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THE QUALITY OF METEOROLOGICAL OBSERVATIONS AND TROPOSPHERIC DELAY FROM EPN/IGS PERMANENT STATIONS LOCATED IN THE SUDETY MOUNTAINS AND IN THE ADJACENT AREAS

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ABSTRACT
The mountain type of climate, which is typical for the Sudety Mountains, is well known for its rapid and frequent changes in pressure, temperature and humidity. The fluctuations in meteorological parameters cause fast changes of the tropospheric delay, as a correlated value, and in consequence difficulties in GPS heights determination. The tropospheric delay is a function of the meteorological parameters obtained directly from synoptic stations and models. The paper presents the procedure of tropospheric delay estimation on the European Permanent Network and International GNSS Service (EPN/IGS) stations, using meteorological observations from synoptic stations (Wrocław Airport, Śnieżka) of the Polish Meteorology Service (IMGW), stations (Cervena, Praha–Kbely) of the Czech Hydrometeorological Institute (CHMU), and sensors mounted close to the antennas of the permanent GNSS stations (BISK, SNEC, WROC, GOPE). The values obtained from Global Pressure and Temperature (GPT) model were bases for the meteorological data calibration at EPN/IGS stations. The tropospheric delay (Zenith Total Delay - ZTD) on EPN/IGS stations was obtained from Saastamoinen formula and compared with ZTD from EPN solutions.

KEYWORDS: GPS for meteorology, tropospheric delay, GNSS permanent stations, precise GPS positioning, Sudety Mountains

1. INTRODUCTION

The distribution of water vapour in the troposphere is a crucial factor in many sciences , e.g. climatology, synoptic meteorology, and nature conservation. There are several factors that influence the amount of moisture in the air: land use, vegetation, amount of water bodies, foreign air masses advection, climatic seasons, and others. However in contrary, there are very few methods to measure its amount and distribution. Among the measurements techniques are: in situ measurements at synoptic stations, radiosondes, refractometers, satellite acquisition by passive sensors, and also the GPS (Shrestha, 2003; Hoyle, 2005; Flores et al., 2000; Hirahara, 2000). The GPS with its architecture of two parts – space and ground has - a special ability to provide data concerning the state of the atmosphere. This ability arises from the GPS signal distortions that influence the signal during its passage through the atmosphere. The magnitude of these distortions is a function of the meteorological parameters: pressure, temperature, and water vapour. While the first two quantities might be derived from other sources (measurements, model estimation), the last quantity might be estimated with the use of GPS data.

This paper is a part of the GPS for meteorology project: "The local spatiotemporal model of troposphere based on GPS observations and meteorological parameters". The main aim of the project is to estimate spatial and temporal distribution of water vapour in the troposphere above the local GPS network connected to EPN/IGS stations. The task would be fulfilled with the use of troposphere tomography model and inverse technique (Shrestha, 2003; Hoyle, 2005; Flores et al., 2000).

There are two main data inputs for the model: first the GPS observations, and second the meteorological parameters used as a reference. In the present stage of the project three tasks have been completed; meteorological data reliability assessment (data completeness, accuracy), meteorological GPT model accuracy assessment, and an evaluation of EPN ZTD product as a proper reference for the Sudety subnetwork.

2. METEOROLOGICAL PARAMETERS

The set of basic meteorological parameters consists of temperature t [ºC], pressure p [hPa], and relative humidity H [%]. These parameters have been measured on four GPS stations (WROC, GOPE, BISK, SNEC) with the use of meteo packs, and on four synoptic stations: WROCLAW AIRPORT, PRAHA-KBELY, CERVENA, SNEZKA (Figure 1).

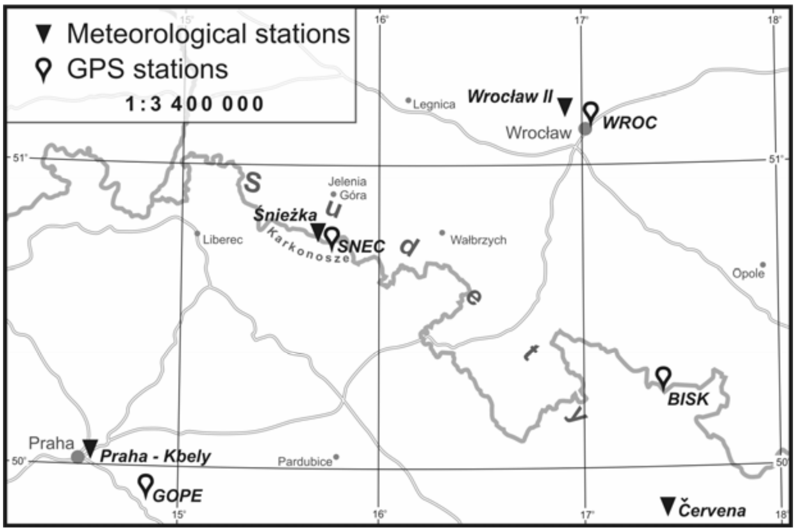


Fig. 1 Meteorological and GPS stations.

Table 1 Data sources with precision.

Quantity	Meteorological labs	IMGW or CHMU	GPT model
• pressure [hPa]	0.3 – 0.5	0.2	5.0
• temperature [^{0}C]	0.3 – 0.5	0.2	3.0
• humidity [%]	3.0 – 5.0	2.0	

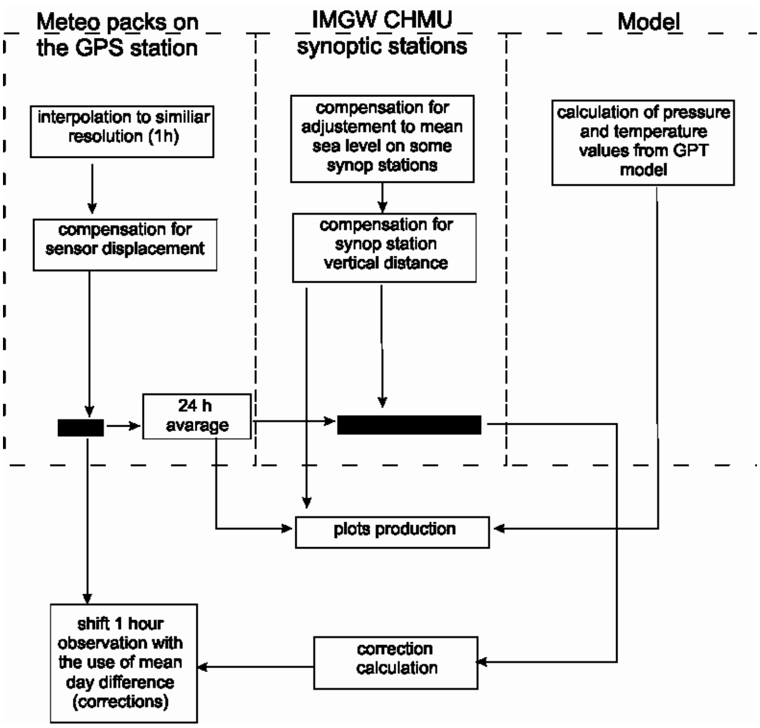


Fig. 2 Data comparison and calibration flow scheme.

Table 2 The precision characteristics of raw data from meteo packs.

Station	pressure [hPa]		temperature [^{0}C]	
	bias	STD	bias	STD
WROC	1.88	0.80	1.48	1.20
GOPE	-1.06	10.04	-5.96	5.60
SNEC	-0.14	0.80	0.41	0.76
BISK	48.74	12.28	-2.06	8.40

Table 3 Meteorological data calibration results.

Station	pressure [hPa]		temperature [^{0}C]	
	bias	STD	bias	STD
WROC	0.94	0.40	0.74	0.60
GOPE	-0.53	5.02	-2.98	2.80
SNEC	-0.07	0.40	0.21	0.38
BISK	24.37	6.14	-1.03	4.20

Table 4 GPT comparison with data from meteo packs.

Station	pressure [hPa]		temperature [^{0}C]	
	bias	STD	bias	STD
WROC	2.64	7.68	1.36	3.75
GOPE	-0.14	4.02	-0.74	6.94
SNEC	-0.32	6.58	1.85	3.92
BISK	48.88	9.14	2.22	4.32

Corresponding values were also obtained with the use of the Global Temperature and Pressure (GPT) model (Boehm et. al., 2006). The period of investigation was the whole year 2006. The institutions and sensors precision are denoted in Table 1.

To compare and calibrate meteorological data from meteo packs with the use of data from synoptic stations, special procedures have been applied (Figure 2).

Concerning the data from meteo labs near GPS antennas there have been three steps. First was to average each station RINEX data set to 1h-resolution, second was to compensate for sensor displacement (if any), and finally, additional data sets with one pressure, temperature and humidity mean value per day were computed. The data from meteorological synoptic stations was also subject to recalculations. They were first compensated for adjustment to mean sea level, then the meteorological parameters were lifted to the antenna level, using Berg (1948) equation with pressure p:

$$p = p_t + \left[1 - 0.0000226 \cdot (h - h_t)\right]^{5.225} \tag{3}$$

where

p_t - is pressure on meteorological station level *[hPa]*,

h and h_t - are the heights of antenna and pressure sensor respectively *[m]*.

Concerning temperature *t,* the classic wet laps rate of –0.68 ^{0}C per 100 m has been used (Mendes, 1999). The humidity values were not edited due to strictly local characteristics of this phenomena.

The next step was to calculate differences between data sets from meteorological synoptic stations and meteo packs (mean 24 hours values), and finally to shift the 1h-resolution meteo pack's data. The results of the calibration are presented in Table 3 and Figures 3 and 4.

At station GOPE the quantity of data caused problems. In 2006 a very small number of data has been registered, see Figure 3.b and Figure 4.b. Some of the RINEX files were temporally corrupt (time-stamp failure), moreover the data sets for pressure, temperature and humidity did not overlap. The pressure bias at the station WROC is probably caused by pressure sensor height miss - measurements. Figures 4.b and 4.d show no synoptic station temperature due to significant distance between sensors.

The GPT model confirmed its accuracy at all stations. The range of temperature and pressure, site biases and standard deviations are presented in Table 4 and Figures 3 and 4 .

The BISK station pressure sensor performs poorly – the bias (almost 50 hPa) might be the result of a lightning stroke (Frantisek Mantlik personal communication, Figure 3 d).

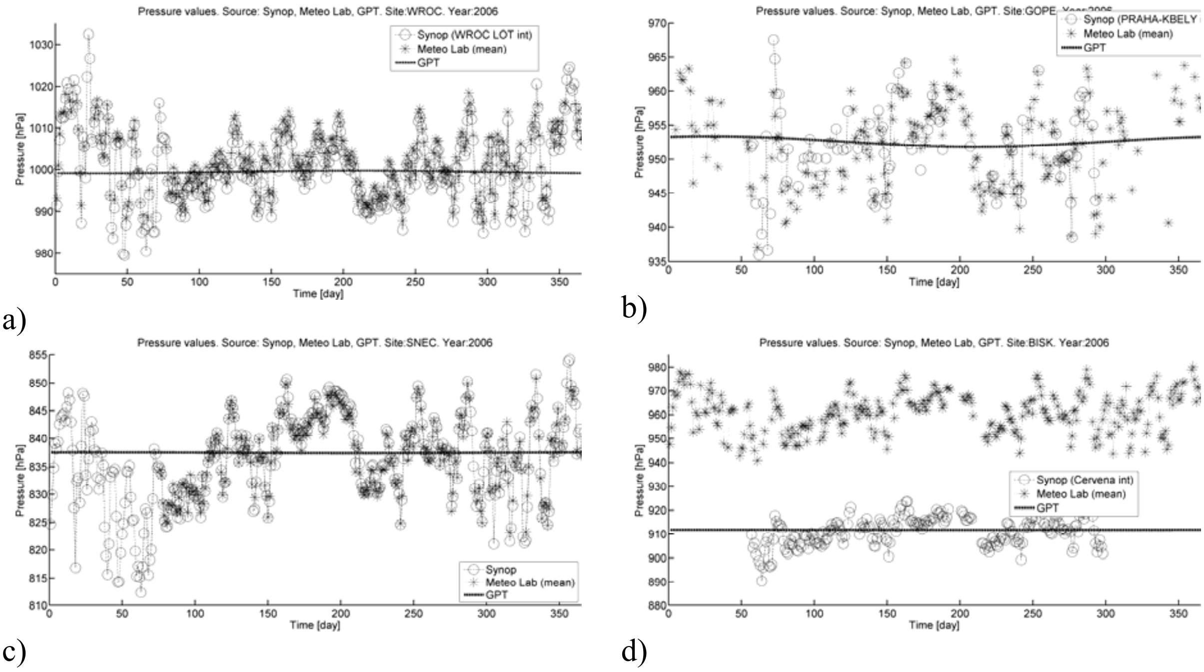


Fig. 3 Pressure values at station: a) WROC b) GOPE c) SNEC d) BISK.

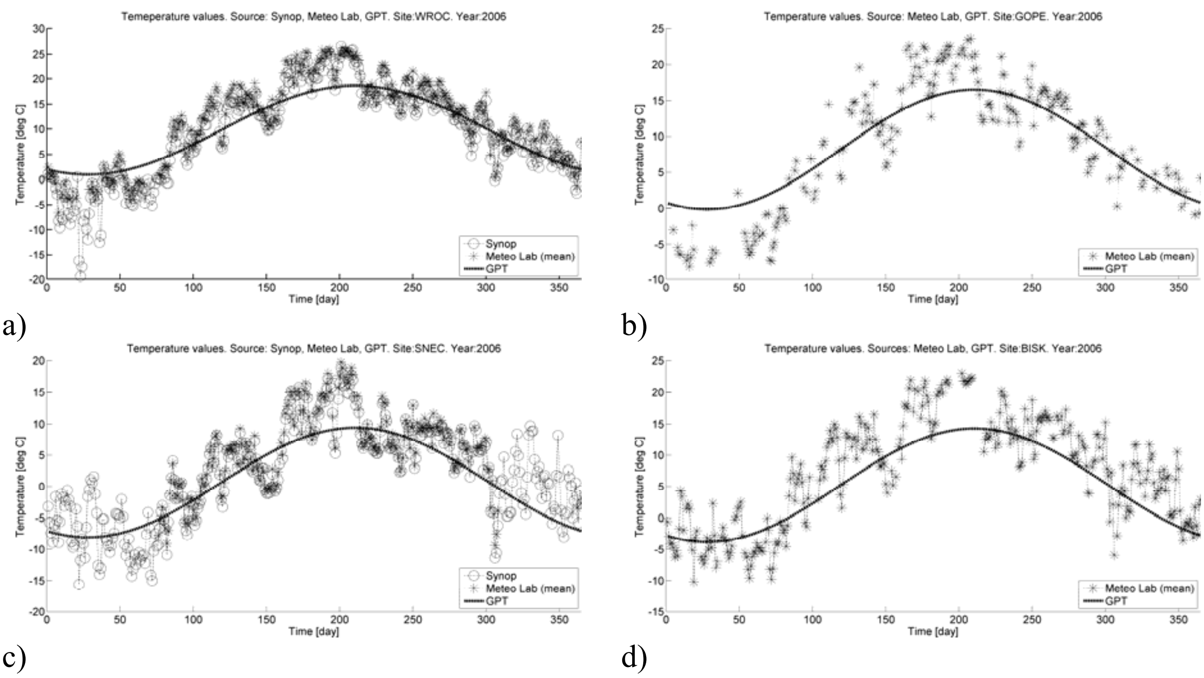


Fig. 4 Temperature values at station a) WROC b) GOPE c) SNEC d) BISK.

3. TROPOSPHERIC DELAY

The GPS signal passing trough the troposphere is subject to bending of the ray path and slowing of the propagation speed – which in result lead to delays in signal arrival. These phenomena are due to differences in refractivity along the ray path. The refractivity:

$$N = N_d + N_w \tag{3}$$

might be separated into two components (Hopfield, 1969); wherein the wet part N_w is caused by the varying amount of water vapour and temperature gradient in the troposphere, and the hydrostatic (dry) part N_d is a result of the pressure gradient. By analogy

Table 5 The results of comparison of two sources of ZTD.

Station		ZTD residuals	
	bias [m]	STD [m]	correlation coeficience
WROC	0.01	0.03	0.89
GOPE	-0.05	0.03	0.83
SNEC	0.01	0.02	0.81
BISK	0.16	0.04	0.88

Zenith Tropospheric Delay (ZTD) can be split into a hydrostatic part *ZHD* and a wet part *ZWD:*

$$ZTD = ZWD + ZHD \tag{3}$$

The two sources of Zenith Tropospheric Delay have been investigated: mean weekly solution data from all Local Analysis Centers (LACs) of the EPN *(http://igs.ifag.de…/EUREF/products)*, and calculated by Saastamoinen formulas (Saastamoinen, 1972) using ground meteorological observations.

$$ZHD = \frac{0.0022767 \cdot p}{1 - 0.00266 \cdot \cos 2\varphi - 0.00000028 \cdot h_e} \tag{4}$$

$$ZWD = 0.002277 \cdot \left(\frac{1255}{T} + 0.05 \right) \cdot e \tag{5}$$

Where φ is station latitude*[^{o}]*, h_e is ellipsoidal high *[m]*, T is temperature *[^{o}K]*, and e is water vapour partial pressure *[%]*. The conversion between relative humidity H *[%]* and water vapour partial pressure e has been done with the use of equation (6) in case of saturated water vapour over the water e_s or (7) in case of saturated water vapour pressure over the ice e_s. The equation (8) have been used to switch from saturated to observed water vapour partial pressure e.

$$e_s = 6.11 \cdot \exp^{\left(\frac{-2.500 \cdot 10^6}{461.525} \cdot \left(\frac{1}{t} - \frac{1}{273.16} \right) \right)} \tag{6}$$

$$e_s = 6.11 \cdot \exp^{\left(\frac{-2.834 \cdot 10^6}{461.525} \cdot \left(\frac{1}{t} - \frac{1}{273.16} \right) \right)} \tag{7}$$

$$e = H \cdot e_s \tag{8}$$

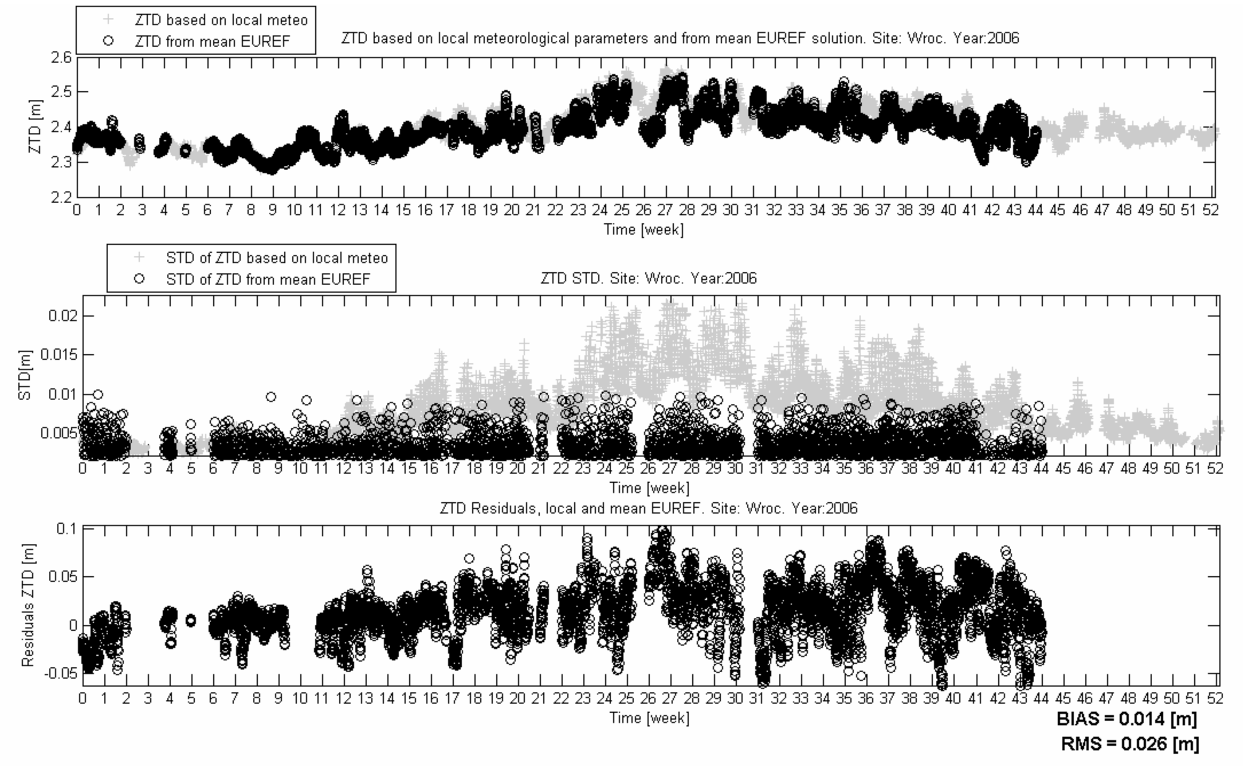
The accuracy of ZTD obtained from ground meteorological observations using equations (4, 5) based on the sensor's precision, forwarded by error propagation is on the level of few centimeters, which has been confirmed by cross validating with radiosonde observations (Mendes and Langley, 1999).

The product of the EPN mean solution originates from different LACs with diverse *ZTD* strategies. The most frequently applied way to obtain *ZTD* is to calculate a priori model (e.g. Saastamoinen model) mapped with Dry New Mapping Function (Niell, 1996) and *ZTD* (time-dependent) parameters with Wet New Mapping Function (Niell, 1996, 2000) estimated at 1-hour intervals for each station (Dach et al., 2007). The horizontal gradient parameters (tilting, 1 per 24 hrs in NS and EW) were estimated for each station per day (Söhne and Weber, 2005). The accuracy of *ZTD* at 1-hour intervals for each station reported by weekly BKG combined EPN solution is on the level of several millimeters. Comparison of these two data sets shows positive and strong correlation (Table 5).

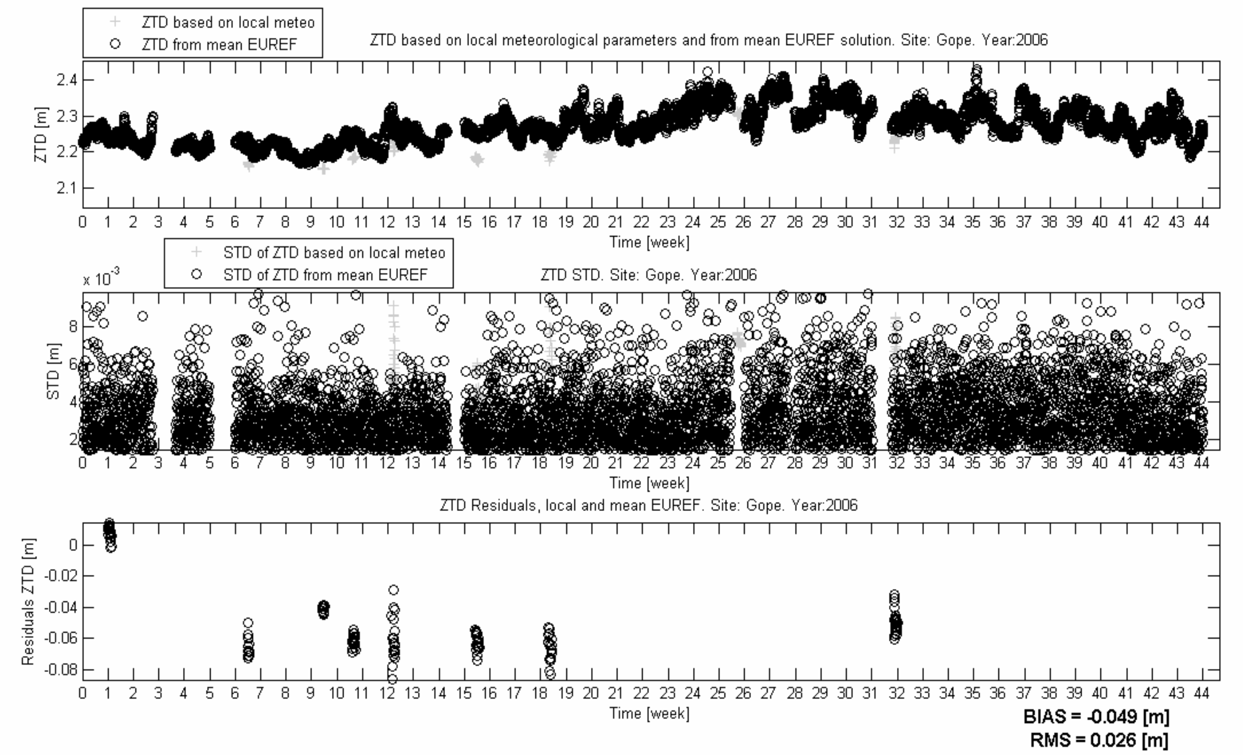
The *ZTD* STD pictured at the middle panel shows that generally *ZTD* derived from GPS is more precise than the *ZTD* from meteorological parameters. The weaker precision during summer on each station originates from higher values of humidity and temperature (Figure 4) during the warm seasons. This leads to the larger scatter in case of the Saastamoinen model. The correctness of this statement has been proofed at the station SNEC, where the summer temperatures are rather small due to high elevation. Thus the meteorological STD values are on the same level as those of the GPS solution.

The residual standard deviations (Table 5) vary from 0.023 m at the station SNEC up to 0.039 m at station BISK. The accuracy at the station SNEC is a consequence of the vicinity of the meteorological station – data were calibrated with the use of very accurate data. On the other hand the weaker accuracy of BISK station is in all probability the result of problems with sensor and/or digital converter (Frantisek Mantlik personal communication) after the lightning stroke. The residuals in all four examples in case of RMS is of the order of several centimeters, which has been proofed as the agreement level between radiosonde data raytracing *ZTD* and the GPS *ZTD* (Mendes and Langley, 1999).

According the bias at station SNEC is 0.007 m, by dint of location of the meteorological station, each meteorological parameter value might be compared directly with the ones obtained at GPS site, the distance between sites is relatively small. The bias at the station WROC (0.014 m) might be the result of significant distance between sites (almost 10 km).The height miss-measurements might also cause the pressure sensor bias. The bias at the station GOPE could not be sorted out due to lack of data. According

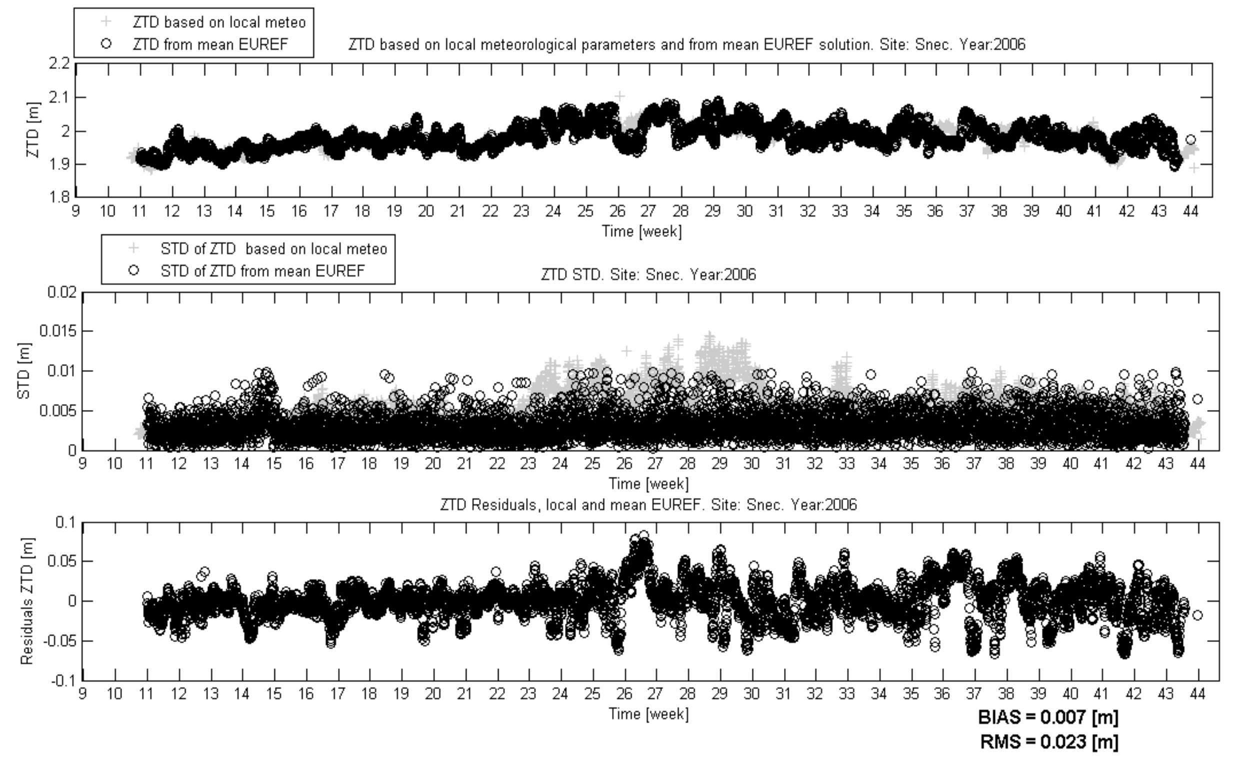


a)



b)

Fig. 5 ZTD for stations: a) WROC, b) GOPE, c) SNEC , d) BISK in the first panel, in the second panel ZTD STD and in the last panel residuals with BIAS and RMS.



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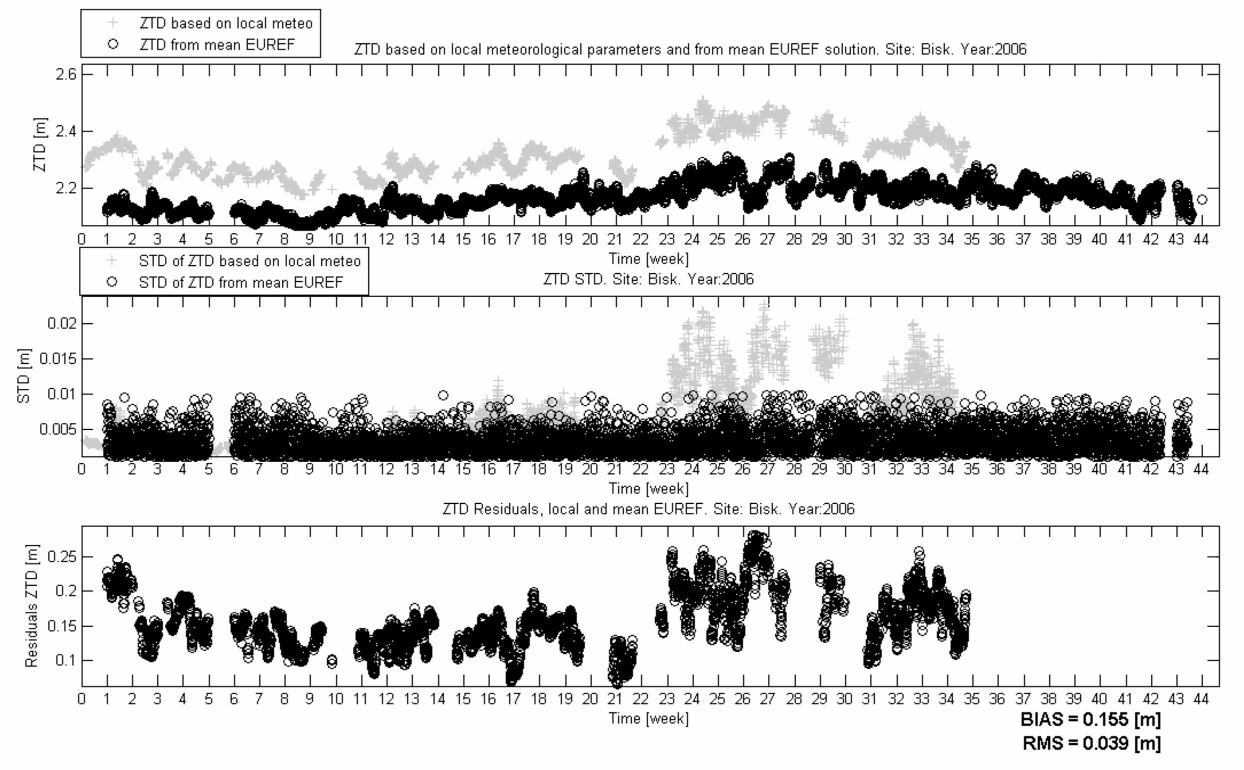

d)

Fig. 5 continue
ZTD for stations: a) WROC, b) GOPE, c) SNEC , d) BISK in the first panel, in the second panel ZTD STD and in the last panel residuals with BIAS and RMS.

to bias at the station BISK (0.155 m) is the result of the pressure sensor damage (Figure 3.d).

Even with the limitations detailed above the *ZTD* from both sources shows positive and strong correlation (Table 5) - *ZTD* from EUREF agrees with the *ZTD* derived with the use of Saastamoinen equations (4, 5).

4. CONCLUSION

We performed a successful validation of meteorological parameters and a comparison using three different sources, meteo labs mounted near the GPS antennas, synoptic meteorological stations working under the standards of World Meteorological Organization, and the GPT model. Also, we were able to confirm GPT model accuracy by comparing values calculated from the model with meteorological parameters obtained from the meteo packs. Different ways to estimate Zenith Tropospheric Delay lead to similar results, which shows that the GPS system may be used as a meteorological data source. The problems encountered with the pressure sensor at the BISK station in all probability caused by lightning stroke, and lack of data at the station GOPE probably by a RINEX construction problem. The next step will be estimation of Slant Tropospheric Delay (*STD*) in local GPS network “KARKONOSZE” in the connection with investigated EPN/IGS permanent stations, and the computation of the amount of water vapour in the troposphere over the network using the tomography technique

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