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UNMODELLED EFFECTS IN THE HORIZONTAL VELOCITY FIELD DETERMINATION: ASG-EUPOS CASE STUDY

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ABSTRACT. Recent space and satellite technologies offer great opportunities to determine crustal movements in the single, global reference frame. The densification of the global network through local area networks leads to increase the resolution of modelled deformations both horizontal and vertical. However, the credibility of the obtained velocity field is limited by several factors associated with unmodelled (or mismodelled) effects at the stage of GNSS data adjustment. Some of them are periodic (the influence of local atmospheric or hydrological impacts), some temporary (natural or anthropogenic seismicity) or related to local influences (snow load or effects associated with the freezing of the ground). This paper presents the usefulness of ASG-EUPOS time series for determination of the regional velocity field. The system has been operating since mid-2008, so the velocities obtained through the processing of 3-year time series are supposed to be reliable. The paper also presents comparison of the velocity determinations to the geological NNR-NUVEL-1A and geodetic APKIM2005 models.
Keywords: GPS, local velocity field, ASG-EUPOS.

1. INTRODUCTION

Increasing number of permanent stations performing observations in the navigation satellite systems (GPS or GLONASS) enlarges the quantity of possible application both to the geophysical and geodynamic research. The basic results of satellite data processing are the coordinates and their changes over time (velocities). The results presented in this publication will state the basis for the implementation of the planned research tasks in two research projects of the Ministry of Science and Higher Education. Within first of them it is planned to develop a deformational model of the Earth's surface using Finite Element Method on the basis of the results of satellite observations' advanced processing (Bogusz et al., 2011b). The second one is a project for building the modules supporting real-time services of ASG-EUPOS system, where geodynamical module is an interpretative part (Figurski et al., 2011).

Many scientific papers deals with the problem of reliable velocity determinations using GPS observations. At the beginning (90s) due to the low density of permanent stations epoch campaigns were organized, such as CEGRN in Europe (Central European GPS Geodynamical Reference Network). The geodetic coordinates time series determined in subsequent measurements were analysed to study the local geodynamics. Grenerczy et al. (2000)

calculated both the strain field and the intraplate velocities by using data from the first phase of CEGRN project. Hefty (2005) determined the velocity field from observations conducted within the CERGOP (Central European Regional Geodynamic Project) which was realised in 1994-1997 and its follow-up CERGOP-2 using the data from annual and bi-annual epoch GPS campaigns.

He evaluated new velocity field which was based on the data set enlarged by inclusion of 2003 CEGRN campaign in relation to the previous determinations (Becker et al., 2002). Hefty (2007) demonstrated a method of combination of regional velocity field into a homogeneous system consisted with ITRF2000 utilizing evaluation of the Euler pole and angular rotation. The intraplate velocities were obtained by reducing with APKIM2000 model and the final set was comprised of the horizontal velocities at 192 sites. Nowadays the permanent GPS sites can be successfully used for studies of dynamic changes (Hefty et al., 2005). But the determination of the velocity field has to be followed by the analysis of the periodic and a-periodic terms in the time series (e.g. Kenyeres and Bruyninx, 2009).

2. ASG-EUPOS

Multifunctional precise satellite positioning system ASG-EUPOS was established by the Head Office of Geodesy and Cartography in 2008 (Bosy et al., 2007). The system consists of three main elements: reference stations, management centre and users segment. According to the agreement between Military University of Technology and the HOGC, the Centre of Applied Geomatics makes independent (apart from the Head Office) processing of the data aimed at monitoring of the reference frame stability.

3. DATA AND PROCESSING

We have considered observations from over 310 ASG-EUPOS and EPN (EUREF Permanent Network) sites. Their distribution is presented in Fig. 1.

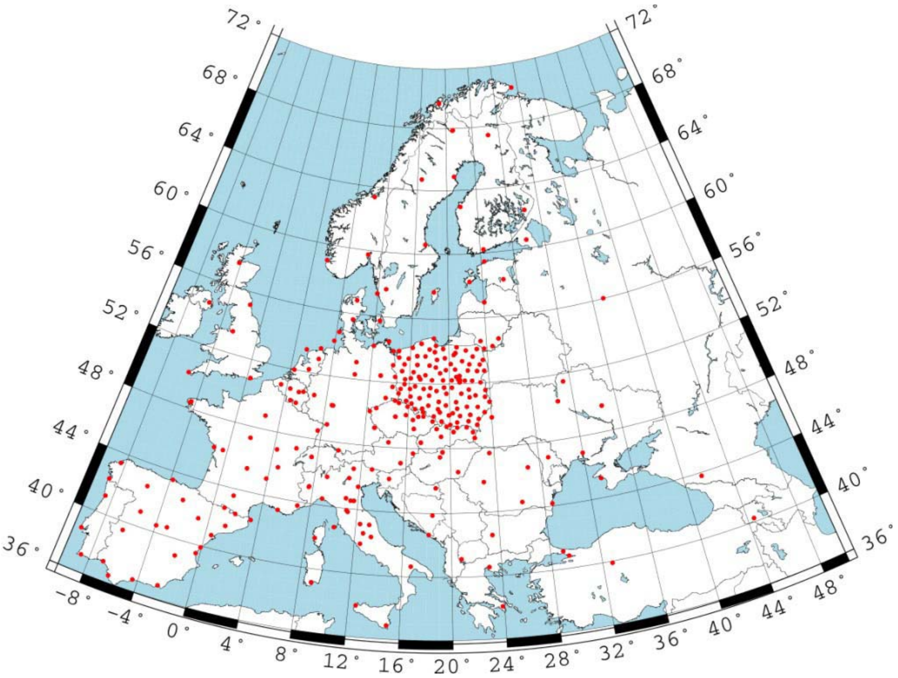

Fig. 1. Distribution of the permanent GNSS sites considered to the data adjustment

Determination of the time-series was made by using normal equations from EPN and ASG-EUPOS, 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 of 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 solution).

As the results coordinates in ITFR2005 reference frame (Altamimi et al., 2007) were obtained. For better interpretation purposes (*XYZ* reference frame is not suitable for interpretations) the differences *dX*, *dY* and *dZ* from the reference position (X_0, Y_0, Z_0) were transformed into *North-East-Up* coordinates.

4. UNMODELLED EFFECTS

There are several unmodelled or mismodelled effects of different origin which could be observed in the GPS time series (coordinates). Not completely modelled gravitational excitation, displacements due to seasonal polar motion or displacement due to the loading cause residual oscillations in the time series. From the other side there are many influences of hydrological origin not modelled even in the advanced GPS data processing. Moreover there are many artificial oscillations related to the GPS system itself. The seasonal errors from satellite orbital models, atmospheric models, water vapour distribution models, phase centre variation models, thermal noise of the antenna, local multipath, and snow cover on the antenna all cause apparent variations in estimated site positions (Dong et al., 2002).

ASG-EUPOS time series reveal the whole spectrum of such influences (Bogusz et al., 2011a). It was pointed out that the reliability of such determinations (and interpretation in consequence) suffers from the effects which were not modelled at stage of data processing. Previous research of the authors showed residual oscillations in the coordinates which has of long and short-period character (Figurski et al., 2010; Bogusz and Hefty, 2011). Penna and Stewart (2003) simulated GPS data and demonstrated that unmodelled diurnal and semidiurnal tidal displacements propagate to spurious longer signals (annual) existed in the daily GPS solutions. Also the effects from the GPS constellation repeat orbit can introduce the artefacts to the daily solutions. But from the other side annual signal in GPS time series could be the real effect of hydrosphere and atmosphere. Separation of these effects is almost unenforceable. Fig. 2 presents an example of long period oscillations in the time series (*North-East* components) of one of ASG-EUPOS site.

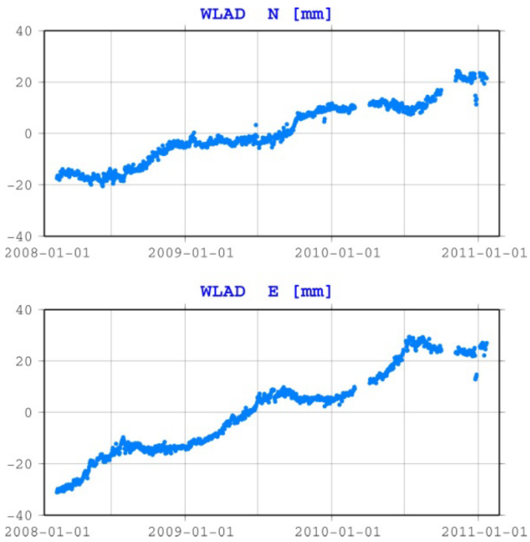

Fig. 2. Annual oscillation in the *North-East* time series of WLAD (Władysławowo, PL) site

From the other side there are many unforeseen changes in the GPS time series which are related do winter or summer phenomenon (extreme snow, frost or rain). Most of these effects are related to wintertime (snow coverage, freezing of the ground), but some of them are also observed during summertime (Fig. 3).

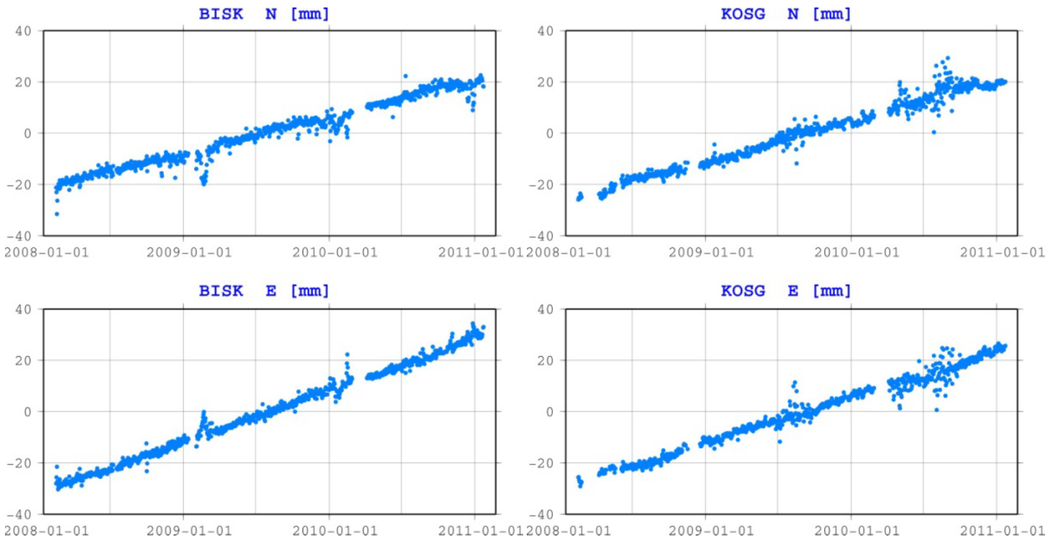

Fig. 3. Seasons-related changes in the time series of BISK (Zlate Hory, CZ - left) and KOSG (Kootwijk, NL - right) sites

These influences affect time series in the unexpected way which is very difficult for modelling. Figs. 4 to 6 present time series with such impacts.

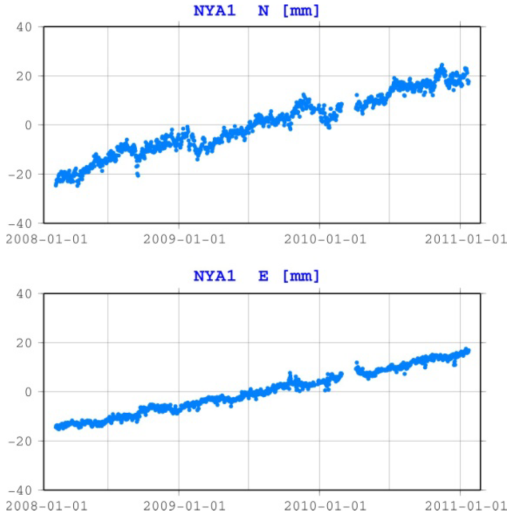

Fig. 4. Jumps observed at the NYA1 (Ny-Alesund, N) GPS site

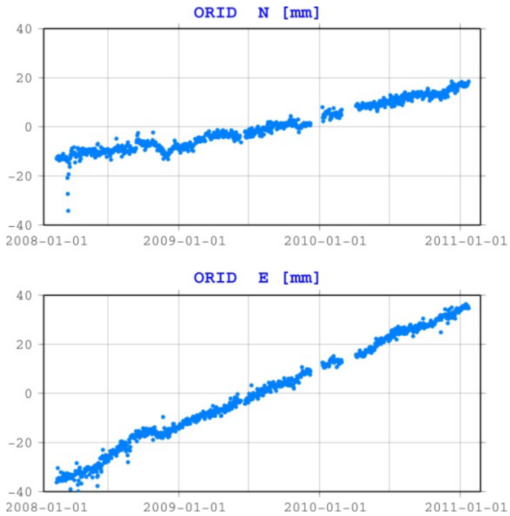

Fig. 5. Non-linearity observed at the ORID (Ohrid, MK) GPS site

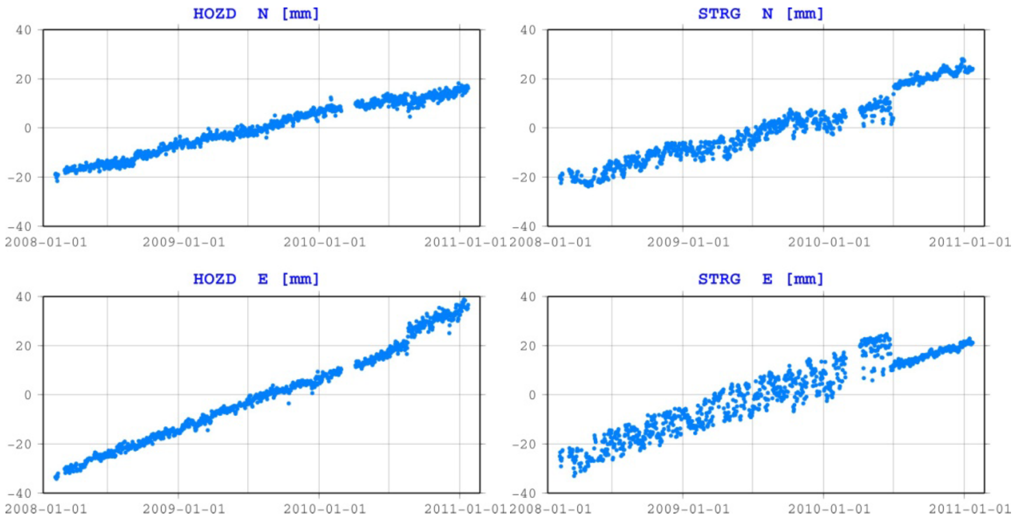

Fig. 6. Noises observed in the HOZD (Horyniec Zdrój, PL) (left) and STRG (Starogard Gdański, PL) (right) GPS sites

Unexpected changes of the time series presented in Figures 4-6 are difficult to explain and often require analysis of a broader context. Often they have no geodynamical background, such as noise at the STRG site, which were caused by the incorrect GPS antenna mounting. Hardware changes (receiver or antenna) could introduce artefacts to be processed GNSS observation, coordinate changes of the sites located in areas with extreme weather conditions (NYA1) involve a number of unmodelled effects, such as increased satellite signal reflections from snow cover apart from its geodynamical contribution.

5. VELOCITY FIELD

Determination of velocity field was 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. The above disadvantage was removed in less propagated methods, e.g. robust estimation, which to estimate the model use the parameters robust for these stand-off values. The several methods to estimate the robust parameters were developed.

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

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

$$\rho(t) = -\log f(t) \tag{1}$$

  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 agreement, 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 the equation $\sum_{i=1}^{n} \rho(x_i - T_n)$. Generally, the M_r estimators are defined by the possibility to minimize the equation $\sum_I \rho_r(x_I - T_n)$, where ρ_r is a continuous convex real-valued function of a real variable *r*, tending to $+\infty$ 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 the shortcut of $(x_{i_1} - T_n,..., x_{i_r} - T_n)$.

The minimalization of the equation $\sum_I \rho_r(x_I - T_n)$ is often realised by differentiation of ρ and solution of the 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 derivatives $\rho(x)$ terms residuum. The weight function $w(x_i)$ is defined by the division of the influence function by residuum:

$$w(x_i) = \frac{\psi(x_i)}{x_i} \tag{2}$$

The amendments v that are to enter to the observations, to gain 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 least squares method. The iteration process is repeated until the stabilization of the solution and the stand-off observations by giving them weights with the values close to zero have no influence on the received values. The weight function $w(x)$ for the normal errors distribution takes the form of (Huber, 1981):

$$w(x) = \begin{cases} 1, |x| < c \\ \frac{c}{|x|}, |x| \geq c \end{cases} \tag{3}$$

where c is the founded error, that is not to exceed by the given value.

The measure of efficiency the robust estimation method is the break point, i.e. the ration of the minimal value of observations with the stand-off errors to the number of all observations at which the estimation is breaking, i.e. the estimation error can be freely large (Kontny, 2003).

Fig. 7. presents results of robust estimation for BISK site, presented as one of the influenced by the seasons-related effects. The trend line determined using weight function is interpreted as velocity.

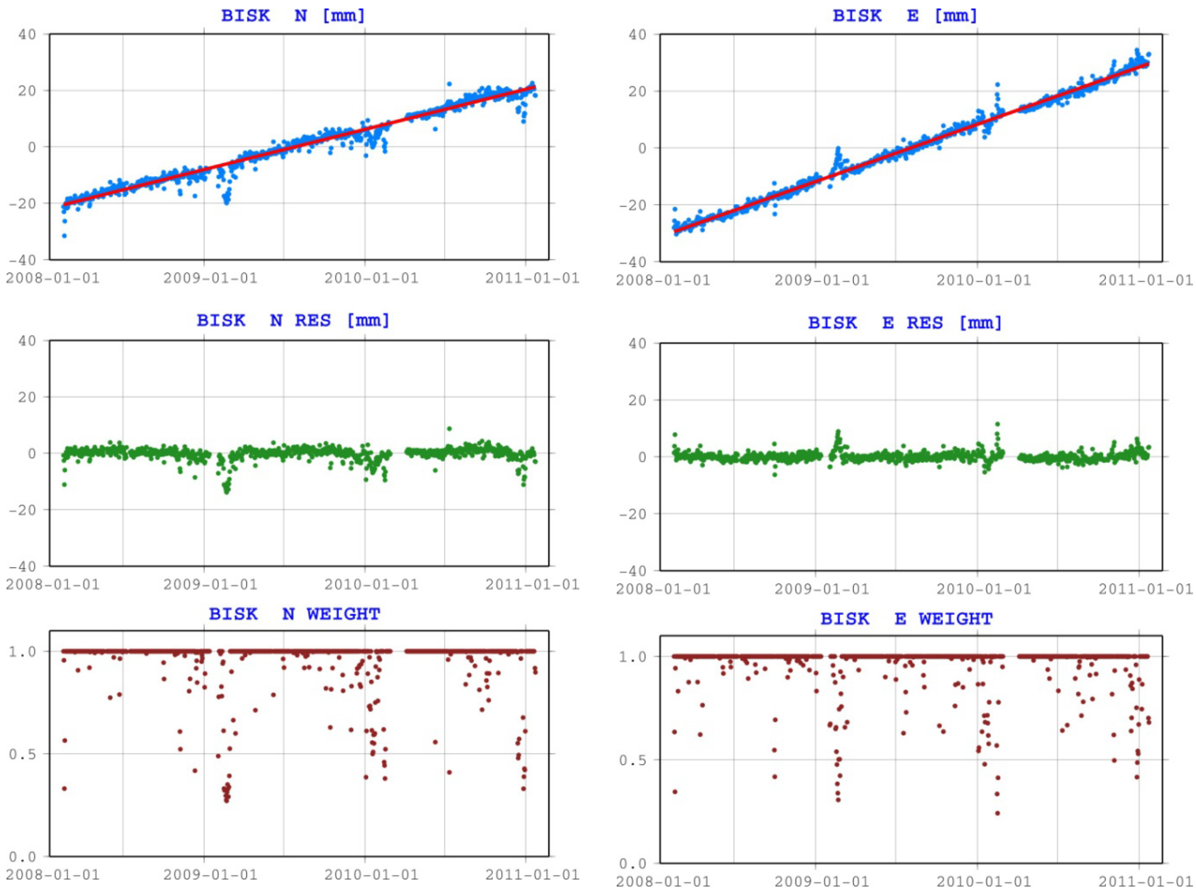

Fig. 7. Results of the robust estimation for BISK time series

Standard deviation of the fitting a line in the time series could be described by (Brockmann, 1997):

$$\sigma_V = \pm \sqrt{\frac{\sum_{i=1}^{n} p_i \cdot v_i \cdot v_i}{(n-2)\sum_{i=1}^{n} (t_i - t_0)^2}} \quad (4)$$

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

Table 1 presents determined velocities for selected GPS sites with standard deviations calculated using equation (4).

Table 1. Velocities (ITRF2005, [mm/y]) and standard deviations of the selected GPS sites.

V_E	V_N	σ_{VE}	σ_{VN}	Name
19.1	14.6	0.05	0.06	0014
19.0	14.6	0.05	0.09	0017
19.3	15.2	0.06	0.07	0022
18.5	14.4	0.07	0.08	0781
22.1	11.1	0.17	0.10	ALCI
24.5	6.9	0.05	0.05	AUT1
19.0	15.2	0.05	0.04	BADH
19.4	13.0	0.04	0.05	BART
20.5	14.2	0.05	0.06	BBYS
19.5	13.4	0.04	0.05	BIAL
20.5	13.6	0.04	0.04	BILG
20.1	14.2	0.05	0.07	BISK
20.0	13.8	0.03	0.04	BOGI

Using this method we can obtain reliable (from the statistical point of view) velocity field, but still very careful treatment of the obtained time series is indispensible. The regional velocity field for Poland (ITRF2005) is presented in Fig. 8 with error ellipses (Fig. 9).

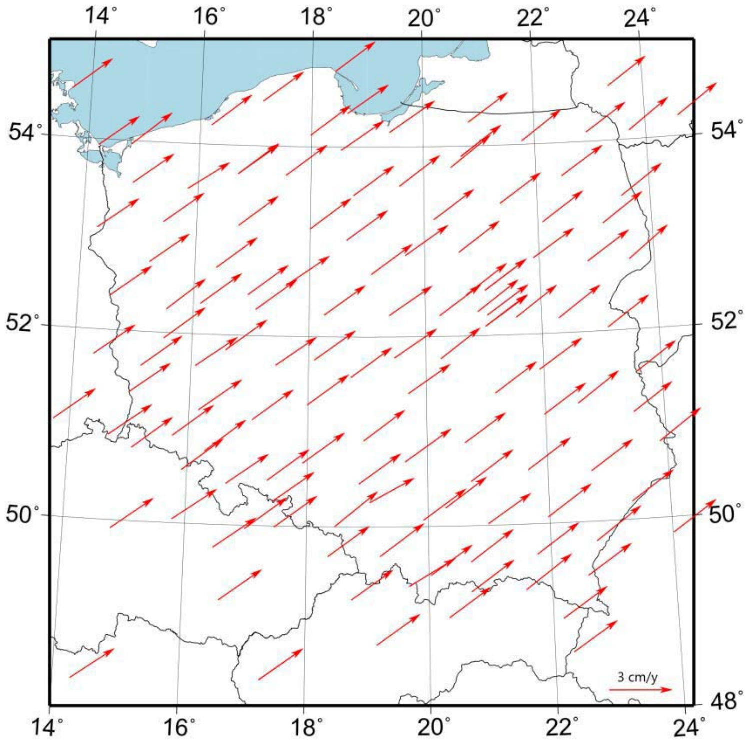

Fig. 8. Regional velocity field for Poland

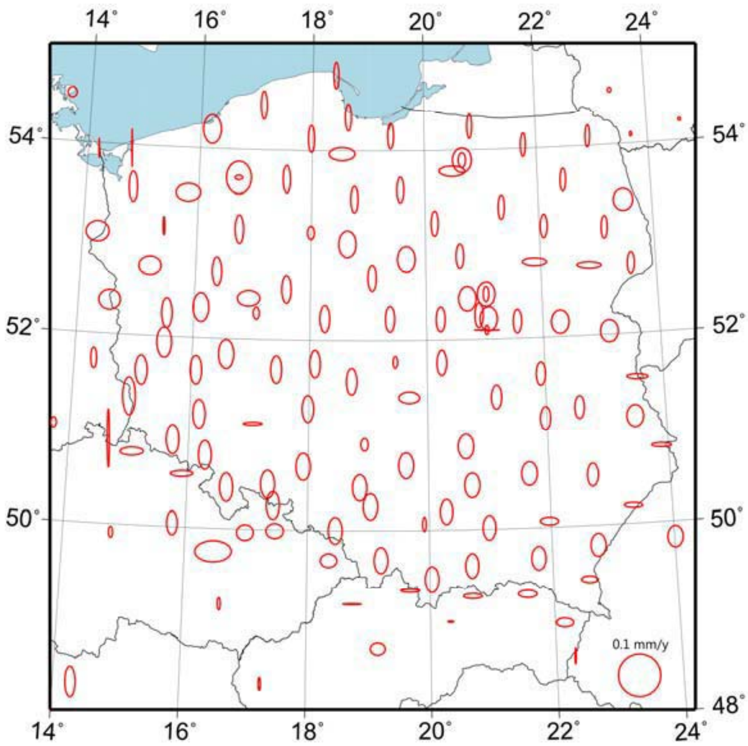

Fig. 9. Standard deviations of the velocity field determination

Figs. 10 and 11 presents residuals from NUVEL (De Mets et al., 1990) and APKIM2005 (Drewes, 2009) velocity models respectively.

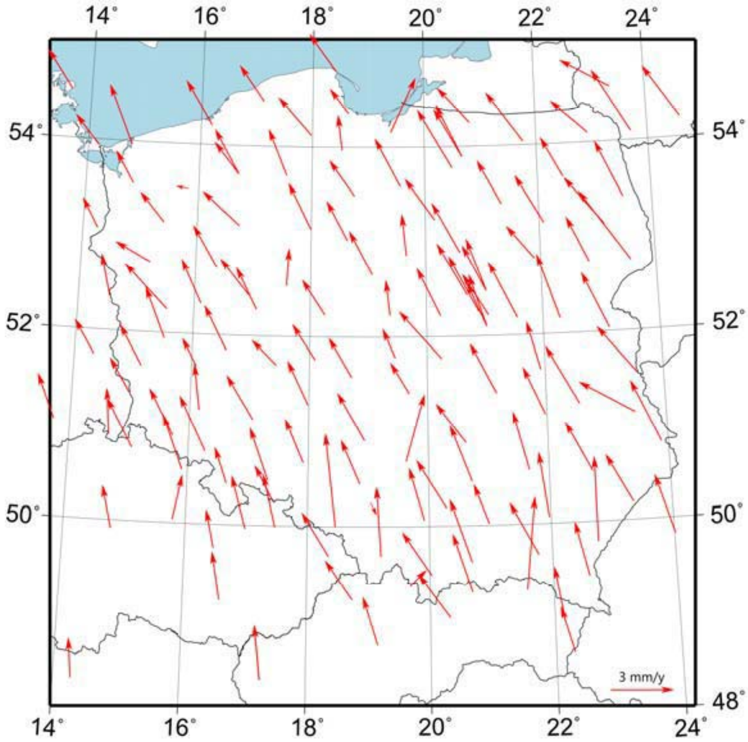

Fig. 10. Residuals from NUVEL model

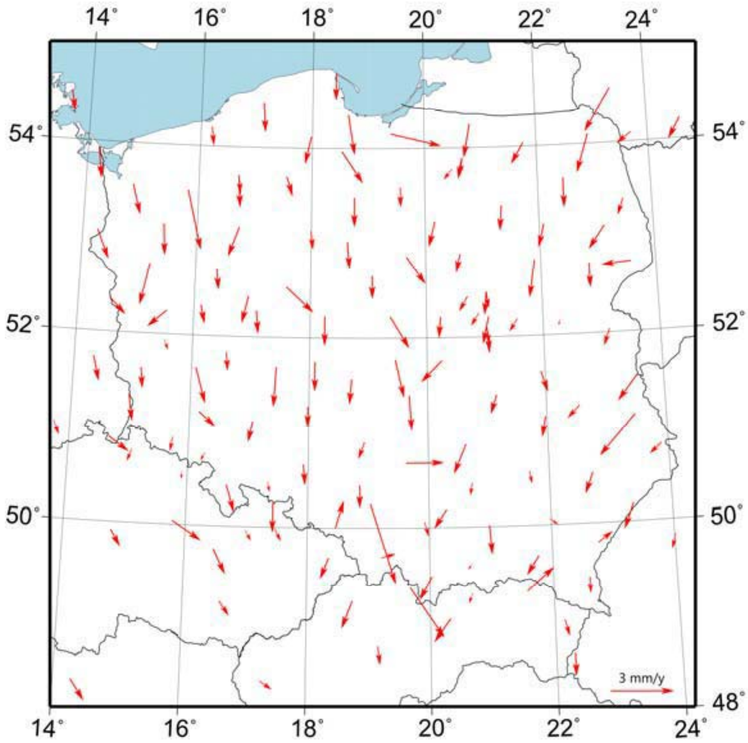

Fig. 11. Residuals from APKIM2005 model

Figures 10 and 11 show the problem intra-plate velocity determination. For a single processing of homogenous data (not epoch campaigns related to different reference frames) intra-plate velocity could be defined as the difference between determined and modelled one, with the fact that the choice of appropriate model seems to be extremely important for further interpretation. The authors have used only two models, although the most popular and recommended in geodynamic research: an older model NUVEL and the latest implementation of the model APKIM with geodetic observations included. It might be noticed slight differences in the magnitude of the intra-plate velocity vector, but mainly in the directions, which may already pose problems of interpretation. Moreover there are some sites (KATO, DRWP and LIE1) which velocities fit into NUVEL model, but do not into APKIM, opposite to the most of the other sites. However their anomalous behaviour (which is known for KATO for a long time) could only be accidentally resulting to small residuals with NUVEL1.

6. SUMMARY

Nowadays the reliable determination of horizontal velocities of permanent stations is an indispensable element in the correct realisation of the reference system. Kinematic reference frame is defined by the stations coordinates and velocities as well. In this paper the velocity field determined from the ASG-EUPOS station are presented, but the authors focus on the factors that could diminish the reliability of these determinations. It was shown that there are many unmodelled effects which diminish the accuracy of linear trend line determination, which is interpreted as the velocity. These factors may be related to the hydrosphere, winter or summer effects and non-linearity due to some local conditioning as well. Moreover there are some artefacts which are strictly associated with the GPS system itself and come from mismodelling of the short-period oscillations related mostly to K1 and K2 frequencies.

Due to these factors the determination of the velocity vectors have to be preceded by the insightful analysis of the time series of coordinates.

ACKNOWLEDGMENTS

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Maps and charts were drawn using the Generic Mapping Tool (Wessel and Smith, 1998).

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