SMA Technical Memo #160 (Revision 1)
Calibrating Dual Rx Polarization Data

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The SMA can measure the polarization of astronomical sources in two ways. If only one receiver can be tuned to the desired frequency, polarization can be measured in single receiver polarization mode (hereafter SRxM). If two receivers, with orthogonal linear polarizations, can be tuned to the desired frequency simultaneously, then dual receiver polarization mode can be used (hereafter DRxM).

In both SRxM and DRxM, 1/4 waveplates are inserted into the optical path, to convert the linear polarization of the waveguide receiver into circular polarization on the sky. These waveplates can be rotated to provide RCP or LCP sensitivity. Rotating the plates takes about 1 second.

In SRxM, the waveplates must be rotated frequently, following a walsh pattern, in order to measure all four combinations of waveplate orientations on each baseline, in the shortest possible time. Each scan from the correlator contains only one of the four possible combinations, RCP×RCP, RCP×LCP, LCP×RCP or LCP×LCP (hereafter RR, RL, LR or LL) on each baseline.

In DRxM, the correlator is configured to measure all four correlation products simultaneously. So, if the 345 and 400 GHz receivers are used for a DRxM observation, each scan taken will result in four scans being stored in the data file, with correlations of 345×345, 345×400, 400×345 and 400×400.

This memo will deal with DRxM only. The only real difference in the data file formats between DRxM and other observations is the use of the ant1rx and ant2rx variables in the baseline structure (the data in the bl_read file). These two variables are used to encode the receiver used on each of the antennas comprising each baseline. For observations in modes other than DRxM, those two variables contain no useful information.

DRxM observations have some unique calibration issues, because this is the only SMA observing mode in which different types of receivers are cross-correlated with each other. It is possible to have no delay error between any of the 345 receivers, and no delay error between any of the 400 receivers, and yet still have a delay error between any 345 receiver cross-correlated with a 400 receiver. For example, if we were to increment the software value for the fiber delays to the 345 receivers by 10 nsec for all pads, that delay change would not show up in observations using only the 345 GHz receivers, because it would be common for all antennas. But it would change the delay between any 345 receiver and any 400 receiver by about one wrap per chunk of the ASIC correlator. There can only be one delay error value between the entire set of 345 receivers, and the entire set of 400 receivers, so measuring the 345x400 delay on a single baseline is adequate to characterize this delay for the entire array.

If the 1/4 wave plates in each antenna are in the same state (R or L), then looking at a strong continuum source will produce a strong detection in the 345x345 and 400x400 spectra, but only a very weak detection in the 345x400 and 400x345 terms, because of the orthogonal polarization states of the two antennas for those receiver pairs. Therefor, we must take some data with the waveplates in different orientations on pairs of antennas, in order to make the 345x400 and 400x345 spectra correspond to the matched polarization (RR or LL) data, which then puts a strong signal in those cross-receiver spectra, allowing the cross receiver delay to be measured, and allowing any phase drift between the receiver sets to be tracked in time.

By convention, when we take data for which the 1/4 wave plates are not all in the same state, we change the source name to something like SOURCE_LR. This is done merely to make it easier to segregate the data during data reduction, and also to facilitate plotting the different waveplate states with different colors. Usually two antennas are placed in the different polarization state. Figure 1 shows the corrPlotter display for a typical DRxM track (150620_04:25:30). Instrumental polarization was measured by tracking 3C279. When the waveplates were not aligned on all antennas, the source name was changed to 3C279_LR. For the complex gain calibration of the science source, the QSO 1927+739 was observe in the waveplate aligned state, and the 1927+739_LR state.

Figure 1

It is important to remember that in DRxM, any particular polarization product can be produced by any pair of receivers. In other words, the RR product (for example) can be produced from the 345x345, 345x400, 400x345 or 400x400 correlator output, depending on what the waveplate orientation was on a particular baseline for a particular scan. These differing ways of producing the same polarization state must be calibrated separately, because the bandpass shape for the RR polarization produced by correlating two 345 receivers will not be the same as the bandpass shape of the same polarization product produced by correlating the 400 receivers.

In MIR, the first step for calibrating DRxM polarization data is to execute the pass_cal_pol routine. This routine calculates antenna-based bandpass shapes from the 345x345 and 440x400 data, and then calculates the

bandpass shapes for 345x400 and 400x345 data. It thereby corrects for the bandpass shape on all four receiver combinations on each baseline.
Since it always produces an antenna-based solution, the tel_bsl switch used by pass_cal is ignored, and a reference antenna must be selected. Only the 345x345 and 400x400 bandpass shapes are plotted. For example, for the track plotted in figure 1, we could use

```
IDL> pass_cal_pol, refant=2, smoothing=1, preavg=4, ntrim=1
These are the sources and their current passband codes
name:  3C279_LR         passband cal: NO
name:  3C279            passband cal: YES
name:  titan            passband cal: NO
name:  1927+739_LR      passband cal: NO
name:  1927+739         passband cal: NO
name:  L1157            passband cal: NO
name:  neptune          passband cal: NO
name:  3c454.3_LR       passband cal: NO
name:  3c454.3          passband cal: YES
Enter source and new cal code. eg: 3C273 YES
```

Note that the reference antenna does not need to be one of the antennas whose orientation was switched when the SOURCE_LR data was taken. Any antenna can be the reference antenna. This command will produce bandpass plots like the one shown in figure 2, for the 345 and 400 receivers. The preavg value vector averages sets of channels before a solution is derived.

If you get error messages like this

```
No convergence at 345 u s23 channel      53
All gains are set to 1.0 (no corrections!)
```

you should try using a different reference antenna or increasing the preavg value.

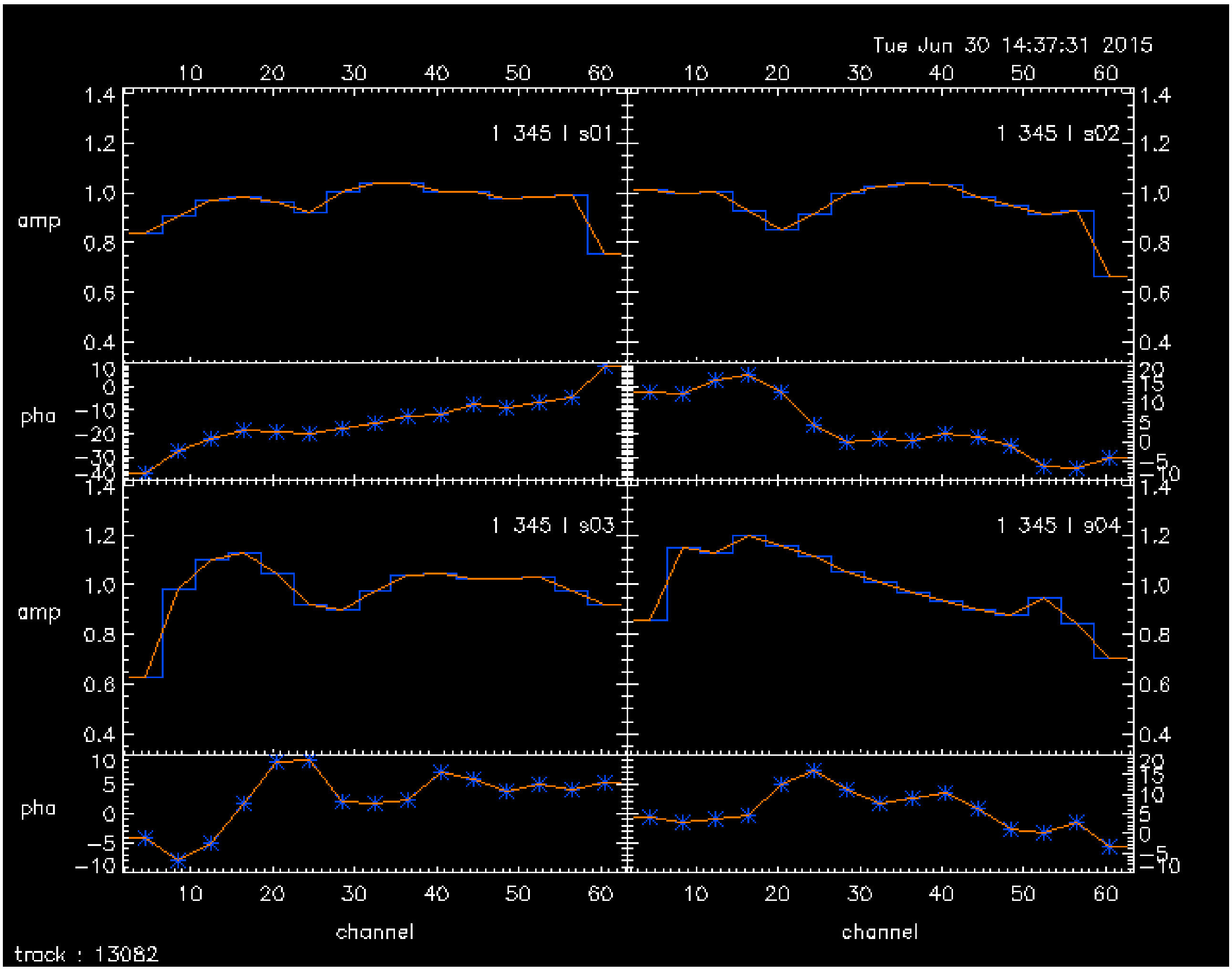

Figure 2

The next step is to correct the chunk offsets and delay errors for the cross receiver (345x400 and 400x345) terms. In MIR, the command to do that could be

IDL> uti_xdelay,reference='3C279_LR',preavg=4,ntrim=1

which will produce plots of the phase ramps in the 345x400 and 400x345 terms, along with a linear fit, as shown in figure 3:

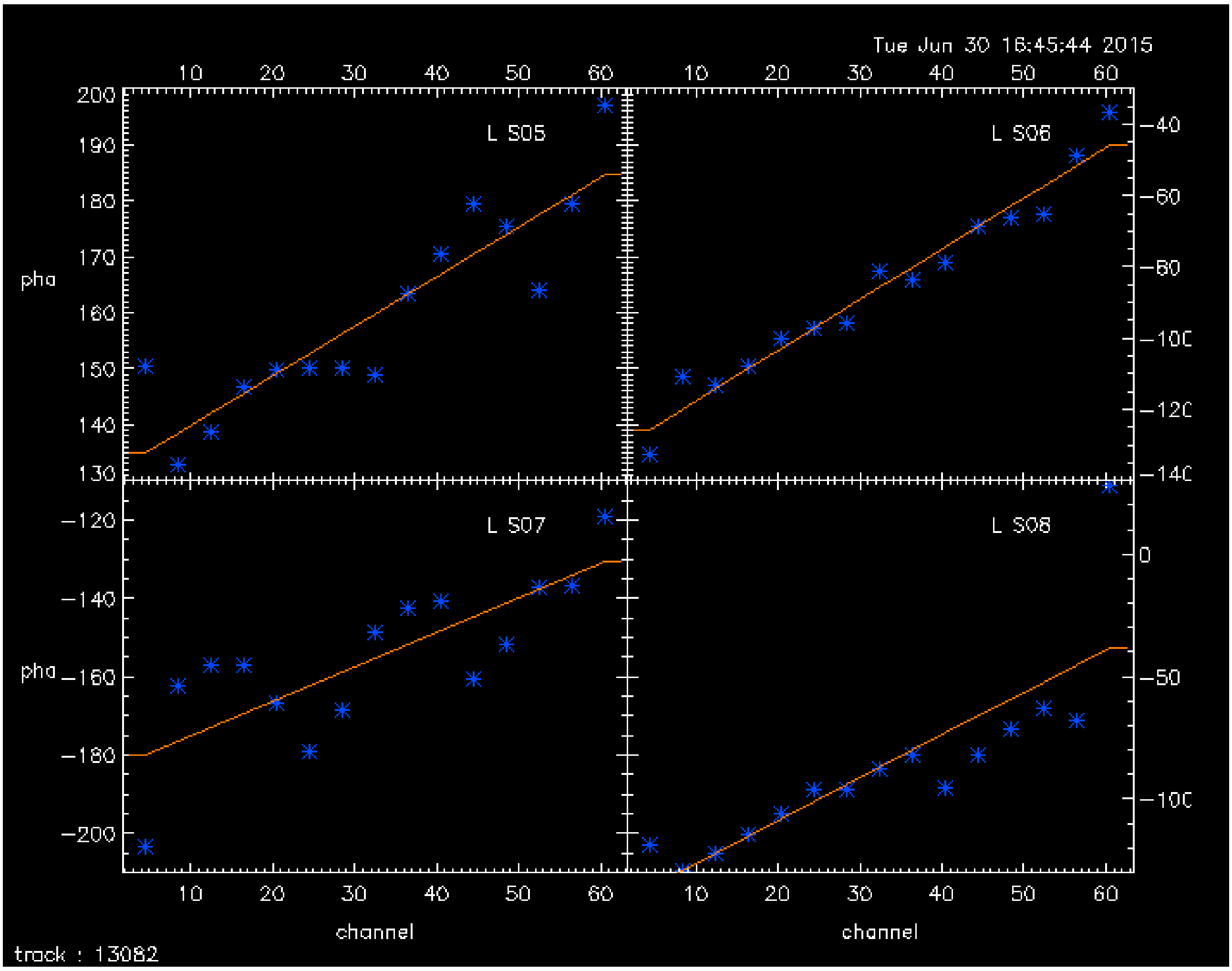

Figure 3

At this point, the different correlator chunks should be able to be vector averaged coherently, so we can rebuilt the pseudo-continuum channel with the command

IDL> uti_avgband

now we can plot the pseudo-continuum, and see the effect of rotating the waveplates for the SOURCE_LR scans. For the track we've been looking at, antennas 1 and 3 were the ones whose waveplates were rotated before the SOURCE_LR scans were taken. So for the 3C279 data, baseline 1-3 shows the same amplitude signal for 3C279 and 3C279_LR, because the waveplates on antennas 1 and 3 always have the same orientation. Let's plot just the 345x345 data for 3C279 on baseline 1-3:

```
IDL> select,/re,/po,sideband='u',source='3C279',baseline='1-3'
IDL> result=dat_filter(s_f,'"ant1rx" eq "0" and "ant2rx" eq "0"')
IDL> plot_continuum,frames=1
```

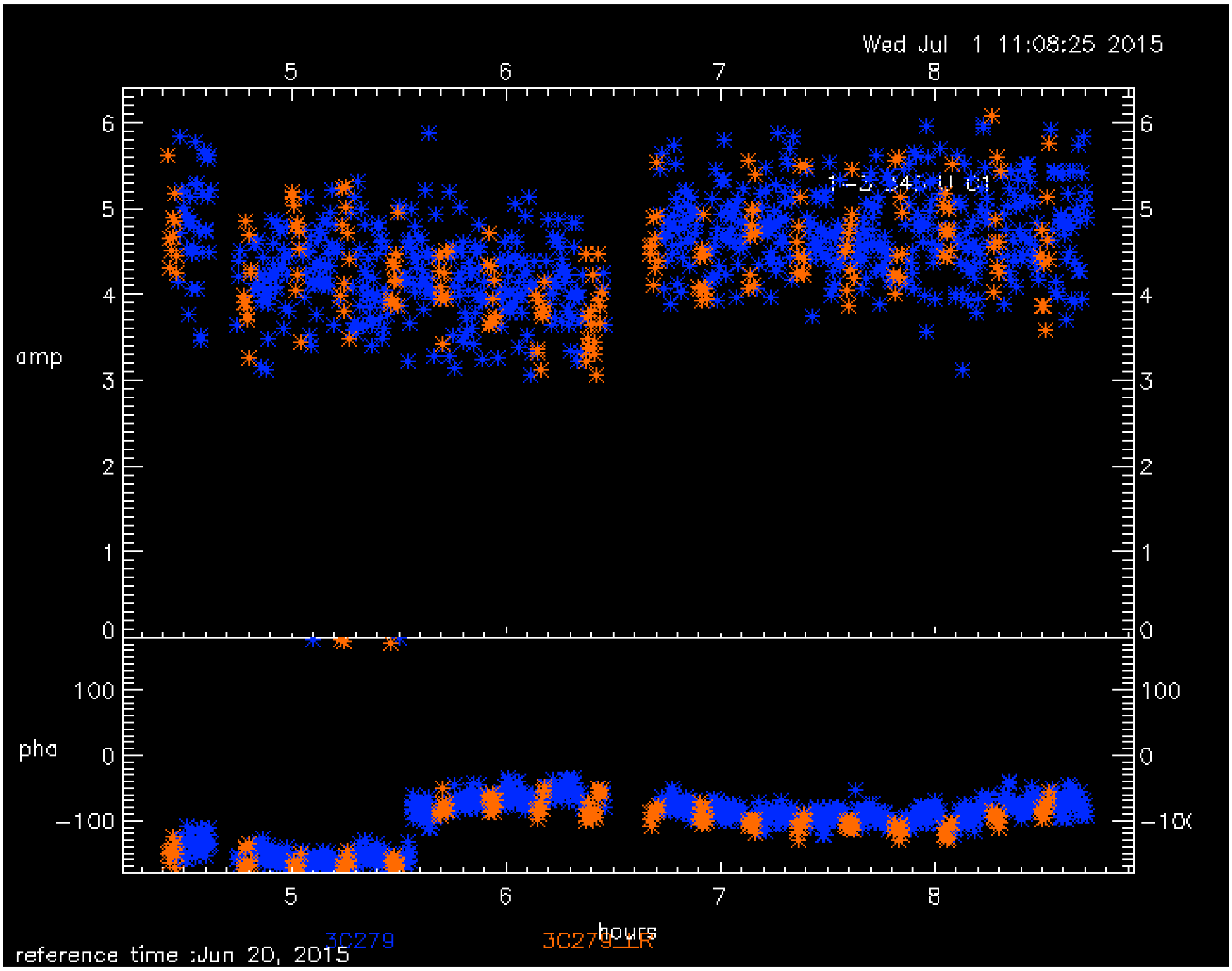

Figure 4

The dat_filter command above is the one which specifies the 345x345 product. The receivers for the two antennas on the baseline are recorded in the variables antRx1[1] and antRx2. 0 specifies the 345 receiver, and 1 specifies the 400 receiver. Figure 4 shows that the amplitude and phase are the same for 3C279 and 3C279_LR, because their waveplates are always in the same state. Figure 5 shows the same plot for baseline 1-2.

1 Note that antRx1 and antRx2 were called iaq and ibq in "old format data" taken before Nov. 15, 2014

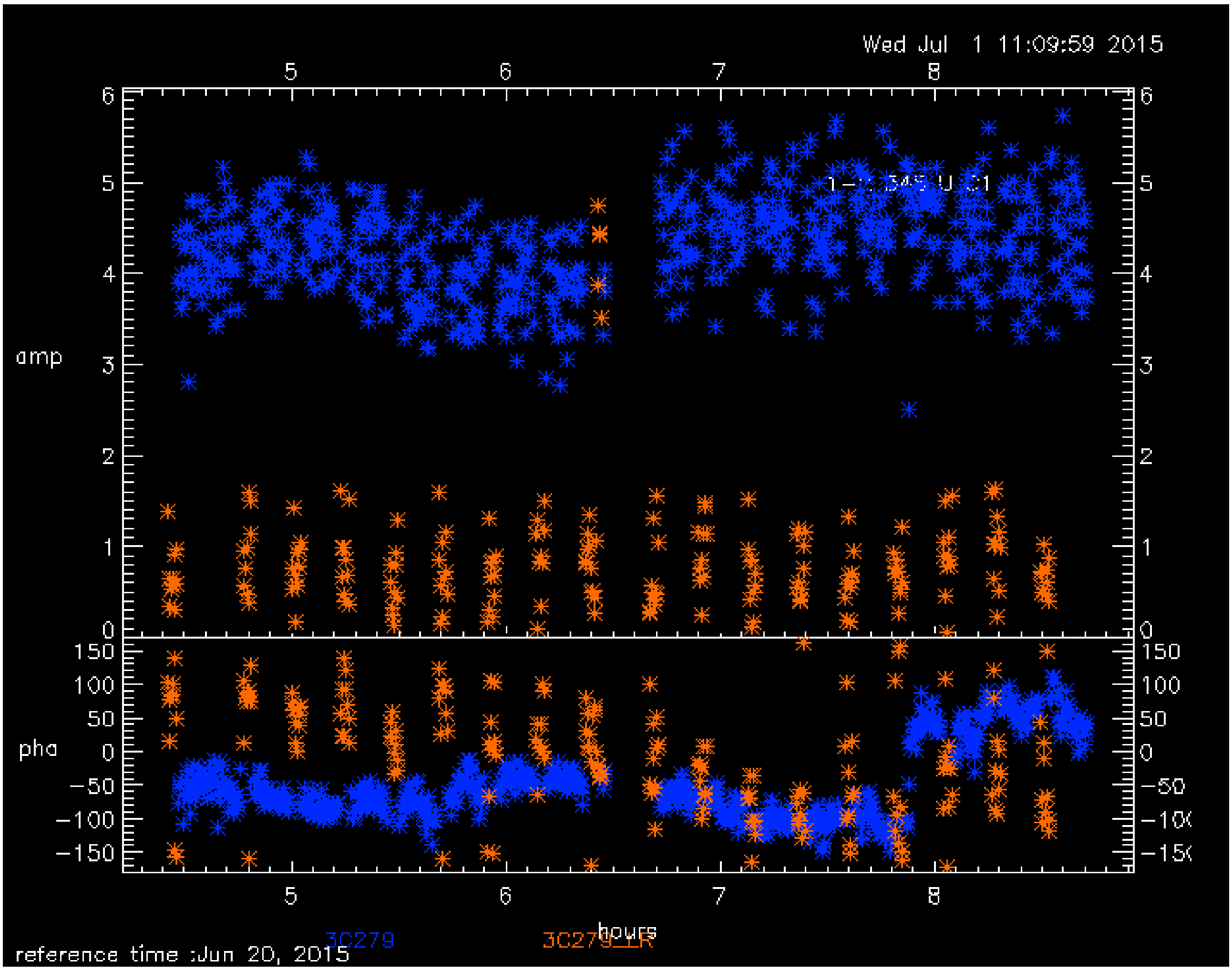

Figure 5

Figure 5 shows that for baseline 1-2, the 345x345 data is much weaker for the 3C279_LR source, because when that source was observed, the waveplates in antennas 1 and 2 were in different orientations, so the 345x345 data corresponds to a cross-polarizations state (in this case, RL).

Figure 5 also shows that four scans taken near UT 6.4 are mislabeled – their amplitudes show they are 3C279 scans, but they are labeled 3C279_LR. These scans, 467 through 470, should be flagged bad. Figure 6 shows the 3C279_LR data for baseline 1-2 after these scans have been flagged out.

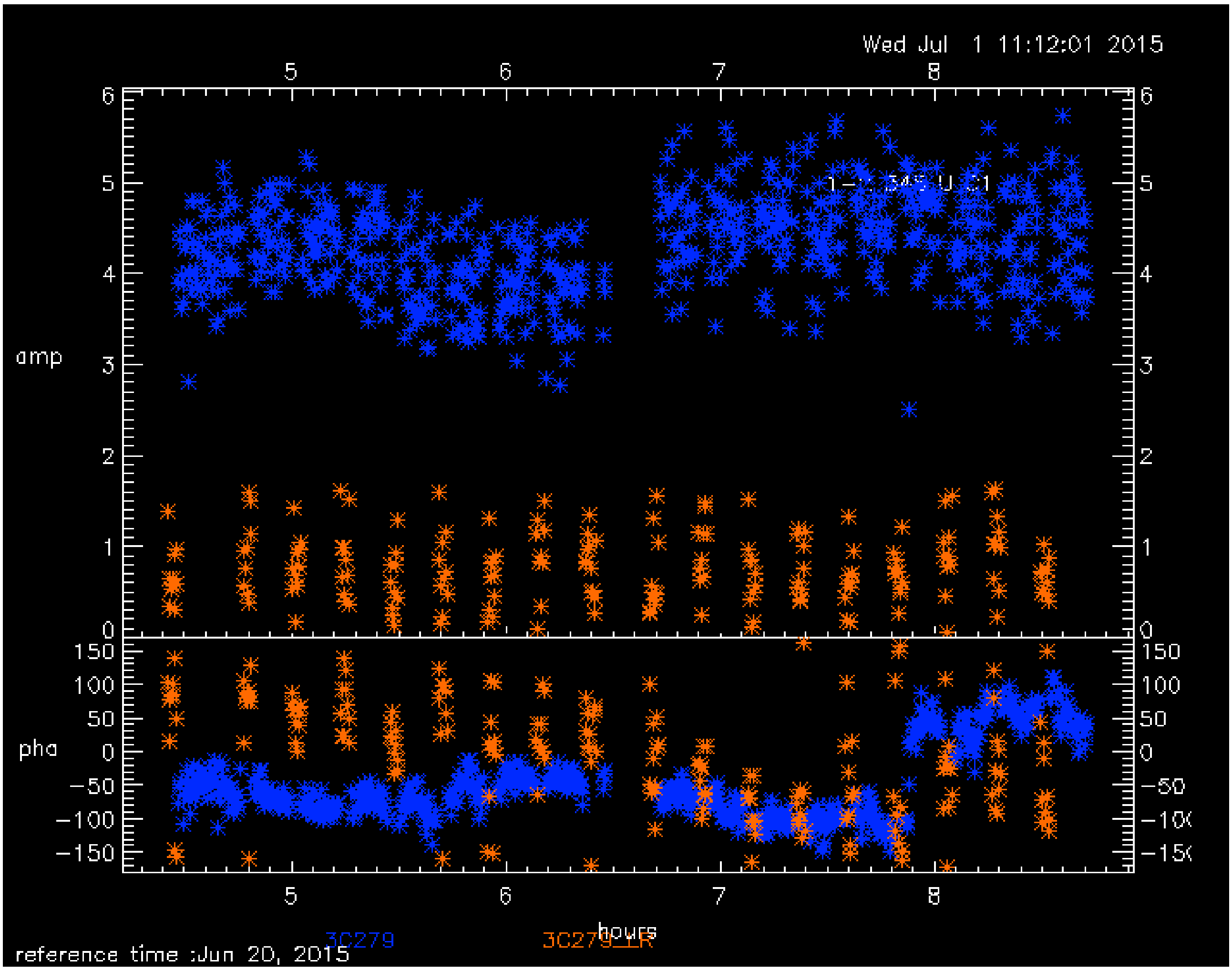

Figure 6

If we select the 345x400 data for baseline 1-2

IDL> select,/re,/po,sideband='u',source='3C279',baseline='1-2'
IDL> result=dat_filter(s_f,'"ant1rx" eq "0" and "ant2rx" eq "1"')
IDL> plot_continuum,frames=1

we get a plot like figure 7, in which the 3C279_LR data shows a higher amplitude than the 3C279 data – the opposite of what is seen in figure 6.

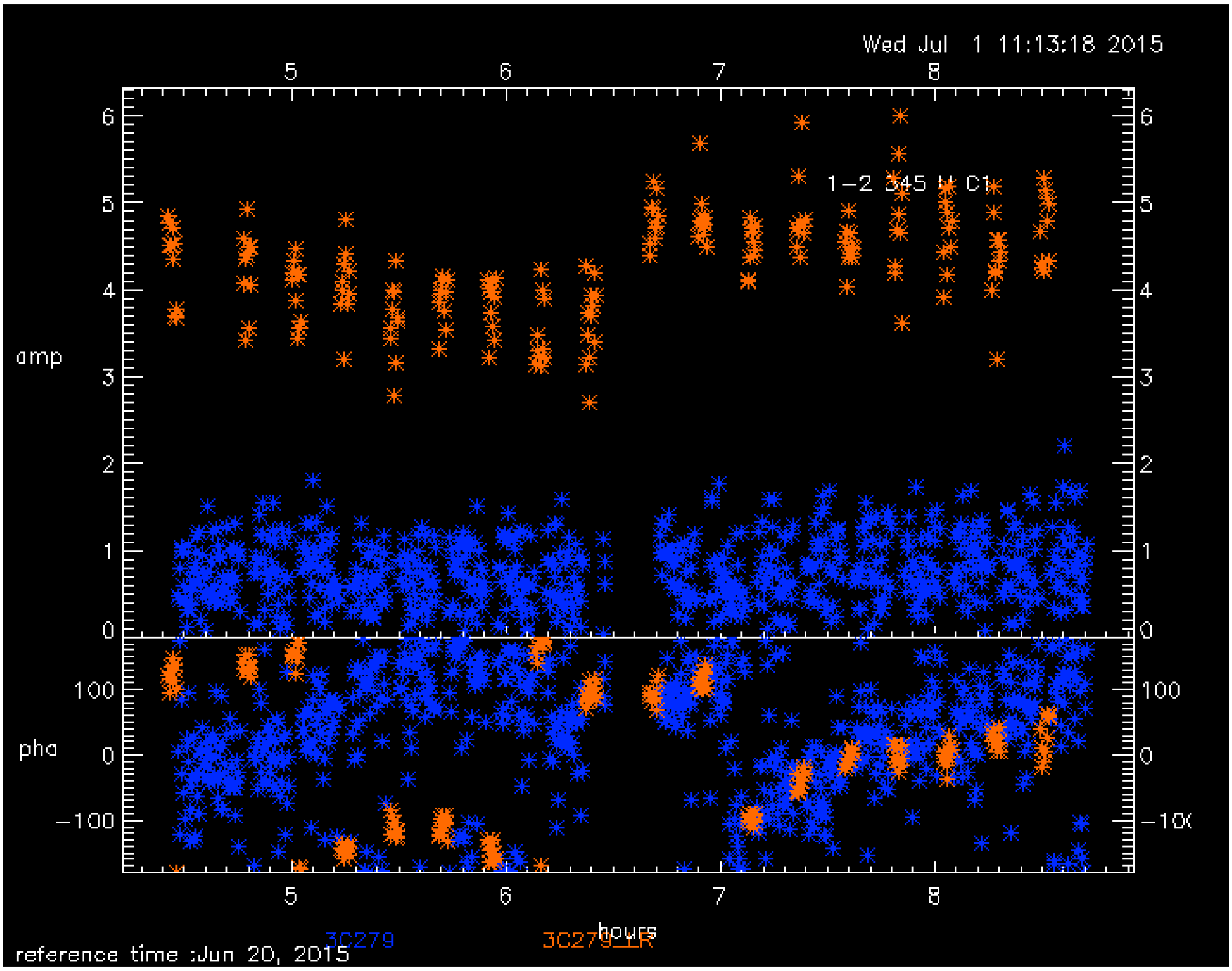

Figure 7

If we self-cal the 3C279_LF data, we can line up the phases, and plot the bandpass of the RR state data (both the 400x400 RR data, such as baseline 1-2 and the 400x345 RR data, such as baseline 1-3). Such a plot is shown in figure 8. It shows that the bandpass is flat across all chunks, even those which were produced by nonaligned waveplate baselines, such as 1-4 and 1-5.

The next step is complex gain calibration. If the script was properly prepared, then the gain calibrator should have been observed in both the SOURCE and SOURCE_LR waveplate configurations throughout the track, so that the phase drift of the set of 345 receivers relative to the 400 receivers could be tracked in time. The MIR task gain_cal_pol will perform antenna-based complex gain calibration for the 345x345 and 400x400 receiver pair combinations.

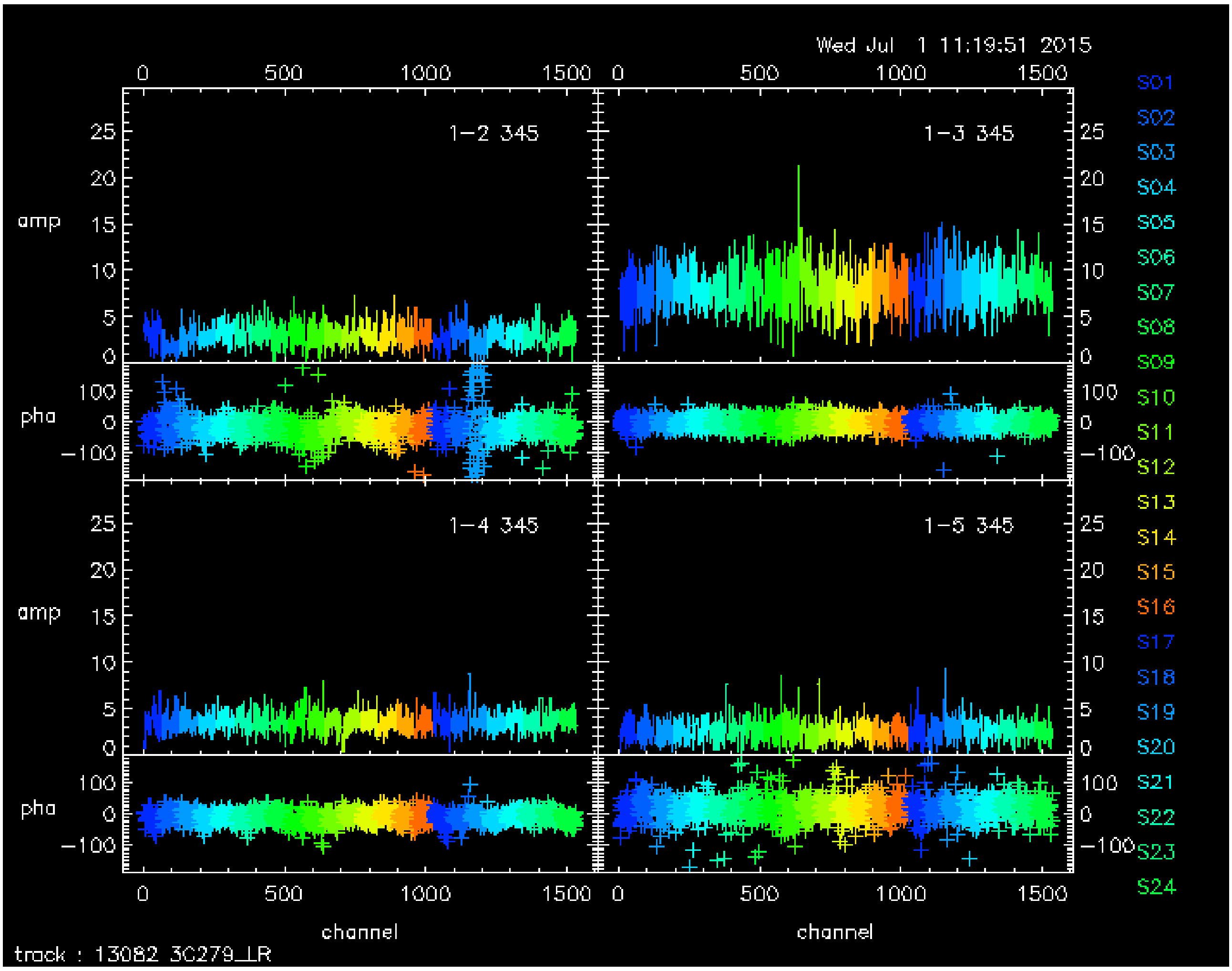

Figure 8

gain_cal_pol generates solutions for 345 and 400 receivers (using only the RR and LL polarization states, which have the strong signal) and applies the solutions to the 345x345 and 400x400 data. Then for the mixed rx data, based on the order of the receivers used for each baseline, gain_cal_pol also generates gain solution using the antenna-based gain solutions for Rx 345 and Rx 400 derived above and applies them to the 345x400 and 400x345 data.

As with pass_cal_pol, a reference antenna must be selected, and the tel_bsl switch used by gain_cal is ignored.   gain_cal_pol produces plots of the complex gain, like the one shown in figure 9.

```
IDL> gain_cal_pol, refant=2, x='hours',smoothing=0.3
These are the sources and their current gain codes
name:  3C279_LR          gain code: NO   flux (Jy):    0.0000000
name:  3C279             gain code: NO   flux (Jy):    0.0000000
name:  titan             gain code: NO   flux (Jy):    0.0000000
name:  1927+739_LR       gain code: YES  flux (Jy):    1.3200001
name:  1927+739          gain code: YES  flux (Jy):    1.3200001
name:  neptune           gain code: NO   flux (Jy):    0.0000000
name:  3c454.3_LR        gain code: NO   flux (Jy):    0.0000000
name:  3c454.3           gain code: NO   flux (Jy):    0.0000000
Enter source, cal code, and if cal, flux in Jy, eg: 3C273 YES 3.1
```

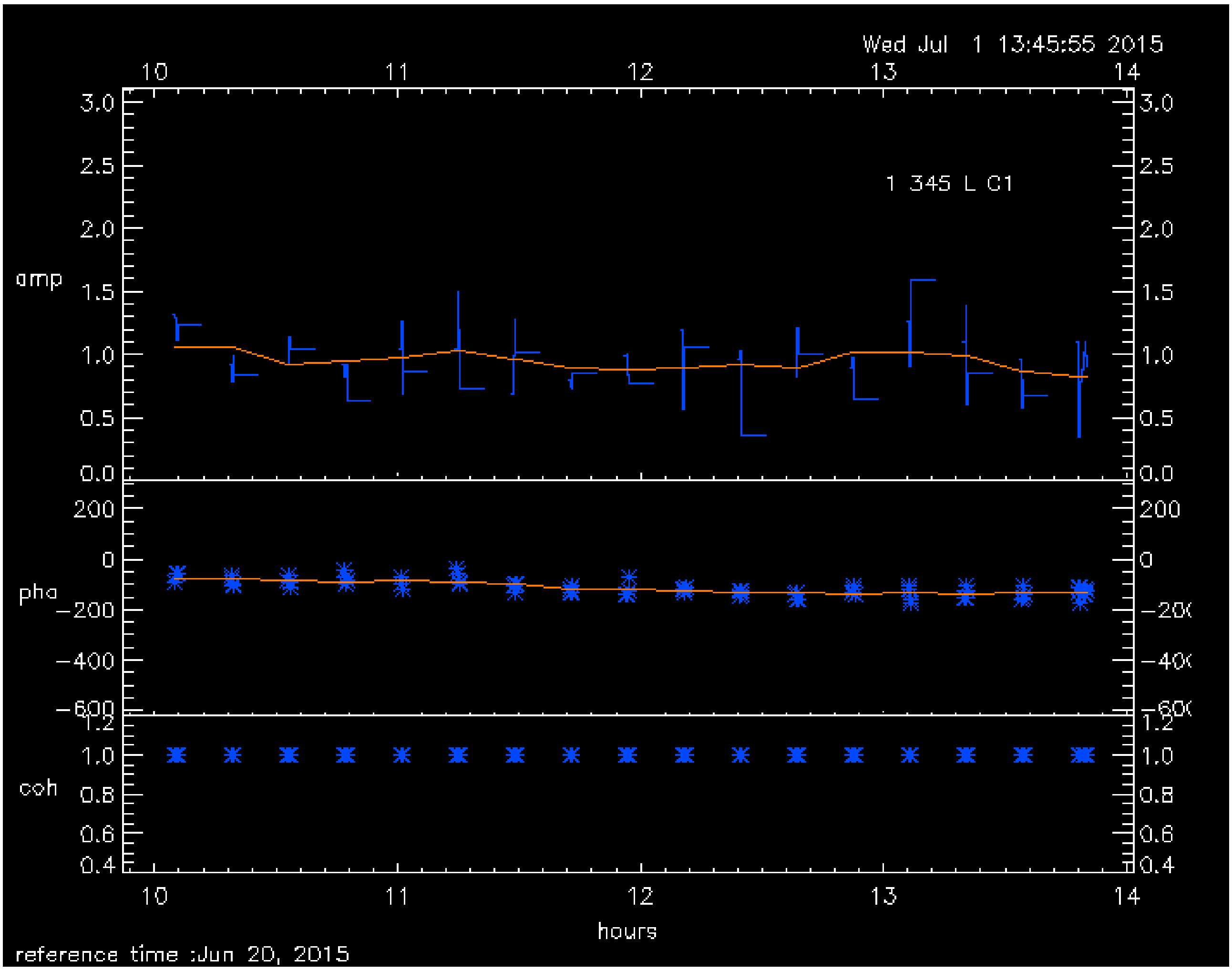

Figure 9

As the last step, we can use the MIR task uti_xgain to derive the 345x400 and 400x345 correlation product gains. This corrects for a phase-only drift between the set of 345 receivers and the set of 400 receivers. All baselines a vector averaged, to improve signal/noise, because there can be only one common phase drift between the sets of receivers.

```
IDL> uti_xgain,x='hours',/preavg,smoothing=0.3
name:  3C279_LR        gain code: NO   flux (Jy):      0.0000000
name:  3C279           gain code: NO   flux (Jy):      0.0000000
name:  titan           gain code: NO   flux (Jy):      0.0000000
name:  1927+739_LR     gain code: YES  flux (Jy):      1.3200001
name:  1927+739        gain code: YES  flux (Jy):      1.3200001
name:  L1157           gain code: NO   flux (Jy):      0.0000000
name:  neptune         gain code: NO   flux (Jy):      0.0000000
name:  3c454.3_LR      gain code: NO   flux (Jy):      0.0000000
name:  3c454.3         gain code: NO   flux (Jy):      0.0000000
Enter source, cal code, and if cal, flux in Jy, eg: 3C273 YES 3.1
```

The uti_xgain command produces plots like the one shown in figure 10. Only one baseline is plotted, because there can only be a single drift in phases of all of the 345s relative to all of the 400s, since the earlier gain calibration of the 345x345 and 400x400 products will have removed any gain fluctuations between members of the two receiver sets.

This concludes the set of calibration steps which are unique to the DRxM observations.

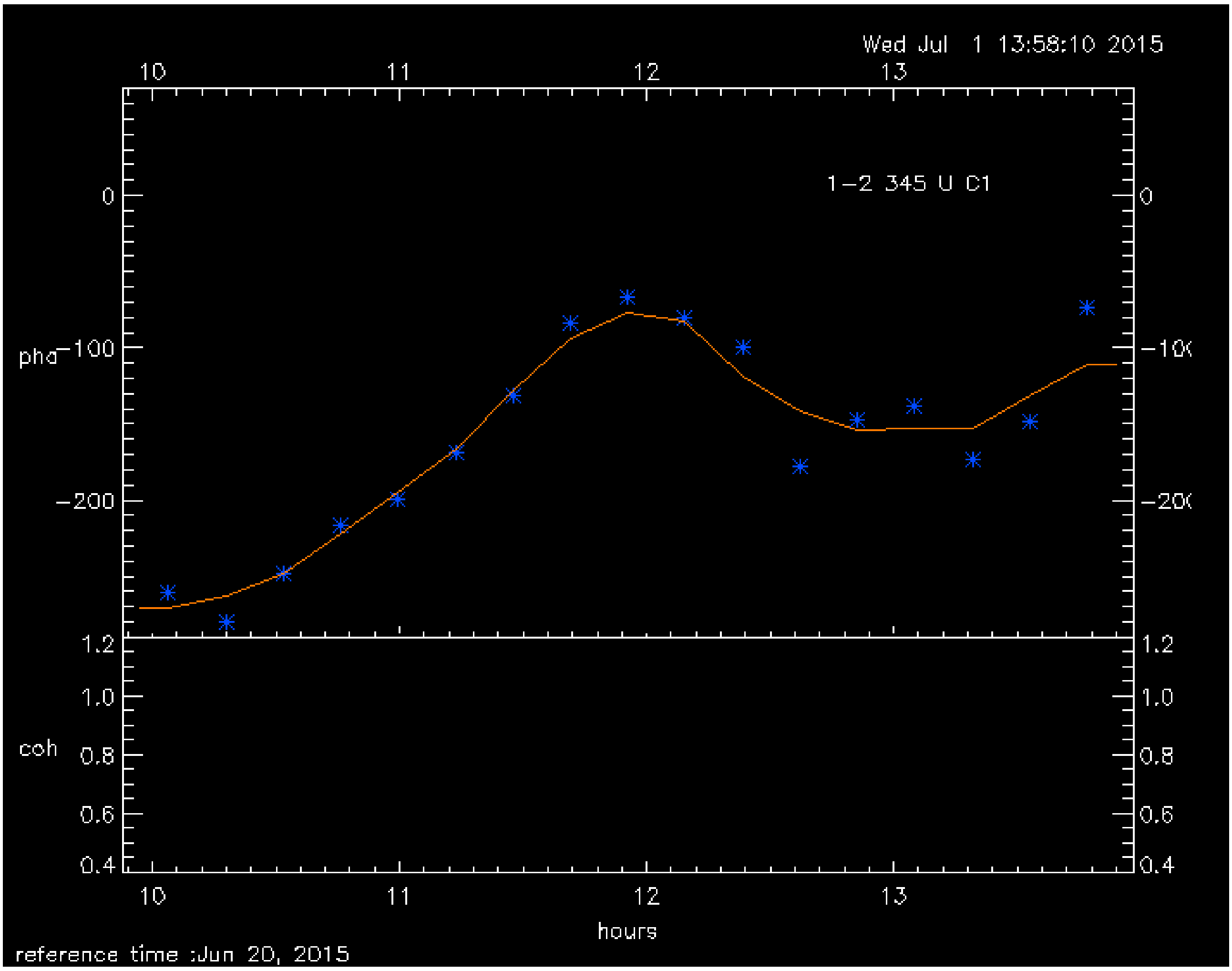
Wed Jul 1 13:58:10 2015
10
11
12
13
1-2 345 U C1
0
pha
-100
-200
1.2
1.0
coh
0.8
0.6
0.4
hours
reference time :Jun 20, 2015

Figure 10