Contributions to Geophysics and Geodesy Vol. 40/3, 2010 (225–247)

# Diurnal and semi-diurnal coordinate variations observed in EUREF permanent GPS network – a case study for period from 2004.0 to 2006.9

Ján HEFTY[1], Miroslava IGONDOVÁ[1]

[1] Department of Theoretical Geodesy, Faculty of Civil Engineering, Slovak University of Technology; Radlinského 11, 813 68 Bratislava, Slovak Republic
Corresponding author's e-mail: jan.hefty@stuba.sk

**Abstract:** The 2.9-year interval of homogeneous and continuous observations at 29 European permanent GPS stations distributed all over the whole continent is analyzed for the short-periodic variations of site coordinates. In the literature seasonal terms in GPS coordinate series are well documented; the main objective of this paper is to investigate the existence of variations with shorter periods. We used the coordinate estimates obtained from 4-hour observing intervals which enabled identification of variations with diurnal and sub-diurnal periods. In the amplitude spectra of station time series we detected a set of dominant periodic terms which have exclusively diurnal and semi-diurnal tidal frequencies. The most significant are the diurnal $S_1$, $K_1$, $O_1$ and semi-diurnal $S_2$, $K_2$, $M_2$ waves. Their amplitudes are different for individual sites and they reach from sub-millimetre values up to $\sim$ 3 mm for some stations situated close to the Atlantic coast. Uncertainties of estimated amplitudes are generally at the 0.3 mm level. The possible origin of the observed periodic variations is very complex. We interpret the observed coordinate variability as a superposition of potential deficiencies in used models of ocean tide loading displacements, effects of atmospheric tides, multipath, troposphere and ionosphere residual effects, and other phenomena with diurnal and semi-diurnal forcing as well as the unidentified GPS analysis imperfection. The geokinematical relevance of detected variations and their possible interpretation are discussed.

**Key words:** coordinate semi-diurnal and diurnal variations, permanent GPS network, observed phenomena with tidal frequencies

## 1. Introduction

The differential GPS positioning in regional or global permanent networks usually yields site coordinates with daily or weekly resolution, and possibly also a set of additional parameters, like site troposphere zenith delays, troposphere gradients, ionosphere models, etc. Time series of daily or weekly coordinates are consecutively analyzed for secular drifts corresponding to long-term horizontal and vertical site motions, and alternatively for parameters of seasonal periodic variations and occasional discontinuities corresponding to monumentation related motions and GPS receiver or GPS antenna changes. Such a standard strategy applied to continental network is documented for EUREF Permanent GPS Network (EPN) analysis *(Kenyeres, 2005)* and for various regional networks of permanent stations, e.g. the permanent GPS network in Central Europe analyzed in *(Hefty et al., 2009)*. EUREF is used as an acronym for the International Association of Geodesy Reference Frame Sub-commission for Europe. Studies of periodic phenomena in GPS position time series are concentrated predominantly on variations with annual and semi-annual frequencies. Also higher-frequency variations, e.g. up to frequencies close 6 cycles per year are sporadically mentioned in *Ray et al. (2008)*. The evidence of higher frequencies in GPS time series is limited by standardly applied processing strategy for global or continental networks which produces one set of coordinates for 24-hour or for one-week interval of GPS observations. However, it can be expected that diurnal and semidiurnal periodicities, which are related to a variety of phenomena affecting the evaluation of GPS observations, will be demonstrated as a long-periodic signal in GPS time series. In addition, part of the observed seasonal signal could be explained as an effect of aliased unmodelled phenomena with diurnal and semi diurnal frequencies *(Penna and Stewart, 2003)*. Information about the behavior of GPS time series in the diurnal and sub-diurnal domain is then valuable for better interpretation of observed coordinates in various applications.

The potential of recent GPS software development allows estimating station coordinates in the continental scale also from shorter than 24-hour intervals of observations. Coordinates with millimeter accuracy can be estimated from several hours of satellite tracking for baselines reaching hundreds of kilometers. This can be utilized for an extension of the usually applied 24-hour strategy. In this way the modified data processing may generate coordinate time series with sub-diurnal resolution. Such series have a potential for subsequent analyzes of phenomena with diurnal and shorter periods. Analyses focusing on GPS inferred positional variations with diurnal or sub-diurnal periodicities are not very frequent in literature, we can mention e.g. papers *(Araszkiewicz et al., 2009; Hefty et al., 2004; Hrčka and Hefty, 2006; Hefty, 2008; Melachroinos et al., 2008; Thomas et al., 2007). Arazskiewicz et al. (2009)* and *Hefty et al. (2004)* point on the existence of diurnal and subdiurnal oscillations with tidal periods in GPS time series. *Melachroinos et al. (2008), Thomas et al. (2007)* and *Hefty (2008)* used GPS observations for analyzing ocean tide loading displacement. In *Hrčka and Hefty (2006)* the stochastic features of GPS coordinate time series with subdaily resolution are investigated.

There is a variety of physical phenomena that can cause short term variations in time series of station coordinates. It is worth mentioning that the periodic effects predominate and they are better detectable than episodic irregular changes. Significant portion of the short periodic phenomena potentially affecting GPS coordinate variations are modelled within the process of reduction of observations and their adjustment consistently with internationally adopted standards maintained by the International Earth Rotation and Reference Systems Service (IERS) – the series of IERS Conventions *(McCarthy, 1996; McCarthy and Petit, 2004)*. Nevertheless, our previous studies *(Hefty et al., 2004; Hrčka and Hefty, 2006; Hefty, 2008)* showed that in the spectra of coordinate time series with sub-diurnal resolution non-negligible terms indicating presence of periodic signal are present. The most probable candidates for the existence of such a signal are mismodelling and local anomalies of solid Earth tides, unmodelled part of ocean-induced tidal loading, atmospheric tides, deficiencies in troposphere and ionosphere modelling, effects of residual errors in satellite orbiting, multipath effects, diurnal polar motion, thermal effects, antenna mounting variability, and possibly other deficiencies in modelling of systematic phenomena.

In this paper we analyze the 2.9-year interval of site coordinates evaluated in 4-hour batches within the activities of the EPN Local Analysis Center at Slovak University of Technology (LAC SUT) in Bratislava. The LAC SUT is continuously analyzing a subnetwork of permanent GPS stations of the EUREF Permanent GPS Network since 2002. The routine processing strategy yields the site coordinates based on 24-hour GPS observation intervals, which are consequently combined into weekly solutions, representing the mean position from one-week permanent observations related to the International Terrestrial Reference Frame (ITRF). In the period from 2004.0

to 2006.9 in parallel to 24-hour interval solution we performed regularly on the daily basis also a set of 6 solutions from separate 4-hour intervals. The termination of this phase of processing was in 2006.9 due to a transition from Bernese GPS Software Version 4.2 – BV42 *(Hugentobler et al., 2001)* used so far, to more recent Version 5.0 – BV50 *(Dach et al., 2007)*. It is worth mentioning that this change, which took place at the majority of GPS analysis centers, was accompanied with slight modifications of processing strategy which were put into effect at the epoch 2006.9. We can mention e.g. the introduction of absolute antenna phase center variation models, estimation of daily troposphere gradients, new version of terrestrial reference frame etc. Many of these modifications probably influenced a short-term coordinate variability. In our preliminary analyses we already observed a different behavior of derived variations in diurnal and semi-diurnal bands after the change in processing strategy, GPS software and adoption of enlarged set of parameters in 2006.9 *(Hefty, 2008)*. This is the reason why we would like in this paper to summarize and analyze the data related to the period before 2006.9. In the estimated coordinate series, a long-term effort related to routine processing of GPS data is accumulated. These time series represent a complete homogeneous period of monitoring the coordinate short-term variability. Such a study will help us to better understand the effect of model changes in 2006.9, e.g. the influence of absolute GPS antenna calibration, changes in troposphere modelling, adoption of IERS Conventions 2003 etc. We found the 2.9-year interval to be sufficient to be representative of periods before 2006.9.

## 2. Main features of the GPS data analysis

The observational background of our analysis comprises of sub-network of Permanent GPS stations situated on the European continent and continually processed by the LAC SUT. The regular analysis of permanent GPS observations is an activity carried out within the EPN, where the LAC SUT subnetwork currently includes 44 permanent sites. The status of network from 2004 to 2006 with 29 sites which are analyzed in this paper are shown in Fig. 1 and listed in Table 1. The majority of the sites has almost continuous observation series without significant gaps or coordinate drifts. Only

Table 1. List of Permanent GPS stations analyzed in this paper

| Marker name | City | Country | Marker name | City | Country |
|---|---|---|---|---|---|
| AJAC | Ajaccio | France | KOSG | Kootwijk | Netherlands |
| BOGI | Borowa Gora | Poland | KRAW | Krakow | Poland |
| BOR1 | Borowiec | Poland | MANS | Le Mans | France |
| BRST | Brest | France | MIKL | Mikolaiv | Ukraine |
| BZRG | Bolzano | Italy | MLVL | Marne-la-Vallee | France |
| CAME | Camerino | Italy | MOPI | Modra-Piesok | Slovak Republic |
| DUBR | Dubrovnik | Croatia | ORID | Ohrid | Macedonia |
| GANP | Ganovce | Slovak Republic | OROS | Oroshaza | Hungary |
| GOPE | Ondrejov | Czech Republic | RIGA | Riga | Latvia |
| HELG | Helgoland Island | Germany | STAS | Stawanger | Norway |
| INVE | Inverness | United Kingdom | SULP | Lviv | Ukraine |
| JOZ2 | Jozefoslaw | Poland | SVTL | Svetloe | Russian Federation |
| JOZE | Jozefoslaw | Poland | TUBO | Brno | Czech Republic |
| KLOP | Kloppenheim | Germany | ZIMM | Zimmerwald | Switzerland |
| | | | ZYWI | Zywiec | Poland |

BRST, CAME and DUBR have only 50% of this interval covered by the relevant observational data. The sites are spread out over the whole continent, including stations in Atlantic Ocean area, Mediterranean, West and Central Europe as well as close to Baltic Sea and Black Sea. We excluded from our analysis the stations Reykjavik (REYK) in Iceland and Qaquortoq (QAQ1) in Greenland, which are routinely processed at LAC SUT. We found them not suitable for analyses of short-period variations because of their eccentric location in the network analyzed, and due to more than 1000 km baselines connecting these stations with the rest of network. The longest baselines among the remaining station are up to 600 km.

The analysis strategy follows the rules accepted in the Guidelines for EPN Analysis Centers (EPN, 2010), with some modifications for additional estimation of coordinates based on 4-hour interval observations. In the first phase of data processing, the daily network solutions, according to the standard EPN procedure, resulting to daily coordinate estimates are computed. Besides the daily site coordinates the corrections to the adopted troposphere model in hourly intervals and ambiguities of double difference phase GPS observations are estimated. The effect of troposphere is then expressed by the Zenith Total Delay (ZTD) representing the actual effect of dry and wet troposphere on GPS observations. We adopted this troposphere ZTD and the resolved ambiguities from the daily solutions as known parameters in the next step, where the separate 4-hour intervals are solved with only coordi-

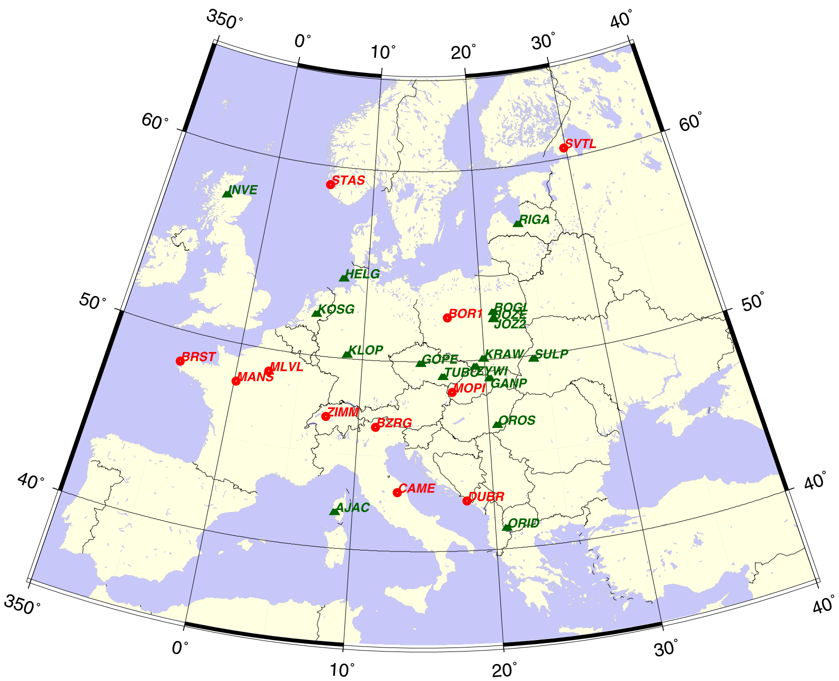


Fig. 1. EPN stations analyzed for diurnal and semi-diurnal variations. Stations which are used as a reference for elimination of global variations common for the whole network are marked with triangles.

nate parameters estimated. We emphasize that no observation overlapping is applied, and so the successive 4-hour estimates are not correlated due to utilization of the identical observed data. All the solutions are strongly constrained to one selected reference station to align the network with the valid International Terrestrial Reference System realization. In the period analyzed in this paper, the BOR1 Permanent GPS station was considered as a reference the network of the International Terrestrial Reference Frame (ITRF), namely the ITRF2000 *(Boucher et al., 2004)*. Selection of BOR1 is motivated by its long-term stability and uninterrupted operation, providing the consistency of network solutions in the period analyzed.

Our analysis is focused on diurnal and sub-diurnal variations of estimated station coordinates. In order to clearly specify those parts of phenomena which are reduced during the parameter estimation process using the GPS analysis software BV42, we will explicitly mention the models and reductions applied. We emphasize that this version of Bernese GPS software was consistent with IERS Conventions from 1996 *(McCarthy, 1996)*.

- Solid Earth tides are in BV42 modelled using the Step 1 and Step 2 corrections according the IERS Conventions *(McCarthy, 1996)*.
- Site displacements due to ocean loading are reduced using the GOT00.2 Global Ocean Tide model (Ray, 1999), including 13 main tidal constituents, namely semidiurnal $M_2$, $S_2$, $N_2$, $K_2$, diurnal $K_1$, $O_1$, $P_1$, $Q_1$ fortnightly $M_f$, monthly $M_m$ and semiannual $S_{sa}$ waves.
- The nutation parameters, and diurnal and subdiurnal polar motions (with terms $M_2$, $S_2$, $N_2$, $K_2$, $K_1$, $O_1$, $P_1$ and $Q_1$) are evaluated according to IERS Conventions *(McCarthy, 1996)*.
- The diurnal variability of troposphere (the difference of actual troposphere with respect to the static model) is evaluated within the 24-hour batches. The estimated stochastic hourly ZTD parameters for each network station are used as known parameters for reduction the observed GPS data in the process of 4-hour coordinate evaluation.

All the mentioned effects are modelled within the BV42 software, the details of algorithms used are given in *Hugentobler et al. (2001)*.

We have to stress that the site multipath effects are not modelled during the adjustment and they may potentially influence the diurnal coordinate variations. The diurnal repeatability of multipath phenomenon is related to the occurrence of identical satellite constellation over the same geographic place, which for GPS is exactly one sidereal day. So the neglect of multipath can theoretically manifest in a diurnal wave with $K_1$ frequency.

The raw time series of station coordinates estimated from 4-hour intervals represent in fact the individual sites behavior relatively to the strongly constrained reference site BOR1. In this way the observed temporal variations are reflecting the cumulative effect of BOR1 and the selected station variations. To reduce the effect of referencing the whole network to the single station (BOR1), we evaluate the reference time series representing the common variations of the dominant part of network. The motivation of such an operation is to spread out the possible influence of performance of single station (BOR1) to the set of more stations. Firstly, we reduced all the individual station time series by their mean position and secular drift, next the time series representing the common network variations was estimated. Each element of such time series was estimated using the least-squares adjustment. Subtracting this common part from all individual station series resulted in the set of site coordinate time series, reflecting the behaviour of individual stations relatively to the network mean. After inspecting the long-term stability, continuity and internal homogeneity of all network sites, we selected a subset of 17 stations marked in Fig. 1, forming the reference for removing the common network variations.

We have to emphasize that the complete covariance matrices of the individual networks resulting from adjustment using the BV42 were taken into account when the reference series was evaluated. The variance-covariance propagation was applied also by the subsequent reduction of the individual site coordinate series. Finally, we have to mention that we alternatively performed all the subsequent analyses also with the original coordinate time series related strictly to a single reference station BOR1. Even though the results differ in details from those presented in this paper, we found that the referencing of series does not significantly change the main features of detected coordinate variability. All the periodic terms observed in series reduced for reference series were observed also in the original coordinate time series related just to BOR1. Of course, the amplitudes and phases at individual stations are modified.

The resulting time series of reduced station coordinates comprises 1045 days of 4-hour estimates. Finally, the local station variations $dX$, $dY$, $dZ$, related to axes parallel to the axes of geocentric Cartesian coordinate system $X$, $Y$, $Z$ *(Xu, 2007)*, are transformed into local horizontal north-south (N–S), east-west (E–W) components and to the vertical – up (U) component. At several stations gaps in the series can be noticed; in our analysis we included stations with individual gaps not longer than 10% of the complete 2.9 year interval.

Time series analysis of all station coordinate series was performed for each triad of local coordinate constituents. We apply two independent methods: spectral analysis aimed to obtain general information about the principal frequencies in the series, and subsequently the least squares adjustment leading to estimates of amplitudes and phases of dominant periodic terms.

- Because of features of analyzed series, we applied spectral analysis based on the least squares approach, introduced by Vaníček, which is suitable for series with small gaps, missing data and variable precision of analyzed data *(Vaníček, 1969a; Vaníček, 1969b).* The analyzed local coordinate time series were firstly reduced by linear trend, annual and semiannual variations and corrected for known biases. Spectral analysis enabled to find out if the local coordinates show short-term variability and to specify which periods are dominant.

- Least-square adjustment approach was used to estimate amplitudes of periodic terms with known diurnal and semi-diurnal frequencies, amplitudes of seasonal terms, constant bias, annual velocity, and magnitude of occasional coordinate biases with known epoch of change (usually due to antenna exchanges, random installation, monumentation modifications etc.).

## 3. Spectral analysis of short-term coordinates variations

The time series of local coordinates, resulting from adjustment of 4-hour observing intervals after reducing for the global network drifts and variations (Eurasia plate motion, common seasonal variations of the whole network), are still influenced by residual-station-dependent seasonal effects and intraplate linear trends. As an example, we show in Fig. 2 time series of N–S, E–W and U components for the two sites: Borowa Gora, Poland (BOGI) and Ohrid, Macedonia (ORID). We clearly observe significant patterns of the time series which are different for the two sites displayed; the dissimilarities are in scatter of the series, linear trend, and the seasonal periodicity (BOGI U component with dominance of semiannual variations, ORID U component with dominance of annual variations). The examples in Fig. 2 are typical and represent the main features for all analyzed stations. The constant bias, linear drift and seasonal terms were removed from all the series consecutively. In case of known shifts in the series also their effect has been removed. Subsequently, the N–S, E–W and U components of all station time series were submitted to spectral analysis.

Some typical examples of spectra focusing into the range of periods from 0.4 to 1.2 days are shown in Fig. 3. Even though the mutual differences among stations are clearly visible, some common properties of all spectra can be stated:

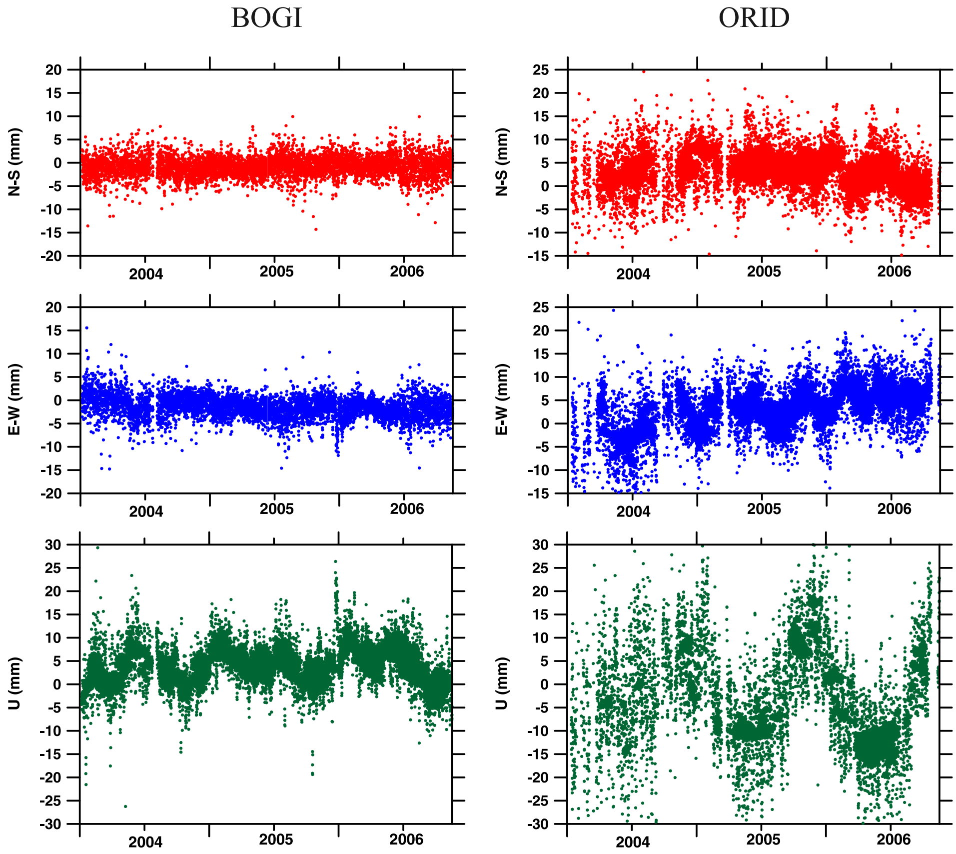


Fig. 2. Examples of time series used for analysis of diurnal and semi-diurnal variations from two stations BOGI situated in Central Europe and ORID situated in Balkan Peninsula.

- Periodic variations with amplitudes exceeding 0.4 mm level are clearly dominating both in horizontal and vertical constituents. They significantly exceed the noise level which is less than 0.2 mm for majority of spectra. Noise estimate is inherent to the method of least squares spectral analysis in *Vaníček (1969b)*. The low level of noise is a consequence of large amount of input data (about 6000 local coordinates for each time series), homogeneity of the time series and successful elimination of all long-term phenomena affecting the original data.

- The spectral peaks are concentrated exclusively around 1.0 and 0.5 day periods. No peaks occur in the range from 0.6 to 0.9 day, as well as with periods less than 0.45 day and with periods longer than 1.1 day. We emphasize that a period corresponding to the Nyquist frequency is 0.33 day.
- Decisive majority of dominant peaks is closely related to one of the six periods of tidal waves, namely the semi-diurnal $K_2$ (0.498634 day), $S_2$ (0.500000 day), $M_2$ (0.517525day) and diurnal $K_1$, (0.997269 day), $S_1$ (1.000000 day) and $O_1$ (1.075805 day). We emphasize that the solid Earth tides are modelled in BV42 consistently with IERS Conventions *(McCarthy, 1996)*.
- The effects observed in horizontal coordinates and the vertical variations are of the same order of amplitude. This is a remarkable feature, because in majority of phenomena related to GPS coordinates variability, the amplitude and scatter of U component exceed the horizontal variations. We interpret this fact as a consequence of better homogeneity of GPS orbits in the radial component than in along-track and cross-track components.
- Peaks with periods different from these mentioned above occur only rarely. We did not detect any other period which was common for more stations or occurring in all three station coordinate constituents.

Besides the common patterns, several differences among the spectra are observed too:

- There are significant differences among amplitudes of the same periods at different stations. Amplitudes are in the range from 0.3 to 3.0 mm; however, the extremes above 2.0 mm at least in one period are observed only at several stations (AJAC, BOR1, BRST, CAME, INVE, MANS, MIKL, STAS, SVTL).
- The occurrence of significant term in one of the coordinate constituent at the specific station is not automatically accompanied with significant amplitude of the other constituents.
- The ratio of amplitudes of pairs in close periods ($K_2$ and $S_2$, $K_1$ and $S_1$) varies from station to station.

To interpret better the observed periodic variations we estimated the possible impact due to difference between the used IERS Conventions 1996

*(McCarthy, 1996)* in the BV42 software, and the more recent version – IERS Conventions 2003 *(McCarthy and Petit, 2004)*. The expected largest differences are due to improved model of diurnal and sub-diurnal polar motions. This effect may reach 0.5 mm in site coordination variation for $K_1$ term. However, we have to realize that our analysis is sensitive only to relative variations which are for the region investigated significantly smaller than the difference mentioned.

Figure 4 shows spectra for three close stations: two in Jozefoslaw – JOZE and JOZ2 (mutually separated only 100 m) and Borowa Gora (BOGI, about 40 km from Jozefoslaw). We can observe some similarities in spectra, e.g. the occurrence of $M_2$ in E–W at all three sites and similar $K_1$ and $S_1$ in the U component. On the other hand, significant differences are e.g. in $K_2$ and $S_2$ in N–S, and in $K_1$ and $K_2$ of the E–W coordinate. This situation documents that in the diurnal and semi-diurnal domains, we have to deal with a combination of regional and local phenomena. The hypothesis about the local influences is supported by the following fact: The JOZE station is mounted on concrete pillar 0.5 above the ground, while JOZ2 antenna is situated on the 2-level high building. The amplitudes and phases of dominant diurnal and semi-diurnal terms of all the analyzed stations will be discussed in section 4 of this paper.

The observed six dominant periodic terms have specific frequencies that open up different possible interpretation of the observed variations.

- The exactly diurnal and semi-diurnal periods $S_1$ and $S_2$ are associated with a variety of phenomena related to 24-hour and 12-hour daily cycles, e.g. troposphere and ionosphere variability, thermal effects on antenna and pillar or building where the antenna is mounted. With the $S_2$ frequency are associated also solid earth tides, atmospheric thermals effects, ocean loading effects and semi-diurnal polar motion.
- The length of $K_1$ and $K_2$ periods is one and one-half of sidereal day, which are closely related to GPS satellites orbiting. Due to the earth rotation and satellite orbital movement, the same satellites configuration occurs above the same place with the $K_1$ period. If there are station multipath effects, they will manifested as variations with $K_1$ frequency. Also the deficiencies in modelling the receiver antenna phase center variations can produce such variations. The unmodelled satellite antenna phase centre variations may introduce regionally distributed

effects with the $K_1$ frequency. The $K_1$ and $K_2$ periods are also associated with solid earth tides and ocean loading effects.

- Periods of $O_1$ and $M_2$ waves are the dominant periods of lunar solid earth tides, ocean loading displacements and polar motion. They are related predominantly to tidally induced station position variation; no other relevant non-tidal phenomena can be associated with these periods.

The similar occurrence of $M_2$ in E–W component and $O_1$ in N–S component in all three spectra in Fig. 4 indicates a deficiency in tidal modelling, most probably in ocean loading. Also $S_1$ and $S_2$ have similar amplitudes and can be related to non-modelled part of local troposphere phenomena. The different amplitudes in $K_1$ are most probably the consequence of differences in multipath effects, as this phenomenon is strongly dependent on local environment and antenna monumentation.

## 4. Analysis of semi-diurnal and diurnal coordinate variations

The evident observability of periodic variations with $K_2$, $S_2$, $M_2$, $K_1$, $S_1$ and $O_1$ frequencies in coordinate series with 4-hour resolution documented by the station spectra is a challenge for a detailed analysis of these phenomena. We performed least-squares adjustment for determination of amplitudes and phases of the terms mentioned for all the site time series. The model included also bias, linear drift, seasonal terms, and constant occasional shifts.

The observing equation for each of 3 coordinate constituents $dx_j(t)$, related to the observational epoch $t$, in N–S, E–W and U directions ($j = 1, 2, 3$), is of the form

$$dx_j(t) = dx_{0_j} + v_j(t - t_0) + \sum_{i=1}^{8} \left[ a_{i,j} \sin \frac{2\pi\,(t - t_{0_i})}{P_i} + b_{i,j} \cos \frac{2\pi\,(t - t_{0_i})}{P_i} \right] + + \sum_{k=1}^{m} c_{k,j}\delta(t, k) + \varepsilon_{t,j}, \qquad (1)$$

where $dx_{0_j}$ is the correction to position of reference station, $v_j$ is the residual station velocity, and $a_{i,j}$ and $b_{i,j}$ are amplitudes of sine and cosine terms

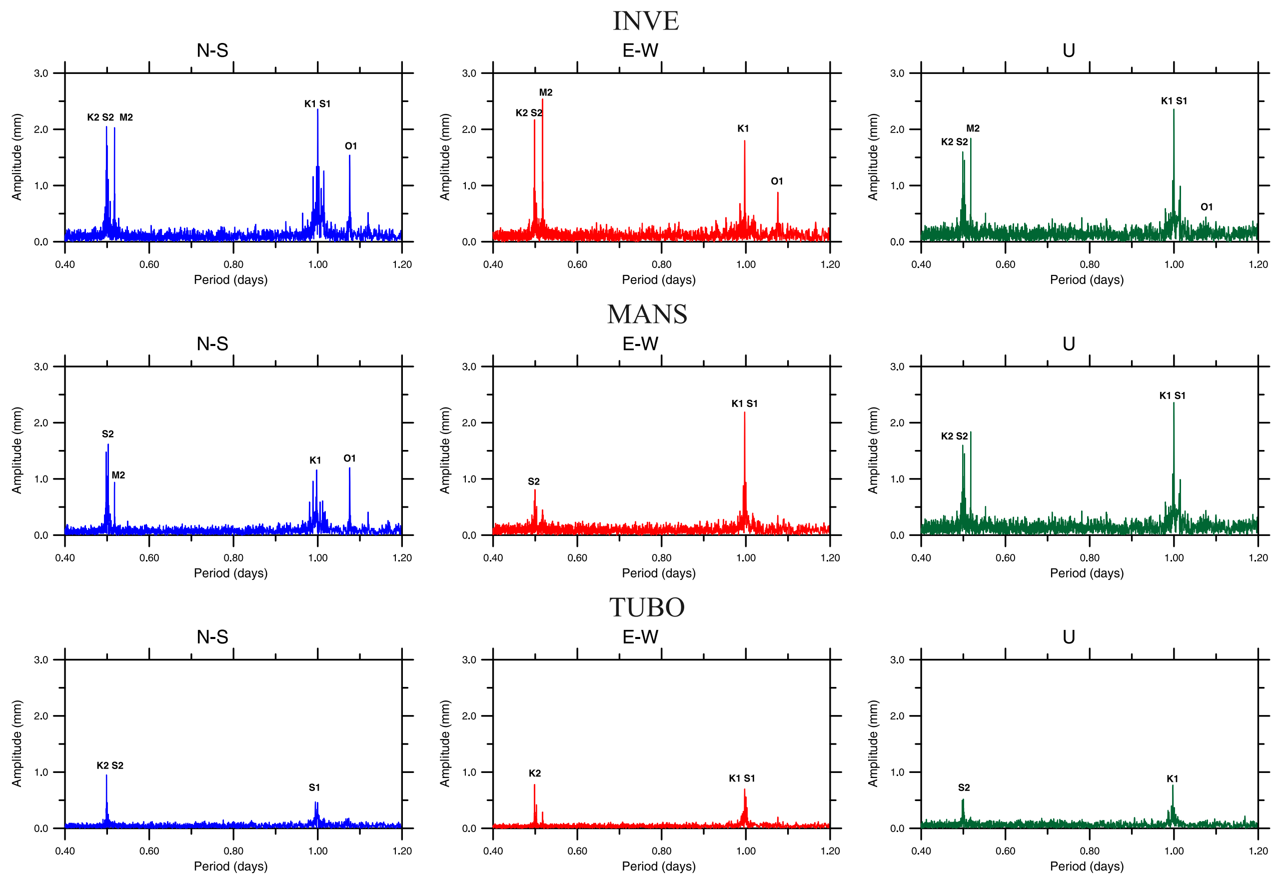


Fig. 3. Examples of least-squares spectra at three different sites – inland station TUBO and stations close to sea coast (INVE and MANS).

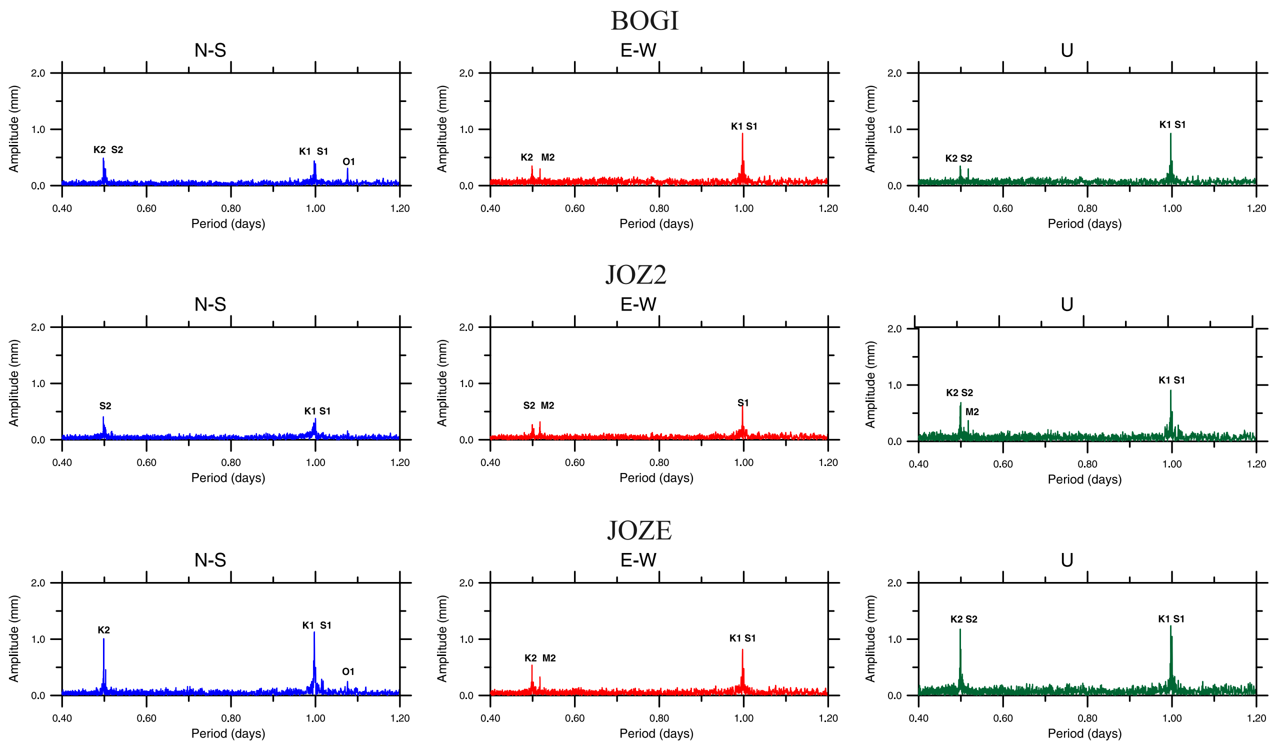


Fig. 4. Comparison of least-squares spectra at three geographically close sites. Besides the general similarity, the differences at individual stations are visible.

with period $P_i$. We included 8 periodic terms into the adjustment model – the semidiurnal $K_2$, $S_2$, $M_2$, diurnal $K_1$, $S_1$, $O_1$ and seasonal $S_a$ and $S_{sa}$ waves. The optional terms $c_{k,j}$ are the magnitudes of the coordinate shifts indicated by the $\delta(t,k)$ function, with $m$ terms – the total number of shifts. The value $\varepsilon$ represents the random error. Initial epochs $t_{0_i}$ of individual waves are selected to be consistent with phase of tidal developments. The estimated parameters $a_{i,j}$ and $b_{i,j}$ are subsequently transformed into amplitudes and phases of each tidal wave, and thus the phases represent the delay of observed variation with respect to the astronomical argument.

For majority of stations, the estimated amplitudes of diurnal and semidiurnal periodic terms in (1) are exceeding their mean errors. However it is not reasonable to list all the estimated significant amplitudes and the related phases for individual stations since we observed their strong regional pattern. Therefore we constrained our presentation to the most relevant results in terms of visualization of geographical distribution of the observed effects. The plots in Figs. 5 and 6 show the amplitudes and phases of estimated coordinate variations. Phases are interpreted by counter-clockwise orientation of the amplitude vectors with zero phase lag oriented to north and 180° phase lag oriented to south. All the vectors are completed by 95% confidence ellipses, resulting from the covariance matrices obtained from the complex adjustment of 2.9-year interval of coordinates in 4-hour spans (confidence ellipses are computed with standard error ellipses with axes multiplied by factor 3). We stress that all the error estimates were based on the assumption of white noise of coordinate time series. In fact, the complex colored noise approach will be more realistic for the amplitudes and phases error modelling. However, this problem is beyond the scope of this paper.

Figure 5 shows the adjusted amplitudes and phases of oscillations with tidal $M_2$ frequency. The $M_2$ wave is unique in our analysis because of two reasons:

1. The tidal effects are dominant among all semidiurnal waves for solid earth tides, ocean tides and polar motion.
2. There are no other geodynamic phenomena which may invoke periodic effects with the $M_2$ frequency, except the variations that have origin in dynamics of the Earth–Moon system. Moreover, there are no other processes associated with GPS data analysis which can produce such a periodic signal.

All the three plots document that $M_2$ variations are correctly modelled for majority of stations at the sub-millimeter level. Larger amplitudes are observed only at some coastal stations or stations close to coast like INVE, STAT, BRST, HELG, MANS, MLVL. This strongly indicates that the observed effects are related to deficiencies of ocean loading modelling. The most significant are the variations at INVE and BRST. Predictions of ocean loading effects according to GOT00.2 model for these stations are relatively large and reach 0.005–0.040 m amplitudes in one or more coordinate constituents.

The consistency of $M_2$ variations determined from GPS analysis with various ocean tidal models – FES2004 (Finite Element Solution ocean tide, *Lefevre et al., 2002*), GOT00.2, CSR4.0 (University of Texas, Center for Space Research, *Eanes and Bettadpur, 1999*) and TPX.7.1 (Oregon State University, TOPEX/Poseidon solution, *Egbert and Erofeeva, 2002*) was analyzed in *Hefty (2008)*. The inconsistencies among the models and GPS derived data at the level 2-3 mm were detected. Visualizations in Fig. 5 prove the potential of GPS analysis for evaluation of reliability of predicted ocean tidal loading variations. At this moment, it is limited by the small number of relevant coastal stations in our analyzed network. In the period after 2006.9 when the network was enlarged, time series from more stations will be available. The detected variations with $M_2$ frequency prove the validity and reliability of analyses of high-frequency GPS coordinate variations.

Interpretation of estimated amplitudes and phases for other diurnal and semi-diurnal terms is more complicated and ambiguous. The main reason is that the frequencies dominating in the spectra are associated not only with effects relating to tides but also to other effects which influence the GPS data modelling and processing. The specific frequencies are discussed below. Some typical examples of geographical distribution of observed variations with tidal frequencies showing their amplitudes and phases at analyzed sites are shown in Fig. 6.

The $K_1$ and $K_2$ waves are associated with GPS orbiting and local effects, like multipath, station environment etc. The $K_2$ period is exactly the orbital period of GPS satellites and $K_1$ is the period of repeating of the same satellite constellation over the same site. Figures 6a and 6b document mixture of regional pattern and local phenomena. Observed phases of $K_1$ E–W

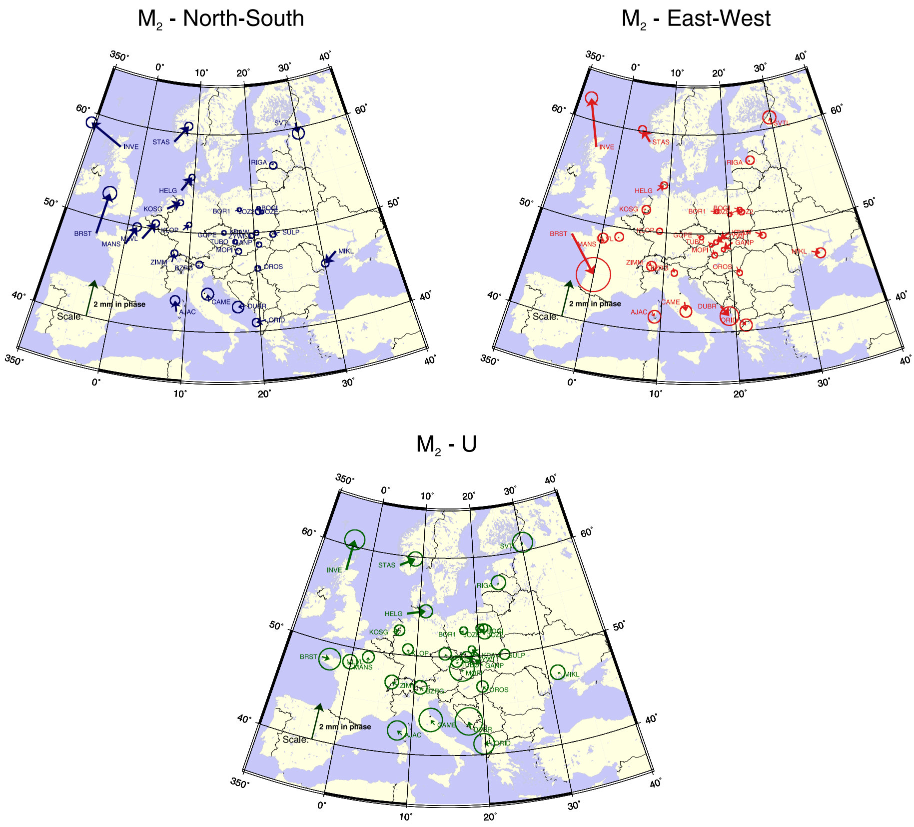


Fig. 5. Amplitudes and phases of N–S, E–W and U components of periodic variations with semi-diurnal $M_2$ frequency. The orientation of arrows indicates the phase with zero phase lag directed to north. Error ellipses show the 95% confidence.

component are predominantly around 90° and 270° and amplitude is rising from the centre of network. Phases of $K_2$ N–S component are grouped in several blocks with similar phase lags. For both $K_1$ and $K_2$, the amplitudes for some stations are exceeding 2 mm and they are dominant in the diurnal and semi-diurnal bands respectively. As this term has relatively small amplitude associated with tidal variations, its existence has to be interpreted as a consequence of orbit modelling or effect of orbit-bias propagation in the site coordinates. The other explanation of the observed variability with $K_1$ and $K_2$ frequencies is a neglect of possible correlations among the 4-hour

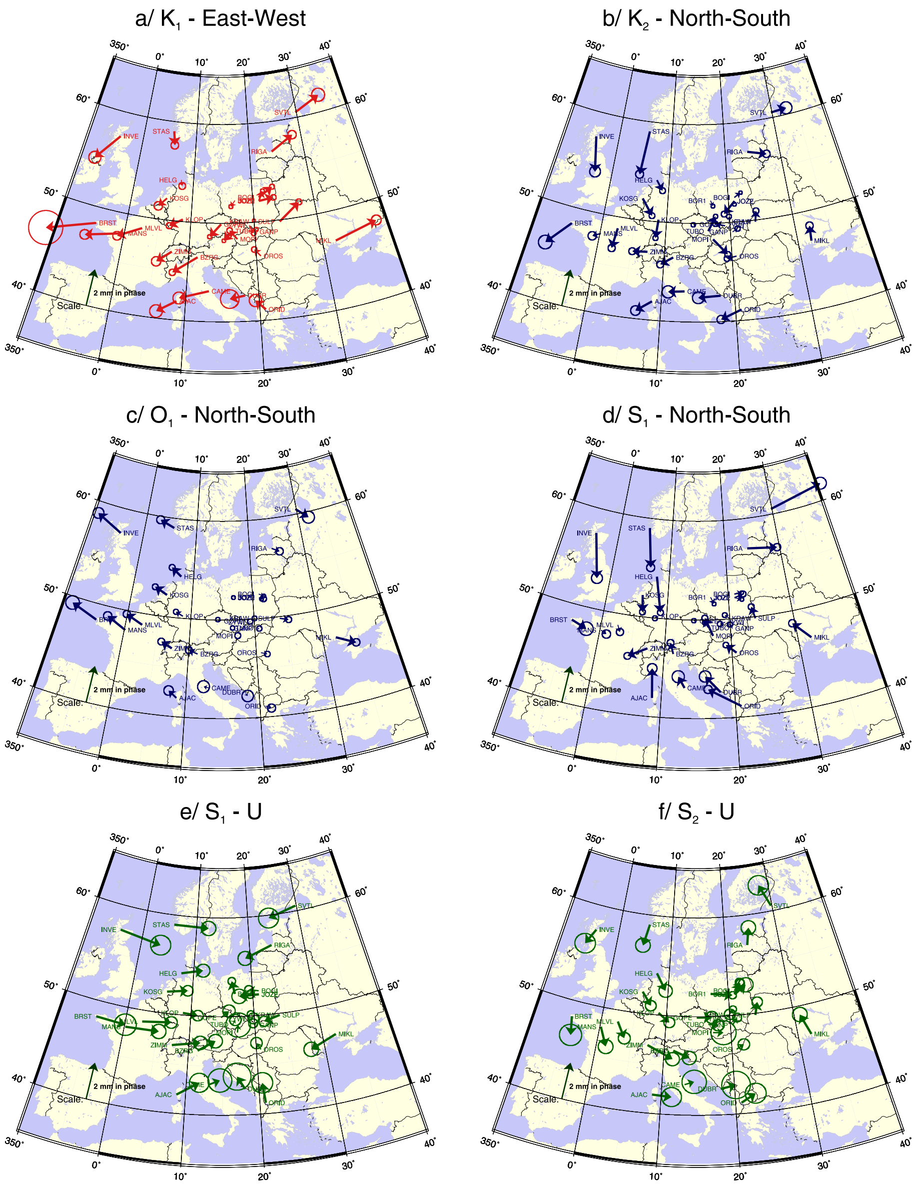


Fig. 6. Geographical distribution of observed amplitudes and phases of semi-diurnal and diurnal periodic variations. The orientation of arrows indicates the phase with zero phase lag directed to the north. Error ellipses show the 95% confidence.

network solutions and their repeatability. This problem of periodic terms related to the satellite orbiting periods could be resolved in future when other global satellite navigation systems like GLONASS and Galileo will by fully operational. Their orbital periods, which are 0.4694 day for GLONASS and 0.5983 day for Galileo, do not coincide with tidal periods. It will allow separating the possible problems of orbits and multipath from phenomena related to tidal potential. We expect that $K_1$ and $K_2$ frequencies will manifest in significantly smaller amplitudes.

Figure 6c shows the $O_1$ N–S component for which the increase of amplitudes from the central meridian to the borders of the network and the opposite phases in western and eastern parts is characteristic. It suggests the existence of some artificial periodic effect in the series. A candidate for interpretation of $O_1$ variations with such a structure could be also the non-complete modelling of diurnal and semi-diurnal polar motions. Of course, due to the occurrence of larger amplitudes in coastal sites, the relation to ocean loading cannot be excluded. The variations with $O_1$ frequency besides the variations excited by dynamics of Earth-Moon are not related to any other relevant phenomena.

The examples of $S_1$ and $S_2$ waves in Figs. 6d, 6e, 6f document serious variability of site coordinates with strictly diurnal and semi-diurnal periods. Regional patterns in phase lags are evident in all three figures. Amplitudes of N-S component with $S_1$ frequency are increasing from centre to the border of the network, the arrows indicating phases being oriented towards the centre. Local behavior can be observed at some sites, e.g. MOPI, CAME, ZIMM, RIGA and SVTL, where the stations have different phases from other close stations. The $S_1$ up component have phases symmetric to the central meridian with some exceptions like ORID and BOR1. The arrows of $S_2$ up component show rotational counterclockwise pattern around the centre of network. It is very probable that the strictly diurnal and semidiurnal variations in site coordinates are mainly a consequence of unknown analysis features, and only partly caused by local phenomena. Majority of amplitudes which are up to 2 mm exceeds their $3\sigma$ confidence interval.

## 5. Discussion and conclusions

We demonstrated that the coordinate adjustment in permanent network, if realized from short observational intervals, is capable to detect diurnal and semi-diurnal variations in coordinate time series. Such variations are completely filtered out if standard 24-hour solutions are performed. In this paper, we analyzed the 2.9-year interval (from 2004.0 to 2006.9) of observations in the sub-network of EPN processed by the Bernese GPS software BV42. The results obtained from this interval are typical for the period before 2006.9, when the analysis strategy described in Section 2 of this paper was applied. Some important changes into the EPN processing, like troposphere gradient estimates, absolute antenna phase centers variations, etc. were introduced in 2006.9. It is a challenge for future analyses to investigate whether these innovations after 2006.9 changed the behavior of the short term coordinate variability.

The main feature of the short-term part of spectra at all the analyzed sites is the dominancy of diurnal variations with tidal $S_1$, $K_1$ and $O_1$ frequencies and semi-diurnal variations with tidal $S_2$, $K_2$ and $M_2$ frequencies. Existence of other periodic terms is marginal and they occur only sporadically. It means that the tidal terms with smaller amplitudes are modelled in GPS software BV42 with better accuracy than is the level of detectability of analyses demonstrated in this paper. According to our results, this level is about 0.3 mm in all three local coordinate constituents.

Time series of all the 29 stations were analyzed by two methods – spectral analysis and least squares adjustment, with inclusion of periodic terms with known frequencies according to model (1). Outputs of these separate approaches were self consistent and prove the reliability of the obtained periodic variations.

Amplitudes of detected variations reach up to 3 mm and can be found in all three N–S, E–W and U coordinate constituents. The noise level of spectra depends on the length and homogeneity of the series, and is typically lower than 0.3 mm for horizontal components and 0.5 mm for U component. We showed that the regional pattern of all detected frequencies was strongly manifested and was typical for diurnal $K_1$ and $S_1$ and semi-diurnal $K_2$ and $S_2$ waves. In addition, we concentrated on situations where the individual station behavior was manifested, what is typical for $M_2$ and to some extent also for $S_1$. It means that the detected diurnal and semi-diurnal variations are superposition of local phenomena and regional effects related to network adjustment. Main candidates for local-station dependent effects are deficiencies of used models of tidal-ocean loading (variations with $M_2$ frequency), local troposphere modelling and monumentation instabilities (diurnal $S_1$ oscillations). We assume that the observed variations with $K_1$ and $K_2$ frequencies, which are related to GPS orbiting, are an artifact of modelling and processing the observations, and indicate some analysis deficiencies.

It is evident that explanation of all the observed periodic variations has to consider and subsequently eliminate the regional patterns, which are dominant for majority of the detected periodic waves. We expect that the modifications of the EPN analysis strategy after 2006.9 will be accompanied by diminishing of effects that are manifested as regional patterns in short-periodic coordinate variations. The analysis of short-period behavior of EPN stations from time series after the modelling and processing modifications in 2006.9 will be the subject of another paper.

***Acknowledgments***. This work was supported by the APVV grant No. LPP-0176-06 of the Research and Development Agency of Slovak Republic and the Grant No. 1/0569/10 of the Grant Agency of Slovak Republic VEGA. Authors also thank to anonymous referees for their criticism and valuable comments.

## References

Araszkiewicz A., Bogusz J., Figurski M., 2009: Investigations on tidal components in GPS coordinates. Artificial Satellites, **44**, 2, 67–74.

Boucher C., Altamimi Z., Sillard P., Feissel-Vernier M., 2004: The ITRF 2000. IERS Technical note No. 31. Fankfurt am Main, Verlag des Bundesamtes für Kartographie und Geodäsie.

Dach R., Hugentobler U., Fridez P., Meindl M. (eds.), 2007: Bernese GPS Software Version 5.0. Astronomical Institute, University of Berne, 612 p.

Eanes R. J., Bettadpur S. V., 1995: The CSR 3.0 global ocean tide model. Technical memorandum CSR-TM-96-05, Center for Space Research, University of Texas, Austin.

Egbert G. D., Erofeeva L., 2002: Efficient inverse modelling of barotropic ocean tides. J. Atmos. Ocean. Technol., 19.

EPN, 2010: EUREF Permanent Network web page: tt www.epncb.oma.be

Hefty J., 2008: Consistency of diurnal and semidiurnal variations estimated from GPS with ocean loading displacements evaluated at some EPN sites. Presented at the EUREF 2008 Symposium, Brussels, Belgium, 18-20 June, 2008.

Hefty J., Igondová M., Kováč M., Hrčka M., 2004: Subdaily coordinate variations in EUREF permanent network. In M. Meindl (ed.): Celebrating a decade of the International GPS service. Berne, Astronomical University of Berne, attached CD.

Hefty J., Igondová M., Droščák B., 2009: Homogenization of long-term GPS monitoring series at permanent stations in Central Europe and Balkan Peninsula. Contrib. Geophys. Geod., **39**, 1, 19–42.

Hrčka M., Hefty J., 2006: Diurnal and semi-diurnal coordinate variations observed in European permanent GPS network: deterministic and stochastic constituents. Contrib. Geophys. Geod., Special issue, 7–16.

Hugentobler U., Schaer S., Fridez P. (eds.), 2001: Bernese GPS Software Version 4.2. Bern: Astronomical Institute, University of Berne, 515 p.

Kenyeres A., 2005: EPN time series analysis SP status report. Presented at the EUREF Symposium, Vienna 1 – 3 July, 2005. Available at: `http://www.euref-iag.net/symposia/2005/Vienna/2-03.pdf`

Lefevre F., Yard F. H., LeProvost C., Schrama E. J. O, 2002: FES99 a global tide finite element solution assimilating tide gauge and altimetric information. J. Atmos. Ocean Technol., **19**, 1345–1356.

McCarthy D. D. (ed.), 1996: IERS Conventions (1996), Central Bureau of IERS, Observatoire de Paris, 95 p.

McCarthy D. D., Petit G. (eds.), 2004: IERS Conventions (2003). Verlag des Bundesamts für Kartographie and Geodäsie, Frankfurt am Main, 127 p.

Melachroinos et al., 2008: Ocean tide loading (OTL) displacements from global and local grids: comparisons to GPS estimates over the shelf of Brittany, France. Journal of Geodesy, **82**, 357–371.

Penna N. T., Stewart N. P., 2003: Aliased tidal signatures in continuous GPS height time series. Geophys. Res. Lett., **30**, 23, 2184 p.

Ray R. D. ,1999: A Global Ocean Tide Model From TOPEX/POSEIDON Altimetry: GOT99.2. NASA Technical Memorandum 209478, 1999.

Ray J., Altamimi Z., Collilieux X., Van Dam T., 2008: Anomalous harmonics in the spectra of GPS position estimates. GPS Solutions, **12**, 55–64.

Thomas I. D., King M. A., Clarke P. J., 2007: A comparison of GPS, VLBI and model estimates of ocean tide loading displacements. Journal of Geodesy, **81**, 359–368.

Vaníček P., 1969a: New analysis of the earth pole wobble. Studia Geophysica et Geodeatica, **13**, 225–230.

Vaníček P., 1969b: Approximate spectral analysis by least-squares fit. Astrophysics and Space Science, **17**, 353–367.

Xu G.,2007: GPS Theory, Algorithms and Applications. Springer, Berlin – Heidelberg, 340 p.