RESIDUAL K1 AND K2 OSCILLATIONS IN PRECISE GPS SOLUTIONS: CASE STUDY

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ABSTRACT. The continuous GPS observations from Polish Ground-Based Augmentation System (ASG-EUPOS) with two different strategies were analysed. Within the first one the adopted 3-hour observation window was shifted every hour to obtain hourly geocentric coordinates for investigation of the short-period oscillations. The second was the daily solution using EPN (EUREF Permanent Network) standards and recommended models. The Eterna 3.4 software was used for determination of the variations in the tidal frequencies. The almost three-year course of data allow for investigation even close tidal frequencies, especially in PSK1 and S2K2 groups. The variations of the Up component in K1 and K2 waves were found to be significant. It turned out that K1 frequency involves the greatest amount of energy reaching even 11 mm for the Up component. Spurious oscillation up to 4 mm and the period of about 1 year in GPS height time series at the selected ASG-EUPOS sites were obtained. Long-period GPS satellite orbit modelling errors could be directly responsible for small periodic biases in station position determinations as well as the repeating geometry of the satellite constellation with respect to the tracking stations. But it is very difficult to distinguish whether it comes from artefacts (transition of K1 ad K2 in long periods) or real effects (local hydrology). Comparison with the geophysical fluid loadings needs further investigations.

Keywords: GPS, precise solutions, periodic variations, ASG-EUPOS.

1. INTRODUCTION

The time series from GPS continuous measurements reveal many periodic variations. These changes could be of short- and long-periods as well. The latter are described as “seasonal” and have a period of one or a half of a year. They appear in many sophisticated ways of processing of global, local and regional GPS networks (e.g. Ray et al., 2008).

Dong et al. (2002) made a breakdown due to the different origin of the oscillations in the GPS observations: “in general, the potential contributors to seasonal variations in site positions can be grouped into three categories. The first category stems from gravitational excitation, mostly from the Sun and Moon. The rotational displacements due to seasonal polar motion, universal time corrected for polar motion (UT1) variations and loading- induced displacements due to solid Earth tides, ocean tides, and atmospheric tides all fall into this category. Pole tide loading also belongs to this category with the spectrum of mostly annual and Chandler wobble periods. The second category of seasonal variations is of thermal origin coupled with hydrodynamics. The loading-induced seasonal deformations from atmospheric pressure, nontidal sea surface fluctuations, and groundwater (both liquid and solid) belong in

this category. Also included in this category are the thermal expansion of bedrock beneath the GPS benchmark and wind shear-induced site displacements. The third category contains various errors, which also generate apparent seasonal variations.

The seasonal errors from satellite orbital models, atmospheric models, water vapor distribution models, phase center variation models, thermal noise of the antenna, local multipath, and snow cover on the antenna all cause apparent variations in estimated site positions. There is another potential but still hypothetical category: tectonic-induced seasonal deformation due to possible seasonal variations in regional fault slip or regional stress.”

For many geophysical applications, continuous GPS data are analyzed to form the time series by processing the data in discrete 24 hour sessions, then unmodeled semidiurnal and diurnal periodic signals cause residual errors remaining and they do not average exactly to zero over the 24 hour processing session. Penna and Stewart (2003) simulated GPS data and demonstrated that unmodeled diurnal and semidiurnal tidal displacements propagate to spurious longer signals existing in the daily GPS solutions. Effects from the GPS constellation repeat orbit can introduce furthermore artefacts to the daily solutions. The aliased periods are presented in Table 1.

Table 1. Aliased periods for the principal diurnal and semi-diurnal tidal waves resulting from daily solutions and effects of the GPS satellites constellation (from Penna and Stewart, 2003).

Constituent	Period (hours)	Aliased period (days)	
		24 hr processing	repeat orbit
M2	12.42	14.76	13.66
S2	12.00	∞	182.63
N2	12.66	9.61	9.13
K2	11.97	182.63	∞
O1	25.82	14.19	13.66
K1	23.93	365.26	∞
P1	24.07	365.24	182.63
Q1	26.87	9.37	9.13

Stewart et al. (2005) investigated the causing mechanism via a simplified mathematical error model, suggesting that artificial long-term oscillations arise from inadequacies in the range functional model commonly used in the GPS software packages. They showed that when the GPS satellites (used as reference stations) are not stationary, the concept of average is a bit misleading, because the output position error function contains many periodic terms dependent on the amplitude, period and phase of the unmodeled ground displacement, the orbital characteristics, the site’s location, the processing session length and the session-to-session overlap.

By analyzing several years of continuous GPS data, Penna et al. (2007) showed that an assumption of averaging of unmodelled periodic ground displacement in the non-overlapping 24-hour processing sessions is erroneous. The result of this study was the conclusion that any periodic unmodelled deformation can spread to long-term artificial oscillations, ranging in period from about 2 weeks to 1 year with admittances dependent on the coordinate component and the considered tidal constituent. The errors in mismodelling of ocean tide loading, atmospheric pressure loading, and solid Earth tide displacement amplitudes can reach several millimetres, and the long-period spurious signals in GPS height may be expected.

Watson et al. (2006) stated that mismodelling of tidal frequencies in diurnal and semi-diurnal bands had significant impact on GPS position and tropospheric time series as well. Ray (2006) presented the spectra of topocentric coordinates residuals in the context of attention which recently has to be paid on apparent deformations due to transport of global fluid mass loads.

King et al. (2008) analysed data collected between 2000 and 2006 at 90 of IGS (International GNSS Service) reference sites using PPP (Precise Point Positioning) strategy in GIPSY/OASIS software. They estimated site coordinates every 5 minutes obtaining unmodelled signals with amplitudes at 10 mm level at frequencies between 1/day and the Nyquist frequency. These are shown to propagate to the daily solutions with annual and semi-annual periods with amplitudes up to 5 mm. They also noted that estimates of seasonal geophysical loading from GPS might be biased by propagated unmodelled sub-daily signals and these characteristics were not well known. Admittance depend on the coordinate component (N, E, U) and the considered tidal constituent (O1, S1, K1, S2, K2 or M2). The paper provided the indication of how such errors propagate and how the spurious fortnightly, semi-annual and annual effects might be then present at some sites. King et al. (2003) proposed theory that a few hours long periods in the spectrum of GPS coordinates are artefacts, especially in the East-West component and could be removed by fixing the carrier phase ambiguities to the integer values. They used GAMIT software and 1-hour non-overlapping segments with each data segment processed as a separate site in the solution.

Krynski et al. (2002b) analysed two months long time series of vector components determined from 4-hour observing sessions with 87.5% overlap. The solutions were obtained by processing data using Bernese 4.2 software. They showed a distinguished periodic behaviour with periods in 24h, 12h and shorter bands which were introduced to the results as biases. Separation between reality and artefacts in precise GPS solutions was described in Krynski et al. (2002a). The strategy of GPS solutions quality analysis based on the concept of overlapping sessions with optimum length and temporal resolution was presented in Krynski and Zanimonskiy (2005). The results of the research confirmed existence of short-term oscillations in the residual variations in the geodetic coordinates and the length of vectors between the stations of terrestrial satellite networks.

2. DATA PROCESSING

We examined the continuous GPS observations from Polish Ground-Based Augmentation System (ASG-EUPOS) with two different strategies. Within the first the adopted 3-hour observation window was shifted every hour to obtain hourly geocentric coordinates for investigation of the short-period oscillations. Second was the daily solution using EPN (EUREF Permanent Network) standards and recommended models. Both are based on similar assumptions: the datum of the solutions was defined by the Minimum Constraint (MC) approach applied for three translation parameters. The list of stations defining the datum included the following 5 IGS core stations: BOR1, METS, ONSA, POTS and WTZR. Definition of the reference frame is based on the minimum constrains method. In our case the method is based on the imposition of conditions on the Helmert's transformation parameters, by means of the translation between centre of the figure based on reference points, which were derived both from observations and taken a priori. This solution is frequently used in the processing of the regional networks, like EPN.

Altogether, this research included a network consisting of over 130 GPS stations in Poland and the neighbouring countries (Germany, Czech Republic, Slovak Republic, Ukraine, Belarus and Lithuania). The considered time span covered the period from 2008 (start of the system) to the beginning of 2011.

The solid Earth tides were eliminated using a model based on the IERS2003 Conventions (McCarthy and Petit, 2004), while the ocean tides with FES2004 (Lyard et al., 2006). Thus the data for further analysis states the residuals from these models. No atmospheric loading corrections were applied. The data were processed in the Centre of Applied Geomatics of the Military University of Technology (one of the 18 EPN Local Analysis Centres) using Bernese 5.0 software (Dach et al., 2007).

Fig. 1 presents the locations of the analysed GPS sites.

Fig. 1. Processed GPS network

Since the deformational tidal effect in the Up component is over 4-5 times larger than the North and East components, the detailed interpretation was performed only on height variations. The obtained hourly time series were quite consistent, the standard deviation varied from 5 to 15 mm. Almost no gaps were obtained but several outliers were removed using 3-sigma criterion. First stage of the research was the spectral analysis using Fourier transform. This gave very distinguished peaks at 24, 12 and 8-hours reaching 11 mm for particular sites (Araszkiewicz et al., 2009, Bogusz and Figurski, 2010). The time series of the Up component of PILA (Piła) site and the result of the FFT are presented in Figure 2.

Fig. 2. Time series (left, in meters with standard deviation) and power spectrum (right) of Up component of PILA GPS site.

The Eterna 3.4 software (Wenzel, 1996) for determination of the variations in the tidal frequencies was used. The almost three-year course of data allow for investigation even close tidal frequencies, especially in PSK1 and S2K2 groups. The values of amplitudes [mm] and phase shifts [°] are given as the results of least squares adjustment. The precision is estimated through the root mean square errors (RMS) of the observations and of the unknowns.

The RMSs are to be determined by means of the sum of squares of residuals (SSQR) of the data. The coloured character of the noise is taken into account through the spectrum of the residuals (Ducarme et al., 2005). Previous analysis on that data provided information on the flicker character of the noise in the GPS coordinate variations (Bogusz and Kontny, 2011).

Trends and seasonal variation were removed during the least squares analysis with the band-pass filter as a standard step of tidal data adjustment. The data gaps less than 12 hours were interpolated using polynomials, greater gaps were left, since Eterna regards such data as separate blocks in the least-squares adjustment. Standard deviation of the amplitudes of particular tidal components after adjustment was below 0.4 mm for each (Bogusz and Figurski, 2010), almost ten times smaller than the amplitudes themselves, which proves the results reliable.

The discussion on the accuracy of the tidal analysis of GPS coordinates of ASG-EUPOS sites is presented in Bogusz and Hefty (2011). More details about data strategy of sub-daily solutions are given in Araszkiewicz et al. (2009) and Bogusz and Figurski (2010), daily solutions are described in details in by Bogusz et al. (2010).

3. RESULTS

Finally, the XYZ coordinates in ITRF2005 reference frame (Altamimi et al., 2005) were transformed to the North-East-Up components for interpretation.

3.1 SUB-DAILY SOLUTIONS

Detection of the energy in very specific tidal frequencies is possible using Eterna software. The idea of tidal grouping was introduced by Venedikov (1961), but there is no strict rule. The separation of the waves follows the so called Rayleigh criterion, which expresses the commensurability of the periods on the given interval under the form: $\Delta f \geq \frac{1}{T}$, where f is frequency. One needs 6 months to separate P1 from S1K1 or S2 from K2. In one year one can separate S1 and PS11 from K1. From a practical point of view this rule should not be strictly applied:

- when a small constituent has to be separated from a very large one in presence of a large noise it is generally better to use a larger data set than the minimum required time span, as the error on the tidal parameters decreases with the square root of the number of data. For example, one will never separate PH11 from S1K1 on a 6 months record;
- inversely the separation rule can be slightly relaxed when the signal to noise ratio is very good. Then the validity of the separation should be checked by means of an external criterion.

More comments on that point are presented in Ducarme (2011).

Fig. 3 presents amplitudes of diurnal and semi-diurnal waves of NTML site. In this case, the dominant diurnal oscillation is K1, in contrast to HRUB station (Fig. 4), where the maximum energy is stored in S1. For semi-diurnal frequencies K2 is dominant in both cases. In this paper the word "energy" refers to the results of spectral analysis as a colloquial term.

Deformation amplitude variations are expressed in millimetres, which are not, of course, units of energy.

Fig. 3. Amplitudes [mm] of the main diurnal (left) and semi-diurnal (right) constituents of NTML (Nowy Tomysl) GPS site (Up component)

Fig. 4. Amplitudes [mm] of the main diurnal (left) and semi-diurnal (right) constituents of HRUB (Hrubieszow) GPS site (Up component)

The variations of the Up component in K1 and K2 waves were found to be significant. It turned out that K1 frequency involves the greatest amount of energy. In principle, K1 is the declinational wave of argument (t') (sidereal day) and is affected by the liquid core resonance that is not well modelled. K2 is a declinational wave of M2, but also appears due to the non-linearity of K1 since its argument is ($2t'$). Less significance was obtained for S1 and S2 waves. S1 is the elliptic wave of K1, but also thermal effect is reflected in this frequency since it depends on the solar day and the period of the Earth's perihelion revolution ($t+pS$). S2 is the solar principal wave, with the strong thermal effect as well. It depends on argument $2t$ (Melchior, 1983). In case of GPS positioning, the possible explanations of K1 and K2 have to be extended to some artefacts related to the satellites repeatability, orbital period and multipath effects. Maximum amplitude of the oscillations in the Up component were found to be almost 11 mm for the diurnal (Fig. 5) and semi-diurnal frequencies (Fig. 6).

Fig. 5. Amplitudes [mm] of the main diurnal constituents of OSMZ (Ostrów Mazowiecka – left) and RWMZ (Rawa Mazowiecka – right) GPS sites (Up component)

Fig. 6. Amplitudes [mm] of the main semi-diurnal constituents of WLDW (Włodawa – left) and 0781 (Schwedt – right) GPS sites (Up component)

Three pairs of stations are located at distances of tens of meters. These are: JOZE and JOZ2 (Figs. 7 and 8), BOGO and BOGI (Figs. 9 and 10), LAMA and LAM6 (Figs. 11 and 12). Only one pair (BOGO and BOGI) exhibits obvious similarity in the distribution of the spectrum with dominant K1 in the diurnal and K2 in the semi-diurnal bands. Other sites are characterized by different conditions of observation (covering of the horizon), so the conclusion which could be drawn is that the effects related to K1 and K2 existence are strictly local, dependent probably on the satellites' visibility and multipath effect.

Fig. 7. Amplitudes [mm] of the main diurnal constituents of JOZE (Józefosław – left) and JOZ2 (right) GPS sites (Up component)

Fig. 8. Amplitudes [mm] of the main semi-diurnal constituents of JOZE (left) and JOZ2 (right) GPS sites (Up component)

Fig. 9. Amplitudes [mm] of the main diurnal constituents of BOGO (Borowa Góra – left) and BOGI (right) GPS sites (Up component)

Fig. 10. Amplitudes [mm] of the main semi-diurnal constituents of BOGO (left) and BOGI (right) GPS sites (Up component)

Fig. 11. Amplitudes [mm] of the main diurnal constituents of LAMA (Lamkówko – left) and LAM6 (right) GPS sites (Up component)

Fig. 12. Amplitudes [mm] of the main semi-diurnal constituents of LAMA (left) and LAM6 (right) GPS sites (Up component)

Figures 3 through 12 present standard distribution of energy, but at some sites the S1 oscillation is dominant in comparison the others. This probably reflects thermal oscillations related to the pillar, building or antenna itself. Figures 13 and 14 present spatial distribution of the dominant oscillations (with respect to the amplitude of the Up component). No clear dependencies were found. In case of diurnal oscillations thermal influences are reflected. In semi-diurnal, the orbital period synchronised with the half of sidereal day (K2) seems to be the most important artefact.

Fig. 13. Dominant oscillations of the Up component in diurnal frequencies

Fig. 14. Dominant oscillations of Up component in semi-diurnal frequencies

Using Eterna software it is possible to determine the phase shifts relative to the tidal model. Based on the consistency (or inconsistency), and the conclusions about spatial relationships of the described effect could be drawn. Figures 15 and 16 presents the geometrical representation of the phase difference (the angle between geographic North and the magnitude vector but it has no relations to the geographic azimuth). The magnitudes of errors in the basic directions of such constructed coordinate frame are at the level of 0.1 mm and could not be visible in the figures. The authors are of the opinion that the error estimation

given by the Eterna for GPS data is too optimistic. Non-homogeneous and completely random distribution of phase shifts for the individual stations of the system allow to conclude that the existence of oscillations in the frequencies K1 and K2 is an artefact.

Fig. 15. Vertical variations (Up component) in K1 frequency [mm].

Fig. 16. Vertical variations (Up component) in K2 frequency [mm].

3.2 DAILY SOLUTIONS

Having in mind the greatest amplitudes of the diurnal and semi-diurnal oscillations (Figs. 5 and 6) the 3-yearly courses of daily solutions (Up components) for selected sites were plotted (Figs. 17 and 18) for investigation whether annual signal caused by the mismodelled high frequencies could be observed.

Fig. 17. Variations of the Up component of OSMZ (Ostrów Mazowiecka – left) and RWMZ (Rawa Mazowiecka – right) GPS sites from daily solutions

Fig. 18. Variations of the Up component of WLDW (Włodawa – left) and JOZE (Józefosław – right) GPS sites from daily solutions

Fig. 19. Variations of Up component of LAMA (Lamkówko) GPS site from daily solutions

The variations of Up component of OSMZ and RWMZ GPS sites obtained from daily solutions are presented in figure 17. These sites are characterised by the greatest amplitudes of K1 oscillations (see Fig. 5). Daily solutions for WLDW and JOZE in figure 17, with respect to the greatest amplitudes of K2 (see Fig. 6) are shown. When comparing with the variations presented in figure 19 (LAMA – K1 and K2 below 1 mm – Figs. 11 and 12) we notice clearly visible long-term oscillation of about 1-year period. However it is very difficult to distinguish whether it comes from artefacts (transition of K1 and K2 in long periods) or real effects (local hydrology). Comparison with the geophysical fluid loadings needs further investigations.

We used Matlab's FFT for investigating periodicity in the daily solutions. The distinct almost annual period and its harmonic components are clearly visible (fig. 20).

Fig. 20. FFT of the daily solutions of OSMZ (left) and WLDW (right) ASG-EUPOS sites

From the point of view of statistics out of 27 sites with the oscillations in K1 which could be regarded as significant (greater than 3 mm), 13 have also annual oscillation in the daily solutions (Table 2). On the other hand out of 104 with insignificant K1, 24 have annual oscillation in the Up component. It means that this periodicity could also have its origin in real geophysical effects. The plus or minus sign in the table concerning annual oscillations comes from the analysis of the daily solutions. Plus was put when the amplitude of the best-fitted annual sine wave (by means of least squares) was greater than $2 \cdot \sigma$ (size of dispersion) of the time series reduced by the determined sine curve.

Table 2. ASG-EUPOS sites with significant K1 and annual oscillation.

	Site name	K1 [mm]	Annual oscillation		Site name	K1 [mm]	Annual oscillation
1	REDZ	3	–	15	NTML	4,5	–
2	WRKI	3	–	16	BOGO	4,6	+
3	KEPN	3,3	–	17	SOKL	4,6	+
4	PITR	3,3	–	18	MYSZ	4,8	+
5	KONI	3,4	+	19	SKSK	4,8	–
6	NYSA	3,4	+	20	NWTG	4,9	+
7	LAM6	3,5	+	21	GOLE	5,2	–
8	BIAL	3,6	+	22	GDAN	5,4	+
9	BOGI	3,8	–	23	JOZE	6	+
10	GNIE	4	–	24	LODZ	6,6	–
11	SIED	4	–	25	SWKI	6,7	–
12	HOZD	4,1	–	26	RWMZ	8	+
13	KOSC	4,1	–	27	OSMZ	10,7	+
14	WLDW	4,2	+				

The period presented in Fig. 20 is not strictly equal to 1 cpy, but a little more (our data span (3 years) seems to be too short for reliable determination and the interpretation could be a little speculative but ASG-EUPOS has worked since 2008 and that is our limitation). In general, several coupling mechanisms are possible:

- the “draconitic year”. Follow Ray et al. (2008) “it is 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 flattening, 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". Hugentobler (2005) showed these effects (with a period of about 350 days) existed in the GPS estimates of geocentre offsets.

- the repeating geometry of the satellite constellation at the tracking stations. (Agnew and Larson, 2007) showed that the daily advance of the constellation repeat geometry (which is about 246.8 seconds), aliases to the period of about 350 days for the standard daily solutions made by IGS. Such biases could be caused by the site-related effects like multipath, antenna or radome calibrations, for instance, or neglecting near-field scattering (Elosegui et al., 1995).
- real long-period effects, like local hydrological and thermal effects.

4. DISCUSSION

The time series of 1-hour GPS observations from ASG-EUPOS sites provide important data to investigate its diurnal and semidiurnal oscillations. The results of this study showed significant variations reaching 11 mm in the Up direction and 4-5 times smaller for the horizontal components with the formal uncertainties of 0.2 mm. Investigation of the spectral components by means of the least squares method showed the dominant oscillation in the K1 (diurnal) and K2 (semidiurnal) frequencies. In the spectrum of GPS coordinates (residuals from IERS2003 model obtained using Bernese software), the lack of energy in the main tidal O1 and M2 frequencies was found. This means that the model describes the effects of the solid Earth tides properly.

The results presented in this article coincide with those obtained by Hefty and Igondova (2010) for selected EPN sites. In 2.9-year period of continuous observations at 29 European permanent GPS stations they detected a set of dominant periodic terms which coincide with the diurnal S1, K1, O1 and S2, K2 and M2 with similar uncertainty (0.3 mm). The differences in O1 and M2 (absent in this paper) come from the lack of coastal stations, which could introduce unmodelled residual oscillations due to the ocean loading effect. Some discrepancies in the amplitudes of K1 and K2 (maximum 3 mm in the mentioned paper) could come from the local character of short-periodic variations in these frequencies.

The spatial distribution of K1 and K2 does not show a clear pattern, so they are probably produced by local phenomena such as the deficiencies in ionosphere and troposphere modelling, effects of residual errors in satellites orbiting or the multipath effect. The large K1 and K2 could also be to some extent the artefacts of the processing strategy and orbiting period of the GPS satellites. The knowledge of amplitudes of each kind of short-period oscillations is crucial, since it could propagate into long period variations of geodetic coordinates which come from precise GPS solutions. Due to the relatively large variability of K1 and K2 amplitudes and no regional pattern of phase shifts the clear and reliable explanation of these variations is not possible. In the paper the Authors indicate some possible reasons of these residual oscillations in the GPS coordinates. Most of them are related to the system itself, so the analysis of the short-time solutions from GLONASS (different orbiting period not coinciding with tidal period) could throw new light on that issue.

The other possible explanation of these variations could be neglecting of the correlations within the 3-hours ASG-EUPOS network solutions (mentioned also in the Hefty and Igondova, 2010). This could be fully investigated by using PPP (Precise Point Positioning) method, but when mm accuracy will be achievable.

The relationship between large value of K1 and K2 amplitudes and long-period (annual) oscillations in daily solutions was found for only 13 out of 27 stations (with significant K1 amplitude), which does not allow to formulate conclusions about the rule. It is still very

difficult to distinguish whether it comes from artefacts (transition of K1 ad K2 into long periods) or real effects (geophysical fluid loadings).

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