UDC 629.056.88+551.51

F. ZABLOTSKYI, Ju. GRESKO, B. PALIANYTSIA

Department “Higher geodesy and astronomy” of Lviv Polytechnic National University, 12, S. Bandera str., Lviv, Ukraine, 79013, e-mail: fzablots@polynet.lviv.ua

MONITORING OF WATER VAPOR CONTENT BY RADIO SOUNDING DATA AT THE KYIV AEROLOGICAL STATION AND BY GNSS OBSERVATION DATA AT THE GLSV STATION

https://doi.org/10.23939/istcgcap2017.01.013

The **purpose** of this paper is determining the water vapor content calculated by the wet component of zenith tropospheric delay (ZTD) obtained by means of radio sounding data and GNSS observations. The investigation **methodology** is the following: the wet component of ZTD is defined as the difference between the total ZTD derived from GNSS measurements and the calculated hydrostatic component. Then the integrated and precipitable water vapor (PWV) is calculated by means of the wet component. The radio sounding data from Kyiv aerological station as well as the zenith tropospheric delay data from the GLSV GNSS station were processed for six days of each month of 2016. The study **results** represent the wet component of ZTD and PWV values obtained by the radio sounding data and derived from GNSS observation data. Accuracy evaluation was carried out by the differences between wet component values obtained from the radio sounding data and defined from GNSS measurement data. An analogical accuracy evaluation was made for the PWV values as well. **The scientific novelty and practical significance** are that the obtained results will serve as the basis for further increasing of determination accuracy of the wet component from GNSS measurements, in particular, to determine its spatial and temporal changes and the PWV content in the atmosphere, which are important for weather forecasting in this region.

Key words: GNSS measurements; radio sounding; zenith tropospheric delay; integrated and precipitable water vapor.

Introduction

Determination questions of the wet component of ZTD, as well as of integrated and precipitable water vapor derived from GNSS measurements are highlighted in many papers, in particular: [Zablotskyj F. D., 2013; Kablak N., 2011a, 2011б; Paziak M., Zablotskyj F., 2015; Palianytsia B. et. al., 2016; Bevis V. S. et. al., 1992; Boccolari M. et al, 2002; Mendes V. B., 1999; Ning T., 2012; Rocken C., 2005; Schueler T., 2001] and others. However the determination accuracy of the ZTD wet component and of the water vapor content in atmosphere is still not fully established.

Purpose

The purpose of this paper is determining the water vapor content calculated by the wet component of zenith tropospheric delay (ZTD) obtained by means of radio sounding data and GNSS observations at the Kyiv aerological station and the GLSV GNSS station [http://weather.uwyo.edu/upperair/sounding.html; http://igs.bkg.bund.de/file/productsearch/].

Methodology

The ZTD components are determined most precisely from atmospheric radiosonde data. Thus, the hydrostatic component is calculated by integration of the N refractivity index:

$$d_h^z = 10^{-6} \int_{H_0}^{H_d} N_h \cdot dH = \\ = 10^{-6} \int_{H_0}^{H_d} K_1 \frac{P}{T} \left(1 - 0.378 \frac{e}{P} \right) \cdot dH, \qquad (1)$$

where H_0 is the height of a station (the level of a receiver antenna); H_d is the top boundary of the dry atmosphere; K_1 is the empirical coefficient of refractivity; P is the pressure of moist air; T is Kelvin air temperature; e is the partial pressure of water vapor.

The ZTD wet component is determined by the formula:

$$d_w^z = 10^{-6} \int_{H_0}^{H_w} N_w \, dH = 10^{-6} \int_{H_0}^{H_w} \left[(K_2 - K_1 \cdot \\ \cdot 0.622) \frac{e}{T} + K_3 \frac{e}{T^2} \right] \cdot Z_w^{-1} dH, \qquad (2)$$

where H_w is the top boundary of the moist atmosphere; N_w is the ZTD wet component of the refractivity index; K_2 and K_3 are the empirical coefficients of refractivity; Z_w^{-1} is the compressibility factor for water vapor.

The approach for determination of the water vapor content in the atmosphere on the basis of tropospheric delay derived from GNSS measurements, became actively used more than twenty years ago. The determination of the ZTD wet component from GNSS measurements is explained. On the basis of the main equation for code or phase pseudoranges of GNSS observations, the total tropospheric delay is determined as:

$$d_{trop} = P_r^s - \rho_r^s, \qquad (3)$$

where P_r^s and ρ_r^s are the code or phase pseudorange and the geometrical distance between the GNSS satellite and the receiver respectively.

The total tropospheric delay obtained from the formula (3) refers usually to non-zenith directions $z \neq 0^\circ$ or to the directions of elevation angles $90^\circ > \varepsilon > 0^\circ$. The value d_{trop} is reduced to the zenith direction by using the dependence:

$$d_{trop}^z = \frac{d_{trop}}{m(\varepsilon)}\ , \qquad (4)$$

where $m(\varepsilon)$ is a mapping function. Since the zenith tropospheric delay includes the hydrostatic component and the wet one

$$d_{trop}^z = d_h^z + d_w^z \qquad (5)$$

then the hydrostatic component of ZTD is determined using *Saastamoinen's* formula mainly:

$$d_{h\,SA}^z = \frac{0.002277 \cdot P_0}{1 - 0.0026 \cdot cos2\varphi - 0.00028 \cdot H_0}\ , \qquad (6)$$

where P_0 is the atmospheric pressure at a station and φ is its latitude; H_0 is the height of a station above sea level.

The integrated water vapor (IWV) is calculated using the equation:

$$IWV = \frac{d_w^z}{10^{-6} \cdot R_w \left[(K_2 - K_1 \cdot 0{,}622) + \frac{K_3}{T_m}\right]}, \qquad (7)$$

where R_w = 461.525 J·kg^1· K^{-1} is the specific gas constant for moist air.

It should be noted that IWV defined as the total mass of water vapor in a column of air with the cross section of 1 m^2 extending from the surface to the top of an atmosphere, is usually given in units of kg/m^2.

The transition from integrated water vapor to precipitable one is implemented by the following formula:

$$PWV = \frac{IWV}{\rho_{H2O}}\ , \qquad (8)$$

where ρ_{H_2O} =10^3 kg/m^3 is the density of liquid water.

The PWV value can be interpreted as the height of an equivalent column of liquid water on the condition that the water vapor would condense to.

Input data characteristics

The following data for processing and analysis:

– the radio sounding data from the Kyiv aerological station, in particular, six-day data for each month of 2016 from the station surface to a height of 25–30 km. The indicated terms of soundings correspond in time with the mean decade of each month, at 0^h UT (Universal time);

– the zenith tropospheric delay data derived from GNSS observations at the GLSV permanent station for the same periods as the radio sounding data.

Data processing and analysis of obtained results

The hydrostatic and wet components of ZTD were obtained as the results of processing the radio sounding data as well as the values of the wet component and the precipitable water vapor derived from the GNSS observations (see Table 1).

The fragment of the processed data for June is shown in Table 1.

Fig. 1 shows the average values of the $d_{w(GPS)}^z$ wet component and of the PWV_{GPS} precipitable water vapor for the different seasons of the year.

As can be seen from the Fig. 1, the maximal values of the wet component and the precipitable water vapor correspond to the summer season, with minimal values in the winter season. This is due to the fact that the external air temperatures correspond to these seasons. It should be noted, since the first and the second values have the metric measure (mm) then the scaled ratio of the $d_{w(GPS)}^z$ values to the PWV_{GPS} values are 6.36:1 in the study region. At the same time the maximal ratio (6.52:1) corresponds to the winter period as well and the minimal ratio (6.19:1) corresponds to the summer season.

Table 1

The ZTD components (mm) obtained by the radio sounding data as well as the values of the ZTD wet delay and of precipitable water vapor (mm) derived from the GNSS observation data

Date	$d^z_{h(aer)}$	$d^z_{w(aer)}$	$d^z_{h(SA)}$	$d^z_{trop\,(GPS)}$	$d^z_{w\,(GPS)}$	PWV_{site}	PWV_{GPS}	Δ
1	2	3	4	5	6	7	8	9
12.06	2239.1	74.4	2241.8	2311.1	69.3	12.3	11.0	1.3
13.06	2238.0	98.8	2241.8	2328.5	86.7	16.3	13.8	2.6
15.06	2216.8	186.0	2219.5	2432.2	212.7	30.7	34.2	-3.5
16.06	2220.9	205.7	2224.0	2447.4	223.4	34.1	35.9	-1.8
17.06	2243.8	149.3	2249.0	2375.1	126.1	25.2	20.4	4.8
18.06	2239.9	219.9	2244.5	2454.1	209.6	37.3	34.0	3.2
mean	2233.1	155.7	2236.8	2391.4	154.6	26.0	24.9	1.1

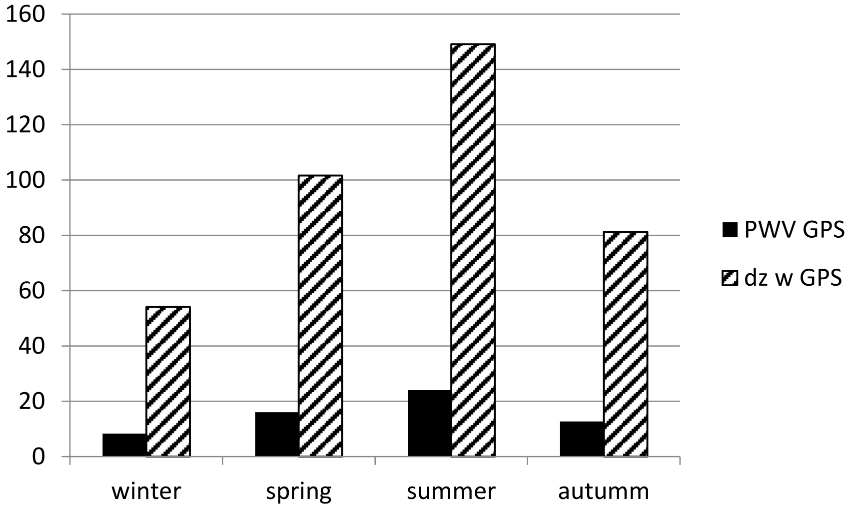

Fig. 1. The $d^z_{w(GPS)}$ and PWV_{GPS} seasonal averages values

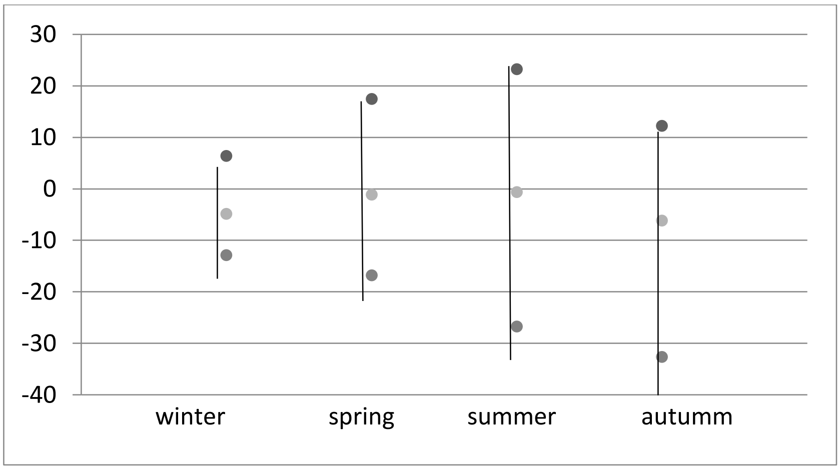

Fig. 2. The Δd^z_w average seasonal values of differences along the horizontal axis and their external deviations along the vertical axis

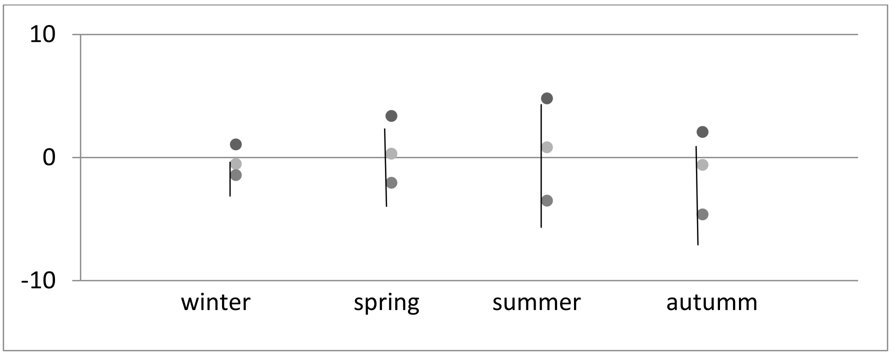

Fig. 3. The ΔPWV averaged seasonal values of differences (along the horizontal axis) and their external deviations (along the vertical axis)

As shown in Fig. 2, the largest amplitude of Δd_w^z values is observed in the summer period and it is equal to 50 mm. It is a little smaller in the autumn period measuring 45 mm. In the winter, this amplitude is the smallest (19 mm) and in the spring it is 34 mm.

Table 2

The mean values (Δd_w^z), the mean square errors (m) as well as the standard deviations (σ)

Season / Estimate	Winter	Springer	Summer	Autumn
mean	-4.9	-1.2	-0.7	-6.2
m	6.9	8.7	13.8	12.0
σ	5.0	8.9	14.2	10.5

The mean square errors and the standard deviations are more than 10mm in the summer and autumn periods.

The *Δ* average seasonal differences of *PWV* values between corresponding selected values were taken from the site [http://weather.uwyo.edu /upperair/sounding.html] and calculated by the wet components of ZTD which were derived from the GNSS observations shown in Fig. 3.

It should be noted that the *ΔPWV* values and their mean square errors are -0.5 and 0.9; 0.3 and 1.4; 0.8 and 2.4; and 0.6 and 1.6 mm for each season respectively.

The scientific novelty and practical significance

The obtained results will serve as the basis for further increasing of determination accuracy of the wet component from GNSS measurements, in particular, to determine its spatial and temporal changes and the PWV content in the atmosphere, which are important for weather forecasting in this region.

Conclusions

The determination accuracy of the ZTD wet delay derived from GNSS observations is15 mm in the summer period. Such estimates were obtained by our study and by studies at other stations in Central Europe. In regards to the determination of accuracy of the precipitated water vapor, its change occurs similarly to the change of the wet component and is 2.5 mm in summer.

REFERENCES

Bevis, M. S. Businger, T. A Herring, C. Rocken, R. A Anthes, and R. H. Ware (1992). "GPS meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System." *Journal of Geophysical Research, v*ol. 97, no. Dl4, pp.15,787–15,801.

Boccolari M., Fazlagic S., Frontero P., Lombroso L., Pugnaghi S., Santangelo R., Corradini S. and Teggi S. GPS Zenith Total Delays and Precipitable Water in comparison with special meteorological observations in Verona (Italy) during MAP-SOP. Annals of Geophysics, october 2002, vol. 45, no. 5, pp. 599–608.

GNSS Data Center, Available at: http://igs.bkg.bund.de/file/productsearch/

Kablak N. I. Remote sensing of water vapor in the atmosphere using satellite navigation systems. Geodesy, Cartography and Aerial Photography, 2011, issue 75, pp. 31–35.

Kablak N. I. Monitoring precipitable water vapor from GNSS data processing. Space science and technology. 2011, vol. 17, no. 4, pp. 65–73.

Mendes V. B. Modeling the neutral-atmosphere propagation delay in radiometric space techniques. Ph.D. dissertation, Department of Geodesy and Geomatics Engineering Technical Report, no. 199, University of New Brunwick, Fredericton, New Brunswick, Canada, 353 p.

Niell A. E. Global mapping functions for the atmosphere delay at radio wavelengths. Journal of Geophysical Research, 1996, vol. 101, no. B2, pp. 3227–3246.

Ning T. GPS Meteorology: With Focus on Climate Applications. Thesis for The Degree of Doctor of Philosophy. Department of Earth and Space Sciences Chalmers University of Technology Gothenburg, Sweden, 2012, p. 82.

Paziak M. V., Zablotskyi F. D. Comparison of wet component of zenith tropospheric delay derived from GNSS observations with corresponding value from radio soundings. Geodesy, Cartography and Aerial Photography, 2015, issue 81, pp. 15–23.

Palianytsia B. B., Oliynyk V. R., Boyko V. V. The research of change of zenith troposperic dealay’s components. Geodesy, Cartography and Aerial Photography, 2016, issue 83, pp. 13–20.

Radiozondirovanie atmosfery. [Radio sounding of atmosphere]. Available at: http://riastk.ru/mi/adetail.php?ID=30717

Rocken, C. “GNSS Meteorology – 1. GPS Observation Equation and Obtaining the Tropospheric Excess Phase”. Available at: http://www.cosmic.ucar.edu/summercamp_2005/presentations/rocken_chris_20050526.pdf

Schueler, T. and G. W. Hein. Tropospheric Correction Services for GNSS Users. Concepts, Status and Future Prospects. University FAF Munich, Germany, 2002, 9 p.

Sluzhba atmosfernykh doslidzhen. [Service of atmospheric study]. Available at: http://weather.uwyo.edu/upperair/sounding.html

Zablotskyi F. D. GNSS meteorology. Tutorial. Lviv: Lviv Polytechnic National University, 2013, p. 95.

Ф. ЗАБЛОЦЬКИЙ[1], Ю. ГРЕСЬКО, Б. ПАЛЯНИЦЯ

Кафедра вищої геодезії та астрономії, Національний університет “Львівська політехніка”, вул. С. Бандери, 12, Львів, Україна, 79013, тел. 067-71-62-152, ел. пошта: fzablots@polynet.lviv.ua

МОНІТОРИНГ ВОДЯНОЇ ПАРИ ЗА ДАНИМИ РАДІОЗОНДУВАННЯ ТА GNSS-ВИМІРЮВАНЬ НА СТАНЦІЯХ КИЇВ І GLSV

Метою цієї роботи є визначення вмісту водяної пари, обчисленої за вологою складовою зенітної тропосферної затримки (ЗТЗ), отриманою за даними радіозондувань і GNSS-вимірювань. **Методика** досліджень полягає в такому: вологу складову ЗТЗ визначають як різницю між повною ЗТЗ, виведеною із GNSS-вимірювань і обчисленою гідростатичною складовою. Далі за отриманою вологою складовою обчислюють інтегровану та осаджувану водяну пару. Для опрацювання використані шестиденні за кожен місяць 2016 року дані радіозондування на аерологічній станції Київ і дані зенітної тропосферної затримки, виведені із GNSS-спостережень для тих самих дат, на перманентній станції GLSV. **Результати** досліджень – це величини вологої складової ЗТЗ і осаджуваної водяної пари, отримані за даними радіозондування і виведені із GNSS-спостережень. За різницями між величинами вологої складової, обчисленими із радіозондування та визначеними із GNSS-вимірювань, зроблено оцінку точності. Аналогічно оцінено і величини осаджуваної водяної пари. **Наукова новизна та практична значущість** полягають у тому, що отримані результати слугуватимуть підґрунтям для подальшого підвищення точності визначення вологої складової із GNSS-вимірювань, зокрема, для визначення просторово-часових змін та вмісту осаджуваної водяної пари в атмосфері, що важливим є для прогнозування погоди в цьому регіоні.

Ключові слова: GNSS-вимірювання; радіозондування; зенітна тропосферна затримка; гідростатична складова; волога складова; інтегрована та осаджувана водяна пара.

Received 11.04.2017