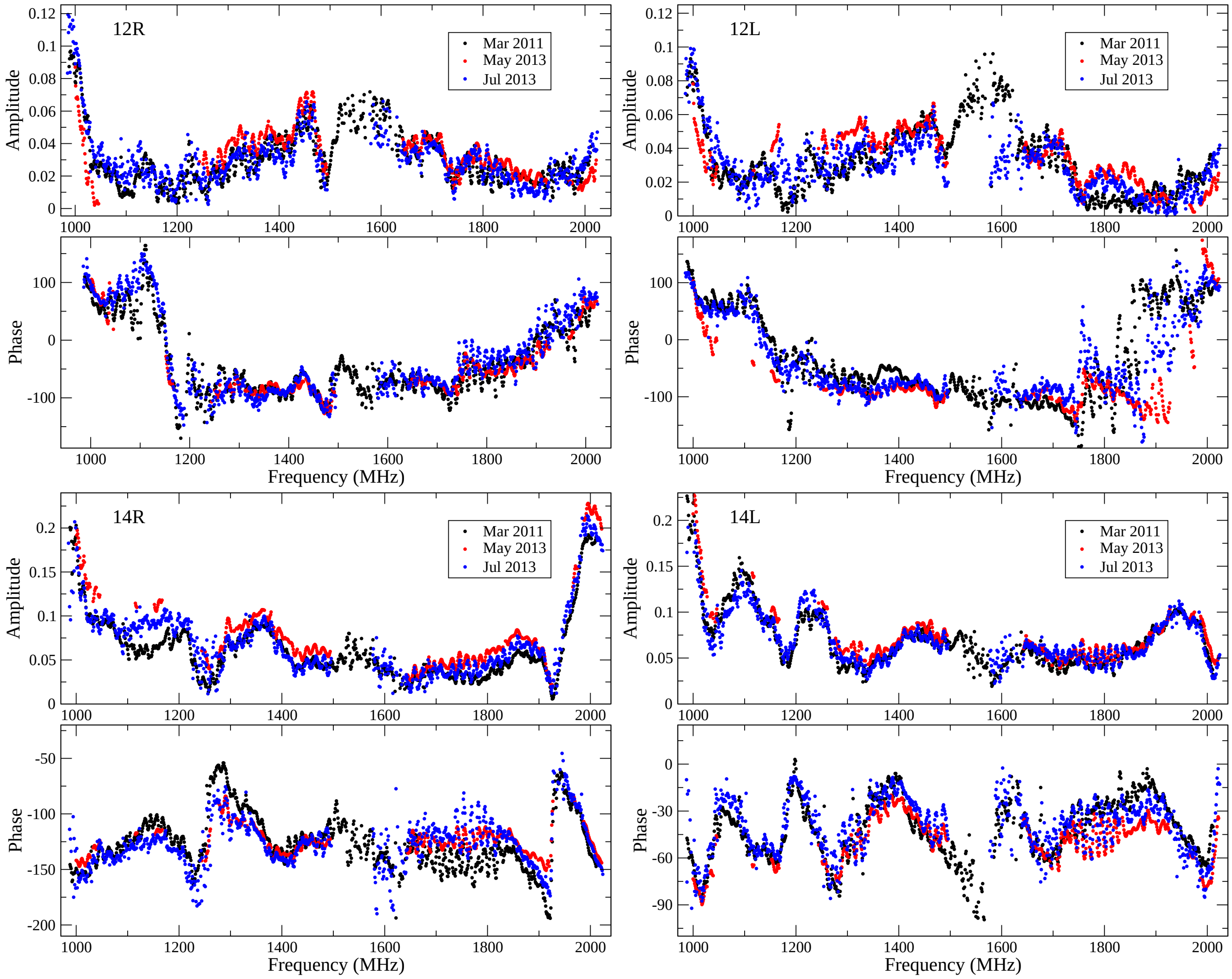

Figure 2: Amplitude and phase of the cross-polarization for antenna 12 (upper half) and antenna 14 (bottom half) over a 0.4 and 2.4 year span at L-band. March 2011 data are in black, May 2013 in red, and July 2013 in blue. Changes are generally less than 1% and 10 degrees. The missing 2013 data (red and blue dots) near 1250 and 1550 MHz are due to satellite RFI.

and other satellite broadcasts), and from 1525 through 1610 MHz (Inmarsat, GPS, Glonass, and others). Note that the B-configuration data (black dots) are by far the most complete.

Changes over the 2.4 year span of these observations are very small, typicall less than 1% and 10 degrees. The offset in the May 2013 data (red dots) may be due to the on-axis antenna polarization, which is not included in the other observations.

4.2.2 S-Band

We show in Fig. 3 typical results for ea10 and ea26. Although S-band is less affected by RFI than L-band, there are zones where polarimetry may not be possible. Most notable is the XM and Sirius systems' downlink band – ∼2310 – 2360 MHz. Also notable are 2180 – 2200 MHz, and the TV downlinks from 3600 through 4200 MHz. As most of these interferors are in geostationary orbits (Sirius being the notable exception), interference is much stronger for equatorial observations.

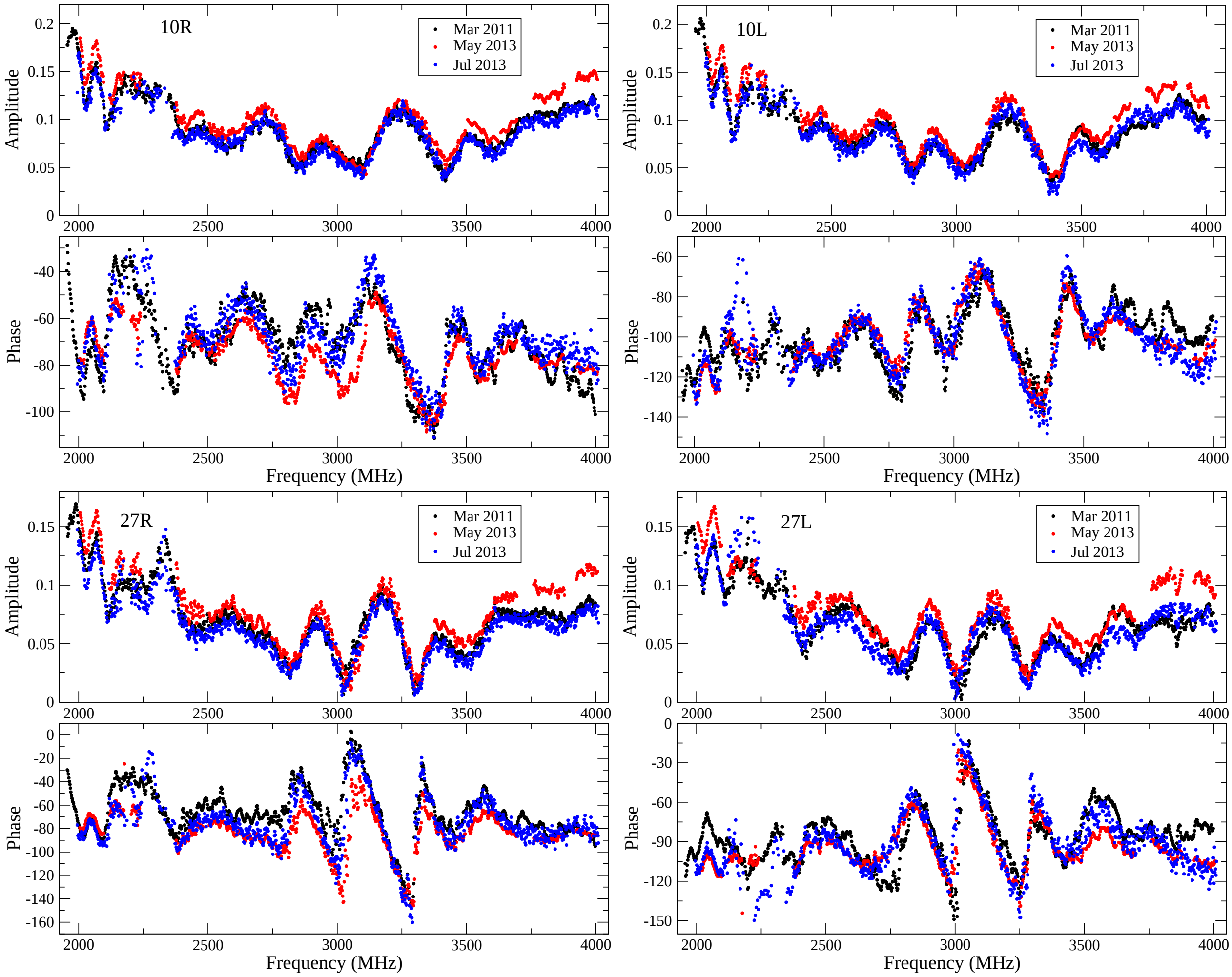

Figure 3: Amplitude and phase of the cross-polarization for antennas 10 (upper half) and 27 (lower half) over a 0.4 and 2.4 year span at S-band. March 2011 obsrevations are in black, May 2013 in red, and July 2013 in blue. Changes are generally less than 1% and 10 degrees.

As at L-band, there is remarkable stability in the cross-polarization. We note that the cross-polarization amplitudes in the May 2013 data are significantly higher above 3.5 GHz than in the other observations. It is not known if this is due to the antenna, or is some manifestation of the RFI environment from the TV downlinks which are strong at these frequencies.

4.2.3 C-Band

Figure 4 shows ea03 and ea24 at C-band. The general trend of higher polarization at the band edges, and lower in the middle is a general feature of the polarizer. A new design quadrature hybrid, which provides lower polarization and possibly better stability, is curretly being installed on the array.

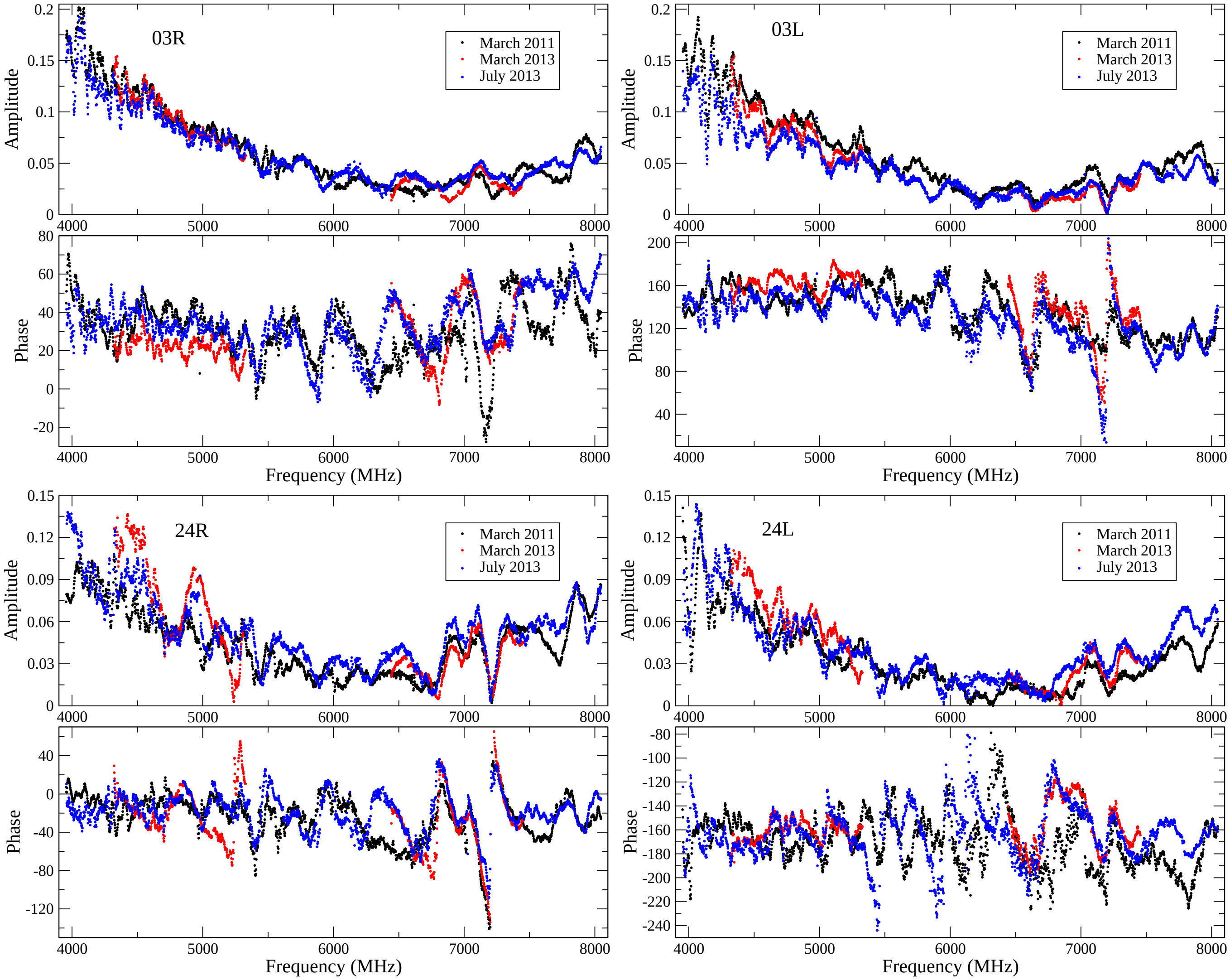

Figure 4: Amplitude and phase of the cross-polarization for antennas 03 (upper half) and 24 (lower half) over a 2.4 year span at C-band. March 2011 data are in black, March 2013 in red, and July 2013 in blue. Changes are generally less than 2% and 20 degrees, although larger deviations are visible, particularly at frequencies where the cross-polarization is low.

It is clear from these two results that the polarization stability is not as good at this band as it is at L and S bands. Although the general trends in polarization with frequency do not change, there are more significant changes on frequency scales of ∼100 MHz. We note that the changes over time are larger for this band than for L or S bands, (or X-band, as shown next). We do not know if this is a general characteristic, or one specfic to these antennas at this time. As noted earlier, we expect that the new design quadrature hybrids, currently being implemented on the array, will offer better long-term stability. The large changes in phase for ea24L are primarily due to the low cross-polarization amplitude, and can be disregarded.

4.3 X-Band

The X-band cross-polarizations for ea06 and ea24 are shown in Fig. 5. The stability for ea06 is very good –

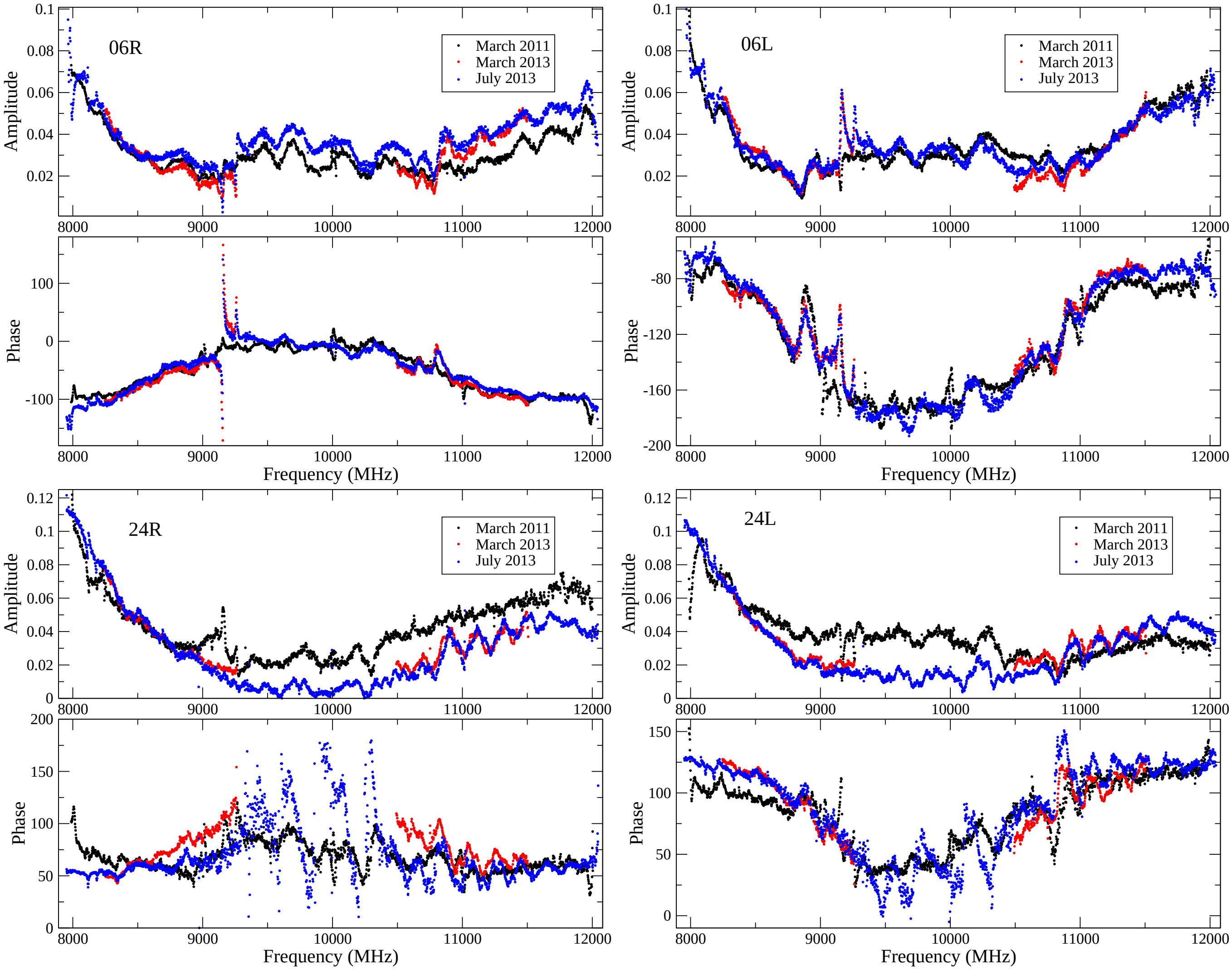

Figure 5: Amplitude and phase of the cross-polarization for antenna 06 (upper half) and ea24 (lower half) over a 2.4 year span at X-band. March 2011 data are in black March 2013 in red, and July 2013 in blue. Changes for ea06 are generally less than 1% and 10 degrees, but a larger change in ea24 is seen between the early and later observations.

similar to that at the lowest two frequency bands. However, ea24 clearly had a significant change, primarily in its cross-polarization amplitude between March 2011 and March 2013. The last two observations are in excellent agreement. The apparently unstable phase for ea24R in July 2013 is a result of the very low cross-polarization amplitude – less than 1%.

5 Discussion and Conclusions

Variations over timescales of days are completely negligible at L and S bands. Examination of our data at C and X bands show similarly minor changes over these short timescales.

Over the more interesting timescales of months to years, variations at L, S, and (probably) X-band, are certainly small enough (1 – 2% and 10 – 20 degrees) that a regimen of occasional accurate measurement of the antenna cross-polarizations should be sufficient, for most observational programs, to permit polarization calibration to be done using recorded values. We see higher (but not high) changes in C-band, but note that with the quadrature hybrids at that band being replaced with a more stable design, more stable performance might be obtained. This will clearly need to be investigated in future years.

Although there are as yet no measurements to prove this, we believe that the high-frequency bands will prove to be more stable than the low frequency bands, due to their usage of extremely stable microwave devices to form the circular polarization signals.

Polarimetric programs requiring higher accuracy than $\sim$1% should still determine the antenna cross-polarizations from the data taken for such programs. Accurate polarization calibration generally requires long scheduling blocks – this must be kept in mind by users requesting highly accurate polarimetry.

We emphasize that the stability shown here is that of the antenna and the front-end electronics. We make no statement about the stability of the R-L phase – which is determined by the IF electronics. There are indications from other work that changing frequency bandd during an observation can introduce changes in the R-L phase of ten degrees or more. This translates into a rotation of the polarization frame of half the phase change.

Although we expect the off-axis polarization characteristics of the antennas to be stable, no observations have yet been made to demonstrate this. Additionally, although we expect changes in off-axis polarization at the higher frequencies to be a simple function of elevation, there are no measurement to show this.

Finally, because fringe winding greatly reduces the effects of RFI, we strongly recommend that further polarimetric observations for the purpose of tracking antenna performance be conducted in the ‘A’ configuration.