TROPOSPHERE MODELING IN LOCAL GPS NETWORK

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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 parameters require the best possible approach to tropospheric delay (TD) estimation expressed by maximum reduction of systematic error caused by tropospheric refraction. The procedure of local meteorological parameters modelling (interpolation) in a GPS network area on the basis of meteorological observations, carried out concurrently to GPS measurements was introduced. The paper presents results of GPS data processing of local network KARKONOSZE (Sudetes, SW Poland) using different input data (standard atmosphere, MOPS model and ground meteorological data) and different methods of tropospheric delay estimation.

INTRODUCTION

The crucial factor for points altitude determination on the basis of GPS observations is tropospheric refraction (tropospheric delay). It may be easily noticed in case of local networks points situated in mountainous areas where great variability of atmospheric conditions is observed. *(Borkowski et al., 2002; Bosy, 2005a)*.

The tropospheric delay may be divided into two components, dry (hydrostatic) and wet. Approximately 90% of tropospheric delay caused by refraction is due to dry (hydrostatic) component of troposphere; it depends mainly on atmospheric pressure on the Earth surface and therefore it is easy to modelling. The hydrostatic component δT_d (Hydrostatic Delay) may be precisely determined on the strength of the ground meteorological measurements or the model of so-called standard atmosphere *(Hugentobler et al., 2001)*. Remaining 10% of total tropospheric delay – wet component δT_w (Wet Delay) depends on the water vapour layout in the atmosphere and it is difficult to modelling *(Mendes, 1999; Schüler, 2001; Bosy and Figurski, 2003)*.

In this paper, comparative analysis of different models of tropospheric delay for dry and wet component are presented. Additionally, the procedure for building local troposphere model on the basis of meteorological conditions ground measurements, which were carried out simultaneously to GPS measurements within the whole network, was rendered. For the purpose of analysis, GPS and meteorological observations of the area covered with *KARKONOSZE* local network points *(Kontny et al., 2002)*, situated in the mountainous area, were applied.

TROPOSPHERE DELAY ESTIMATION

The tropospheric delay may be divided into dry and wet components and written as:

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

Hence, tropospheric refraction coefficients for dry and wet components may be defined as *(Kleijer, 2004)*:

$$N_d^{trop} = k_1 R_d \rho_m \tag{2}$$

$$N_w^{trop} = \left[k_2^{'} \frac{e}{T_k} + k_3 \frac{e}{T_K^2} \right] Z_w^{-1} \tag{3}$$

$$k_2^{'} = k_2 - k_1 \frac{R_d}{R_2} \tag{4}$$

where:

- k_i – empirically determined coefficients *(Mendes, 1999)* [K hPa^{-1}] (table 1),
- e – water vapor pressure at the receiving antenna altitude (wet component *w*) [hPa],
- T_K – temperature at the receiving antenna altitude [K],
- ρ_m – air masses density for wet component In [kg m^{-3}],
- R_d, R_w – gas constant respectively for dry component d and wet component w, determined empirically *(Owens, 1967)* [J kg^{-1} K^{-1}],
- Z_w^{-1} – air compression coefficient for wet component determined empirically *(Owens, 1967)*.

Values of k_i coefficients estimated empirically by different authors are presented in table 1.

Table 1 Empirical values of coefficients k_i

Reference	k_1 *[K hPa^{-1}]*	k_2 *[K hPa^{-1}]*	k_3 10^5*[K hPa^{-1}]*	k'_2 *[K hPa^{-1}]*
(Boudouris, 1963)	77.59 ± 0.08	72 ± 11	3.75 ± 0.03	24 ± 11
(Smith and Weintraub, 1953)	77.61 ± 0.01	72 ± 9	3.75 ± 0.03	24 ± 9
(Thayer, 1974)	77.60 ± 0.01	64.79 ± 0.08	3.776 ± 0.004	17 ± 10

Tropospheric slant delay δT (1) is the function of zenith distance z or satellite elevation $\varepsilon = (90 - z)$ and having factorized it into dry and wet components it may be written in the form of the following equation:

$$\delta T(z) = m(z)\delta T_0 = m_d(z) \cdot \delta T_{d,0} + m_w(z) \cdot \delta T_{w,0} \tag{5}$$

where:

- $m(z)$ – mapping function for dry (hydrostatic) $m_d(z)$ and wet $m_w(z)$ components,
- δT_0 – tropospheric zenith delay which consists of dry (hydrostatic) and wet components: $\delta T_0 = \delta T_{d,0} + \delta T_{w,0}$.

Tropospheric zenith delay models for dry and wet components $\delta T_{d,0} + \delta T_{w,0}$ are basically meteorological parameters functions. Table 2 depicts particular models of tropospheric zenith delay for dry and wet component including its parameters.

Table 2 Input parameters for troposphere zenith delay models

Model		e	T	P	φ	h	β	λ	other
(Hopfield, 1969, 1971, 1972)	*dry*		√	√					
	wet	√	√						
(Goad and Goodman, 1974)	*dry*		√	√					
	wet	√	√						
(Saastamoinen, 1973)	*dry*		√	√					
	wet	√	√						
(Baby et al., 1988)	*dry*		√	√		√	√		*G*, R_e
	wet		√			√	√		
(MOPS, 1998)	*dry*		√	√	√	√	√		*DOY,g*
	wet	√	√		√	√	√	√	*DOY,g*

e *– partial water vapor pressure,* ***T*** *– temperature,* ***P*** *– pressure,* ***φ*** *– latitude,* ***h*** *– altitude,* ***β*** *- temperature lapse rate,* ***λ*** *– dimensionless lapse rate of water vapor*

Mapping functions for slant tropospheric delay estimation are also dependent on meteorological parameters. They have limitations resulting from minimal satellite altitude. *(Mendes, 1999; Bosy, 2005a)*.

METEOROLOGICAL PARAMETERS MODELING

The rudimentary model on the basis of which plane meteorological parameters are designated are: temperature T_C in [*C*], pressure P in [*hPa*] and humidity H in [*%*] is the standard atmosphere model ***SA***:

$$\begin{aligned} T_C &= T_r - 0.0065(h - h_r) \\ P &= P_r(1 - 0.0000226(h - h_r))^{5.225} \\ H &= H_r e^{-0.0006396(h - h_r)} \end{aligned} \tag{6}$$

where reference parameters are values: h_r = 0 m, P_r = 1013.25 hPa, T_r = 18 ^{0}C and H_r = 50%.

The standard atmosphere model ***SA*** is fundamental for most software applied in processing of GPS data *(Hugentobler et al., 2001)*.

The other model which constitutes the base for designating plane meteorological parameters is ***MOPS*** (***M****inimum* ***O****perational* ***P****erformance* ***S****tandards for Global Positioning System*) *(MOPS, 1998)*. This model is founded on standard meteorological parameters dependences on geodetic latitude φ and seasonal changes of these parameters. Each of these meteorological parameters ξ is designated on a particular day of the year (*DOY*) as the geodetic latitude function φ according to dependency *(Schüler, 2001)*:

$$\xi(\varphi, DOY) = \xi_0(\varphi) - \Delta\xi(\varphi)\cos\left[\frac{2\pi(DOY - DOY_0)}{365.25[d]}\right] \tag{7}$$

where ξ_0 embraces mean values of meteorological parameters at the sea level ($h = 0m$) for given geodetic latitudes intervals φ (table 3) and $\Delta\xi_0$ are their seasonal changes (table 4) as the geodetic latitude φ functions (κ – dimensionless constant describing water vapor variation *(Smith, 1966)*) were empirically determined *(Schüler, 2001)*.

Table 3. Average values for the meteorological parameters ξ_0 used for tropospheric delay prediction

φ	$P_0[hPa]$	$T_0[K]$	$e_0[hPa]$	$\beta_0[K/m]$	$\kappa_0[-]$
≤ 15	1013.25	299.65	26.31	0.00630	2.77
30	1017.25	294.15	21.79	0.00605	3.15
45	1015.75	283.15	11.66	0.00558	2.57
60	1011.75	272.15	6.78	0.00539	1.81
≥ 75	1013.00	263.65	4.11	0.00453	1.55

Table 4. Seasonal variations of the meteorological parameters $\Delta\xi_0$ used for tropospheric delay prediction

φ	$\Delta P_0[hPa]$	$\Delta T_0[K]$	$\Delta e_0[hPa]$	$\Delta\beta_0[K/m]$	$\Delta\kappa_0[-]$
≤ 15	0.00	0.00	0.00	0.00000	0.00
30	-3.75	7.00	8.75	0.00025	0.33
45	-2.25	11.00	7.24	0.00032	0.46
60	-1.75	15.00	5.36	0.00081	0.74
≥ 75	-0.50	14.50	3.39	0.00062	0.30

Parameters $\xi_0(\varphi)$ and $\Delta\xi_0(\varphi)$ are denoted by interpolation the data included in tables 3 and 4:

$$\begin{aligned} \xi_0(\varphi) &= \xi_0(\varphi_i) + \left[\xi_0(\varphi_{i+1}) - \xi_0(\varphi_i)\right]\frac{\varphi-\varphi_i}{\varphi_{i+1}-\varphi_i} \\ \Delta\xi_0(\varphi) &= \Delta\xi_0(\varphi_i) + \left[\Delta\xi_0(\varphi_{i+1}) - \Delta\xi_0(\varphi_i)\right]\frac{\varphi-\varphi_i}{\varphi_{i+1}-\varphi_i} \end{aligned} \tag{8}$$

Model ***MOPS***, in case of lacking meteorological parameters observations, may be used for tropospheric delay determination as the standard atmosphere model ***SA*** substitute.

One of the methods to reflect the atmosphere conditions within the local GPS network is a local troposphere model ***LT***. Input data for this model composes meteorological observations which are conducted simultaneously to GPS measurements at the same points. Unless measurements are carried out at all points, observations from meteorological stations may be additional advantage to take of. In this case, it is essentials to designate meteorological parameters of all GPS points by modeling (interpolation) *(Borkowski et al., 2002; Bosy, 2005a,2005b)*.

In this model meteorological parameters values ξ in GPS points (temperature T_{GPS}, pressure P_{GPS} and humidity H_{GPS}) are denoted as weighted average $\bar{\xi}_{GPS}$:

$$\bar{\xi}_{GPS} = \frac{\sum_{i=1}^{n} \xi_i w_i}{\sum_{i=1}^{n} w_i} \tag{9}$$

where: ξ_i are meteorological parameters T_i, P_i i H_i from n points, at which meteorological observations were made (meteorological points), while weights w_i are computed depending on interpolated parameters.

For temperature $\xi = T$ weight w_i is computed on the basis of equation:

$$w_i = (h_{GPS} - h_i)^{-4} \tag{10}$$

where $h_{GPS} - h_i$ is the height difference between GPS and meteorological point i.

For pressure $\xi = P$ weight w_i is computed from the equation :

$$\frac{1}{w_i} = (x_{GPS} - x_i)^2 + (y_{GPS} - y_i)^2 \tag{11}$$

where:

x_{GPS} i y_{GPS} – plane coordinates of a GPS point,

x_i i y_i – plane coordinates of a point with meteorological observations, where the dependence occurs *(Kluźniak, 1954)*:

$$\log P_i = \log P_j + \frac{h_j - h_{GPS}}{\bar{\mu}\left(1 + \frac{T_{GPS} + T_j}{546}\right)} \qquad i = j \tag{12}$$

coefficient $\bar{\mu}$ (standard $\bar{\mu} \approx 18400$ [m/C]) is computed as an arithmetic average for network, which is based on points from meteorological observations

$$\bar{\mu} = \frac{h_i - h_j}{\left(1 + \frac{T_i + T_j}{546}\right)\log\frac{P_j}{P_i}} \qquad \begin{array}{l} i = 1, 2, \ldots, n \\ j = i, i+1, \ldots, n-1 \end{array} \tag{13}$$

The coefficient $\bar{\mu}$ may be also locally designated, on the strength of pressure and temperature values which were measured at points. In the presented algorithm, the coefficient $\bar{\mu}$ is computed locally in each of TIN network triangles, which is made of points at which meteorological parameters had been measured. In this way coefficient $\bar{\mu}$ reflects also a model error (12) within the given area. Then, this coefficient is used for pressure interpolation at other points situated inside a specific triangle or in its vicinity. Coefficient $\bar{\mu}$ values distribution within *KARKONOSZE* network *(Kontny et al., 2002)* and the method for pressure values local interpolation is presented in fig.1. In mountainous areas the coefficient μ value hesitates considerably during the day.

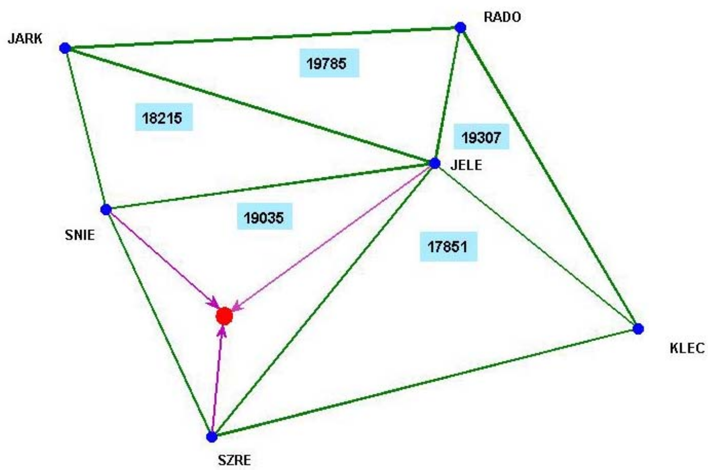

Fig. 1 Coefficient $\bar{\mu}$ values distribution within KARKONOSZE network and atmospheric pressure local interpolation.

Fig. 2 depicts time changes of coefficient μ for one of the *KARKONOSZE* network points. Therefore, coefficient μ is computed locally for the given moment in time.

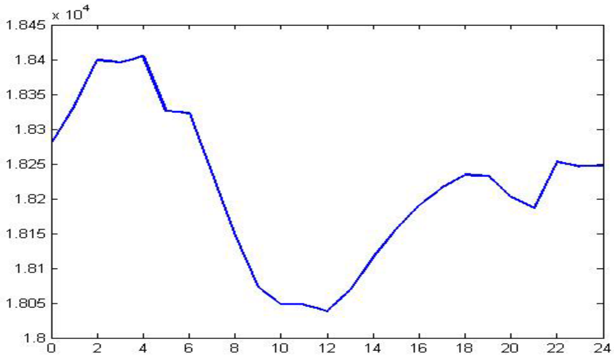

Fig. 2 Coefficient $\overline{\mu}$ *time distribution for baseline SNIE-JELE of KARKONOSZE network.*

The weight for humidity $\xi = H$ derives from equation:

$$\frac{1}{w_i} = (x_{GPS} - x_i)^2 + (y_{GPS} - y_i)^2 + (h_{GPS} - h_i)^2 \tag{14}$$

Local troposphere model ***LT*** features greater time resolution than ***SA*** i ***MOPS*** models, what comes from meteorological parameters observation resolution. The resolution may be the same as GPS observation interval (for example 30 sec.).

Figures 3, 4 and 5 show differences between day average values of meteorological parameters (temperature T , pressure P and humidity H) designated on the basis of local troposphere model ***LT***, standard atmosphere ***SA*** and ***MOPS*** models for the area covered with *KARKONOSZE* local network, registered 24th August 2002 (*DOY 236, 12:00*).

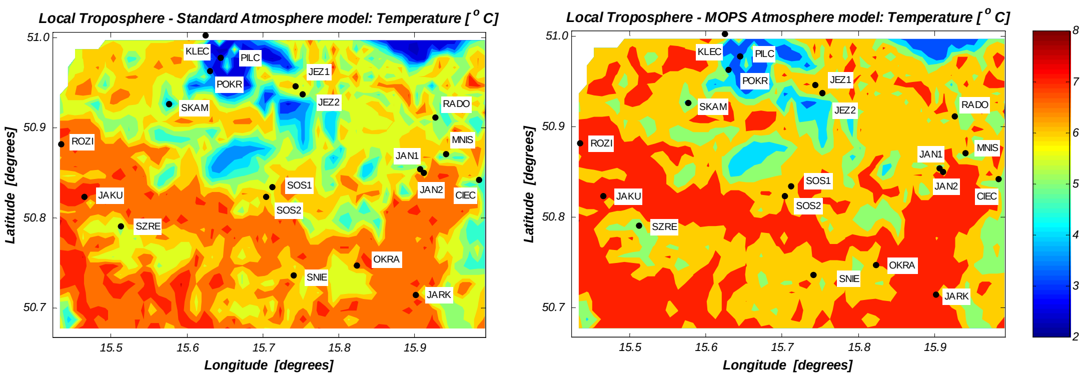

Fig. 3 Differences between local troposphere model LT and models of standard atmosphere SA and MOPS in the area of KARKONOSZE network: temperature distribution

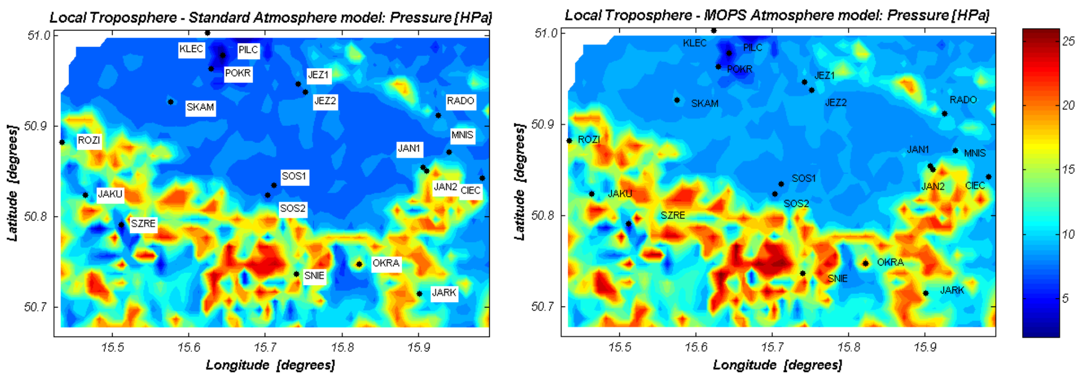

Fig. 4 Differences between local troposphere model LT and models of standard atmosphere SA and MOPS in the area of KARKONOSZE network: pressure distribution

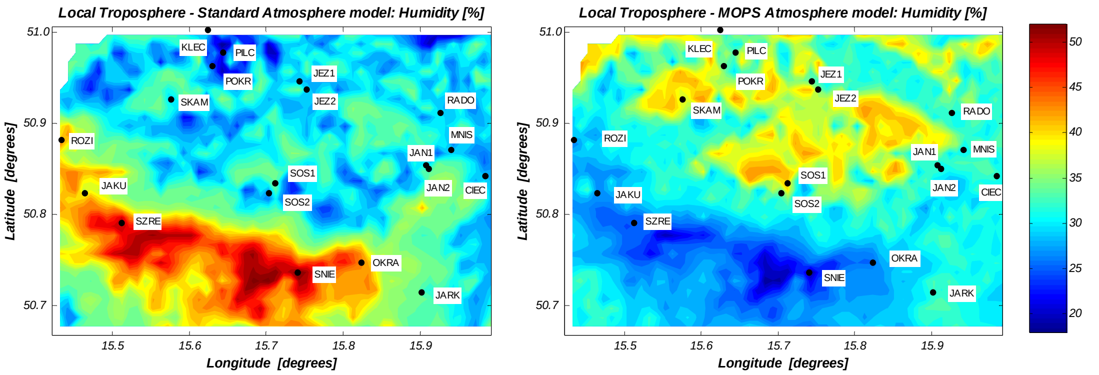

Fig. 5 Differences between local troposphere model LT and models of standard atmosphere SA and MOPS in the area of KARKONOSZE network: humidity distribution

As it may be concluded from figures 3, 4 and 5 differences between local troposphere model ***LT*** and standard atmosphere ***SA*** and ***MOPS*** models for temperature belong to interval (1 ^{o}C, 7 ^{o}C). Maximal differences values for pressure are 25 hPa, and for humidity they are considerably greater and reach 42%.

COMPARISON OF TROPOSPHERIC DELAY ESTIMATIONS RESULTS

Meteorological parameters designated on the basis of local troposphere model ***LT*** and standard atmosphere models ***SA*** i ***MOPS*** were foundation for tropospheric zenith delay estimation for dry component (Zenith Hydrostatic Delay: ZHD) $\delta T_{d,0}$ and wet component (Zenith Wet Delay: ZWD) $\delta T_{w,0}$. For the purpose of tropospheric zenith delay estimation from local troposphere model ***LT*** and standard atmosphere model ***SA*** Saastamoinen's function was used. *(Sastamoinen, 1973)*.

Figure 6 shows tropospheric zenith delay values (*ZHD* i *ZWD*) calculated on the basis of local troposphere model ***LT*** for the area covered with *KARKONOSZE* local network for one day of observation: 24th August 2002 (*DOY 236, 12:00*).

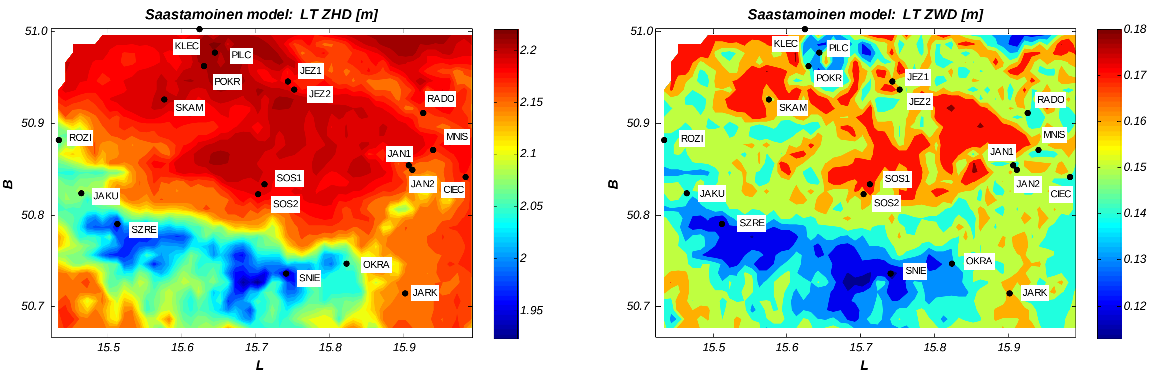

Fig 6. Tropospheric zenith delay (ZHD and ZWD) computed from local troposphere model LT for area of KARKONOSZE network (DOY 236 12:00)

Figures 7 and 8 present tropospheric zenith delay values comparisons for dry *ZHD* and wet *ZWD* components designated on the strength of the above meteorological parameters models for the territory included in *KARKONOSZE* local network coming from one day observations: 24th August 2002 (*DOY 236, 12:00*).

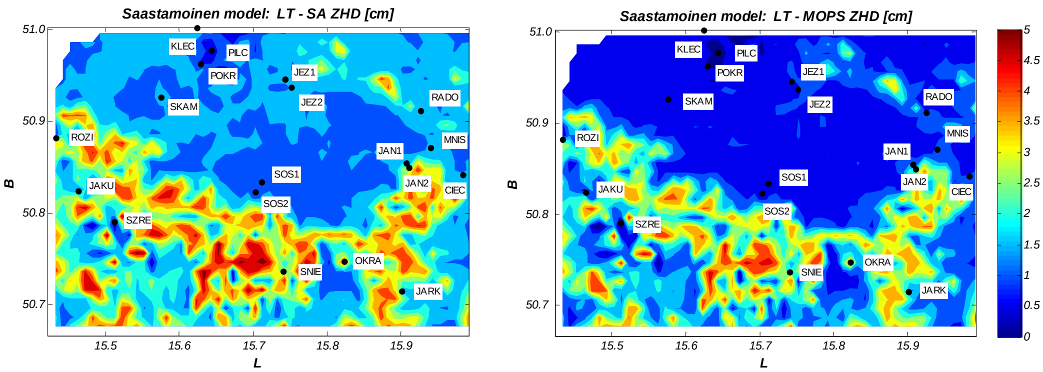

Fig 7. Difference between zenith hydrostatic delay (ZHD), computed from local troposphere model LT, standard atmosphere SA and MOPS models for area of KARKONOSZE network (DOY 236 12 : 00)

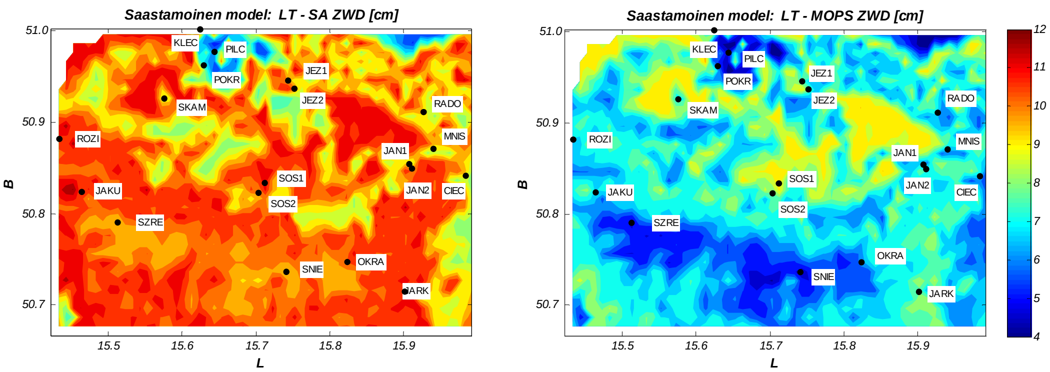

Fig 8. Difference between zenith wet delay (ZWD), computed from local troposphere model LT, standard atmosphere SA and MOPS models for area of KARKONOSZE network (DOY 236 12 : 00)

As it may be inferred from figure 7 differences between delay computed for dry component *ZHD* from local troposphere model ***LT*** and ***SA*** and ***MOPS*** models are comparable and their values belong to interval (0–5 cm). For wet component *ZWD* big values of differences follow standard atmosphere model ***SA*** (max 12 cm), for ***MOPS*** (max 9 cm).

CONCLUSIONS

Tropospheric delay modeling is the crucial factor determining the fixing accuracy of points coordinates (particularly heights components) in local GPS networks, especially for those located in mountainous regions. Due to great variability of meteorological parameters, both temporal and spatial, difficulties may arise in process of modeling of tropospheric delay wet component. The method presented in this paper, suggests using local troposphere model, which considers temporal and spatial aspects of changes, allows to designate adequate model of tropospheric delay. This model has appropriate time resolution and doesn't demand, unlike other global models, time correction.

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