

Seasonal Position Variations and Regional Reference Frame Realization

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Abstract. Many GPS sites show significant seasonal position variations (especially in the vertical), resulting from a combination of geophysical loading and systematic errors. It is common to realize a regional reference frame or align a time series with a model by transforming each epoch solution into ITRF (or a local or regional frame) using a regional set of sites, where these reference frame sites are assumed to move linearly with time. Seasonal variations in the frame sites can bias this frame realization and the seasonal variations are then aliased into the site coordinates.

I estimate seasonal variations at a set of sites across northern North America and the Arctic using an iterative non-parameteric approach. Seasonal variations at most sites exceed 4-5 mm in the vertical. A test with synthetic time series shows that ignoring these variations when realizing a daily or weekly reference frame can cause apparent seasonal variations in other sites as large as 4 mm amplitude. We should work toward a linear + seasonal model as part of our reference frame definition.

Keywords. Reference frame, GPS, seasonal displacement.

1 Introduction

Seasonal variations in positions are commonly observed, especially in height component. For example, seasonal variations in height for sites in Japan are significant, and spatially coherent in phase and amplitude (*Murakami and Miyazaki, 2001*). *Heki (2001, 2003)* showed that these variations could be explained primarily in terms of hydrological loading, mainly due to snow loading in northern Honshu. *Dong et al. (2002)* analyzed contributions to seasonal variations globally.

Hydrological loading can cause substantial variations in vertical displacement, and these variations are often annual in period. For example, *van Dam et al. (2001)* calculated model vertical displacements from the convolution of loads predicted by a global hydrological model with elastic surface loading Greens functions (*Farrell, 1972*). The resulting model displacements had peak-to-

peak extreme values (over several years) of 10-30 mm in many places, and a predominantly annual period, and were in-phase with the observed seasonal variations at many sites. They further found that the variance reduction in height variations at 147 globally distributed GPS sites when the model variations were removed was consistent with that expected from the variance of the model. However, as noted by *Ray (2006)*, systematic errors in the GPS system and models can also produce seasonal variations, so matching loading models to data in detail has proven difficult.

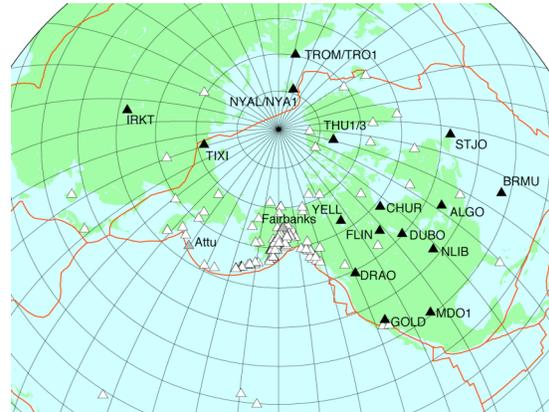


Fig. 1 Sites used in this study. White triangles show sites in the solutions used in the study, and black triangles are sites used to realize reference frame. No sites in Alaska are used to realize the reference frame because of earthquake displacements and non-linear postseismic motion, common problems in many regional networks. The gray triangles show the location of two test sites discussed in section 5.

It is less widely recognized that seasonal variations, if present in the data, will bias the reference frame transformation parameters estimated as part of regional reference frame realization, and the alignment of epoch solutions with a long-term velocity model. In the case of small networks, this is exploited to use the regional frame as a regional filter (e.g., *Wdowinski et al., 1997*). In the case of global networks, only long-wavelength variations, such as low degree global loading (e.g., *Blewitt et al., 2001*), may remain to bias frame parameters. However, many regional networks are of intermediate scale, and as I will show, seasonal variations in positions of sites used to realize the frame can

have a substantial impact on the effective reference frame and the resulting position time series.

2 Data Set

I study the impact of seasonal variations on reference frame realization using 6 years of daily solutions from a continuous GPS network spanning the northern part of North America and surrounding regions (Figure 1). The network is focused on studying active tectonic and volcanic deformation in Alaska. The number of sites used in the solutions varies from about 60 to more than 120 over the time span studied, with the number of sites increasing steadily with time.

Each daily solution was analyzed as a network solution using the GIPSY-OASIS software version GOA4. A uniform data analysis strategy was used for all data. Every day, data from all stations were used simultaneously to estimate satellite clocks, station positions, time-dependent tropospheric path delays and gradients, and phase ambiguities. I used an ambiguity-free solution for this analysis. One station, usually ALGO, had its clock held fixed as a reference clock. Orbits were fixed to the JPL non-fiducial orbit, a frame-free orbit based on JPL's IGS submission, and the JPL-estimated EOPs were also used here. I applied the IGS relative antenna phase center models without radome corrections, and ocean tidal loading corrections based on the TPXO.2 tidal model. Outliers were removed from the time series; most outliers resulted from incomplete days of data.

Each daily solution is in an indeterminate frame, and must be transformed into ITRF by estimating a 7-parameter transformation between the daily coordinate estimates and the ITRF model prediction for that day. I evaluate ITRF2000 (IGSb00) at each day, and use 17 sites to estimate the transformation (solid triangles in Figure 1). The sites are weighted according to the combined uncertainty in the ITRF predicted position and the daily estimate for that site. The reference frame sites were chosen because they have well-determined velocities in ITRF, and do not have any known problems or anomalies in their time series that might bias the frame estimation. A few of the sites do have small discontinuities identified within this time period. I compared daily position estimates where the frame was realized both with and without these sites, and the effect of the discontinuities on daily position estimates is at no more than the mm level.

3 Non-parametric Estimation of Seasonal Variation

Sinusoidal parametric functions are commonly used to estimate seasonal components in geodetic time series. However, some potential seasonal loading sources will not show a perfectly sinusoidal form, and a non-parametric approach may be more suitable. For example, snow loading should vary in amplitude with the weight of the snow load, which in high northern latitudes increases from October or November through March, and then rapidly melts in the spring. I use a non-parametric approach to estimate seasonal deformation to avoid any assumptions about the source other than an annual period. A parametric approach using a sufficient number of sinusoids should produce equivalent results, but the non-parametric approach also allows for easy temporal smoothing of the estimated seasonal variation.

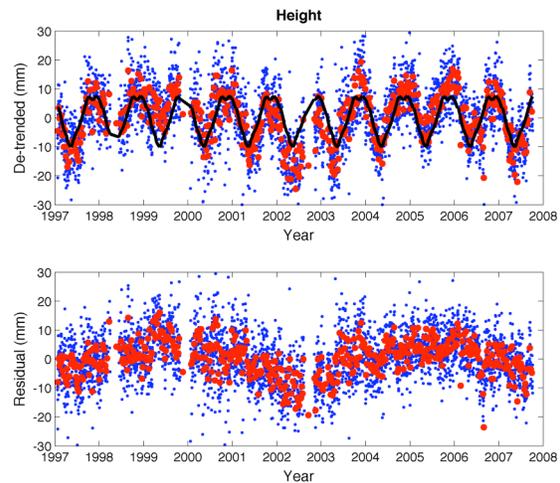


Fig. 2 Original (top) and corrected (bottom) detrended time series for GUS2. Blue dots are daily height estimates, and red dots are weekly averages. The black curve on the top figure is the estimated seasonal variation (Figure 3). Vertical axis spans ± 30 mm.

The method is similar to techniques used in a variety of other applications, including the removal of seasonal variations from tide gauge data (e.g., Larsen et al., 2003). The time series is detrended (Figure 2, top), and the residuals are sorted into seasonal bins by fractional year. I used 40 bins to represent the full year, so each bin represents 8-9 days. The first bin consists of the first days of the year, January 1-9, and the average residual for January 1-9 of all years is the mean seasonal correction for that bin (Figure 3). I then applied a 5-point smoother to the raw bin averages to get a smoothed seasonal correction. The seasonal averages were then interpolated and subtracted from the original time series to get a corrected time series (Figure 2, bottom).

Figures 2 and 3 show the time series for a site in

Gustavus, Alaska (GUS2). The station height reaches its lowest point on average at about 30-35% of the way through the year, or in April. This is the time of year when significant melt and runoff begins, as temperatures rise above the melting on a consistent basis. The site reaches its highest point between 70% and 100% of the way through the year, or September to December. The timing of the start of significant snow accumulation varies from year to year, but usually falls within this time range. Interannual variations are also clearly visible to the eye in this time series. The timing of this record suggests that snow loading dominates the seasonal variation at this site, and other high-latitude sites show similar timing.

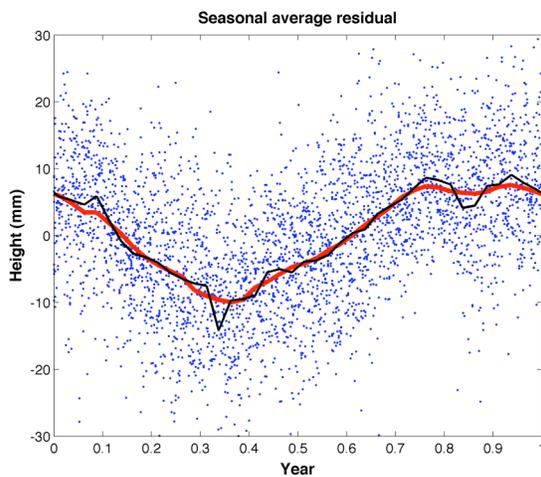


Fig. 3 Estimated seasonal variation for GUS2. Blue dots are daily height estimates, plotted by fractional year. Black curve is interpolated from the raw bin averages, and red curve on the smoothed bin averages. Vertical axis spans ± 30 mm. The figure shows 1.5 years of data to emphasize the seasonality of the residuals.

4 Seasonal Variations at Frame Sites

The sites used to realize the reference frame also are expected to have seasonal variations. Because we normally ignoring seasonal variations and realize the reference frame using a linear model in time for the station coordinates, the seasonal variations will bias the estimated frame parameters and, through the frame, may be aliased into the positions of all sites. The process of realizing the frame may “damp down” actual seasonal variations at the sites used to define the frame for the same reason: some component of the seasonal variation in the sites will leak into the frame estimate. Therefore, seasonal variations at these sites should be estimated using time series that are generated without using that site to define the frame.

I evaluate the seasonal variations at frame sites

through an iterative approach. To estimate the seasonal variation at one frame site, I first realize the frame using the other $N-1$ sites, and I use the procedure outlined in section 3 to estimate the seasonal contribution. This process is repeated for all sites. I then repeat the entire procedure, this time using a model consisting of linear ITRF velocities plus the seasonal correction from the previous iteration. For most sites, this process converged within 2-3 iterations. For the sites YELL and IRKT (and to a lesser extent, TIXI), however, convergence was not reached until 4-5 iterations, because both sites have strong seasonal variations and the seasonal corrections converged in a damped oscillatory fashion toward convergence.

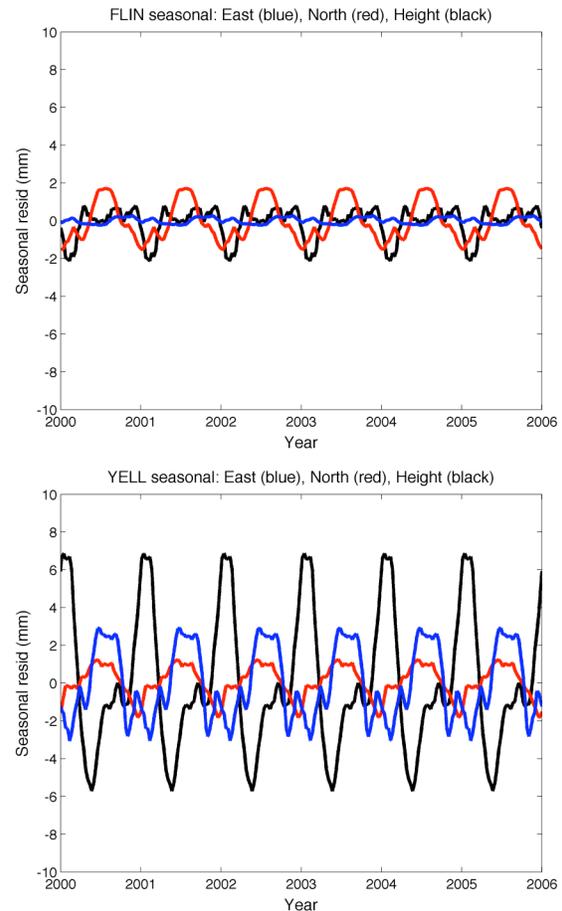


Fig. 4 Estimated seasonal variations at two sites: FLIN (top) and YELL (bottom). Black curve is seasonal height estimate, red curve is seasonal north estimate, and blue curve is seasonal east estimate. Vertical axis spans ± 10 mm, horizontal axis in years.

At most sites, the seasonal variation was the largest in the vertical component, as would be expected if loading was the major cause of the seasonal variation (Figure 4). Only four sites had seasonal height variations smaller than 4 mm ampli-

tude: DUBO, FLIN, STJO and TIXI. Five sites showed vertical seasonal variations of $\sim 4\text{--}5$ mm amplitude: ALGO, CHUR, MDO1, NLIB, DRAO. The remaining sites had vertical seasonal amplitudes in excess of 5 mm, although none were greater than 10 mm amplitude.

Few of the estimated seasonal patterns were sinusoidal. At most sites, the high and low parts of the seasonal curve were asymmetrical, and in most cases the low part of the curve covers less than half the year (Figure 4 bottom, site YELL). In general, the sites begin to uplift between 1/3 and 1/2 of the way through the year, and begin to subside late in the year. Qualitatively, this matches the pattern at GUS2, although not all sites are in the sub-arctic and each site's pattern is different.

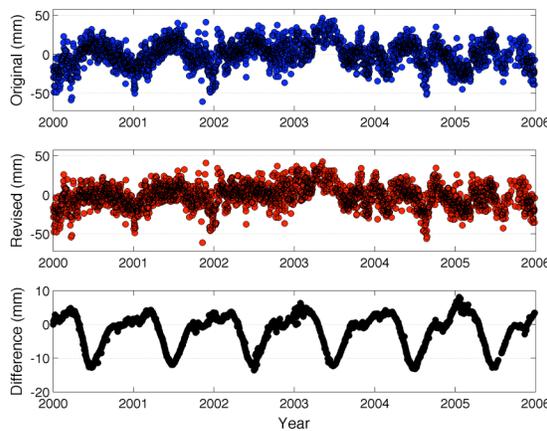


Fig. 5 Time series for Irkutsk (IRKT) where the reference frame is realized via an estimated transformation (top) with the standard linear model for ITRF, (middle) with the linear model plus seasonal corrections. The bottom panel shows the difference between the two series. In both cases, IRKT is not used in the alignment of the daily solution with the frame. When seasonal variations at the other sites are accounted for, the seasonal variation at IRKT is visibly reduced.

There are two co-located sites at Tromsø, Norway, TROM and TRO1. The two sites have different monuments, with TROM located on a tower and TRO1 on a pillar atop a building. The vertical seasonal variation is almost identical at these two sites, ~ 7 mm amplitude, suggesting that it is dominated by a geophysical signal and not simply error in the time series. Ray (2006) showed that electrical effects such as multipath and scattering can cause significant apparent seasonal variations, but with different local environments this error source should be different at the two sites. However, the horizontal seasonal variations at the two sites are quite different, with the estimated variation curves differing by 2–3 mm during much of the year, so it is possible that the seasonal variations are biased

at this level by non-geophysical noise. The same holds for the adjacent sites NYAL and NYA1 in Ny Ålesund, Norway.

The fact that several iterations were needed for convergence shows that time series can change significantly when seasonal variations are included in the reference frame definition. In the case of Irkutsk (Figure 5), this change can be significant and easily visible. Irkutsk is located at the edge of the network, and far from any site other than TIXI. Any bias in realizing the reference frame would be amplified in the position of this remote site, thanks to the long lever arm between IRKT and the centroid of the network. The final estimated time series for IRKT shows a smaller seasonal variation than the initial time series based on the unmodified ITRF, which shows that the additional variations in the time series result from aliasing of reference frame realization errors into the site coordinates. This change is particularly notable in the first half of the time series, where the variation is dominated by an annual period. After the summer of 2003, the time series is dominated by shorter period variations. The cause of this change is not certain, but the pattern is unique to this site.

5 Impacts on Time Series

I further evaluated the impact of seasonal variations in the frame sites on time series using a test with synthetic data. If seasonal variations are present in frame sites, but ignored, how much error will be aliased into apparent seasonal biases in other sites? I generated a one-year daily synthetic time series for all of the frame sites based on their ITRF positions and velocities and the final estimated seasonal variation. I also generated synthetic time series for two test sites, which had no seasonal variations. The test sites were located in Fairbanks, Alaska, and on Attu Island, western Aleutians, to represent a typical point in the center of the area of main interest, and a site near the edge of the network (Figure 1). Each daily synthetic solution was transformed into ITRF in the same way as the actual data, ignoring the seasonal variation at the frame sites.

Seasonal variations were found in the resulting time series of test sites, which indicates that aliasing of seasonal variation at the frame sites into the reference frame parameters, and then into all site coordinates, biased the ultimate site coordinates. Both test sites showed apparent seasonal variations, but of different magnitude. The error from ignoring seasonal variations at the frame sites thus varies with space. Figure 6 shows the results for the test site in the western Aleutians. The time

series shows apparent horizontal seasonal variations of 1-2 mm amplitude, and vertical variation of ~4 mm amplitude, from a true time series that had no seasonal variation. Amplitudes were about half as large for the site closer to the center of the network.

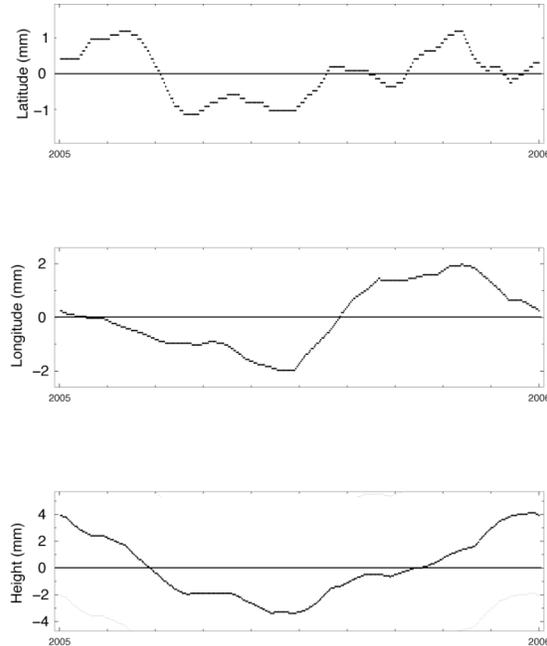


Fig. 6 Apparent seasonal variations in a test site, which had no seasonal variation in the true time series. The apparent variations are due entirely to aliasing of seasonal variations in the sites used to realize the reference frame, when only a linear model of site motion is used. There is considerable complexity and time-variability in this systematic error, which could be interpreted erroneously as time-varying tectonic signal or geophysical loading.

The induced bias is roughly opposite in phase to the seasonal variations in the frame sites: if the frame sites are high in the middle of the year, the test site is low. The aliased seasonal signal at the test sites did not exactly match the seasonal at any single frame site, but presumably reflects a weighted average of the frame sites. This result also suggests that if one of the frame sites is missing from the solution for a time, a subtle change in the reference frame realization bias will result, which might be interpreted as time-varying tectonic signal.

6 Discussion

The biases discussed in this paper do not result from errors in the ITRF model, but instead from the user's realization of the frame. Where significant seasonal variations are present, the ITRF may be considered limited in that it describes only the

average secular motion of sites, and not the seasonal variation. I have shown that seasonal variations have a significant impact on practical reference frame realization and thus on the use of the frame. We should consider moving toward an ITRF model that includes seasonal as well as secular terms to describe the motion of sites.

This study needs to be repeated on a global basis, because the impact of seasonal variations will be different for a global network than for a continental-scale network. I hypothesize that the dominant effect on a global network will be the long-wavelength seasonal variations that are now often modeled through low degree harmonic loading (*Blewitt et al., 2001*). With a continental-scale network, the biases in time series from aliasing of seasonal deformation may be largest in a case where the seasonal deformation varies systematically across the network, for example due to snow loading in the north, or where there is extreme hydrological loading in one part of the network, such as the Amazon Basin in South America. These cases may induce erroneous "tilts" in the user's realization of the reference frame, and will produce fictitious apparent seasonal variations in other sites used in the same solution.

When a small network is used, and daily reference frame transformation parameters are estimated to align the solution with a linear model of site motion, the result is a regional filter (e.g., *Wdowinski et al., 1997*). Regional filters can be very effective in removing truly common-mode seasonal and other variations, but if these variations are not truly common mode, then use of a regional filter may produce a time series in which the variations appear more temporally complex than they actually are. Imagine a case where sites in a network have similar seasonal variations but there is a systematic change of the phase of the variation across the network. Removing the average common mode variation with a regional filter would introduce beat frequency variations in time caused by differencing two similar but phase shifted periodic signals. Removing seasonal variations using a realistic geophysical model would be a better approach than removing most of the variations using a regional filter.

The impact of seasonal variations can be important even in cases where a user may not always recognize that they are making a regional reference frame realization. For example, one common practice is to estimate a velocity solution from a time series of minimally constrained solutions. This velocity solution would not be biased in itself, but if the time series of solutions was then aligned with the velocity solution, the aligned time

series may be biased if there are significant seasonal variations in the sites used to align the time series.

7 Conclusions

Based on analysis of 6 years of a regional GPS solution, seasonal variations in most GPS sites equal or exceed 4-5 mm amplitude in height. The seasonal variations at most sites are not sinusoids, nor do the curves match an annual plus semi-annual model well. At most sites, the negative part of the seasonal variation in height is larger in amplitude than the positive part, but shorter in duration. In northern North America, the seasonal variations are generally consistent with the expected phase from snow loading, and the amplitudes are reasonable based on other studies of snow and hydrologic loading.

When a set of sites are used to estimate a transformation to align a solution with ITRF or a regional velocity solution, ignoring the seasonal variations bias the reference frame parameters, and thus the coordinates of all sites in the transformed solution. A synthetic test shows that these biases can have amplitudes as large as a few mm, and can display considerable complexity in time.

When seasonal variations are present, reference frame realization or alignment of time series to a velocity solution should incorporate accurate seasonal variations for all sites used to estimate the frame transformation. These variations should be estimated on a global basis, and we should move toward a time-dependent ITRF model that incorporates seasonal variation in site coordinates as well as position and secular velocity.

Incorporating seasonal variations into the ITRF model would not be simple. The first problem is that some of the seasonal variation is due to technique-dependent systematic error rather than a geophysical signal (Ray 2006). However, based on the results shown here, I propose that the variations at sites that show large seasonal variations are dominated by signal rather than technique-dependent noise. Further research is required to test this hypothesis and isolate geophysical seasonal variations from systematic errors and noise. Seasonal residuals to the ITRF model at co-located multi-technique sites should be examined to test whether they are coherent, which should give insight into the magnitude of noise and technique-dependent systematic errors.

I propose that empirical studies of seasonal variation such as this study be combined with geophysical modeling to develop a set of first order seasonal corrections to the linear ITRF model. I

suggest that deformation caused by geophysical loading from load variations with dominant periods greater than tidal periods (greater than daily) be incorporated into a seasonal variation model rather than being incorporated into observation models. That is, seasonal variation models should include hydrologic loading, non-tidal ocean loading, and atmospheric loading. Geophysical models for some of these components may be good enough to provide a priori estimates of these deformations. Broad agreement on both the strategy and particular models would be required before seasonal variations can be incorporated into ITRF.

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