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HORIZONTAL VELOCITY FIELD DERIVED FROM EPN AND ASG-EUPOS SATELLITE DATA ON THE EXAMPLE OF SOUTH-WESTERN PART OF POLAND

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ABSTRACT
Presently the determination of the velocity field in the global reference frame is possible by using different space techniques and dense terrestrial networks from global to local and regional scales. However, the reliability of such determinations is strongly limited by the restricted number of unmodeled effects. Some of them are periodic (atmospheric or hydrological effects), some instantaneous (natural or man-made seismicity) or seasons-related (snow cover, freezing). This elaboration deals with the unmodeled effects observed in the ASG-EUPOS (Polish Active Geodetic Network) time series. The whole network consists of over 130 permanent GNSS sites with different levels of stability. The paper presents the analysis of 3-year's time-series of geodetic coordinates (in the topocentric projection) in order to obtain best-possible local velocity field. On the example of the Sudeten region, where 19 sites are located, the possible effects on the decrease in reliability of the velocity field determination are described. Finally the local velocity field in ITRF and ETRF frames are presented.

KEYWORDS: GPS, ASG-EUPOS, regional velocity field

INTRODUCTION

The area of Lower Silesia (South-Western part of Poland) is embracing three large tectonic units formed mainly in the period of young-alpine movements. Stiff mass of crystalline rocks was broken to tectonic blocks: Sudeten Mountains, Fore-Sudetic Block and Fore-Sudetic Monocline, separated by the Sudetic Marginal Fault and the Odra River Fault Zone. Within individual blocks numerous fault zones, grabens and horsts were recognized. This area is still tectonically active, and earthquakes have been observed here for over one thousand years. This activity is also confirmed by hydrothermal activity, underground water flows and precise leveling geodetic data gathered for over 140 years (Kontny, 2003).

From the beginning of the nineties of the 20th century a geodetic research on contemporary Earth's crust movements has been conducted in local research areas and in the regional GPS network named GEOSUD, covering the area of Lower Silesia. Due to insufficient resolution of permanent GPS stations in this area, repeated epoch-making GPS campaigns have been made every year, so far (e.g. Kontny, 2003; Bosy et. al., 2006). However, epoch-making observations give reliable results for estimating the velocity field only after a relatively long period (Schenk et al., 2010).

The national network of permanent ASG-EUPOS stations has been working since 2008. The density and spatial distribution of the stations and a three-year-old observation period already allow to determine the velocity field from permanent observations, independently of epoch-making observations, or in the integrated way, using both these approaches (Kontny et al., 2006). However, is the three-year period of permanent observations sufficient for reaching credible values of velocities? The answer to this question constitutes, among others, the crucial objective of the described work.

GENERAL ASSUMPTIONS

This study is a part of a larger project to assess the applicability of Polish GBAS (Ground-Based Augmentation System) stations for geodynamic studies (Figurski et al., 2011). In general, processing of GPS observations is based on a number of dependencies of the network character. The coordinates and velocity of individual stations are determined based on the satellite network, created for the needs of a particular study. To obtain a solution that will be reliable in view of geodynamics the network has to be based on the stations that are located on other active and dynamic geological units. In other words, its geometry has to go beyond national borders. The range of this network was established using the assumptions concerning boundary conditions presented in Figure 1. From the other side the Sudeten region is the area of the most dynamic changes in terms of modern tectonics.

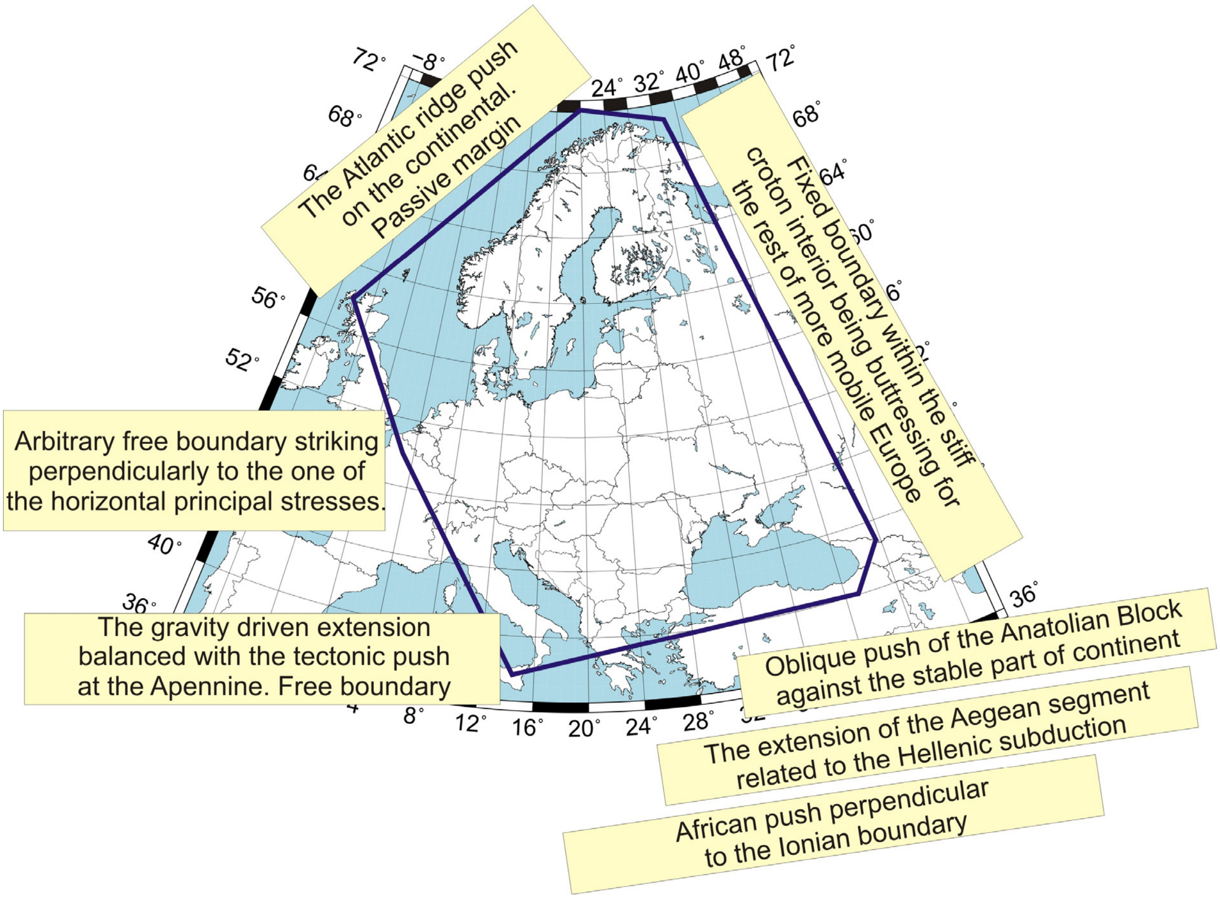

Fig. 1 Determination of boundary conditions for selecting network coverage.

Within the designed borders there are over 250 ASG-EUPOS and EPN (EUREF Permanent Network) GNSS (Global Navigation Satellite System) sites. Their layout is presented in Figure 2. 18 EPN stations are located in the Polish territory and they are regarded as fundamental horizontal control network. The processing of the whole ASG-EUPOS network is made in relation to these sites (Figurski et al., 2009).

GPS DATA AND PROCESSING

The time-series were determined by using normal equations from EPN and ASG-EUPOS, according to the method based on (Brockmann, 1997):

- parameters pre-elimination in order to keep the normal equation system small;
- stacking of normal equation system. This means the correct treatment of the parameters common to more than normal equation system;
- constraining of parameters – including the additional information about the parameters that repair the rank deficiency (Minimum Constraint).

by means of Bernese 5.0 software (Dach et al., 2007).

In result, the coordinates in the ITRF2005 (International Terrestrial Reference Frame, Altamimi et al., 2007) were obtained. For better interpretation purposes (*XYZ* reference frame is not suitable for such interpretations), the coordinates were transformed into the *North-East-Up* coordinates. The velocities were determined in two ways:

- using CATREF (Combination and Analysis of Terrestrial REference Frames) software (Altamimi et al., 2004);
- using robust estimation after recognition made on the time series of geocentric coordinates.

Additionally, the station coordinates were determined in the ETRF (European Terrestrial Reference Frame).

Coordinates and velocities (realization of ETRS'89 - European Terrestrial Reference System) were determined using CATREF. This software was created to combine different space and satellite techniques (GNSS, SLR – Satellite Laser Ranging, VLBI – Very Long Baseline Interferometry and DORIS – Doppler Orbitography and Radiopositioning Integrated by Satellite) and to determine global reference frames (mostly ITRF). Terrestrial Reference Frame is constructed by CATREF independently for individual epoch. For each TRF it may be written:

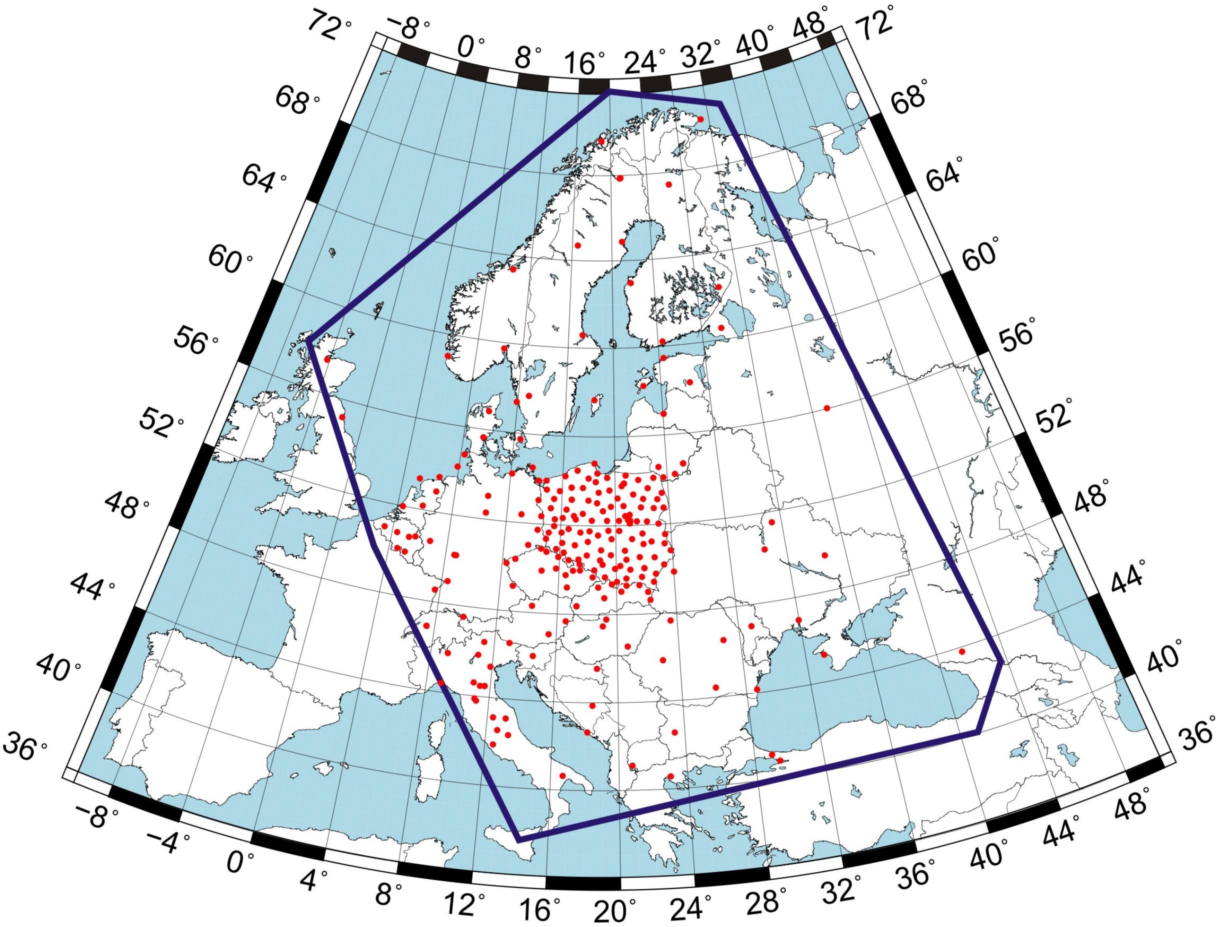

Fig. 2 Layout of the permanent GNSS sites used for data adjustment.

$$X_R = X_C + T + D \cdot X_C + R \cdot X_C \rightarrow X_R = X_C + A \cdot \theta$$
$$\dot{X}_R = \dot{X}_C + \dot{T} + \dot{D} \cdot X_C + \dot{R} \cdot X_C \rightarrow \dot{X}_R = \dot{X}_C + A \cdot \dot{\theta} \quad (1)$$

where θ stands for vector of Helmert transformation parameters calculated by the means of the least squares method, X_R is a reference solution and X_C – combined solution. T, D and R mean translation, rotation and scale, respectively. A means matrix of observations equations.

To express X_C in the same frame as X_R (θ=0), it is assumed that:

$$B\left(X_R - X_C\right) = 0 \quad (2)$$

where B is:

$$B = (A^T P A)^{-1} A^T P$$

P means a weighting matrix. After choosing reference TRF (X_R), minimum constraints (MC) equations for selected sites (in this case only translation parameters) are appended to the combined solution.

The authors used CATREF to combine weekly SINEX (Solution Independent Exchange Format) files (results of GNSS data processing in BERNESE 5.0 software) with variance-covariance matrices in order to determine the cumulative solution (by means of coordinates and velocities). The solution is referred to the epoch 2005.

Determination of the velocity field was also performed using robust estimation, because the least squares method has its disadvantages, e.g. the small robustness for the large errors values (stand-off values), that have significant impact on the estimated parameters values. This disadvantage was removed in some less disseminated methods, e.g. robust estimation, which uses stand-off values robust parameters to estimate the model. Several methods of estimating the robust parameters were developed.

They can be divided in three groups (Kontny, 2003):

- *M*-estimators, based on the estimation with the most reliable methods, used most often in geodesist elaborations; it was proven that the most robust *M*-estimator is the maximum likelihood estimator (ρ), described by (Huber, 1981):

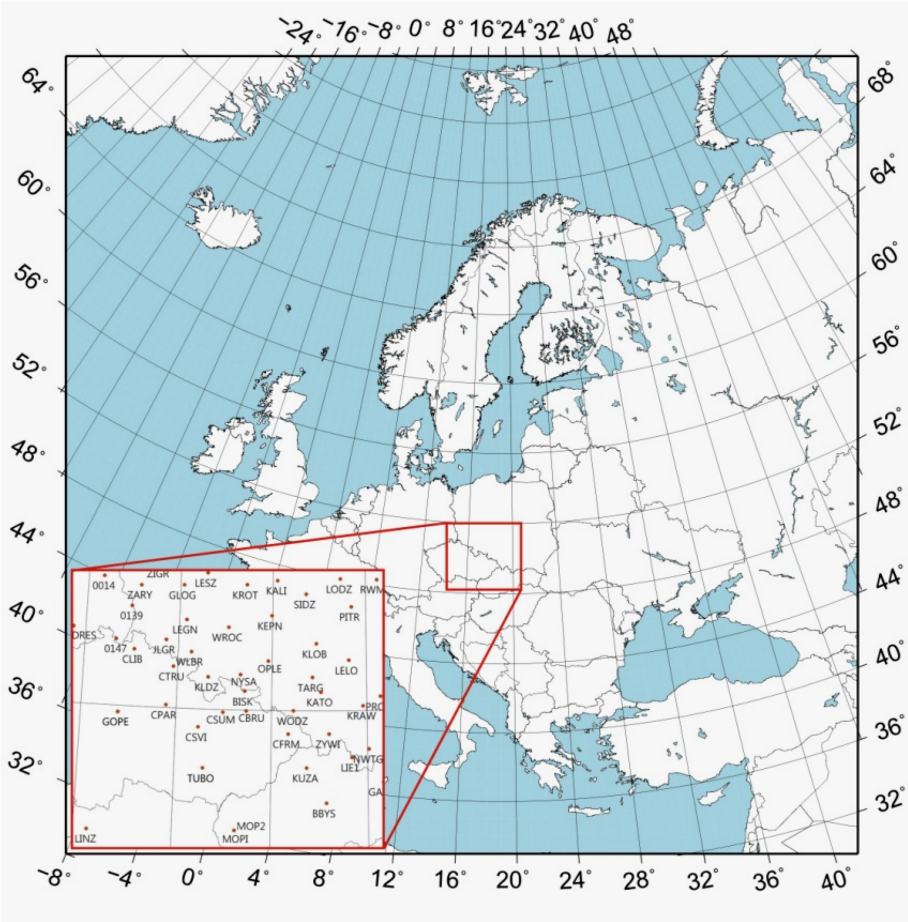

Fig. 3 Layout of the permanent GNSS sites in the Sudeten and adjacent areas.

$$\rho(t) = -\log f(t) \qquad (3)$$

where f is the assumed density of the untranslated distribution;

- *L*-estimators based on linear combinations of sequence statistics, e.g. LMS – least median squares method (Hubert and Rousseeuw, 1997);
- *R*-estimators based on test of distributions consistency, e.g. Wilcoxon test (Press et al., 1993).

M-estimators $T_n = T_n(x_1,...x_n)$ where defined as the values that minimize term $\sum_{i=1}^{n}\rho(x_i - T_n)$. Generally, the M_r estimators are defined by the posibility to minimize $\sum_{i=i_1}^{i_r}\rho_r(x_I - T_n)$, where ρ_r is a continuous convex real-valued function of a real variable r, tending to +∞ as $r\to\pm\infty$ and summing is extended to $\binom{n}{r}$ components $I=\{i_1,...,i_r\}\subset\{1,2,...,n\}$, containing r elements, while $(x_I - T_n)$ is a short form of $(x_{i_1} - T_n,...,x_{i_r} - T_n)$.

The minimization of $\sum_{i=i_1}^{i_r}\rho_r(x_I - T_n)$ is often realised by differentiation of ρ and solving equation $\sum_{i=1}^{n}\psi(x_i) = \frac{d\rho(x)}{dx} = 0$, provided that ρ is differential.

Function $\psi(x_i)$ is called the function of influence and contains partial residuum derivatives of $\rho(x)$ terms. The weighting function $w(x_i)$ is defined by the division of the influence function by residuum:

$$w(x_i) = \frac{\psi(x_i)}{x_i} \qquad (4)$$

The amendments v that are to be entered to the observations, to obtain their real values, are never given at the beginning of the calculations. The real values are estimated by the choice of the suitable function $\rho(x_i)$, and then by using the iteration of the least squares method. The iteration process is repeated until the stabilization of the solution is reached and the stand-off observations have no influence on the received values due to assigning to them the weights of values close to zero. The weighting function $w(x)$ for the normal errors distribution takes the form of (Huber, 1981):

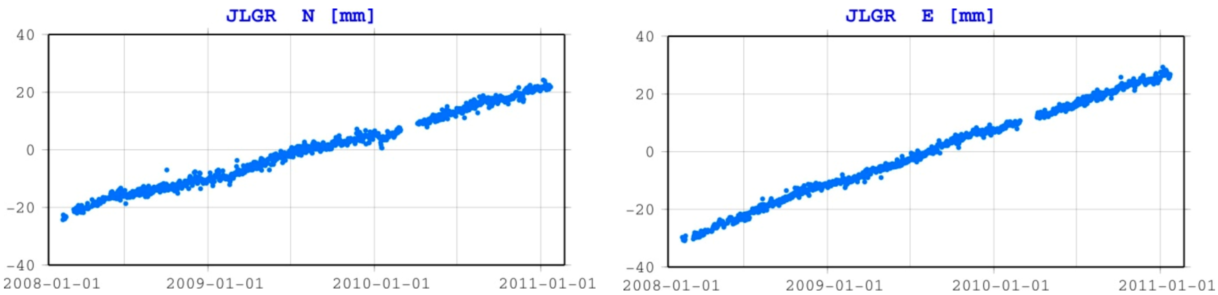

Fig. 4 Time series of JLGR (Jelenia Góra, PL) GPS site.

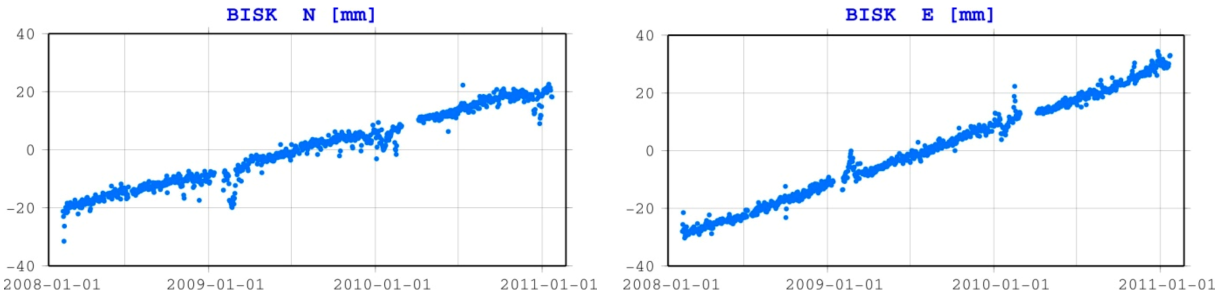

Fig. 5 Time series of BISK (Zlaté Hory, CZ) GPS site.

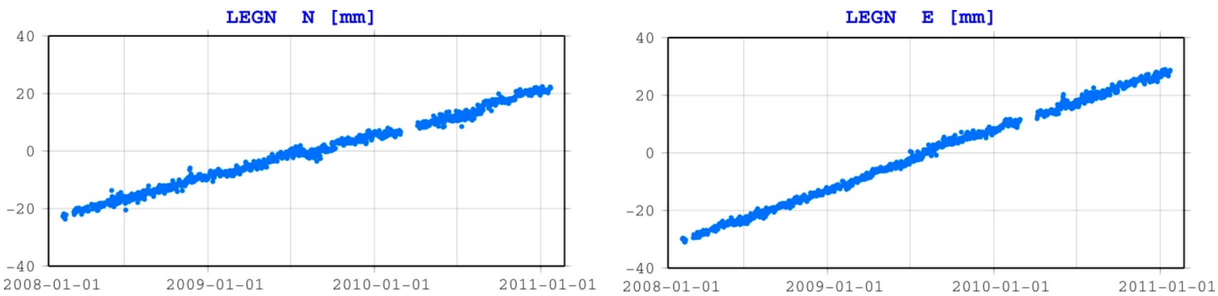

Fig. 6 Time series of LEGN (Legnica, PL) GPS site before (left) and after trend removal.

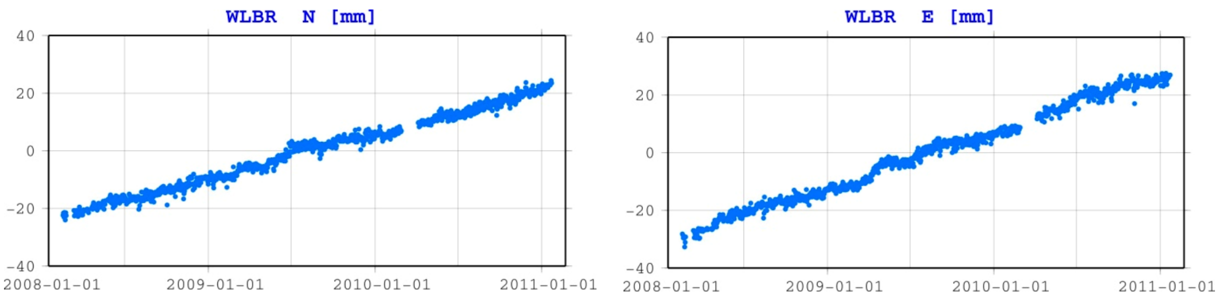

Fig. 7 Time series of WLBR (Wałbrzych, PL) GPS site.

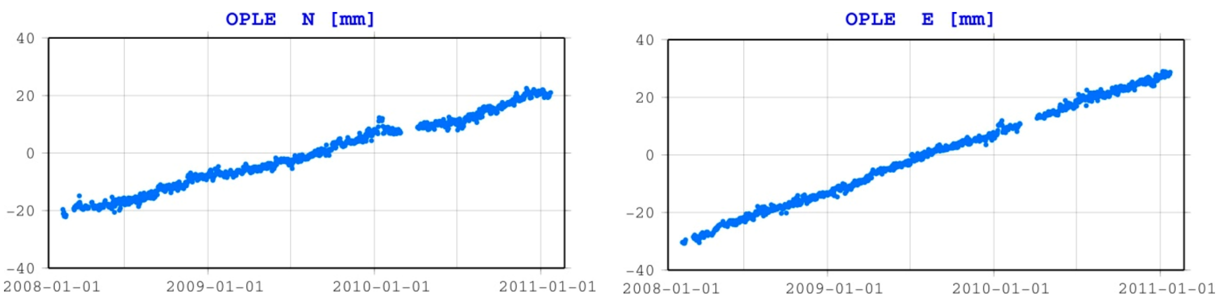

Fig. 8 Time series of OPLE (Opole, PL) GPS site.

$$w(x)=\begin{cases}1, |x|<c\\ \dfrac{c}{|x|}, |x|\geq c\end{cases} \quad (5)$$

where c is an assumed error, that is not to be exceeded by the given value.

The measure of efficiency of the robust estimation method is the so called break point, i.e. the ratio of the minimum number of observations with the stand-off errors to the number of all observations for which the estimation breaks, i.e. the estimation error may be freely large (Kontny, 2003).

In general, the effects which could decrease the velocity estimation reliability may be grouped into the following categories:

- annual oscillations effects (e.g. JLGR site, Fig. 4 and OPLE site, Fig. 8);
- seasons-related changes (winter or summer) (e.g. BISK site, Fig. 5);
- jumps (e.g. LEGN, Fig. 6);
- non-linearity;
- noises (e.g. WLBR site, Fig. 7).

Issues related to the stability of ASG-EUPOS permanent stations were previously analyzed and presented in the papers by Figurski et al. (2010) and Bogusz et al. (2011). Figures 4 through 8 present time series of the selected permanent sites (North and East components) in which the effects mentioned above reflect. Statistically, 9 of 19 sites located in the considered area revealed the described effects in North or East components.

Annual oscillations shown in Figures 4 and 8 may be explained by the real geophysical effects or artefacts of the GPS system. Periodic effects associated with the seasons, particularly evident in the state of atmosphere or hydrosphere (e.g., groundwater level and soil moisture variations) might be responsible for their existence. Artefacts manifested by the existence of annual sinusoidal changes may come from short-term unmodeled or mismodelled effects. Previous studies of the authors (Bogusz and Figurski, 2012) confirmed the existence of such effects in the K1 and K2 frequencies. They do not come from the gravitational interactions, but from such phenomena as reflections, residual orbital errors or repeated period of GPS satellites. It was proved that unmodelled diurnal and semidiurnal tidal displacements could propagate to spurious longer signals existing in the daily GPS solutions (Penna and Stewart, 2003). Deviations from the trend shown in Figure 5 are frequent disturbances observed in the geodetic coordinates' time series. They are mainly caused by heavy snowfall (loading effect), ground frost in the winter and the impact of local hydrosphere (rainfalls) during the summertime. Accumulation of snow and ice on the radome and antenna should also be mentioned (Johansson et al., 2002). Among the possible causes, the effect of the satellite signal reflection from snow (amplification of multipath) has to be mentioned. An example of the analysis of factors causing anomalies in coordinate time series of the Polish GPS permanent stations was described, among others, in the paper by Bosy and Kujawa (2002).

Finally, the horizontal velocities in the North-South and East-West direction with standard deviations were calculated using robust estimation for comparison with those determined by CATREF. Figure 9 presents determination of the trend line dependent on the weight of a single coordinate.

Table 1 presents results for the sites located in the considered area. Determinations using both methods are presented in columns referred to ITRF2005 (superscript C means CATREF, R – robust estimation, dash – no determination from time series was performed). The maximum difference for the *North* component is 0.7 mm/y, minimum 0.1 mm/y, average 0.3 mm/y, the *East* component: 0.7, 0.0 and 0.2 mm/y, respectively. The extreme values were found for WROC and GOPE sites, but their time series do not reveal the changes described previously. Authors could not find explanation for that fact. Robust estimation for the ETRF time series was not performed.

Standard deviation of the trend line fitting in the time series are described by (Brockmann, 1997):

$$\sigma_V = \pm\sqrt{\frac{\sum_{i=1}^{n} p_i \cdot v_i \cdot v_i}{(n-2)\sum_{i=1}^{n}(t_i-t_0)^2}} \quad (6)$$

where:
n – number of epochs;
p – weight taken from robust estimation;
v – deviation from the trend line;
t_i – epoch of the position determination [years];
t_0 – zero-epoch.

Standard errors obtained for ETRF and ITRF velocities were exactly the same, so they are presented only with respect to the European frame. These are too optimistic, because the white noise error model is applied. For better evaluation of the reliability of velocities the coloured noise approach has to be implemented. Estimated uncertainty could be 3-4 times larger when applying coloured noise (Lidberg et al., 2010). However, the assessment of the reliability of the velocity vectors should be performed not only with respect to statistical parameters, but mainly in connection with the geological situation in the region. Figures 10 and 11 present local velocity field of the considered area in the ITRF2005 and the ETRF2000(R05) frames, respectively. For interpretation purposes the geological structure was also shown.

Table 1 Horizontal velocities (mm/y) of the selected sites located in the vicinity of the Sudeten Mts. in the North-East description. Coordinates are expressed in ETRF2000 (R05).

Site	Name	X [m]	Y [m]	Z [m]	ITRF2005				ETRF2000 (R05)			
					V_N^C	V_N^R	V_E^C	V_E^R	V_N^C	m_{VN}	V_E^C	m_{VE}
JLGR	Jelenia Góra	3878289.745	1092566.852	4928217.849	15.2	15.0	19.4	19.4	0.3	0.03	-1.0	0.07
KLDZ	Kłodzko	3900141.957	1166529.637	4894068.337	14.5	14.3	20.2	20.3	-0.3	0.03	-0.4	0.07
LEGN	Legnica	3846687.760	1114288.333	4947658.625	15.1	14.8	20.3	20.4	0.3	0.03	-0.1	0.07
NYSA	Nysa	3882469.846	1211762.860	4896966.235	15.2	14.9	20.1	20.0	0.5	0.03	-0.7	0.07
OPLE	Opole	3854338.105	1246354.206	4910366.308	14.7	14.4	20.1	20.1	0.1	0.03	-0.7	0.06
WLBR	Wałbrzych	3880292.346	1133211.863	4917654.523	15.5	15.2	19.4	19.5	0.7	0.03	-1.1	0.07
WROC	Wrocław	3835751.614	1177249.742	4941605.044	14.8	14.1	19.5	20.0	0.1	0.04	-1.0	0.01
CBRU	Bruntal	3919707.996	1233461.344	4862456.354	15.1	14.9	20.4	20.1	0.4	0.04	-0.6	0.04
CLIB	Liberec	3903195.519	1050232.259	4917869.634	15.4	-	19.2	-	0.5	0.05	-1.1	0.02
CPAR	Pardubice	3949919.084	1116467.041	4865832.540	15.0	-	21.1	-	0.1	0.03	0.5	0.06
CSUM	Šumperk	3931871.957	1200665.084	4860558.934	15.3	15.1	20.2	20.1	0.4	0.04	-0.6	0.04
CSVI	Svitavy	3959346.539	1170655.496	4845811.295	14.7	-	20.5	-	-0.1	0.09	-0.3	0.05
CTRU	Trutnov	3904532.785	1112857.856	4903151.716	15.5	15.3	19.6	19.5	0.7	0.05	-0.8	0.01
BISK	Zlate Hory	3898946.251	1223993.138	4881826.234	14.4	14.2	20.0	20.1	-0.3	0.03	-0.8	0.07
GOPE	Pecny	3979316.434	1050312.252	4857066.895	15.2	15.3	20.0	19.3	0.1	0.01	-0.5	0.03
0139	Rothenburg	3856023.694	1030742.706	4958467.532	14.7	-	19.4	-	-0.3	0.03	-0.8	0.09
0147	Zittau	3899907.511	1020318.396	4926621.086	15.3	-	20.2	-	0.3	0.00	0.1	0.14
CFRM	Fridek-Mistek	3924573.172	1301971.022	4840464.493	14.6	14.5	19.9	19.7	0.0	0.04	-1.3	0.03
WODZ	Wodzisław Śl.	3896698.776	1300673.699	4863029.361	16.9	16.6	20.7	20.6	2.3	0.03	-0.4	0.06

DISCUSSION OF THE RESULTS

Estimated values of the horizontal velocities of the ASG-EUPOS stations in the ITRF2005 reference frame (Fig. 10) do not differ from the generally known model of the EURA plate movement (e.g. Legrand et al., 2006). Differences with respect to other published results (e.g. Hefty, 2007; Legrand et al., 2006; Lidberg et al., 2007) are seen at the level of the intraplate velocities (Fig. 11). There may be various real causes of these discrepancies. Anomalous velocity vectors of some stations (KATO and WODZ) result from their location in the zone of influences of anthropogenic deformations (mining). Velocities of a few of other stations (e.g. BISK, JLGR, LEGN, OPLE, WLBR) may be biased by the influence of the unmodelled effects, described in details above. The GPS solution does not contain atmospheric loading corrections, which have to be included at the stage of GNSS data processing giving some improvement (Tregoning and van Dam, 2005). Among possible factors introducing limitations in the velocity solution, the following have to be mentioned: GPS satellite block type (Ge et al., 2005), higher order ionospheric terms (Kedar et al., 2003), phase center variations, mapping functions and foundation of the antennas.

Concerning all the effects mentioned in this publication, velocity of the station should be determined using a formula containing $6+n_g$ parameters for each component (Nikolaidis, 2002):

$$y\left(t_i\right) = a + b \cdot t_i + c \cdot \sin\left(2\pi \cdot t_i\right) + d \cdot \sin\left(2\pi \cdot t_i\right) + \\ + e \cdot \sin\left(4\pi \cdot t_i\right) + f \cdot \sin\left(4\pi \cdot t_i\right) + \sum_{j=1}^{n_g} g_j \cdot H\left(t_i - T_{gj}\right) + v_i \tag{7}$$

where t_i are epoch time in years for the daily solutions, and v_i denote noise. Seasonal variations are modeled by estimating the amplitude of annual and semi-annual sine functions, the position shifts are described by the Heaviside step function (*H*), but sudden jumps related to snow should be concerned using robust estimation. It is worth mentioning that in our case semi-annual oscillations were not found.

Generally, different orientation of velocity vectors than in the Hefty's determination results mainly from the way of the reduction of the ITRF2005 velocities to the intraplate velocities (transformation to the ETRF2000 instead of using the APKIM2000 geokinematic model used by Hefty). It is similar in case of the model described in (Legrand et al., 2006), where the reduction of the velocities was done by means of subtracting the components of the plate rotation derived from the EPN data located on the rigid part of the tectonic plate. Hence, the way of determining the intraplate velocities (from geocentric ITRF velocities) is crucial for the resulting image of the horizontal velocity field.

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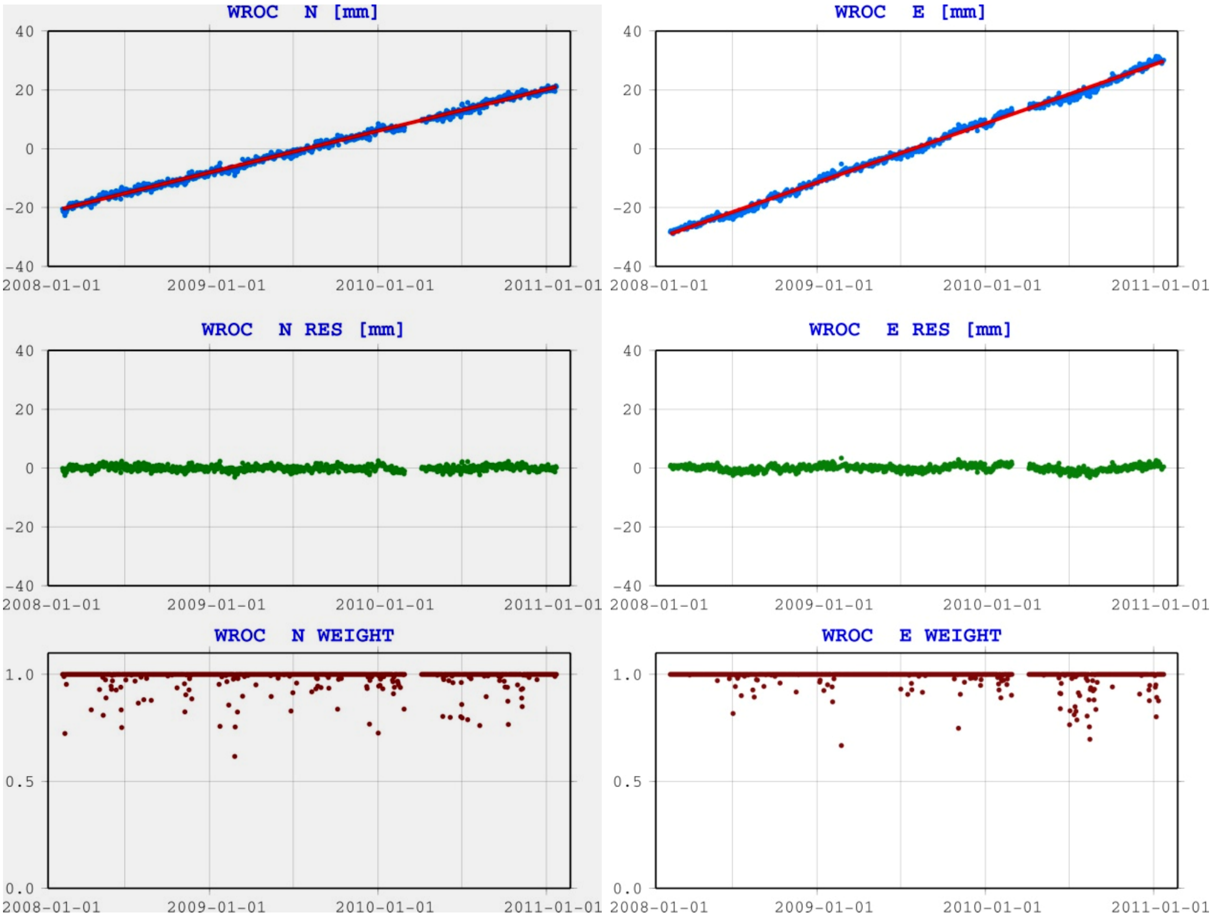

Fig. 9 Trend line (velocity) determination for WROC (Wrocław, PL) GPS site. From top: time series and trend line, residuals after trend line removal and weights for particular coordinates determined using robust estimation.

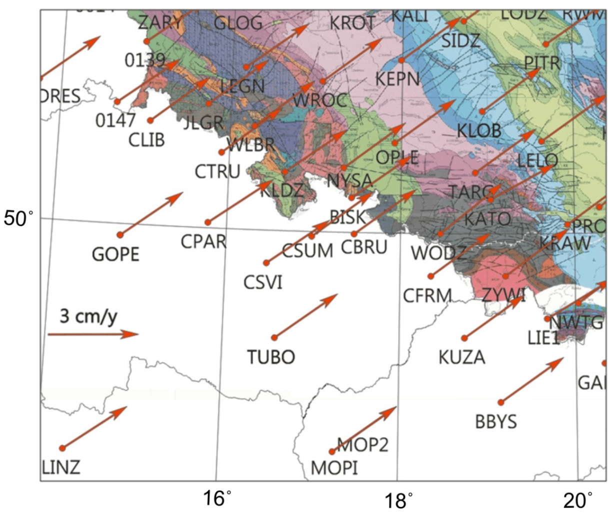

Fig. 10 Velocities in the ITRF2005 reference frame.

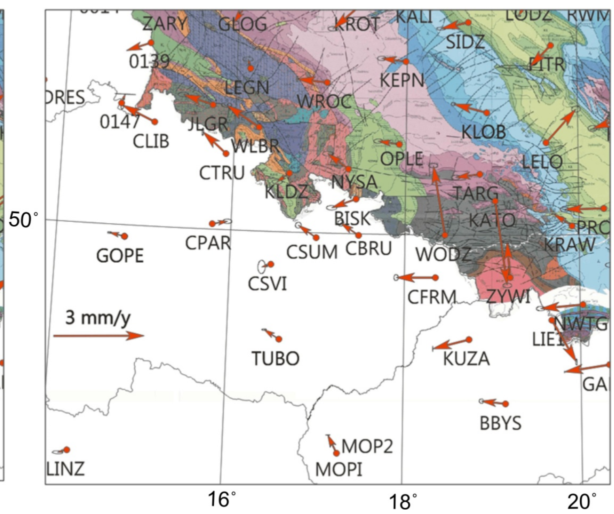

Fig. 11 Intraplate velocities in ETRF2000(R05) reference frame with uncertainties in the shape of ellipses.