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DETERMINATION OF THE NOT-MODELLED SHORT PERIODIC VARIATIONS IN THE GPS PERMANENT SITES' POSITIONS

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ABSTRACT

This paper describes the researches upon the precise short-time GPS solutions made in the Centre of Applied Geomatics, Military University of Technology. The data from ASG-EUPOS (Polish Active Geodetic Network) was processed using Bernese 5.0 software and EPN (EUREF Permanent Network) standards and models. In this study, the adopted 3-hour observation window is shifted every hour obtaining geocentric coordinates in ITRF2005 reference frame. The adjusted network consisted of over 130 stations from Poland and the neighbouring countries, the period covered observations collected from 8.06.2008 to 18.06.2010. These two years of observations allowed to examine short-period oscillations which we found as closely related to the tidal (dynamic) frequencies. The analysis of the residua from IERS2003 tidal model was performed using least squares method with the Eterna software upon the idea of Chojnicki. It confirmed existence of the significant energy in the frequencies corresponding to S1, K1 and K2. The effects in S1 frequency reflect thermal influences, but the reasons of K1 and K2 existence could be both: dynamic (liquid core resonance and non-linearity of K1 are very difficult for modelling as well as the annual modulation of S1) or artificial (GPS satellites' orbiting period, dynamic changes of satellites' constellation and network geometry, multipath, residual tropospheric and ionospheric errors etc.). Since the phase of K1 for all 130 sites is very inconsistent the local effects could be also taken into account as one of the possible reasons. The paper describes the idea of the data processing and analysis, presents the results of vertical (Up component) oscillations in main tidal frequency bands, but also includes the discussion on the possible explanation of existence of short period oscillations in GPS precise solutions.

KEYWORDS: GPS, short-time solutions, periodic signals, ASG-EUPOS

INTRODUCTION

The increasing demand for precise positioning in the near-real time generates a requirement for research on short-term changes in the designated coordinates. Nowadays geodetic space techniques have reached a level of precision that make them an important tool for Earth system sciences. Most of the phenomena related to the mass transport and mass distribution characteristics could be detected through the satellite observations (navigational, altimetric and gravimetric as well), but the effect with diurnal and sub-diurnal time resolution are very difficult to be interpreted due to the limitation of the standard processing strategy. Determination of the absolute position of points with millimetre accuracy using the GNSS (Global Navigation Satellite System) measurements requires a sufficiently long observation periods in an appropriately designed measurement network (geometry), but also time-consuming data processing. With the increase of the length of the session, the number of degrees of freedom grows, which causes the enhancement of the solution's reliability.

The differential GNSS positioning in regional or global permanent networks usually yields site coordinates with daily or weekly resolution. It means that for determination of ambiguities of double differenced phase GPS observations the daily "window" is applied. The weekly solutions come from the "cumulating" process. But the mass distributions related to the tidal effects, atmospheric and ocean loadings, even part of local hydrology effects incorporate their contribution to the diurnal and sub-diurnal coordinates' changes.

PROCESSING OF THE GPS DATA

The research described in this paper is related to the processing of the Polish national precise GNNS network ASG-EUPOS which was made in the Centre of Applied Geomatics (CAG), Warsaw Military University of Technology. In December 2009 the 17^{th} EPN LAC (EUREF Permanent Network Local Analysis Centre) was established in the CAG. Results analyzed in this paper come from independent data processing, but according to the EPN standards. Data

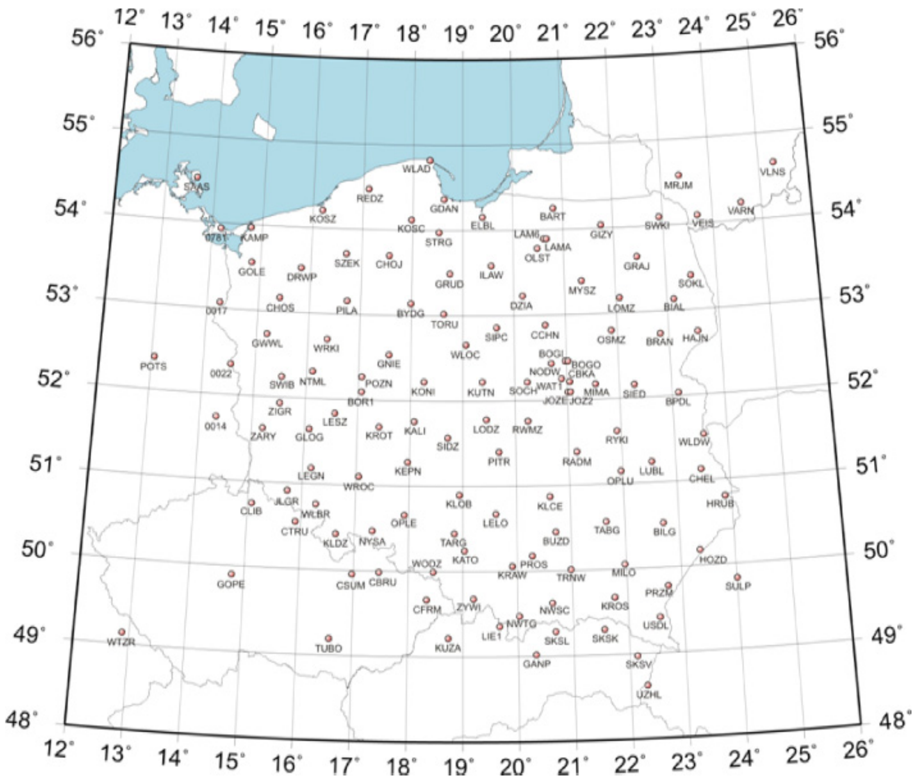

Fig. 1 Adjusted GPS network.

processing strategy as well as the applied models are widely described in the paper by (Araszkiewicz et al., 2010). Time resolution of GPS solutions' sequences is related to the density of sampling. The longer sessions are processed in common batch, the more smoothed solution we get. The effect of random and systematic errors is suppressed, especially the short-periodic effect are diminished. Shortening of sessions, however, is qualified by solvability of vectors, in particular the possibility of phase ambiguity determination.

The way to increase the time resolution of GNSS solutions is the use of overlapping sessions. Advantages and disadvantages are discussed in the literature (e.g. Webley et al., 2002). The use of overlapping sessions increases the possibility of detection of variations in sub-diurnal frequencies, but it also increases the occurrence of the strong correlation relationships of the subsequent solutions. This is however not a problem in the case studies of the nature of periodicity in time series, since these correlation relationships can affect only the values of statistical parameters. In this study, the adopted 3-hour observation window is shifted every hour, which produces the 67 % correlation between the solutions. For the 3-hour window during the tests we were able to get satisfactory results (standard deviation of the geodetic coordinates better than 1 cm). The n-hour observation window introduces 2n-hour artificial frequency (Nyquist). The 8-hour changes come from third harmonic component of the diurnal period, so in case of 4-hour windowing the superposition of oscillations will be observed. It does not disturb diurnal and semidiurnal frequencies, but allows also investigations on 8-hour energy and states the advantage of 3-hour over 4-hour windowing. At this point it is just worth mentioning that the solid Earth tides model implemented to the data processing was created according to the IERS2003 standards (McCarthy and Petit, 2004), ocean loading effects were removed using the FES04 model (Lyard et al., 2006) and no tidal atmospheric correction were applied. Adjustment was made using Bernese 5.0 software (Dach et al., 2007). The adjusted network consisted of 130 stations (Fig. 1), the period covered observations collected from 8.06.2008 to 18.06.2010.

TIDAL DATA ADJUSTMENT

The tidal analysis of the residua from IERS2003 model was performed using least squares method with the Eterna software (Wenzel, 1996) upon the idea of Chojnicki (1972).

We can write at epoch ti observation equation under the form:

$$l_i + v_i = \sum_j \sum_k d_j \cdot A^T_{j,k} \cdot \cos(\alpha^T_{i,j,k} + \phi_j) \qquad (1)$$

where:

l, v – observation and its correction;
i – subscript related to epoch t_i;
j – tidal group;
k – wave inside tidal group;
$d_j = \frac{A_j}{A_j^T}$ – the ratio (amplification) of the observed to the theoretical amplitude of the group j;
$A_{j,k}^T$ – the theoretical amplitude of a tidal constituent k inside of the group j;
$\alpha_{i,j,k}^T$ – the argument at instant t_i of a tidal constituent (j,k)
ϕ_j – the phase difference supposed constant inside group j.

The estimated values during the least squares adjustment are d_j and φ_j.

The precision is estimated through the root mean square errors (RMS) of the observations and of the estimated unknowns. The RMSs are to be determined through 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. It uses the so called "average noise levels" at frequency f, which are arithmetic means of the amplitudes.

This method also uses the RMS for unit weight (σ_0), called in the output "Standard deviation" and computed according to least squares under the condition of white noise. Then Eterna determines the so called "Average noise level" at "white noise" $L(wn)$ through (Ducarme et al., 2005):

$$L(wn) = \sigma_0 \sqrt{\frac{\pi}{n}} \tag{2}$$

where n is the number of the hourly data.

Further Eterna determines the RMS of d_j, again for the case of white noise, as:

$$\sigma_{wn}(d_j) = C_j \cdot \sigma_0 \tag{3}$$

where C_j is a coefficient, obtained through the matrix of the LS normal equations.

Finally, Eterna determines the colored RMS of d_j as:

$$\sigma_{et}(d_j) = \sigma_{wn}(d_j)\frac{L(f)}{L(wn)} = C_j \frac{L(f)}{\sqrt{\frac{\pi}{n}}} \tag{4}$$

where $L(f\ )$ is the average noise levels at the frequencies f = 1, 2, 3 & 4 cpd (cycles/day), determined as arithmetic means of the amplitudes in the intervals. With a good enough approximation we can put $C_j \cong \frac{1}{h_j\sqrt{\frac{n}{2}}}$, where h_j is the minimal theoretical amplitude in the group j. By using this we finally get (Ducarme et al., 2005):

$$\sigma_{et}(d_j) \cong \frac{L(f)}{h_j \cdot \sqrt{\frac{\pi}{2}}} \tag{5}$$

In a similar way we get, for the RMS of the phase lag φ_j (Ducarme et al., 2005):

$$\sigma_{et}(\phi_j) \cong \frac{L(f)}{h_j \cdot d_j^2 \cdot \sqrt{\frac{\pi}{2}}} \tag{6}$$

RESULTS

It has been proved that this method of GNSS data processing allows for dynamic changes in diurnal and sub-diurnal frequency bands (Araszkiewicz et al., 2010). In this study the method of least squares will allow a closer recognition of energy in the particular tidal bands. Since in our analyses the horizontal deformations are of one dimension order less than vertical, only changes in Up component are presented here.

Initially the results from a single station will be described. As the example the Polish EPN site BOR1 was chosen. This site is one of the most stable one in the whole EPN. Table 1 presents the results of tidal data processing for 18 short-term tidal constituents (this number follows from the analyzed observation time – 2 years) together with the error characteristics, noise level and the standard deviation of the tidal observation after adjustment (σ_0).

The noise values for 0.1 cpd was not able to be determined due to the data filtering at the pre-processing stage.

The ETERNA grouping relies on the fact, that the Earth's response to tidal forcing is smooth in these frequency bands except for the band including P1-S1-K1-Psi1-Phi1, where we have the strong nearly diurnal resonance. In GNSS data the forcing is at least partially atmospheric with strong amplitudes at exactly the solar periods (S1 and partially S2). In that case the grouping must be modified accordingly by isolating the solar waves in order to accommodate the different amplifications of solar and lunar waves. Otherwise we get averaged amplitudes instead of realistic ones and periodic signals left in the residual spectrum.

Figure 2 presents magnitude of the modelled deformations (Up component) for comparison with the changes of the residual deformational amplitudes in the diurnal and semi-diurnal frequencies respectively (Fig. 3).

From the tidal theory comes that the main dynamic changes (not affected by the other phenomena) are observable in the O1 and M2 frequencies. O1 is the lunar principal diurnal wave with the argument of (τ-s) (τ is the lunar day, s – the

Table 1 Eterna report file.

adjusted tidal parameters:

from [cpd]	to [cpd]	wave	theor. ampl. [mm]	ampl.fac. d_j	stdv.	ph.lead φ_j [deg]	stdv. [deg]
0.721500	0.906315	Q1	11.3593	0.00975	0.00848	134.4344	49.8275
0.921941	0.940487	O1	59.3283	0.00223	0.00161	103.9971	41.1939
0.958086	0.974188	M1	4.6635	0.01939	0.02320	-55.8237	68.5601
0.989049	0.998028	P1	27.6007	0.01464	0.00389	-87.8542	15.2442
0.999853	1.000147	S1	0.6525	1.08883	0.24164	128.3894	12.7156
1.001825	1.003651	K1	83.4035	0.02819	0.00121	89.7472	2.4519
1.005329	1.005623	PSI1	0.6528	0.31195	0.16153	6.8994	29.6695
1.007595	1.011099	PHI1	1.1877	0.07202	0.09581	-111.1994	76.2225
1.013689	1.044800	J1	4.6652	0.02544	0.02060	70.6944	46.3968
1.064841	1.216397	OO1	2.5519	0.03712	0.03212	-176.4024	49.5754
1.719381	1.872142	2N2	1.7234	0.00895	0.04703	-18.1624	301.0314
1.888387	1.906462	N2	10.7907	0.00535	0.00959	-26.2638	102.7875
1.923766	1.942753	M2	56.3582	0.00225	0.00188	129.0243	47.9367
1.958233	1.976926	L2	1.5931	0.00900	0.06590	-45.3728	419.7066
1.991787	2.002885	S2	26.2184	0.01168	0.00388	-119.3081	19.0345
2.003032	2.182843	K2	7.1244	0.28030	0.01219	96.2589	2.4912
2.753244	3.081254	M3	0.2175	0.26436	0.43311	-161.0713	93.8713
3.791964	3.937897	M4	0.0011	30.46302	65.28263	-74.9194	122.7839

Average noise level at frequency bands in mm:

0.1 cpd*********** 1.0 cpd 0.144160 2.0 cpd 0.129826
3.0 cpd 0.119920 4.0 cpd 0.095526 white noise 0.055880

Standard deviation: 4.2 mm

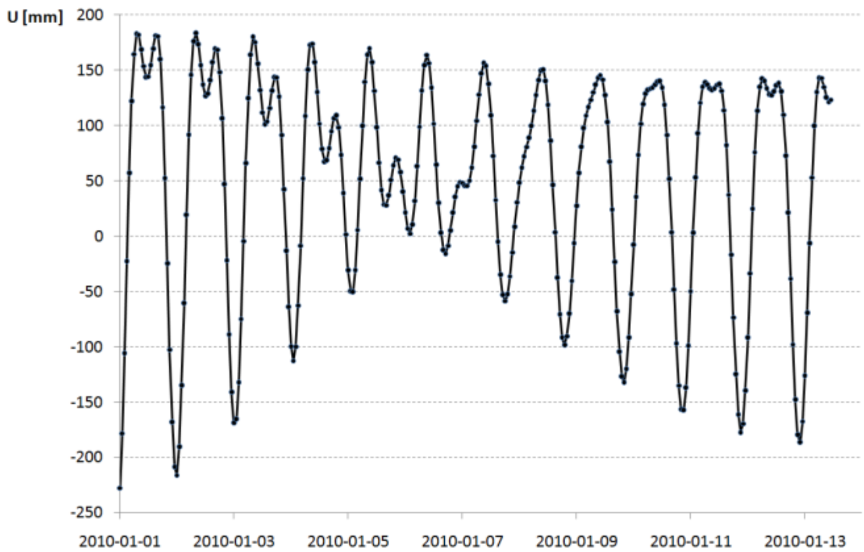

Fig. 2 Model tidal deformations in Up component [mm] for BOR1 site.

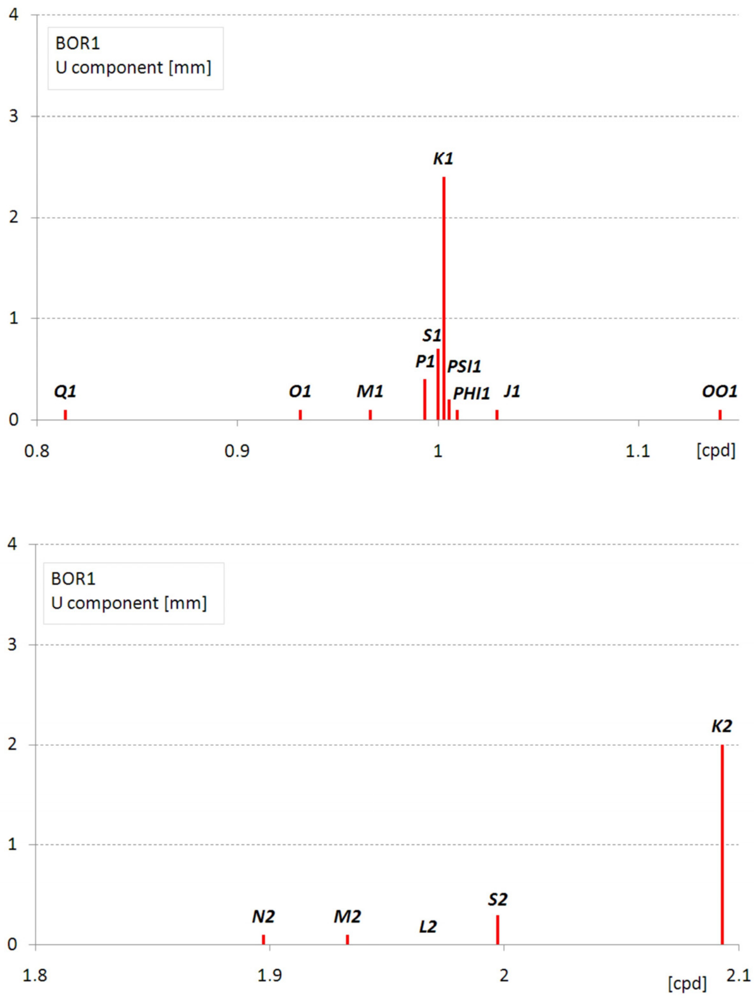

Fig. 3 Estimated residual amplitudes in the diurnal (left) and semi-diurnal (right) frequencies of residual Up component of BOR1 site.

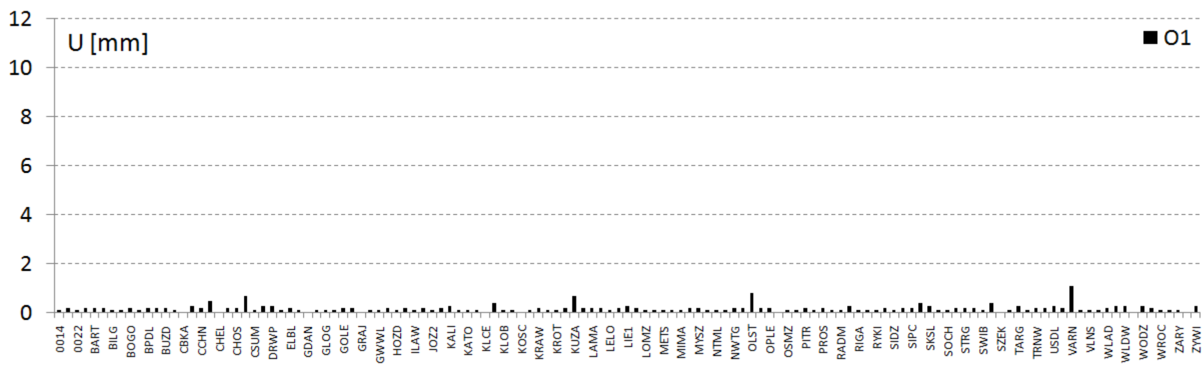

Fig. 4 Amplitudes of the O1 deformational wave of Up component [mm].

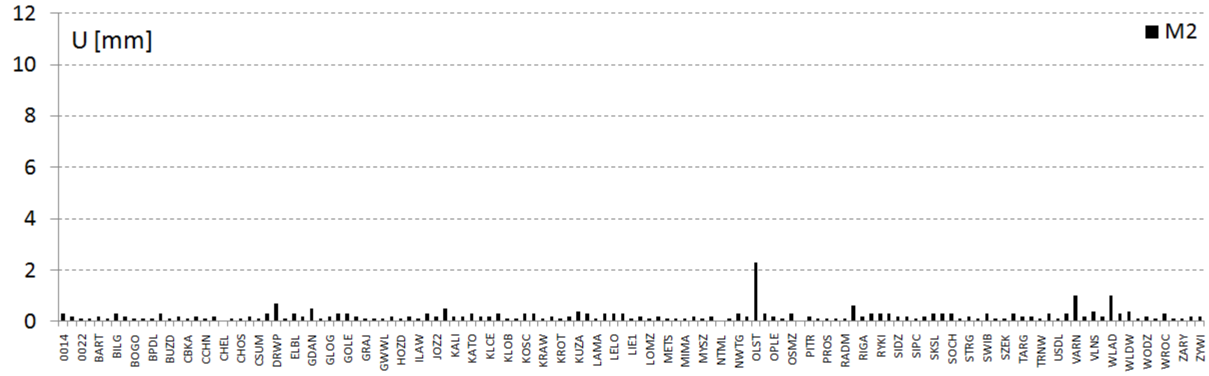

Fig. 5 Amplitudes of the M2 deformational wave of Up component [mm].

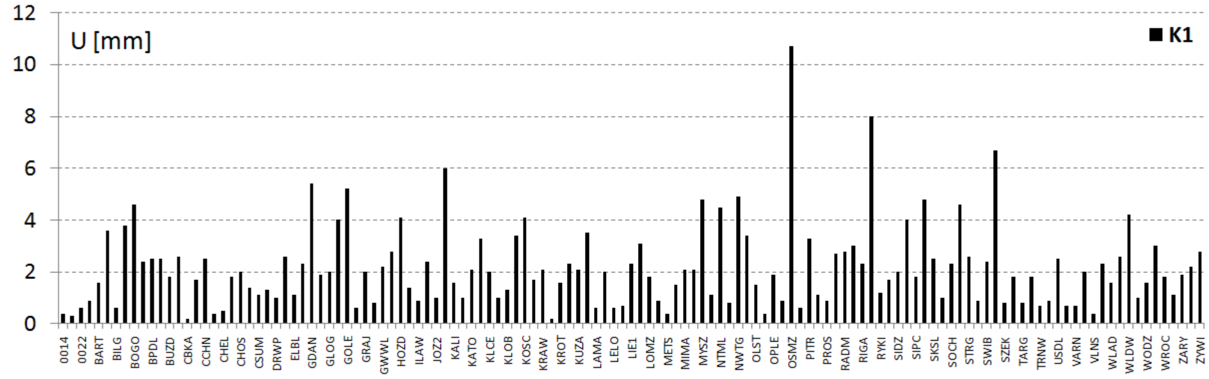

Fig. 6 Amplitudes of the K1 deformational wave of Up component [mm].

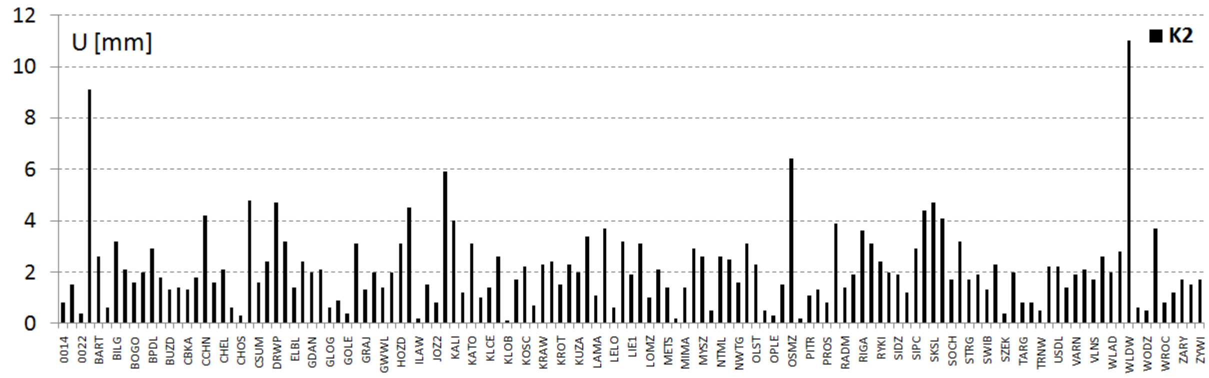

Fig. 7 Amplitudes of the K2 deformational wave of Up component [mm].

sidereal month). M2 is the principal semi-diurnal wave of argument (2τ) (Melchior, 1983). In the data from our adjustment no significant energy in these frequency bands were found (Figs. 4 and 5 present the results for all 130 GPS sites). This could mean that the solid Earth tides model which was used at the stage of data processing truly reproduces dynamical effects in these frequencies.

K1 is the declinational wave of argument (t') (sidereal day). It turned out that this frequency involves the most amount of energy. K2 is a declinational wave of M2, but also appears due to the non-linearity of K1 since its argument is ($2t'$) (Melchior, 1983). The deformational changes in Up component in these frequencies were found to be significant (Figs. 6 and 7).

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 ($t+p_S$). S2 is the solar principal wave, with

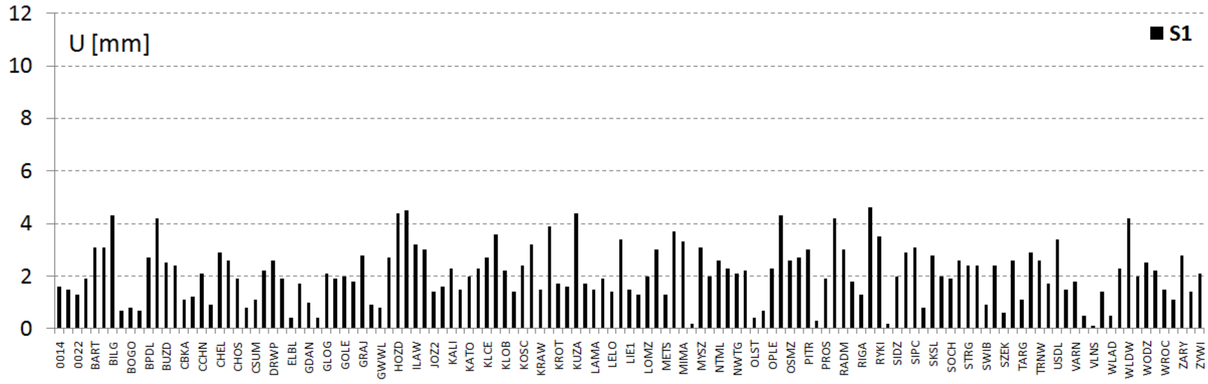

Fig. 8 Amplitudes of the S1 deformational wave of Up component [mm].

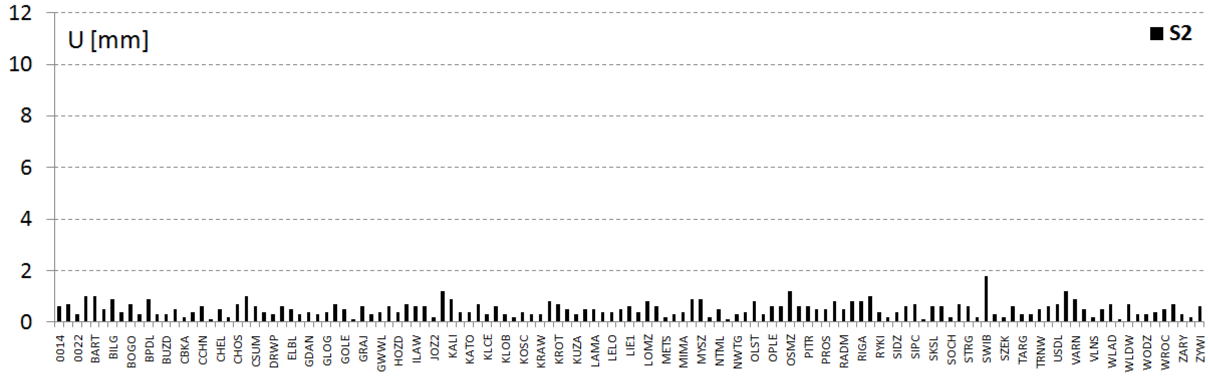

Fig. 9 Amplitudes of the S2 deformational wave of Up component [mm].

the strong thermal effect as well. It depends on argument 2*t*. The observed effects related to these frequencies are in Figs. 8 and 9.

Figure 10 presents phase changes (φ_j) of the selected sites of the network for the K1 component since they contain most of the energy of all. In this geometrical representation phase is the angle between geographic North and the magnitude vector (it has no relations to the geographic azimuth). From this figure we can also draw some conclusions about spatial distribution of the observed deformational parameters.

DISCUSSION ON THE RESULTS

The conclusion from our analysis is that we have unambiguously detected the residual oscillations in tidal frequency bands. But the question arises if there is a geodynamic origin of these oscillations? No residual oscillations in O1 and M2 tidal waves were discovered. It means that the solid Earth tides model (IERS2003) fits very well and the ocean loading as well. Influence of gravitational atmospheric tides (the model was not implemented) could be neglected in data processing.

Significant oscillations in K1 and K2 needs more detailed interpretation: K1 is affected by the liquid core resonance that is not well modelled. K2 can be due to non linearity of K1. K1 is also modulated by the S1 annual changes since:

$$2\cdot\cos(h)\cdot\cos(S1)=\cos(K1)+\cos(P1) \qquad (7)$$

with h – tropical year. From the other side the orbiting period of GPS satellites' is equal exactly to K2 period. This could be transferred to the variability of resulting coordinates.

Changes in S1 may be a consequence of thermal effect on GNSS site. These could be caused either by the method of monumentation (pillar or building) or by the antenna itself. The thermal atmospheric tides could also affect the coordinates, but this effect is also very difficult for modelling.

Phase changes are ambiguous, but this is mainly due to the LSM deficiency when the amplitudes are small.

In case of GNSS data processing some outward influences have to be stated such as the deficiencies in ionosphere and troposphere modelling, effects on residual errors in satellites' orbiting, multipath effect or diurnal polar motion.

The GNNS data adjustment is done upon the vectors between individual stations. Some of them are assumed to be referenced for the reference frame transfer. During the processing of the network a kind

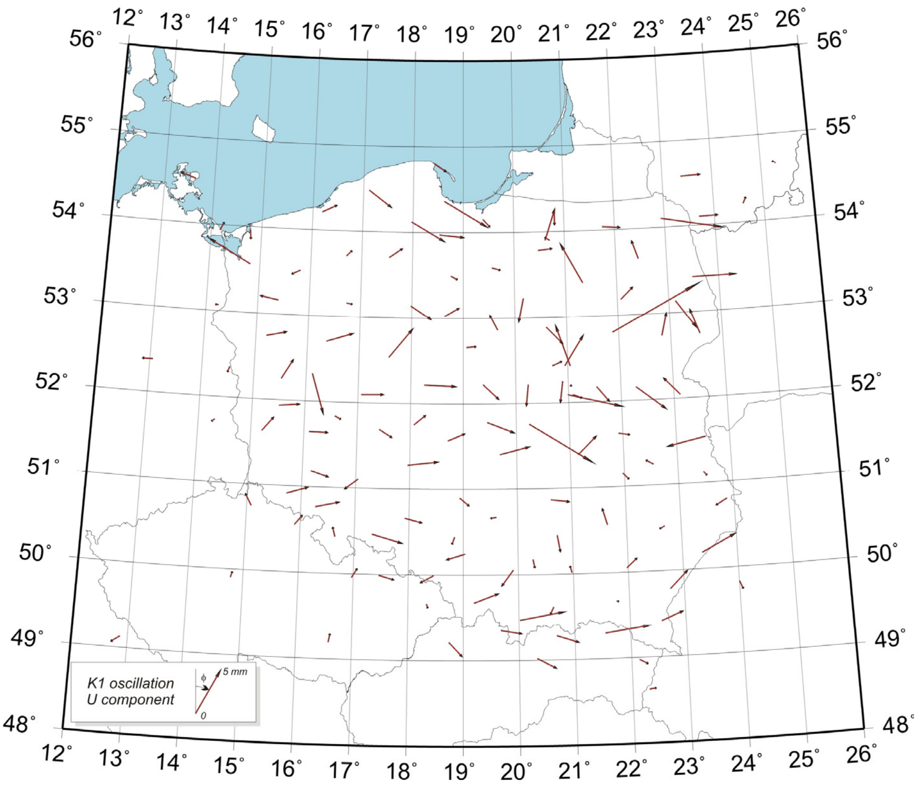

Fig. 10 Amplitudes and phases of the K1 deformational wave of Up component [mm].

of propagations could be seen. The question which could be pointed out is: are the oscillations able to be propagated over the whole network? This was not proved by our research, because it had to be reflected in the spatial distribution of the oscillations.

It is also worth mentioning that all the observed variations are of ‘relative’ character, i.e. relative to the ‘stable’ mean of reference sites. The large K1, K2 could be in some extend the artefacts of processing strategy.

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