Acta Geodyn. Geomater., Vol. 12, No. 2 (178), 117–126, 2015
DOI: 10.13168/AGG.2015.0010
journal homepage: http://www.irsm.cas.cz/acta

ORIGINAL PAPER

INVESTIGATION OF NOISES IN THE EPN WEEKLY TIME SERIES

Anna KLOS *, Janusz BOGUSZ, Mariusz FIGURSKI,
Marta GRUSZCZYNSKA and Maciej GRUSZCZYNSKI

Faculty of Civil Engineering and Geodesy, Military University of Technology,
00-908 Warsaw, Kaliskiego St. 2

**Corresponding author's e-mail:* aklos@wat.edu.pl

ARTICLE INFO

Article history:
Received 13 January 2015
Accepted 26 March 2015
Available online 15 April 2015

Keywords:
EPN
Noises
Spatio-temporal filtering

ABSTRACT

The constantly growing needs of permanent stations' velocities users cause their stability level to increase. To this research we included more than 150 stations located across Europe operating within the EUREF Permanent Network (EPN) with weekly changes in the ITRF2005 reference frame. The obvious long-range dependencies in the stochastic part of GPS time series were proven by Ljung-Box test. Moreover, the results of Detrended Fluctuation Analysis (DFA) comprised in 90 % in the long-time range dependency, indicated an autocorrelation of the signal with a possible coloured noise, similar to the flicker one. The noise in the GPS time series was analysed here with the Maximum Likelihood Estimation (MLE). The amplitudes of white noise for the white, flicker and random-walk combination vary between 0.5 to 3 mm for horizontal components and between 1.5 up to 9 mm for the vertical component. The amplitudes of white and flicker noise show a clear geographical latitude dependence with a correlation with its minimum centred at approximately 50°N. The assumption of white plus flicker plus random-walk noise led to stations' velocity errors from 0 to 3 mm/year for the flicker noise and from 0 up to 7 mm/year for the random-walk. The spectral indices for an approach assuming the occurrence of the white and power-law noise model in weekly time series varied between –1.7 to –0.2 and –1.4 to –0.2 for horizontal and vertical changes. The performed spatial filtering (weighted stacking method) resulted in decreasing the power-law amplitudes by averagely 1-2 mm/year$^{-\kappa/4}$ and moving the spectral indices closer to zero, with amplitudes and indices median decreased by 5 %, compared to the time series before stacking.

1. INTRODUCTION

The growing needs of users of precise GPS positioning are reflected in increasing accuracy regimes. The velocities of permanent GPS stations are determined by fitting first order polynomial into topocentric time series using the least square estimation method with an assumption of no correlation in residual data. This assumption implies velocity errors' underestimation from 2 up to 11 times (i.e. Zhang et al., 1997; Mao et al., 1999) or up to 5 mm/year for ETRF2000 reference data (Klos et al., 2014a). Nevertheless, papers published so far (i.e. Williams et al., 2004; Beavan, 2005; Langbein, 2008; Wang et al., 2012) mention power-law noise occurrence in GPS time series caused by a faulty positioning of GPS signal tracking antennas, large-scale atmospheric effects or systematic satellite orbits' modelling errors of power spectral density equal to:

$$P_x(f) = P_0\left(\frac{f}{f_0}\right)^{\kappa} \tag{1}$$

where P_0 and f_0 are the normalising constants, f is the frequency (from lowest frequencies indicating the long-term changes to highest ones), κ is the spectral index (Mandelbrot and Van Ness, 1968). The above equation describes what power P is included in certain frequency bands f of the GPS data. Depending on the assumed spectral index, the power-law character (PL) for time series can be represented by various models. For the white noise (WN) the corresponding index equals 0 with flat power spectrum, for the flicker noise (FL) κ = –1 while for the random-walk (RW) caused by a monument instability the index equals –2 (Johnson and Agnew, 1995; Klos et al., 2014c). The assumption that residuals reflect only the white noise seems to be very optimistic. The linear parameters estimated by this assumption are less credible and may lead to misinterpretation. The combination of the aforementioned errors causes a correlation of the residuals of time series with hyperbolically decaying values of autocorrelation function (ACF), which results in a long-range dependence with power-law characteristics (Tserolas et al., 2013).

These correlations reflect in amplitudes and types of noises recognised in GPS time series. Zhang et al. (1997) described the noises for daily time series for stations located across Southern California. They proved that noises in the GPS time series differ from the white noise assumption and indicate some coloured noise at the lowest of analyzed frequencies. Using the slope of time series power spectra, they estimated the spectral indices of noises to be close to –0.4. Williams et al. (2004) proved that noises in the GPS time series calculated with the Maximum Likelihood Estimation (MLE) are best described by a combination of white and flicker noise models for global solutions. In contrast, for regional solutions it is better to solve both for spectral index and amplitude of noise, as time series can be disrupted by the aforementioned combination of effects. They reduced the noise amplitudes by the removal of common mode error (CME). Kenyeres and Bruyninx (2009) were the first ones to describe noises in the EPN network. They analysed time series with MLE approach and found that the stochastic part of time series follows the assumption of white plus power-law noise with spectral indices close to –1 (flicker noise). Hackl et al. (2011) analysed noises with the Allan variance (AVR) for time series recorded in the South Africa GPS network TrigNet. They proved that these can be described well with a combination of power-law noise and annual signal. Bogusz and Kontny (2011) focused on noises in the diurnal and sub-diurnal frequency bands from ASG-EUPOS Polish permanent stations. They found out that the average level of noise of these frequency bands of GPS time series does not exceed 1 mm. King et al. (2012) showed that the ambiguities fixed series spectra are between flicker and random walk. They proved the need to account for the effect of the monument that the antenna is placed on, especially in analysis of vertical time series. Wang et al. (2012) used the 26 continuous GPS sites of CMONOC Chinese network to analyse the noise content with MLE. They removed the common mode error and found that it causes the spectral indices to be closer to zero. Klos et al. (2014b) analysed more than 40 stations with 5 years of observations from the area of Sudeten mountains (Central Europe). For the combination of white plus power-law character of the GPS residua, the obtained spectral indices range from –1.6 to –0.4 for the horizontal components and from –1.0 to –0.4 for the vertical component, which confirms the prevalence of fractional white and Brownian motion quite close to flicker noise with amplitudes of power-law noise of 2 to 5 mm/year$^{-\kappa/4}$ and 4 to 12 mm/year$^{-\kappa/4}$, respectively.

2. THE EPN WEEKLY TIME SERIES

In our analysis we included over 150 stations operating within the EUREF Permanent Network (EPN), evenly distributed over the European region (Fig. 1). Weekly North, East, Up components' changes time series were obtained from stations stabilized directly on bedrock or on concrete pillars, buildings' roofs or steel masts with or without domes. Topocentric changes in the ITRF2005 reference frame (Altamimi et al., 2007) for time spans of up to 16 years were obtained within the 'repro1' project (Figurski et al., 2009). The observations were processed by the Military University of Technology Local Analysis Centre (MUT LAC). The 'repro1' project aimed to conduct a unified adjustment providing daily and weekly EPN solutions, utilising new approaches, models and analysing tools. As a result, the reference coordinates and new regional velocity fields were calculated. The re-processing of archive GPS observations from the EPN network was based on modified Bernese software (Dach et al., 2007). As the major change the software was replaced from a workstation to a high performance supercomputer with implementation of Bernese Processing Engine (BPE). Whole computation was divided into two parts. The first one included the processing of daily RINEX observation files downloaded from a pre-prepared local database. Currently it is the most extensive European database in Poland, containing more than 280 stations and dating from 1995 to 2014. The second part involved daily and weekly data processing based on the normal equations, obtained from the processing of daily solutions.

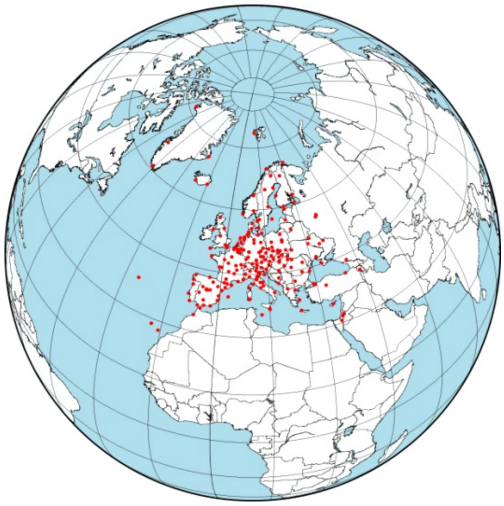

Fig. 1 Distribution of the EPN stations included into the research.

Each of the topocentric components (North, East or Up) can be described as the sum of the deterministic part, modelled, e.g. with the least square estimation or wavelet decomposition, and the stochastic part (residuals), formed by deducting the deterministic part from the respective observations:

$$x(t) = x_0 + v_x \cdot t + \sum_{i=1}^{n} \left[A_i \cdot \sin(\omega_i \cdot t + \varphi_i) \right] + \\ + O_t + \sum_{j=1}^{m} p_j \cdot x_j^{off} + \varepsilon_x(t) \tag{2}$$

where x_0 corresponds to the initial value, v_x is the station velocity, modelled by fitting a first order polynomial trend into the time series, 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_t are the outliers, x^{off} are the offsets' amplitudes and ε_x are the residuals of the time series. At the pre-processing stage the outliers were removed from the weekly EPN time series by the Median Absolute Deviation (Mosteller and Tukey, 1977; Sachs, 1984); where the offsets, by application of the STARS (Sequential t-test Analysis of Regime Shifts)

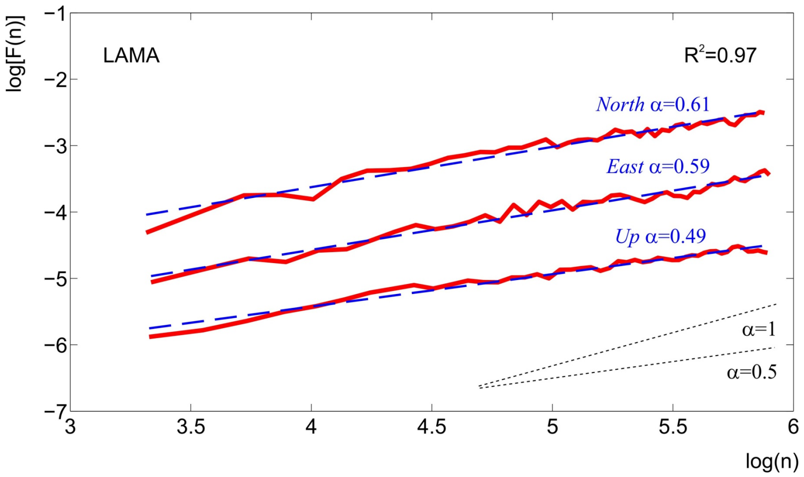

Fig. 3 Results of the DFA method analysis, LAMA station (Lamkowko, Poland), for the North, East and Up components. The curve slope contained within the long-range dependencies limits of 0.5 and 1 indicates an autocorrelation occurring in the time series' stochastic part, possibly with the flicker noise. The plots were shifted vertically.

algorithm, which is a combination of the Student's t-test and the standard deviations test (Rodionov, 2004):

$$d = t\sqrt{\frac{2\sigma_l^2}{l}} \tag{3}$$

where l corresponds to the length of the analysed subseries, t is the Student's t-distribution value for $2l$-2 degrees of freedom on the α significance level, whereas σ is the standard deviation of the respective time subseries. For the weekly EPN time series, the values which on the significance level of 0.01 were assumed as offsets varied between 4-12 mm. The missing observations shorter than 1 month were interpolated by a combination of the trend, seasonal components modelled with the least squares estimation and the white noise of the amplitude equal to a variance of the interpolated series. In order to obtain the time series' residuals (Fig. 2), the deterministic part was modelled with the least squares estimation approach, assuming a linear trend model and constancy of both amplitudes and phases of the seasonal components:

$$\begin{aligned} x(t) = x_0 + v_x \cdot t + A_A^I \cdot \sin 2\pi t + A_A^O \cdot \cos 2\pi t + \\ + A_{SA}^I \cdot \sin 4\pi t + A_{SA}^O \cdot \cos 4\pi t \end{aligned} \tag{4}$$

where A_A and A_{SA} are the amplitudes of the annual and semi-annual components, I – in-phase and O – out-of-phase, respectively. As is shown in Figure 2 (especially the BOR1 series) the amplitudes of seasonal variations are probably not constant for the whole analyzed time span. This affects the residuals and may influence the noise analyses getting its character closer to flicker noise.

3. NOISE ANALYSIS

As Agnew (1992) noticed, most of the geophysical phenomena' time series contain time correlated power-law behaviour. This correlation determines long-range dependency and auto-correlation of the signal with hyperbolically decaying values. The occurrence of long-range dependencies in the stochastic part of GPS time series was proven by Ljung-Box test, of which values close to zero let to neglect the null hypothesis assuming no autocorrelation in series' residuals on the 0.05 confidence level. Moreover, the long-range dependencies were analysed in weekly EPN time series' residuals by the Detrended Fluctuation Analysis method (DFA; Peng et al., 1994, 1995). In this approach, by deducting the trend from a specified-length time series components, the autocorrelation of non-stationary time series is detected, indicating their possible power-law correlations of nature (Peng et al., 1994):

$$F(n) \sim n^{\alpha} \tag{5}$$

where $F(n)$ is the root-mean-square fluctuation, n is the window length, where α is the scaling exponent. The results of DFA comprised in 90 % (for all of the components) in the long-time range dependency (from 0.5 to 1) indicated an autocorrelation of the signal with a possible coloured noise, similar to the flicker one (Fig. 3).

The realistic assumption that GPS data residuals are autocorrelated, tantamount to neglecting the optimistic approach which assumes their randomness, directly influences all of the linear parameters determined from these series. In our research, the vectors of topocentric time series' residuals were analysed with the maximum-likelihood approach (MLE; Langbein and Johnson, 1997):

$$lik(\hat{\mathbf{v}},\mathbf{C_x}) = \\ = \frac{1}{(2\cdot\pi)^{N/2}\cdot(\det\mathbf{C_x})^{1/2}}\cdot\exp\left(-0.5\cdot\hat{\mathbf{v}}^T\cdot\mathbf{C_x}^{-1}\cdot\hat{\mathbf{v}}\right) \tag{6}$$

where $\mathbf{C_x}$ is the covariance matrix, $\hat{\mathbf{V}}$ is the vector of series' residuals, determined by removing the deterministic part, modelled with the least squares estimation method, *lik* is the likelihood function value. In the analysis, the occurrence of a combination of the white, flicker and random-walk noises was assumed (WN-FL-RW), which means that covariance matrix looks like:

$$\mathbf{C_x} = a_{WN}^2\mathbf{I} + b_{FL}^2\mathbf{J}_{FL} + b_{RW}^2\mathbf{J}_{RW} \tag{7}$$

as well as the white and power-law noises (WN-PL):

$$\mathbf{C_x} = a_{WN}^2\mathbf{I} + b_{PL}^2\mathbf{J}_{PL} \tag{8}$$

where a_{WN}, b_{FL}, b_{RW}, b_{PL} are the amplitudes of the white, flicker, random-walk and power-law noises, respectively, **I** is the identity matrix, **J** is the particular noise covariance matrix (Zhang et al., 1997).

Amplitudes of the white noise for the WN-FL-RW combination vary between 0.5 to 3 mm for horizontal components and between 1.5 up to 9 mm for the vertical component. The time series for the stations where only the white noise was detected were presumably not long enough to reliably detect a coloured noise occurrence. Amplitudes of the white and flicker noise summarised in the stations' geographical latitude function clearly indicate a correlation with its minimum centred at approximately 50°N (Fig. 4), where the barycentre of the EPN network is located. These results are consistent with the ones published previously by Williams et al. (2004) for global networks or Bogusz et al. (2014), when the minimum of both correlations (also 50°N) and noise amplitudes values are studied. On the other hand, the noise estimates are based on EPN network solution using the double differences as the input data. The way how the baselines are defined is influencing the covariance matrix of the estimated parameters (including the coordinates). In this way, the latitude dependence and spatial correlations may arise partly due to this fact.

Amplitudes of the flicker noise vary between 0 up to 14 mm/year$^{0.25}$, whereas those of the random-walk noise vary from 0 to 10 mm/year$^{0.5}$ (Fig. 5). These noises, associated with local effects for a particular station, i.e. for example wrong antenna placing, or with effects resulting from not accurate enough modelling of Earth orientation parameters or satellite orbits, or else atmospheric noise are commonly recognised in GPS observations (e.g. Santamaria-Gomez et al., 2011).

When considering two noise combinations – white and flicker noises and white and random-walk noises, the first one is always deliberated as more appropriate for GPS time series as a wrong antenna placing is not the only and major GPS observation error source. As Williams et al. (2004) stated, in order to reliably detect white and flicker noises of amplitudes 3.5 mm and 8.5 mm/year$^{0.25}$ in simulated data, over 2000 sample points are required (in case of random-walk noise even more), which for a weekly series gives up to 40 years of permanent observations. The random-walk amplitudes were not equal to zero at only a few EPN stations, which confirms the thesis that the flicker is the major noise among GPS data (e.g. Mao et al., 1999; Zhang et al., 1997). However, an absence of random-walk noise does not indicate that antenna placing has no effect on the series characteristics. The zero amplitude may be caused by predominant flicker noise, which is considered to be spatially-correlated, or by the time series which are too short for the random-walk to be detected. Nonetheless, as King and Williams (2009) noticed, if random-walk determined by wrongly placed antenna occurs in a time series, its amplitude does not exceed 0.5 mm/year$^{0.5}$, which indicates the monument's dislocation by 0.5 mm from the assumed position after one year, while for our 16-year time series, up to 2 mm. Assuming the occurrence of the WN-FL-RW noise combination in the GPS time series leads to stations' velocity errors from 0 to 3 mm/year for the flicker noise and from 0 up to 7 mm/year for the random-walk (Fig. 5). In order to reach the velocities' credibility of 0.1 mm/year for amplitude of random-walk equal 0.5 mm/rok$^{0.5}$ (as suggested by King and Williams, 2009), weekly time series of 25 years' time span were needed. On the contrary a credibility equal to 0.1 mm/year for time series of weekly solutions with the flicker noise amplitude equal to 3 mm can be reached after 18 years, whereas after reducing the amplitude by 1 mm the required credibility level will be reached six years faster.

The spectral indices for an approach assuming the occurrence of the WN-PL model in weekly time series varied between –1.7 to –0.2 and –1.4 to –0.2 for horizontal and vertical changes, respectively, with amplitudes being rather consistent for the horizontal components (1 to 6 mm/year$^{-\kappa/4}$) and more variable for the vertical component, ranging from 2.5 up to 14 mm/year$^{-\kappa/4}$ (Fig. 6). Comparatively significant variation of the amplitudes and spectral indices shows that GPS observations are jammed by miscellaneous types of noises and it is not possible to unambiguously distinguish their main source. The particular effects overlap, forming combinations of regional and local effects which affect the quality of GPS observations. The differences in the log-likelihood function (δMLE) for the WN-PL and WN-FL-RW (WN-PL-WN-FL-RW) models with median equal to 10 indicate that residuals of weekly time series most likely have the power-law characteristics of a varied spectrum index, formed mostly by fractional white noise which approaches to the flicker noise.

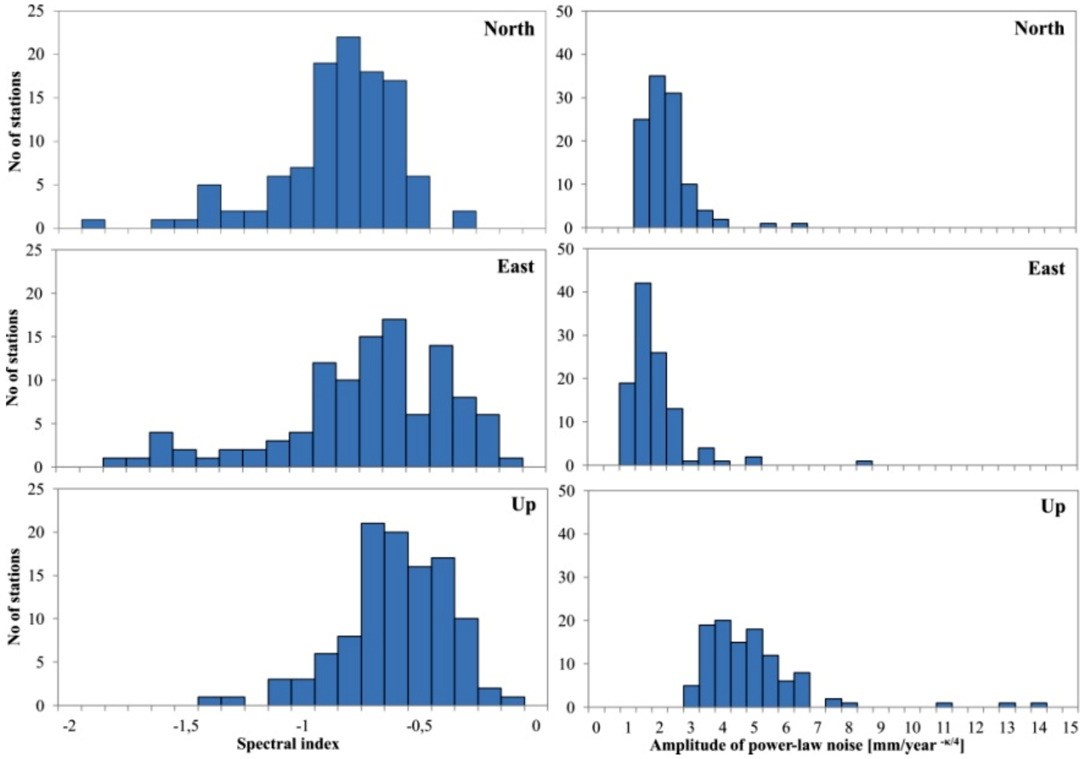

Fig. 6 Spectral indices' histograms calculated using the maximum likelihood method (on the left) and the noises amplitudes (mm/year$^{-\kappa/4}$) (on the right) caused by them. The consecutive plots are corresponding to the North, East, Up components, respectively.

4. SPATIAL CORRELATIONS

The occurrence of spatial correlations which are up to a few hundred kilometres wide in GPS time series in the form of common mode error (Wdowinski et al., 1997) causes a dividing of GPS networks into local and regional ones. The research published so far prove strong spatial correlations, the eliminating of which significantly improves the quality of computations derived from GPS time series (Williams et al., 2004; Dong et al., 2006). Hence, the time-correlated noise predominant in GPS observations can be described as flicker noise with strong latitudinal dependencies. Williams et al. (2004) found spatial correlations at the level of up to 0.7 for 10° angular distance between regional network stations. Moreover, they have noticed that stations located close to the centre of the network have lower values of common mode noise. Dong et al. (2006) or Marquez-Azua and Demets (2003) demonstrated, that common mode error is spatially correlated for permanent GPS observations, and may be caused by systematic errors of modelling large-scale atmospheric effects, Earth orientation parameters or loadings from the atmosphere or hydrosphere (Van Dam et al., 2001). Wdowinski et al. (1997) used the stacking method for filtering of a spatial time series registered at the Californian region. Williams et al. (2004) showed that for networks where the common mode error was removed, the noises are characterized by a spectral index closer to 0. Based on analysis from global 275 sites Santamaria-Gomez et al. (2011) proved, that noise model for global networks is best described by variable white noise plus power-law noise with mean amplitudes of 2 and 6 mm. They also stated that correlated noise content is dependent on the length of time series. Spatial correlations between weekly EPN observation's' time series (each combination of pairs) for stations located up to 4000 km apart were computed for residuals, which excluded a possible influence of the trend and seasonal components on the results. The correlation coefficients varied between -0.4 to 0.7. The minimum correlation for the Up component was derived for a 2500 km long base line (Fig. 7). In the present research the EPN stations' time series were assumed to be coherent during the spatial filtering by the method proposed by Nikolaidis (2002), which uses errors of particular observations from adjustment as stored in the SINEX files. The stations characterised by strong local effects were excluded from the computations before performing the stacking process.

The performed spatial filtering of weekly EPN time series resulted in decreasing the power-law amplitudes by averagely 1-2 mm/year$^{-\kappa/4}$ and moving the spectral indices closer to zero (Fig. 8), with amplitudes and indices median decreased by 5 %, compared to the time series before stacking filtering. This confirms the results obtained by Williams et al. (2004) for regional networks. Spatial filtering caused a decrement in flicker noise for most of the EPN stations, and in consequence allowed to detect random-walk there, where it was not distinguished

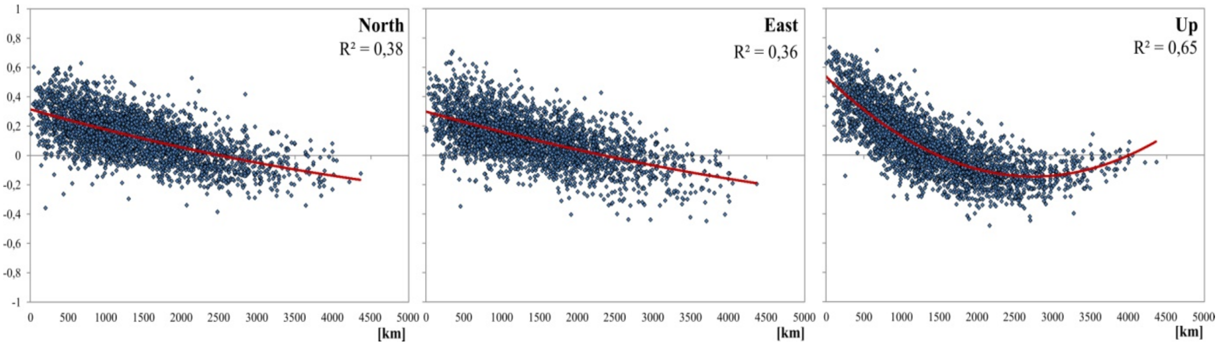

Fig. 7 Spatial correlations between the EPN stations – weekly solutions' time series. The correlations are represented as a function of distance between the stations (km). For each of the fitted polynomials, an R^2 value, describing the goodness-of-fit was given.

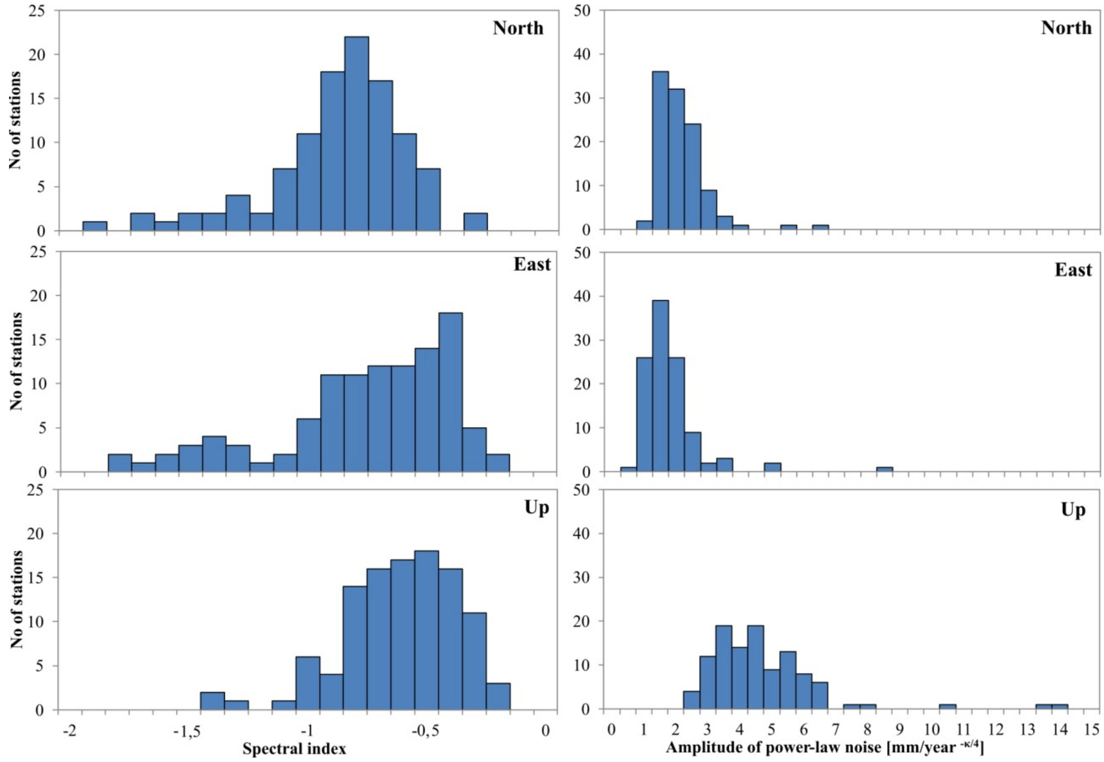

Fig. 8 The histograms obtained for characteristics of the stochastic part assumed to be a combination of the white and power-law noises. Spectral indices were shown on the left, while on the right, amplitudes of the power-law noise for the EPN stations after the stacking filtering.

due to predominant flicker noise amplitude (Fig. 9). Unexpected flicker amplitude increment was observed only for stations with time series shorter than 6 years. Referring to prior published researches stating that common mode error is mostly the flicker noise, the stochastic part was assumed to be characterised by the flicker noise and its amplitudes were computed before and after stacking filtering. Differences in the flicker noise were up to 2 mm/year$^{0.25}$ high, which indicates a decrement in velocity error by 0.25 mm/year for 5 years weekly solutions' series, while for 16 years series, from 0.15 mm/year to 0.07 mm/year.

5. DISCUSSION

Our paper shows results of noise analysis for weekly data from European EPN network up to 16 years long. As Williams et al. (2004) noticed, removing the trend associated with tectonic plates' movement may disrupt noises spectral indices' calculations, moving them closer to zero. That's why the residuals of topocentric time series were derived by modelling the deterministic part in the time series, consisting of the plate-related trend, seasonal components and offsets. This is caused by a trend occurring in power-law, which cannot be separated from the trend associated with tectonic plates' movement. The stochastic part was examined for two

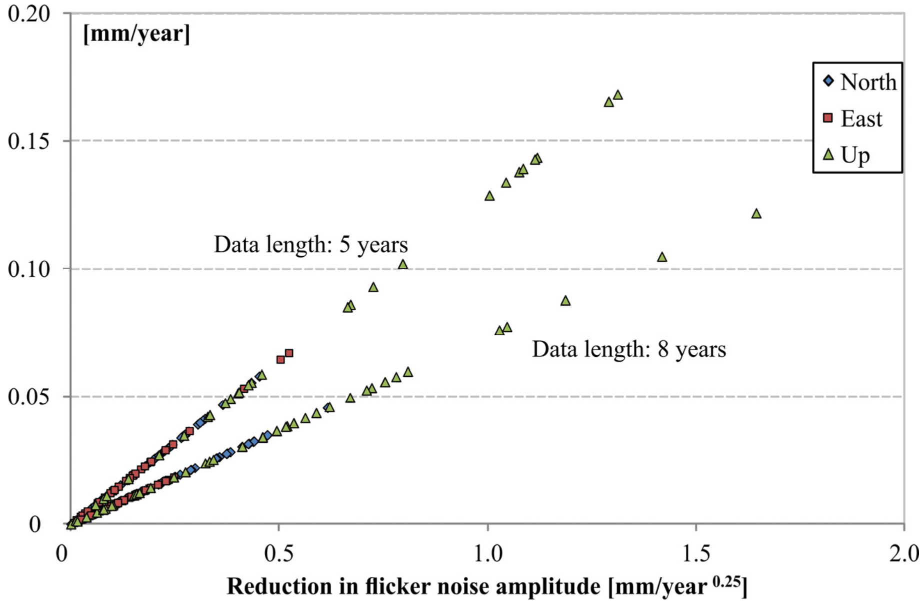

Fig. 10 Decrement in permanent stations' velocity error described by a function of differences between flicker noise amplitude before and after spatial filtering for two time spans of data series 5 and 8 years.

characteristics assumptions the combinations of white, flicker and random-walk noises and white and power-law noises. Amplitudes of the white and flicker noises show a clear correlation with its minimum centred at approximately 50°N, where the barycentre of the EPN network is located. Williams et al. (2004) emphasised, the characteristics of stochastic part are better described with the assumption of occurrence of the power-law noise, compared to using a fixed values of spectral indices. This assumption does not impose a source of the noises' occurrence, but reflects their comprehensive nature, caused by interference of various disturbances. For the EPN network stations, the power-law spectral indices varied from –1.7 to –0.2 and from –1.4 to –0.2 for horizontal and vertical changes, respectively, with amplitudes being rather consistent for the horizontal components (1 to 6 mm/year$^{-\kappa/4}$) and more variable for the vertical component, ranging from 2.5 up to 14 mm/year$^{-\kappa/4}$. In our approach, the EPN network stations were processed by spatial filtration, assuming their homogeneity for the whole area. Common mode error removed from the time series caused a decrement in power-law noise amplitudes by 1-2 mm/year$^{-\kappa/4}$ and moving the spectral indices closer to zero, what confirms the prior results obtained for regional networks (Williams et al., 2004). The decreased amplitudes of flicker noise, which is considered to be one of the sources of CME occurrence, causes a decrement in derived velocity error of up to 0.2 mm/year for 5 years long weekly series (Fig. 10).

ACKNOWLEDGEMENTS

This research was financed by the Faculty of Civil Engineering and Geodesy Young Scientists Development funds. Map and charts were drawn in the Generic Mapping Tool (Wessel et al., 2013).

REFERENCES

Agnew, D.C.: 1992, The time-domain behaviour of power-law noises. Geophysical Research Letters, 19(4), 333–336. DOI: 10.1029/91GL02832

Altamimi, Z., Collilieux, X., Legrand, J., Garayt, B. and Boucher, C.: 2007, ITRF2005: A new release of the International Terrestrial Reference Frame based on time series positions and Earth Orientation Parameters. Journal of Geophysical Research, 112, B09401. DOI: 10.1029/2007JB004949

Beavan, J.: 2005, Noise properties of continuous GPS data from concrete pillar geodetic monuments in New Zealand and comparison with data from U.S. deep drilled braced monuments. Journal of Gephysical Research, 110, B08410. DOI: 10.1029/2005JB003642

Bogusz, J., Figurski, M., Klos, A. and Araszkiewicz, A.: 2014, The latitude dependencies in the stochastic part of EPN time series. Proceedings of the 14th International Multidisciplinary Scientific Geo Conference (SGEM 2014), 537–544. DOI: 10.5593/sgem2014B22

Bogusz, J. and Kontny, B.: 2011, Estimation of sub-diurnal noise level in GPS time series. Acta Geodyn. Geomater., 8, No. 3 (163), 273–281.

Dach, R., Hugentobler, U., Fridez, P. and Meindl, M.: 2007, Bernese GPS Software Version 5.0. Astronomical Institute, University of Bern, Switzerland.

Dong., P., Bock, Y., Webb, F., Prawirodirdjo, L., Kedar, S. and Jamason, P.: 2006, Spatiotemporal filtering using principal component analysis and Karhunen-Loeve expansion approaches for regional GPS network analysis. Journal of Geophysical Research, 111, B03405. DOI: 10.1029/2005JB003806, 2006

Figurski, M., Kamiński, P. and Kenyeres, A.: 2009, Preliminary results of the complete EPN reprocessing

computed by the MUT EPN Local Analysis Centre. Bulletin of Geodesy and Geomatics, 1, 163–174.
Hackl, M., Malservisi, R., Hugentobler, U. and Wonnacott, R.: 2011, Estimation of velocity uncertainties from GPS time series: Examples from the analysis of the South African TrigNet network. Journal of Geophysical Research, 116, B11404. DOI: 10.1029/2010JB008142, 2011
Johnson, H. and Agnew, D.C.: 1995, Monument motion and measurements of crustal velocities. Geophysal Research Letters, 22, No. 21, 2905–2908. DOI: 10.1029/95GL02661
Kenyeres, A. and Bruyninx, C.: 2009, Noise and periodic terms in the EPN time series. Geodetic Reference Frames, International Association of Geodesy Symposia, 134, 143–148. DOI: 10.1007/978-3-642-00860-3_22.
King, M., Bevis, M., Wilson, T., Johns, B. and Blume, F.: 2012, Monument-antenna effects on GPS coordinate time series with application to vertical rates in Antarctica. Journal of Geodesy, 86, 53–63. DOI: 10.1007/s00190-011-0491-x
King, M.A. and Williams, S.D.P.: 2009, Apparent stability of GPS monumentation from short-baseline time series. Journal of Geophysical Research, 114, B10403. DOI: 10.1029/2009JB006319
Klos, A., Bogusz, J., Figurski, M. and Kosek, W.: 2014a, Irregular variations in the GPS time series by the probability and noise analysis. Survey Review. DOI: 10.1179/1752270614Y.0000000133, in press
Klos, A., Bogusz, J., Figurski, M. and Kosek, W.: 2014b, Uncertainties of geodetic velocities from permanent GPS observations: the Sudeten case study. Acta Geodynamica et Geomaterialia, 11, No. 3 (175), 201–209. DOI: 10.13168/AGG.2014.0005.
Klos, A., Bogusz, J., Figurski, M. and Kosek, W.: 2014c, Noise analysis of continuous GPS time series of selected EPN stations to investigate variations in stability of monument types. Accepted for publication by Springer in the IAG Symposium Series volume 142, Proceedings of the VIII Hotine Marussi Symposium.
Langbein, J.: 2008, Noise in GPS displacement measurements from Southern California and Southern Nevada. Journal of Geophysical Research, 113, B05405. DOI: 10.1029/2007JB005247
Langbein, J. and Johnson, H.: 1997, Correlated errors in geodetic time series: Implications for time-dependent deformation. Journal of Geophysical Research, 102, No. B1, 591–603. DOI: 10.1029/96JB02945
Mandelbrot, B. and Van Ness, J.: 1968, Fractional Brownian Motions, fractional noises, and applications. SIAM Rev., 10, 422–439.
Mao, A., Harrison, Ch.G.A. and Dixon, T.H.: 1999, Noise in GPS coordinate time series. Journal of Geophysical Research, 104, No. B2, 2797–2816. DOI: 10.1029/1998JB900033
Marquez-Azua, B. and DeMets, C.: 2003, Crustal velocity field of Mexico from continuous GPS measurements 1993 to June 2001: implications for the neotectonics of Mexico. Journal of Geophysical Research, 108, B9. DOI: 10.1029/2002JB002241.
Mosteller, F. and Tukey, J.: 1977, Data Analysis and Regression. Upper Saddle River, NJ: Addison-Wesley.
Nikolaidis, R.: 2002, Observation of geodetic and seismic deformation with the Global Positioning System. Ph.D. thesis, Univ. of Calif., San Diego.
Peng, C.-K., Buldyrev, S.V., Havlin, S. et al.: 1994, Mosaic organisation of DNA nucleotides. Phys. Rev. E49, 1685–1688,
Peng, C.-K., Havlin, S., Stanley, H.E. and Goldberger, A.L.: 1995, Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series. Chaos, 5, 82–87.
Rodionov, S.: 2004, A sequential algorithm for testing climate regime shifts. Geophysical Research Letters, 31, L09204. DOI: 10.1029/2004GL019448
Sachs, L.: 1984, Applied Statistics: A Handbook of Techniques. New York: Springer-Verlag, 253 pp.
Santamaria-Gomez, A., Bouin, M.-N., Collilieux, X. and Woppelmann, G.: 2011, Correlated errors in GPS position time series: Implications for velocity estimates. Journal of Geophysical Research, 116, B01405. DOI: 10.1029/2010JB007701
Tserolas, V., Mertikas, S.P. and Frantzis, X.: 2013, The Western Crete geodetic infrastructure: Long-range power-law correlations in GPS time series using Detrended Fluctuation Analysis. Advances in Space Research, 51, 1448–1467. DOI: 10.1016/j.asr.2012.08.002
Van Dam, T.M., Wahr, J.M., Milly, P.C.D., Shmakin, A.B., Blewitt, G., Lavallee, D. and Larson, K.M.: 2001, Crustal displacements due to continental water loading. Geophysical Research Leters, 28, No. 4, 651–654. DOI: 10.1029/2000GL012120
Wang, W., Zhao, B., Wang, Q. and Yang, S.: 2012, Noise analysis of continuous GPS coordinate time series for CMONOC. Advances in Space Research, 49, 943–956. DOI: 10.1016/j.asr.2011.11.032.
Wdowinski, S., Bock, Y., Zhang, J., Fang, P. and Genrich, J.: 1997, Southern California Permanent GPS Geodetic Array: Spatial filtering of daily positions for estimating coseismic and postseismic displacements induced by the 1992 Landers earthquake. Journal of Geophysical Research, 102, No. B8, 18057–18070. DOI: 10.1029/97JB01378
Wessel, P., Smith, W.H.F., Scharroo, R., Luis, J.F. and Wobbe, F.: 2013, Generic Mapping Tools: Improved version released. EOS Trans. AGU, 94, 409–410.
Williams, S.D.P., Bock, Y., Fang, P., Jamason, P., Nikolaidis, R.M., Prawirodirdjo, L., Miller, M. and Johnson, D.J.: 2004, Error analysis of continuous GPS position time series. Journal of Geophysical Research, 109, B03412. DOI: 10.1029/2003JB002741
Zhang, J., Bock, Y., Johnson, H., Fang, P., Williams, S., Genrich, J., Wdowinski, S., and Behr, J.: 1997, Southern California Permanent GPS Geodetic Array: Error analysis of daily position estimates and site velocities. Journal of Geophysical Research, 102, No. B8, 18035–18055. DOI: 10.1029/97JB01380

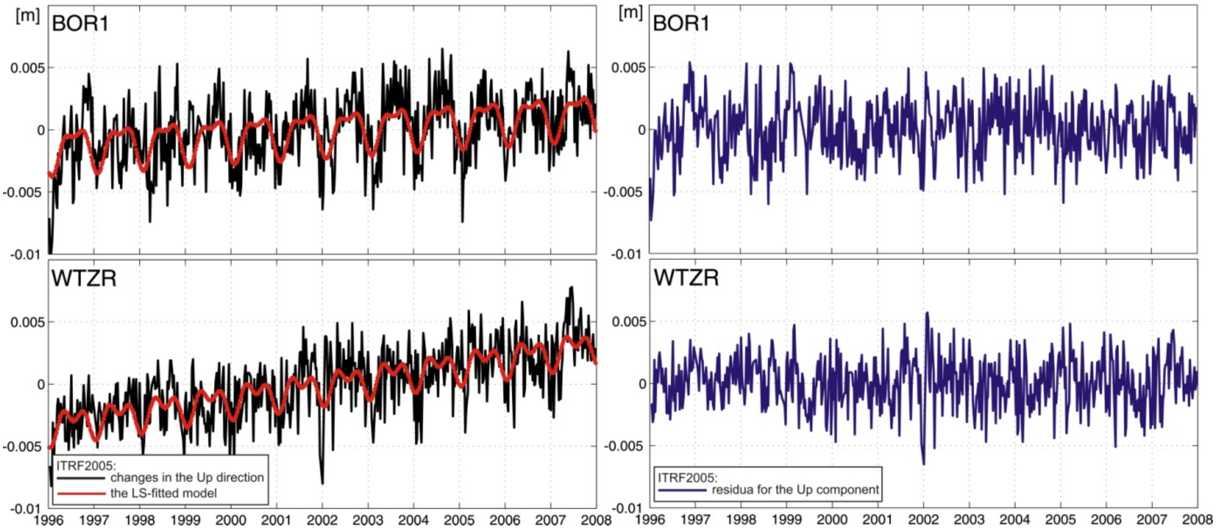

Fig. 2 Time series of Up changes for BOR1 station (Borowiec, Poland; upper plot) and WTZR (Bad Koetzting, Germany; lower plot). Changes of the Up component were shown on the left (in metric units) after fitting a model containing the trend and annual and semi-annual components with the least square estimation, whereas on the right the time series' residuals after deducting the deterministic part were plotted.

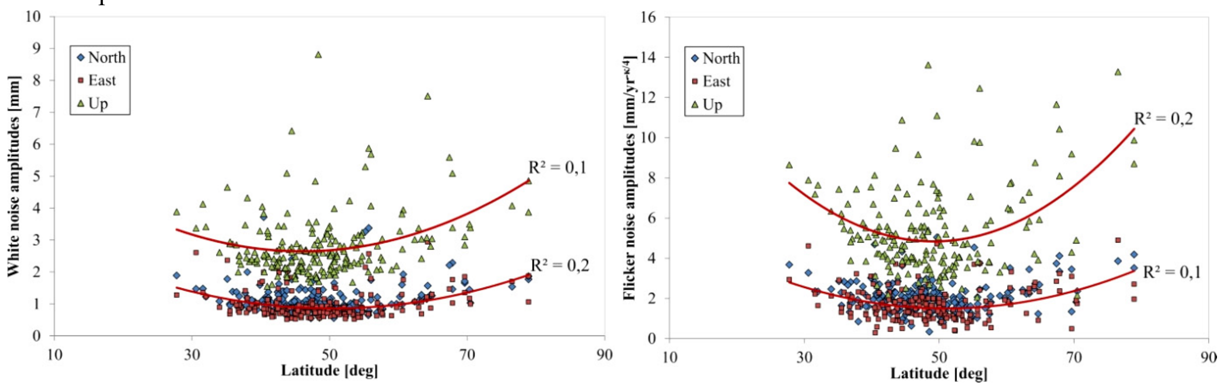

Fig. 4 Latitudinal dependencies of the white and flicker noise amplitudes [mm] and [mm/year$^{0.25}$]. The stations' distribution clearly indicates a correlation with its minimum centred at approximately 50°N, where the barycentre of the EPN network is located.

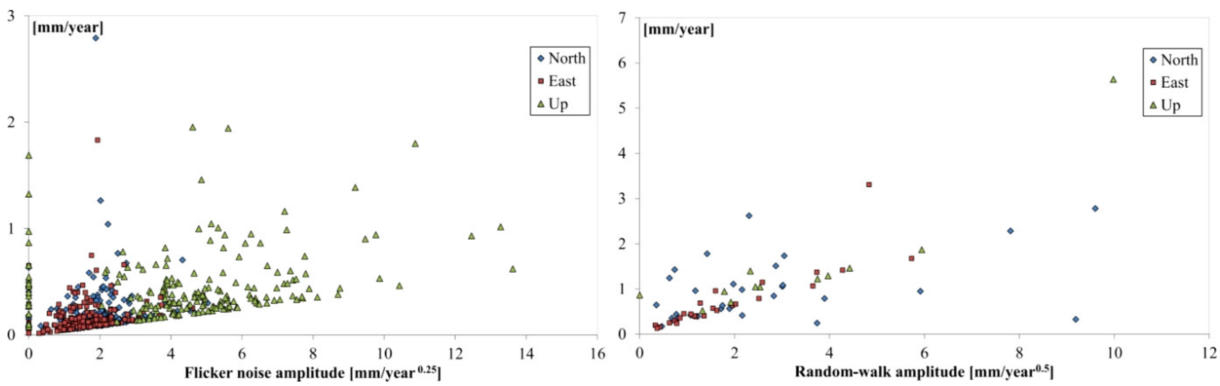

Fig. 5 Amplitudes of the flicker noise (mm/year$^{0.25}$) (on the left) and the random-walk (mm/year$^{0.5}$) (on the right) for EPN weekly solutions' time series, together with stations' velocity errors (mm/year) caused by these. The clear line, along which the observation are formed, originates from the length of the series' time span.

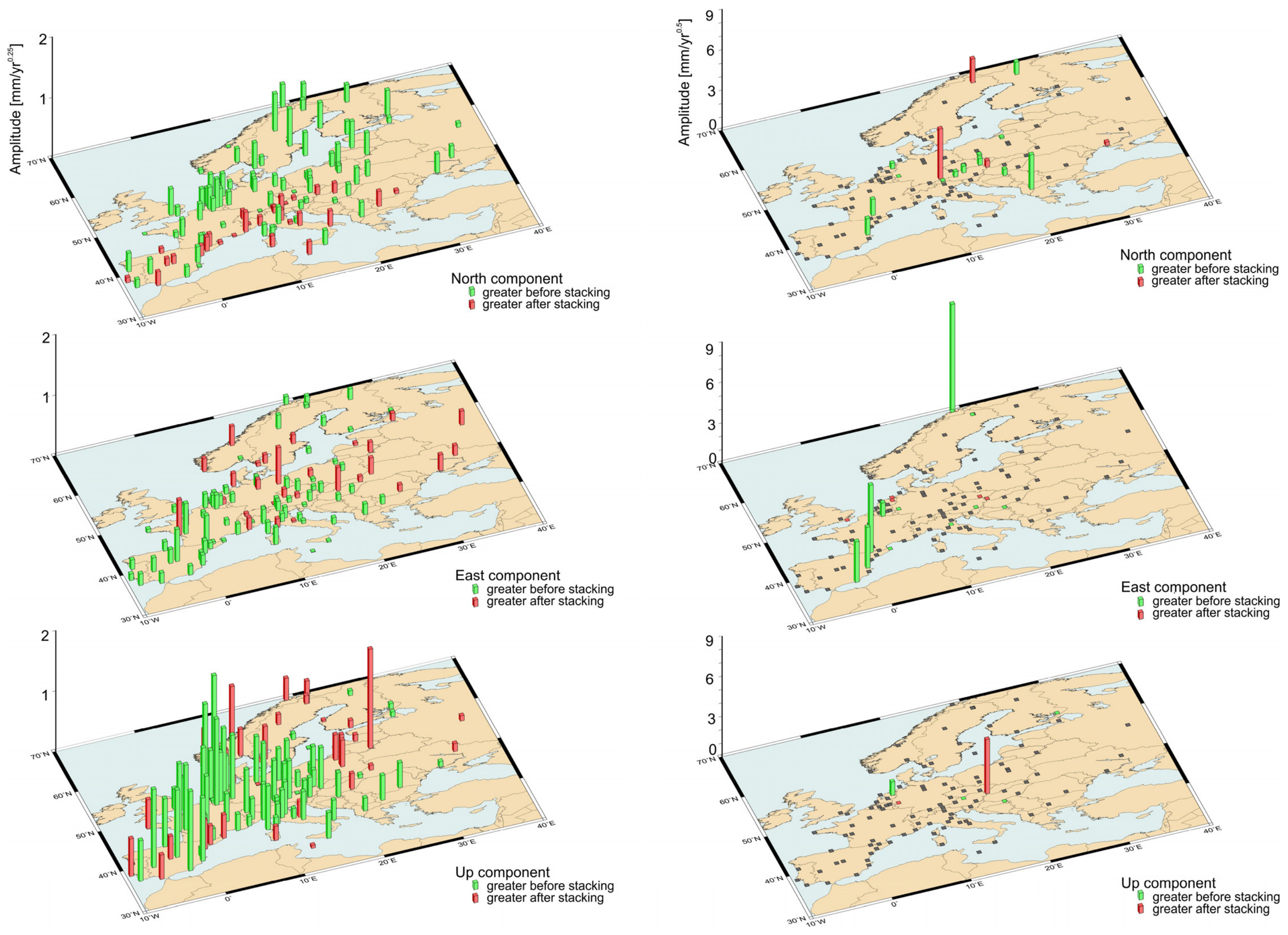

Fig. 9 Compared amplitudes of the flicker and random-walk filtering for EPN network stations' time series before and after stacking filtering. Differences of the flicker noise were shown on the left. The green colour represents decreased noise amplitudes after performing the filtration, whereas the red colour shows increased ones, observed mainly for short time series. On the right differences of the random-walk were plotted with inversed colour representation. The consecutive plots are corresponding to the North, East, Up components, respectively.