BBDEV. MEMO #021
2008 June 12

To: VLBI2010 Broadband Development Group

From: Brian Corey

Subject: Phase cal performance during 2008 May 23 GGAO-Westford BBD test

The purpose of this note is to provide detailed information about the phase cal behavior during the last 80 minutes of the May 23rd test, after the 1/20-Hz modulation disappeared.

1. Phase cal data

The phase cal amplitudes and phases plotted in figures 9 and 10 in my June 8 overview of the correlator data were averages over entire scans. As a result, some very interesting amplitude and phase variations got washed out.

The phases and amplitudes presented in this memo are 20-second coherent averages spaced one minute apart. The integration time is short compared with the time scales of any significant phase drift, so the amplitudes are not affected by coherence loss. The pcal parameters were obtained by fringe-fitting each scan ten times with different start and stop epochs spaced a minute apart and then extracting the parameters from the type-2 files with aedit. Each start (stop) epoch was 5 (25) seconds after a minute mark.

The pcal parameters shown in the plots here are all for the 4-MHz baseband tone. The frequency channels are numbered in increasing frequency order. The RF frequency of each pcal tone is 8636 + (channel# - 1) * 64 MHz.

Figures 1-14 all have the same general layout. Each figure shows data for one station, with GGAO data in odd-numbered figures and Westford in even. The lefthand panels are L (or V) pol, the righthand R (or H) pol. RF frequency increases from top to bottom.

2. Amplitude and phase time series

Figures 1 and 2 show the amplitude time series, and figures 3 and 4 the phase.

The amplitudes exhibit sizeable and, in some cases, distinctly periodic variations. What is most striking, however, is the phase behavior: the phases vary cyclically by 70-90º with a period of ~25 minutes in all eight channels for both polarizations *at both stations*. The cyclic behavior is a tad unusual in itself, but the similarity in the phase plots between the two stations is amazing. Not only are the waveforms similar, but they are nearly synchronized as well!

The logical explanation for this surprising result is that I got the data mixed up and that figures 3 and 4 are for the same station. Two facts argue against this hypothesis and for the reality of the similarities between GGAO and Westford:

1. Like snowflakes, no two of the 32 panels in figures 3 and 4 are identical, so I did not simply copy the data from one station to the other.

2. The pcal phases plotted at the bottom of the fringe plots vary in the same way as the phases in the figures. Within each scan, the general trends (though not the details) of the GGAO and Westford phases are the same, as they increase, hold steady, or decrease together.

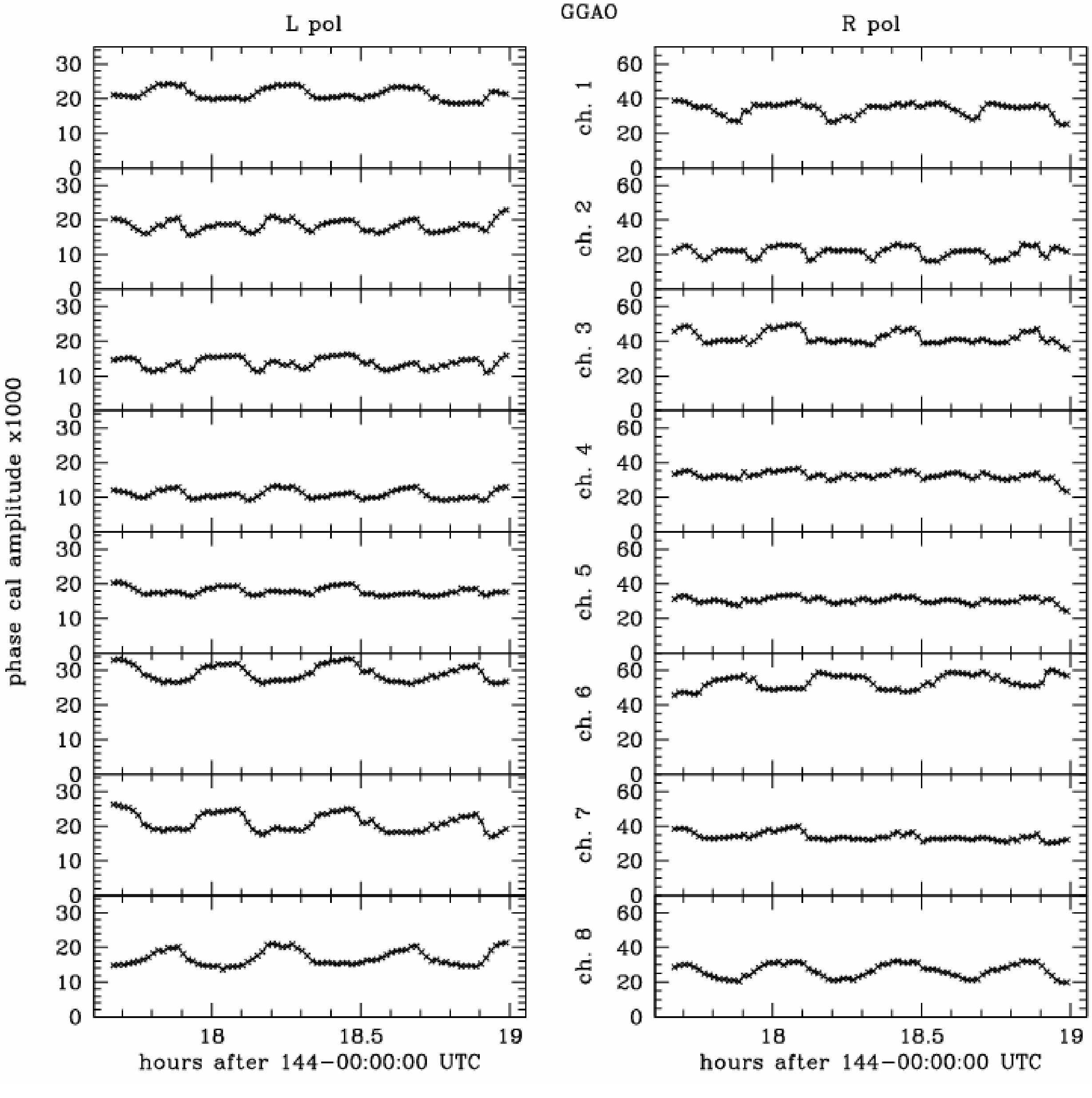

Figure 1. GGAO phase cal amplitudes vs. time. Vertical scales for the L-pol plots on the left are all the same (0-35), as they are for the R-pol plots on the right (0-70).

Further reassurance that the pcal phases extracted at the correlator and reported by fourfit are not jumbled up is provided by the presence of a 5-6 minute offset (corresponding to roughly a quarter of the oscillation period) between the GGAO and Westford phase time series earlier in the session, when the 1/20-Hz modulation was present. It appears the two phase curves gradually drew into sync over the first hour, and that their near synchronism during the last 80 minutes of the session was just a (remarkable!) coincidence.

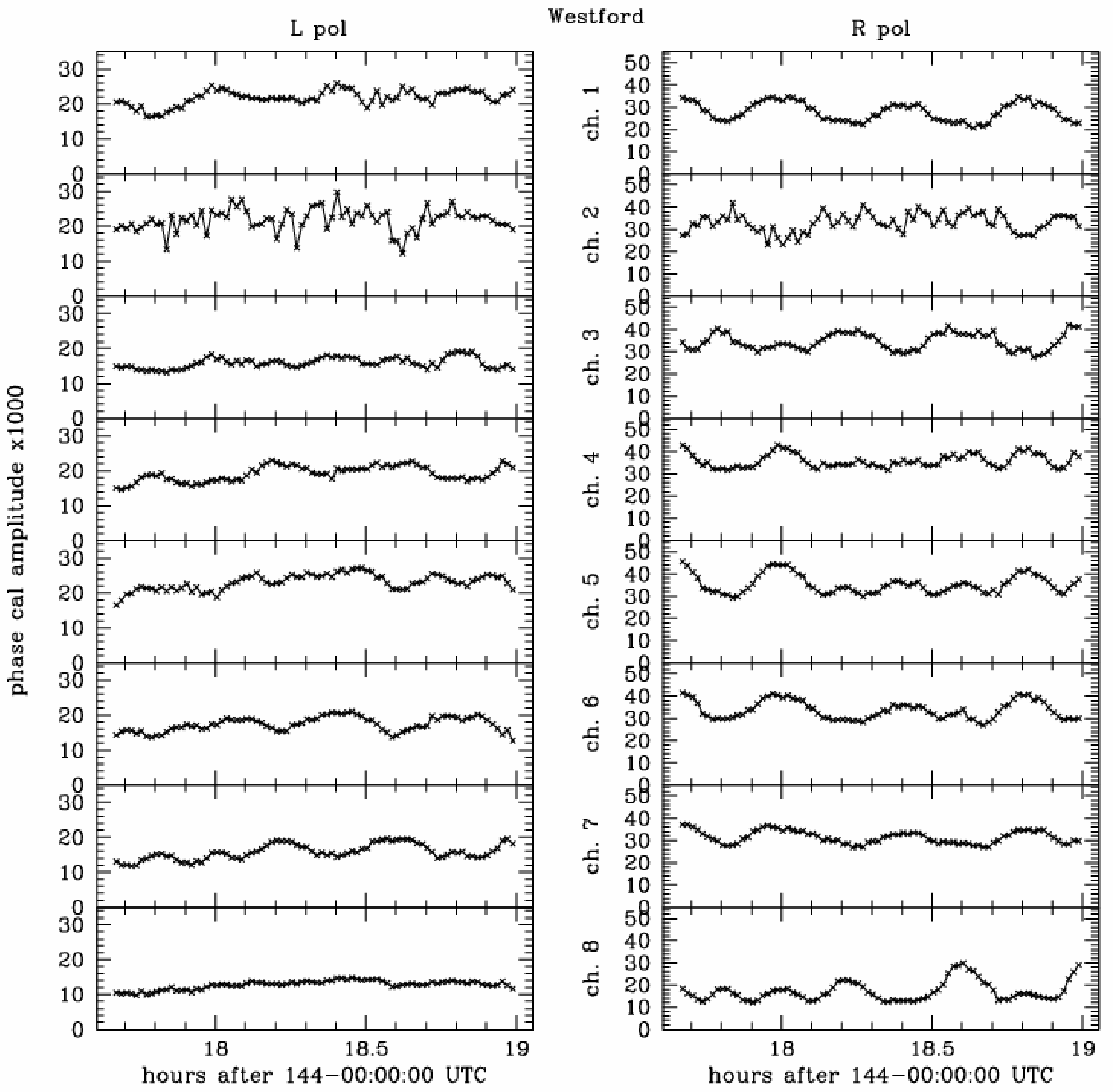

Figure 2. Westford phase cal amplitudes vs. time. Vertical scales for the L-pol plots on the left are all the same (0-35), as they are for the R-pol plots on the right (0-55).

Where might these common-mode phase variations have originated? The phase stability of the pcal antenna unit should be far better than 20-30 ps (which corresponds to 70-90º at 9 GHz) over 10 minutes. The 5 MHz was sent up to the antenna unit over coax at both sites. Cable stretching or bending could conceivably be the cause, but why the periodic pattern at both sites? The likeliest culprits (by process of elimination and because I know little about them!) are the LOs in the UDCs and the fiber links carrying the RF signals down from the receiver. Can anyone rule these either in or out?

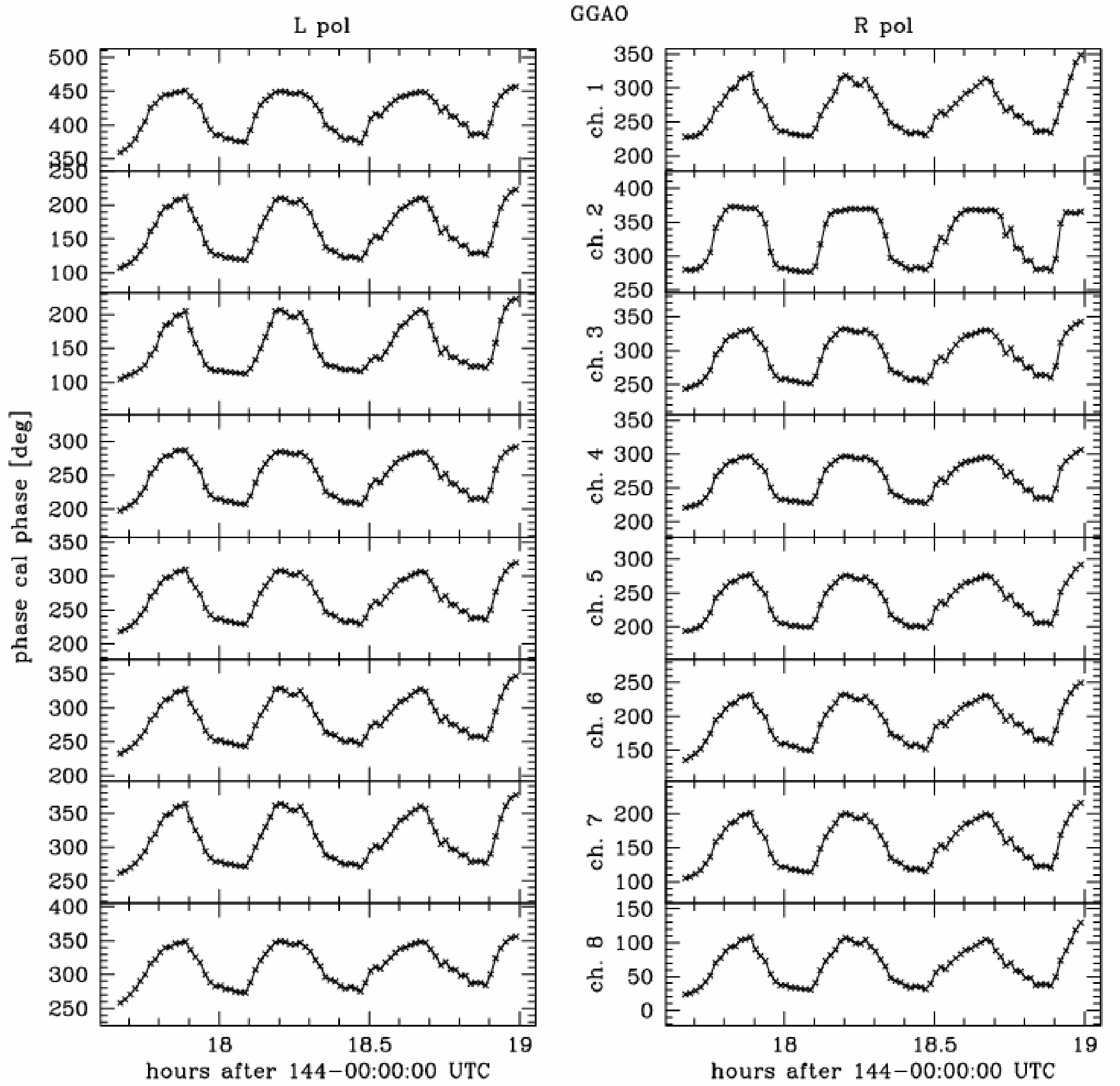

Figure 3. GGAO phase cal phases vs. time. Ordinate max-min span is 180º for all plots.

The fact that the amplitude and phase curves are *not* identical for the eight channels of a given polarization should not be used as an argument against the UDC LO causing the variations. Evidence presented in later sections indicates the presence of spurious signals, which generally differ in their effects from channel to channel.

The "ratty" amplitudes and phases in channel 2 at Westford are probably caused by spurious signals that vary on short time scales, as discussed briefly in the last section.

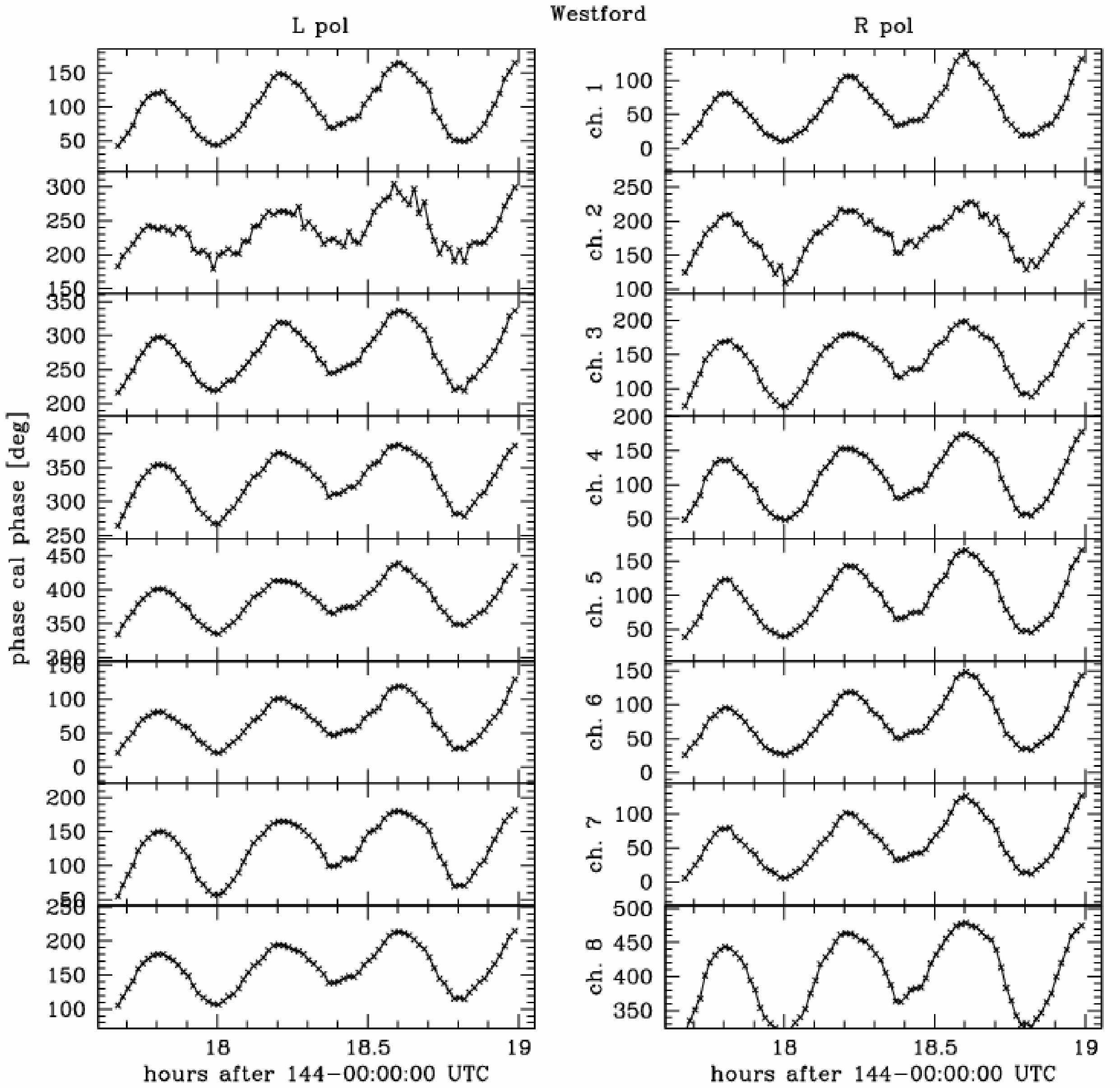

Figure 4. Westford phase cal phases vs. time. Ordinate max-min span is 180° for all plots.

3. Phase differences between channels

A common VLBI data quality test is to compare the fringe or pcal phases between neighboring (in frequency) channels. Figures 5 and 6 show the pcal phase differences. In the absence of spurious signals, the phase cal variations in a DBE-based system should be far smaller than what is observed. The typical pk-pk variations of 20-30º observed between channel pairs are consistent with contamination by spurious signals that would also cause amplitude fluctuations at the levels seen in figures 1 and 2.

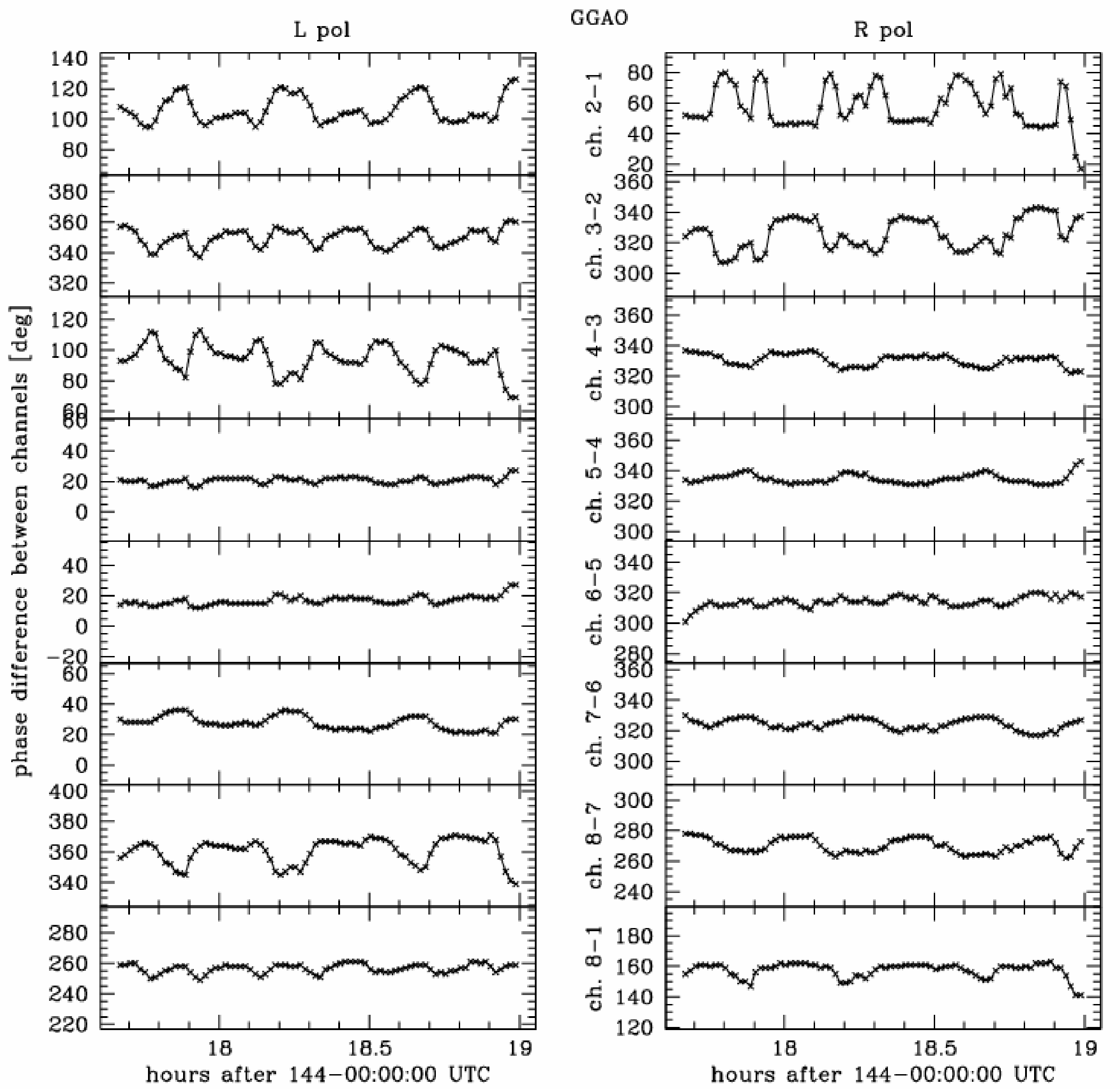

Figure 5. GGAO phase cal phase differences between channels vs. time. Ordinate max-min span is 80º for all plots.

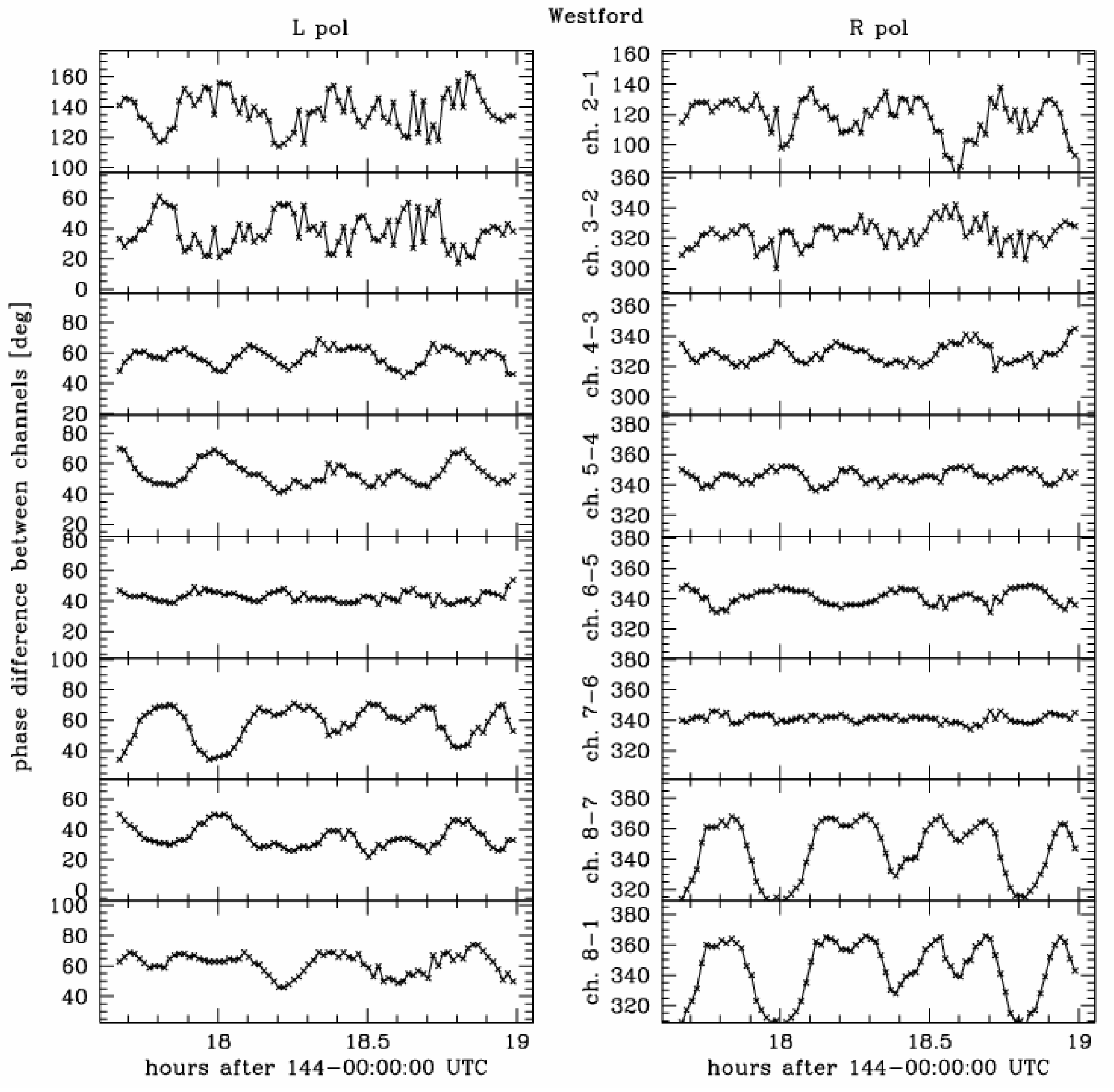

Figure 6. Westford phase cal phase differences between channels vs. time. Ordinate max-min span is 80º for all plots.

4. Channel phases relative to mean phase over all channels

Trying to use figures 5 and 6 to quantify the nature of the spurious signals in the different channels is complicated by having to disentangle which channel of each pair contributes how much phase variation to the difference. An alternative is to construct a pseudo-“absolute” phase reference against which individual channel phases can be compared. I chose to use the average phase over all eight channels of the same polarization as that reference. It will of course be corrupted by spurious signals, just as are most of the individual channels. But on the assumption the corrupting effect on the phase is “incoherent” from channel to channel, those effects should average out somewhat, and the mean phase should be cleaner than the individual channel phases.

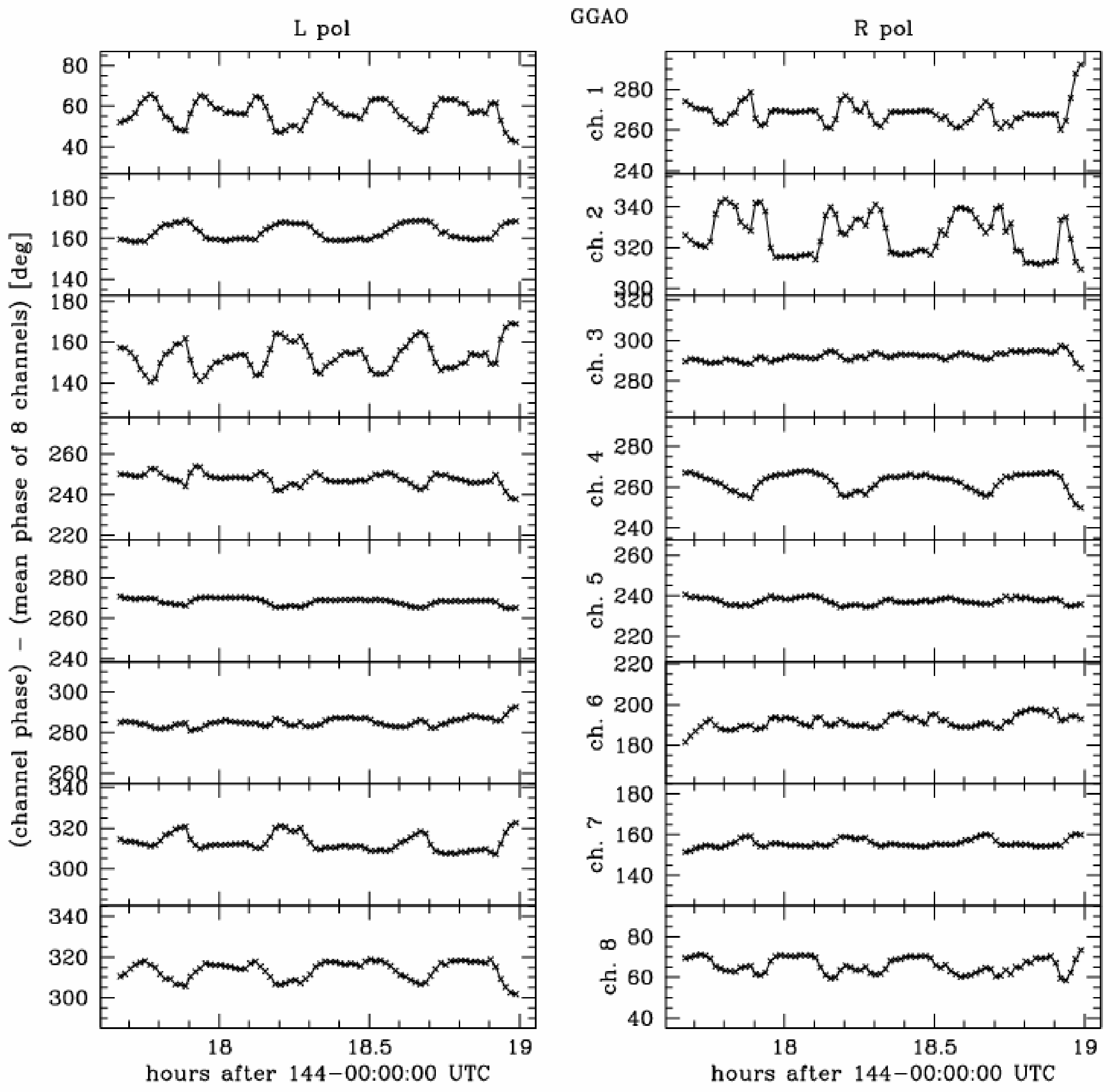

Figure 7. GGAO phase cal channel phase minus mean phase over eight channels vs. time. Ordinate max-min span is 60º for all plots.

In figures 7 and 8 are plotted the channel phase differences relative to the mean phase. Because the assumption of "errors averaging out in the mean" is invalid at some level, and because 1/8th of the channel phase variation is lost when the mean is subtracted from the channel phase, these plots should not be treated as more than qualitative, and perhaps semi-quantitative, guides to what is happening in individual channels.

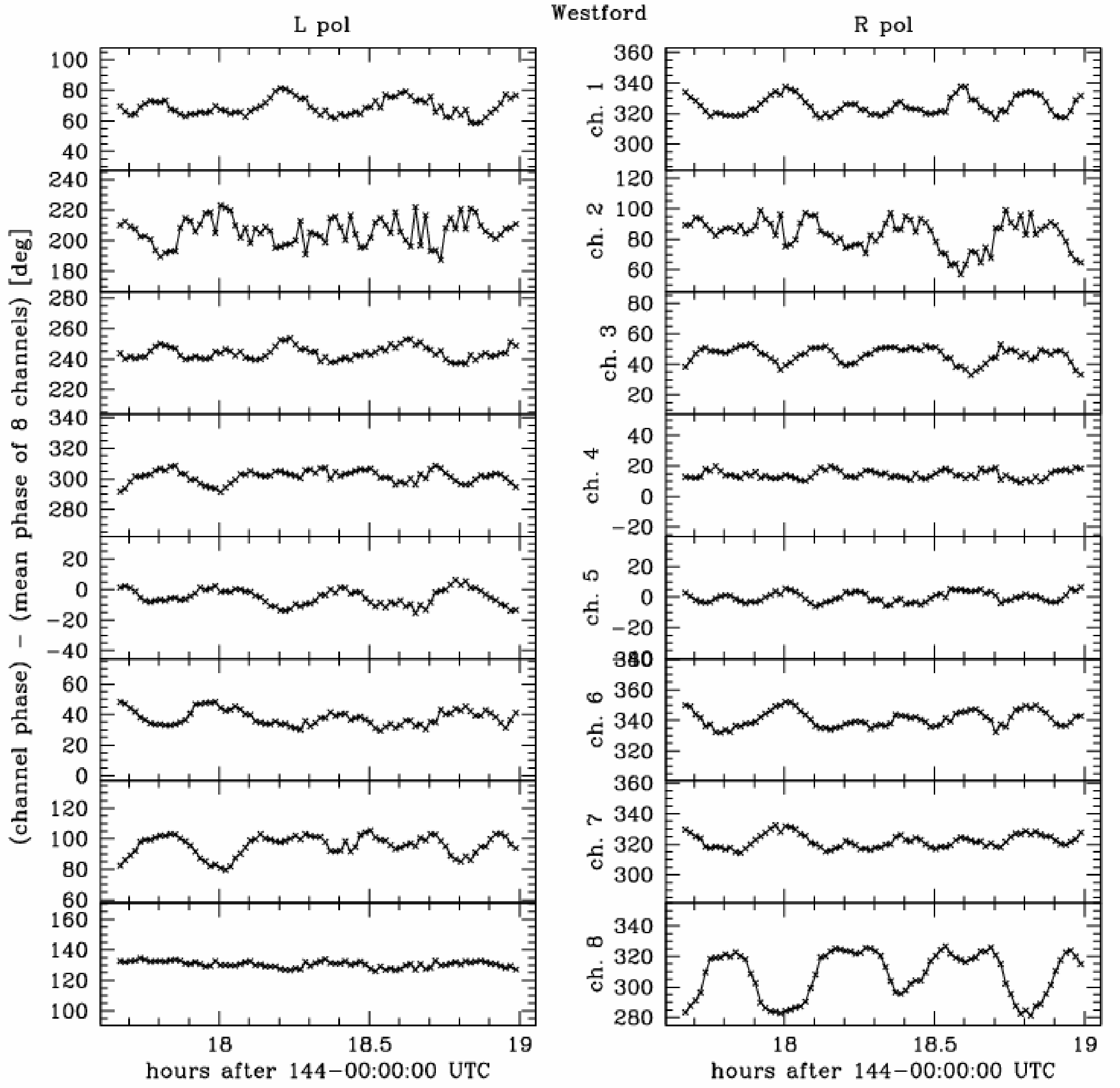

Figure 8. Westford phase cal channel phase minus mean phase over eight channels vs. time. Ordinate max-min span is 80° for all plots.

More interesting than the time series are the plots of phase minus mean vs. the mean phase itself, as depicted in figures 9 and 10. In most cases, there is a tight correlation, which must have persisted over the 3+ cycles of phase variations seen in figures 3 and 4. This behavior is one characteristic of spurious signals. For a garden-variety, constant (in amplitude and phase) spurious signal, the characteristic curve is a single sinusoid over 360º; for a spurious signal at an image frequency, it is a double sinusoid. Unfortunately the total range over which the mean phase varied is less than 130º at both sites, and it is difficult in general to determine definitively whether the plots are single or double sinusoids or something else, although in cases like GGAO R-pol channel 1, it is clearly something else.

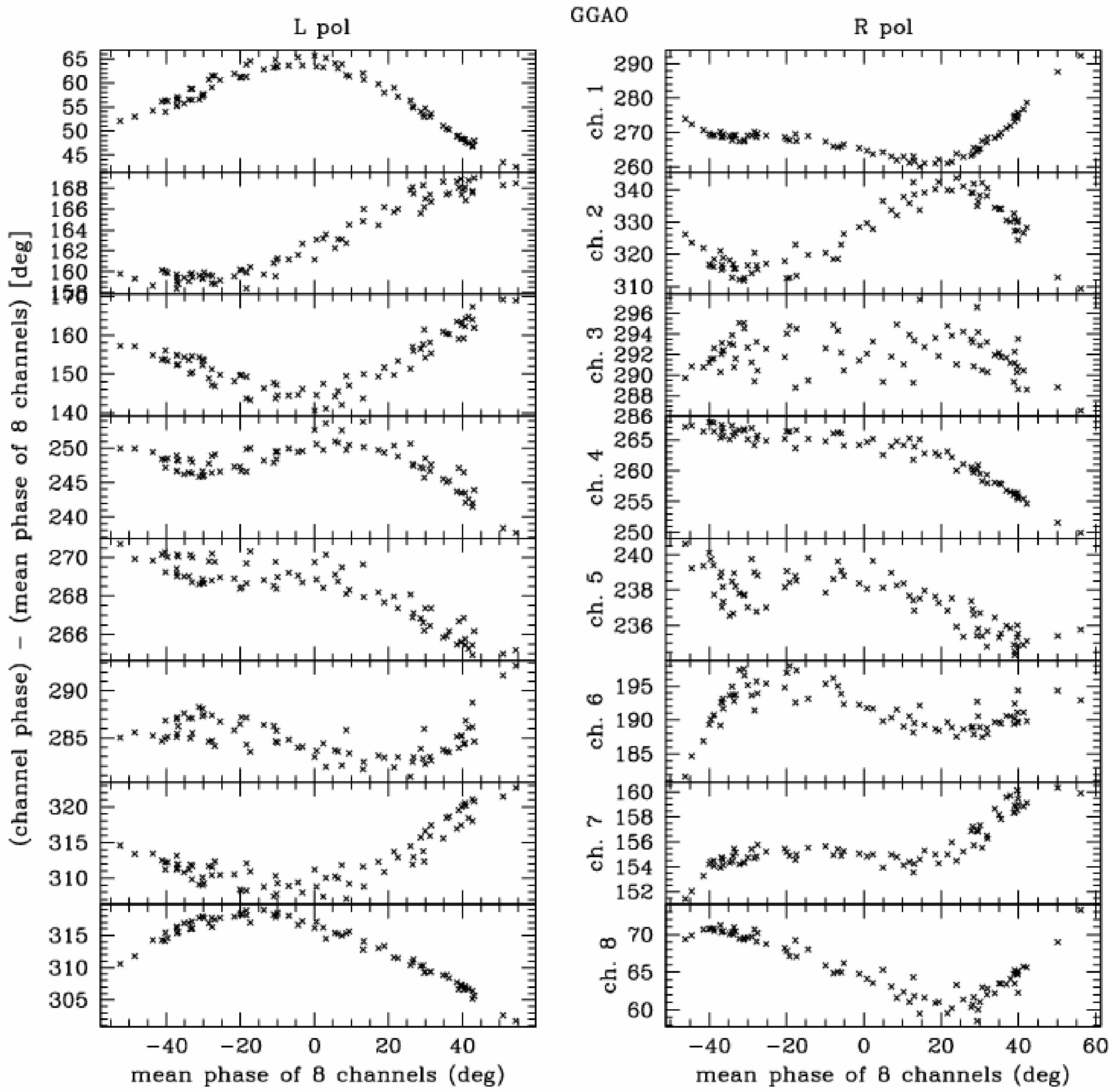

Figure 9. GGAO phase cal channel phase minus mean phase over eight channels vs. mean phase over eight channels. Ordinate in each plot is auto-scaled.

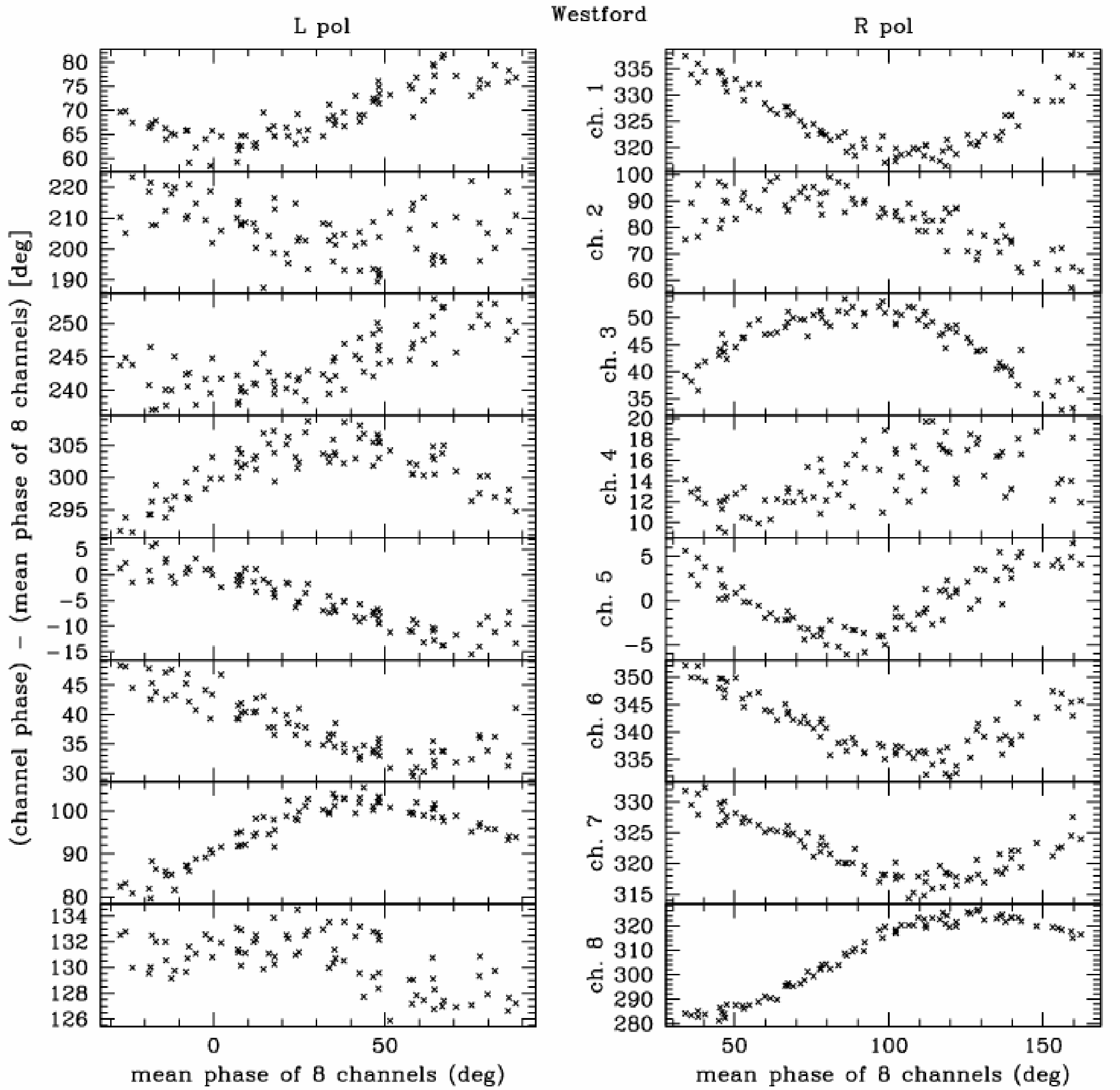

Figure 10. Westford phase cal channel phase minus mean phase over eight channels vs. mean phase over eight channels. Ordinate in each plot is auto-scaled.

5. Phase cal amplitudes vs. mean phase

A more conventional test for spurious signals is to plot amplitude against phase. The advantage over plotting the channel – mean phase differences is that the amplitudes are truly independent between channels, so a corrupted amplitude in one channel will not affect the amplitudes in other channels. The disadvantage is that the amplitude can be affected by variable Tsys due to RFI or weather. In the absence of radiometric data, there is no way to correct the amplitudes for Tsys variations.

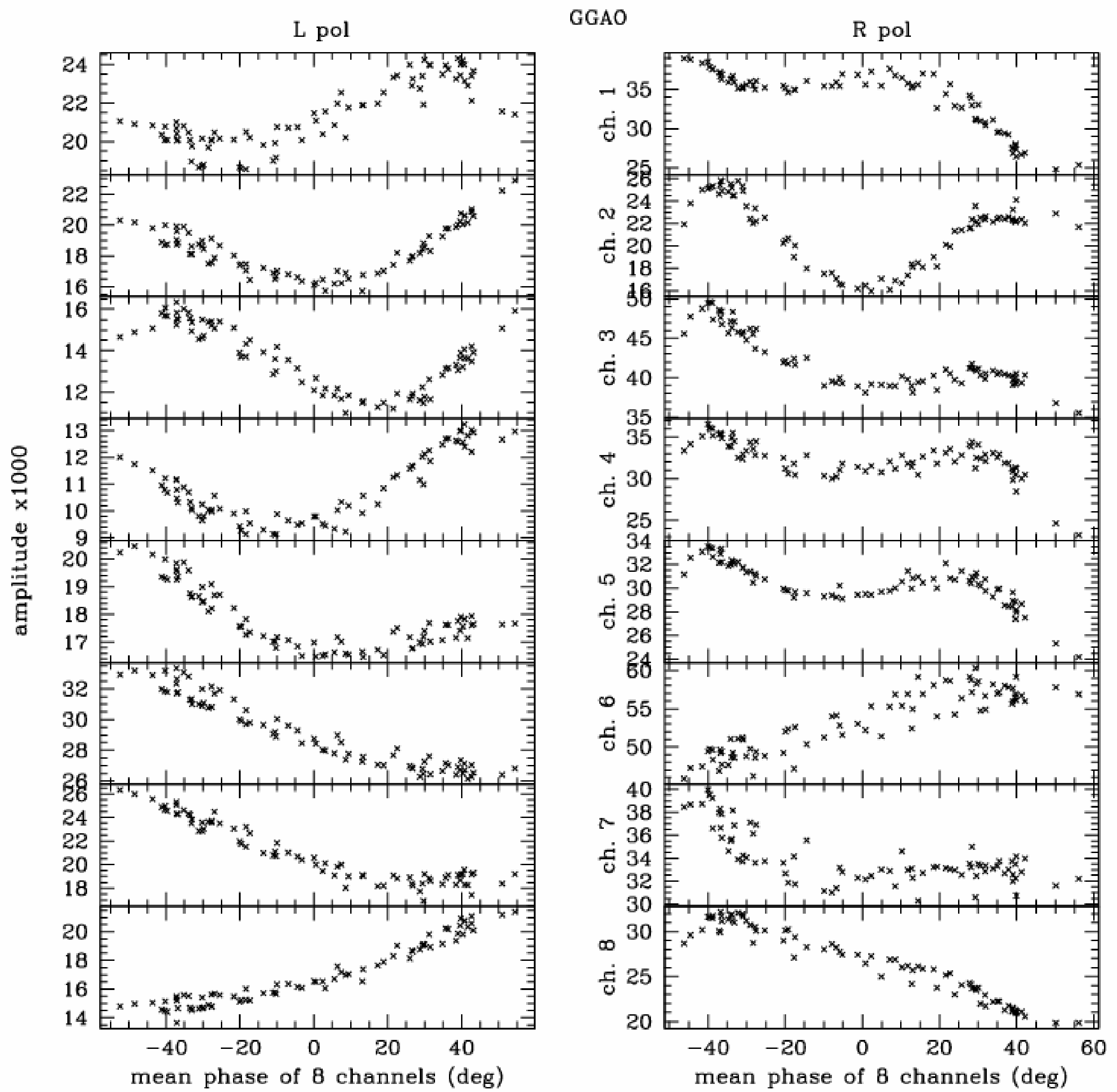

Figure 11. GGAO phase cal amplitude vs. mean phase over eight channels. Ordinate in each plot is auto-scaled.

Figures 11 and 12 show the pcal amplitudes plotted against mean phase. Figures 13 and 14 are the same, except that the amplitudes in each channel have been normalized to the mean amplitude of that channel.

Because the mean phase is not free of spurious signal contamination, the plots will differ from what would be observed if the "correct" phase were available for plotting. Because we are mainly interested in looking for single and double sinusoids and the like, however, the errors introduced by using the mean phase as a substitute for the corruption-free phase should be small.

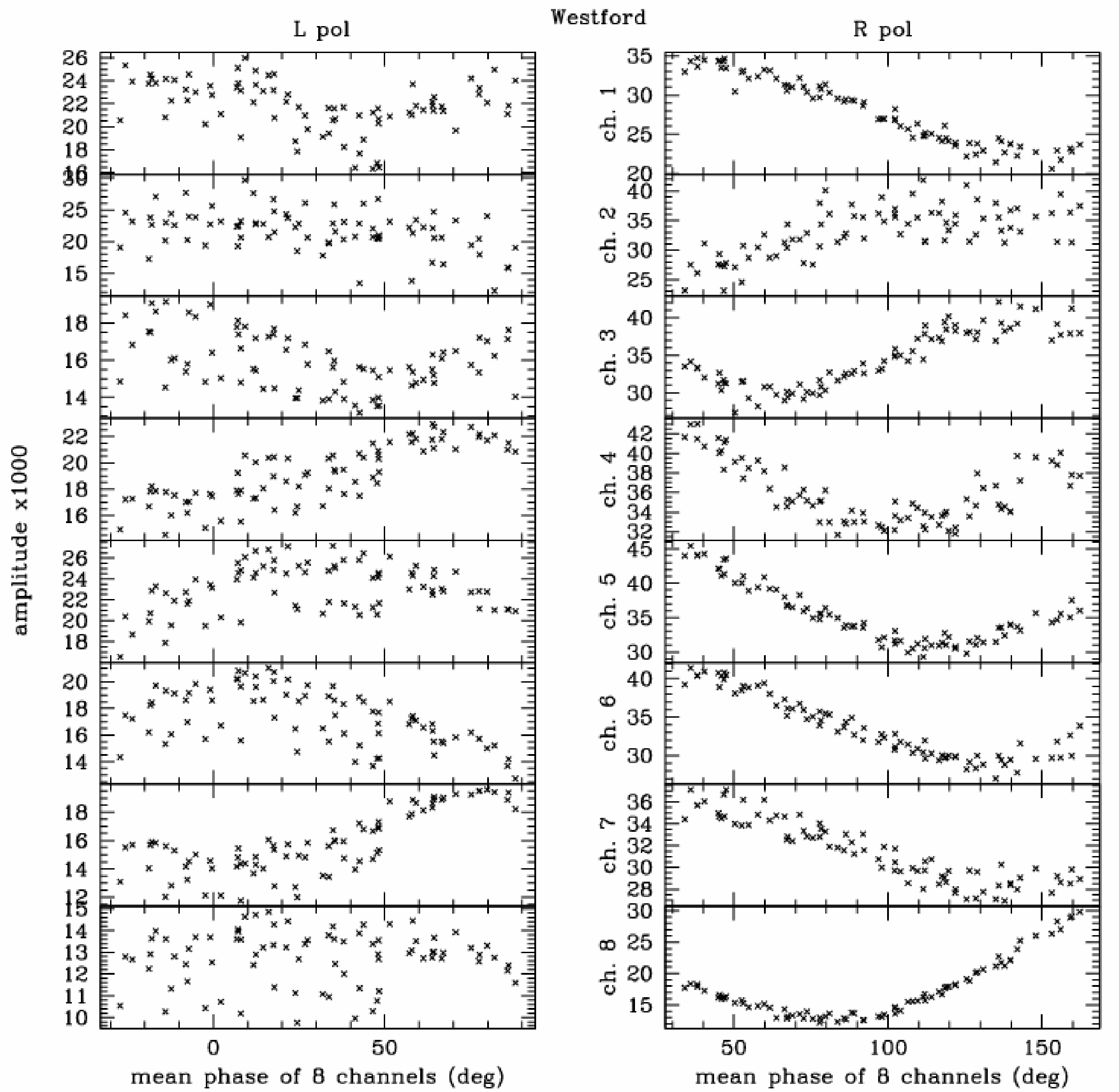

Figure 12. Westford phase cal amplitude vs. mean phase over eight channels. Ordinate in each plot is auto-scaled.

The main purpose of this memo is to present the 14 plots, without attempting a detailed analysis (and extending an already over-long memo). But I can't help making a few remarks.

- At GGAO, the dominant signature in some channels (e.g., R-pol #2 and maybe L-pol #3) appears to be a ~quadruple(!) sinusoid (i.e., one cycle over ~90º) in both amplitude and phase – cf. figures 9 and 13. The amplitude and phase curves have the requisite relative phase offset in the abscissa of ¼ turn to be caused by a spurious signal.
- Some of the more complicated GGAO waveforms (e.g., R-pol #1) could be caused by combinations of sinusoids with different periods.

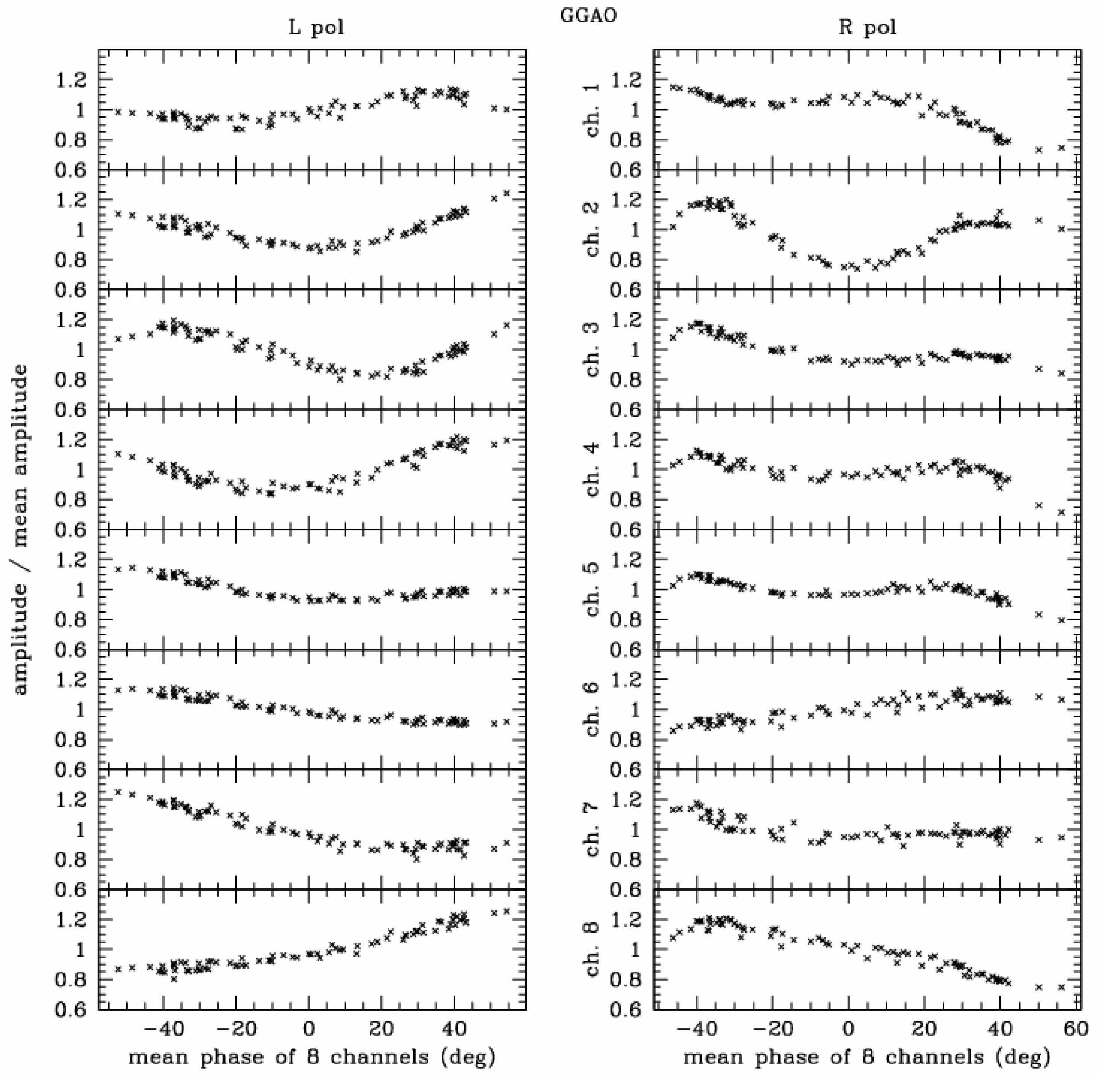

Figure 13. GGAO phase cal channel amplitude relative to mean channel amplitude over all epochs vs. mean phase over eight channels. Vertical scale runs from 0.6 to 1.4 in each plot.

- The Westford L-pol amplitudes are fractionally much noisier than the R-pol. Polarization-dependent RFI?
- Some Westford channels (e.g., R-pol #8) show the image-type double sinusoids with the customary ¼-turn offset between amplitude and phase curves (cf. figures 10 and 14).
- Typical amplitude (voltage) variations at both sites are ±20%. If they are caused by spurious signals, typical phase variations should then be ±10º, which they are.

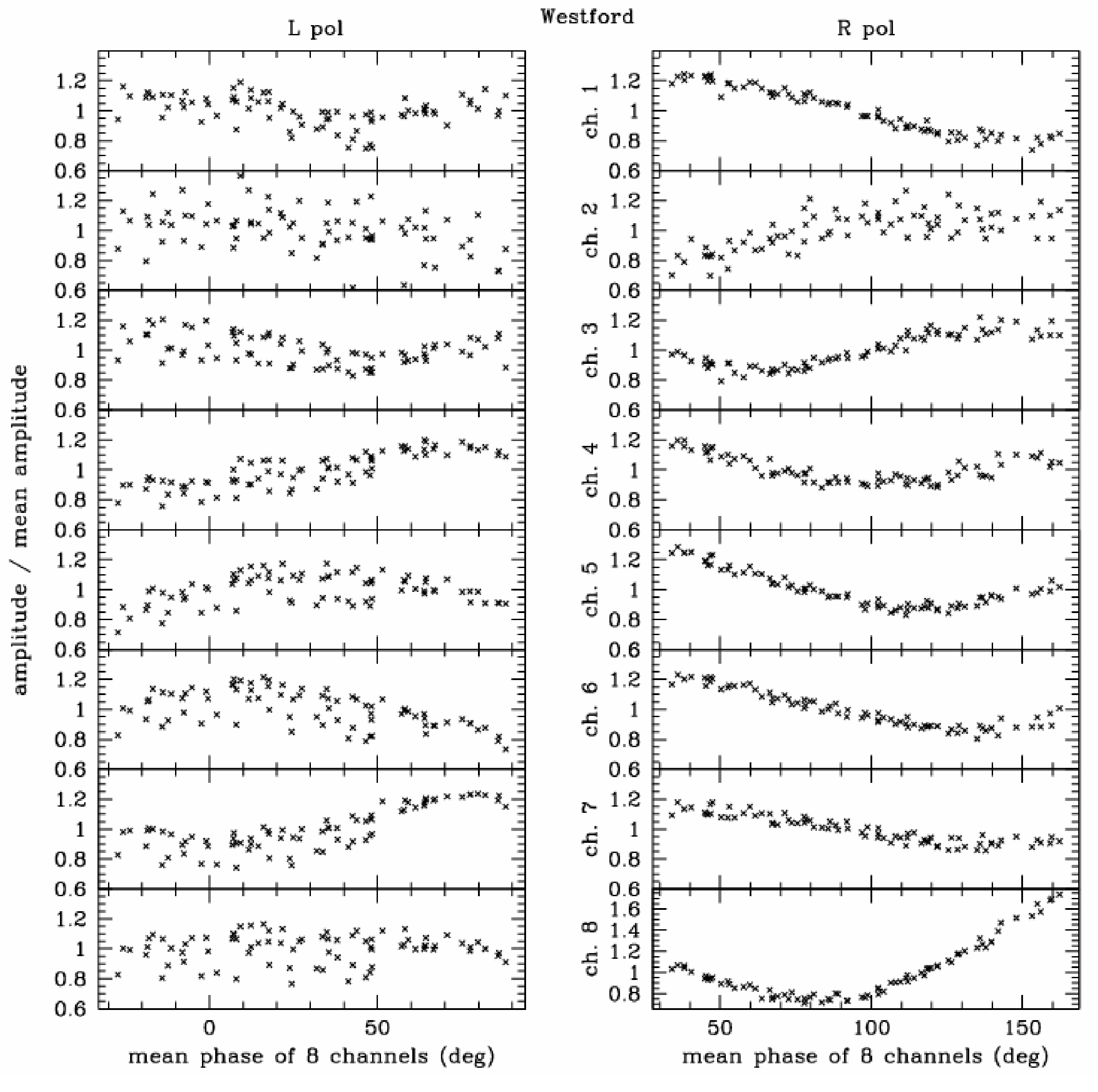

Figure 14. Westford phase cal channel amplitude relative to mean channel amplitude over all epochs vs. mean phase over eight channels. Vertical scale runs from 0.6 to 1.4 in each plot except for R-pol channel 8 in the lowermost righthand panel.

- The plots in this memo are all for the 4-MHz tones. There are 30 more tones available in the 32-MHz-wide channels, should their analysis be deemed worthwhile.

6. Some speculations on the origin of the spurious signals

The UDC is a potential source for spurious signals that could cause double and higher-order sinusoids in plots of amplitude or differential phase vs. phase. The number and strength of such sinusoids in figures 9-14 appears to me to be excessive, however, to come from the UDC.

With the pcal being radiated into the feed, as it was during the test, multipath from other antenna structures could lead to a delayed version of the pcal pulse also entering the feed. This type of spurious signal could cause constant phase offsets between frequency channels when the correlator data are fringed with normal pcal. It could also cause variations in the measured pcal amplitude and phase as the distances between antenna reflecting surfaces vary with elevation or wind loading. In my simple mental model of this effect, however, I do not see how it could lead to the sorts of phase-dependent amplitude and phase variations seen in the GGAO and Westford data.

7. Spurious signal in Westford channel 2

The phase of the Westford pcal tone in channel 2 exhibits variations of tens of degrees on time scales of seconds and longer. The variations shown as the green line in figure 15 are typical of those on intermediate time scales. In later scans the variations are smaller but faster. R-pol variations are about half as large as L-pol. By comparison, the GGAO variations shown as the magenta line are much smaller; they are typical also of what is observed at Westford in channels other than #2 and, most significantly, in pcal tones in Westford channel 2 other than at 4 MHz.

The fact that the RF frequency of this tone – 8700 MHz – is a harmonic of 100 MHz leads me to believe a piece of equipment in the Westford radome was radiating a signal at this frequency into the feed. The equipment may have been locked to a rubidium or a cesium.

The moral is to choose more carefully the frequencies of the pcal tones used in fringe-fitting.

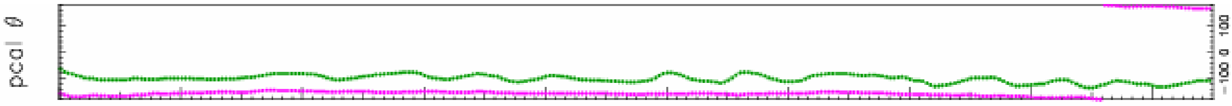

Figure 15. Phase of 8700 MHz L-pol phase cal tone (4 MHz tone in LSB baseband channel X7L, referred to in this memo as L-pol channel 2) at Westford (green line) and GGAO (magenta line) for scan 144-1810, vs. time. Time span is 9 minutes 30 seconds; major tick marks are every minute. Ordinate spans -180º to +180º.