INVESTIGATION ON STABILITY OF MOUNTAINOUS EUPOS SITES' COORDINATES

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ABSTRACT
The paper concerns analysis of solutions obtained during common processing of data from GNSS permanent stations situated on mountainous terrain: the Western Carpathians, the Sudetes Mountains and adjacent areas. As the outcome daily and weekly solutions (ellipsoidal coordinates) of forty Polish, Czech, Slovak, Ukrainian and German sites were obtained. Weekly solutions were used to determine velocity field and vertical movements, daily solutions enabled quality and precision of sites' coordinates estimation to check if permanent GNSS sites can be used as a stable reference frame for geodetic, geological and geodynamical measurements in the mountainous area. First investigations concerning data from permanent GNSS stations in the Sudetes Mountains were made in 2007 using daily solutions from EPN sites obtained in test reprocessing of the whole regional network performed in Centre of Applied Geomatics. Since that time, national systems became operational increasing density of GNSS network, so the data can be used for wider range of investigations. As the majority of examined stations started to gather data in 2008, analysis were based on relatively short observation period, so they rather play a role of tests for further investigations and they give the preliminary estimation of individual sites' activity.

KEYWORDS: GNSS permanent stations, EUPOS, reference system, GNSS, processing

INTRODUCTION

Nowadays, a strong increase of GNSS (Global Navigation Satellite Systems) significance not only for geodetic purposes can be observed. Permanent networks like IGS (International GNSS Service) or EPN (European Permanent Network) plays a role of a fourth, beside space, control and users, GNSS segment. Through gathering the data from long period and processing them according to the highest standards, they give precise and reliable solutions (ellipsoidal coordinates) of stations and enable reference systems realization. Cumulative solutions from IGS sites form TRF (Terrestrial Reference Frame) based on GNSS technique, which is combined with other techniques' (SLR – Satellite Laser Ranging, VLBI - Very Long Baseline Interferometry and DORIS - Doppler Orbitography and Radiopositioning Integrated by Satellite) solutions to obtain ITRF (International Terrestrial Reference Frame). Proper datum realization is crucial, because it has an impact on all geodetic measurements. EPN is the official densification of the global network. There are about 200 stations evenly distributed along Europe that realize ETRS89 (European Terrestrial Reference System), firmly connected with the European part of Eurasian plate. In 2007, the authors made analysis basing on data from five EPN sites located in Czech Republic, Slovak Republic and Poland. Investigations concerned variations of vectors' lengths using wavelet transformation analysis of daily vectors time series were made (Figurski et al., 2007). In the meantime, national systems became operational, so there are more possibilities of satellite data application for scientific and non-scientific purposes. As an example of GNSS sites usage for geodynamical researches, GEONAS (GEOdynamic Network of the Academy of Sciences of the Czech Republic, http://www.geonas.irsmcas.cz/) can be given, (Schenk et al., 2010).

Currently, ETRS89 densification efforts on the local level are being made in the majority of European countries. Densification means common data (from EPN and local sites) processing according to guidelines described in (Bruyninx et al., 2009). Applying this procedure, solutions are analyzed by EUREF (Reference Frame Sub Commission for Europe, International Association of Geodesy) to obtain validation, which guarantees that the national densifications are homogenous and coherent. In this paper the results of the first common elaboration of data from different national satellite positioning systems are presented. The analysis focuses on scientific usage of GNSS permanent sites on mountainous terrain. The chosen stations are distributed in the Western Carpathians, the Sudetes Mountains and adjacent areas.

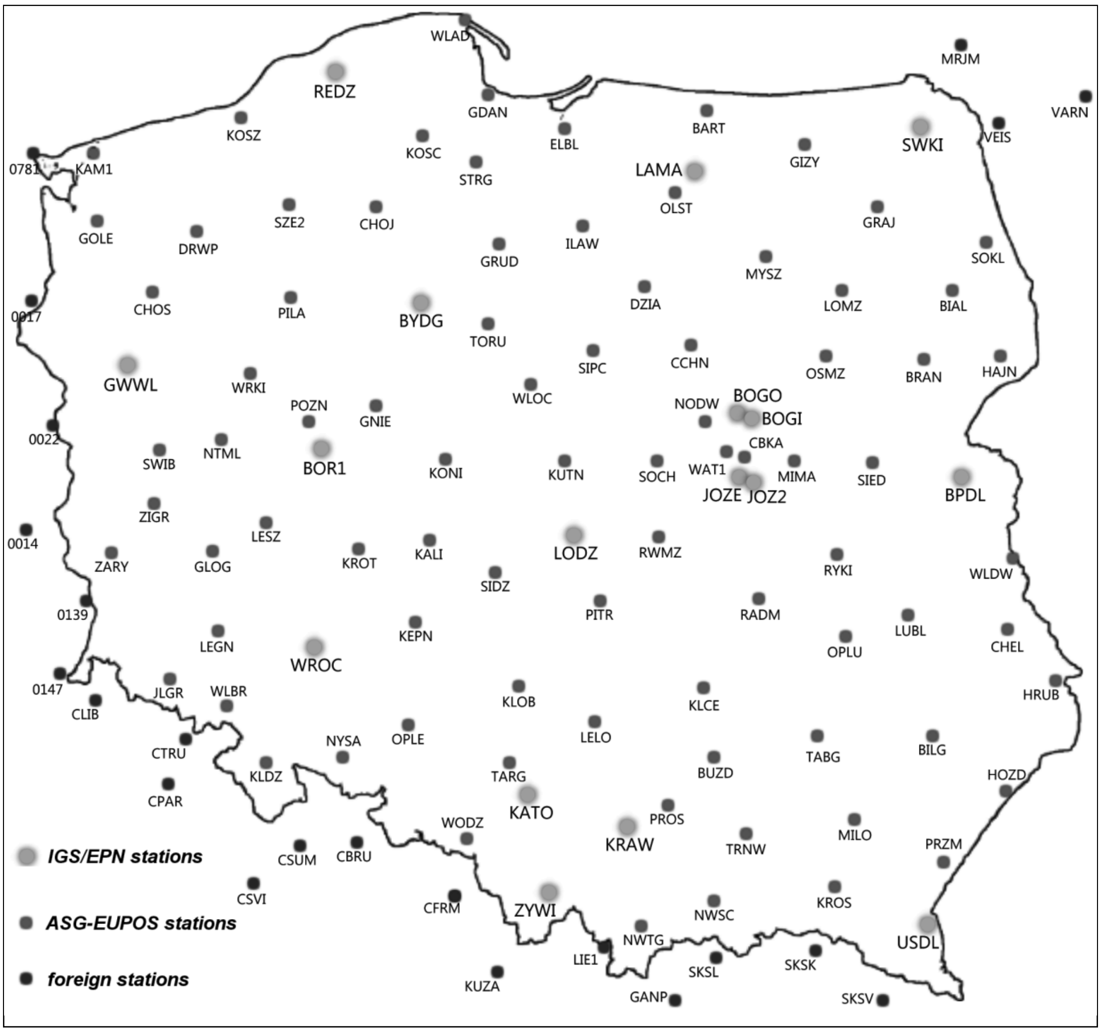

Fig. 1 ASG-EUPOS network.

NATIONAL SATELLITE POSITIONING SYSTEMS

EUPOS (European Position Determination System) is the international initiative of compatible GBAS (Ground Based Augmentation Systems) GNSS establishment. Seventeen countries (e.g. Germany, Czech Republic, Slovak republic, Poland, Hungary, Latvia) created national satellite positioning systems on the same basis to allow a high accuracy and reliability for positioning and navigation. This paper concerns analysis of data from 24 Polish stations (ASG-EUPOS) and 16 stations from Czech Republic (CZEPOS), Slovak Republic (SKPOS), Germany (SAPOS) and Ukraine (EPN sites). As the majority of analyzed stations is placed in Poland, only ASG-EUPOS as an example of national satellite positioning system is described here. The ASG-EUPOS name stands for Active Geodetic Network - European Position Determination System (http://www.asgeupos.pl/). It consists of 98 sites distributed in Poland and 18 foreign sites (Fig. 1). Although some stations gather data since 2006 (or even longer – EPN stations), system became operational in June 2008. Beside being the IGS and EPN densification, it delivers real time or post-processing corrections for surveyors using GNSS receivers (differential technology). Polish Head Office of Geodesy and Cartography (HOGC) manages the system, while Centre of Applied Geomatics of Military University of Technology (CAG MUT) processes the data and analysis solutions to ensure additional control and monitoring of the system. ASG-EUPOS plays a role of ETRF conservation and it will become main national geodetic frame in a near future.

DATA PROCESSING

Strategy of processing was very similar to EPN test reprocessing strategy (Kenyeres et al., 2007) and compatible with EPN processing strategy used by Local Analysis Centres. Elaboration was made using Bernese 5.0 software (Beutler et al., 2006). Only GPS observations in RINEX format were used with carrier phase as a basic observable. Elevation angle cut-off was 3 degrees and elevation dependent weighting was done using cos(z). As modelled observable double-differences (ionosphere-free linear combination) were used. Table 1 presents basic elements of strategy. Models used during processing are gathered in Table 2. As a reference (datum definition) a few EPN stations were used (BOR1, WTZR, METS, POTS, ONSA). Strategy used in local sites' data processing

Table 1 Processing strategy.

Modeled observable: double-differences, ionosphere-free linear combination;

Ground and Satellite antenna phase center calibrations: absolute model if available; if not, antenna corrections were converted from relative antenna calibrations or copied from the same antenna type without radome;

Troposphere: During the processing Saastamoinen-based dry component mapped with the Dry-Niell mapping function was used as a priori model. The Wet-Niell mapping function was employed to map the wet component (without a priori model).

Ionosphere: For the final adjustment, ionosphere was cancelled out due to ionosphere - free linear combination used, but CODE (The Centre for Orbit Determination in Europe) global iono models helped to increase the number of resolved ambiguities in the QIF, the L5/L3 and the L1/L2 ambiguity resolution;

Orbits and ERPs: IGS precise final orbits and ERPs;
Ambiguity: Method of ambiguity determination depended on the length of a baseline. For baselines up to 1300 km length QIF strategy in a baseline processing mode using CODE global iono models was used. For baseline lengths shorter than 200 km L5/L3 approach was employed and for baselines shorter than 20 km - L1/L2 approach.

Table 2 Models used in processing.

Planetary ephemeris: **DE405**
Ocean tides: **OT_CSRC**
The Earth geopotential is modeled using: **JGM3**
Nutation model: **IAU2000**
Subdaily pole model: **IERS2000**
Tidal displacements:
Solid tides: **according to the IERS 1996/2000 standards**
Ocean loading model: **FES2004**

was almost identical with MUT LAC (Military University of Technology Local Analysis Centre) strategy of EPN data processing, so more detailed information can be found on official EPN website (http://www.epncb.oma.be).

Weekly and daily solutions (ellipsoidal coordinates: North, East, Up components) were obtained in SINEX (Solution Independent EXchange Format) format. The solutions of processing were expressed in ITRF2005, the transformation according to 7th version of (Altamimi and Boucher, 2008) was done to obtain coordinates in ETRF2000.

ANALYSED NETWORK AND DESCRIPTION OF SOLUTIONS

The main goal of these tests was to determine sites coordinates with the highest possible accuracy basing on long-term observation period, to check stability of mountainous sites coordinates and to estimate their usefulness for geodetic, geodynamic and geological research. Forty Polish, Czech, Slovak, German and Ukrainian stations from the Western Carpathians, the Sudetes Mountains and adjacent areas were chosen (Fig. 2).

Data gathered by these stations was processed and as a result time series of daily and weekly solutions (North, East, Up components for every station) in ETRF2000 were obtained. Solutions expressed in ETRF2000 were created from solutions in ITRF2005 by taking into consideration Eurasian plate movement (Altamimi and Boucher, 2008). Figure 3 presents exemplary weekly residuals of all three components from Polish station JLGR (Jelenia Góra) expressed in ETRF2000 and ITRF2005, where linear trend related to Eurasian plate movement can be observed.

As the GNSS permanent sites are going to constitute a reference system, their coordinates have to be determined with the highest precision and accuracy. Such reference system is the natural, uniform densification of European frame (ETRS89 realization) – homogenous for the whole Europe. Precise coordinates are determined as a 'cumulative solution' (Altamimi et al., 1994) using data gathered during a long period. The solutions described here are the result of relatively short observation period so they should be treated only as preliminary tests. It concerns not only coordinates, but especially velocities and

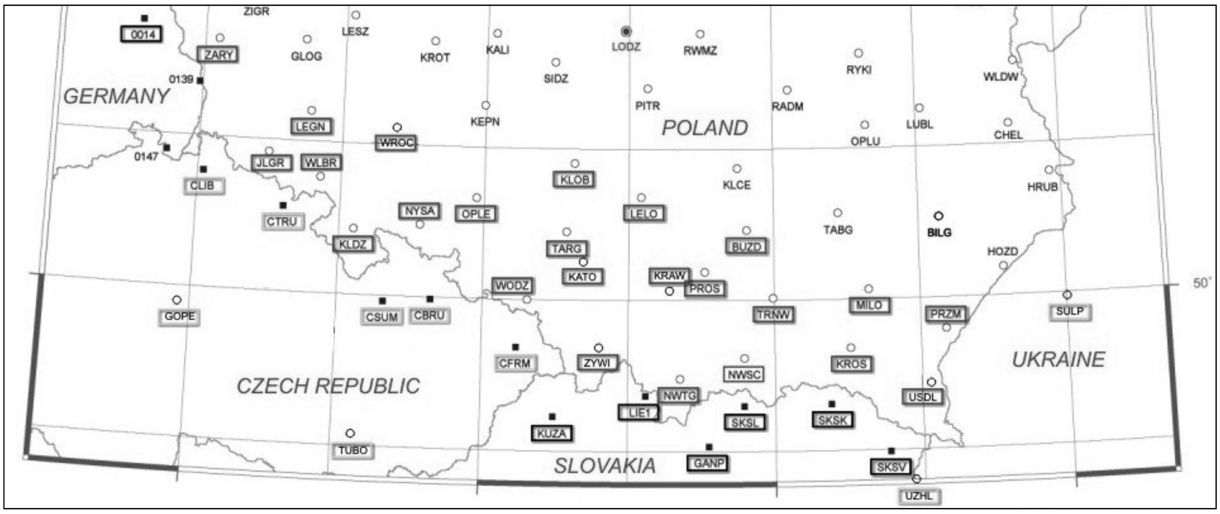

Fig. 2 Analysed stations.

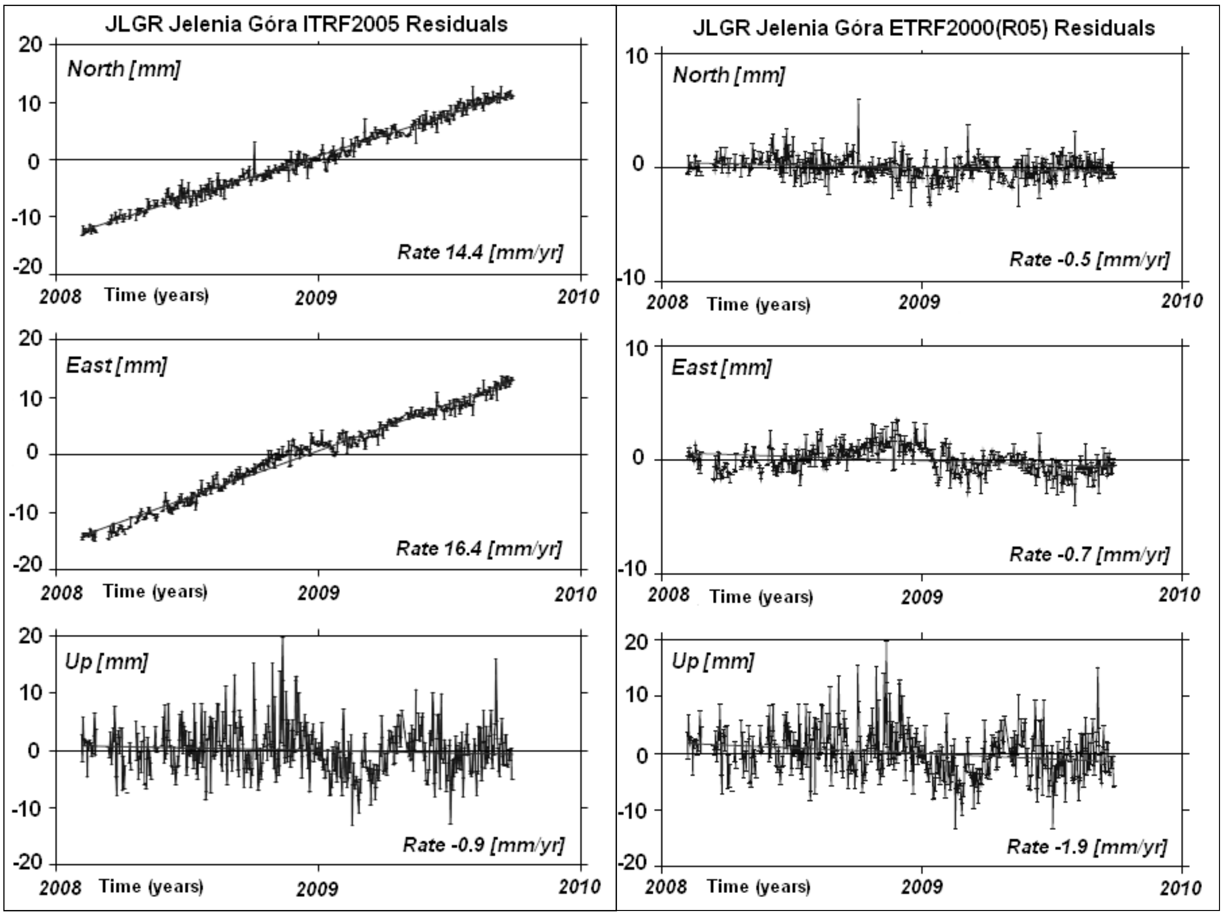

Fig. 3 Weekly time series of North, East, Up components expressed in ITRF2005 (on the left) and ETRF2000 (on the right) – station JLGR (Jelenia Góra).

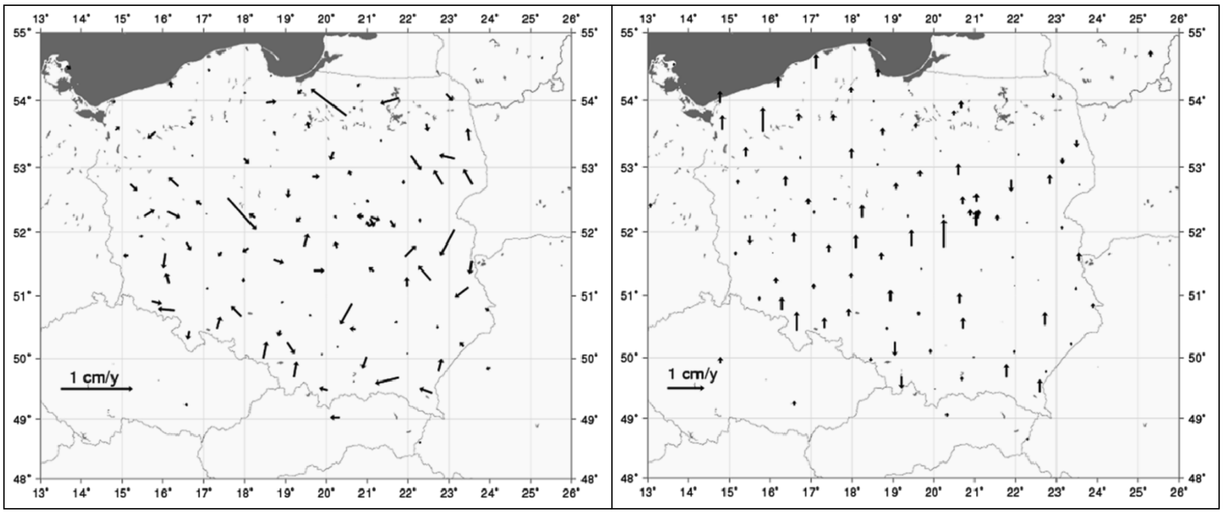

Fig. 4 Horizontal velocities (North-East components, on the left) expressed in ETRF2000 and vertical movements (Up component, on the right) of analyzed stations.

vertical movements. To obtain reliable velocities the data from at least 30 months is required (Blewitt and Lavallée, 2002).

Permanent GNSS sites are presently the main source of information for the Earth's surface deformation determination (http://epncb.oma.be/IAG/). Horizontal velocities obtained from long-term GNSS observations are naturally expressed in ITRF, so they are a great confirmation of theories about current plate movements. After eliminating Eurasian plate movement (e.g. using (Altamimi and Boucher, 2008)), solutions expressed in ETRF can be calculated. Determination of velocities in the frame strictly connected with the plate gives information about local crust movements.

Solutions from national stations can be used to increase density of European velocity field (Regional Dense Velocity Fields Programme, http://epncb.oma.be/IAG/). Figure 4 presents velocities expressed in ETRF2000 and vertical movements determined for Poland and some boarder areas, but they should be treated only as an introduction to further investigations due to short time series. Currently, kinematic ETRF model is based on data from EPN stations only. National systems will supply this model with data, which enable consideration of local Earth's crust deformations. Data from the most reliable ASG-EUPOS stations will be used for investigating the correlation of their movements with the stresses occurring on Poland's territory.

ESTIMATION OF SOLUTIONS' QUALITY AND STATIONS' CLASSIFICATION

To provide the most reliable products, stations operation has to be controlled and solutions quality estimated. EPN classification takes into account solutions' quality and the length of available observation period. Regular official updates of the ITRS/ETRS89 coordinates/velocities of the EPN stations are released every 15 weeks. After every update, sites are divided into two classes (Kenyeres, 2009). The criteria are related to the length of observation period, the precision of position and the agreement (in terms of repeatability) between the velocity estimations from the last 10 consecutive cumulative solutions. Determination of stable and reliable velocities from cumulative solutions requires at least few years of observations. Analyzed stations' time series are very short (8-21 months), so there cannot be reliable velocity estimation – different criteria of solutions quality estimation had to be used. To check stations' proper activity time series of daily solutions were used. Due to lack of information about any changes on stations, they were not taken into consideration, that is why there are few discontinuities in time series. To investigate accuracy and correctness of ASG-EUPOS solutions, standard deviation for time series of each station was calculated separately for North, East and Up components expressed in ETRF2000 (linear detrend was made to eliminate local velocities for statistical purposes). Basing on these values, all stations were divided into classes. The criteria are given in Table 3.

As the majority of ASG-EUPOS sites is placed on the roofs of public buildings, there was a question raised if the data collected by those stations will be suitable for scientific usage especially for geodynamical researches. Classifications of sites in the context of repeatability of their solutions enable the exclusion of unreliable ones and the possibility to choose the best ones for further researches e.g. investigation of stations movements in correlation with the stresses occurring on Poland's territory. Sites with the highest values of standard deviation will be examined to find the reasons of such cases. The classification of horizontal and vertical components was done separately on purpose. It is very common

Table 3 Criteria of stations' division into classes.

	Class I	Class II	Class III
Horizontal	σ < 1.5 mm	1.5 < σ < 3.5 mm	3.5 mm < σ
Vertical	σ < 3.5 mm	3.5 < σ < 5.0 mm	5.0 mm < σ
3D	σ < 4.0 mm	4.0 < σ < 5.0 mm	5.0 mm < σ

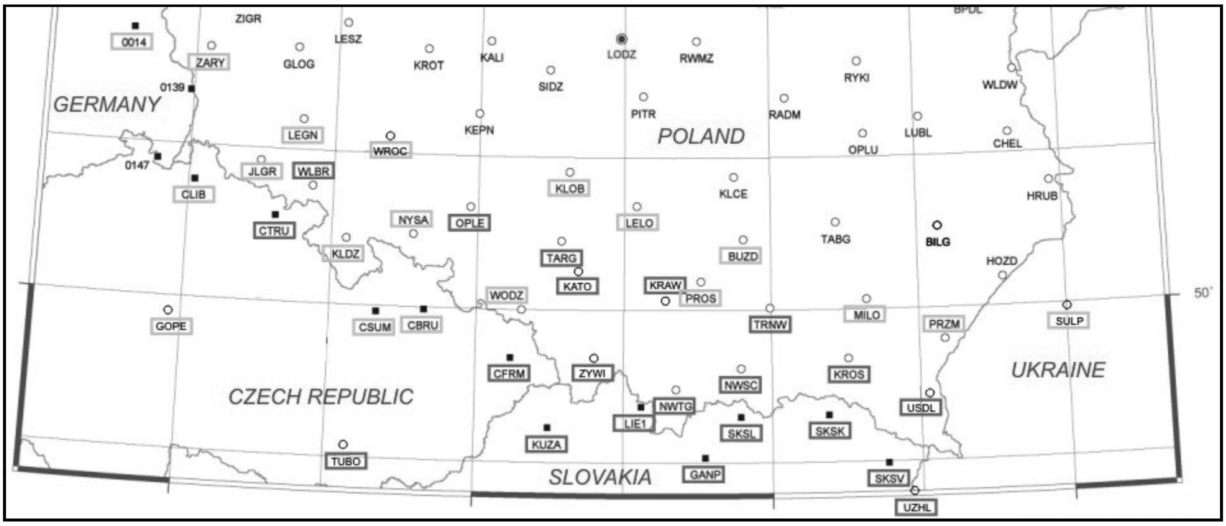

Fig. 5 Stations assigned to 1st (light grey) and 2nd (grey colour) class regarding horizontal solutions (North-East components).

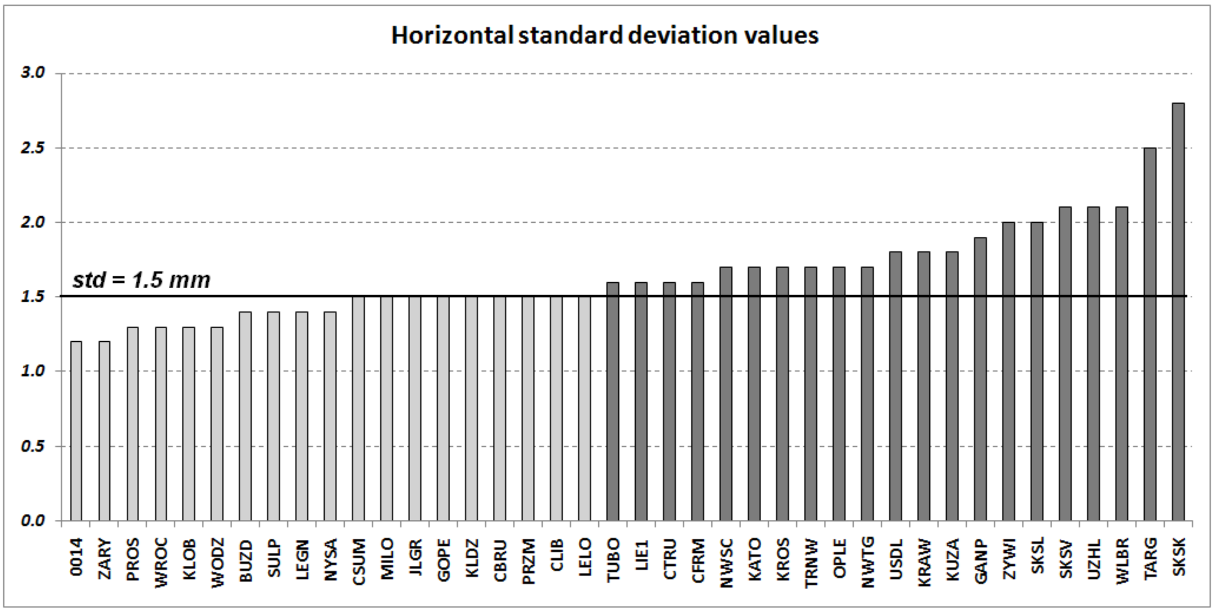

Fig. 6 Stations assigned to 1st (light grey colour) and 2nd class (grey colour) regarding horizontal solutions (North-East components) with standard deviation values [mm].

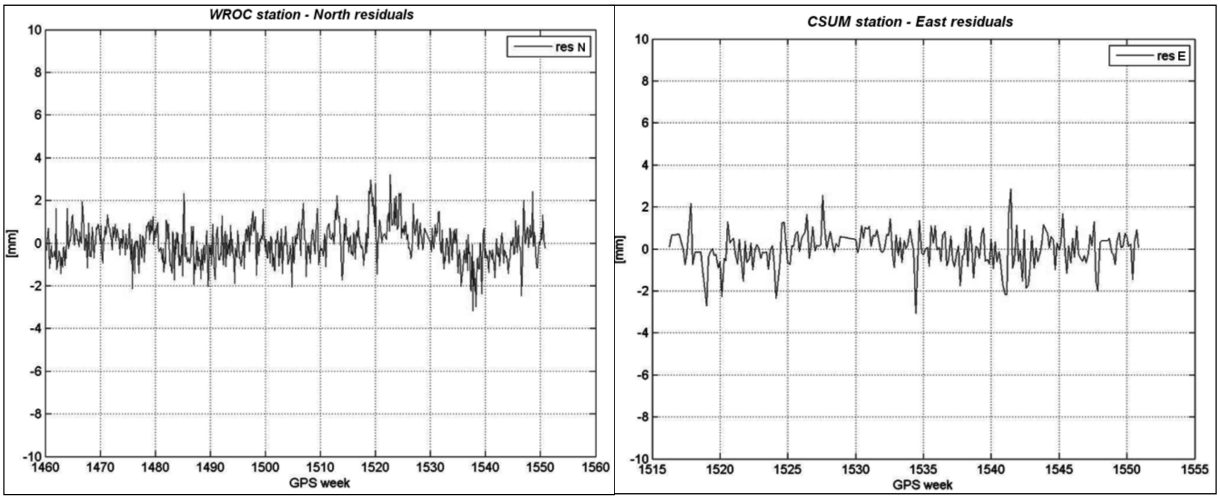

Fig. 7 Examples of horizontal residual time series assigned to 1st class. On the left North component for Polish WROC station, on the right – East component for Czech CSUM station.

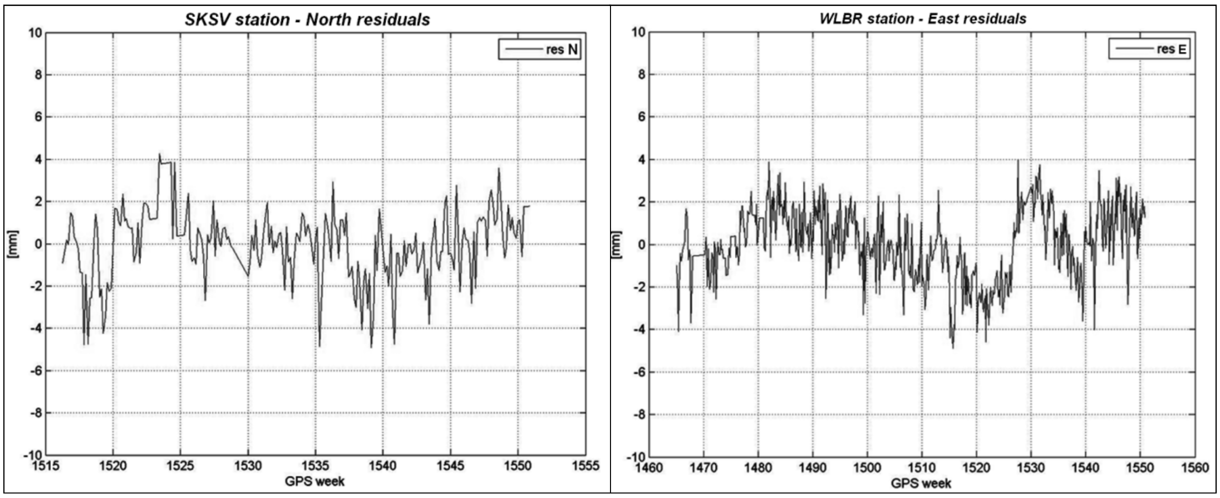

Fig. 8 Examples of horizontal residual time series assigned to 2nd class. On the left North component for Slovak SKSV station, on the right – East component for Polish WLBR station.

that particular site has a very stable horizontal solutions and scattered vertical solutions (and vice versa). Some factors can be observed especially in vertical component e.g. tidal effects, which have not been eliminated by means of model or thermal influence.

Stations were categorized separately concerning horizontal (North and East components) and vertical (Up component) solutions. Figure 5 presents stations divided into 1st and 2nd class in terms of their precision (repeatability). Values of residuals standard deviation for each station expressed in millimetres is shown in Figure 6. In Figure 7 there are examples of time series of stations, which belong to the 1st class – Polish site WROC (Wrocław) and Czech CSUM (Šumperk), in Figure 8 time series of chosen sites from the 2nd class: SKSV (Snina, Slovak Rep.) and WLBR (Wałbrzych, Poland). Standard deviation of horizontal solutions does not exceed 3 millimetres on any of the station.

Similar division was done concerning vertical solutions (Fig. 9), which are more scattered than horizontal ones. Examples of time series of representative stations are presented in Figure 11 (CFRM – Frydek-Mist, Czech Rep., JLGR – Jelenia Góra, Poland and SKSL – Stará L'ubovňa, Slovak Rep.) and all stations' standard deviation values are gathered in Figure 10. Only two stations have standard deviation higher than 5 millimetres, both have short observation history.

Categorization regarding all three components (three-dimensional) is presented in Figures 12 and 13. Examples of time series are shown in Figure 14 (Czech EPN station TUBO and Polish station KLDZ).

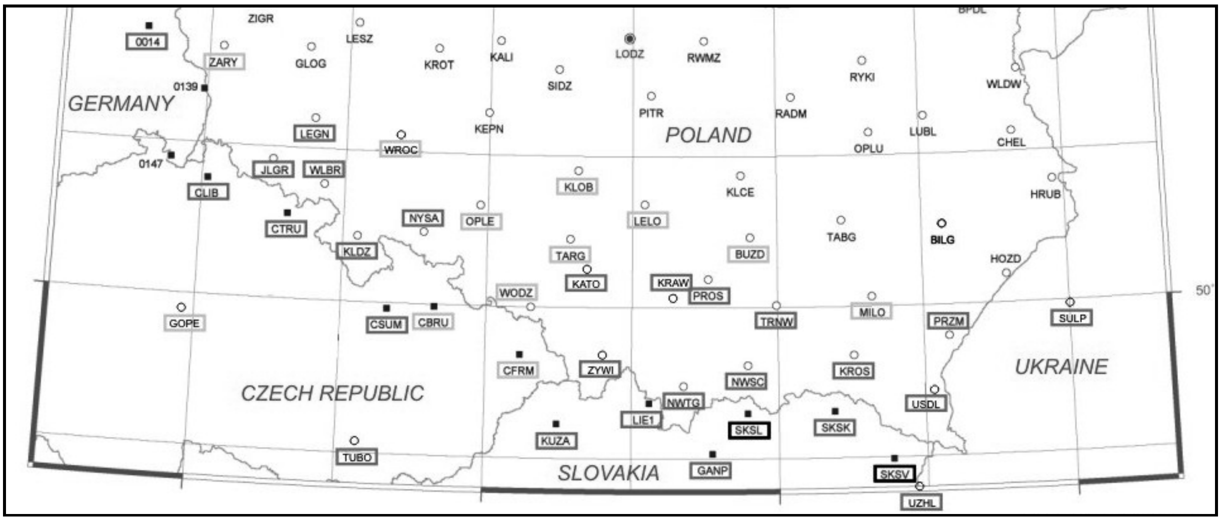

Fig. 9 Stations divided into 1st (light grey), 2nd (grey) and 3rd (black colour) class regarding vertical solutions (Up component).

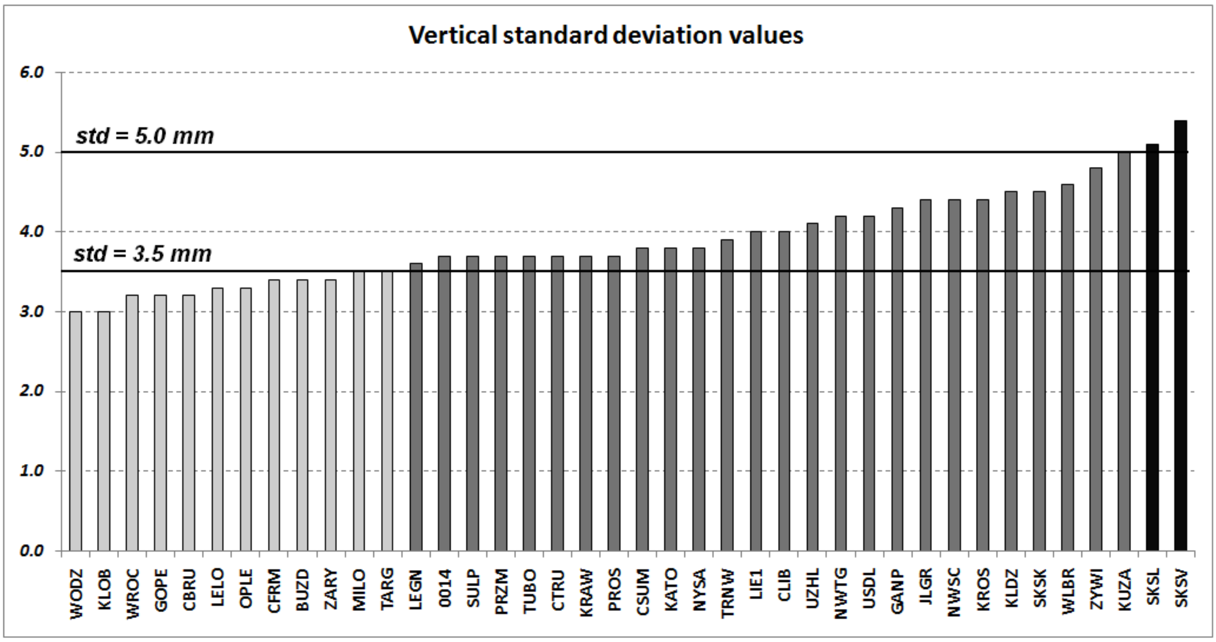

Fig. 10 Stations assigned to 1st (light grey), 2nd (grey) and 3rd (black colour) class regarding vertical solutions (Up component) with the values of their standard deviation [mm].

In Figure 15 there is an example of a station (KUZA, Žilina, Slovak Rep.), which solutions were strongly disturbed. A few outliers caused standard deviation increase up to 15 millimetres. Residuals of Up component reached almost 10 centimetres. After outliers elimination three-dimensional standard deviation value decreased to about 5 millimetres, which still places this station in a group of stations, which solution should be observed regarding their precision. All these stations are situated near Polish – Slovak boarder.

Beside such picks – values, which significantly differ from others - there are other types of disturbances that occurred on few stations. To get the highest precision of sites coordinates and to obtain a very accurate reference frame they should be detected and eliminated. In Figure 16 there are time series of two stations (OPLE and KATO), on which discontinuities were noticed. Usually they are the result of equipment change (especially antenna) or changes in observation strategy (elevation mask), but in these cases there is no information about such modifications. In case of common elaborations gathering such information and exchanging them between countries is necessary. Some regular periodic disturbances can be also observed (Fig. 17 – stations KRAW and TARG, both Polish). As the oscillations period is about 1 year it is possible that they are caused by thermal influence.

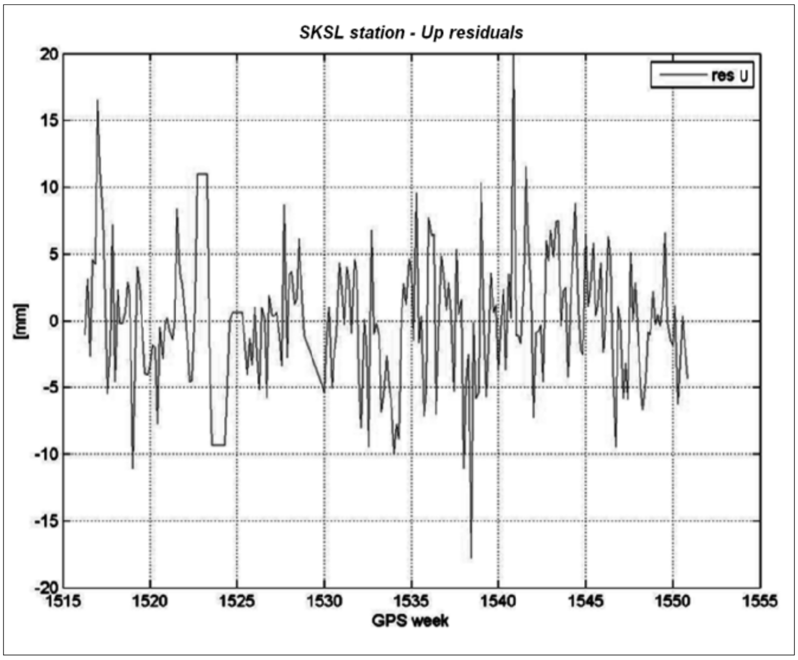

Fig. 11 Examples of vertical residual time series assigned to 1st class – Czech station CFRM, 2nd class – Polish station JLGR and 3rd class – Slovak station SKSL.

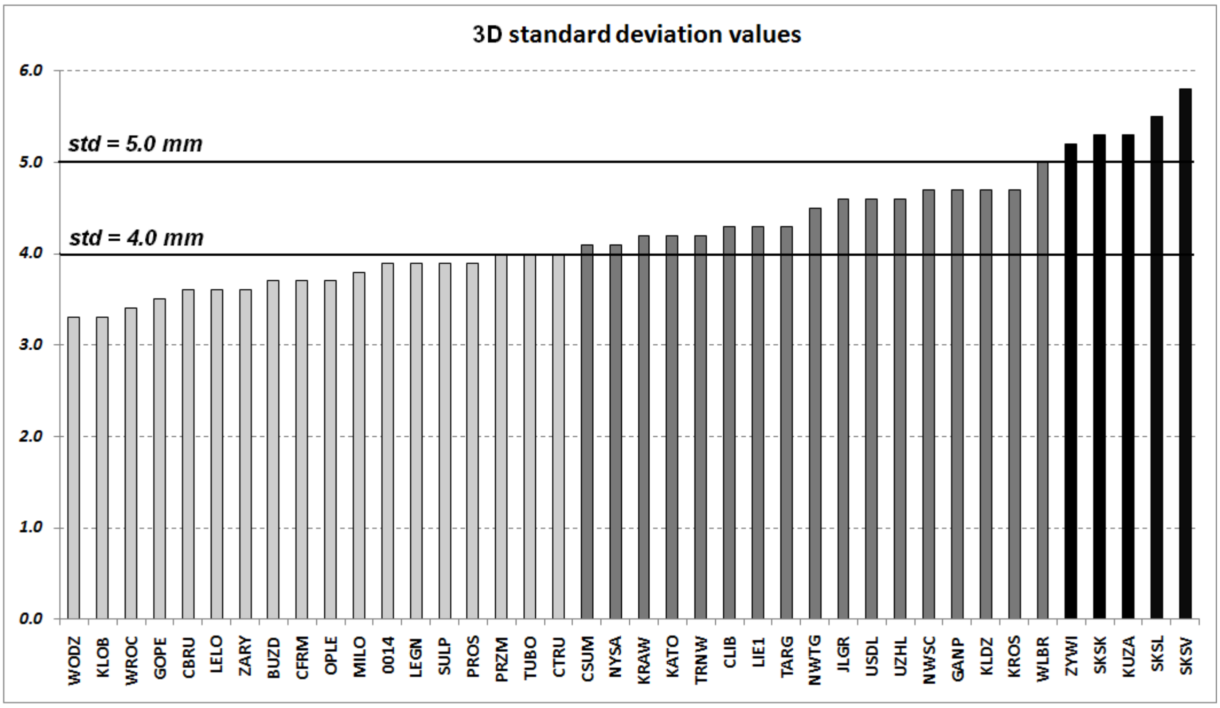

Fig. 12 Stations divided into three classes regarding 3D solutions (North, East, Up components) with the values of their standard deviation [mm].

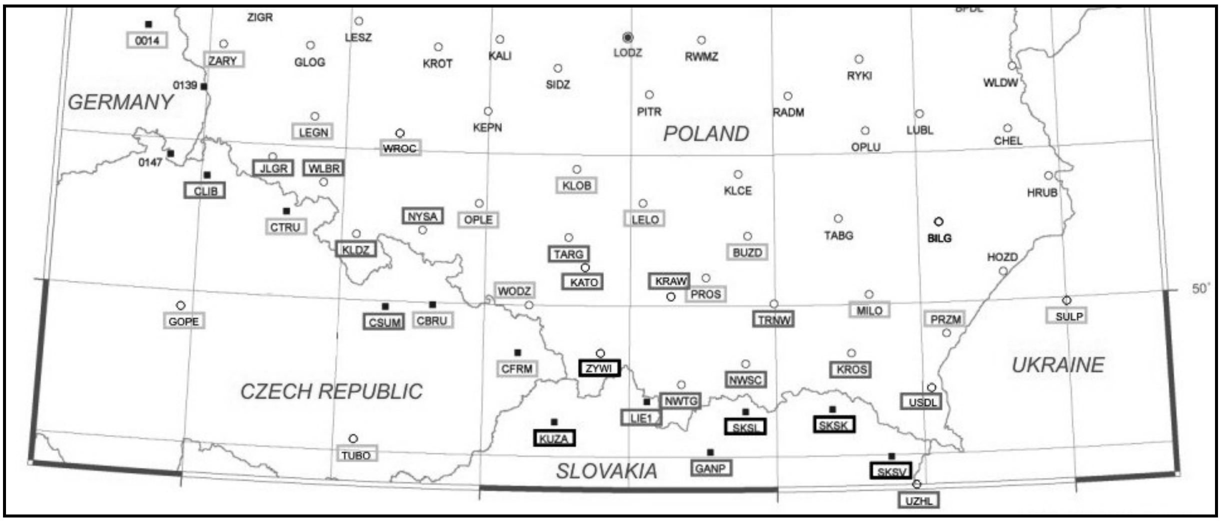

Fig. 13 Stations divided into classes regarding North, East, Up components (1st class – light grey, 2nd class - grey, 3rd class – black colour).

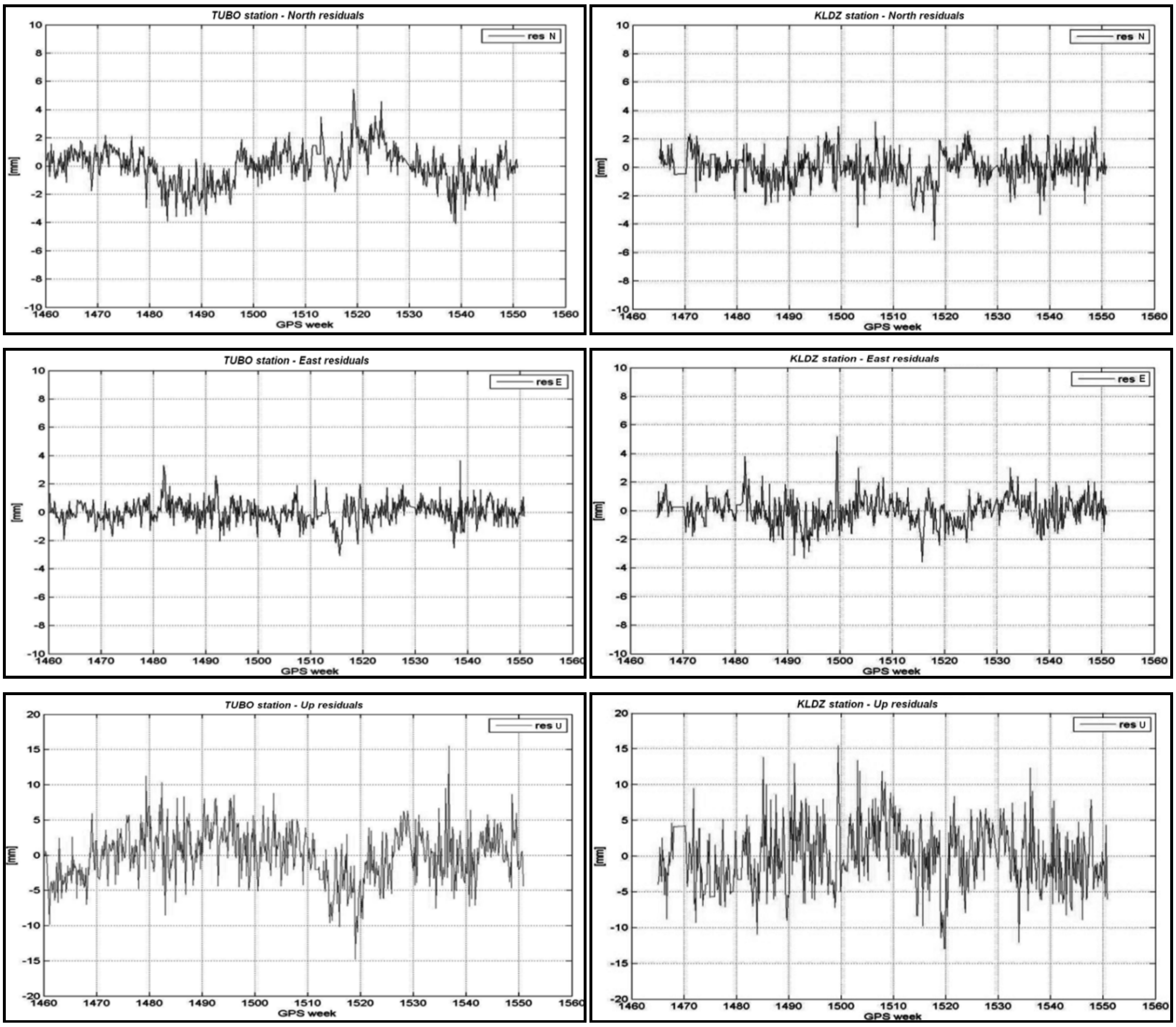

Fig. 14 North, East, Up residual time series of station TUBO (1st class – on the left) and KLDZ (2nd class - on the right).

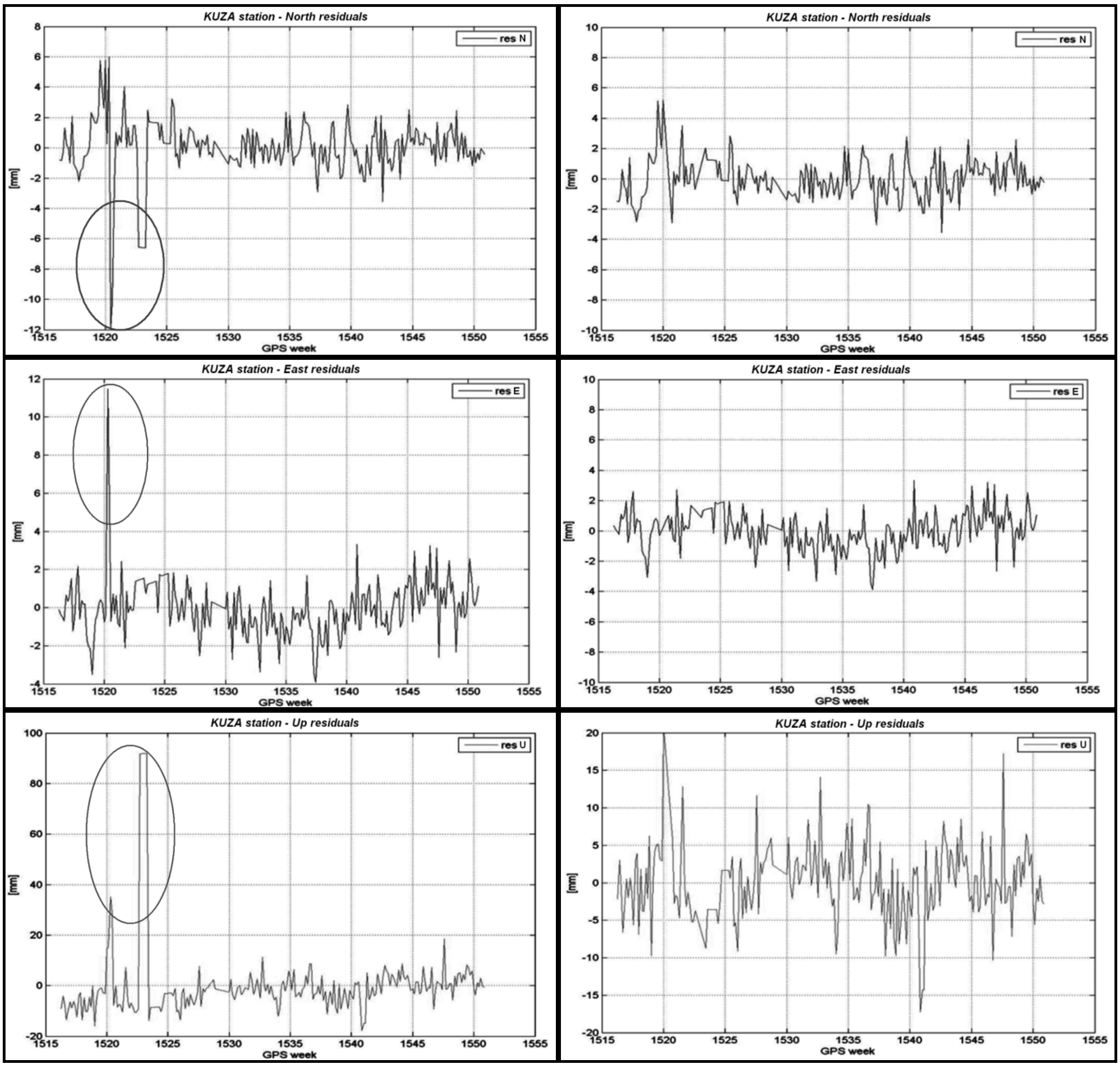

Fig. 15 Examples of residual time series assigned to 3rd class - Slovak station KUZA (North, East and Up component); On the left – original time series, on the right - after removing outliers.

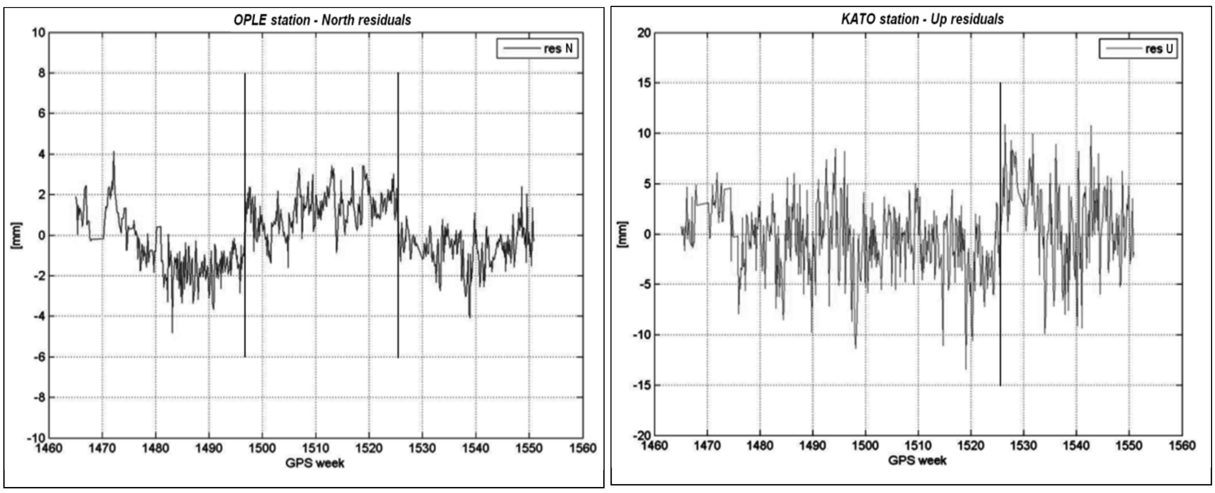

Fig. 16 Examples of time series in which discontinuities can be observed; on the left North residuals (OPLE), on the right Up residuals (KATO).

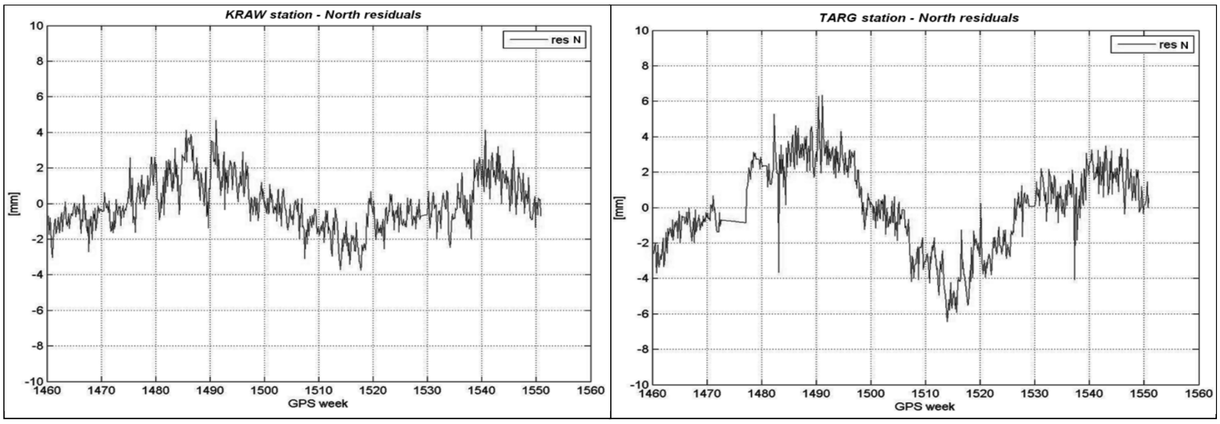

Fig. 17 Examples of time series in which significant oscillations in North component can be observed; on the left station KRAW, on the right – TARG.

Methodology of data processing and estimation of daily solutions quality used here were analogous with methodology applied for sites from other areas. It allows to check if quality of data gathered on mountainous terrain is comparable with data from other geological areas. The authors analyzed all ASG-EUPOS sites using the same criteria and it was proved that geographic location of stations do not impact quality of solutions in terms of their precision. Diversity of time series dispersion and solutions reliability is rather related to some environmental factors (e.g. thermal effect or snow cover, which, however can have higher significance in mountainous areas) or methods of antennas' fixing (the authors did not notice any rule, which could prove that sites with antennas placed on the buildings could deliver data with lower quality than the ones with antennas located next to the ground).

SUMMARY

Analysis of chosen stations' time series prove that quality of solutions from mountainous EUPOS sites do not differ from quality of solutions from other areas. National GNSS networks can realize stable datum for the whole region for different geodetic and geodynamical measurements as the natural ETRS89 densification. International elaborations (joint for stations from different national systems) enable mutual control of different systems, so cooperation and sites' information exchange between countries is necessary. Daily solutions give information about quality of stations' observation and can be helpful, when using them as a reference for precise measurement. Time series presented in this paper are based on short period of observations - it is hard to draw any conclusion about their long-term stability or local velocities. To obtain higher accuracy and more reliable solutions data from a longer period is needed. The authors did not find any relations between sites' localization and the quality of their solutions, although daily time series will be investigated in the context of different disturbances factors influence. These analysis play a role of preliminary tests and they will be continued.

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