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PRECISION OF THE WET COMPONENT OF ZENITH TROPOSPHERIC DELAY DERIVED FROM GPS OBSERVATIONS

F. Zablotskyj, M. Savchuk
Lviv Polytechnic National University

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Problem statement

The neutral atmosphere (troposphere, stratosphere) is the lower layer of the Earth's atmosphere, which consists of a mixture of dry gases and water vapor. It extends about to 50 km above the Earth's surface. Propagation of radio signal from navigation satellites to ground receivers through the neutral atmosphere is accompanied by a decrease in it velocity. This phenomenon is called tropospheric delay. It varies from about 2 m to 25 m and more depending on the angle of the satellite direction. The minimum value of delay which coincides with the direction of the plumb line is called zenith tropospheric delay (ZTD). The total tropospheric delay in zenith direction at sea level is about 2.4 m. It is divided into hydrostatic and wet components. The hydrostatic component which is approximately 90% of the total quantity is determined rather reliably by the accurately measured surface atmospheric pressure. The wet component which is although only 10%, practically impossible to model due to the dynamic nature of the water vapor in the atmosphere. Some technologies exist today for the accounting of the wet component of ZTD, specifically by radio sounding of the troposphere or using other technical facilities of the remote sensing. However, they are uneconomical and also have several shortcomings such as time shifts due to a duration of measurements, weather conditions (clouds, rain) etc. [1].
One approach to solving this problem is the use of signals of global navigation satellite systems for the determination of the tropospheric delay and then of it wet component. The essence of this approach is that the wet component of ZTD defined as the difference between the total ZTD value obtained from GPS observations and hydrostatic component, calculated by a model approximation.

Analysis of recent studies and publications

Many of scientific papers have been published over the past few decades, in particular [2, 3, 4, etc.] in which the problem of the accuracy increasing of ZTD components was shown. And still no clear answer to the question of what kind the accuracy of the wet component of zenith tropospheric delay by the data of GPS observations is determined.

Problem definition

The purpose of this paper is to evaluate the accuracy of zenith wet delay (ZWD) values obtained by the data of GPS observations at the SULP (Lviv, Ukraine), GANP (Ganovce, Slovakia) and GOPE (Onrejov, Czech Republic) stations [5] in comparison with the ZWD values obtained from radio soundings at the Lviv (Ukraine), Poprad-Ganovce (Slovakia) and Praha-Libus (Czech Republic) aerological stations [6].

Statement of the main material

Zenith tropospheric delay is determined via hydrostatic and wet components of refractivity of air:

$$d_{trop}^{z} = 10^{-6}\int_{H_S}^{H_d} N_h dH + 10^{-6}\int_{H_S}^{H_w} N_w dH\,, \qquad (1)$$

where H_s is a station surface elevation, km; H_d and H_w are the heights of an upper boundary of the dry atmosphere and respectively wet one; N_h and N_w are hydrostatic and wet components of refractivity; dH is the elevation of the current interlayer of atmosphere.
Hydrostatic component of the refractivity is determined by the equation:

$$N_h = K_1 \frac{P}{T}(1 - 0.378\frac{e}{P}), \qquad (2)$$

where K_1 is an empirical coefficient; P and e are partial pressure of air moisture and water vapor respectively, hPa; T is air temperature on Kelvin scale;

The wet component of the refractivity is given by the formula:

$$Nw = \left[K_2 - K_1 \cdot 0.622\frac{e}{T} + K_3 \frac{e}{T^2} \right] \cdot Z_w^{-1}\,, \qquad (3)$$

where K_2, K_3 are empirical coefficients; Z_w^{-1} is the compressibility factor for water vapor [3].
Aerological stations are mostly located around airports therefore the appropriate sounding data can not be choose for all GPS stations. For the consideration of the impact of tropospheric delay in GPS observations the Saastamoinen model mainly is used. It was laid into the basis for many softwares for processing of the GPS data, so we have adopted the Saastamoinen model as the main to determine the hydrostatic component of ZTD:

$$d_h^z = \frac{0.002277 \cdot P_s}{1 - 0.0026 \cdot \cos 2\varphi - 0.00028 \cdot H_s} \qquad (4)$$

where φ is latitude of a station; P_s is surface pressure of moist air on the level of a station, hPa.

To study this problem, there were used three aerological stations and next to them three GPS stations belonging to the EPN network [7]. Coordinates of all stations are given in Table 1.

Table 1.

Aerological and GPS Stations Coordinates

	Name, number	Country	Latitude ° '	Longitude ° '	Height, m	Distance, km
Aerological stations	UKLL Lviv 33393	Ukraine	49 48,6	23 57,0	323,0	5,5
GPS station	SULP	Ukraine	49 50,4	24 00,6	379,1	
Aerological stations	Poprad-Ganovce 11952	Slovak Republic	49 01,8	20 18,6	706,0	0,7
GPS station	GANP	Slovak Republic	49 01,8	20 19,2	745,2	
Aerological stations	Praha - Libus 11520	Czech Republic	50 00,0	14 27,0	303,0	26,3
GPS station	GOPE	Czech Republic	49 54,6	14 47,4	592,6	

Since the distance between the SULP and Lviv stations is about 6 km, and between GANP and Poprad-Ganovce ones it is less than 1 km we can assume that the nature of neutral atmosphere for both stations is the same. The distance between the Praha-Libus and GOPE stations is larger and is about 26 km but we assume that the structures of meteorological fields of these stations are similar to each other.

For analysis there were used the ZTD data derived from GPS observations at the SULP, GANP and GOPE permanent stations [5]. The radio sounding data were selected at the Lviv aerological station as well as at the Praha–Libus and Poprad-Ganovce aerological stations. A choice of these stations was due to the fact that they are almost on the same parallel. By the sounding data at the Praha-Libus and Poprad-Ganovce stations was selected on 10 dates, corresponding to the middle ten-day periods of January and July of 2013. Taking into consideration the significant elevation between Praha-Libus aerological station and GOPE GPS one the meteorological parameters on the lower sounding boundary of the Praha-Libus station were reduced to the height (above sea level) of the GOPE station. As for the Lviv station, the radio soundings are carried out here unfortunately not periodically (in most cases not reaching of the conventional heights of soundings). In this regard, it was not possible to choose the sounding data for the middle ten-day periods of some month and so they had been chosen for extended period of 2013. In general 17 soundings were selected.

During the research we will take the values of hydrostatic and wet components of ZTD obtained by the radio sounding data as reference (though of course, this is a relative conception, since the value of tropospheric delay will contain errors primarily by measuring of the parameters such as pressure, temperature and humidity). The averaged results of calculations for each of the stations are given in Table 2.

Table 2

Averaged hydrostatic and wet components ZTD (mm) according to the aerological and GPS stations (2013)

	$d_h^z aer$	$d_w^z aer$	$d_h^z SA$	$\Delta d_h^z SA$	$d_{trop}^z GPS$	$d_w^z GPS$	$\Delta d_w^z GPS$
	1	*2*	*3*	*4*	*5*	*6*	*7*
	Lviv and SULP						
	May - october						
average	2224,8	152,8	2229,9	-5,2	2362,0	132,0	20,8
	σ =			3,8			19,9
	Poprad-Ganovce and GANP						
	January						
average	2095,9	64,4	2097,3	-1,4	2163,9	66,6	-2,1
	σ =			1,2			4,2
	July						
average	2131,2	119,6	2135,3	-4,1	2262,6	127,3	-7,7
	σ =			0,5			16,9
	Praga-Libus and GOPE						
	January						
average	2135,1	43,9	2141,4	-3,3	2190,8	49,4	-5,6
	σ =			3,6			2,4
	July						
average	2168,9	117,0	2172,6	-3,7	2298,3	125,8	-8,7
	σ =			4,7			13,5

The following values are given in columns of the table:

$d_h^z aer$ and $d_w^z aer$ are hydrostatic and wet components of ZTD obtained from radio sounding data; $d_h^z SA$ is hydrostatic component of ZTD obtained from Saastamoinen model; $\Delta d_h^z SA$ is the difference between hydrostatic component obtained according the radio sounding data and Saastamoinen model; $d_{trop}^z GPS$ is total ZTD obtained from GPS observations; $d_w^z GPS$ is ZTD wet component, derived from GPS observations; $\Delta d_w^z GPS$ is the difference between wet component obtained according the radio sounding data and GPS observations; σ is a standard deviation.

Analyzing the data of Table 2 we note the following. For all aerological stations the averaged differences express essentially a precision of the hydrostatic component of ZTD obtained by the Saastamoinen model, are within -5,2 ÷ -1,4 mm. It should be noted that they are somewhat greater in summer than in winter, because of the much higher content of water vapor in the troposphere. Turning to the accuracy of the hydrostatic component of ZTD obtained by Saastamoinen formula, we will analyze the values of standard deviation for each $\Delta d_h^z SA$ quantity. So, at the Poprad-Ganovce and Praga-Libus stations the σ values are lower in winter too, which indicates to less scattering of $\Delta d_h^z SA$ differences. This is also confirmed by the lower content of water vapor in the troposphere in winter.

As for the averaged $\Delta d_w^z GPS$ differences, it should be noted the following. At the GOPE and GANP stations, these differences are also smaller in winter than in summer, and their values are 4-5 times lower in winter than in summer, indicating not only a lower content of water vapor in the atmosphere in winter, but as well as the weaker dynamics of water vapor. As to the nature of $\Delta d_w^z GPS$ difference at the SULP station, then here both itself quantity and it value are much higher than at the previous stations. This is explained, in our opinion, not only because most soundings and corresponding tropospheric delays derived from GPS observations occur in summer, but the fact that the overwhelming majority of

radio soundings do not include a humidity at the top of the troposphere. Confirmation of this is that only 30 % sensors measure the relative humidity to the height of about 9 km (in 50 per cents of soundings it is only 7 km). At the same time, as the upper boundary of the troposphere is here in summer near 12 km.

Conclusions

In the result of analysis of the processed data of aerological stations and of corresponding adjacent GPS stations the values of wet component were obtained from GPS observations. The accuracy of these values is agreed with the corresponding estimations stated in the recent scientific literature.
In the sequel, to our opinion, is reasonably to extend these research by selection of other aerological stations and corresponding to them GPS stations located both the east and west along of the 50th parallel.

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Accuracy analysis of wet components of zenith tropospheric delay was carried out by the observation data derived from three GPS stations as well as by the radio sounding data obtained on three aerological stations.