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SHORT-PERIOD INFORMATION IN GPS TIME SERIES

Janusz Bogusz, Mariusz Figurski
Centre of Applied Geomatics, Military University of Technology, Warsaw
e-mail: jbogusz@wat.edu.pl, mfigurski@wat.edu.pl

ABSTRACT. This paper presents results of the Polish Active Geodetic Network (ASG-EUPOS) processing. The analyses on the GPS coordinates from sub-diurnal solutions of ASG-EUPOS and EPN data provided by Warsaw Military University of Technology were performed. The aim of this research is to find out how the tidal models used in Bernese software (solid Earth and ocean tides as well) fit to the individual conditions of GPS stations. The 1-hour solution technique of GPS data processing was utilized to obtain coordinates of above 130 Polish and foreign stations. This processing technique allowed us to recognize residual diurnal and sub-diurnal oscillations which could be next utilized for validation of the tidal models used in GPS software.
Keywords: GPS, Earth tides, frequency analysis.

1. INTRODUCTION

The recent potential of satellite systems and software development allows estimation of sites' coordinates with arbitrary resolution. The weekly or daily solutions provide us coordinates with millimetre accuracy, but the similar is able to be achieved from shorter solutions. These analyses were not so frequent yet, from literature we could mention e.g. papers by Rogowski (2001), Rogowski et al. (2004) and Bogusz et al. (2000) where the analysis of 1-hour GPS solutions were presented and the existence of diurnal and semi-diurnal variations were stated, in presentation by Hefty et al. (2004) the existence of oscillations with tidal periods were pointed out, in Hefty (2008) and Melachroinos et al. (2008) the possible explanation by ocean tidal loading was presented. This paper is also the continuation of the researches started at the Military University of Technology on the diurnal and sub-diurnal GNSS coordinates variations (Araszkiewicz et al., 2009) using permanent satellite systems.

One of those is Polish ASG-EUPOS, which is the multifunctional precise satellite positioning system established by the Head Office of Geodesy and Cartography in 2008. It consists of 84 Polish sites with GPS module, 14 Polish sites with GPS/GLONASS module and 20 foreign sites (state for June 2010). The adjusted network consisted of over 100 stations, the period covered observations collected since June 2008. The method of adjustment elaborated in the CAG, the newest, seventeenth EPN LAC (EUREF Permanent Network Local Analysis Centre) established at the end of 2009 as MUT LAC, is similar with the one applied in EPN. It is based on the Bernese 5.0 software with the newest models and solution ideas available. The difference to the EPN solutions lies in the resolution time of adjustment. In the presented research the 1-hour sampling rate with 3-hour windowing is applied. This allows to make the interpretations concerning short-period information in GPS coordinates series. The time span (over 1 year) permits the separation between the pure dynamic phenomena (tides) and other (thermal oscillations) in the diurnal and sub-diurnal frequency bands.

2. DATA AND PROCESSING STRATEGY

The adjusted network consists of 132 GPS sites located in Poland and neighbouring countries (Germany, Czech Republic, Slovakia, Ukraine, Belorussia, and Lithuania). 4 stations were assumed as referenced in the adjustment (ONSA, METS, POTS and WTZR), 24 of them are simultaneously the EPN sites (Fig. 1). The data covered period from 8.06.2008 to 9.06.2009.

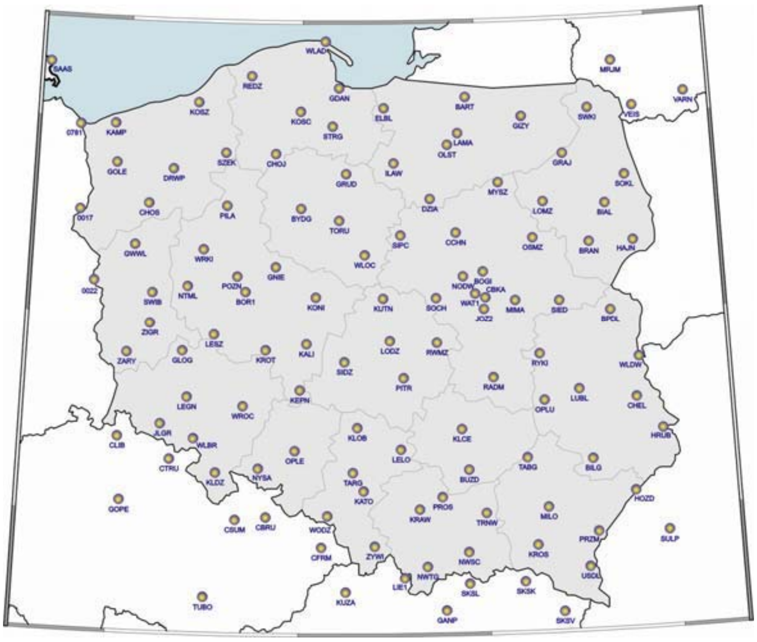

Fig. 1. GPS sites used in analyses

Only GPS observations (RINEX format) were used with carrier phase as a basic observable (double-differences, ionosphere-free linear combination).

The processing strategy contains:

- software – Bernese 5.0 (Beutler et al., 2006);
- elevation angle cutoff – 3 degrees, elevation dependent weighting using cos(z);
- orbits and ERPs: IGS precise final orbits and ERPs;
- troposphere: Saastamoinen – based dry component (Dry-Niell mapping function) as a priori model and the Wet-Niell mapping function;
- ionosphere – CODE global iono models (help to increase the number of resolved ambiguities),finally cancelled out due to ionosphere-free linear combination;
- ambiguity – QIF strategy – for baseline lengths shorter than 100 km - L5/L3 approach, for baselines shorter than 20 km - L1/L2 approach;
- only GPS observations (RINEX format) were used with carrier phase as a basic observable (double-differences, ionosphere-free linear combination);
- models:
  - planetary ephemeris – DE405;
  - ocean tides – OT_CSRC;
  - Earth geopotential model – JGM-3;
  - nutation model – IERS2000;
  - tidal displacements: solid tides-according to IERS2003 standards;
    ocean loading model – FES2004.

Furthermore the innovation of presented study is the usage of 3-hourlong observational window, moved with 1 hour step, which made obtaining orthocartesian coordinates with 1-hour resolution possible.

As the result 8760 normal points from 132 GPS sites for further analyses were obtained.

3. TIME SERIES

The geocentric XYZ coordinates in ITRF2005 reference frame for 132 GPS sites were determined. For interpretation purposes these coordinates were recalculated to the topocentric North-East-Up coordinate frame:

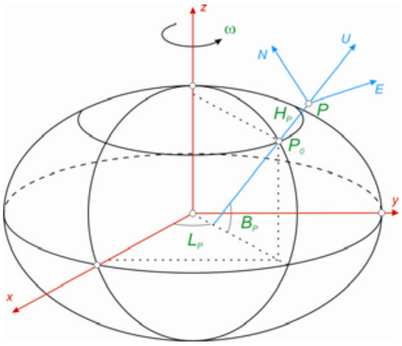

Fig. 2. Topocentric NEU reference frame

$$\begin{bmatrix} E \\ N \\ U \end{bmatrix} = \mathbf{R}_x \cdot \mathbf{R}_z \cdot \begin{bmatrix} X - \bar{X} \\ Y - \bar{Y} \\ Z - \bar{Z} \end{bmatrix} =$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \sin\bar{B} & \cos\bar{B} \\ 0 & -\cos\bar{B} & \sin\bar{B} \end{bmatrix} \cdot \begin{bmatrix} -\sin\bar{L} & \cos\bar{L} & 0 \\ -\cos\bar{L} & -\sin\bar{L} & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X - \bar{X} \\ Y - \bar{Y} \\ Z - \bar{Z} \end{bmatrix}$$

Time-series of the chosen station's coordinates together with the standard deviations are presented in Fig. 3:

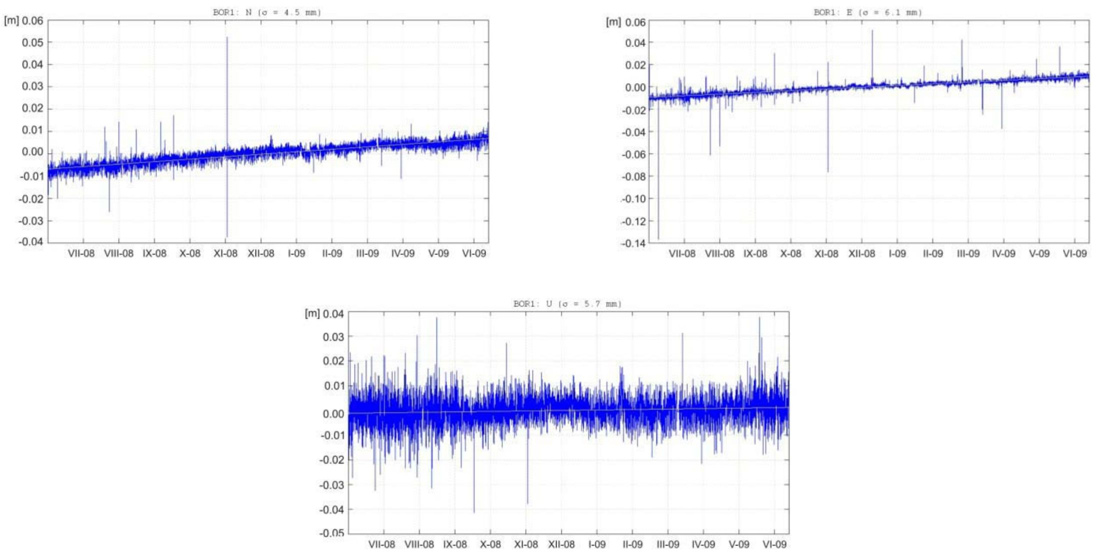

Fig. 3. Changes of the N, E and U coordinates [m] of Polish BOR1 EPN site

4. SHORT-PERIOD OSCILLATIONS

Fast Fourier Transformation provided information about the frequencies of the site's coordinates. All analyses were performed in the MATLAB® Technical Computing Environment. In figures 4-5 the examples of diurnal, semi-diurnal and 8-hour oscillations are presented. 6-hour oscillation, which comes from 3-hour windowing (Nyquist frequency) applied in the data processing was omitted.

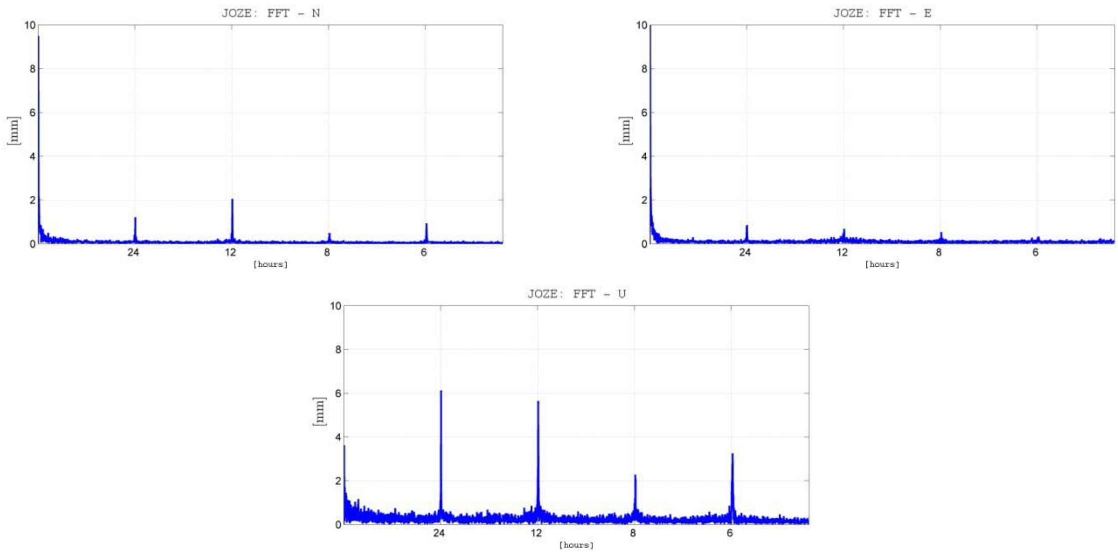

Fig. 4. Oscillations in N, E and U coordinates [mm] of Polish JOZE EPN site

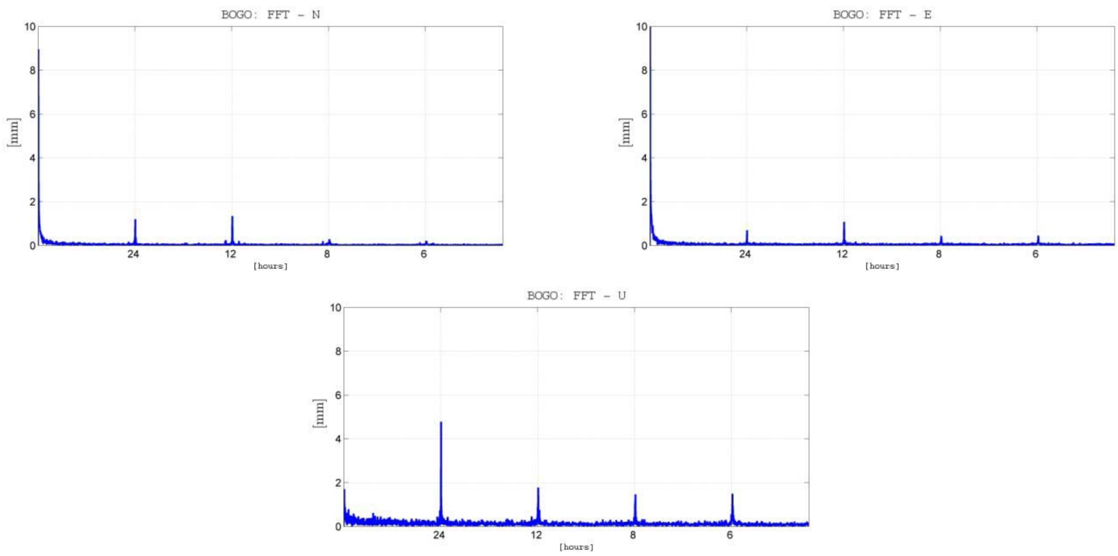

Fig. 5. Oscillations in N, E and U coordinates [mm] of Polish BOGO EPN site

These examples show that there is no regularity in the short-period oscillations in the GPS coordinates. Some stations have dominant oscillations in diurnal, some in semi-diurnal frequency bands. No regularity has been found. Table 1 presents the composition of maximum amplitudes of oscillations.

Table 1. Maximum amplitudes of oscillations.

	24-hours			12-hours			8-hours		
Site name	**N [mm]**	**E [mm]**	**U [mm]**	**N [mm]**	**E [mm]**	**U [mm]**	**N [mm]**	**E [mm]**	**U [mm]**
RWMZ	4.0	3.4	-	-	7.0	-	-	-	8.3
OSMZ	-	-	10.6	5.0	-	-	2.8	-	-
WLDW	-	-	-	-	-	11.8	-	-	-
DRWP	-	-	-	-	-	-	-	3.0	-

5. SPATIAL INFORMATION

The spatial distribution of the diurnal and semi-diurnal oscillations is not regular and rather local effects are reflected there (Fig. 6-7).

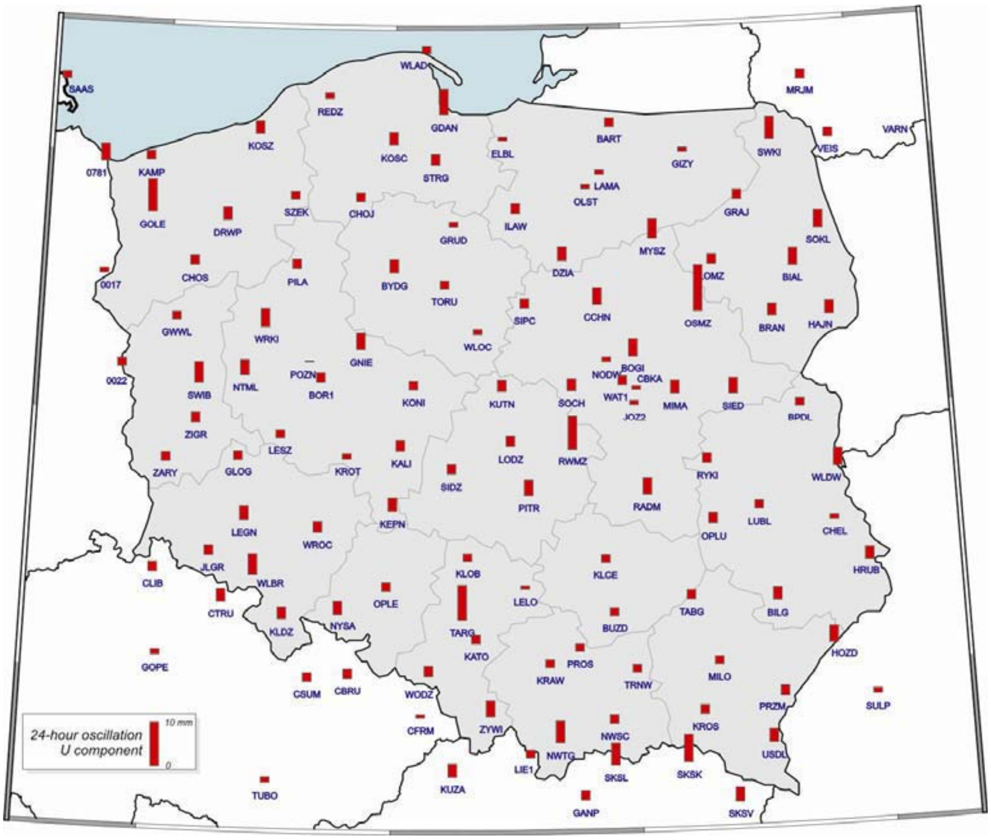

Fig. 6. Spatial distribution of the diurnal oscillations [mm] in the U component

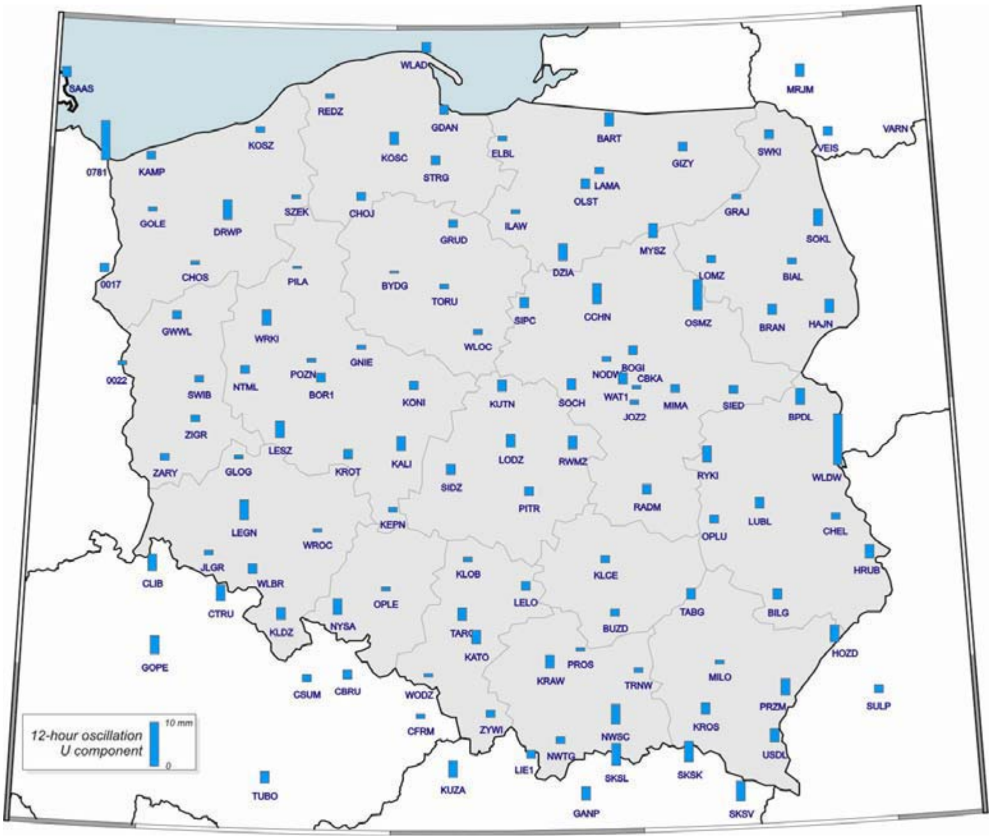

Fig. 7. Spatial distribution of the semi-diurnal oscillations [mm] in the U component

6. TIDAL ANALYSIS

In order to investigate which frequencies have the energy in diurnal and semi-diurnal bands the tidal analysis of the chosen stations was performed. The manner based on the least squares method was used (Chojnicki, 1977).

The idea is to compare the tidal model according to the HW95 (Hartmann and Wenzel, 1995) tidal potential development to the observations, but in the particular, formerly assumed, frequency bands. The normal equations are formed according to the assumption that the correction to the observation is the function of the model Earth tides and some parameters relevant to the measuring instrument (*C* and *D*, in GPS observations out of importance).

Observed values of the Earth tides are proportional to the modelled ones (P_t^{th}) and two parameters dependent on the Earth's crust properties: amplitude factor (δ) and phase shift ($\Delta\Phi$). The observation equation is:

$$v_t = \sum_{i=1}^{n} R_i \delta_i \cos\left(\Phi_{it} + \Delta\Phi_i\right) - P\left(P_t^{th}, \delta, \Delta\Phi\right) - D_t + C$$

where R and Φ are model amplitude and phase respectively.

The proper tidal wave grouping is very essential in this method. The grouping depends on the observational time span. In this study (one year) it is (courtesy of Bernard Ducarme):

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WAVEGROUPI=  0.000133  0.501369   1.00000     0.000 MF   #ETERNA wavegroup
WAVEGROUPI=  0.721500  0.906315   1.00000     0.000 Q1   #ETERNA wavegroup
WAVEGROUPI=  0.921941  0.940487   1.00000     0.000 O1   #ETERNA wavegroup
WAVEGROUPI=  0.958086  0.974188   1.00000     0.000 M1   #ETERNA wavegroup
WAVEGROUPI=  0.989049  0.998028   1.00000     0.000 P1   #ETERNA wavegroup
WAVEGROUPI=  0.999853  1.000147   1.00000     0.000 S1   #ETERNA wavegroup
WAVEGROUPI=  1.001825  1.003651   1.00000     0.000 K1   #ETERNA wavegroup
WAVEGROUPI=  1.005329  1.005623   1.00000     0.000 PSI1 #ETERNA wavegroup
WAVEGROUPI=  1.007595  1.011099   1.00000     0.000 PHI1 #ETERNA wavegroup
WAVEGROUPI=  1.013689  1.044800   1.00000     0.000 J1   #ETERNA wavegroup
WAVEGROUPI=  1.064841  1.216397   1.00000     0.000 OO1  #ETERNA wavegroup
WAVEGROUPI=  1.719381  1.872142   1.00000     0.000 2N2  #ETERNA wavegroup
WAVEGROUPI=  1.888387  1.906462   1.00000     0.000 N2   #ETERNA wavegroup
WAVEGROUPI=  1.923766  1.942753   1.00000     0.000 M2   #ETERNA wavegroup
WAVEGROUPI=  1.958233  1.976926   1.00000     0.000 L2   #ETERNA wavegroup
WAVEGROUPI=  1.991787  2.002885   1.00000     0.000 S2   #ETERNA wavegroup
WAVEGROUPI=  2.003032  2.182843   1.00000     0.000 K2   #ETERNA wavegroup
WAVEGROUPI=  2.753244  3.081254   1.00000     0.000 M3   #ETERNA wavegroup
WAVEGROUPI=  3.791964  3.937897   1.00000     0.000 M4   #ETERNA wavegroup
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The tidal processing was made using Eterna 3.4 software (Wenzel, 1996). The results are presented only for U component, since the effect of the tidal deformation is significant in comparison to the GPS precision.

Table 2 presents results of tidal analysis for JOZE and BOGO stations, by means of amplitude and phase with their standard deviations. These site were chosen because the GPS antennas are mounted on the concrete pillars, so the movement of the high buildings does not affects results of the observations. In figures 8-9 there are presented the amplitudes of residual tidal deformational effect in U component for both sites.

Table 2. Results of the tidal analysis of U component.

Group name	JOZE				BOGO			
	Amplitude [mm]	Std. dev. [mm]	Phase [°]	Std. dev. [°]	Amplitude [mm]	Std. dev. [mm]	Phase [°]	Std. dev. [°]
MF	0.4	0.2	146.5	26.4	0.6	0.1	199.1	8.7
Q1	0.1	0.2	258.0	85.1	0.2	0.1	336.3	42.2
O1	0.5	0.2	210.5	24.7	0.4	0.1	155.5	18.5
M1	0.6	0.4	239.9	35.1	0.8	0.2	9.8	13.5
P1	1.9	0.3	196.7	7.6	0.4	0.1	213.9	18.9
S1	3.2	0.4	80.1	6.6	1.5	0.2	328.5	7.7
K1	4.0	0.2	301.5	3.3	3.3	0.1	176.9	2.1
PSI1	3.9	0.2	261.8	3.5	2.1	0.1	137.7	3.5
PHI1	0.8	0.3	80.0	19.5	0.9	0.1	14.4	8.9
J1	0.8	0.2	250.4	15.9	0.2	0.1	120.7	41.8
OO1	0.3	0.2	318.8	28.9	0.1	0.1	102.9	38.3
2N2	0.3	0.2	160.8	40.5	0.1	0.1	181.2	89.1
N2	0.2	0.2	35.3	60.3	0.2	0.1	329.7	32.4
M2	0.0	0.3	178.4	315.2	0.1	0.1	52.7	56.6
L2	0.5	0.2	11.2	24.8	0.2	0.1	211.0	47.5
S2	1.3	0.2	314.0	10.8	0.8	0.1	53.9	9.6
K2	3.7	0.2	246.6	3.2	1.6	0.1	330.2	4.0
M3	0.1	0.2	306.9	111.5	0.1	0.1	146.7	63.2

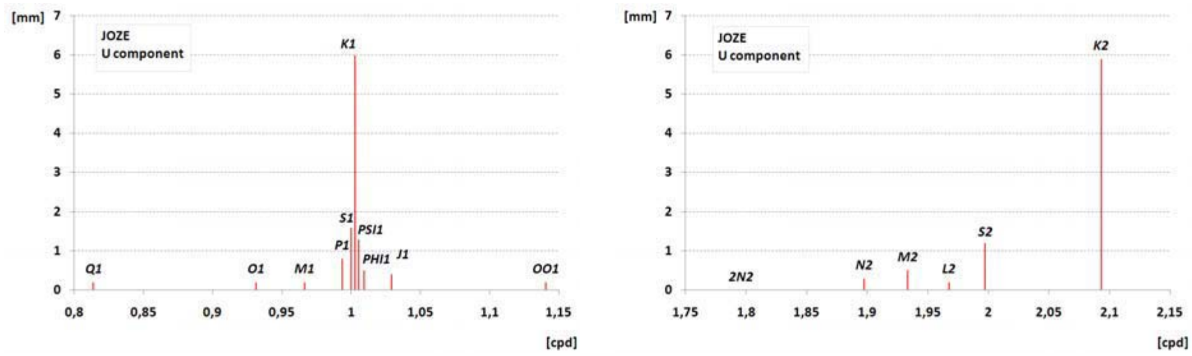

Fig. 8. Diurnal (left) and semi-diurnal (right) constituents
in U component [mm] for JOZE station

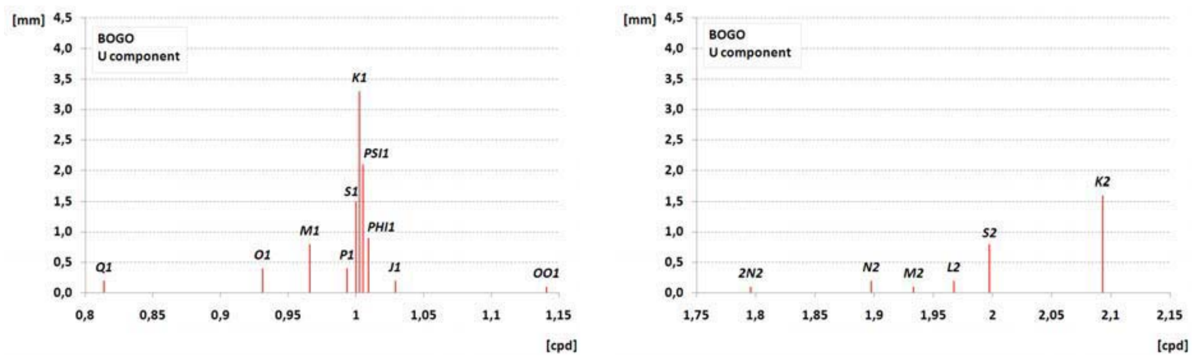

Fig. 9. Diurnal (left) and semi-diurnal (right) constituents
in U component [mm] for BOGO station

One should pay attention that predominant effect comes not from thermal S1 and S2, but tidal K1 and K2 waves. The explanation of this fact need further investigations. There is no energy in pure tidal frequencies so-called O1 and M2, which means that the model used in the GPS data processing approximate the effect of the solid Earth and ocean tides in these frequencies very precise.

But the question which should be put at this stage is: are we able to obtain such precise coordinates to observe such small effects?

7. CONCLUSIONS

This method of the GPS data processing allows determination of the short-period information in the Earth's crust deformation. The comparison of the FFT and least squares method gave significant consistency.

The national GNSS networks such as Polish ASG-EUPOS give the opportunity to investigate the spatial distributions of the deformational-related phenomena, despite its imperfectness in antenna's fixing (mostly at the high buildings).

Main diurnal and semi-diurnal frequency components are clearly seen in the spectra. Even separation of the PSI1 and PHI1 tidal waves from 1-year time span with 1-hour resolution is possible.

The XYZ coordinates in ITRF frame are residuals of Earth tide model (IERS2003 standards used in Bernese software), so each kind of short-period determination can be very useful in the efficiency of the Earth tides effect elimination. This research showed that the model fits very well in the main tidal frequencies O1 and M2. K1 (affected by the liquid core resonance) and K2 (due to non linearity of K1) tidal waves which are dominant in the spectra, are very difficult for modelling. Detailed explanation of this fact needs further researches and longer time series. No long period tides (fortnightly) were found.

In general the results are consistent with the other authors (Hefty et al., 2002 and Hefty et al., 2008b) which proves correctness of the applied method of GNSS data processing in short time intervals.

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