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Search for geodynamic signals in time series of astrometric observations

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Abstract. Since 1963 astronomical observations are conducted at Borowa Gora Geodetic-Geophysical Observatory of the Institute of Geodesy and Cartography with the use of transit instrument. Instrumental, technological and methodical improvements in acquiring and pre-processing of rotational time observations make the time series inconsistent over the whole period of operation of the instrument. The rotational time determined was initially referred to the FK5 catalogue system; starting from the data of 1986 it is also referred to the Hipparcos catalogue system. Data series from last almost 25 years is particularly valuable for the analysis. Complex spectral analysis of a long-standing rotational time data series from 1986.0-2010.6 was performed. A number of periodic terms were separated from the series investigated and the numerical model of the series has been formed.

The effects of beat observed in the numerical model were discussed. The existence of a distinguished weekly term in the data investigated has been observed. The results obtained were compared with the spectra of EOP from the analysis of IERS data.

Keywords: astrometric observations, rotational time, local variation of the plumb line

1 Introduction

Space techniques developed in last few decades of 20th century slowly superseded classical astrometric observations as a tool for monitoring Earth rotation and for determining its parameters. The number of observatories providing regular astrometric determinations of astronomic latitude and/or longitude dramatically decreased.

Although astromertic observations are not used any longer to calculate Earth Orientation Parameters (EOP) provided by the International Earth Rotation and Reference Systems Service (IERS), they, in contradiction to all space techniques (VLBI, SLR, GNSS, DORIS) contain information on the direction of the plumb line. As such they are of special interest for geodynamic research as well as for classical geodesy that uses surveying instruments oriented with respect to the actual plumb line. The observed variations of astronomical coordinates of the station, after removing the effects of irregularity of Earth rotation, reflect local variation of the plumb line. Time series of astrometric observations of latitude and longitude (time) provide information on variations of meridional and prime vertical component of the deflection of the vertical, respectively.

There are other important reasons to continue astrometric observations as well to analyse the acquired data. The data from last decades exhibit larger homogeneity and higher precision. The use of the Hipparcos catalogue for pre-processing of the observed data improves the quality of the product (Kruczyk *et al.*, 1999; Krynski *et al.*, 2005). The growing length of the time series allows for its more reliable harmonic analysis. Limited access to recent observational data results in limited research activity concerning the analysis of time series of variations of astronomic latitude and longitude that reflects in a very little number of papers on the subject. There are, however, few papers dedicated to the analysis of astrometric data. For example, time series of astronomic latitude observations obtained with the use of zenith telescope at the Astro-Geodetic Observatory of the Warsaw University of Technology at Jozefoslaw from more than 30 years was analysed (Kruczyk *et al.*, 1999). Interesting analysis of time series of astronomic longitude observations from the period 1960.0-2000.0 obtained with the use of transit instrument at the Pulkovo Main Observatory of the Russian Academy of Sciences was conducted (Gorshkov and Shcherbakova, 2002). The extensive analysis of the variations of astronomical longitude with the use of data acquired with transit instrument at the Borowa Gora Geodetic-Geophysical Observatory of the Institute of Geodesy and Cartography within the time span 1986.0-2005.5 was performed (Krynski *et al.*, 2005). A number of periodic terms were separated from the time series investigated and the numerical model of the series was formed. Further studies resulted in modelling time variations of the prime vertical component of the deflection of the vertical at the Borowa Gora Observatory (Krynski *et al.*, 2006).

Extension of the time series of astrometric observations the Borowa Gora Observatory by 20% due to high quality of data from last 5 years makes it much more attractive for the analysis. The results of the analysis are presented in this paper.

2 Astrometric data from Borowa Gora Observatory and its quality

Astrometrical observations at the Borowa Gora Observatory (BG) are conducted since 1963 with the use of transit instrument of Zeiss Jena equipped with photoelectric registration unit. Inconsistence of the time series of data due to instrumental, technological and methodical improvements in acquiring and pre-processing of rotational time observations as well as due to gaps in archive data results in substantial shortening of time series that qualifies to further analysis. The rotational time determined was initially referred to the FK5 catalogue system; starting from the data of 1986, after the magnetic tape recorder was employed for recording the time of the transit of the stars through the local meridian it is also referred to the Hipparcos catalogue system. A long-standing rotational time data series from 1986.0-2010.6, i.e. from last almost 25 years is available for complex analysis. Observations were acquired during 1865 nights when either one group of stars (481 nights) or two groups of stars were observed. Each group that corresponds to a single determination of rotational time consists of 10-11 stars. The differences between mean universal time $UT1^{BG}$ determined at Borowa Gora and mean universal time $UT1^{BIH}$ of the Bureau

International de l'Heure (BIH) (offset of UT1 obtained in Borowa Gora with respect to that of BIH) are the subject of analysis. Time span of consecutive data in time series investigated substantially varies from 1 day to 167 days, mainly due to weather conditions and availability of the observers. Average time span equals to about 4.82 days. Uncertainty of data (averaged result of observation session of a number of stars) in the time series investigated varies from $\pm 0.0034^s$ to $\pm 0.0155^s$ (Krynski *et al.*, 2005). They are compatible with the respective once from the Pulkovo Observatory (Gorshkov and Shcherbakova, 2002).

3 Spectral analysis of the observed time series of the offset of UT1 determined at Borowa Gora from 1986.0 – 2010.6

Rotational time $(UT1 - UTC)^{BG} - (UT1 - UTC)^{BIH}$ data series from Borowa Gora, i.e. time series of UT1 determined at Borowa Gora was investigated. Spectral analysis of this time series of non-uniform time span cannot be directly done with standard statistical packages; it needs re-sampling of the data using interpolation. Such approach was applied, e.g. in the analysis of time series of astronomic latitude observations in the Jozefoslaw Observatory (Kruczyk *et al.*, 1999). Due to significant time spans that occur in the data, the interpolation does not, however, guarantee the satisfactory restoration of the data. Moreover, the interpolation introduces new features to the time series - the artefacts - that distort its spectral parameters.

Like the paper (Krynski *et al.*, 2005), the current work implements the technique of iterative spectral analysis (Box and Jenkins, 1976; Nuttall and Carter, 1982), well suited for the unevenly spaced data. The technique, also known as "whitening of the residuals", sequentially eliminates periodic components from the data, till the residuals meet certain criteria of the random process with the quasi-uniform spectral density, like that of the white noise.

To implement the technique, the correlation of the raw data with model signals having unit amplitudes and periods from 2 to 5500 days, and incremented by 1 day, with the initial phase scanned from

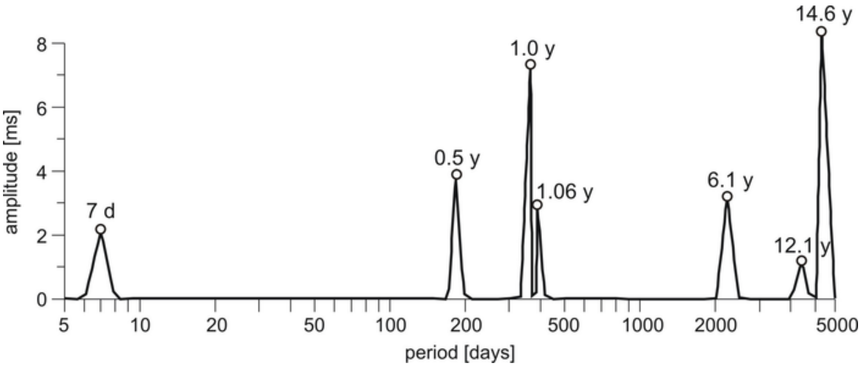

Figure 1. *Spectrum of rotational time* $(UT1-UTC)^{BG}-(UT1-UTC)^{BIH}$ *data series from Borowa Gora*

Table 1. *Amplitudes of periodic terms in the model of the time series of* $(UT1-UTC)^{BG}-(UT1-UTC)^{BIH}$ *from Borowa Gora*

period [d]	period [y]	amplitude [ms]
7	0.019 2	2.1
182.625	0.5	3.74
365.25	1	7.32
387.7	1.06	2.9
2 230	6.1	3.1
4 430	12.1	1.2
5 320	14.6	8.4

0 to 180 degrees was investigated. The regression coefficient obtained for the maximum correlation in this scan, served as estimate of the amplitude of the corresponding periodic component.

The results obtained this way (Figure 1, Table 1) cannot be, strictly speaking, interpreted as Fourier transform of the original data, because the uneven sampling of the data leads to non-orthogonality of the spectral components. The principle of approximate orthogonality, however, enables to represent those results as spectrum with some degree of uncertainty that depends on the quality of the original data (random errors and different time span).

In the next stage of the analysis dominating spectral components are chosen and eliminated one by one, till the remaining components yield the white noise. Following the physical interpre-

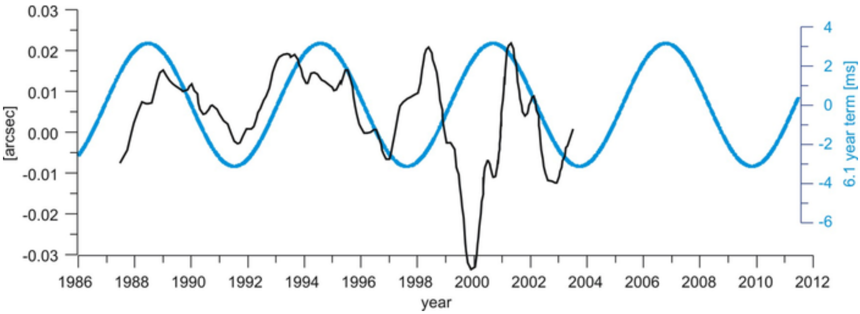

Figure 2. *Long-periodic oscillations of the vertical at the Plana observatory, after filtration of the seasonal and 500-day oscillations (applying 500 days sliding window). The long-periodic oscillations consist of 5.5 year cycles, the first of them is not complete and the last contains a disturbance with duration of 3 years, which is centred over the epochs of the disaster earthquakes in Turkey in 1999 (Chapanov* et al.*, 2005). The thick line corresponds to 6.1 year term in the model of the offset of UT1 in Borowa Gora*

tation, the components of 182.5 and 365 days were first eliminated. The application of exact theoretical values of 182.62 and 365.24 was not straightforward, because the grid was taken with 1-day increment. Additional analysis has shown that the theoretical components differ insignificantly from those tied to the grid, so the theoretical periods of components were taken for the modelling.

No simple ratios between the frequencies in a spectrum of the offset of UT1 were found.

The term with period of 6.1 years was attempted to be associated with local variations of the direction of the plumb line (Chapanov *et al.*, 2005) (Fig. 2). 12.1 year periodic term is rather connected with variations of solar activity (Fig. 3). The term with period near 14 years has been mentioned in literature but it has not been associated with any physical phenomenon.

4 Local variations of UT1 derived from astrometric observations using "observatory equation"

Seasonal variations of Earth rotation ΔT_s represented by UT1 time scale, initially referred to UT2 time scale, are since 1964 referred to UTC (Kryński, 2004). It is expressed as follows (Mulholland, 1972):

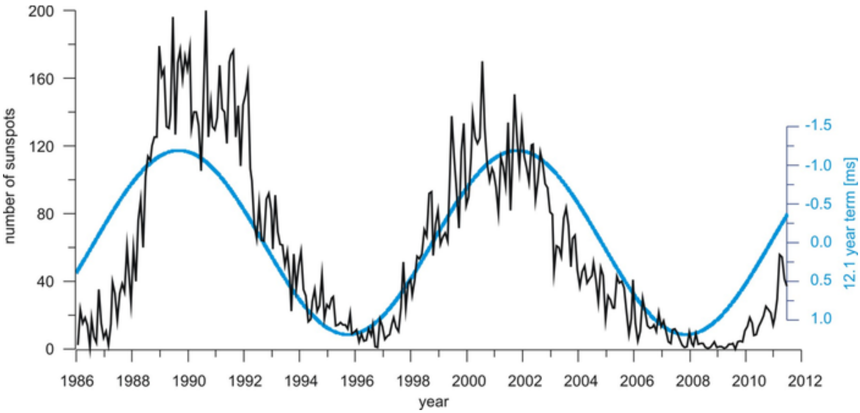

Figure 3. *Comparison of time series of monthly average of sunspot number (Wolf' numbers) with the term with period of 12.1 years in the model of the offset of UT1 in Borowa Gora*

$$\Delta T_s = b' \sin 2\pi\tau + c' \cos 2\pi\tau + d' \sin 4\pi\tau + e' \cos 4\pi\tau \qquad (1)$$

where τ is a fraction of a tropical year. Following the resolution of the IAU General Assembly in Dublin in 1955, coefficients b′, c′, d′, e′ were determined and published by BIH. Those coefficients reflected seasonal variations of Earth rotation, averaged over all observatories providing measurements for maintaining universal time. They were practically constant over almost five decades, until astrometric data became fully replaced by new space techniques in the determination of EOP.

Variations of $UT1 - UTC$ obtained from the astrometric observations at a specific Observatory with respect to that of BIH, i.e. $(UT1 - UTC)^{Obs} - (UT1 - UTC)^{BIH}$, correspond to an offset of $UT1$ obtained at the Observatory with respect to that of BIH. Annual and semiannual variations of an offset of $UT1$ are modelled using the so called "observatory equation" of the form

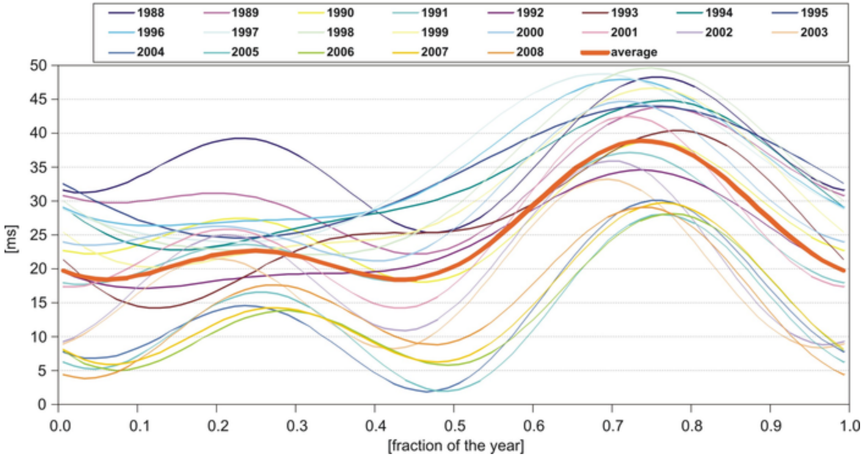

Figure 4. *Seasonal variations of the offset of* UT1 *at Borowa Gora expressed by the observatory equation for Borowa Gora referred to the Hipparcos catalogue system calculated for the data from 1986.0-2010.6 using 4 year window (Table 2)*

$$(UT1 - UTC)^{Obs} - (UT1 - UTC)^{BIH} = a + b\sin 2\pi\tau + c\cos 2\pi\tau + d\sin 4\pi\tau + e\cos 4\pi\tau \quad (2)$$

The parameters a, b, c, d, e of the observatory equation for Borowa Gora

$$(UT1 - UTC)^{BG} - (UT1 - UTC)^{BIH} = a + b\sin 2\pi\tau + c\cos 2\pi\tau + d\sin 4\pi\tau + e\cos 4\pi\tau \quad (3)$$

were traditionally calculated annually using 1.5 year window (Radecki, 1977). Coefficients of the observatory equation for Borowa Gora and their uncertainties referred to the Hipparcos catalogue system calculated for the data from 1986.0-2010.6 using 4 year window are given in Table 2. Seasonal variations of the offset of UT1 at Borowa Gora expressed by the observatory equation for Borowa Gora are shown in Figure 4.

Table 2. *Coefficients of the observatory equation for Borowa Góra and their uncertainties referred to the Hipparcos catalogue system calculated for the data from 1986-2010 using 4 year window*

Time tag	a (0.0001^s)	b (0.0001^s)	c (0.0001^s)	d (0.0001^s)	e (0.0001^s)
1988	362 ± 7	−46 ± 8	29 ±10	3 ± 9	−75 ± 9
1989	321 ± 8	−66 ± 9	38 ±12	3 ±10	−50 ±10
1990	270 ± 8	−58 ±10	19 ±12	5 ±10	−61 ±11
1991	247 ± 8	−67 ±10	−12 ±12	16 ±10	−55 ±10
1992	239 ± 8	−78 ±10	−14 ±13	−1 ±11	−29 ±11
1993	267 ± 8	−99 ±11	−21 ±13	−39 ±11	−32 ±11
1994	324 ± 9	−100 ±12	−10 ±15	−17 ±11	−23 ±12
1995	338 ±10	−97 ±13	−6 ±15	−3 ±13	−06 ±14
1996	345 ±10	−102 ±13	−25 ±16	9 ±13	−29 ±14
1997	344 ±11	−116 ±14	−42 ±15	16 ±14	−13 ±15
1998	328 ±10	−136 ±14	5 ±15	3 ±14	−33 ±14
1999	307 ±10	−120 ±13	−13 ±15	−10 ±13	−40 ±14
2000	299 ±10	−93 ±13	−9 ±15	25 ±13	−50 ±14
2001	255 ±11	−85 ±14	−1 ±16	34 ±14	−80 ±15
2002	204 ±12	−50 ±15	−25 ±18	53 ±15	−86 ±17
2003	181 ±14	−55 ±18	−19 ±20	59 ±18	−72 ±19
2004	138 ±13	−78 ±16	25 ±20	0 ±17	−85 ±17
2005	132 ±12	−56 ±15	21 ±19	−14 ±17	−90 ±16
2006	137 ±11	−71 ±13	10 ±16	−28 ±14	−68 ±14
2007	146 ± 9	−77 ±11	8 ±13	−19 ±12	−72 ±12
2008	151 ± 8	−58 ±10	−24 ±11	−4 ±11	−82 ±10
mean	254 ±10	−81 ±13	−3 ±15	4 ±13	−54 ±14

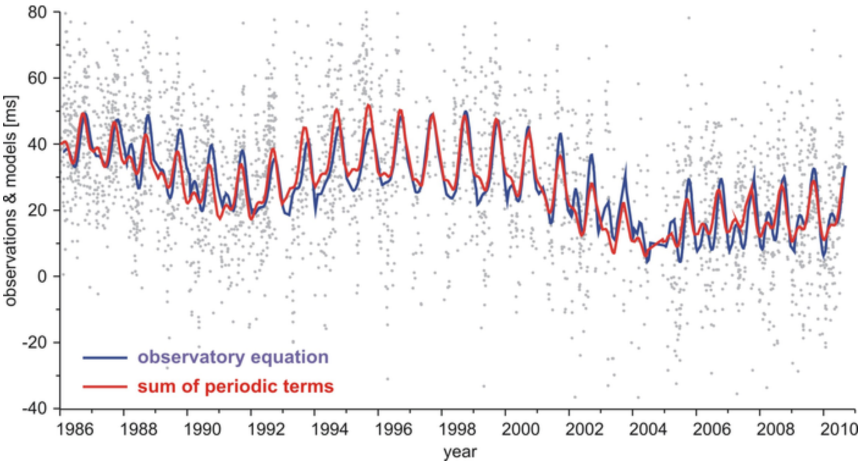

Figure 5. *Time series of observations (dots), observatory model (blue) and model as the sum of periodic terms (red) of local rotation time at Borowa Gora*

Coefficients of the observatory equation for Borowa Gora are not constant as it took place in case of BIH solution. Results presented in Table 2 and in Figure 4 show variability of amplitudes of both annual and semiannual components of the seasonal variations of the offset of UT1 at Borowa Gora.

5 Comparison of two models of time series of the offset of UT1 determined at Borowa Gora

Time series based on the two rotational time models, i.e. "observatory equation" and the sum of periodic terms (shown in Fig. 1 and Table 1 except of those with 7 day period) converge very closely (Fig. 5), with the mean square difference of only 3.9 ms. Comparison of the two models is out of the scope of the current work.

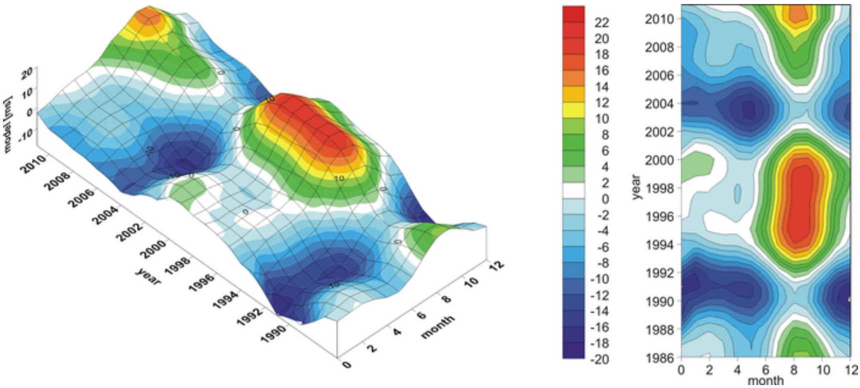

Figure 6. *Model of the time series of the offset of UT1 at Borowa Gora*

6 Some considerations about numerical models of the time series of the offset of UT1

The model of the time series of the offset of UT1 represented by the sum of periodic terms (except of 7 days component and a trend) is shown in Figure 6.

Variations of the position of annual maximum within the range of one month can be observed in Figure 6. Such periodic shift may be connected with a beat effect of two periodic terms – annual one and the one with a period of 387.7 days. The period of this beat modulation is about 18 years. The sum of these two terms is presented in Figure 7.

The model consisting of the annual and 387.7 day components is further shown in Figure 8 against variations of coordinates of the celestial pole (from the web site of IERS) and the de-trended time series of the difference $(UT1 - UTC)$ without leap seconds with thick lines indicating the envelopes of the beat. It should be noted that variations of coordinates of the celestial pole in Figure 8 are shown after the initial data smoothing twice by sliding averaging with Parzen window of 51 and 121 days. The consistency of variations of partial model of the offset of UT1 and variations of coordinates of a celestial pole as well as of the difference $(UT1 - UTC)$ is observed. Beat leads to the regular change of phase of

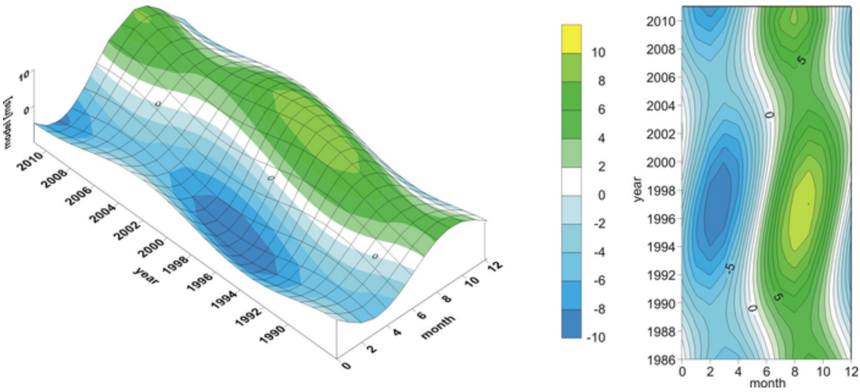

Figure 7. *Partial model of the time series of the offset of* UT1 *at Borowa Gora as the sum of annual and 387.7 day components*

annual variations according to changes of amplitude. Other words, the largest deviation takes place in the autumn and in the regular way it slides approximately for one month within 18-19 years (Fig. 6). The source of the observed consistency is not clear and it should be investigated.

Due to differencing "double" differences $(UT1 - UTC)^{BG} - (UT1 - UTC)^{BIH}$ investigated are practically free of the effects of variations in the Earth rotation. Very essential, however, is that the data on the difference $(UT1 - UTC)^{BIH}$, accessible, for example on the internet on the web site of IERS `http://hpiers.obspm.fr/eop-pc/products/combined/eopcomb.html`, are smoothed in time domain. On the other hand, the data obtained using astronomical methods, analysed in the present work was not smoothed. Therefore, in the investigated "double" differences it is possible to find out variations with short periods of even a few days.

The results of the spectral analysis performed indicated the existence of such variations with the period of 7 days.

Figure 9a shows the one year fragment of (UT1 - UTC)^{BIH} time series which besides annual and semiannual periodic terms contains also well visible tidal terms of the periods of 2 and 4 weeks with the variable phase; such variations can be seen as well in a monthly fragment (Figure 9b). In Figure 9 there is also shown

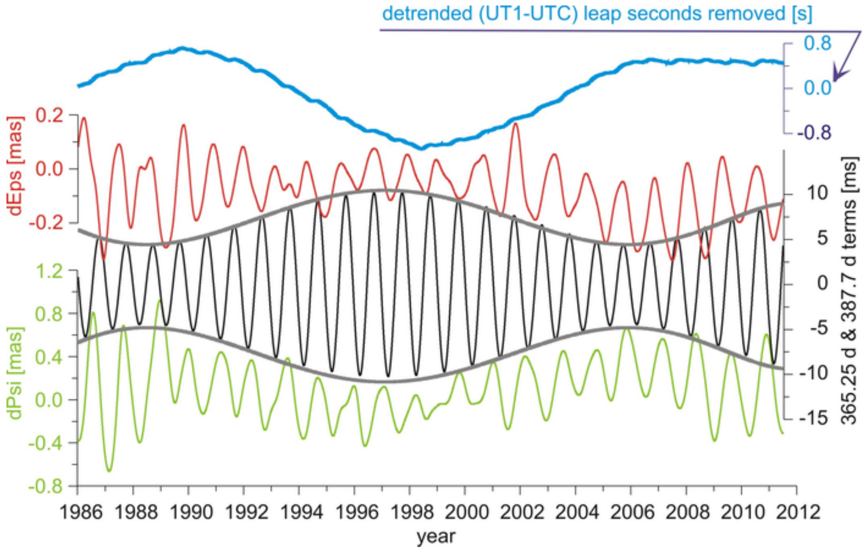

Figure 8. *Comparison of the time series of partial model of the time series of the offset of* UT1 *at Borowa Gora, variations of dPsi and dEps, as well as detrended difference* $(UT1 - UTC)$

the model of $(UT1 - UTC)^{BG} - (UT1 - UTC)^{BIH}$ representing the variations with periods and phases fixed within the interval 1986.0-2010.6.

7 Summary and conclusions

Iterative spectral analysis of the observed time series of the offset of UT1 has enabled to allocate seven periodic terms. Weekly component may not be connected with any astronomical or geophysical processes; it could be associated with a weekly rhythm of human activity. Available literature signalizes the presence of weekly variations of meteorological parameters, an amount of atmospheric aerosols and storm activity. It means that corresponding redistribution of moisture occurs changing of the moment of inertia of troposphere so causes the variations of LOD.

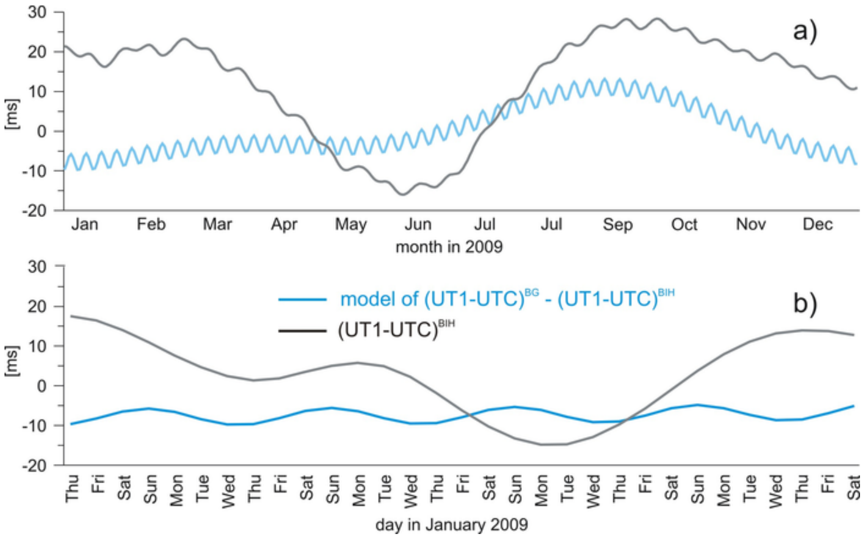

Figure 9. *Annual (a) and monthly (b) fragments of the time series of the model of* $(UT1-UTC^{BG}-(UT1-UTC)^{BIH}$ *at Borowa Gora and* $(UT1-UTC)^{BIH}$ *from* EOP *internet site*

Semiannual and annual periods may be associated with seasonal redistribution of the atmospheric and hydrological masses. The mechanism connecting those seasonal processes with the variations of the direction of the plumb line might be the same as the one observed in variations of the gravity field determined from GRACE data.

Annual term have an adjacent component with period near 387 days. Beat effect of those two terms produces an amplitude modulation of the offset of UT1 with period about 18 years. The consistency of modulation of the offset of UT1 and variations of coordinates of a celestial pole as well as of the difference $(UT1-UTC)$ is clearly visible. Beat leads to the regular change of phase of annual variations according to changes of amplitude. The largest deviation takes place in the autumn and in the regular way it slides approximately for one month within 18-19 years.

The term with period of 6 years was attempted to be associated with local variations of the direction of the plumb line. 12 year periodic term is rather connected with variations of solar activity. The term with period near 14 years is mentioned in literature but it has not been associated with any physical phenomenon.

The astrometric determination of rotational time variations, and consequently, time variations of derived prime vertical component of the deflection of the vertical may be considered as absolute observation technique. Thus, contrary to differential geodetic methods, systematic errors (e.g. instrumental drifts or improperly modelled effects in the observation data) do not cancel out. Therefore, observations repeatedly performed in different nights (under changing atmospheric conditions) and comparative measurements with different data types are necessary to obtain reasonable accuracy estimates and to monitor the instrumental stability. Since anomalous refraction is believed to be the dominant error source limiting the accuracy of astrometric observations (Hirt and Bürki, 2006) it is also considered a dominant error in the determination of time variations of the deflection of the vertical with the use of astronomic methods.

Even though the observations in Borowa Gora were taken in different nights, most stars were observed shortly after the sunset, so the bias due to abnormal refraction is quite possible. Seasonal variations of the refraction can follow the variations due to the weather conditions. Less likely, but still possible are weekly and long-periodic variations of the refraction. Simultaneous observations using different techniques, in particular those including space gravity missions may bring new material that will help to draw more certain conclusions.

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