Sub-daily signals in GPS observations and their effect at semi-annual and annual periods

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Abstract: Estimates of seasonal geophysical loading from GPS may be biased by propagated unmodeled sub-daily signals. Although the major geophysical signals at semi-diurnal and diurnal frequencies are now routinely modeled in GPS analyses, the characteristics of unmodeled or mismodeled sub-daily signals are not well known. Here, using site coordinates estimated every 5 minutes, we examine the sub-daily coordinate spectral characteristics for ~90 global GPS sites. Unmodeled signals with amplitudes at the 10 mm level are present at frequencies between ~1/day and the Nyquist frequency. These are shown to propagate into 24 h solutions with (among other frequencies) annual

and semi-annual periods with amplitudes up to 5 mm, with a median amplitude in the height component of 0.8 mm (annual) and 0.6 mm (semi-annual). They are shown to bias low-degree spherical harmonics estimates of geophysical loading at the level of 5-10%, although the exact effect will be network dependent.

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1. Introduction

Geodetic measurements of periodic deformations of the Earth at annual and semi-annual timescales provide important information on the global water cycle [*Blewitt et al.*, 2001; *Mangiarotti et al.*, 2001; *van Dam and Wahr*, 1998; *Wu et al.*, 2003]. GPS measurements are of particular importance due to the spatial density and distribution of the global GPS network [*Wu et al.*, 2003]. However, GPS estimates of long (semi-annual to annual) period surface deformations are not currently in close agreement with independent GRACE estimates, for example [*King et al.*, 2006; *van Dam et al.*, 2007]. Of particular relevance is the effect of propagation of unmodeled or mis-modeled sub-daily GPS signals into annual, semi-annual and other long-period signals [*Penna and Stewart*, 2003; *Stewart et al.*, 2005], sometimes occurring with admittances of greater than 100% [*Penna et al.*, 2007]. For example, using conventional precise point positioning (PPP) techniques with data from International GNSS Service (IGS; [*Dow et al.*, 2005]) site KARR (21°S, 117°E), *Penna et al.* [2007] showed that an unmodeled signal of 3.4 mm amplitude with period 12 h (S2) in the north component propagates into a 4.2 mm amplitude semi-annual signal in the height component, an admittance of >120%. The accurate estimation of deformation (normally of the order of a few mm) at seasonal timescales using GPS therefore requires a rigorous treatment of sub-daily geophysical and non-geophysical systematic error sources.

Sub-daily periodic signals affecting GPS observations may originate from relatively well-known phenomena such as solid Earth tides, ocean tide loading, atmospheric pressure loading and higher-order ionospheric delays. Other sub-daily effects include inadequate satellite orbit modeling, tropospheric mapping function errors and multipath (see also *Ray* *et al.* [2007]). However, only solid Earth tide and ocean tide loading displacements are currently routinely modeled at the observation level in GPS data analyses and given the potential impact of the aforementioned admittances, errors in the modeling of all sub-daily phenomena must be considered (see *Watson et al.* [2006] for an example dealing with two disparate solid Earth tide models). The spectral characteristics of the unmodeled signal sources are sparsely understood [*Fritsche et al.*, 2005; *Tregoning and van Dam*, 2005] and we note that sub-daily signals have been identified in Earth orientation parameters [*Rothacher et al.*, 2001], tropospheric zenith delay estimates [*Humphreys et al.*, 2005] and coordinate time series [*Khan and Scherneck*, 2003] derived from GPS observations. In each of these cases the sub-daily spectrum has only been partially explained and the influence of these signals on standard 24 h GPS coordinate time series is not yet known.

To better understand the range and distribution of signals at sub-daily periods influencing GPS analyses, we examine the frequency content of sub-daily coordinate time series for ~90 globally distributed GPS sites. Through the simultaneous analysis of conventional 24 h GPS solutions we also investigate and quantify the propagation of these high-frequency signals into spurious low-frequency signals at annual and semi-annual periods.

2. Method and data

We analyzed GPS data collected between 2000.0 and 2006.0 at 90 of the IGS IGb00 reference sites (Figure 1) using the PPP strategy in GIPSY/OASIS v4 [*Zumberge et al.*, 1997]. In contrast to conventional positioning analyses, we estimate site coordinates every 5 minutes, refining a strategy previously used to measure ocean tides [*King and Aoki*, 2003] and ocean tide loading displacements [*King*, 2006]. First, the pseudorange data for each site session are smoothed using the carrier phase and then both the pseudorange and carrier data are decimated to 5 minute intervals. Next, the Jet Propulsion Laboratory (JPL) fiducial satellite orbits, clocks and Earth orientation parameters are held fixed, while station coordinates and tropospheric zenith delays are estimated at each epoch as random walk parameters and receiver clocks as a white noise process. Random walk process noise was set at 60 mm/√h and 4.8 mm/√h for the coordinates and tropospheric parameters respectively. A range of coordinate process noise values were tested with little difference found in the amplitude of the dominant sub-daily spectrum. The selected value is loose [*King and Aoki*, 2003] in order to avoid any possibility of over-smoothing the time series. Ambiguities were not fixed to integers. Solid Earth tides and ocean tide loading displacements were modeled according to IERS2003 standards [*McCarthy and Petit*, 2004] and the TPXO6.2 ocean tide model convolved through Green's functions respectively [*Egbert and Erofeeva*, 2002; *Agnew*, 1997]. To reduce day boundary jumps, data were processed in 30 h batches and then subsequently windowed to span a single 24 h period covering one UT day.

We note that using a simplified GPS model for site coordinates estimated every 24 h, the work of *Stewart et al.* [2005] predicts the existence of spurious low frequency signals in coordinate time series as a result of unmodeled periodic signals at diurnal and semi-diurnal frequencies. The same theory allows for spurious signals to be present even when coordinates are generated at high rates, such as in our 5 minute solutions, since the effect of the repeat period of the satellite constellation remains. To examine this, Eq. 30 of *Stewart et al.* [2005] was evaluated for the major tidal constituents for a period of ten years. Analysis of the resultant time series spectra suggests that in addition to the real input signal, spurious sub-daily signals may exist in our time series at sub-daily frequencies, but with amplitudes three orders of magnitude smaller than the real signal. No long-period spurious signals were predicted using the 5 minute solutions. These results were confirmed using a realistic GPS simulator [*King et al.*, 2003]. Since these effects are small, the high-frequency component of our 5 minute solution coordinate time series is expected to be influenced most significantly by unmodeled or mismodeled signals as previously discussed. The low-frequency component of the 5 minute solution spectra is, however, expected to be free from spurious propagated signals.

To compare with these solutions, we repeated the GPS data analysis except that site coordinates were estimated every 24 h and using only data in that window (i.e., conventional 24 h GPS PPP analyses with ambiguities not fixed to integers). Otherwise, the solutions were identical to those from which the sub-daily signals were estimated, including the modeling of ocean tide loading displacements and solid Earth tides.

3. Coordinate time series analysis

3.1 Sub-daily spectra

We computed the coordinate time series amplitude spectra, using the approach of *Scargle* [1982] as described in *Press et al.* [1992], after sub-sampling to one coordinate per 0.5 h and removing outliers defined by a tolerance of ±4 times the inter-quartile range. Typical high-frequency spectra for the three coordinate components are shown for site GOLD in Figure 2. Signals are evident and observed at all sites at or near several major tidal frequencies, such as K1, K2, S1, S2, but also at other frequencies including the harmonics of K1. The spectra show some site-to-site and component-to-component variability with respect to relative signal magnitude and the exact period of the signal near K1 varies from site to site, possibly due to multipath [*Georgiadou and Kleusberg*, 1988]. Amplitudes are typically several millimeters at ~K1, K2, S1 and S2, although can exceed 10 mm at some sites at these frequencies. This variability shows no obvious geographical correlation or dependence.

To test the constancy of these signals over the time series, we computed short-time Fourier transforms (spectrograms) for each site and compared these with those produced from simulated time series. The spectrograms used a second-order Goertzel algorithm [*Burrus and Parks*, 1985] approach enabling specific attention to the diurnal and semi-diurnal bands. To generate the simulated time series, firstly a harmonic analysis was performed on the entire time series and then a coordinate time series prediction made based on the determined time-constant (in amplitude and phase) constituent frequencies. The spectrogram was computed for this predicted time series and therefore shows only the effect of the diurnal and semi-diurnal constituents shifting in and out of phase.

Through comparison, the spectrograms of the observed time series suggest a time-varying behavior in the semi-diurnal and diurnal frequency bands, with Figure 3 an example for the height component of BAHR. This time-varying behavior will add complexity to any resulting long-period signals since it is not a simple time-constant systematic error as considered in *Penna et al.* [2007].

The sources of these sub-daily signals can, at present, only be partially explained. Previous analyses have reported biases in K1 and K2 estimates using GPS (see e.g., *Schenewerk et al.* [2001]) with inadequate satellite orbit modeling and multipath suggested as possible causes. For the S1 and S2 signals, *Tregoning and van Dam* [2005] show atmospheric pressure loading displacements of the order of 0.5-1.5 mm at these frequencies, although these are too small to explain a large portion of the signal observed in our time series. The clear latitude dependent relationship of the S1 and S2 atmospheric loading displacements is also not evidenced in our time series. Residual tropospheric delay errors may contribute to the S1 signals, and higher-order ionospheric effects (not taken in consideration in our analysis) may be partially responsible for the signal in the diurnal frequency band, but its sub-daily characteristic at a wide range of sites is not yet well known [*Fritsche et al.*, 2005]. Residual solid Earth tide and ocean tide loading signals are expected to be typically less than 1-2 mm at these frequencies at the majority of sites [see *Penna et al.*, 2007]. The observed spectra are therefore largely unexplained at present. However, as previously mentioned, their presence in GPS analyses involving conventional 24 h sessions, regardless of their origin, may result in spurious long-period signals at periods of distinct geophysical interest.

3.2 Propagation to long periods

In order to assess the effects of these signals on 24 h solutions, the conventional 24 h solution was compared with the high rate analysis. The 24 h coordinate time series were linearly interpolated to 0.5 h and differenced from the time series described in Section 3.1. This differencing removes any common geophysical signal and common mode noise. The resultant difference time series then contains unmodeled sub-daily signals (from the 0.5 h solutions) and any resulting long-period propagated signals. It is important to note for clarity that *i)* all common long-period (>1 day) geophysical signal is differenced, and *ii)* that sub-daily signals in all three coordinate components propagate into the height coordinate time series [*Penna et al.*, 2007]. The amplitude spectra of these differenced time series were then computed, revealing significant signals with, or close to, annual and semi-annual periods. In some cases, signals were evident also at 1/3 and 1/4 years. Amplitude spectra for a selection of sites are shown in Figure 4.

Fitting offset, linear rate and annual and semi-annual periodic terms to these differenced time series reveals the level of propagation at each site, as shown in Figure 1. Annual propagated signals reach ~4.2 mm (height), 1.0 mm (north) and 2.4 mm (east), with corresponding median values of 0.8 mm, 0.3 mm and 0.6 mm. Semi-annual propagated signals reach ~3.8 mm (height), 0.9 mm (north) and 5.5 mm (east), with corresponding median values of 0.6 mm, 0.2 mm and 0.4 mm.

Fitting only annual, semi-annual and linear terms leaves long-period signal (periods longer than ~3 months) in the time series, which we attribute to arise from the time-varying sub-daily signals producing broad spectral peaks. These include the harmonics of one year plus signal just greater than one year which could bias velocity estimates [*Blewitt and Lavallée*, 2002]. This residual noise contributes to GPS coordinate time series noise at the level of a few millimeters, on average.

4. Discussion and Conclusions

The signal present in these differenced time series would normally be indistinguishable from real geophysical signals of interest in conventional 24 h time series and hence would bias per-site estimates of low frequency geophysical loading and mass transfer signals. Comparing the amplitudes and phases of the semi-annual and annual terms (Figure 1) over western Europe, where the site density is greatest, suggests a level of signal coherence. However, signal coherence is not evident over larger regions (e.g., Australia), where the site density is lower. The level of bias will, therefore, be specific to each chosen study region. .

Computing their effect on low-degree (n<=4) spherical harmonic coefficients of non-secular global surface mass loading, reveals that, for this 90-site network, they may bias estimates by up to 5-10%, plus add random noise to their solution. Inferred loading estimates from time periods earlier than those considered here (pre-2000) may be subject to larger site-by-site biases due to worse sub-daily modeling at that time [*Watson et al.*, 2006] and greater effects from individual stations due to decreased station density. For example, *Blewitt et al.* [2001], used a cumulative IGS time series that, from 1994 until at least 2004, included insufficient or erroneous sub-daily solid earth tide models and fewer stations than used here. Furthermore, inter-comparison of GPS time series with GRACE data at semi-annual annual periods [*e.g., King et al., 2006*] will be affected by these errors.

Different orbit/clock products may also induce different sub-daily errors. Indeed, determining sub-daily solutions on a 15 site subset of the network using IGS products instead of JPL ones produced similar results but, when compared to the JPL spectra, the IGS spectra contained considerably broader peaks at sub-daily frequencies with typically larger amplitudes. Greater levels of site-by-site long-period signal bias would therefore be expected, with consequently larger (systematic and/or random) errors in low degree spherical harmonics derived from them.

To address the biases we have identified, the source(s) of these unmodeled signals must be determined. Satellite orbit modeling error is perhaps the most likely source of large (>2 mm) signals around K1 and K2 frequencies together with multipath [*Ray et al.*, 2007]. Candidate causes of the S1 and S2 signals are residual tropospheric delay and mapping function errors as well as atmospheric pressure loading and higher order ionospheric effects. In the absence of models accurate to ~0.1 mm, conventional 24 h 'static' solutions are not ideal and alternative parameterizations may need to be considered when analyzing GPS observation data for seasonal atmospheric, hydrologic and oceanic loading studies.

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Figures

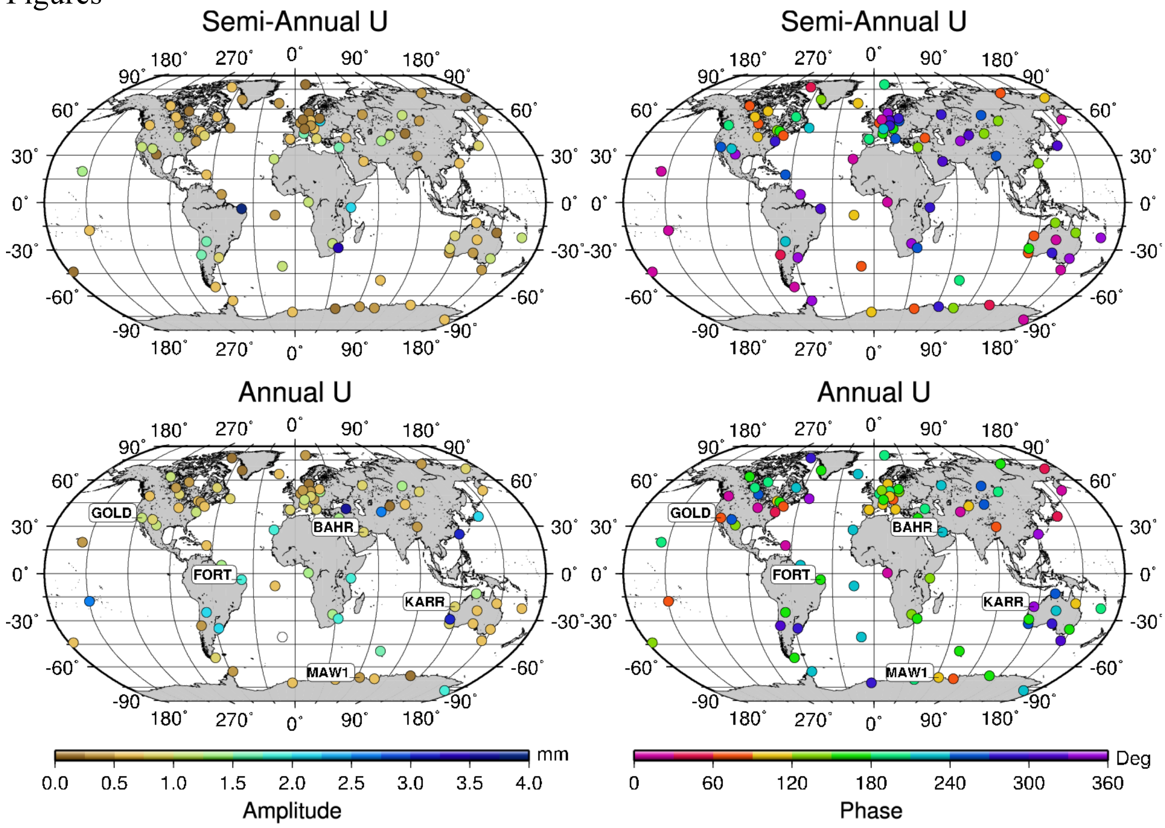

Figure 1:Height component semi-annual (top) and annual (bottom) amplitudes (left) and phases (right) due to the propagation of unmodelled sub-daily signals.

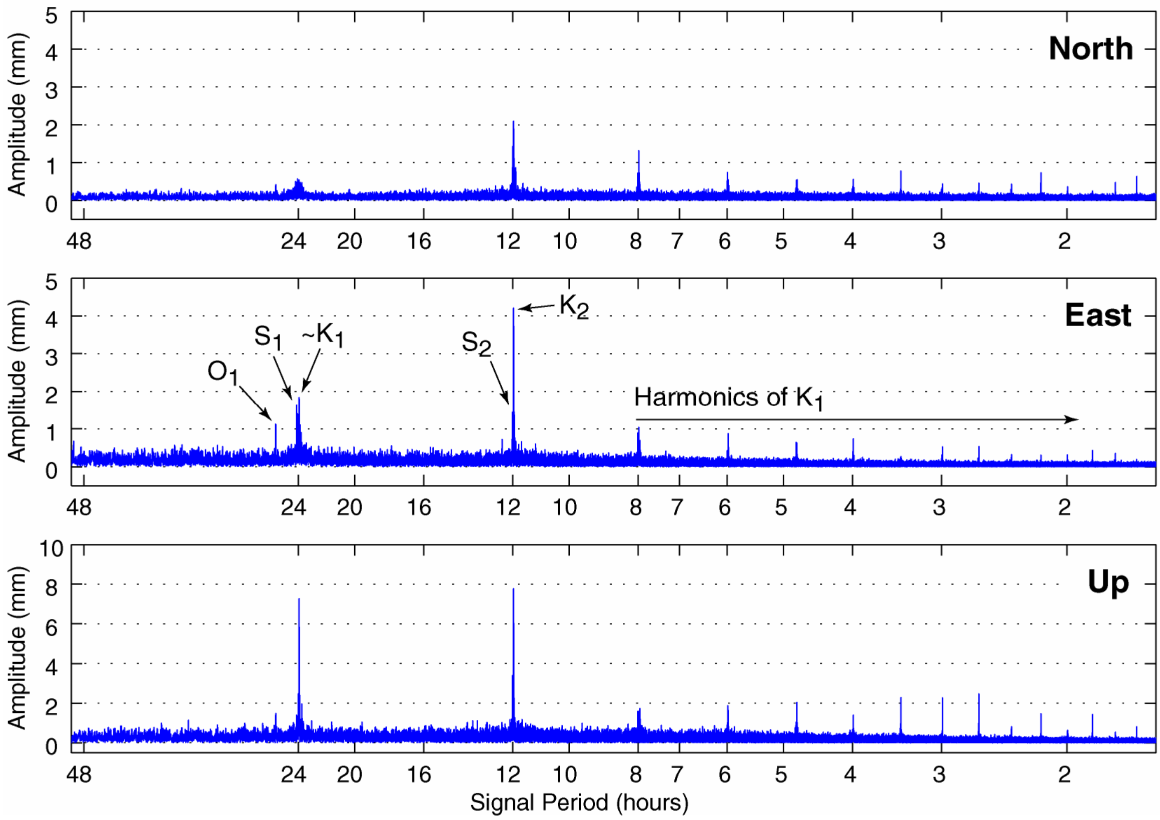

Figure 2: Spectra of the GOLD coordinate time series generated from the sub-daily PPP time series.

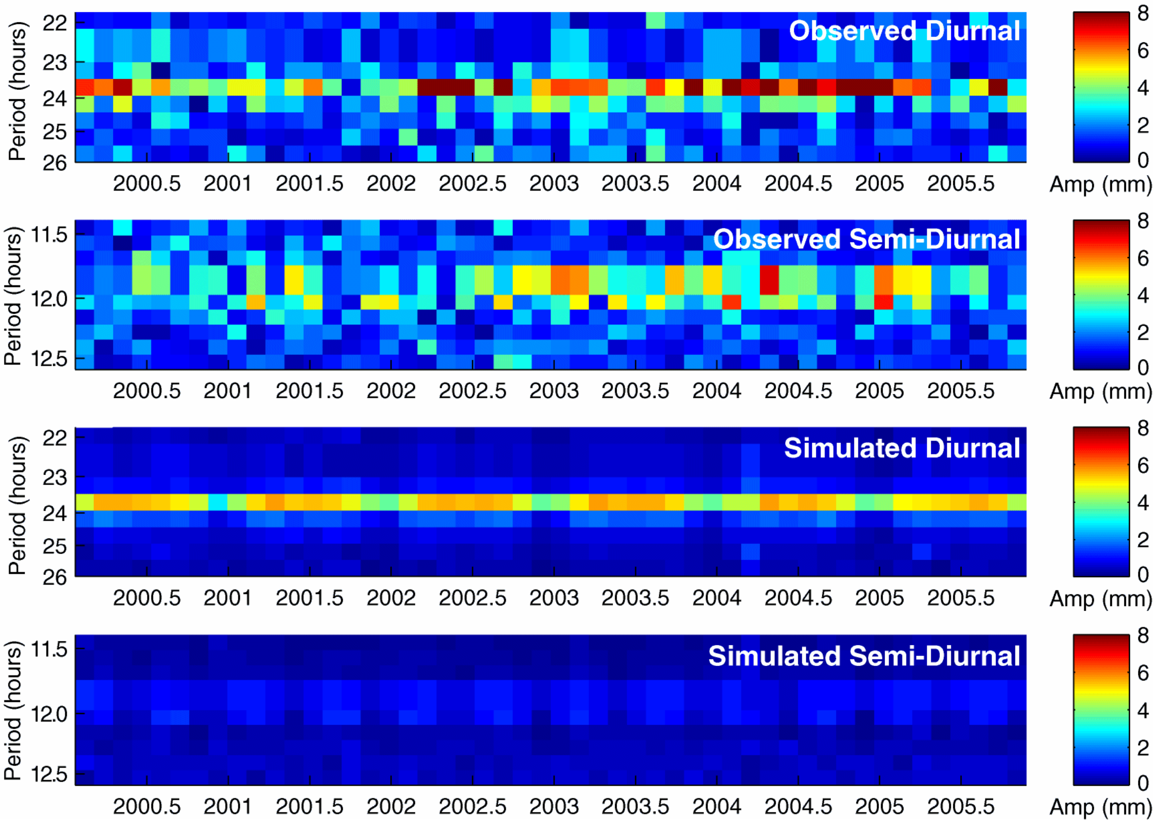

Figure 3: Spectrogram for the height component of site BAHR in the diurnal and semi-diurnal frequency bands using the observed time series and a simulated time series for BAHR based on assumed time-constancy of each constituent.

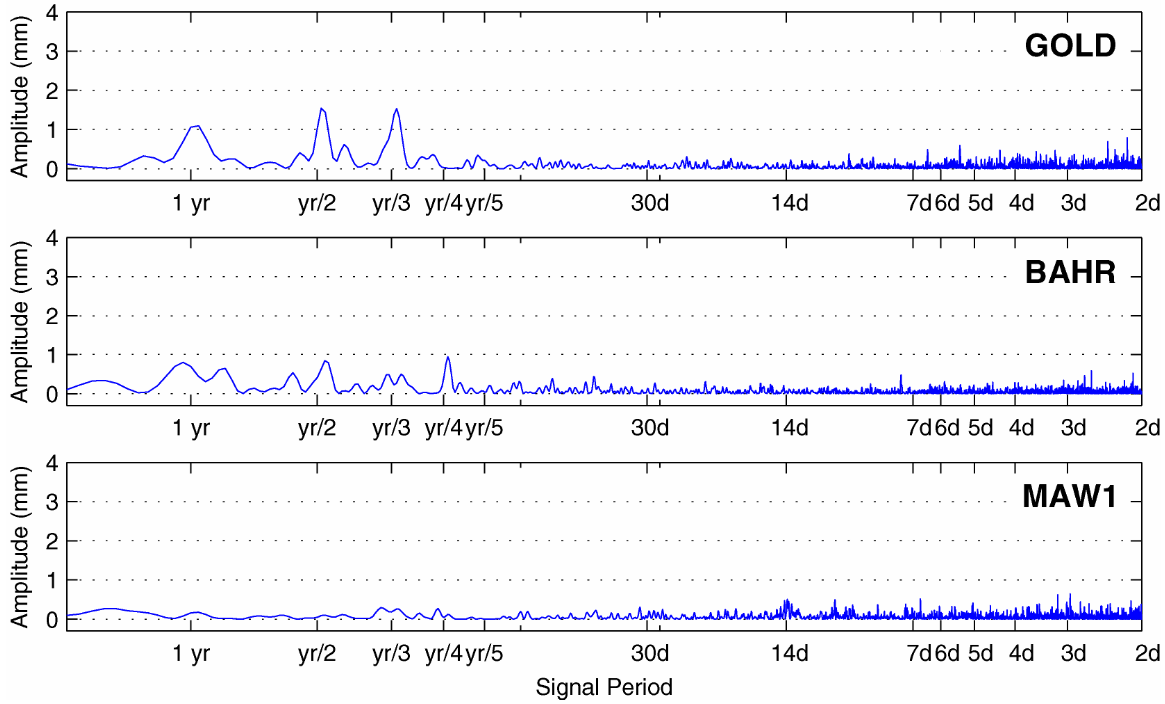

Figure 4: Long-period spectra of the differences between the 24 h and sub-daily PPP solutions for GOLD, BAHR and MAW1, arising from the propagation of unmodeled sub-daily signals.