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ORIGINAL ARTICLE

Anomalous harmonics in the spectra of GPS position estimates

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Abstract Prior studies of the power spectra of GPS position time series have found pervasive seasonal signals against a power-law background of flicker noise plus white noise. Dong et al. (2002) estimated that less than half the observed GPS seasonal power can be explained by redistributions of geophysical fluid mass loads. Much of the residual variation is probably caused by unidentified GPS technique errors and analysis artifacts. Among possible mechanisms, Penna and Stewart (2003) have shown how unmodeled analysis errors at tidal frequencies (near 12- and 24-hour periods) can be aliased to longer periods very efficiently. Signals near fortnightly, semiannual, and annual periods are expected to be most seriously affected. We have examined spectra for the 167 sites of the International GNSS (Global Navigation Satellite Systems) Service (IGS) network having more than 200 weekly measurements during 1996.0–2006.0. The non-linear residuals of the weekly IGS solutions that were included in ITRF2005, the latest version of the International Terrestrial Reference Frame (ITRF), have been used. To improve the detection of common-mode signals, the normalized spectra of all sites have been stacked, then boxcar smoothed for each local north (N), east (E), and height (H) component. The stacked, smoothed spectra are very similar for all three components. Peaks are evident at harmonics of about 1 cycle per year (cpy) up to at least 6 cpy, but the peaks are not all at strictly 1.0 cpy intervals. Based on the 6th harmonic of the N spectrum, which is among the sharpest and largest, and assuming a linear overtone model, then a common fundamental of 1.040 ± 0.008 cpy can explain all peaks well, together with the expected annual and semiannual signals. A flicker noise power-law continuum describes the background spectrum down to periods of a few months, after which the residuals become whiter. Similar sub-seasonal tones are not apparent in the residuals of available satellite laser ranging (SLR) and very long baseline interferometry (VLBI) sites, which are both an order of magnitude less numerous and dominated by white noise. There is weak evidence for a few isolated peaks near 1 cpy harmonics in the spectra of geophysical loadings, but these are much noisier than for GPS positions. Alternative explanations related to the GPS technique are suggested by the close coincidence of the period of the 1.040 cpy frequency, about 351.2 days, to the ‘‘GPS year’’; i.e., the interval required for the constellation to repeat its inertial orientation with respect to the sun. This could indicate that the harmonics are a type of systematic error related to the satellite orbits. Mechanisms could involve orbit modeling defects or aliasing of site-dependent positioning biases modulated by the varying satellite geometry.

Keywords GPS · Positions · Reference frames · VLBI · SLR · Geophysical surface loads

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Introduction

Spectra of time series of GPS position residuals (after fitting and removing the linear trends expected for purely tectonic motions) have been studied by a number of investigators. The general features are considered fairly well known. Seasonal signals (defined to consist of annual plus semiannual variations) are pervasive, superposed against approximately power-law backgrounds. Overall residual power declines with increasing frequency (''red'' spectrum) consistent with a flicker noise distribution plus white noise at high frequencies (Williams et al. 2004). The physical mechanisms giving rise to temporal correlation of the GPS residuals, as implied by the flicker spectra, have not been positively identified though a variety of causes can be suggested. Possibilities include both geophysical effects (mismodeled tides, non-tidal loading displacements, etc.) and technique errors (long-term orbit mismodeling, long-wavelength multipath, etc.). Nevertheless, the significance of non-white processes is widely recognized and is routinely taken into account to compute formal errors for integrated quantities such as site velocity estimates (e.g., Zhang et al. 1997; Mao et al. 1999).

Seasonal position variations, especially in height, are expected due to a variety of geophysical loading effects associated with the large-scale transport of terrestrial fluids. GPS time series can thus be viewed as monitors for such dynamics (e.g., Blewitt et al. 2001) and their inferred loading signatures can be compared with the attendant gravity field changes (e.g., Wu et al. 2006). However, Dong et al. (2002) estimated that less than half the observed GPS seasonal height variation can be explained by movements of geophysical fluid mass loads. Much of the residual seasonal power is probably caused by unidentified GPS technique and/or analysis errors. Among possible mechanisms, Penna and Stewart (2003) have shown how unmodeled analysis errors at tidal frequencies in the diurnal and semidiurnal bands can be efficiently aliased to longer periods. Artifactual signals near fortnightly, semiannual, and annual periods are expected to be most serious.

Instrumental effects have also been implicated as contributing non-geophysical seasonal variations. Dong et al. (2002) suggested that local multipath biases, site-specific environmental changes, and antenna phase center modeling (Hatanaka et al. 2001) could all be important. Ray et al. (2005) and Ray (2006) showed clear correlations between GPS position variations (mostly annual) and various data quality metrics, such as code multipath levels, data yields, and number of phase cycle slips. Onset and disappearance of annual signals were also found to coincide with changes in receiver models at a number of GPS stations (e.g., FORT, NOUM, MCM4, IISC, MAC1, FLIN). Large horizontal shifts each winter in the YAKT position (and data quality) were found to be caused by snow covering the antenna (Steblov and Kogan, 2005). Such observations do not necessarily imply a direct causal connection between data quality and position changes, though that is possible. The more general conclusion is that a common instrumental basis is likely responsible, at least partially, for variations in both positions as well as data metrics. Whatever the underlying instrumental source, it appears to respond sensitively to seasonal forcing.

Most prior spectral studies have examined time series of individual stations, albeit sometimes for large numbers (Williams et al. 2004). Resolution of spectral features, and even the background power-law spectral index, has consequently been limited by noise. To average down uncorrelated background noise, Blewitt and Lavallée (2002) stacked periodograms of height residuals for 23 sites. They noted the appearance of ''annual harmonics'' up to 5 cycles per year (cpy), but their stacked spectrum was still poorly resolved and they did not discuss more than the annual and semiannual signals. Ray et al. (2005) reported an anomalous common-mode peak near 4 cpy in the height spectra for 14 continuous GPS time series.

We have extended such analyses using a much larger set of continuously observing GPS stations, each with longer time spans, and including horizontal as well as vertical components. Our goal is to improve the resolution of common spectral features and to clarify the character of the power-law background. In addition, GPS-based position residuals are compared to similar geodetic results from very long baseline interferometry (VLBI) and satellite laser ranging (SLR) in an effort to assess any technique-dependent effects, and compared to expected geophysical loading displacements to assess the role of geophysical effects. A preliminary presentation of our results was given by Ray et al. (2006).

Spectra of raw GPS time series: stacked and smoothed

The GPS time series used here are the non-linear residuals generated in the ITRF2005 combination (Altamimi et al. 2007) from the weekly combined global frames produced by the International Global Navigation Satellite System Service (IGS) (Ferland, 2004). In the ITRF2005 combination, each weekly IGS frame has been aligned to a self-consistent secular reference by applying a 7-parameter Helmert transformation relative to the long-term stacking. The full variance-covariance matrix for each IGS weekly frame has been used. Strictly linear site motions have been assumed except when discrete discontinuities have been introduced, usually based on empirical evidence but often corresponding to equipment changes.

A Lomb-Scargle periodogram (Press et al. 2001) has been computed for each of the 167 IGS stations having more than 200 weekly points during the period 1996.0–2006.0. The local north (N), east (E), and height (H) components have been handled separately. The normalized spectra have been stacked (that is, aggregated into a single file) by component and each smoothed using a boxcar smoother with full width of 0.050 cpy. Figure 1 shows the results we obtain, where the N and E components have been offset for clarity. Vertical dashed lines have been plotted in Fig. 1 for harmonics of 1.0 cpy as an aid.

All three components exhibit very similar behavior. Even though the amplitudes of the height variations are larger than those in the horizontal directions, the precision of height determinations is correspondingly poorer, so the relative power distributions are alike. A harmonic comb of peaks is seen in all three spectra at a common set of frequencies. While the two lowest frequency peaks seem to match annual and semiannual periods, it becomes progressively more apparent at the higher frequencies that harmonics of 1.0 cpy do not fit the observed peaks. The main peaks are instead shifted to slightly higher frequencies.

Still, there are minor indications of very small, narrow sideband peaks that fall closer to the annual harmonics. These are most apparent as possible ‘‘shoulders’’ on the 3rd harmonic band, small side peaks in the 4th H and E bands, and a modest peak near 6.0 cpy in the H spectrum. We will examine this question more closely in the next section.

Filtered GPS spectra: seasonal fits removed

Next we examine the same spectra but first remove seasonal (annual plus semiannual) fits before computing the periodograms. All other processing and data selection is the same as before. There are two reasons to consider such a filter. Periodograms of unevenly sampled data (as is inevitable in these time series) always run some risk of creating artificial peaks in the presence of large low-frequency peaks, especially if there are regular patterns in the sampling. The gaps in our time series are usually caused by irregular and infrequent data outages and so such risks should be minor. In addition, we expect significant seasonal power for both geophysical (Dong et al. 2002) and technique-related (Penna and Stewart 2003) reasons. By removing that signal first, we can then better search for any others that might also be present.

Figure 2 shows filtered versions of the same spectra as in Fig. 1. Except for the seasonal bands, the remaining peaks in Fig. 1 persist after filtering with almost no change. This implies that they are not artifacts of the large seasonal power being redistributed due to uneven sampling. Separately, Collilieux et al. (Spectral and correlation analyses of ITRF2005 VLBI, GPS and SLR height residuals: How well do space geodetic techniques agree?. J Geophys Res) have conclusively detected the first four peaks in the height spectra of individual GPS stations using a more robust least-squares estimation method that is insensitive to sampling irregularities. However, they were unable to resolve the frequencies of the peaks as precisely as our stacking over many GPS stations. Using sinusoidal fits for

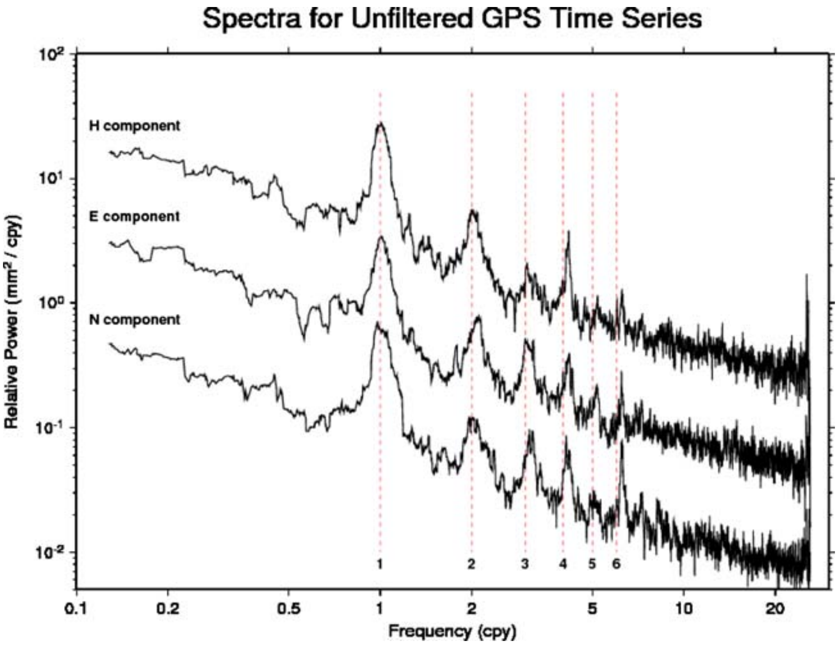


Fig. 1 Stacked periodograms of the non-linear position residuals for the 167 IGS stations having more than 200 weekly measurements between 1996.0 and 2006.0. Each has been smoothed using a boxcar smoother with full width of 0.050 cycles per year (cpy). The E and N components have been shifted downward for clarity (by factors of 5.3 and 33, respectively). *Vertical dashed lines* indicate harmonics of 1.0 cpy

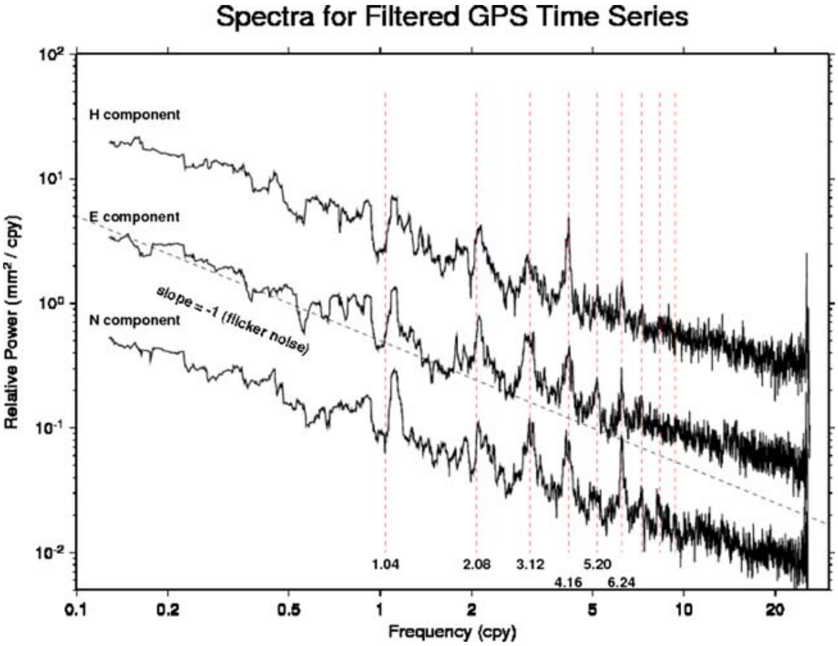


Fig. 2 The same spectra shown in Fig. 1 except that annual and semiannual fits have been removed from each time series before computing the periodograms. The same smoothing and plotting specifications have been used, but that the *vertical dashed lines* indicate harmonics of 1.04 instead of 1.0 cpy. The power-law behavior of flicker noise is illustrated by the *dashed line* with slope –1 (labeled)

a 4.14 cpy wave, Collilieux et al. were able to map the global distribution of that height harmonic. The largest amplitude is 4.6 ± 0.5 mm at the Alert station (in north-eastern Canada) but most detections (with signal-to-noise detections of >3.5) are less than 2 mm. The strongest 4th height harmonics are generally at high-latitude stations, especially in North America, and there are clear spatial correlations there and in western Europe.

The vertical dashed lines in Fig. 2 are now drawn for harmonics of 1.04 cpy rather than 1.0 cpy. The fundamental tone was determined by examination of the 6th harmonic of the N spectrum, one of the sharpest and largest, at 6.240 ± 0.050 cpy, and assuming a linear overtone model (The uncertainty quoted here is conservatively taken as the half-width of the peak at half maximum). That implies a fundamental generating tone of 1.040 ± 0.008 cpy. It is evident from Fig. 2 that such a harmonic overtone model fits the observed sub-seasonal spectral peaks well, especially for the relatively narrow 4th, 5th, and 6th peaks of all three components. There are suggestions of peaks extending to the 7th, 8th, and 9th harmonics in the N component. Furthermore, there is clear power remaining on the high-frequency sides of 1.0 and 2.0 cpy even after the seasonal filtering. This is a strong indication that the observed seasonal bands actually consist of (1.00 + 1.04 cpy) and (2.00 + 2.08 cpy) components, albeit all seem to be broadband. Given the spans of our GPS series and the broadband nature of the seasonal peaks, it is not possible to separate the nearby frequency pairs more clearly.

In addition to the 1.04 cpy harmonics, the previous indications of very small, narrow annual harmonics also persist largely unchanged after filtering. Since the strong seasonal peaks were already removed, it is unlikely that the higher harmonics are generated artificially by the periodogram algorithm. Figure 3 shows an expanded view of a portion of the spectra in Fig. 2; here the vertical dashed lines mark harmonics of 1.0 cpy. Possible small peaks are observed near 4.0 for all three spectra and near 5.0 and 6.0 for E and H. However, none can be considered significant above the background noise. Their appearance is intriguing nonetheless. All seem to be shifted to very slightly higher frequencies than would be expected for exact 1.0 cpy harmonics (most clearly seen in the relatively distinct H peak nearest 6.0 cpy). If they are indeed really present, then they are more likely to be consistent with the 364.10-day alias period (1.0032 cpy) found by Penna and Stewart (2003), who used simulated GPS data and introduced analysis errors at various tidal frequencies to determine the long-period responses in height time series. Errors at the K1 tidal period (23.93 hours) produced a spectral peak at 364.10 days. Our spectra are not sufficiently robust to claim detection of this alias feature but they do justify future closer, high-resolution studies.

As can be seen by comparing the spectra in Fig. 2 with the dashed line with slope –1, the overall behavior for all three components is consistent with flicker frequency noise down to periods of a few months. The spectral peaks confuse the interpretation somewhat and would do so even more in spectra for individual (unstacked) time series. At higher frequencies the background noise becomes whiter, either due to the intervention of a white noise frequency floor or because of a change in the basic character of the underlying noise process to some type of non-integer

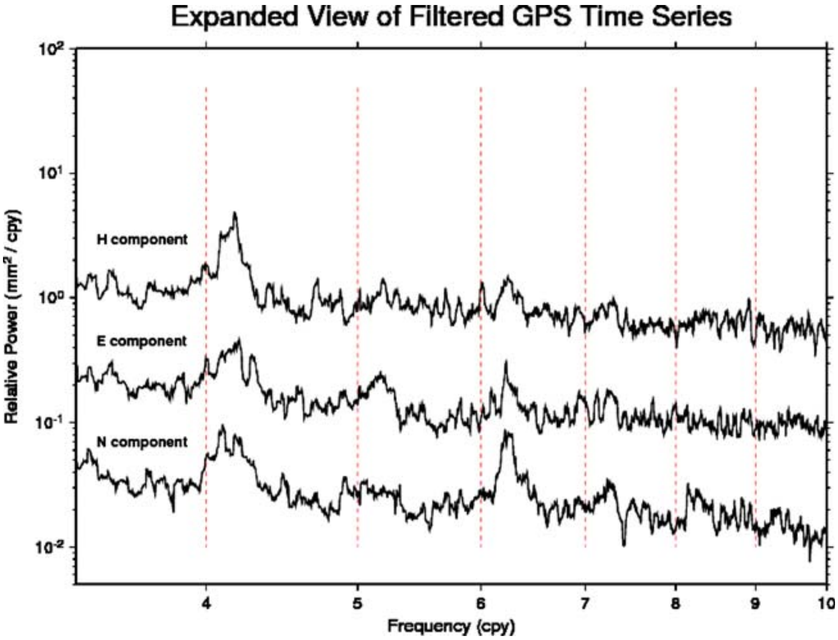


Fig. 3 An expanded view of the spectra shown in Fig. 2. *Vertical dashed lines* indicate harmonics of 1.0 cpy

power law intermediate between flicker and white distributions.

Compare to VLBI and SLR spectra

In an attempt to determine whether the near-annual harmonics seen in the GPS spectra might arise from genuine motions of the observing sites, we next examine smoothed, stacked spectra for time series of independent VLBI and SLR positions. As with the GPS results, the non-linear VLBI and SLR position residuals were produced in the ITRF2005 combination process. In general, the same or equivalent a priori geophysical models have been used in the reduction of raw data from GPS, VLBI, and SLR. The VLBI solutions were computed by the analysis coordinator for the International VLBI Service (IVS) using a combination of analyses by six independent groups (Vennebusch et al. 2007). The position time series consist of integrations for each 24-h VLBI observing session. The VLBI sessions occur non-continuously at irregular intervals, as opposed to the weekly, continuous integrations for GPS and SLR. VLBI data are available from 1980.0 to 2006.0 but only the 23 stations having more than 200 daily position determinations were used. Spectra (unfiltered) were generated in the same way as for Fig. 1 and shown in Fig. 4; only points with formal errors less than or equal to 25 mm have been used.

Figure 5 presents comparable spectra for the 27 SLR stations with more than 200 weekly points based on data collected from 1993.0 to 2006.0. The weekly frames were computed by the analysis coordinator for the International Laser Ranging Service (ILRS) using a combination of SLR solutions from five independent groups (Luceri and Pavlis The ILRS solution, itrf.ensg.ign.fr/ITRF_solutions/2005/doc/ILRS_ITRF2005_description.pdf). Even though the ILRS solutions are continuous and reported at regular mid-week intervals, the underlying station ranging data are not continuous. Data quality can vary and there are occasional observational gaps. All points with formal errors greater than 25 mm have been excluded.

Inspection of Figs. 4 and 5 fails to find much similarity with the corresponding GPS results in Fig. 1. There is no comb of near-annual harmonics in either the VLBI or SLR spectra. The VLBI heights have a prominent annual peak, which is also weakly present in the N but not in the E. Semiannual variations are either absent or obscured by noise. Annual peaks are pronounced in all three SLR components. Inter-annual variability is also evident in the SLR time series but not semiannual or other sub-seasonal signals. The lack of strong annual variations in the VLBI horizontal positions is striking in view of the SLR, GPS, and expected geophysical loading (see next section) results. We speculate that the horizontal motions of the VLBI stations might be substantially absorbed into time-varying biases of the associated polar motion estimates and Helmert transformation parameters due to the limited number of stations and sub-global coverage of most individual observing networks.

Using a novel method, Collilieux et al. (2007) have shown elsewhere that co-located GPS and VLBI height time series are well correlated for every site with sufficient data. The finding is robust whether annual signals

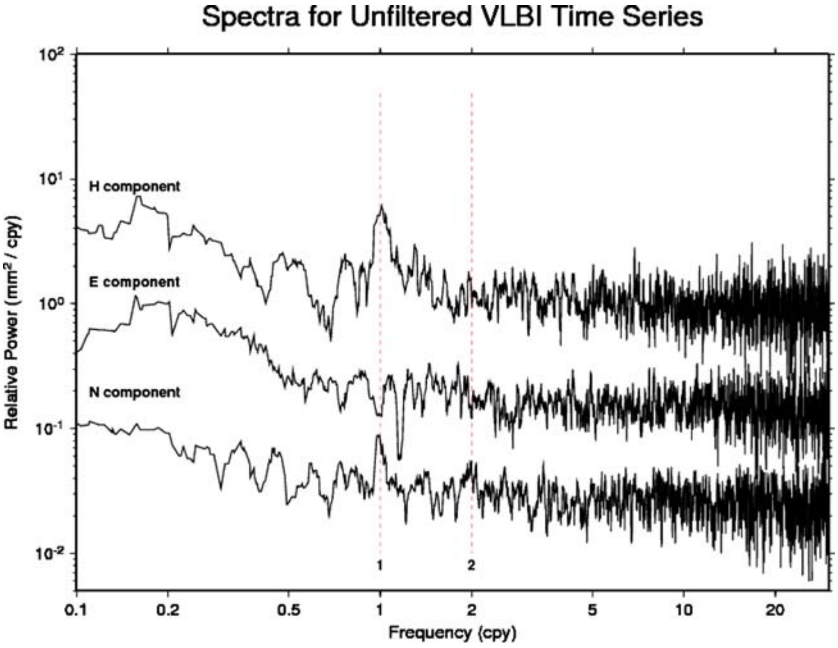


Fig. 4 Stacked, smoothed periodograms of the non-linear position residuals for the 23 VLBI stations having more than 200 daily measurements between 1980.0 and 2006.0. Each has been processed and displayed as in Fig. 1 except the *vertical dashed lines* mark only annual and semiannual frequencies

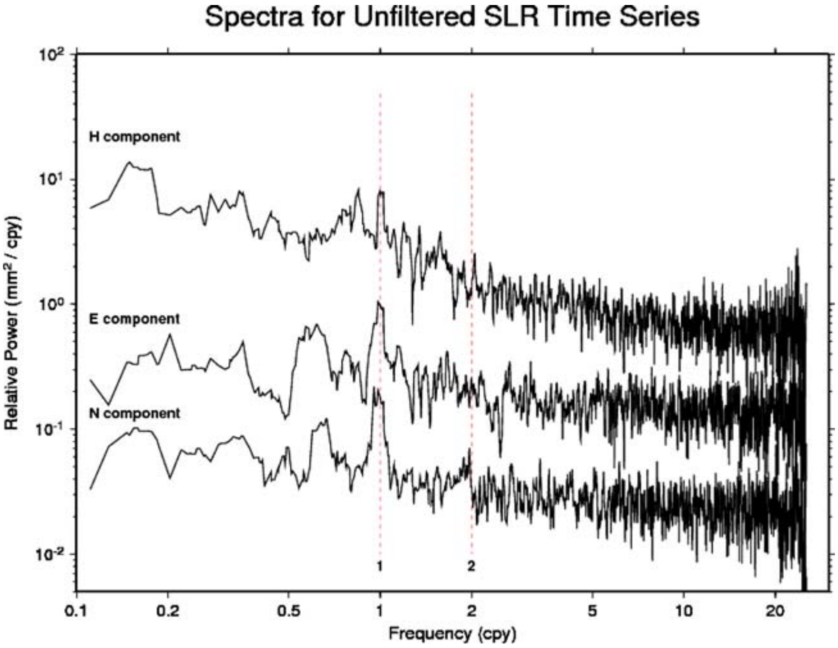


Fig. 5 Stacked, smoothed periodograms of the non-linear position residuals for the 27 SLR stations having more than 200 weekly measurements between 1993.0 and 2006.0, as in Fig. 4

are included or removed. Results are less certain for the very few co-located GPS and SLR stations with usable data sets. In addition, the annual GPS height signals are spatially correlated over some continental regions and match VLBI and SLR annuals in areas like Australia and South Africa. Those findings support the conclusion that all three techniques sense geophysically based height displacements, at least in part. On the other hand, our present VLBI and SLR spectral results from a relatively limited set of sites do not support genuine site motions as the origin of the GPS sub-seasonal harmonics due to the relatively high noise levels, predominantly white. To test the effect of the larger number of GPS stations, a 90% decimation was applied to the stacked GPS periodograms before smoothing. While producing much noisier spectra (not shown), the use of fewer data did not fully obscure the 4th harmonic in all three components. It should also be noted that stacked spectra of the GPS position formal errors are featureless except for peaks at 2 cpy for each component.

Compare to geophysical fluid loadings

To evaluate the extent to which geophysical fluid loadings are responsible for the GPS harmonics, we have computed spectra for the expected effects due to variation in atmospheric pressure (van Dam and Wahr 1987), non-tidal ocean pressure (van Dam et al. 1997), and continental water storage (van Dam et al. 2001). The atmospheric loading is calculated from 6-hourly estimates of global atmospheric surface pressure from the National Center for Environmental Predictions' Reanalysis data (Kalnay et al. 1996). The 6-h pressure data (2.5° × 2.5°) are convolved with Farrell's Green's functions (Farrell, 1972) and averaged into weekly values centered on the GPS week. For the non-tidal ocean load estimates, we have used the bottom pressure from the National Ocean Partnership Program Estimating the Circulation and Climate of the Ocean (ECCO) model (www.ecco-group.org). These data are provided at 12-h intervals on a 1° × 1° global grid. As with the atmospheric pressure, they were averaged to the GPS weekly epochs. The loads from the continental water storage were derived from the LaDWorld-Euphrates land-energy balance model (Milly and Shmakin 2002; Shmakin et al. 2002). The water storage model consists of monthly estimates of water storage due to snow, ground water, and soil moisture variability at 1° × 1° spacings over the land surface of the Earth. We ignore the loading due to the snow component of the model at latitudes north of 75N and south of 60S as the snow dynamics in the model are not considered reliable in these regions. These monthly loads are then interpolated to the GPS week using a cubic spline. The atmospheric and oceanic time series are for the 313 weeks from 2000.0 to 2006.0 while the water storage series is available only for the 280 weeks from 2 January 2000 to 14 May 2005. Such series have been assembled for the same set of 167 GPS sites discussed above. Periodograms were generated in the same way as for the geodetic series, including stacking and smoothing. The resulting spectra are shown in Figs. 6, 7, and 8.

The atmospheric loading has prominent seasonal peaks, but no comb of sub-seasonal harmonics; see Fig. 6. Possible variations near 3 cpy can be seen in the H and N spectra but these are not distinct above the background noise and no other harmonics are visible. The overall power distribution is approximately flat down to periods of about one month, after which it declines. The characteristics of the oceanic loading spectra (Fig. 7) are quite similar, the main difference being that the break between flat and declining power is at periods of about two months.

The surface water spectra (Fig. 8) are highly dissimilar. The peaks are less well resolved due to the shorter span of data but harmonic combs are nevertheless prominent in all three components, extending to at least ~8 cpy. The sub-seasonal variations fall at multiples of 1.0 cpy, rather than near the GPS harmonics, and the overall power distribution declines steeply. The general behavior probably reflects a predominantly climatological hydrologic model with limited assimilation of in situ observations. The annual harmonics are almost certainly an artifact of the weekly interpolation of monthly grids.

Our loading results generally confirm prior demonstrations of strong seasonal site displacements (e.g., Dong et al. 2002). However, the anomalous sub-seasonal peaks seen in our GPS spectra do not find an obvious geophysical explanation.

GPS ''draconitic'' year

As far as we know, our inferred harmonic generating tone at 1.040 ± 0.008 cpy (or period of 351.2 ± 2.8 days) does not correspond to any significant geophysical frequency or expected alias. However, U. Hugentobler (private communication, 2006) suggested a possible link with the ''GPS draconitic year'', the interval needed for the Sun to return to the same point in space relative to the GPS orbital nodes (as viewed from the Earth). Since the GPS nodes drift in space by about –14.16° per year, primarily due to the effect of the Earth's oblateness, a GPS year equals 351.4 days, or a frequency of 1.039 cpy. The very close correspondence of these periods is striking, suggesting a possible causal connection.

At least two types of coupling mechanism are possible. Long-period GPS satellite orbit modeling errors could be directly responsible for small periodic biases in station position determinations. The sun-satellite interactions, which are important in forcing the satellite dynamics, are also particularly difficult to model effectively. A dramatic example is the behavior during the twice-yearly eclipse periods when the Earth blocks the exposure to the sun once per revolution for all satellites in the same orbital plan. Hugentobler (2005) has shown, for example, how GPS estimates of geocenter offsets repeat with a period of about 350 days due to such orbital effects.

Other mechanisms could involve the repeating geometry of the satellite constellation with respect to the tracking stations. The daily advance of the constellation repeat geometry is about 246.8 s, which aliases to the same period of about 350 days for the standard 24-hour sampling used by the IGS (Agnew and Larson, 2007). Any local direction-dependent observational biases, such as due to multipath, could be expected to show up with a 350-day repeat period. Since high-frequency multipath variations are more likely to average to a minimal bias level, long-wavelength (i.e., near-field) reflections are most suspect. Errors or approximations in the antenna or radome calibrations, for instance,

Fig. 6 Stacked, smoothed periodograms of the expected motions due to atmospheric pressure loading for the 167 IGS stations used in Fig. 1. Weekly averages for the period 2000.0 to 2006.0 (313 weeks) were used. The processing and display characteristics are the same as in Fig. 1 except that the vertical dashed lines indicate seasonal signals (1.0 and 2.0 cpy) and the anomalous GPS harmonics at 3.12, 4.16, 5.20, and 6.24 cpy

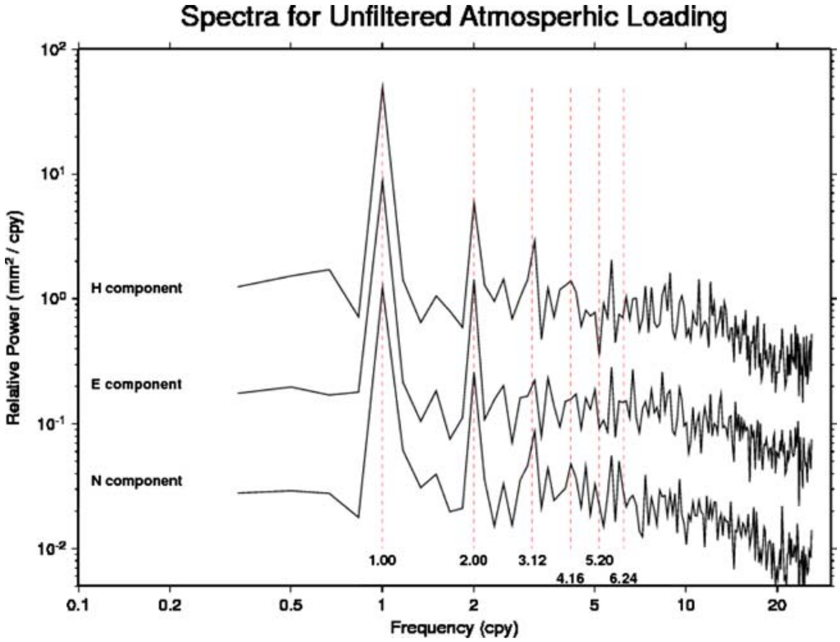
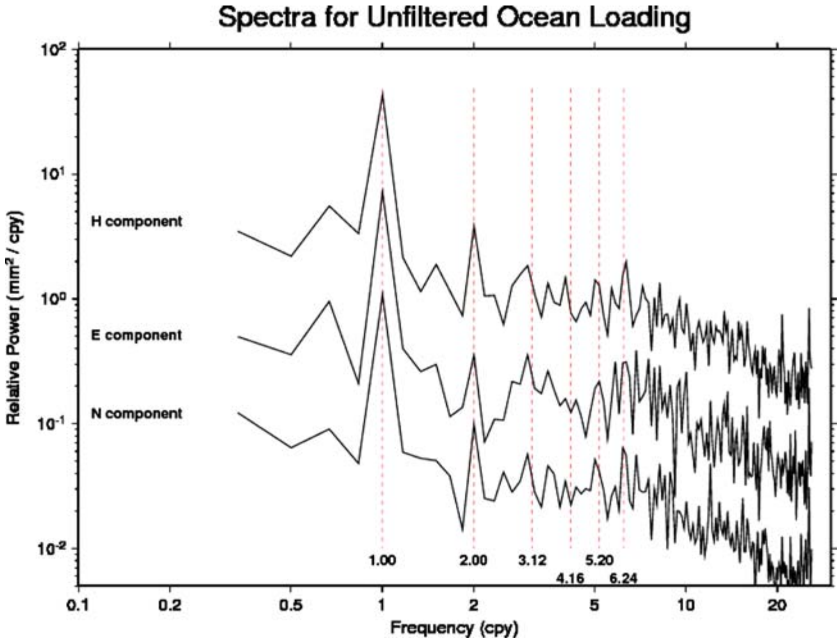


Fig. 7 Stacked, smoothed periodograms of the expected motions due to non-tidal ocean loading for the 167 IGS stations used in Fig. 1, as in Fig. 6



or neglect of near-field scattering (Elósegui et al. 1995) are prime candidates for such biases. There is, of course, the possibility that both orbit and antenna-based mechanisms affect the IGS position time series.

Conclusions

We find no confirmation of the anomalous GPS position harmonics (multiples of ~1.04 cpy) in corresponding results from VLBI or SLR, nor in geophysical loadings due to atmospheric pressure, non-tidal ocean bottom pressure, or continental water storage. Because of this and the fact that the anomalous period of ~350 days matches the GPS constellation repeat cycle, it seems likely that the harmonics are a consequence of some technique error. To isolate the dominant effect to orbit mismodeling or to local site geometry-dependent biases will require further detailed studies.

It is worth noting that the presence of 1.00 and 1.04 cpy variations should generate beat modulations at 0.04 and 2.04 cpy, or periods of about 25 years and 179 days, respectively. The long-period beat period could bias

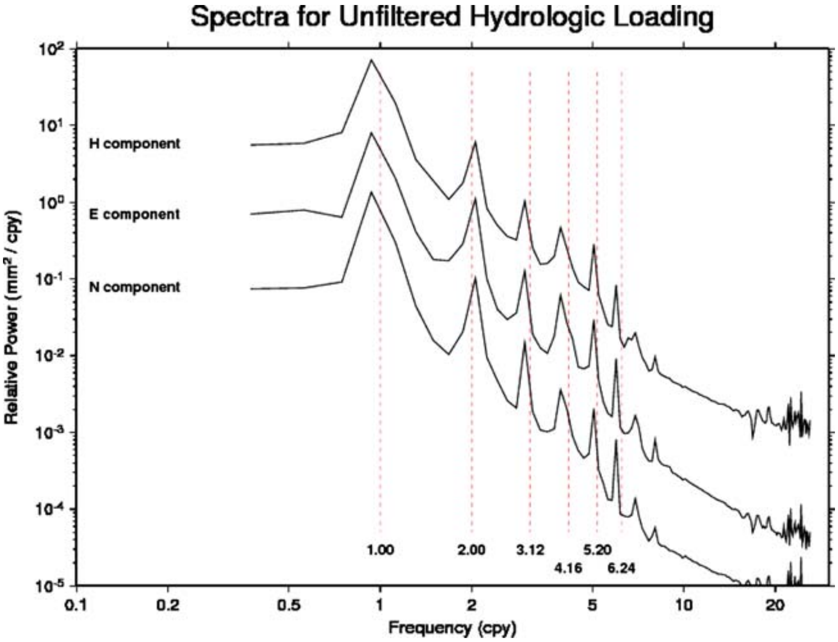


Fig. 8 Stacked, smoothed periodograms of the expected motions due to loading by continental water for the 167 IGS stations used in Fig. 1, as in Fig. 6 except that weekly averages for the 280 weeks from 2 January 2000 to 14 May 2005 were used

velocity estimates if samples are not collected often enough (or long enough) to average out the effects. In addition, fits for seasonal geophysical signals will be contaminated by the 1.04 cpy harmonic unless the geophysical effects are overwhelmingly larger.

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References

Agnew DC, Larson KM (2007) Finding the repeat times of the GPS constellation. GPS Solutions 11:71–76

Altamimi Z, Collilieux X, Legrand J, Garayt B, Boucher C (2007) ITRF2005: a new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters. J Geophys Res, in press

Blewitt G, Lavallée D (2002) Effect of annual signals on geodetic velocity. J Geophys Res 107(B7):2145. doi: 10.1029/2001JB000570

Blewitt G, Lavallée D, Clarke P, Nurutdinov K (2001) A new global mode of Earth deformation: seasonal cycle detected. Science 294:2342–2345

Collilieux X, Altamimi Z, Coulot D, Ray J, Sillard P (2007) Spectral and correlation analyses of ITRF2005 VLBI, GPS and SLR height residuals: How well do space geodetic techniques agree? J Geophys Res, submitted

Dong D, Fang P, Bock Y, Cheng MK, Miyazaki S (2002) Anatomy of apparent seasonal variations from GPS-derived site position time series. J Geophys Res 107(B4):2075. doi: 10.1029/2001JB000573

Elósegui P, Davis JL, Jaldehag RTK, Johansson JM, Niell AE, Shapiro II (1995) Geodesy using the Global Positioning System: The effects of signal scattering on estimates of site position. J Geophys Res 100(B7):9921–9934

Farrell WE, (1972) Deformation of the Earth by surface loads. Rev Geophys Space Phys 10:761–797

Ferland R (2004) Reference frame working group technical report. In: Gowey K, Neilan R, Moore A (eds) IGS 2001–2002 technical reports, Jet Propulsion Laboratory Publication 04-017, Pasadena, pp 25–33 (available electronically at igscb.jpl.nasa.gov/overview/pubs.html)

Hatanaka Y, Sawada M, Horita A, Kusaka M, Johnson J, Rocken C (2001) Calibration of antenna-radome and monument-multipath effect of GEONET—Part 2: Evaluation of the phase map by GEONET data. Earth Planets Space 53:23–30

Hugentobler U (2005) Models in GNSS data analysis. Presentation at ‘‘Advances in GPS Data Processing and Modelling for Geodynamics’’ held at University College London, 9–10 November 2005 (available electronically at www.research.ge.ucl.ac.uk/COMET/)

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetma A, Reynolds R, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Jenne R, Joseph D (1996) The NCEP/NCAR 40-year reanalysis project. Bull Am Meteorol Soc 77:437–47

Mao A, Harrison CGA, Dixon TH (1999) Noise in GPS coordinate time series. J Geophys Res 104:2797–2816

Milly PCD, Shmakin AB (2002) Global modeling of land water and energy balances. Part I: the land dynamics (LaD) model. J Hydrometeorol 3(3):283–299

Penna NT, Stewart MP (2003) Aliased tidal signatures in continuous GPS height time series. Geophys Res Lett 30(23):2184. doi: 10.1029/2003GL018828

Press WH, Teukolsky SA, Vetterling WT, Flannery BP (2001) Numerical recipes in Fortran 77: the art of scientific computing (2nd edn). Vol. 1 of Fortran numerical recipes, Cambridge University Press, Cambridge, pp 569–577

Ray J (2006) Systematic errors in GPS position estimates. Presentation at IGS 2006 workshop, Darmstadt(available electronically at nng.esoc.esa.de/ws2006/ERRO6.pdf)

Ray J, Gendt G, Ferland R, Altamimi Z (2005) Short-term instabilities in the IGS reference frame. Geophys Res Abstr 7:02864

Ray J, van Dam T, Altamimi Z, Collilieux X (2006) Anomalous harmonics in the spectra of GPS position estimates. Eos Trans AGU 87(52): Fall Meet. Suppl, Abstract G43A-0985

Shmakin AB, Milly PCD, Dunne KA (2002) Global modeling of land water and energy balances. Part III: Interannual variability. J Hydrometeorol 3(3):311–321

Steblov G, Kogan M (2005) YAKT: Winter position anomaly removed, IGS Station Mail 365. http://igscb.jpl.nasa.gov/mail/igsstation/2005/msg00048.html

van Dam TM, Wahr J (1987) Displacements of the Earth's surface due to atmospheric loading: Effects on gravity and baseline measurements. J Geophys Res 92:1281–1286

van Dam TM, Wahr J, Chao Y, Leuliette E (1997) Predictions of crustal deformation and geoid and sea level variability caused by oceanic and atmospheric loading. Geophys J Int 99:507–517

van Dam T, Wahr J, Milly PCD, Shmakin AB, Blewitt G, Lavallée D, Larson K (2001), Crustal displacements due to continental water loading. Geophys Res Lett 28:651–654

Vennebusch, M, Böckmann S, Nothnagel A (2007) The contribution of very long baseline interferometry to ITRF2005. J Geodesy doi: 10.1007/s00190-006-0117-x

Williams SDP, Bock Y, Fang P, Jamason P, Nikolaidis RM, Millar M, Johnson DJ (2004) Error analysis of continuous GPS position time series J Geophys Res 109:B03412. doi: 10.1029/2003JB002741

Wu X, Heflin MB, Ivins ER, Fukumori I (2006) Seasonal and interannual global surface mass variations from multisatellite geodetic data. J Geophys Res 111:B09401. doi: 10.1029/2005JB004100

Zhang J, Bock Y, Johnson H, Fang P, Williams S, Genrich J, Wdowinski S, Behr J (1997) Southern California permanent GPS geodetic array: error analysis of daily position estimates and site velocities. J Geophys Res 102(B8):18035–18055