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GNSS REFERENCE SOLUTION FOR PERMANENT STATION STABILITY MONITORING AND GEODYNAMICAL INVESTIGATIONS: THE ASG-EUPOS CASE STUDY

Karolina SZAFRANEK *, Janusz BOGUSZ and Mariusz FIGURSKI

Kaliskiego St. 2, 00-908 Warsaw, Poland, Centre of Applied Geomatics, Military University of Technology
**Corresponding author's e-mail:* kszafranek@wat.edu.pl

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ABSTRACT
The aim of this paper is to present the strategy of determination of the reference solution for the ASG-EUPOS (Active Geodetic Network – European Position Determination System) coordinate monitoring system. ASG-EUPOS is a network of permanent GNSS (Global Navigation Satellite System) stations controlled by the Polish Head Office of Geodesy and Cartography (HOGC), which main role is to realize the ETRS89 (European Terrestrial Reference System) in the territory of Poland. The Centre of Applied Geomatics (CAG) of the Military University of Technology (MUT) performs a control processing of the network and it is the leader of the ASG+ (the supporting modules for ASG-EUPOS system real-time services) project within which the coordinate monitoring system was developed. The coordinate monitoring is aimed to assess the actual performance of the GNSS stations and the reliability of the system and its services. The Polish realization of the ETRS89 is also controlled, where the deviation of the actual coordinates from the reference values are monitored. Furthermore, the monitoring enables the analysis of factors that degrade the individual GNSS stations and assess the solution stability which has impact on the quality of the determined geodynamic parameters.
The reference solutions (coordinates and their changes over time) were determined according to the recommendations of the IAG sub-commission for the European Reference Frame concerning densification of EUREF. The paper presents the determination of the reference cumulative solution and the results of the processing of a few years long series of GNSS observations. The analysis are performed by the Bernese 5.0 and CATREF software. The results consists of daily and sub-daily ASG-EUPOS reference solutions. They are also considered as input data for geodynamic studies to determine the horizontal and vertical velocity fields. Estimation of the individual station velocities is of crucial importance for the ETRF (European Terrestrial Reference Frame) reference frame maintenance to assess the compatibility of the current station position with its catalogue (reference) value and apply coordinate correction if necessary.

KEYWORDS: GNSS stations monitoring, reference frame, ASG-EUPOS

1. INTRODUCTION

The paper presents the strategy of determination of the coordinates and velocities for all stations belonging to the ASG-EUPOS (Active Geodetic Network – European Position Determination System) which constitute the EPN (EUREF Permanent Network) densification and realizes the ETRS89 (European Terrestrial Reference System) in the territory of Poland. According to the Regulation of the Minister of Administration and Digitalization concerning geodetic, gravimetric and magnetic networks, the main horizontal network in Poland is divided into the fundamental (EPN stations belonging to the ASG-EUPOS system) and base networks (among others the remaining stations of the ASG-EUPOS system). It means that the coordinates of the ASG-EUPOS system have to be determined with the highest reliability so that they may be used as a stable reference for geodetic measurements and geodynamic studies – the stations perform the reference functions enabling differential determination of position using the GNSS (Global Navigation Satellite System) technique. The Centre of Applied Geomatics (CAG) of the Military University of Technology (MUT), according to a cooperation agreement with the Head Office of Geodesy and Cartography (HOGC), performs processing of the data collected on ASG-EUPOS stations since June 2008, when the system was officially activated. The analysis is being done according to the recommendations of IGS (International GNSS Service) and EUREF (Bruyninx et al., 2009). The already published results, based on short series of observations (Figurski et al., 2009; Figurski et al., 2010a; Figurski et al., 2010b) may only be considered as preliminary because reliable velocities require at least 30-month observation series (Blewitt and Lavallée, 2002). The presented solutions are the results of 4-year series of observations processing. They were included as reference solution to the module of ASG-EUPOS coordinate monitoring realized within the ASG+ development project (Figurski et al., 2011) and they may be treated as the official coordinates of the ASG-EUPOS stations - they were provided to HOGC. There are plans for renewed periodic processing taking into consideration the recent observations as in the EPN (Kenyeres, 2009; Kenyeres, 2012). The paper also presents various applications of the obtained solutions – from realizing the ETRS89 system and the ETRF2000 maintenance to research using intraplate velocities for geodynamic purposes.

Currently (as of February 2013) the ASG-EUPOS system consists of 121 permanent GNSS stations, where 99 are located in Poland (Fig. 1). Eighteen of them are equipped with combined GPS+GLONASS receivers. Some of the stations were started already in 2006 and stations belonging to EPN even earlier, however, the official start-up of the system took place on 2 June 2008. The stations are serving as reference for differential measurements conducted both in real time (RTK – Real Time Kinematic) and in post-processing modes. The system is controlled by HOGC. According to the Polish law (Regulation of the Minister of Administration and Digitalization concerning geodetic, gravimetric and magnetic networks), the ASG-EUPOS system performs the role of the state base horizontal geodetic network.

The fundamental network consists of the reference stations of the ASG-EUPOS system, which belong to the EPN (15 stations). Their mean position errors may not exceed 0.01 m for horizontal components and 0.02 m for the ellipsoidal height (Regulation of the Minister of Administration and Digitalization concerning geodetic, gravimetric and magnetic networks). The base geodetic network consists, among others, of the remaining stations of the ASG-EUPOS system.

The new Regulation of the Council of Ministers concerning national reference system implements the PL-ETRF2000 and PL-ETRF89 geodesic reference frames realizing the national spatial reference system. The transfer of the PL-ETRF2000 system into the territory of Poland is realized by the ASG-EUPOS permanent stations. The ASG-EUPOS tasks include also frame maintenance by continuous or periodical control of the coordinates and velocities constancy.

The particular horizontal network is being established by GNSS technique using ASG-EUPOS stations as fiducial. Consequently all problems occurring at the reference permanent stations may have impact on the reliability of the newly established network stations. Determination of reliable coordinates of the ASG-EUPOS stations and maintaining the reference system is essential to keep the network consistency. Determination of solutions according to European standards is also important to keep the homogeneity of reference systems both for geodetic and geodynamic research conducted in the areas at state borders.

The main goal of the described research is to present the methodology of determination of all ASG-EUPOS stations coordinates, which ensure the most reliable ETRS89 realization in the territory of Poland and to propose a method of permanent control of current coordinates values. During the GNSS data processing EUREF recommendations were applied, but detailed strategy was matched to the ASG-EUPOS character (e.g. geographical location of Poland had an impact on the selection of the fiducial stations). The velocities determined by using the optimal strategy became a subject of many geodynamical studies.

The problem of automated permanent GNSS stations' coordinates monitoring using RegNet software package was described in (Biagi and Caldera, 2011). In Switzerland, an automated GPS network is operating by The Swiss Federal Office of Topography (Brockmann et al., 2006). It maintains the reference frame and serves for geodynamical and atmospheric researches. Processing made on a daily and hourly basis allows permanent monitoring of all stations coordinates and gives the information about exceeding the accuracy criterion between catalogue and estimated values. In some European countries (Germany, Switzerland, Austria, (Personal communications, 2012)) corrections of the coordinates are introduced as soon as discrepancies from the catalogue values are observed (a common criterion of 1 cm for the horizontal components and 2 cm for the vertical component is applied), however, this issue is still analyzed and there are no formal recommendations.

2. METHODOLOGY

The GNSS processing strategy was implemented according to the IGS and EUREF recommendations, and in most cases it was in agreement with previous studies conducted by the CAG of MUT (Kenyeres et al., 2009; Figurski et al., 2010a). Daily RINEX (Receiver Independent Exchange Format) data files, available at 30 seconds intervals from all the ASG-EUPOS stations were used. Only the GPS observations have been processed, because fairly few stations could collect GLONASS observations. The processing was done using the Bernese 5.0 software (Dach et al., 2007).

In order to model the refraction at low elevation satellites weighting of observations was introduced using the cos(z) mapping function (z is the zenith distance) and additionally an elevation mask of 3° was applied to reject observations below this mask. The processing were based on double differenced carrier phase observations and the L3 linear combination to eliminate the impact of the ionosphere. Absolute antenna (ground and satellite) PCV (Phase Center Variation) models were used when such calibrations were available. Relative calibrations or values corresponding to the given antenna type were taken in the remaining cases. All data were processed using models compatible with IGS08 (*igs08.atx* file) to avoid coordinates change at GPS week 1631 related to the change of reference frame (from IGS05 to IGS08; Rebischung et al., 2012). The „dry" component of the tropospheric delay was modelled by the Saastamoinen model with the Dry-Niell mapping function (a priori model). The „wet" component has been modelled by the Wet-Niell mapping function. The influence of the ionospheric delay was eliminated by the L3 ionosphere-free linear combination, but the global ionosphere CODE (The Centre for Orbit Determination in Europe) model was also introduced into the processing to increase the number of the fixed ambiguities. The method of ambiguity fixing was depended on the length of the baselines. For the longest baselines (up to 1300 km), the QIF (Quasi-Ionosphere-Free) method, for vectors up to 200 km – L5/L3, and for the shortest (up to 20 km) – the L1/L2 method was used. The final satellite orbits and the ERPs (Earth Rotation Parameters) from the global IGS network were used. Applying the same products as in the EPN processing enables to obtain homogeneous solutions. Models compatible with (Petit and Luzum, 2010) were used for computations.

According to (Legrand and Bruyninx, 2010) the reliability of the densification results increases with the number of fiducial stations and their geographical extent. The authors made several numerous tests using different configuration of reference stations to transfer ETRF2000 frame into Poland area and to choose the best strategy of ASG-EUPOS alignment to the EPN (Szafranek et al., 2013). Therefore 22 EPN stations from outside Poland and majority of EPN stations located in Poland (Fig. 2) were used for the processing. These stations belong to the class_A stations of the recent realization of the ETRS89 system and they are available on the EPN website (EPN_A_ETRF2000 _C1680 file of October 16, 2012 prepared by A. Kenyeres, FÖMI).

Daily and weekly solutions (geocentric *XYZ* coordinates in the IGS08) in SINEX (Solution Independent Exchange Format) files were obtained as the result of the processing. The daily solutions are mainly used for system monitoring, checking station

Fig. 2 EPN stations used as fiducial (datum for ASG-EUPOS solution).

performance and solution correctness, verifying strategy and models as well as analyzing the influence of the environmental factors. Since weekly solutions having greater stability and they are usually used for the reference frame realization, in this case they were also used for further processing. Furthermore, the analyzed data was used in a slightly different strategy for obtaining sub-daily solutions, applied mainly to models and strategy verification and to assessment of the individual station performance (Bogusz et al., 2010; Bogusz et al., 2011; Bogusz and Figurski, 2012).

Station coordinates and velocities corresponding to the realization of the ETRS89 reference frame were determined using the CATREF software (Altamimi et al., 2004). CATREF is mainly applied for combining results from various satellite and space techniques (GPS, SLR, VLBI, DORIS) for the global reference frame realizations. CATREF stacks the SINEX files containing station coordinates of the stations with full variance-covariance matrices and computes a cumulative coordinate and velocity solution referring to a given reference epoch.

At ASG-EUPOS the combination means determination of cumulative coordinates and velocity for the individual stations based on the input of consecutive weekly solutions available at various epochs. Coordinates of all stations for epoch 2011.0 and station velocities were obtained as a basic product. Additionally, CATREF computes the values of the Helmert-transformation parameters and their changes over time between each input and the combined SINEX solutions. Figure 3 presents time series of the Helmert transformation parameters (translation, rotation and scale) for the weekly solutions. Although these parameters have no direct physical interpretation, they reflect consistency of the solutions and their compatibility with the cumulative solution.

Figure 3 shows that the values of the parameters vary around zero, which proves the good agreement of the input and the reference solution. Lack of linear trend in scale parameter time series shows the internal coherency of the network, distances between stations are relatively constant. Since the beginning of 2010, a systematic shift can be observed for the X (about 2 millimetres) and Z (about 1 millimetre) components of translation and for Y component of rotation (about 1 mas). Seasonal variations with period of one year can be noticed in all time series, especially for Y component of translation, X component of rotation and for the scale. About GPS week 1666 higher values of scale can be observed, but this temporal effect is related to the winter time and strong snowfalls, which caused malfunction at many ASG-EUPOS stations. In general, all parameters proves the good match between cumulative solution and consecutive weekly solutions.

CATREF may consider discontinuities (e.g. changes of equipment or introducing a new reference

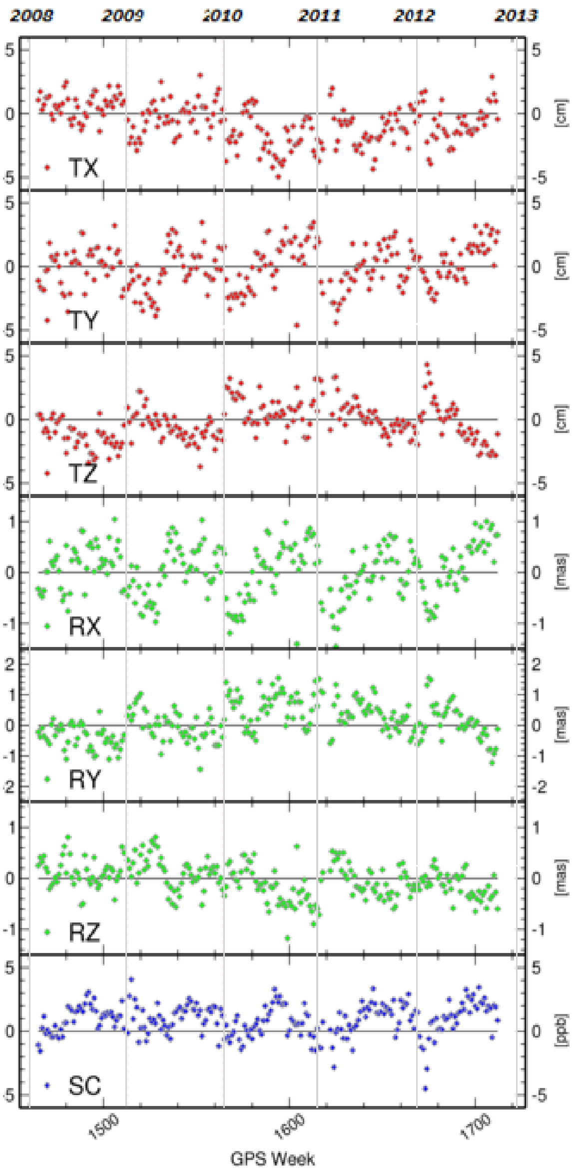

Fig. 3 Helmert transform parameters (translation, rotation, scale) for the ASG-EUPOS solution.

frame) dividing the entire observation period for a station into sub-periods, so called solution numbers. For each such sub-period independent coordinates are determined. They should be used as reference value for the given sub-period. It means that each antenna change at a station requires the re-determination of the reference coordinates. Coordinates from the recent sub-period should then be used as actual values.

The processing provided cumulative coordinates and velocities both in the IGS08 and ETRF2000(R08) frames. The transformation of the solutions initially obtained in the IGS08 to the ETRF2000 was performed according to the procedure described in (Altamimi and Boucher, 2008) assuming that the global Helmert transformation parameters from ITRF2008 to IGS08 are equal zero.

The subject of the geodynamic research in this case is first of all the estimation of horizontal and vertical velocities based on the results of the above described procedure. In this processing, the accumulation of the weekly solutions yielded velocities of all stations expressed in the IGS08 system, which then were converted into ellipsoidal system using the GRS80 reference ellipsoid (see Figs. 4a-c). In Figure 4a the Eurasian plate movement is dominating in the horizontal velocities while in Figure 4b the intraplate velocities (ETRF2000) are well observable after the plate motion model has been removed. The vertical velocities are presented in Figure 4c. The horizontal velocity field determined using the ASG-EPOS observations was discussed in details in (Bogusz et al., 2013), the vertical movement models obtained from GNSS data and precise levelling in (Kontny and Bogusz, 2012), and a study of the horizontal velocity field for south-eastern Poland (Sudety region) in (Bogusz et al., 2012).

3. THE ASG-EUPOS CASE STUDY

Velocities expressed in the ETRF2000 are of great importance for the maintenance of the reference frame. Considering the fact that the GNSS stations in Poland carry the function of the basic geodetic network, their coordinates have to comply with high accuracy criteria. The station coordinate variations due to non-zero intraplate horizontal velocities (in the ETRF) have to be monitored and the catalogue values have to be changed when needed to render in the best possible way their actual real position at any epoch. Although in Poland the values of the intraplate velocities are small in comparison with e.g. Greece or Italy, the velocities of some stations are significant enough (Fig. 4b) which should not be disregarded in the process of the reference frame maintenance.

The ETRF2000 frame is still not kinematic, although stations are attributed not only with coordinates but also with their velocities. In the not far future the reliable determination of the individual station velocities will have crucial importance, this is why EUREF started to make efforts to take full advantage of deformation models (Lidberg, 2012). One of their potential applications is the maintenance of the national realizations of the ETRS89 system. The problem of coordinates changes due to significant intraplate velocities is especially important in the regions like the Mediterraneum, Fennoscandia and Iceland, Greenland. Forecasts concerning expiration of the ETRS89 realisation coordinates in individual states due to apparent velocity are presented in (Caporali et al., 2011). The initial accuracy criterion was set to 3 cm, while the expected accuracy of the stations constituting the fundamental network in Poland is 1 cm for the horizontal components, which means that newly determined station coordinates most probably have to be corrected in a few years if the intraplate station velocity is more than 2 mm/year. In order to be able to estimate when the actual coordinates exceed the assumed criterion, it is necessary to analyze the current coordinate solutions.

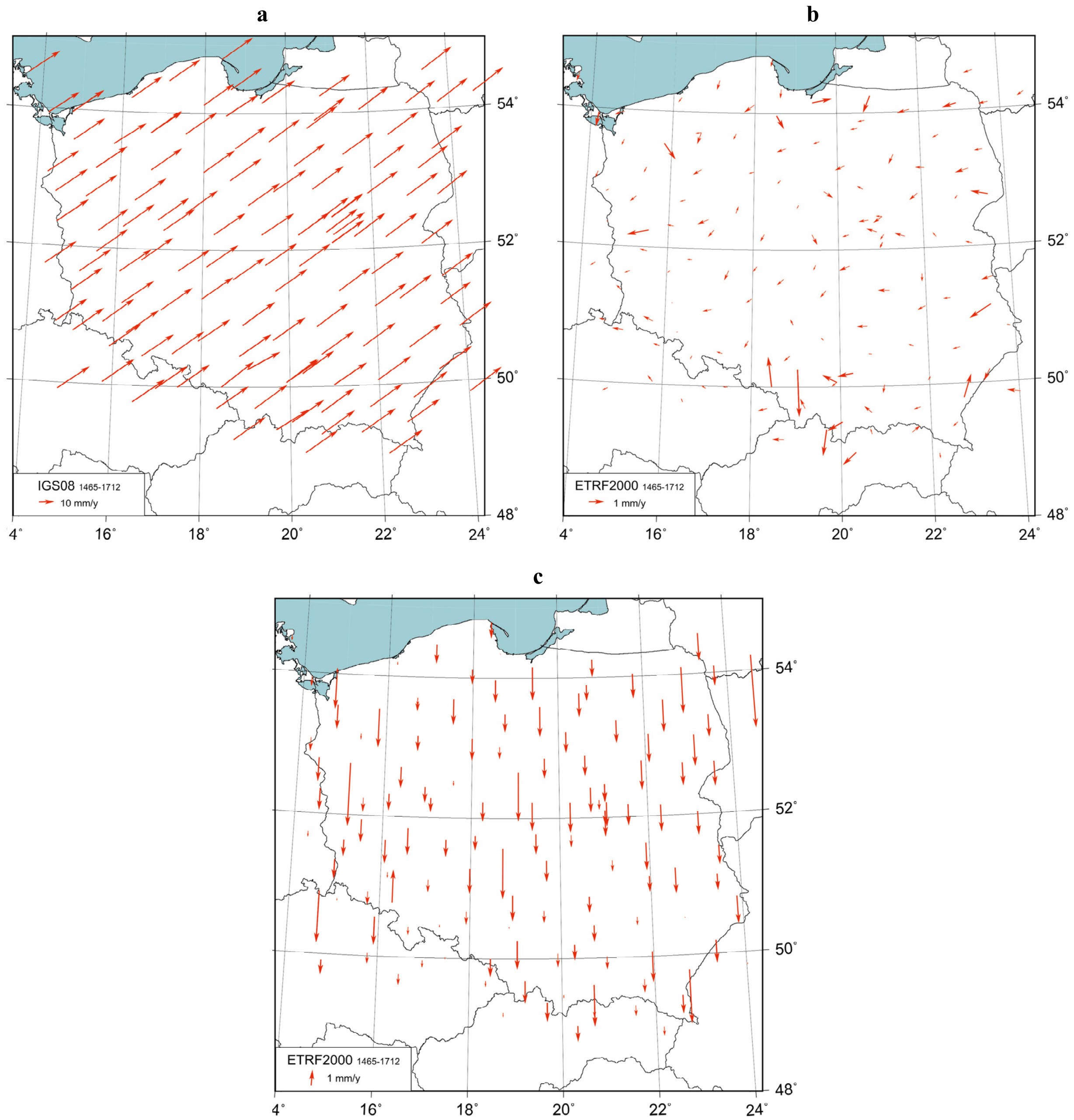

Fig. 4 a, b, c Horizontal (a – in the global IGS08, b – in the regional ETRF2000(R08)) and vertical velocities of the ASG-EUPOS stations.

Analysis of ASG-EUPOS coordinates temporal validity were described in (Szafranek, 2012). Additionally, at each antenna change new coordinates have to be estimated due to the expected position change. Monitoring of potential antenna dislocations have also primary importance as such events may cause undesirable reference coordinate offsets. Although Poland is located in a steady geodynamic area, some stations have significant intraplate velocities (e.g. KATO, WODZ, WLAD, Fig. 4b). It may be caused by miscellaneous factors, e.g. station location in a mining area or on a roof of an unstable building (mainly subsiding). This problem has no significant negative influence on the realization of the reference frame under the condition that the velocity values are stable and well determined (the velocity stability criterion is one of the basic conditions at the categorization of the EPN stations). All these factors are highly supporting the necessity of the GNSS reference coordinate monitoring. Initial results of such station monitoring solutions in the Sudeten region are presented in (Figurski et al., 2007).

Since 2010 the CAG of the MUT in cooperation with the Wroclaw University of Environmental and Life Sciences and University of Warmia and Mazury in Olsztyn are realizing a research and development grant “Supporting Modules for Real-time Services of Polish GBAS” (ASG+). The module of GNSS station coordinate monitoring has been developed in the frame of this project. The above cumulative solution

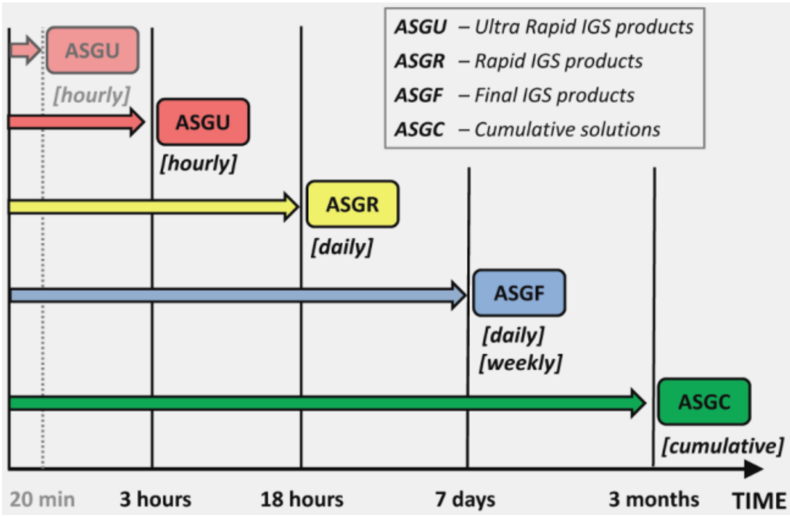

Fig. 5 Various types of ASG-EUPOS solutions depending on products used.

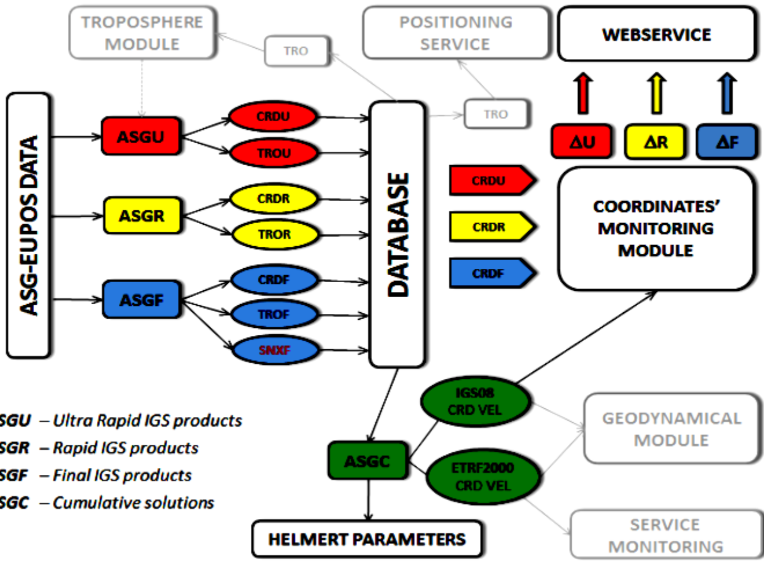

Fig. 6 Diagram of the monitoring module developed within the ASG+ project.

is used as reference for the recent coordinates obtained with various delays depending on the applied products. It is also the input data for the geodynamic interpretation module. Figure 5 presents a diagram of the various types of ASG-EUPOS solutions used in the module. The cumulative solution (ASGC) is obtained from observations gathered over a long period of time using the most accurate products (ephemerides and Earth Rotation Parameters of the 'final IGS' type) and should be periodically supplemented with new observations. The update rate according to Figure 5 is 3 months, but this is still under discussion. The ASGF acronym indicates daily or weekly solutions obtained using the most accurate IGS products, which are available of about one week delay with respect to the observations. ASGR and ASGU are respectively daily and sub-daily solutions determined using IGS 'rapid' and 'ultra rapid' type products. The delay of these solutions depends on the availability of the appropriate products.

Figure 6 presents a diagram of the monitoring module operation. The files containing coordinates (CRD) and tropospheric parameters (TRO) obtained from the ASGU, ASGR and ASGF solutions (here also SINEX files) are archived. The ASGC reference solution expressed both in the global (IGS08) and regional (ETRF2000) frames for the selected epoch (2011.0 this study, but the reference epoch can be taken freely) is made of the ASGF solution using weekly SINEX files. These values are used for comparing the current results from the ASGU, ASGR and ASGC solutions. The results of the comparison are published at http://www.cgs.wat.edu.pl/ASG_PLUS/ in the form of diagrams. The diagram also indicates the possibility of using the cumulative solution for geodynamic research (e.g. deformation analysis, Bogusz et al., 2013b).

Figure 7 presents an example diagram showing monitoring of one of the ASG-EUPOS system stations (BOR1, Borowiec, Poland) using the ASGF solutions. The monitoring enables to find out whether the current position of the station falls within the assumed error criterion (here 1 cm in horizon and 2 cm in vertical with respect to the reference solution) and to assess the performance of the station as well as the potential negative influence of the environmental factors on the solutions (e.g. winter 2010). This problem is described in more details in (Bogusz et al., 2011).

4. CONCLUSIONS

According to Resolution No. 2 published at the EUREF2010 Symposium in Gavle, Sweden EUREF recommends to adopt the ETRF2000 system in national realizations of the ETRS89 system for ensuring uniformity of reference systems in Europe. The results, determined according to EUREF recommendations may be used as reference values of coordinates of the ASG-EUPOS stations constituting the basic horizontal network in Poland. The methodology presented within this paper takes into consideration the ASG-EUPOS characteristic.

The obtained values are used as reference coordinates in the system of the ASG-EUPOS station position monitoring (on the weekly, daily and subdaily basis), which enables to control the maintenance of the PL-ETRF2000 frame by investigating the discrepancies between the current and reference values and assessment of present performance of the system stations and its reliability. Such monitoring gives a guarantee of accuracy standard required by Polish law – differences between reference coordinates values and subsequent daily solutions cannot exceed 1 centimetre for horizontal and 2 centimetres for vertical components except some seasonal disturbances related e.g. to the extreme snowfalls.

The results presented in this study have also wide range of application in the geodynamic researches related mainly to the determination and analysis of the horizontal and vertical velocity fields and the strain investigations as well. Application of the velocity field for maintenance of the reference frame is one of the tasks of the recently established EUREF Working Group on Deformation Models. Due to significant values of velocities at some stations and strong accuracy criteria concerning the basic network, it is necessary to monitor the coordinates of the CORS system stations to ensure reliable reference for geodetic measurements and maintenance of the ETRF2000 frame. It is also obvious that over longer time span it will be necessary to make periodic corrections of the catalogue coordinates of the stations.

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Maps and charts were drawn in GMT (Wessel and Smith, 1998).

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REGULATIONS

Rozporządzenie Ministra Administracji i Cyfryzacji z dnia 14 lutego 2012 roku w sprawie osnów geodezyjnych, grawimetrycznych i magnetycznych (Dz. U. No. 63, poz. 352), 2012 (Regulation of the Minister of Administration and Digitalization concerning geodetic, gravimetric and magnetic networks), in Polish.
Rozporządzenie Rady Ministrów z dnia 15 października 2012 r. w sprawie państwowego systemu odniesień przestrzennych (Dz.U. 2012, poz. 1247), 2012 (Regulation of the Council of Ministers concerning national spatial reference system), in Polish.

WEB PAGES

http://www.asgeupos.pl/
http://www.cgs.wat.edu.pl/ASG_PLUS/
http://www.epncb.oma.be

Personal communications (2012) with Elmar Brockmann, Alessandro Caporali, Jan Dousa, Heinz Habrich, Ambrus Kenyeres, Martin Lidberg and Guenter Stangl.

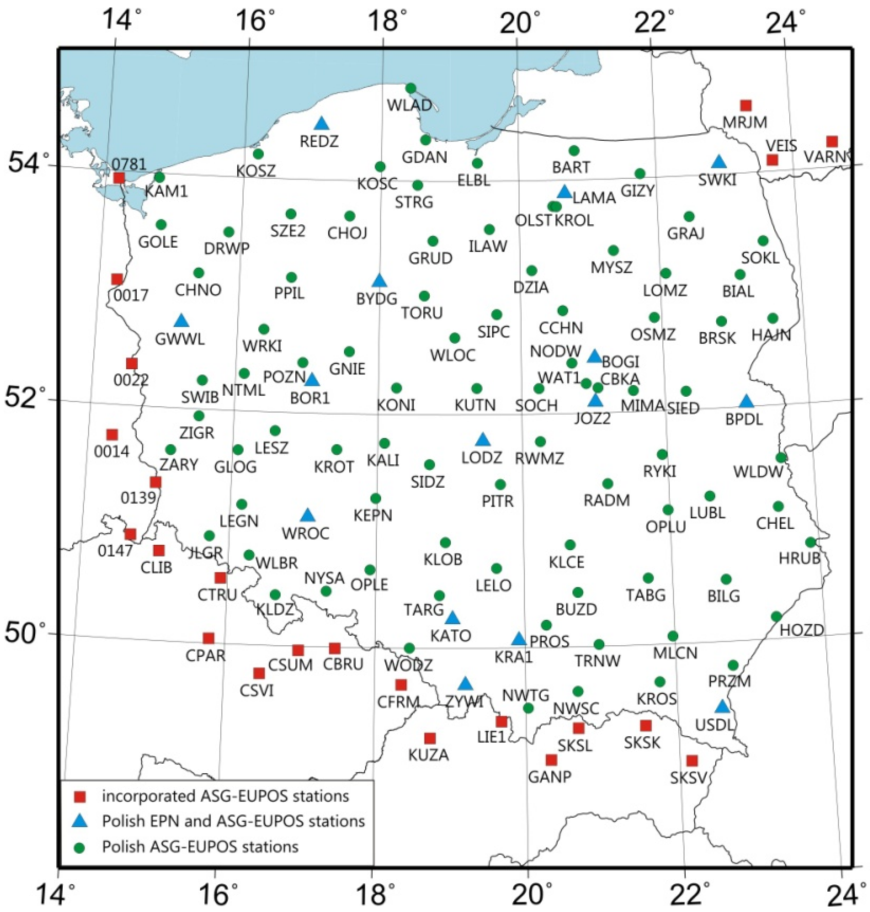

Fig. 1 ASG-EUPOS network (as of February 2013).

Fig. 7 Monitoring of BOR1 station coordinates by comparing the values of the daily coordinates with the reference values (ASGF type solutions, NEU components, ETRF2000).