# Annual Signals in Continuous GPS Time series

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## 1 Introduction

Seasonal signals are a potentially important part of the error budget for continuous GPS sites (Bock et al. 1997). I have searched for seasonal signals in the height time series produced by four different data centers. These data sets are too large and heterogeneous to use a fixed set of reference stations, and there are significant systematic errors for some sites. I have developed a method to stabilize the reference frame discussed below, and analyzed the resulting time series to find significant correlation between the time series at certain sites and the local surface pressure.

## 2 Refining the Global Reference Frame

To construct the most stable reference frame possible, we need the largest possible set of reference sites with the best-determined locations. Unfortunately all GPS solutions are subject to both stochastic and systematic errors which can map into the reference frame. I

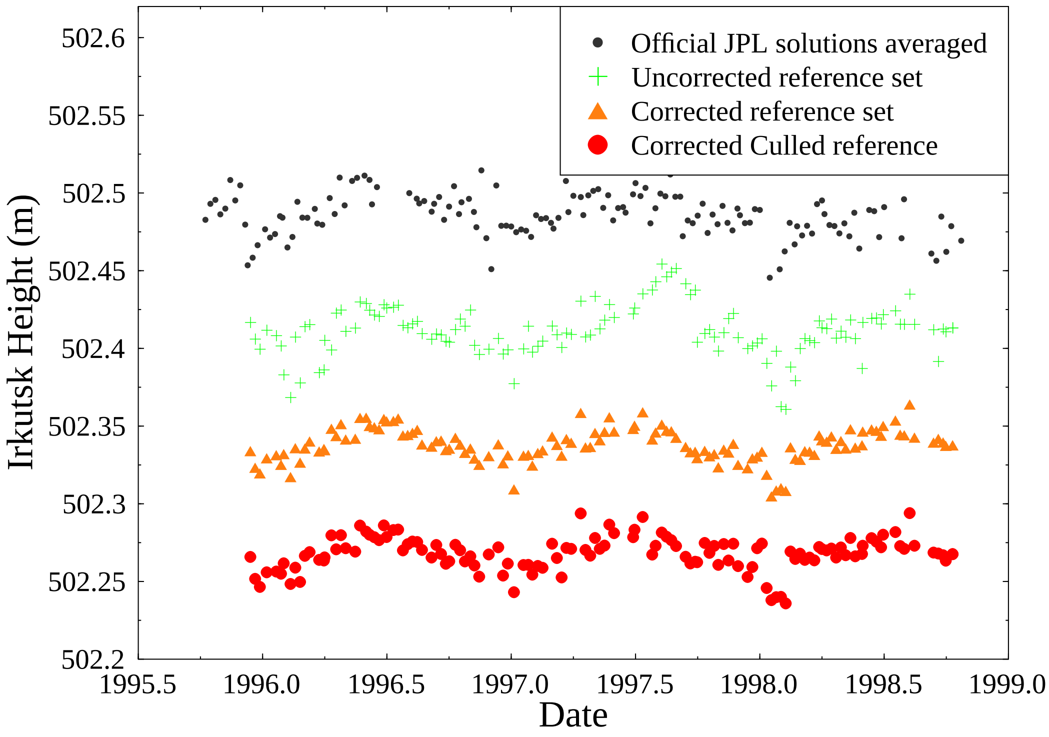


Figure 1: These time series of IRKT height show how a stabilized reference frame permits seasonal signals to be observed.

have used a station-editing procedure in combination with corrections to the station locations to combat these errors. In order to apply these corrections it is necessary to apply the reference frame to the data at least three times, - first to estimate systematic errors in the locations of reference sites, and secondly to assess the stochastic errors and select those stations with stable enough solutions to permit their inclusion in the final reference network. In the third application of the reference frame, only the most consistent set of reference sites are used.

Figure 1 illustrates different stages in the correction of the reference frame, using IRKT height time series from JPL (Fang and Bock, 1996) as an example. The top trace (dots) is an average of the daily solutions available from JPL, using their corrected reference frame. The second trace (+'s) is a simple application of the standard ITRF96 reference frame, applied to SINEX solutions using a set of 30 continuous GPS stations: ALGO, BRMU, CHAT, DAV1, EISL, FAIR, FORT, HART, IISC, KELY, KERG, KIT3, KOKB, KOSG, KOUR, LHAS, MADR, MALI, MAS1, MCM4, OHIG, PAMA, PERT, PIE1, SANT, STJO, USUD, WETT, YAR1 and YELL. This set of stations was primarily selected for geographic distribution and duration of available data in JPL SINEX files. It is a more restricted set than that used by JPL to apply the reference frame, which may explain the difference between this time series and the official JPL series. The third trace (triangles) uses exactly the same set of data and the same stations to apply the reference frame, but now the station locations have been corrected, so that the average de-trended offset is zero, and biases created by the constantly changing subset of reference stations available in a given SINEX file does not map into changing biases in the reference frame. This technique was borrowed from earthquake location programs, which frequently employ station corrections - delays added to compensate for the slow surface layer beneath seismic stations. The final trace on the plot (circles) also uses corrected reference stations, but in its case only 15 of the 30 possible stations were kept and finally used to define each reference frame. The 15 stations with the smallest residuals for that particular week are used, so that outliers produced by stochastic factors are eliminated.

Figure 2 illustrates seasonal effects at several stations, plotted together with scaled pressure traces from the same stations. The SINEX files in this case are from MIT, and they

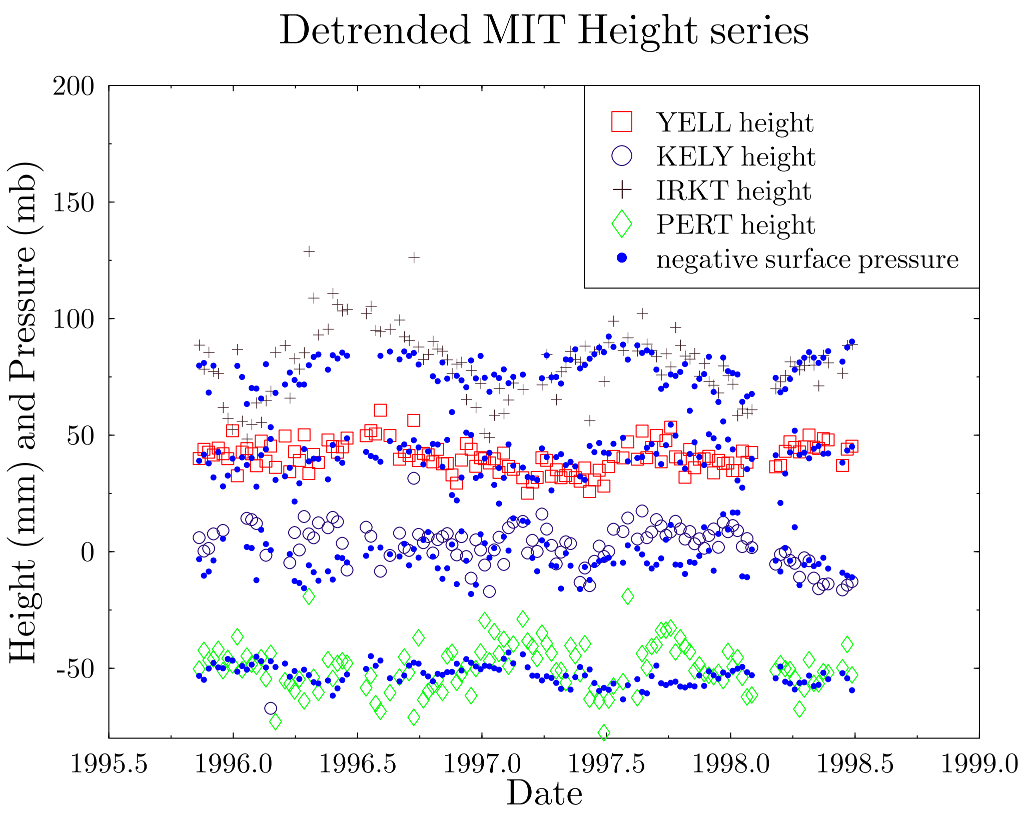


Figure 2: These detrended time series are from stations which show the strongest seasonal effects, plotted with pressure.

combine data from many analysis centers, so some of the differences between centers should be averaged out. With the height series are plotted the negative of surface pressure, in millibars. This illustrates that the relationship between surface pressure and height is approximately consistent station to station. Correlation coefficients show that only 20-5% of the variance is explained by pressure variations.

## 3 The search for seasonal signals

To look for seasonal effects in these data, I correlated various seasonal observables with the detrended time series. The candidate seasonal signals came from the Global Surface Observation Database, a vast collection of daily averaged meteorological observations available under ftp://ftp.ncdc.noaa.gov/pub/data/globalsod. I then selected the meteorological station closest to each of our continuous sites, and extracted all the associated observations from the archives. I averaged the daily weather data and combined them with the detrended weekly SINEX solutions in order to search for correlations. I performed rank correlations, a robust version of the linear correlation, and compared those rank correlations with each other. I expect that both the GPS and weather series may contain seasonal effects which are unrelated to one another - but produce significantly nonzero correlation coefficients. In order to control for this effect, I compared correlations between GPS height series and local weather timeseries with correlations between GPS heights and distant weather series.

Figure 3 illustrates the different atmospheric observables investigated in this study. The station shown is again Irkutsk, which has the strongest seasonal signal in the height timeseries. The pressure signal (dots at the bottom of the plot) is somewhat earlier in phase than the temperature (squares) and dew point (triangles) plotted above the height series shown for comparison (circles). Snow depth observations were not taken for Irkutsk, and the precipitation series (+'s) is shorter than the other observations. Figure 4 illustrates how different GPS timeseries for a single station can be, as processed by the different analysis centers. It is likely that the JPL series benefit from the particular choice of reference sites, but the most of the differences are unexplained. The four analysis centers are JPL (Jefferson

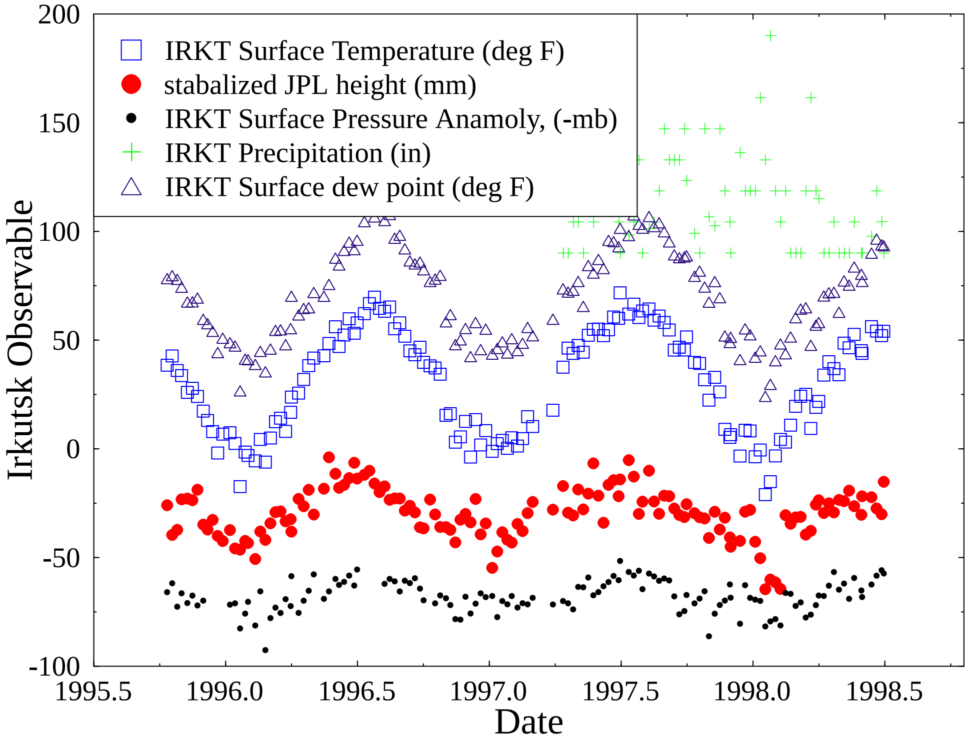


Figure 3: These IRKT timeseries of atmospheric observables show the signals which were compared to GPS height timeseries.

et al. 1997), Scripps (Fang and Bock 1996), MIT, and CODE (Rothacher et al. 1997).

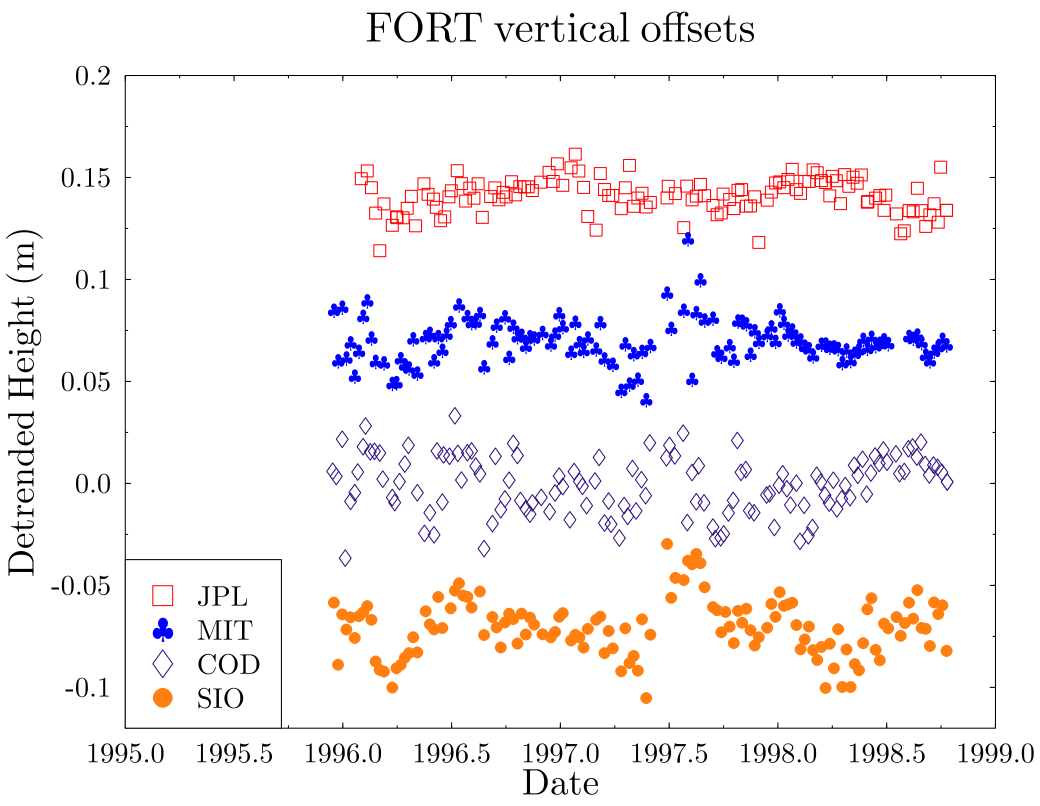


Figure 4: These FORT GPS height timeseries illustrate the differences between the four analysis centers. All timeseries use a stabilized reference frame.

Statistics Comparing Seasonal Signals with GPS Height Series

| | JPL | MIT | SIO | COD |
|---|---|---|---|---|
| Temperature | | | | |
| median | -0.021185 | 0.027736 | -0.011706 | 0.050438 |
| num > | 14 19 | 11 19 | 10 19 | 7 19 |
| probability | 0.990394 | 0.820357 | 0.676196 | 0.179640 |
| Dewpoint | | | | |
| median | -0.031594 | 0.015274 | -0.015451 | 0.046663 |
| num > | 13 17 | 9 17 | 8 17 | 8 17 |
| probability | 0.993629 | 0.685463 | 0.499992 | 0.499992 |
| Pressure | | | | |
| median | -0.027328 | 0.022752 | -0.0092 | -0.000684 |
| num > | 3 12 | 3 12 | 3 12 | 4 12 |
| probability | 0.072754 | 0.072754 | 0.072754 | 0.193604 |

Precipitation

| | | | | |
|---|---|---|---|---|
| median | -0.114157 | -0.100159 | -0.084122 | -0.069881 |
| num > | 8 17 | 6 17 | 8 17 | 8 17 |
| probability | 0.499992 | 0.166145 | 0.499992 | 0.499992 |

Snowfall

| | | | | |
|---|---|---|---|---|
| median | -0.04164 | 0.042636 | 0.021341 | 0.035301 |
| num > | 3 6 | 3 6 | 2 6 | 2 6 |
| probability | 0.640625 | 0.640625 | 0.328125 | 0.328125 |

**Table 1** Statistics summarizing seasonal effects by counting the number of rank correlations between local height and weather series more significant than the median rank correlation between height and weather series observed at widely separated locations.

If there is a relationship between GPS height and pressure, we would expect stronger correlations between the local height and pressure series than series recorded at different sites. If there is no relationship between pressure and GPS height, we would expect that the local pressure series should be no different than distant pressure series insofar as correlations with GPS height are concerned. Specifically, we would expect that there is a 50% probability of a rank correlation between local weather timeseries and local height to be greater than the median correlation between distant weather series and height.

The probabilities in Table 1 use the binomial probability distribution to estimate the chance that the observed number of rank correlations between local timeseries would exceed the median rank correlation between non-local timeseries. Each comparison is described by three lines of numbers. The first line, marked median in the table, lists the median rank correlation for comparisons between widely separated GPS height series and weather observations. The second line, marked num > in the table, shows the number of rank correlation coefficients comparing height and weather series observed for the same station which are greater than the median in the above line, as well as the total number of local comparisons made. This pair of integers should be approximately in the ratio 1:2 if there is no relationship between the height and weather series. The final line labeled probability for each comparison is a probability of getting the observed count of correlations greater than the median, assuming that the probability of exceeding the median is 50%. Since the median is defined to be the midpoint of a distribution, the assumption is justified - and a good test of how similar the distribution of local rank correlation coefficients is to the distribution of rank correlations made between stations and weather sites that are widely separated. The probabilities can show significance at either end of the distribution, near 0 or 1, with a value of 0.5 being the expected result for no relationship between the weather series and GPS.

The table shows quite a few probabilities near 0 or 1, indicating negative or positive correlations between height and weather series. The strongest relationships on the table are positive correlations between height and temperature for JPL and height and dewpoint, also for JPL. These relationships seem to apply to the JPL timeseries only, perhaps because the JPL timeseries have some advantage over the other series as a result of the selection of reference sites, or maybe there is a significant difference between the modeling assumptions made by the different analysis centers. The only consistent relationship in the table appears to be the unusually low probability (inverse correlation) of the height series with surface pressure. This is the same relationship illustrated in Figure 2, with approximately a one millimeter decrease in height for every millibar increase in surface pressure. The sign is right for both atmospheric delay and surface loading to be viable explanations. The amplitude of the response is roughly consistent with atmospheric loading, assuming that the weather systems are several hundred kilometers across and that the earth responds in a purely elastic manner to the transient load.

# 4 Conclusions

I have found statistically significant correlations between surface pressure and GPS height - but the pressure effect typically explains only a few percent of the total height variance. Less significant correlations with surface temperature have also been found, but there appears to be little relationship between humidity or precipitation and height series. A few stations show much stronger relationships with pressure - IRKT, PERT, MCM3, and YELL, for example, with 20-5% of the variance explained. I have developed a method to stabilize the reference frame of global GPS solutions and applied it to 3 years of weekly solutions by JPL, MIT, Scripps and Berne. These solutions are distributed as SINEX files. Comparisons of detrended GPS height signals with weather observations provided by the National Climate Data Center's Global Surface Observation Database were made for a set of 21 continuous GPS stations which had weather observations an average of 14 km away from the GPS instrumentation. I found strong correlations with surface pressure. Correlations with precipitation, surface temperature, and dew point were less significant. Pressure correlations were strongest for stations not included in the reference frame, and were most often negative, suggesting that unmodeled atmospheric delay could be a cause. There are many other possible causes, including vegetation, snow cover, seasonal changes in water vapor, and chance correlation with some other annual signal.

## Acknowlegements

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