Common Position Changes of Collocated VLBI and GPS Stations

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SUMMARY

The modern geodetic observations, based on high-accuracy space techniques, provide decadal time series of station coordinates. These time series are suitable to detect and research small ground motion due to local and global geodynamical sources. Some space technique stations are collocated and the comparison of their data may reveal common periodical oscillations and impulse variations due to global changes of gravity, earthquakes, climate and environment. Any different behavior of the time series of collocated stations should be interpreted as a restricted local ground motion, or as a systematic data error. The periodical and impulse variations of the coordinates of collocated VLBI and GPS stations at the observatory Wettzell are compared and analyzed. The data jumps are determined by means of a new useful high-sensitive method of impulse detection, which is able to estimate very small changes of mean data values and velocities. The periodical oscillations of the station coordinates are determined by means of partial Fourier approximation. The amplitudes and phases of common seasonal, interannual and 11-year variations of Wettzell VLBI and GPS stations are compared. This research may prove the reliability of modern geodetic time series and the possibility to use them in the field of various geodynamical investigations.

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1. INTRODUCTION

The global changes play important role in all human activity. A significant part of the modern knowledge is obtained from the results of time series analysis. It is possible to study global changes by means of high density geodetic time series obtained by the space based techniques like GPS, VLBI, SLR etc. The VLBI and SLR observations from great number permanent stations with global location form large massive of high density geodetic data since 1983 and GPS observations - since 1993.

The interannual and decadal oscillations of the VLBI stations and baselines are highly correlated with the climatic variations and solar activity cycles (Chapanov et al., 2012b). The 11-year and 22-year oscillations of the VLBI station coordinates exactly match Wolf's numbers variations with time delay 0.5a-1.5a. The interannual site displacements are in good agreement with the smoothed time series of the equatorial solar asymmetry and the geomagnetic index AA with time delay of about 1.5a. The interannual site oscillations are strongly affected by the climatic variations (represented by PDSI) with irregular phase reverses in 5- to 8-year intervals. (Chapanov et al., 2012b). The ENSO variations are partially connected with site displacements at some frequencies. The comparision of time sries variations of coordinates of colocated statins may help to determine the existence of systematics in modertn observational data and to prove the reality of periodical motions of the stations in different frequency bands and their connection with the real envirenmental changes.

2. TIME SERIES AND DATA PROCESSING

2.1 GPS and VLBI time series

The time series of collocated GPS and VLBI station coordinates are taken from IGN solution (Collilieux et al., 2007), applied to ITRF2008 station position residual time series. The latest IGN solution for ITRF2008 station position residual time series has advantage of uniform determination of all coordinates in a common reference frame, so many systematics, due to individual solutions of different space techniques, are avoided. The GPS and VLBI data from stations WETZEL are shown in Fig.1, where the VLBI time series cover the period 1983.9-2009.0 and GPS time series – the period 1997.0-2009.5, and only the common data from the period 1997.0-2009.0 will be processed.

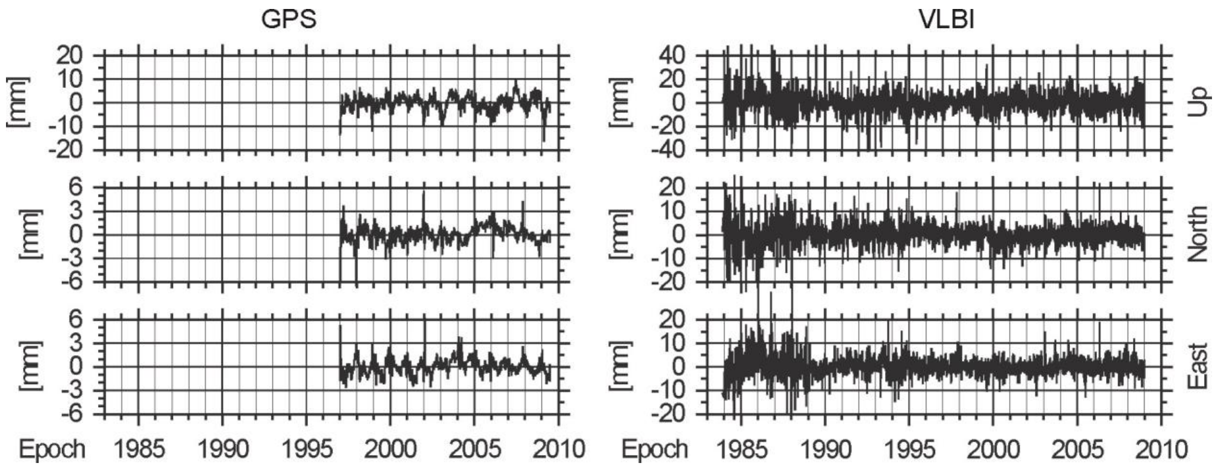

Figure 1. Time series of GPS and VLBI stations WETZEL.

2.2 Data processing methods

The GPS and VLBI time series will be processed by well recommended methods of robust estimation, moving average and normal point determination, partial Fourier approximation and small impulses detection

2.2.1 Normal point and moving average

The data noise reduction is easily solved by averaging in moving window, which is widely applied for filtration of the high frequency noise from the time series. Let consider time series $f(t_i)$ with epochs t_i and step Δt. The remove of all oscillations with periods below T is possible by n-points moving average ($n=T/\Delta t$), which yields new time series $g(t_i)$

$$g(t_k) = \frac{1}{n}\sum_{i=k}^{k+n-1} f(t_i), \qquad t_k = \frac{1}{n}\sum_{i=k}^{k+n-1} t_i, \quad k = 1,\ldots,N-k. \tag{1}$$

The moving average yields time series with the same discretion as the original data. If the data is rather dense, it is useful to determine normal points with step equal to T instead of original step Δt. The data of transformed time series obtain significantly less errors, then the original observations, especially in case of robust estimation of the normal points. This method had been successfully applied in processing of high-dense Earth orientation data and gravimetric time series in (Chapanov, 2005).

2.2.2 The Danish Method of robust estimation

The use of the robust estimation methods in the processing of the geo observations is necessary not only to be detected the observations with gross errors and significant deviation from the normal distribution. Another important advantage of the robust estimation is accounting of the observations with small deviation from the normal distribution. As Rey (1978) points out, the methods of robust estimation are stable as in the case of small deviations of the distribution function as in the case of the observations with gross errors. The application of the robust estimation method is a necessary condition to obtaine estimates with adequate accuracy. The Danish method is very flexible and convenient to determine mean values of the observations or other parameters, which are constants in the time. This method is iterative and the observation weights are functions of the absolute value of the observation corrections from the previous iteration (Kegel, 1987; Kubik, 1982).

Let p_0 are the weights of the observations at the zero iteration, v_0 - the corrections of the observations after first estimation by the least-squares method, and μ_0 is the standard. Then the weights of the observations at the next iterations i+1 are computed by the formula (Kegel, 1987)

$$p_{i+1}(v_i) = p_i e^{-0.05\left(\frac{v_i\sqrt{p_i}}{\mu_i}\right)^6}, \ i = 0,1,2,\ldots n \quad (2)$$

Kegel (1987) use the following scheme

$$\begin{aligned} & p_1 = p_0 \ , \\ & p_{i+1}(v_i) = p_i e^{-0.05\left(\frac{v_i\sqrt{p_i}}{\mu_i}\right)^{4.4}} \quad ,i = 2,3, \\ & p_{i+1}(v_i) = p_i e^{-0.05\left(\frac{v_i\sqrt{p_i}}{\mu_i}\right)^{3}} \quad ,i = 4,\ldots . \end{aligned} \quad (3)$$

In the process of the iterations the weights of the observations and the standard decrease continuously. The iterations stop when the standard reaches to the empirical value μ_s which leads to the acceptable number of the observations with small value of the weights (p_i<0.1). The robust normal points application for geo time series processing yields high frequency noise filtration, outliers detection and significant improve of the time series accuracy level.

2.2.3 Method of Partial Fourier Approximation

The periodical variations are derived from the data by means of partial Fourier approximation based on the Least-Squares estimation of Fourier coefficients (Chapanov et al., 2012a, 2015; Ron et al., 2012). The Partial Fourier approximation $F\left(t\right)$ of discrete data is given by

$$F(t) = f_0 + f_1\left(t-t_0\right)+\sum_{k=1}^{n} a_k \sin k \frac{2\pi}{t_E - t_B}\left(t-t_0\right)+b_k \cos k \frac{2\pi}{t_E - t_B}\left(t-t_0\right), \qquad (2)$$

where t_0, t_B and t_E are the mean, first and last epochs of observations, f_0, f_1, a_k and b_k are unknown coefficients and n is the numbers of harmonics of Fourier approximation, which covers all oscillations with periods between $(t_E\text{-}t_B)/n$ and $(t_E\text{-}t_B)$. The application of the Least-Squares estimation of Fourier coefficients needs redundant number of observations, so the number of harmonics n is chosen significantly less than the number N, corresponding to the Nyquist frequency, which is ½ of the sampling rate of the discrete signal. The small number of harmonics n yields to LS-estimation of the coefficient errors, too. The period of the first long-periodical harmonic in (2) depends on the observational time span in case of classic Fourier approximation, but here it is possible to decrease the value of the first harmonic, so the estimated frequencies may cover the desired set of real oscillations. This method allows flexible and easy separation of the harmonic oscillations into different frequency bands by the formula

$$B(t) = \sum_{k=m_1}^{m_2} a_k \sin k \frac{2\pi}{t_E - t_B}\left(t-t_0\right)+b_k \cos k \frac{2\pi}{t_E - t_B}\left(t-t_0\right), \qquad (3)$$

where the desired frequencies ω_k are limited by the bandwidth

$$\frac{2\pi m_1}{t_E - t_B} \le \omega_k \le \frac{2\pi m_2}{t_E - t_B}, \qquad (4)$$

so it is possible to compare common cycles from different observational techniques. The superposition of several oscillations from a given frequency band allows to compare both phase and amplitude variations of the common cycles.

2.2.4 Method of impulse determination in time series

Some parts of the Method of impulse determination in time series have been applied in (Chapanov et al., 2007, 2008; Gambis et al., 2012) and final version was developed by Chapanov et al. (2013). The method of data jumps determination consists of several steps. The first step is a removal of linear trend from the original data, followed by the integration of the resulting time series. The new integrated time series consists of oscillations with the amplitudes smaller than in the original data and of the parts with visible piecewise significant linear or parabolic trends. The parts with linear trends of integrated data correspond to the constant mean behavior of the original data, the sudden changes of the linear trends occur at the epochs of the jumps in the original data. The parts of integrated data with significant parabolic trends point out to the linear variations of the original data. The second step of the method is the creation of the table containing all the epochs of data jumps. The next step consists in calculating the mean values or trends in the original data parts, corresponding to the table of jump epochs, and the last step is the calculation of jump values between neighboring data parts.

The time series are integrating numerically by the well known trapezoid rule. Let consider function f of argument x, discretized into N+1 equidistant points $f(x_i)$, i=1, 2, ..., N+1. Let the first argument $x_1=a$, and last argument $x_{N+1}=b$. Then the grid spacing is $h=(b-a)/N$ and the trapezoid approximation to the integral is

$$\int_a^b f(x)\,dx \approx \frac{h}{2}\sum_{k=1}^{N}\left(f(x_{k+1})+f(x_k)\right)$$

(5)

$$= \frac{b-a}{2N}\left(f(x_1)+2f(x_2)+2f(x_3)+\ldots+2f(x_N)+f(x_{N+1})\right).$$

When the grid spacing is non-uniform, we can use the formula

$$\int_a^b f(x)\,dx \approx \frac{1}{2}\sum_{k=1}^{N}\left(x_{k+1}-x_k\right)\left(f(x_{k+1})+f(x_k)\right). \qquad (6)$$

To obtain integral of a given time series $f(t_i)$, i=1, 2, ..., N+1 it is necessary to integrate N times the function f with boundaries $a=t_1$ and $b = t_i$, i=2, ..., N+1.

2.3 Normal points of station coordinates

The normal points of the coordinates of GPS and VLBI station WETZEL are determined by formula (1) every 0.1 years (Fig. 2). Each normal point of GPS data is calculated from 5-6 original values by the Danish method of estimation, while VLBI normal points include 9-12 observations. Most of high-frequency oscillations are removed and the obtained new time series have significantly better accuracy.

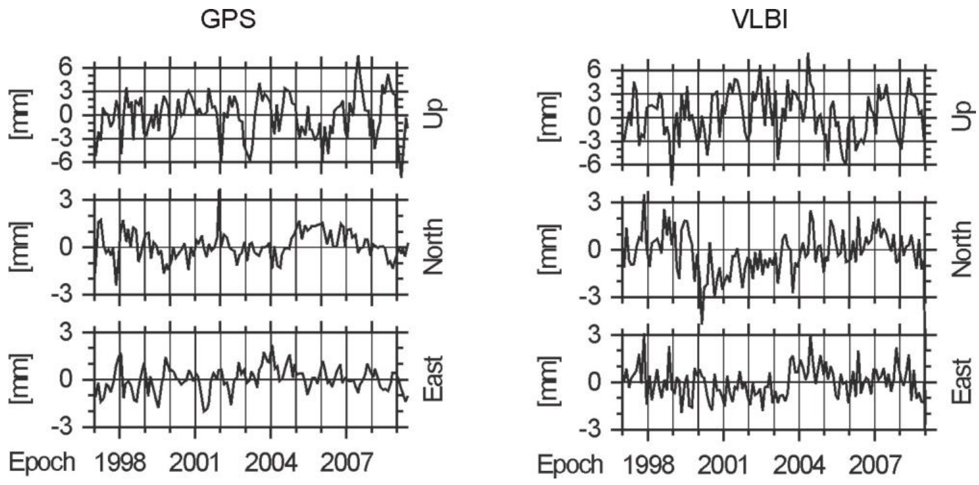

Figure 2. Normal points of GPS and VLBI stations WETZEL for the period 1997-2009.

Most of high-frequency oscillations are removed and the obtained new time series have significantly better accuracy. The original time series have mean errors for the period 1997-2009 1.1-3.7mm for GPS data and 0.7–1.6mm for VLBI data (Fig.3), while the corresponding normal points have errors 0.09-0.33mm and 0.2-0.6mm.

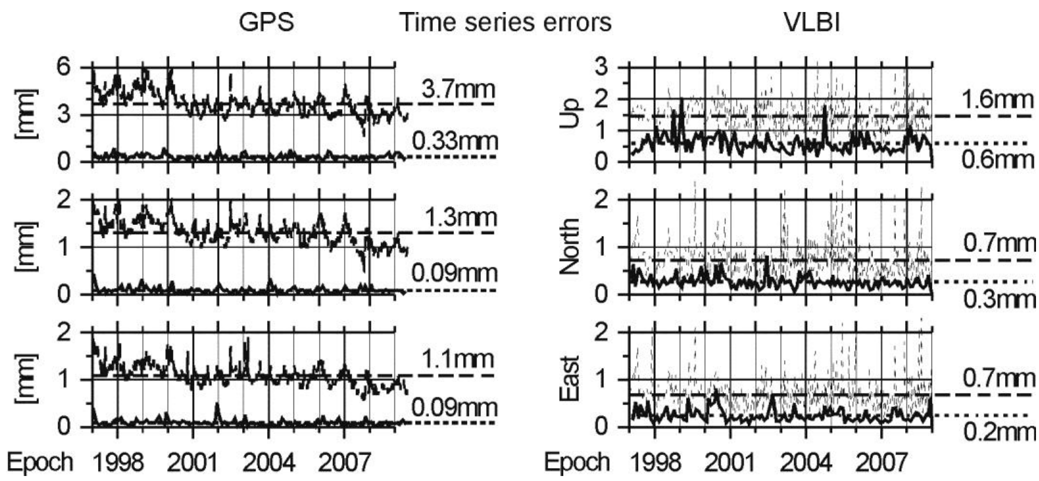

Figure 3. Time series errors of GPS and VLBI stations WETZEL for the period 1997-2009. The errors of the original data are denoted by dashed lines and errors of normal points – by bold lines. The mean values are marked by horizontal lines.

3. COMMON VARIATIONS OF COLLOCATED VLBI AND GPS STATIONS

3.1 Time series spectra

The amplitude spectra (Fig.4) of coordinate time series variations are determined from the partial Fourier approximation of GPS and VLBI data, where the amplitudes A_k are determined from the Fourier coefficients a_k and b_k by the expression (7) and their errors are given in Table 1. All components have common seasonal oscillations. The Up components are expected to have common interannual cycles.

$$A_k = \sqrt{a_k^2 + b_k^2} \quad (7)$$

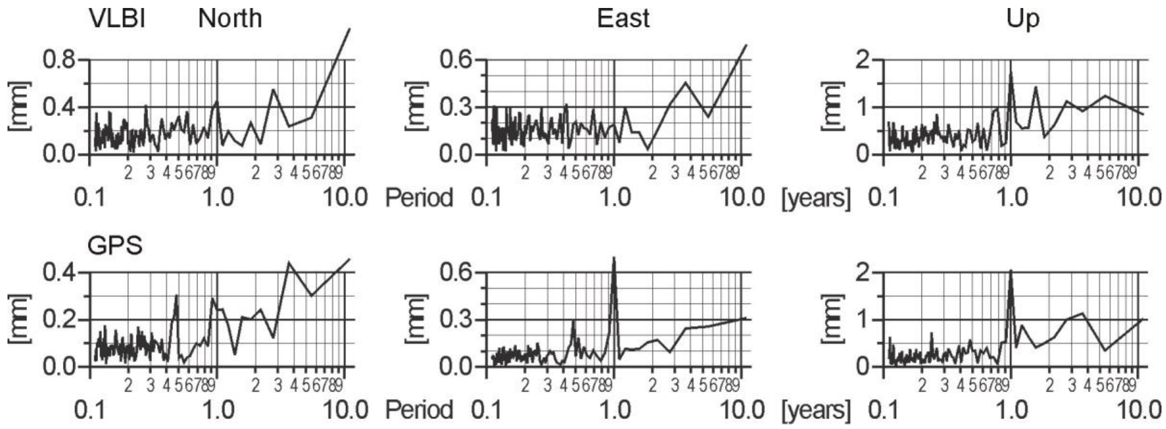

Figure 4. Amplitude spectra of VLBI and GPS stations WETZEL variations for the period 1997-2009.

Table 1. Errors of estimated amplitudes A_k by the Least Squares Method.

Coordinate	GPS [mm]	VLBI [mm]
North	0.03	0.14
East	0.02	0.12
Up	0.08	0.30

3.2 Mean station motions

The mean station motions are determined by formula (1) in moving window with size 1 year (Fig.5). Generally, a good agreement exists between the variations of the mean components of VLBI and GPS stations, especially for the component in East direction. Small differences exist between the mean components in North direction in 2000-2003 and 2005-2007. The mean vertical components have discrepancies during 2000-2005 due to shifted interannual oscillations.

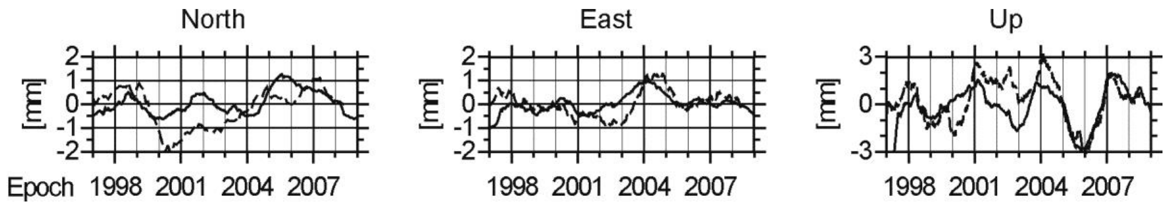

Figure 5. Mean motion of VLBI (dashed line) and GPS (solid line) stations WETZEL determined in 1-year moving window.

3.3 Common periodical cycles

Common 11-year interannual and seasonal periodical cycles of GPS and VLBI time series are investigated by means of the method of partial Fourier approximation, where the main first harmonic is chosen with period equal to 11 years.

3.3.1 Schwabe-Wolf cycle with 11-year period

The Schwabe-Wolf cycles with 11-year period of the coordinates of GPS and VLBI time series are compared with the smoothed monthly mean Wolf's numbers of the solar activity (Fig.6).

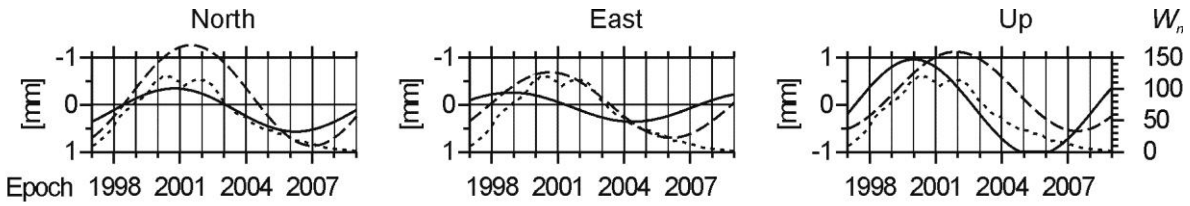

Figure 6. 11-year cycles of VLBI (dashed line) and GPS (solid line) stations WETZEL compared with the smoothed monthly mean Wolf's numbers (dotted line).

The phases of 11-year GPS and VLBI cycles are shifted by 1 year in North direction and by 2 years in East and Up directions. The VLBI oscillations better agree with the Wolf's numbers, so this is a signature of some disturbing systematic in GPS data.

3.3.2 Interannual oscillations

The interannual oscillations are determined in two frequency bands with periods 1.2-2.2 years and 2.7-5.5 years (Fig.7). The oscillations from the first band are composed from 5 harmonics with numbers 5-9 and the oscillations from the second band - from 3 harmonics with numbers 2-4 of the partial Fourier approximations of GPS and VLBI data. The oscillations from both bands contain parts with synchronized oscillations and parts with differences between the GPS and VLBI due to phase reverses (marked by ellipses in Fig.7). Relatively good agreement exist between the interannual GPS and VLBI oscillations in vertical direction for the period band 2.7-5.5 years. These results means that some systematics exist in interannual cycles of station motions.

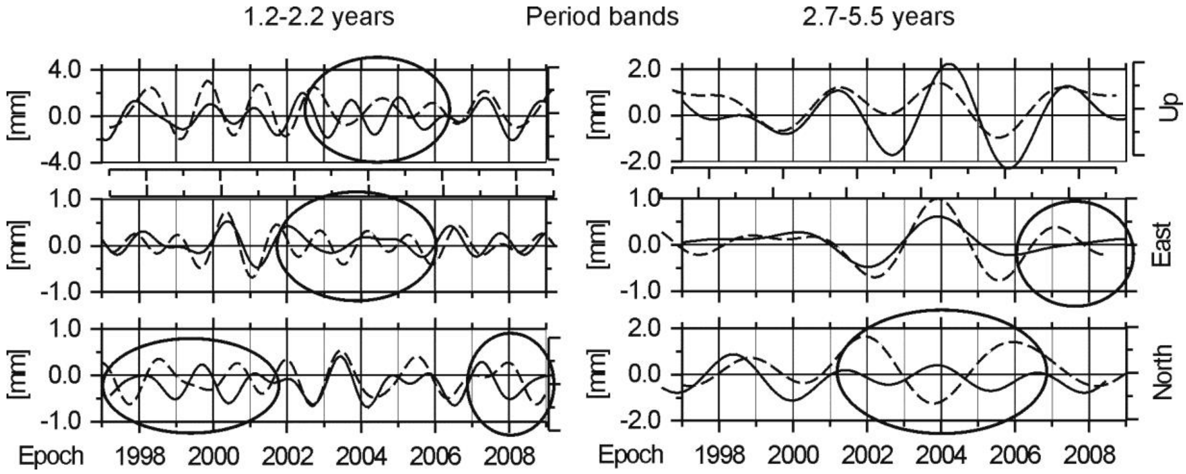

Figure 7. Interannual cycles of VLBI (dashed line) and GPS (solid line) stations WETZEL in period bands 1.2-2.2 years and 2.7-5.5 years. The ellipses surround parts with significantly discrepant variations.

3.3.3 Seasonal oscillations

The seasonal oscillations of GPS and VLBI coordinates are determined by 3 harmonics of the partial Fourier approximation with numbers 10-12. They cover periods between 0.9 and 1.1 years (Fig.8). The semi-annual oscillations are composed by harmonics 21-23 with period band 0.48-0.52 years (Fig.8). Almost perfect agreement between seasonal GPS and VLBI phases is visible, but the amplitude variations differ significantly. The semi-annual oscillations of GPS and VLBI stations have periods with good agreement and parts with significantly discrepant variations, probably due to the relatively high-level noise at this frequency band.

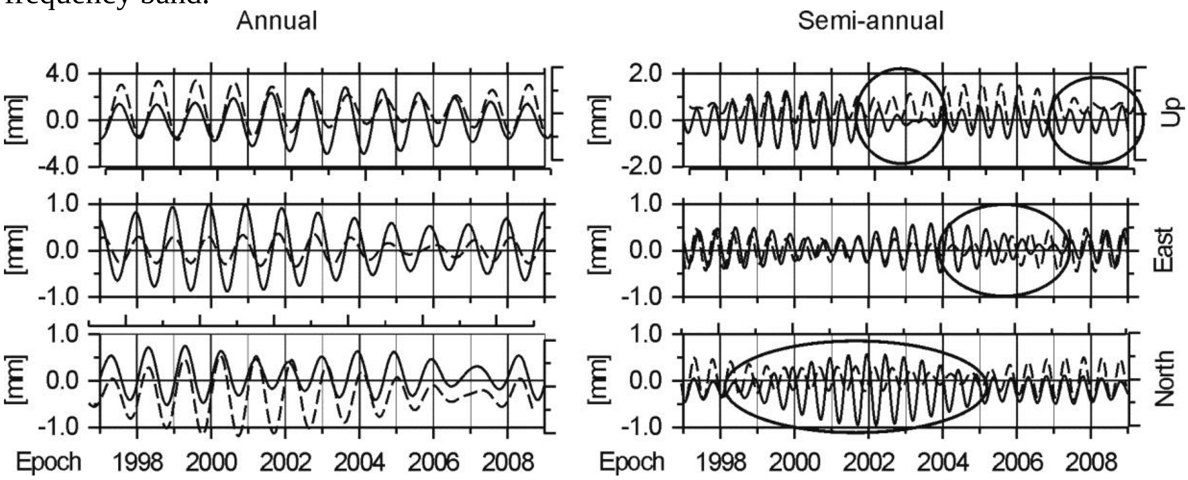

Figure 8. Annual and semi-annual cycles of VLBI (dashed line) and GPS (solid line) stations WETZEL. The ellipses surround parts with significantly discrepant variations.

3.4 Common impulse variations

The integrated GPS and VLBI normal point time series are shown in Fig.9. The North and East components have a common system of 4 parts with parabolic trends, while the Up components have the same common system with two additional parts with parabolic trends. These parabolic trends correspond to the mean value and velocity jumps in the original data. All GPS and VLBI components are affected by some impulses occurred around the epochs 1999.7, 2002.0, 2005.0 plus two additional impulses of Up component around the epochs 2003.4 and 2006.6. The GPS and VLBI common impulse variations, corresponding to the above parabolic trends of integrated data, are shown in Fig.10.

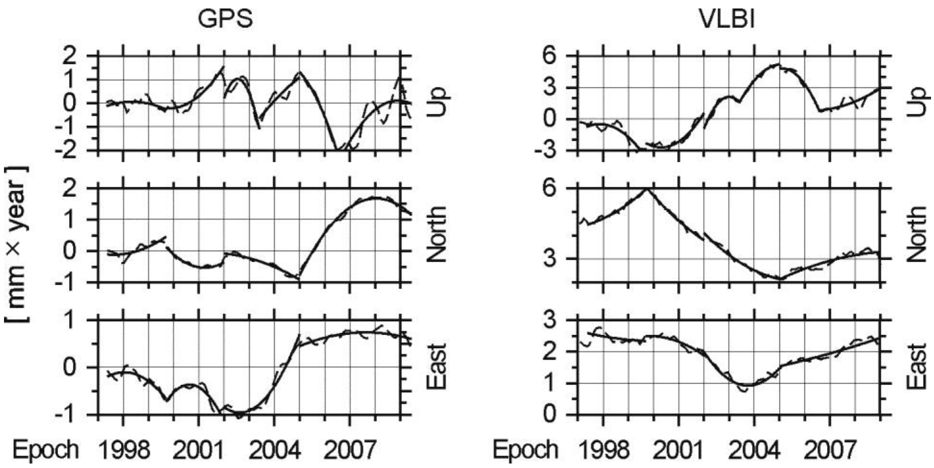

Figure 9. Integrated time series of GPS and VLBI stations WETZEL for the period 1997-2009.

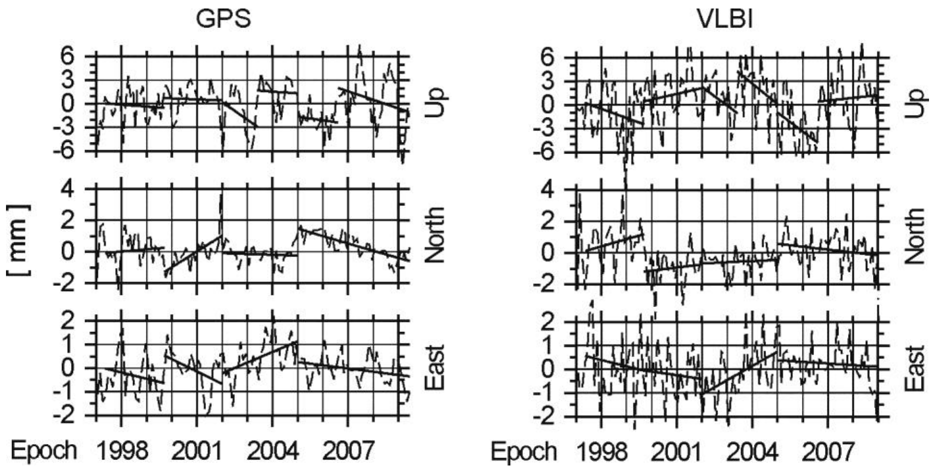

Figure 10. Impulse variations of time series of GPS and VLBI stations WETZEL for the period 1997-2009.

4. CONCLUSIONS

The time series of collocated GPS and VLBI stations WETZEL determined from the IGN solution in the ITRF2008 have significant common changes for the period 1997-2009. The mean station motions, determined by 1-year moving average expose relatively good agreement between the components of VLBI and GPS stations, especially for the component in East direction. Small differences exist between the mean components in North direction in 2000-2003 and 2005-2007. The mean vertical components have discrepancies during 2000-2005 due to shifted interannual oscillations. The 11-year oscillations of the coordinates of VLBI time series have good agreement with the smoothed monthly mean Wolf's numbers of the solar activity, while the 11-year GPS cycles expose significant phase shift due to systematic errors. The interannual oscillations determined in two frequency bands with periods 1.2-2.2 years and 2.7-5.5 years expose parts with synchronized oscillations and parts with significant differences between the GPS and VLBI phases. The GPS and VLBI time series parts with phase reverses are signature of systematic errors due incorrect modeling of atmosphere influence on the measurements. Almost perfect agreement between seasonal GPS and VLBI variations exist according their phases, but the amplitude variations differ significantly. The semi-annual oscillations of GPS and VLBI stations have some periods with good agreement and parts with significantly discrepant variations due to the high-level noise. It is remarkable that all GPS and VLBI components have a common system of impulse variations, where the impulses occurred around the epochs 1999.7, 2002.0, 2005.0 plus two additional impulses of Up component around the epochs 2003.4 and 2006.6. These impulse variations produce jumps of the mean data values up to 2mm for North and East components and up to 5mm for Up component. The corresponding velocity jumps are up to 1mm/year for North and East components and up to 2.4mm for Up component. We should note that at least part of seasonal, interannual and 11-year oscillation and all impulse variations of the WETZEL GPS and VLBI time series have a common origin connected with the external natural influences and these time series are suitable to detect and research small ground motion due to local and global geodynamical changes.

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