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# DATA PROCESSING OF LOCAL GPS NETWORK LOCATED IN A MOUNTAIN AREA

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**ABSTRACT**
Precise position determination of network points, particularly their vertical component is especially difficult in mountainous areas. Significant altitude differences and spatial variations of atmospheric conditions require the best possible approach to tropospheric delay (*δT)* estimation expressed by maximum reduction of systematic error caused by tropospheric refraction. The study of influence of tropospheric refraction on GPS measurements was performed on the example of local network *KARKONOSZE.*

**KEYWORDS:** GPS network, GPS data processing, tropspheric delay estimation

## 1. INTRODUCTION

The accuracy of determination of the vertical component of points' coordinates for both global and regional networks is contained within the ±10 mm limit (daily or weekly determination repeatability). Therefore, in this case, one can speak of an accuracy of ellipsoidal height determination at a centimeter level. In the instance of local networks, particularly those with epochal measurements, such accuracy can be obtained only when processing strategy including specificity of such network in relation to its location, geometry, as well as observation material is used. This is especially the case for networks located in mountainous terrain (Brockmann et al., 2000; Borkowski et al., 2002; Vigny et al., 2002; Makowska, 2003; Mojzeš et al., 2004; Mojzeš and Papco, 2004). As there is no unambiguous solution of the problem associated with determination of GPS network points' heights located in mountainous areas in the before mentioned studies, research in this field is being conducted.

In mountainous terrain one experiences large fluctuations of atmospheric conditions. Standard atmosphere models, used in GPS observation processing with *Bernese GPS Software* and other computer programmes, adequate for global and regional networks do not render these fluctuations of atmospheric conditions in the case of networks located in mountainous areas. The resolution of these models, constructed generally from radiometric probing is low and may be used for vertical transposition of surface meteorological conditions (pressure, temperature and humidity) (Mendes, 1999; Niell, 1996, 2000).

In this paper methodology of tropospheric delay modelling adapted for networks located in mountainous areas has been discussed. Satellite GPS observations, realised between 2001 and 2003 by the Department of Geodesy and Photogrammetry of the Agricultural University of Wroclaw in the local, precise, geodynamic network *KARKONOSZE* has been used in the tests (Kontny et al., 2002).

## 2. LOCAL GPS NETWORK KARKONOSZE

The *KARKONOSZE* GPS network has been established in the Western Sudetes and consists of 19 points located in the area of the Karkonosze Mts. and its foreland (Fig. 1).

The local network *KARKONOSZE* covers an area (40km x 35km) characterised by large elevation differences (up to 1200 m) and significant changes of meteorological conditions.

## 3. TROPOSPHERE DELAY ESTIMATION METHODOLOGY

The trophosphere is a nondispersive (neutral) medium for waves with frequency up to 15GHz, therefore propagation of both GPS frequencies is not mutually correlated. The troposphere's influence (i.e. refraction or tropospheric delay) cannot be eliminated through linear combinations of two frequencies as in the case of ionospheric refraction. The tropospheric delay can be split into the dry (hydrostatic) and wet parts.

$$\delta T = \delta T_d + \delta T_w = 10^{-6} \int_s N_d^{trop} ds + 10^{-6} \int_s N_w^{trop} ds \qquad (1)$$

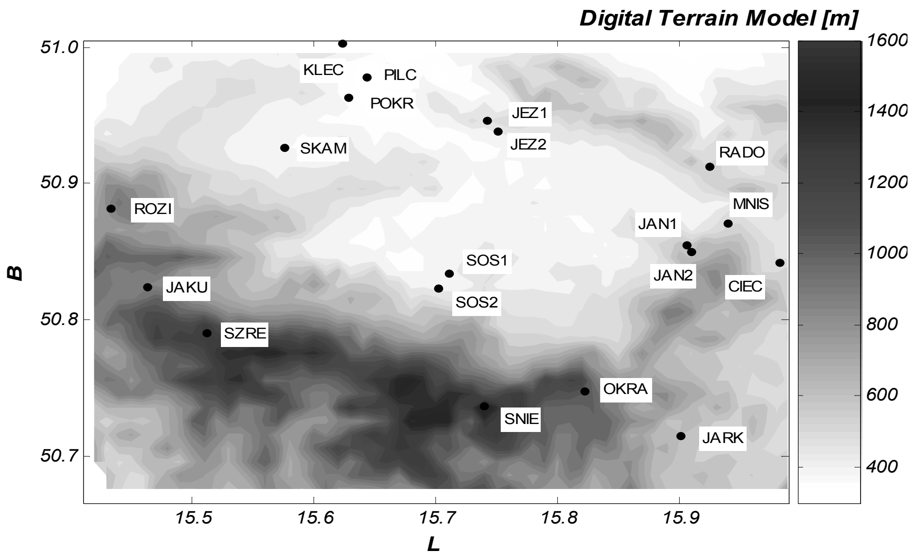


**Fig. 1** Points of the local GPS network KARKONOSZE on the background of a DTM model.

**Table 1** Input parameters for troposphere zenith dry delay models

| Model | e | T | P | B | h | β | λ | other |
|---|---|---|---|---|---|---|---|---|
| (Hopfield, 1969, 1971, 1972) | | √ | √ | | | | | |
| (Goad and Goodman, 1974) | | √ | √ | | | | | |
| (Saastamoinen, 1973) | | √ | √ | | | | | |
| (Davis et al., 1985) | | | √ | √ | √ | | | |
| (Baby et al., 1988) | | √ | √ | | √ | √ | | G, $R_e$ |
| (Elgered et al., 1991) | | | √ | √ | √ | | | |
| (MOPS, 1998) | | √ | √ | √ | √ | √ | | DOY,g |

The tropospheric slant delay $\delta T$ (1) is a function of zenith $z$ or elevation $\varepsilon = (90 - z)$ angle of a satellite and can be given by the following formulae:

$$\delta T(z) = m(z)\delta T_0 \tag{2}$$

where:

$m(z)$ – mapping function of transition from zenith direction $(z = 0)$ to slant (satellite) direction (zenith angle) $z$,

$\delta T_0$ – tropospheric zenith delay, which is divided into the dry (hydrostatic) and wet parts $\delta T_0 = \delta T_{d,0} + \delta T_{w,0}$.

Basing on the relationships (1) and (2) the tropospheric slant delay may be given by the formulae:

$$\delta T = m_d(z) \cdot \delta T_{d,0} + m_w(z) \cdot \delta T_{w,0} \tag{3}$$

where:

$m_d(z)$, $m_w(z)$ – mapping function for the dry and wet components.

Table 1 shows selected functions modelling tropospheric zenith delay for the dry (hydrostatic) component $\delta T_{d,0}$ including input parameters.

Figure 2 shows the results of comparison of tropospheric zenith delay determined for the dry (hydrostatic) component using two models MOPS *(MOPS, 1998)* and Saastamoinen *(Saastamoinen, 1973*) for standard atmosphere in the *KARKONOSZE* network area.

In Table 2 selected functions modelling tropospheric zenith delay for the wet component $\delta T_{w,0}$ including input parameters have been presented.

The results of comparison of tropospheric zenith delay determined for the wet component have been shown in Figure 3.

The hydrostatic (dry) part $\delta T_{d,0}$ (Zenith Hydrostatic Delay) can be precisely determined on the basis of ground meteorological observations or using

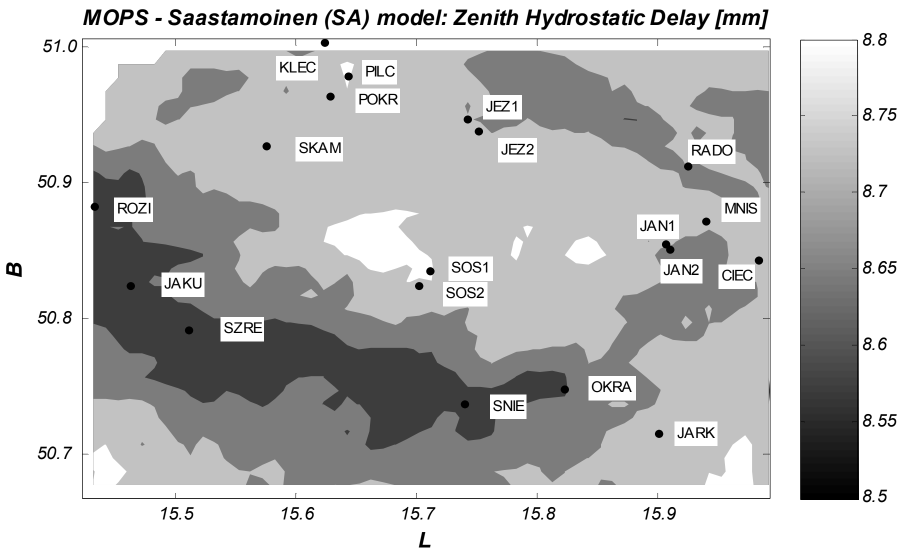


**Fig. 2** Difference between Tropospheric Zenith Hydrostatic Delay $\delta T_{d,0}$ computed from MOPS model and Saastamoinen model for area of KARKONOSZE network

**Table 2** Input parameters for troposphere zenith wet delay models

| Model | e | T | P | B | h | β | λ | other |
|---|---|---|---|---|---|---|---|---|
| (Hopfield, 1969, 1971, 1972) | √ | √ | | | | | | |
| (Goad and Goodman, 1974) | √ | √ | | | | | | |
| (Saastamoinen, 1973) | √ | √ | | | | | | |
| (Chao, 1972) | √ | √ | | | | √ | | |
| (Ifadis, 1986) | √ | √ | √ | | | | | |
| (Mendes and Langley, 1998) | √ | | | | | | | |
| (Baby et al., 1988) | | √ | | | √ | √ | | |
| (Askne and Nordius, 1987) | √ | √ | | √ | √ | √ | √ | $g_m$ |
| (MOPS, 1998) | √ | √ | | √ | √ | √ | √ | DOY,g |

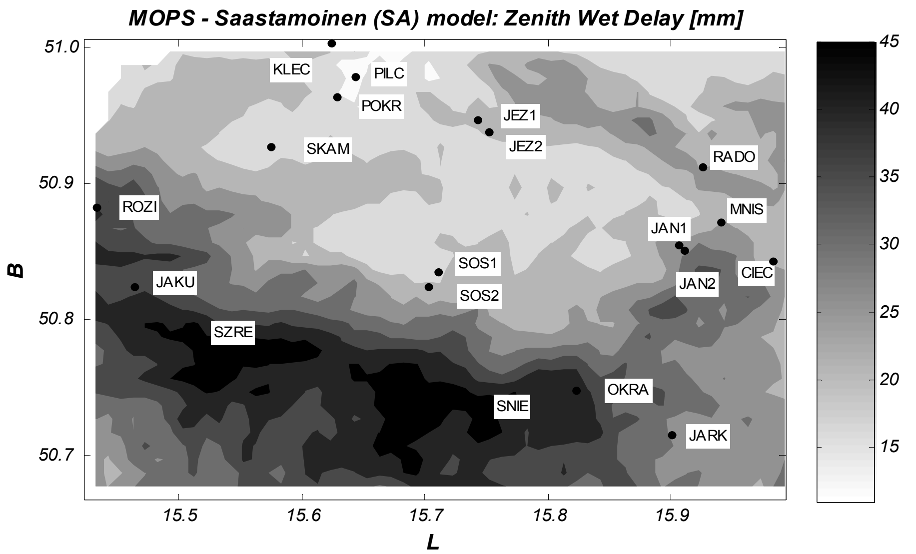


**Fig. 3** Difference between Tropospheric Zenith Wet Delay $\delta T_{w,0}$ computed from MOPS model and Saastamoinen model for area of KARKONOSZE network

**Table 3** Comparison of selected mapping functions

| Mapping function | P | T | e | β | $h_T$ | h | B | other | $\varepsilon_{min}$ |
|---|---|---|---|---|---|---|---|---|---|
| (Baby et al., 1988) | √ | √ | √ | | | √ | | | 10° |
| (Davis et al., 1985) | √ | √ | √ | √ | √ | | | | 5° |
| (Goad and Goodman, 1974) | √ | √ | √ | | | √ | | | n/a |
| (Herring, 1992) | | √ | | | | √ | √ | | 3° |
| (Hopfield, 1969) | | √ | | | | √ | | | n/a |
| (Ifadis, 1986) | √ | √ | √ | | | | | | 2° |
| (Niell, 1996) | | | | | | √ | √ | DOY | 3° |
| (Saastamoinen, 1973) | √ | √ | √ | | | √ | | | 10° |
| (Guo and Langley, 2003) | | | | | | √ | √ | | 2° |

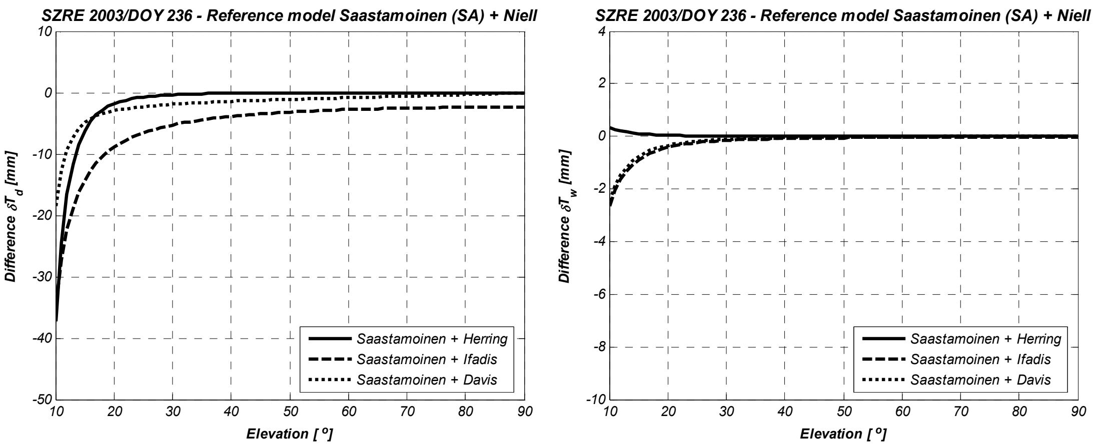


**Fig. 4** Comparison of selected hydrostatic $\delta T_{d,0}$ and wet $\delta T_{w,0}$ mapping functions with the Niell model serving as reference - in mm

the so called standard atmosphere model. The wet part $\delta T_{w,0}$ (Zenith Wet Delay) is difficult to model because of heterogeneous distribution of water vapor in the atmosphere (Schüler, 2001). The results of comparisons presented in Figures 2 and 3 showing large divergences in the case of wet component and comparable values for the dry one, confirm this.

Table 3 shows selected mapping functions tropospheric slant delay as functions of atmosphere parameters and minimum elevation angle.

In the Figure 4 comparisons of selected mapping functions with reference to the Niell function (Niell, 1996) for the hydrostatic and wet components on the example of the SZRE point from the *KARKONOSZE* network (Fig. 1) has been presented.

## 4. TROPOSPHERE DELAY ESTIMATION AND COORDINATES DETERMINATION IN LOCAL NETWORK KARKONOSZE

During GPS observations processing for precise determinations with programmes such as *Bernese GPS Software* (Hugentobler et al., 2001) both the deterministic and stochastic models are used. The tropospheric slant delay is determined as a function of observation time *t* (1h or 2h intervals) and zenith distance *z* (alternatively elevation $\varepsilon = (90 - z)$) of a satellite.

$$\delta T(t,z) = m_{apr.}(z) \cdot \delta T_0 + m(z)\delta T_0(t) \quad (4)$$

where

$\delta T(t, z)$ – troposhperic slant delay in the satellite direction as a satellite observation time *t* and zenit angle *z*,

$\delta T_0$ - tropospheric zenith delay determined on the basis of an *a priori* model deterministic model) $\delta T_0$ (2),

$m_{apr.}(z)$ – mapping function the a priori model $\delta T_0$ from the zenith direction to the slant (satellite) direction,

$\delta T_0(t)$ – tropospheric zenith delay as a function of observation time *t*, time correction (stochastic model),

$m(z)$ - function mapping delay $\delta T_0(t)$ from the zenith direction to slant (satellite) direction.

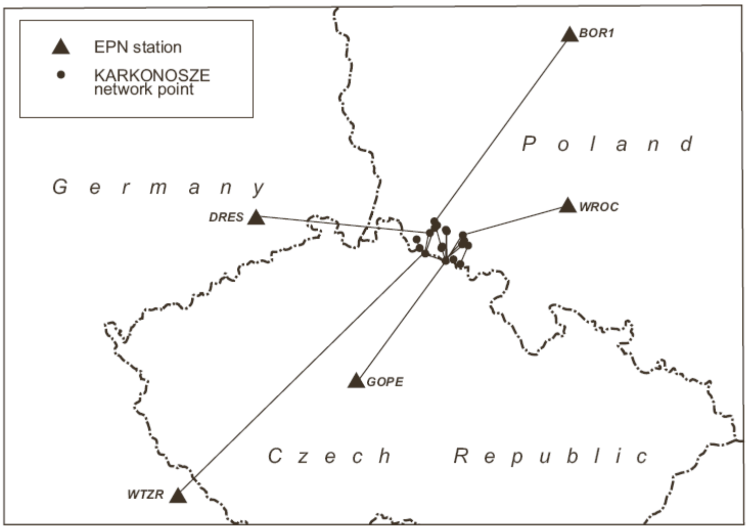


**Fig. 5** Scheme of the KARKONOSZE network connection to EPN stations

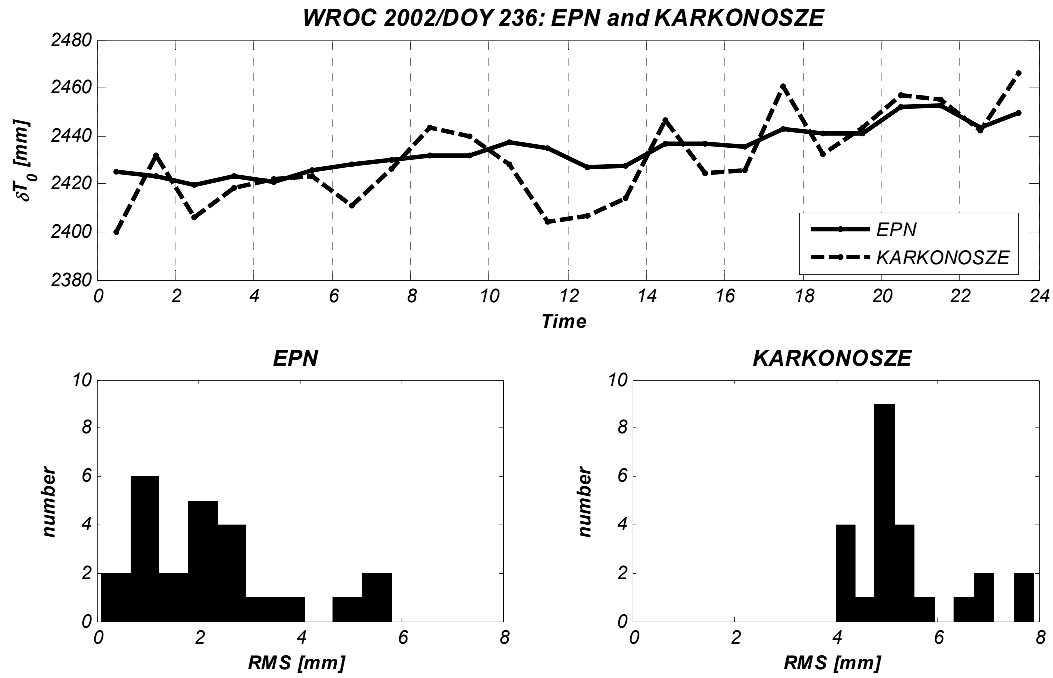


**Fig. 6** Comparison of estimated tropospheric zenith delay $\delta T_0$ from EPN solution and KARKONOSZE solution (without meteo data) for the WROC station

The processing of the KARKONOSZE network has been done with strategy dedicated for local networks (Bosy and Figurski 2003; Bosy et al., 2001). Tropospheric delay estimation has been performed according to the relationship (4) using the *a priori* Saastamoinen model ($\delta T_0$) with the Niell mapping functions ($m_{apr.}(z)$ and $m(z)$) (Niell, 1996) for 1 h intervals ($\delta T_0(t)$) in connection to IGS/EPN stations (BOR1, DRES, GOPE, WROC, WTZR) (Fig. 5). GPS observation processing is performed at an 10° elevation mask and with $w(z)=cos^2 z$ weighting function.

Figure 6 shows the estimated values of delay $\delta T_0$ and RMS errors for the WROC station from weekly solution of the EPN network and local network *KARKONOSZE* connected to IGS/EPN stations.

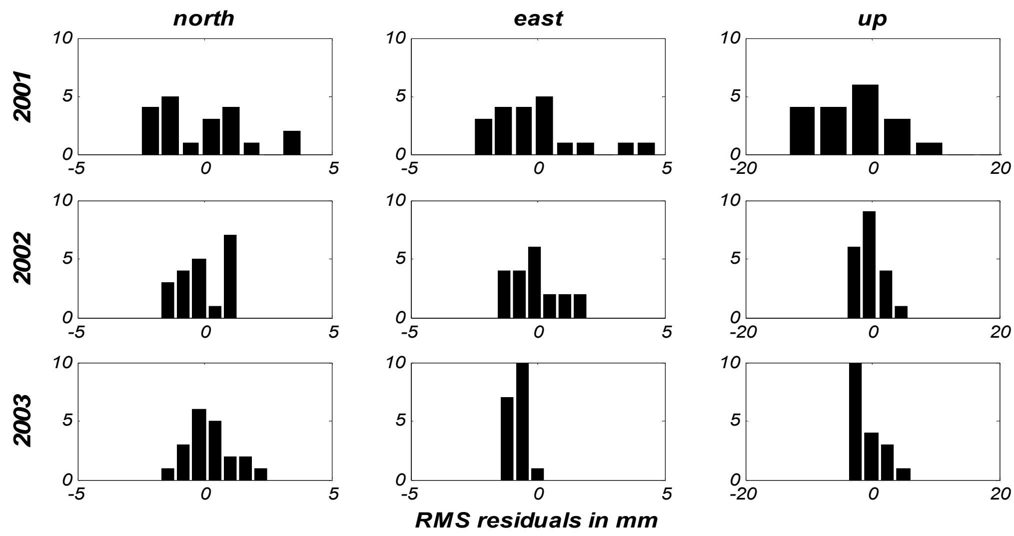


**Fig. 7** Distribution of non-weighted RMS values [mm] of coordinates residuals for campaigns 2001, 2002 and 2003

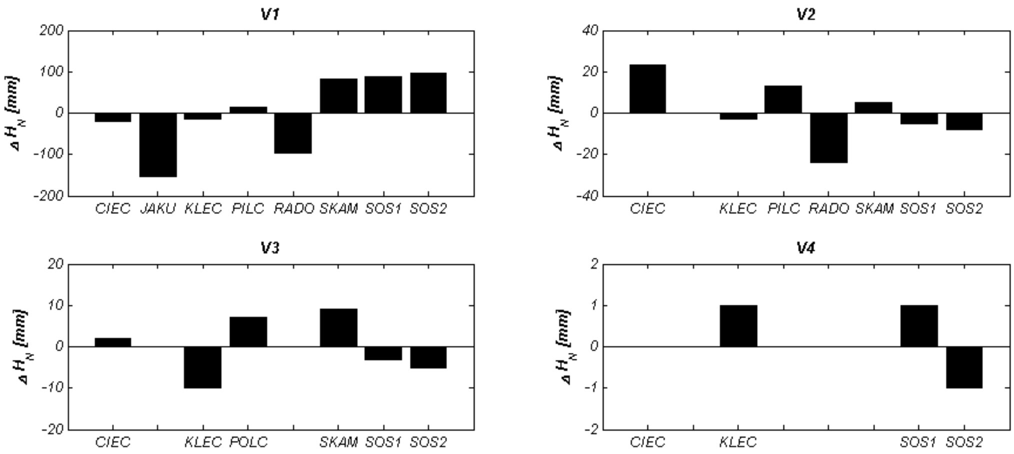


**Fig. 8** Transformation of ellipsoidal heights $h_{GPS}$ into normal heights $H_N$

The estimated values of tropospheric zenith delay $\delta T_0$ from the EPN solution are the averaged values from minimum three EPN sub-networks' solutions for each of the stations. The values of differences between EPN and KARKONOSZE solutions for all five IGS/EPN stations are contained within the −30mm ÷ +20 mm. The RMS errors for the KARKNOSZE network solution are twice as high compared with the EPN network solution.

The quality of solutions presented as histograms of mean error distribution of the RMS coordinate components residuals in the KARKONOSZE network for all the measurement campaigns between 2001 and 2003 has been given in Figure 7.

The results of KARKONOSZE network solutions for particular campaigns have shown better accuracy in the case of 2002 and 2003 measurements in comparison to the 2001 one. The increase of accuracy, particularly for vertical component of coordinates in 2002 and 2003 is a result of observation time extended to 24 hours.

Normal heights have been determined for selected GPS points of the KARKONOSZE network by connecting them to the national levelling network benchmarks to verify the estimated heights of these points. The connection has been realised using the precise geometrical levelling method. The choice of points has been limited by topography (large elevation differences) and proximity of national benchmarks. As a result, no points have been selected located on mountain peaks.

Ellipsoidal heights $h_{GPS}$ have been fitted into the normal heights $H_N$ using 1st degree transformation (planar). Figure 8 shows deviations on the control points for four fitting variants.

The V1 variant fitting included all the points with given heights $h_{GPS}$ and $H_N$ . The largest deviation in this variant has been obtained for the JAKU point (152 mm). The 2nd class benchmark of the national levelling network to which the GPS network point had been connected. The benchmark in Jakuszyce has been excluded from the last measurements of national levelling lines and is not listed in the newest catalogues according to which the heights of the remaining 1st and 2nd class benchmarks have been again verified. The JAKU point has been excluded from fitting in the V2 variant. This has caused significant reduction of deviations on the remaining control points (Fig. 8). Points with maximum deviation values have been removed in the V3 and V4 variants but the values of deviations on control points were no more as significant as in the V1 variant.

## 5. CONCLUSIONS

Local network should be connected to IGS/EPN permanent GPS stations. This allows processing of the network in a specified reference frame. The troposphere parameters in the form of tropospheric zenith delay in 1-hour intervals for permanent GPS stations are the connecting element. These should be used as input data in the process of troposphere delay estimation for the remaining network points.

In the case of local networks located in mountainous terrain estimation of tropospheric delay is the most important stage of processing. It has key influence on the determined coordinates of points, particularly the vertical component. The tropospheric delay estimation procedure presented in this study, basing on standard atmosphere model for the KARKONOSZE network has yielded twice as high RMS error values as in the case of EPN networks. An alternative solution is to use estimation of delay based on local atmosphere model having large time resolution where tropospheric delay estimation procedure does not require time correction.

Fitting ellipsoidal heights into normal ones through transformation has shown high accuracy, however verification for points situated on mountain peaks in not possible in this way. The national Geoid model is used to reduce ellipsoidal heights of network points to normal heights. However full verification requires use of centimetre geoid model, which for mountainous areas is not available at the moment.

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