In-situ GPS antenna phase center calibration

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Abstract.
In-situ GPS antenna phase center calibrations can be determined from several days of data from a single receiver. Phase center variations can introduce both elevation cutoff dependence and increased scatter in GPS solutions. A new method of calibration based on precise point positioning yields phase center maps unique to each station and its environment. These maps include not only the true phase center variation of the antenna but also the effects of repeating stationary multipath, delays from radomes, and any other stationary signal perturbations. Previous methods of calibrating phase center variations in GPS antennas have relied on either antenna range measurements, or differential techniques involving a second "known" antenna on a short baseline. Both these approaches fail to adequately address the environment of the antenna. The new insitu maps will be available via anonymous FTP from sideshow.jpl.nasa.gov.

1. Introduction

It has been known for some time that the apparent location of the phase center for a given GPS antenna varies as the elevation (and sometimes azimuth) of the incoming signal varies. (e.g. [*Braun* 1994] [*Mader* 1997] [*Niell* 1997] [*Rothacher et al.* 1995] [*Schupler et al.* 1994]) These phase center variations can cause significant errors in the solution for the station position if not treated properly.

This effect has been dealt with by either using all the same type of antenna in a survey, or by using phase center maps during the analysis of the GPS data. For each measurement, a correction determined from the map is added to the raw measurement.

Several methods have been suggested and used to measure these phase center variations. Initial efforts focused on the determination of a phase center map for the various antenna types in a calibrated antenna range ([*Schupler et al.* 1994], [*Dunn* 1992]]. Recently, several investigators ([*Mader* 1997] [*Rothacher et al.* 1995]) have determined phase center maps from short baseline studies, wherein a reference antenna with an assumed known phase center variation is used on a short, known baseline to remove the effects of geometry, signal propagation, and other noise sources to isolate the effect of the phase variations of the antenna under test.

In 1994 the IGS recommended that phase center maps based on short baseline studies incorporating only an elevation dependence be used in the analysis of GPS data. These maps are all relative to a particular type of Dorn-Morgolan antenna with a choke ring [*Mader* 1997].

For many stations, there are site-dependent effects which can not be corrected by using phase center maps based solely on the antenna type.

In this paper we present a method of determining insitu phase center maps directly from the GPS data, and demonstrate that these site-specific maps provide improved solutions.

We have used this method to establish phase center calibrations for over 100 stations so far. Almost all stations showed some measure of improvement.

2. Construction of Phase Center Maps

We construct phase center variation maps by binning one-way postfit phase residuals over many days. We used the GIPSY-OASIS II analysis software in a fiducial-free, point positioning mode [*Zumberge et al.,* 1997] to analyze one station at a time. A random walk zenith tropospheric delay and a random walk tropospheric gradient were included in the estimated parameters. The "ionospheric free" linear combinations $LC(L1, L2)$ and $PC(P1, P2)$ were used. We used an elevation cutoff of 7 degrees above the horizon.

Typically, if the station is a continuous station with a long data history, we use 90-100 days of data spanning 300-360 days. In this way we average the phase residuals over many weather patterns and many other sources of noise.

If a given bin has no data after all days have been stacked, the value from the nearest bin is assigned. The bin size is 2 degree elevation by 5 degree azimuth. When the phase center maps are used, the correction applied to a given measurement is determined through bi-linear interpolation between the bins to the elevation and azimuth of the measurement.

The binned post-fit residuals are added to any input phase center map to arrive at an improved map. We have found that this iterative procedure converges after 3 iterations.

This method will include not only the intrinsic phase center variation from the antenna itself, but also any consistent noise sources which always occur at a given elevation and azimuth. Thus, phase multipath from stationary objects, and phase center variations induced, for example, by the antenna mount structure, will be incorporated into the final phase center map.

3. Effects of using Phase Center Maps

There are two primary effects of using the new phase center maps. The first is an order of magnitude reduction in the sensitivity of the final solution for station position to the elevation angle cutoff. The second is an improved solution for some stations. An improved solution in this case is judged by rejection of fewer phase data points, reduction in the RMS of the postift phase residuals, and improved consistency of daily solutions. Stations with RMS postfit phase residuals exceeding 8 mm show improved solutions. In all cases examined so far, use of the phase center maps resulted in RMS postfit phase residuals in the 5-8 mm range.

3.1. Reduced Elevation Angle Cutoff Dependence

[*Niell* 1997] and [*Rothacher et al.* 1995] noted a dependence in the solution for the station position on the elevation cutoff which can be as large as 10 cm.

This elevation dependence of the solution can cause a systematic error if either the analysis strategy changes to use a different elevation cutoff, or the station changes the percentage of data collected at lower elevations as a function of time. Such a change at a station might be induced by such things as firmware changes in the receiver or growing vegetation around the antenna.

Station HARV (Harvest Oil platform off the California coast) provides an example of a station that has recorded less data at low elevation recently than it did earlier. (Figure 1)

In a test of the sensitivity of the station position solution to the elevation angle cutoff at FORT (Forteleza Brazil), the use of our phase center map reduced the elevation cutoff sensitivity by almost an order of magnitude. Without a phase center map, the station height changed by 31 mm when the elevation cutoff was changed from 15 to 7 degrees. With our phase center map, the station height changed by only 3.6 mm.

FORT uses a Dorn-Morgolan chokering (Turborogue) antenna, so the IGS phase center maps could not affect the elevation cutoff sensitivity because the IGS map for this antenna is identically zero.

Another way to assess the effect of the phase center maps is to plot post fit phase residuals as a function of elevation. Such a plot is shown in figure 2. Station CIT1 uses a Turborogue antenna, and although the overall scatter is decreased, there is not much change in the shape of the envelope of the postfit residuals. Station HVLK is a Trimble 4000St L1/L2 antenna, and shows a noticeable dip in the postfit residuals above 70 degrees. The use of our phase center map removes this dip.

3.2. Improved Solution Quality

Quality of the solution here is determined from the RMS of the postfit phase residuals, number of measurement points included, and scatter in daily solutions. A reduction in the RMS postfit residual, an increase in the number of measurement points (implying fewer points rejected), and a reduced chi square for the combination of 2 weeks of daily solutions are indicative of an improved solution.

Most stations showed a small improvement in the daily repeatability, with about 1/10 of the stations showing greater than 10% reduction in the daily repeatability. We take this as evidence that the station installers did a good job at most sites of locating the antenna in a relatively benign environment. Those stations with postfit residuals larger than 8 mm typically showed some improvement in the solution when the new phase center map was used.

3.3. Comparison with IGS phase center maps

[*Mader* 1997] has determined phase center corrections for various GPS antennas relative to a Dorn-Morgolan choke ring (Turborogue antenna). The Dorn-Morgolan is assumed to have zero phase center variation. These calibrations have been recommended by the IGS and are available from the IGS central bureau.

In figure 3 we compare a map we generated from postfit phase residuals for station HVLK (Kansas USA), a station using a Trimble 4000ST L1/L2 Geodetic antenna, with the corresponding map constructed from the IGS phase center variations. In both maps, we see a high at an elevation of about 45-50 degrees, and a low at zenith which goes down to about 25 mm below this high in our map, and about 35 mm below the high in the IGS map. Other antennas of this type display similar patterns if the site is not noisy.

We note that we also see non-zero phase center variations for Dorn-Morgolan choke ring antennas. In particular, the elevation cutoff test described above was done with a Dorn-Morgolan cokering antenna. Since the IGS maps assume that this antenna has no phase center variations, they would be unable to remove the dependence of the solution on the elevation angle cutoff. Using our phase center map for this station, we reduced the apparent station height change from 31 mm to 3.6 mm when the cutoff changed from 15 to 7 degrees.

4. Conclusion

It is possible to construct insitu phase center maps with GPS data from a continuously operating station. Use of these maps results in reduction of elevation cutoff dependence to insignificant levels and improves the consistency of daily station position solutions for some stations. Maps for many continuously operating stations will be available via anonymous FTP from sideshow.jpl.nasa.gov.

Acknowledgments. Ken Hurst wishes to thank Arthur Niell for his support and encouragement in initiating this work. Bruce Haines kindly provided the figure demonstrating the decreasing percentage of low-elevation measurements collected at station HARV as a function of time. The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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(Received January 3, 1996; revised February 27, 1996; accepted March 31, 1996.)

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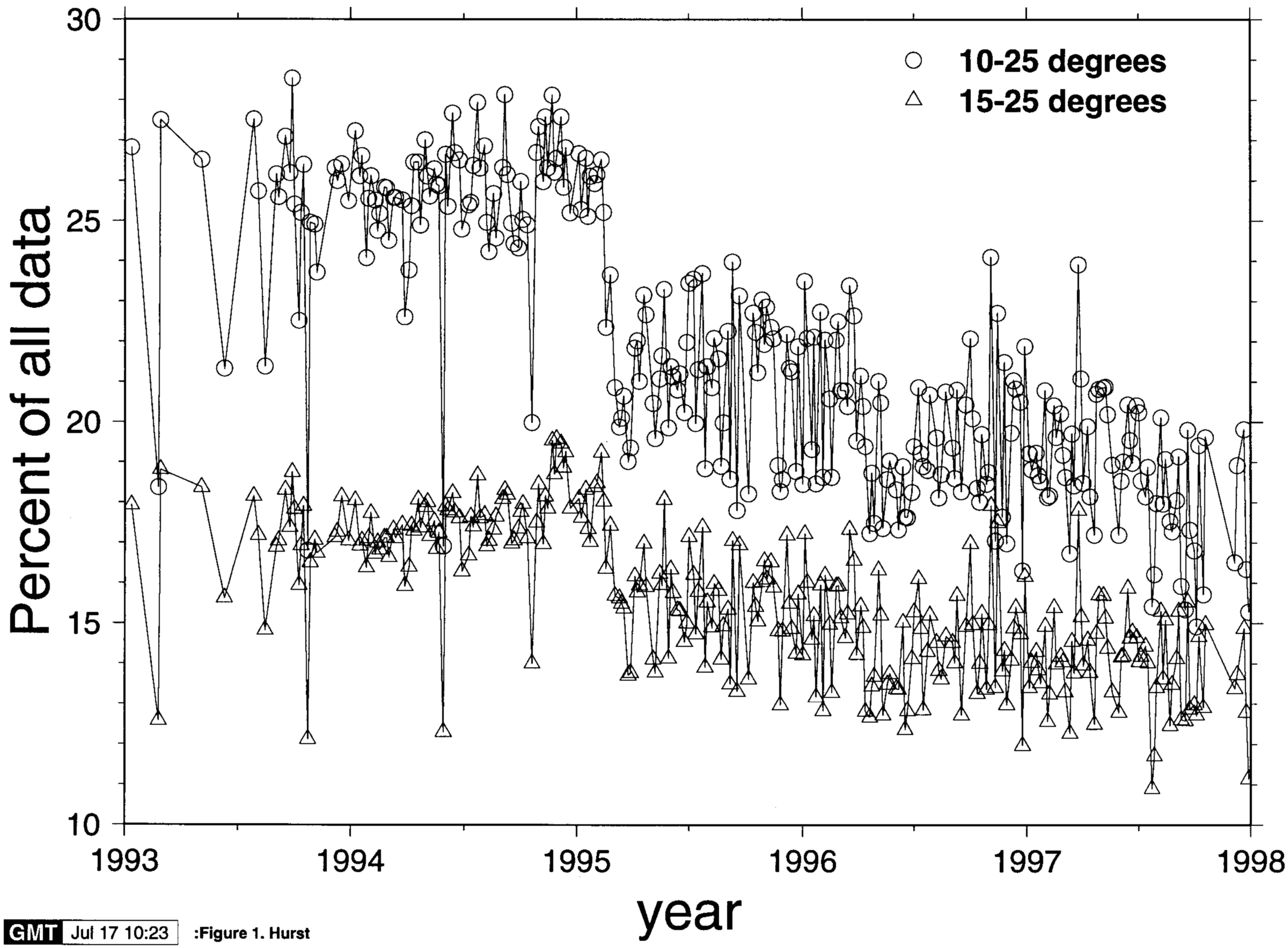
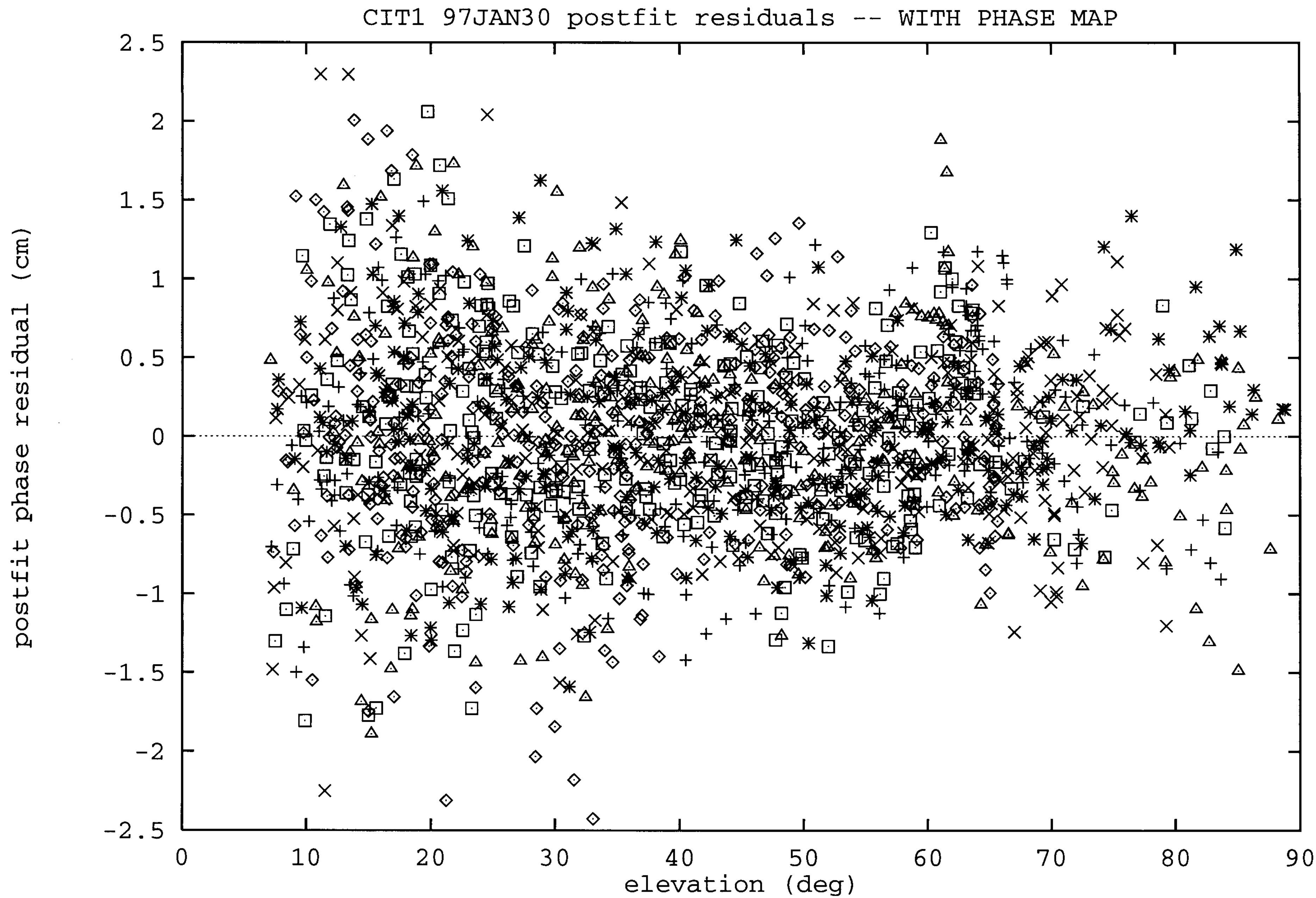
HARV low elevation data fraction



:Figure 1. Hurst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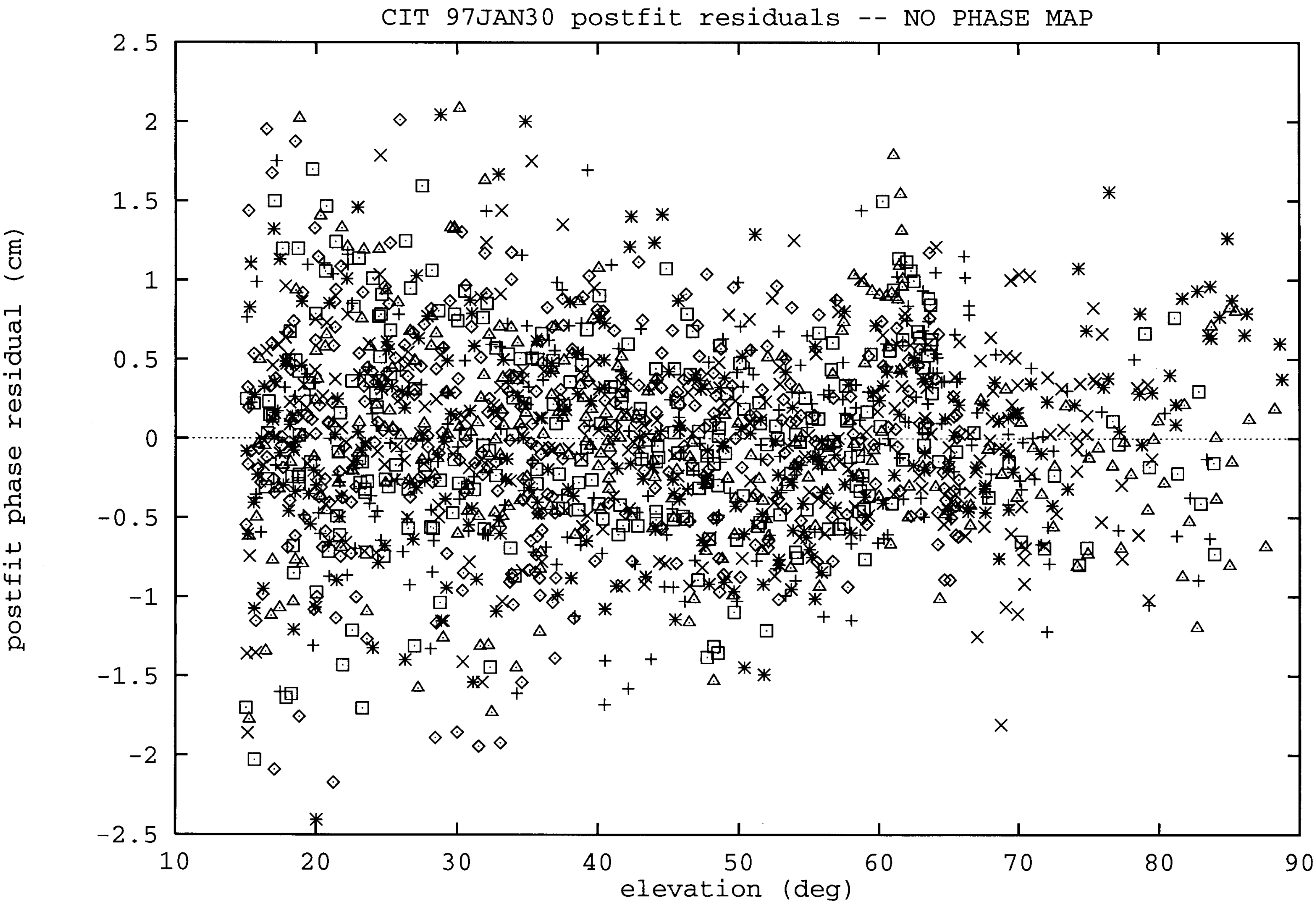
postfit phase residual (cm)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
10
20
30
40
50
60
70
80
90
elevation (deg)


CIT 97JAN30 postfit residuals -- NO PHASE MAP
postfit phase residual (cm)
elevation (deg)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
10
20
30
40
50
60
70
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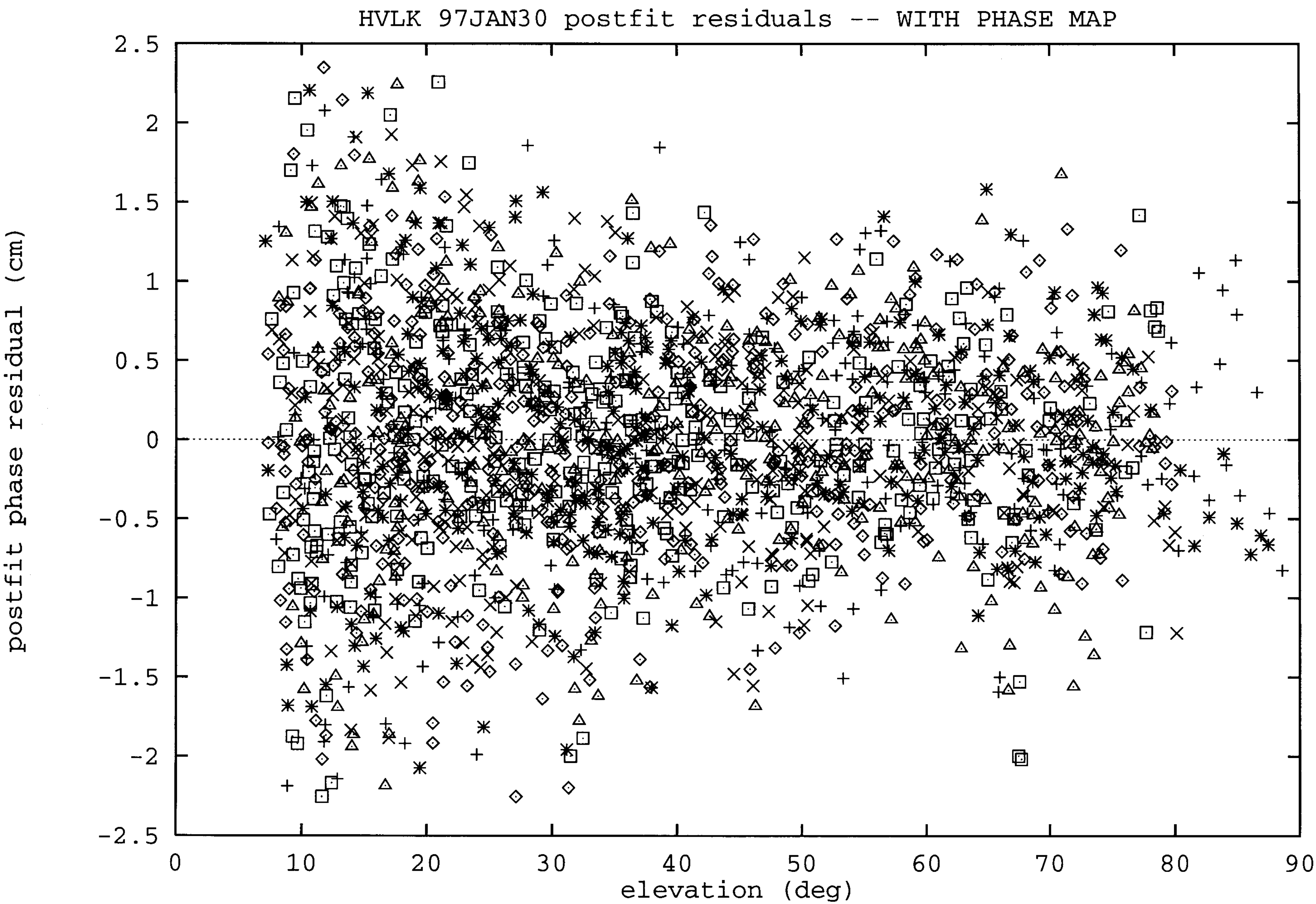
HVLK 97JAN30 postfit residuals -- WITH PHASE MAP
postfit phase residual (cm)
elevation (deg)
2.5
2
1.5
1
0.5
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-1
-1.5
-2
-2.5
0
10
20
30
40
50
60
70
80
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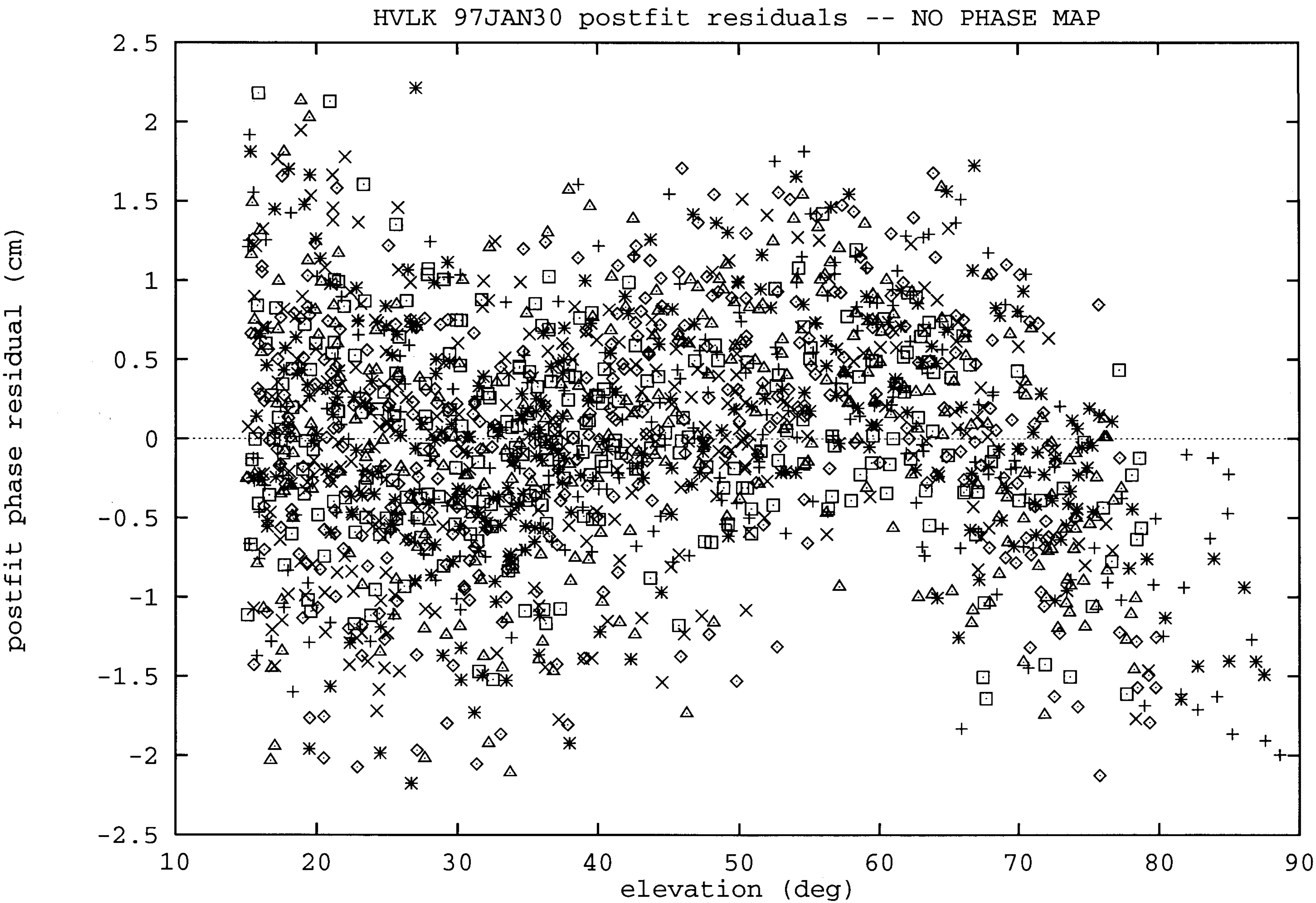
HVLK 97JAN30 postfit residuals -- NO PHASE MAP
postfit phase residual (cm)
elevation (deg)
2.5
2
1.5
1
0.5
0
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-1
-1.5
-2
-2.5
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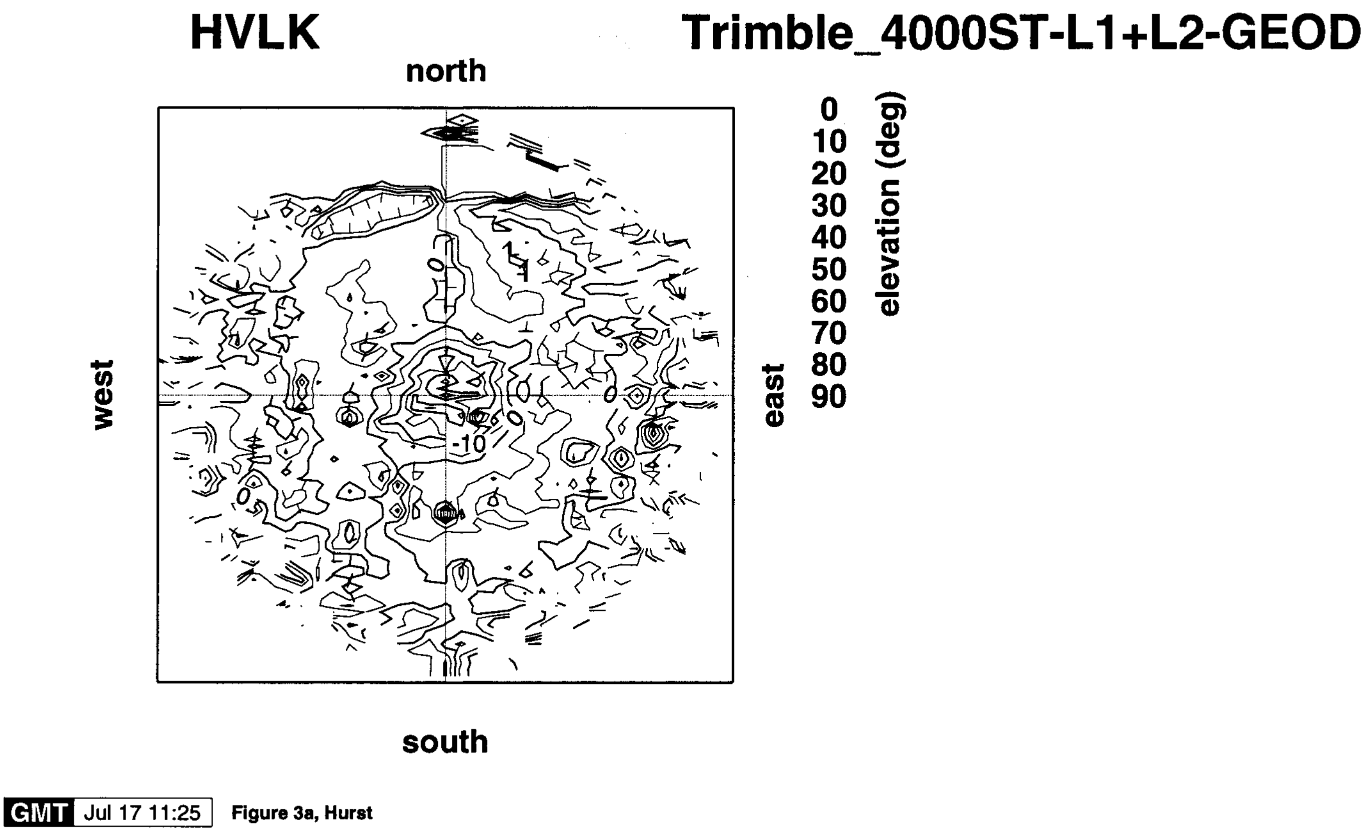

Figure 3a, Hurst

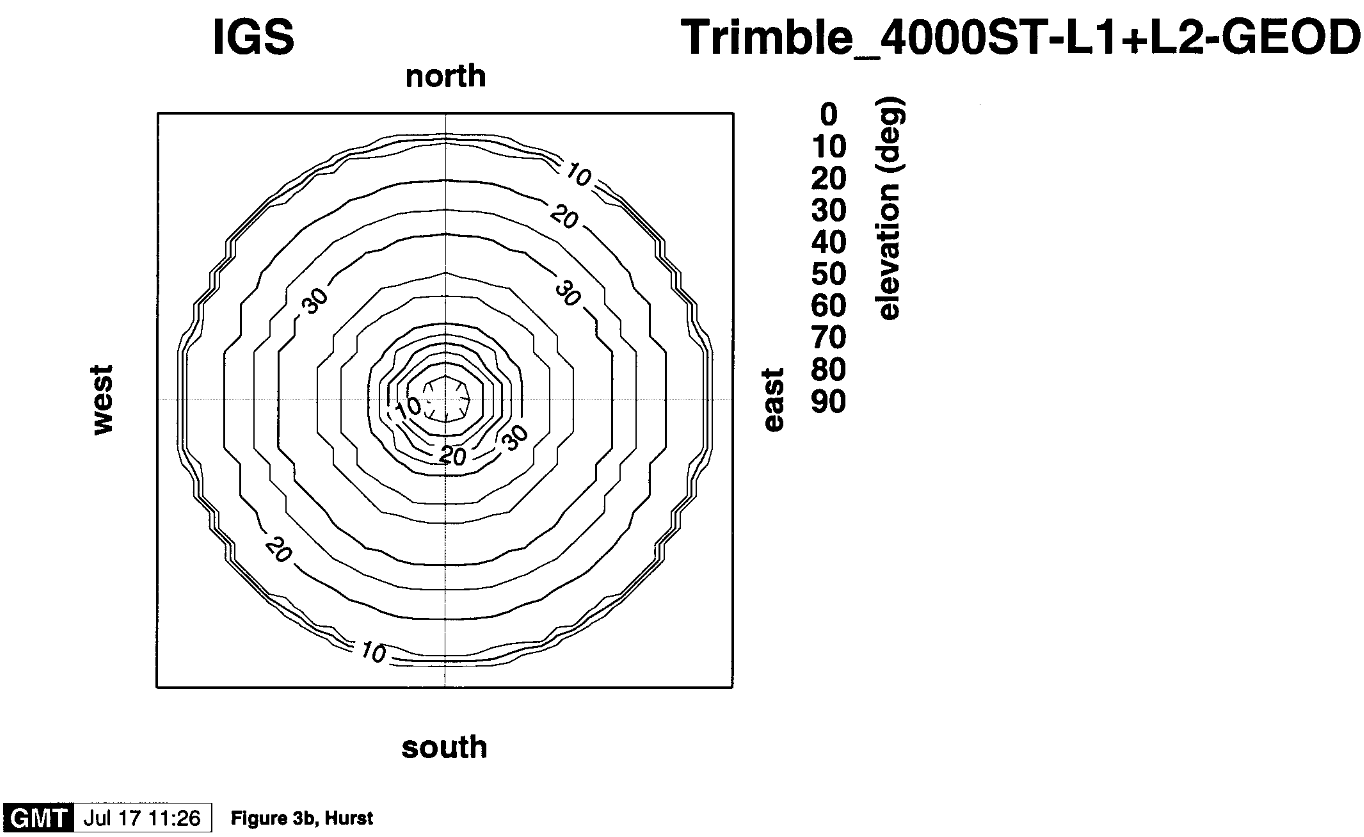

Figure 3b, Hurst