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Review article

TOWARDS RELIABLE VELOCITIES OF PERMANENT GNSS STATIONS

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Abstract

In the modern geodesy the role of the permanent station is growing constantly. The proper treatment of the time series from such station lead to the determination of the reliable velocities. In this paper we focused on some pre-analysis as well as analysis issues, which have to be performed upon the time series of the North, East and Up components and showed the best, in our opinion, methods of determination of periodicities (by means of Singular Spectrum Analysis) and spatio-temporal correlations (Principal Component Analysis), that still exist in the time series despite modelling. Finally, the velocities of the selected European permanent stations with the associated errors determined following power-law assumption in the stochastic part is presented.

Keywords: *GNSS, time series, noise analysis, velocities*

1. Introduction

The International Terrestrial Reference Frame (ITRF) is being defined, inter alia, by GNSS (Global Navigation Satellite System) permanent stations that constantly register navigation data for observing changes of their position in time. According to GGOS (Global Geodetic Observing System) resolutions, the ITRF should be stable at the level of 0.1 mm/yr with respect to the velocities (Plag nad Pearlman, 2009). Furthermore, the EPN (EUREF Permanent Network) guidelines recommend to move the permanent station into A (the highest) class when the formal uncertainty of the last velocity estimate is below 0.5 mm/year (Bruyninx et al., 2013). These demands make that the several topics during the process of velocity estimation from the topocentric (North, East and Up) component time series have to be complied.

2. Data

The number of permanent GNSS stations is constantly growing and starting to cover almost the entire world with a global network. In consequence, the time span of the GNSS-derived time series (position, ZTD or EOP) is getting longer and longer. For our research we used selected position (North, East and Up) time series processed by Nevada Geodetic Laboratory with PPP (Precise Point Positioning) mode and expressed in IGS08 (Rebischung et al., 2012) reference frame.

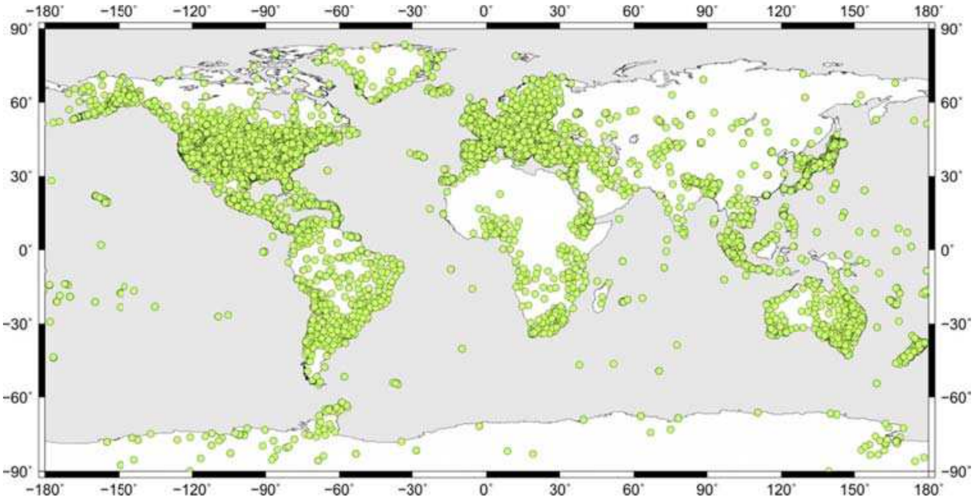

Fig. 1. Layout of stations being processed by the NGL

3. Deterministic model

The time series of each topocentric component (North, East or Up) can be expressed as:

$$x(t) = x_0 + v_x \cdot t + \sum_{i=1}^{n} \left[A_i \cdot \sin(\omega_i \cdot t + \phi_i) \right] + O_x + \sum_{j=1}^{m} H_j \cdot x_j^{off} + \varepsilon_x(t) \qquad (1)$$

where x_0 corresponds to the initial value, v_x is the station's velocity, A_i, ω_i and ϕ_i are the amplitude, angular velocity and phase shift of the i-th frequency component of the time series, O_x are the outliers, x^{off} are the offsets' amplitudes. ε_x are the residuals of the time series. First 5 terms form the deterministic model, while the last one (stochastic part) is the underlying noise. Long-term trend (linear or non-linear) is interpreted as the velocity of station, widely used in modern geodesy to maintain the terrestrial reference frames (e.g. Altamimi et al., 2011) or for geodynamical interpretations (e.g. Caporali et al., 2013; Schenk and Schenkova, 2013 or Bogusz et al., 2014).

Proper pre-analysis consisting of outliers and offsets removal is a crucial issue since it can affect the character of the time series. We used Median Absolute Deviation (MAD) criterion (for detail see Klos et al., 2015) for outliers and Sequential t-test Analysis of Regime Shifts (STARS) algorithm (Rodionov and Overland 2005) for offset detection.

The origins of frequency components should be searched within (Dong et al., 2002):

1. real geophysical processes (tides, loadings or thermal effects coupled with hydrodynamics etc.);
2. numerical artefacts (draconitics (Agnew and Larson, 2007; Amiri-Simkooei, 2013) or aliasing (Penna and Stewart, 2003)).

To estimate the influence of the seasonal signal on the trend determination we defined the General Dilution of Precision (GDP, Klos et al., 2016) as a ratio of velocity uncertainties when two different deterministic parts are assumed: with and without seasonal terms. This is a slight modification of a Dilution of Precision introduced by Blewitt and Lavallée (2002). However, they did not considered coloured noise in a data, but simply assumed white process. Bos et al. (2010) discussed their results introducing a model with a coloured noise. They concluded, that the noise character plays as important role as amplitude of periodic signals in the data. In this research we initially assumed the deterministic model consisting of annual, draconitics and Chandler oscillations as well as selected fortnightly periodicities (Bogusz and Klos, 2015) and then computed the inverse of covariance matrix for the general power-law process to estimate the variances of the determined parameters, including station's velocity. Fig. 2 presents the reduced value of GDP for North component of BOR1 (Borowiec, Poland) station. If we assume that the relative error of the GNSS-derived velocity should not exceed 1%, we noticed that 6 years of data is indispensable to reliably estimate velocity.

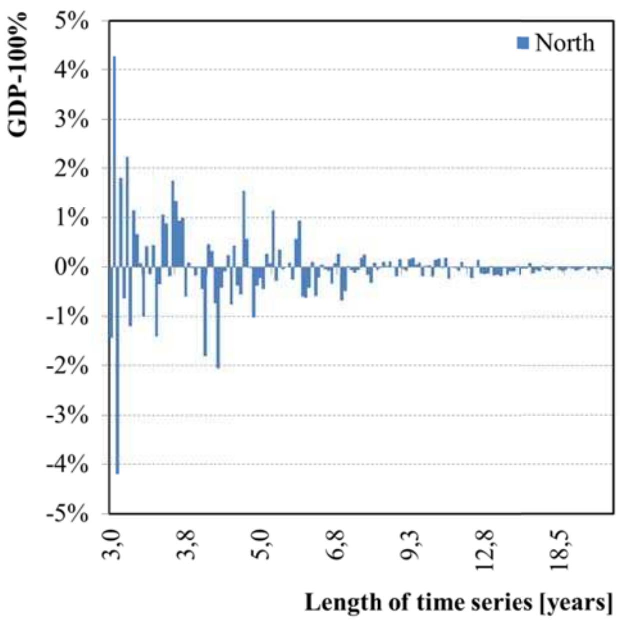

Fig. 2. Reduced General Dilution of Precision for North component of BOR1 (Borowiec, Poland) station. We can notice that the stability at the level of 1% was obtained with 6 years of continuous observations

It is widely acknowledged, that the most powerful oscillations are concentrated near tropical year and its overtones (Ray et al., 2008) and are widely modelled by the Least Squares Estimation (LSE) (e.g. Blewitt and Lavallée, 2002 or Kenyeres and Bruyninx, 2009). However, this method assumes constancy of amplitudes and phase shift in time. There is no basis to claim that either real geophysical effects or numerical artefacts introduce oscillations that are constant in time. So, any of the non-parametric estimations should be applied (e.g. Freymueller 2009; Bogusz et al., 2015). One of them is the Singular Spectrum Analysis (SSA) provided by Broomhead and King (1986), Vautard et al. (1989) or Ghil and Taricco (1997) and previously used to analyse GNSS time series by Chen et al. (2013), Zerbini et al. (2013) or Gruszczynska et al. (2016).

In SSA approach, the Reconstructed Components (RC) are produced for the original time series (Vautard and Ghil, 1989):

$$R_k(t) = \begin{cases} \frac{1}{t}\sum_{j=1}^{t} A_k(t-j+1)E_k(t) & \text{for} \quad 1 \le t \le M-1 \\ \frac{1}{M}\sum_{j=1}^{M} A_k(t-j+1)E_k(t) & \text{for} \quad M \le t < N' \\ \frac{1}{N-i+1}\sum_{j=t-N+M}^{M} A_k(t-j+1)E_k(t) & \text{for} \quad N' \le t \le N \end{cases} \tag{2}$$

with M, N being length of the window and number of data in the time series, respectively, and $N' = N - M + 1$. In this research we adopted $M = 3$-year sliding window, confirmed previously to be optimal to retrieve the annual and semi-annual oscillations (Gruszczynska et al., 2016).

This way, we can choose specified periodic signals of interest (e.g. annual and semi-annual), and investigate their changes in time (Fig. 3).

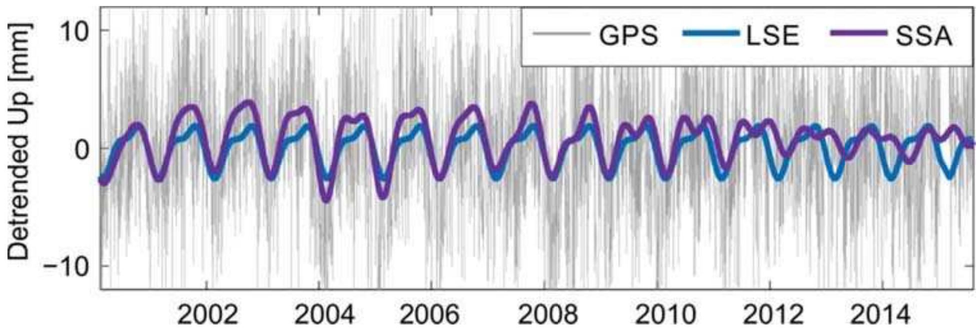

Fig. 3. Difference in the seasonals estimation using LSE and SSA approaches. Up component of CAGS (Gatineau, Canada) GPS permanent station.

As the results of SSA-based analysis, we obtained the variance contribution of annual and semi-annual signals, as a percentage of the total variance of data in the Up component. For the set of permanent stations considered here, we noticed, that the stations located in the South-Eastern part of Europe are characterized by larger variance in the annual signal compared to other stations (more than 30% of the total variance is explained by the annual signal) (Gruszczynska et al., 2016).

4. Stochastic part

Agnew (1992) stated that almost all geophysical phenomena follow the power-law noise being characterized by spectral index and amplitude of the colored noise. It assesses the goodness of fit by finding the value of likelihood function that best fits the data in a procedure called parameter estimation (Langbein and Johnson, 1997):

$$lik(\hat{\mathbf{v}}, \mathbf{C_x}) = \frac{1}{(2 \cdot \pi)^{N/2} \cdot (\det \mathbf{C_x})^{1/2}} \cdot \exp\left(-0.5 \cdot \hat{\mathbf{v}}^T \cdot \mathbf{C_x}^{-1} \cdot \hat{\mathbf{v}}\right) \quad (3)$$

where lik represents the likelihood function, $\hat{\mathbf{v}}$ is the time series residua matrix, $\mathbf{C_x}$ is the covariance matrix of the observations. The integer spectral indices, i.e. -2, -1 and 0 correspond successively to: random-walk (RW), flicker (FN) and white noise (WN), respectively. As was previously shown by e.g. Zhang et al. (1997), Williams et al. (2004) or Santamaría-Gómez et al. (2011) the GPS time series are characterized well by the power-law dependencies being quite close to flicker noise, that is the effect of mismodelled satellite antenna phase centers (APC), Earth Orientation Parameters (EOP), SV orbits as well as large-scale atmospheric or hydrologic effects not being considered to a standard processing of the navigation data.

However, the residua being the ordinary difference between time series and the deterministic model still are either temporally or spatially correlated (Wdowinski et al., 1997). The possible reasons of those correlations should be searched within mismodelling of Earth Orientation Parameters, satellite orbits, clocks and Antenna Phase Centre (APC) variations as well as unmodeled large scale effects originated from atmosphere and hydrosphere. Computing algorithms and methods should also be mentioned as the potential contributors (Dong et al., 2006). That is why we need to define the Common Mode Error (CME), which is the sum of environmental and technique-dependent systematic errors in GPS position time series. The CME, which is a kind of the temporally correlated noise, can be seen in the time series from regional GNSS networks that span hundreds of kilometers. The method of subtracting CME was firstly presented by Wdowinski et al. (1997). Nikolaidis (2002), implemented method called “weighted stacking” by taking individual position Root Mean Square (RMS) error into consideration. For the set of European stations associated to the EPN (EUREF Permanent Network) it was successfully investigated by Bogusz et al. (2015).

In this research we used Principal Component Analysis (PCA), which implements Empirical Orthogonal Functions (EOF) to reveal common signals in residual time series (Dong et al., 2006). PCA is a statistical procedure, that uses orthogonal transformation to subtract the CME stored in particular Principal Components (PC, Williams et al., 2004). Using this method, we found p-first numbers of significant PCs, and we then computed CME as follows (Dong et al., 2006):

$$\mathrm{CME}_j(t_i) = \sum_{k=1}^{p} \mathbf{a}_k(t_i)\mathbf{v}_k(r_j) \quad (4)$$

with

$$\mathbf{a}_k(t_i) = \sum_{j=1}^{n} \mathbf{R}(t_i, r_j)\mathbf{v}_k(r_j) \quad (5)$$

being the k-th principal component of matrix $\mathbf{R}$ and $\mathbf{v}_k$ is corresponding eigenvector. PCA is an effective algorithm for removing CME. Figure 4 presents normalized response of the considered network, which can be identified with positive station contribution into the amount of variation of Up component in first PC.

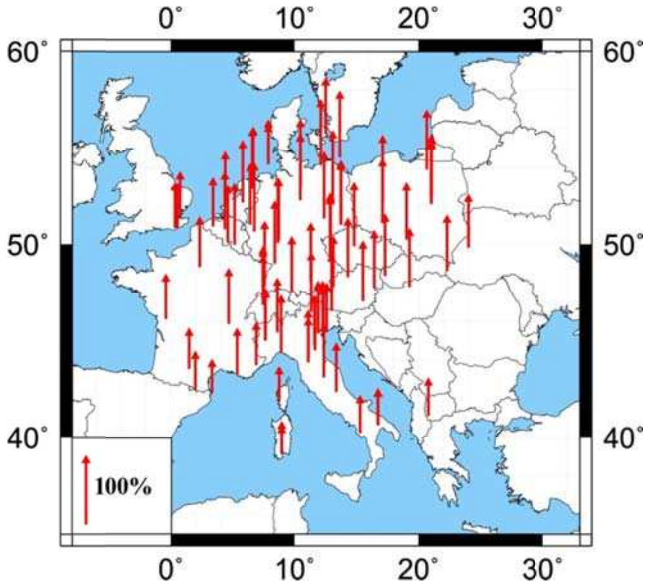

Fig. 4. Positive response to the 1st PC for Up component of the selected European stations

The effectiveness of spatio-temporal filtration was proved by the average reduction of velocity uncertainty of 0.2 mm/year, while maximal reduction was 0.8 mm/year, which means that the after-filtration reduction of accuracy is about 70% on average (Gruszczynski et al., 2016).

5. Summary

The term "reliable velocities" has to be understood twofold: in the sense of optimally determined accuracy as well as consistency with the current knowledge of dynamic processes that are being occurred in the considered region of the world. In this paper we focused on the first meaning, the second one was widely described in the paper by Bogusz et al. (2013). Nowadays, it is widely acknowledged that the stochastic part of GNSS-derived time series shows the existence of power-law dependencies with the focus on flicker noise. Omitting that property may lead to overestimation of the uncertainty of velocity. The velocity values determined with linear regression should be estimated with taking into consideration the colored noise of the residuals following (Bos et al., 2008):

$$m_v \approx \pm \sqrt{\frac{A_{PL}^2}{\Delta T^{2-\frac{\kappa}{2}}} \cdot \frac{\Gamma(3-\kappa)\cdot\Gamma(4-\kappa)\cdot(N-1)^{\kappa-3}}{\left[\Gamma\left(2-\frac{\kappa}{2}\right)\right]^2}} \tag{6}$$

where N is the data length, κ means the estimated spectral index, ΔT is the sampling rate, A_{PL} represents the amplitude of noise, with Γ being the gamma function. Table 1 presents the final product of our analysis by means of the velocities of the selected European permanent stations with the associated errors determined following power-law assumption in the stochastic part.

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Tab. 1. Velocities [mm/y] of the selected European permanent station with the errors

Name	Location	Time span [decimal year]	Velocity [mm/y]			Velocity error [mm/y]		
			N	E	U	m_N	m_E	m_U
AJAC	Ajaccio, France	2001.0-2005.8	15.29	21.38	0.10	0.04	0.03	0.11
ANKR	Ankara, Turkey	2000.8-2007.9	12.43	0.41	-2.61	0.04	0.04	0.10
BOR1	Borowiec, Poland	1996.0-2016.0	14.65	20.12	-0.69	0.01	0.01	0.03
CRAO	Simeiz, Ukraine	2003.1-2008.4	11.37	24.20	1.31	0.09	0.10	0.28
EBRE	Roquetes, Spain	1999.0-2016.0	16.19	19.70	-0.33	0.03	0.02	0.03
GLSV	Kiev, Ukraine	1998.1-2016.0	12.03	22.48	0.11	0.02	0.02	0.06
GOPE	Ondrejov, Czech Republic	1996.0-2016.0	15.71	20.18	1.56	0.01	0.01	0.03
GRAS	Caussols, France	1996.0-2016.0	16.54	20.70	0.51	0.01	0.01	0.03
GRAZ	Graz, Austria	1996.0-2016.0	15.93	21.64	0.35	0.01	0.01	0.03
HERS	Hailsham, United Kingdom	2001.6-2016.0	16.41	16.48	0.04	0.02	0.01	0.05
HOFN	Hoefn, Iceland	2002.0-2016.0	14.78	13.98	13.12	0.02	0.02	0.05
KIRU	Kiruna, Sweden	1996.0-2016.0	14.89	16.09	6.80	0.02	0.03	0.10
KOSG	Kootwijk, Netherlands	1996.0-2003.0	16.22	18.45	-0.96	0.03	0.02	0.08
LAMA	Olsztyn, Poland	2008.0-2012.0	14.12	20.03	-0.98	0.08	0.04	0.17
MAR6	Maartsbo, Sweden	1999.1-2016.0	14.12	18.19 83	7.31	0.01	0.01	0.06
MATE	Matera, Italy	1996.0-2016.0	19.45	23.22	0.97	0.02	0.01	0.04
MDVO	Mendeleevo, Russian Federation	1999.0-2002.8	10.65	23.74	0.89	0.10	0.13	0.49
METS	Kirkkonummi, Finland	1996.1-2010.5	12.66	20.00	4.51	0.02	0.02	0.07
NICO	Nicosia, Cyprus	2009.0-2016.0	14.12	18.89	0.17	0.08	0.06	0.20
NOTO	Noto, Italy	1996.0-2000.7	18.91	20.66	0.69	0.14	0.07	0.22
NSSP	Yerevan, Armenia	2007.0-2009.7	16.39	29.37	-1.76	0.14	0.16	0.59
NYA1	Ny-Alesund, Norway	2000.0-2016.0	14.61	10.94	8.34	0.03	0.01	0.10
NYAL		1996.0-2016.0	14.08	10.65	8.25	0.03	0.02	0.10
ONSA	Onsala, Sweden	1996.0-2016.0	14.77	17.25	2.54	0.01	0.01	0.02
PDEL	Ponta Delgada, Portugal	2000.2-2016.0	16.22	12.28	-0.68	0.05	0.04	0.11
PENC	Penc, Hungary	2008.0-2016.0	14.24	22.44	-1.65	0.07	0.05	0.17
POTS	Potsdam, Germany	1996.0-2016.0	15.15	19.15	-0.27	0.01	0.01	0.04
QAQ1	Qaqortoq / Julianehaab, Greenland	2004.0-2011.0	13.53	-17.24	3.44	0.04	0.07	0.24
RAMO	Mitzpe Ramon, Israel	2006.0-2012.0	19.22	23.06	1.11	0.07	0.06	0.23
REYK	Reykjavik, Iceland	1996.0-2016.0	20.86	-10.57	-1.13	0.02	0.02	0.06
RIGA	Riga, Latvia	2001.0-2016.0	13.56	20.13	0.28	0.02	0.02	0.09
SFER	San Fernando, Spain	2001.0-2016.0	16.99	14.75	0.65	0.03	0.02	0.09
SULP	Lviv, Ukraine	2004.0-2010.6	13.97	21.64	-0.01	0.04	0.03	0.13
TRO1	Tromsoe, Norway	2005.0-2016.0	15.09	14.83	4.24	0.05	0.03	0.23
TROM		2004.0-2009.4	14.65	14.25	3.04	0.02	0.02	0.20
UPAD	Padova, Italy	1996.0-2001.9	17.85	21.60	2.54	0.06	0.03	0.09
VILL	Villafranca, Spain	1996.0-2016.0	16.96	18.95	-0.93	0.03	0.03	0.06
WTZA	Bad Koetzting, Germany	2001.0-2016.0	15.25	19.93	-0.39	0.02	0.01	0.04
WTZR		1996.0-2016.0	15.50	20.35	-0.85	0.02	0.01	0.03
WTZS		2009.0-2016.0	13.78	19.14	-0.46	0.10	0.05	0.23
WTZZ		2002.4-2016.0	15.22	20.19	-0.11	0.03	0.02	0.08
ZIMM	Zimmerwald, Switzerland	1996.0-2013.0	16.43	19.45	2.64	0.02	0.01	0.05

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We accessed NGL time series from: http://geodesy.unr.edu/.
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