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DETERMINATION OF PRECIPITABLE WATER VAPOUR, FROM THE DATA OF AEROLOGICAL AND GNSS MEASUREMENTS AT EUROPEAN AND TROPICAL STATIONS

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The purpose of the given work lies in the studies of the atmospheric precipitable water vapour (PWV), based on the processing of aerological and GNSS (Global Navigation Satellite System) measurements, as well as the comparing of PWV values, determined according to the data of aerological and GNSS stations, located both in temperate and tropical latitudes. **Methodology.** The algorithm for determination of precipitable water vapour, based on GNSS observations, is divided into several stages: 1) the total tropospheric delay is determined by the basic equation of code or phase pseudodistances of GNSS measurements; 2) select zenith tropospheric delay (ZTD) values at the time of GNSS observations [ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/new/]; 3) according to the analytical Saastamoinen model, the hydrostatic component of the zenith tropospheric delay (ZTD) is calculated; 4) according to the ZTD values and hydrostatic component, the wet component values of the ZTD are obtained; 5) the conversion from the wet component to the integrated water vapour (IWV) component and the precipitable water vapour PWV is realized. The IWV and PWV values are also defined by upper-air sounding data. **Results** In the course of the performed research, the ZTD components and the PWV values were determined. A comparative characteristics of the present values was carried out, which were defined according to the data of both aerological and GNSS stations. Generally, the accuracy of the hydrostatic component of the ZTD determination is about 10 mm, and the accuracy of the wet component definition of ZTD, deducted from GNSS measurements, is approximately 20 mm. The PWV values mainly vary by analogy to the values of wet component of ZTD, and the accuracy of its definition reaches 3 mm. **Novelty and practical significance.** For the first time, simultaneous studies of the ZTD and its components and the water vapor content at five stations in the middle latitudes and three stations of the tropical zone were conducted. The obtained results can further be used in the studies of changes in climatic processes.

Key words: GNSS measurements; wet component of the zenith tropospheric delay; upper-air sounding; water vapour.

Introduction

Water vapour is constantly present in the atmospheric air (water in a gaseous state). More than 90 % of it is located in the troposphere. The water vapour can develop from the gaseous state into a liquid or solid state, therefore, it is constantly changing in space and time. It is the dynamic circulation of water in the atmosphere that the most important weather processes and climatic peculiarities are connected to. Consequently, a number of methods have been developed to consider the content of water vapour in the atmospheric air and, accordingly, the wet component (ZWD). However, all these methods do not provide sufficient accuracy of the definition of the ZWD component, and, accordingly, the accuracy of ZTD in modern geodetic measurements. The solution to this problem was established in [Bevis at al, 1992]. Solving the inverse problem of GNSS measurements, determine the value of ZWD, and from it, by conversion, obtain the values of IWV (kg / m^2), and then PWV (mm).

Over the last few decades, a number of investigations have been carried out in the given direction, some of which are highlighted in the works [Fernandez, et al., 2010; Suelynn Choy, et al., 2015; T. Yanxin, et al., 2013; Biyan Chen, et al., 2018; C. Suresh Raju, et al., 2007; J. Haase, et al., 2003, Julio A. Castro-Almazán, et al., 2016]. The analysis of the zenith tropospheric delay and PWV in the middle latitudes is presented in the works [Kablak, 2011 a, 2011 b; Zablotskyi, et al., 2017; Savchuk, Zablotskyi, 2016; Kablak, Savchuk, 2012]. The peculiarities of the zenith tropospheric delay and the precipitable vapour in the tropical zone, determined according to radiosounding data, as well as by analytical models and other methods, are covered in the articles [Zablotskyi, Zablotska, 2010; Bock, et al., 2007; Manandhar et al., 2018; Realini, et al., 2014]. Particularly, the authors carried out extensive research of the zenith tropospheric delay and its components, obtained in 2011 and 2013 at 9 stations of upper-air sounding and 9 reference GNSS stations, located in the temperate and tropical latitudes [Zablotskyi, Savchuk, 2014; Paziak, Zablotskyi, 2015 a, 2015 b; 2018]. In the given work, the focus is on the investigation of accuracy and the comparison of the zenith tropospheric delay and PWV values, obtained according to aerological and GNSS stations data.

Purpose

The main purpose of the given research is to study the atmospheric precipitable water vapour PWV, based on the processing of aerological and GNSS measurements, as well as the comparing of PWV values, determined according to the data of aerological and GNSS stations, located both in the temperate and tropical latitudes.

Research methodology

The nearest corresponding active reference GNSS station was selected for each aerological station, which produced the known zenith tropospheric delays. For the correct comparison of measurements results, reduction of the main meteorological values (atmospheric pressure P, air temperature t, relative humidity U) were carried out at the aerological stations to the heights of the corresponding GNSS stations. Since the maximum heights achieved by bullets – probes during radiosounding at selected stations – were, for the most part, approximately 35 km, then from this height to 80 km the pressure and temperature were chosen from the standard model of the atmosphere SMA-81.

The algorithm for determining the precipitable water vapour on the basis of GNSS observations is divided into several stages: 1) by the basic equation of the code or phase pseudodistances of the GNSS measurements, the total tropospheric delay is determined; 2) select ZTD values at the time of GNSS observations [ftp://cddis.gsfc.nasa.gov/ gps/products/ troposphere/ new/]; 3) according to the analytical Saastamoinen model, the hydrostatic component of the zenith tropospheric delay is calculated; 4) according to the zenith tropospheric delay values and hydrostatic component, the values of the wet component of the zenith tropospheric delay is obtained; 5) the conversion from the wet component of the zenith tropospheric delay to the integrated IWV and the precipitable water vapour PWV is realized. All the formulas necessary for calculating are described in the paper [Zablotskyi, et al., 2017]. It should be noted that the PWV values are also determined by the vertical profiles of the main meteorological values, that is, in the process of upper-air sounding of the atmosphere, its values are presented on the website [http://weather.uwyo. edu/upperair/ sounding.html]. However, in terms of the correct comparison of the data, the PWV values were taken into account, which were calculated by the wet component of the zenith tropospheric delay, determined from upper-air sounding, considering the reduction of meteorological variables.

Characteristics of the source data

The vertical profiles of the main meteorological values, obtained from radiosoundings for ten-day period in January and July of 2018 at five aerological stations, were taken as the initial data in the research [http://weather.uwyo.edu/ upperair/ sounding.html]. In general, the stations were selected in the central and eastern region of Europe, located near the 50th parallel. Similar data were also selected for three stations, located in the equatorial zone. The values of the total zenith tropospheric delay, according to the data of the corresponding GNSS stations for the specified days were selected [ftp://cddis.gsfc. nasa.gov/gps/ products/ troposphere/new/]. The coordinates of the stations are listed in Table 1.

Table 1

Coordinates of stations

Aerological stations			GNSS stations			Country *M*	Distance, km
Latitude 0° 00'	Longitude 0° 00'	Height, m	Latitude 0° 00'	Longitude 0° 00'	Height, m		
Middle latitudes							
Praha, 11520			GOPE			Czech Republic	28.0
50 00	14 27	303.0	49 54	14 47	592.6		
Kyiv, 33345			GLSV			Ukraine	4.0
50 23	30 33	167.0	50 22	30 30	226.8		
Legionowo, 12374			BOGI			Poland	10.9
52 23	20 57	96.0	52 28	21 02	139.9		
Poprad, 11952			GANP			Slovakia	1.2
49 02	20 18	706.0	49 02	20 19	745.2		
Beauvecchain, 06458			BRUX			Belgium	29.4
50 45	4 46	127.0	50 47	4 21	158.3		
Tropical latitudes							
Guam, 91212			GUAM			USA	15.8
13 28	144 47	75.0	13 35	144 52	201.9		
Singapore, 48698			NTUS			Singapore	35.4
1 22	103 59	16.0	1 20	103 40	79.0		
Pago Pago, 91765			ASPA			USA	1.8
-14 20	-170 43	3.0	-14 19	-170 43	53.7		

Table 2

The averaged values

Stations	$d^{z}_{h(aer)}$	$d^{z}_{w(aer)}$	$\Delta d^{z}_{h(SA)}$	$d^{z}_{trop(GPS)}$	$\Delta d^{z}_{w(GPS)}$	$PWV_{(aer)}$	ΔPWV
1	2	3	4	5	6	7	8
January							
Praha-Libus – GOPE	2151.2	52.4	0.7	2207.7	-4.9	8.1	-0.75
Kyiv – GLSV	2269.4	39.3	8.7	2297.3	2.6	6.0	0.40
Legionovo – BOGI	2301.1	46.4	4.1	2343.2	0.1	7.1	0.02
Beauvecchain – BRUX	2266.0	71.7	4.9	2337.3	-4.5	11.1	-0.70
Poprad-Ganovce – GANP	2106.5	41.4	-1.9	2155.2	-5.4	6.3	-0.82
Guam – GUAM	2249.9	179.2	-7.7	2447.4	-10.7	29.5	-1.76
Singapore – NTUS	2278.1	337.6	-7.1	2614.9	7.9	55.1	1.30
Pago Pago – ASPA	2284.0	290.9	-8.2	2613.4	-30.3	48.0	-5.01
July							
Praha-Libus – GOPE	2153.0	132.6	-4.2	2302.2	-12.5	21.3	-2.01
Kyiv – GLSV	2224.9	187.5	-7.2	2436.4	-16.7	30.3	-2.70
Legionovo – BOGI	2259.7	215.9	-1.9	2477.5	-0.1	34.8	-0.01
Beauvecchain – BRUX	2264.8	154.9	-9.4	2452.2	-23.2	25.2	-3.77

Continuation of Table 2

1	2	3	4	5	6	7	8
Poprad-Ganovce – GANP	2109.0	158.3	-5.2	2277.9	-5.4	25.3	-0.87
Guam – GUAM	2243.0	339.4	-9.1	2612.5	-21.0	55.8	-3.46
Singapore – NTUS	2275.5	329.2	-8.1	2606.0	6.7	54.2	1.11
Pago Pago – ASPA	2288.9	229.4	-8.7	2548.8	-21.9	37.8	-3.61

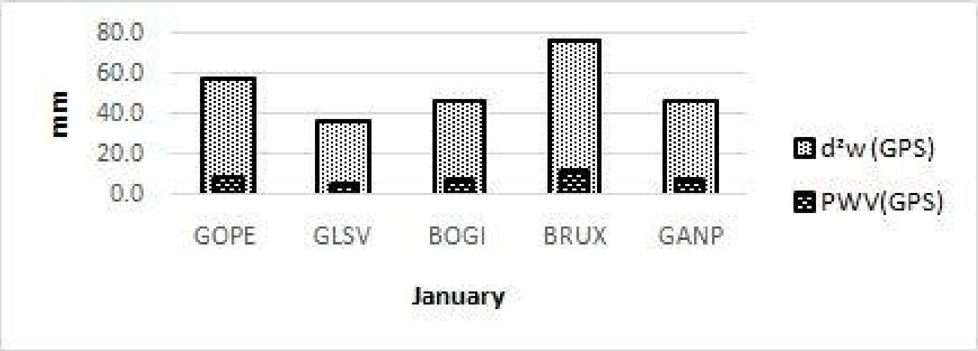

Fig. 1. The averaged values of $d^z_{w(GPS)}$ and $PWV_{(GPS)}$ according to the data of the middle latitudes stations in January

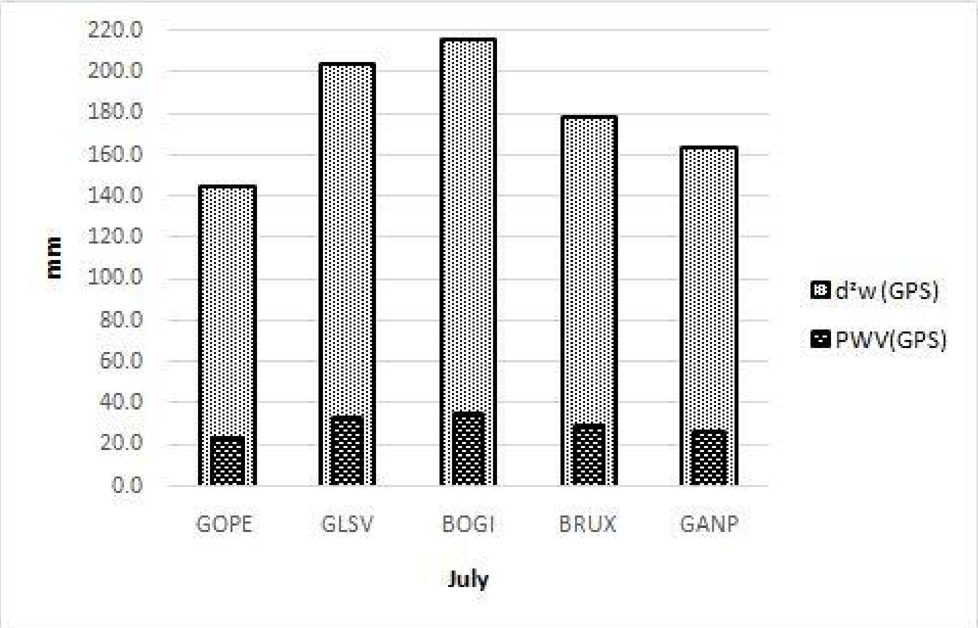

Fig. 2. The averaged values of $d^z_{w(GPS)}$ and $PWV_{(GPS)}$ according to the data of the middle latitudes stations in July

Data processing and the analysis of the obtained results

As a result of the conducted research and after processing the specified data, the following was obtained: the hydrostatic and wet components values of the zenith troposoheric delay, defined by radiosounding data $d^z_{h(aer)}$ and $d^z_{w(aer)}$; $\Delta d^z_{h(SA)}$ – are the differences of the hydrostatic component, calculated according to radiosounding data $d^z_{h(aer)}$ and the Saastamoinen model $d^z_{h(SA)}$; the differences $\Delta d^z_{w(GPS)}$ – were deducted from radiosounding $d^z_{w(aer)}$ and GNSS observations $d^z_{w(GPS)}$; the differences of the precipitable water vapour ΔPWV, calculated by the data of radiosounding $PWV_{(aer)}$ and GNSS observations $PWV_{(GPS)}$; the values of the total zenith tropospheric delay, deducted from GNSS observations $d^{z}_{trop(GPS)}$. Due to the large amounts of data, there is no opportunity to represent all available calculations, however, in order to reflect the general picture in Table 2, the averaged values of the above mentioned values are given.

It is clear from Fig. 1 and 2 that at end of the observations at the middle latitudes stations the values of $d^{z}_{w(GPS)}$ and correspondingly $PWV_{(GPS)}$ are much larger in July, than in January, first of all, it is caused by different temperature conditions in the given seasons, as well as the higher content of water vapour in the atmosphere in summer period. Since, the specified values are presented in mm, the scaling relations ($\frac{d^{z}_{w(GPS)}}{PWV_{(GPS)}}$) for it, according to the data of the middle latitudes stations, range from 6.44 to 6.60 in January. In July, the given relations are somewhat lower and range from 6.14 to 6.25.

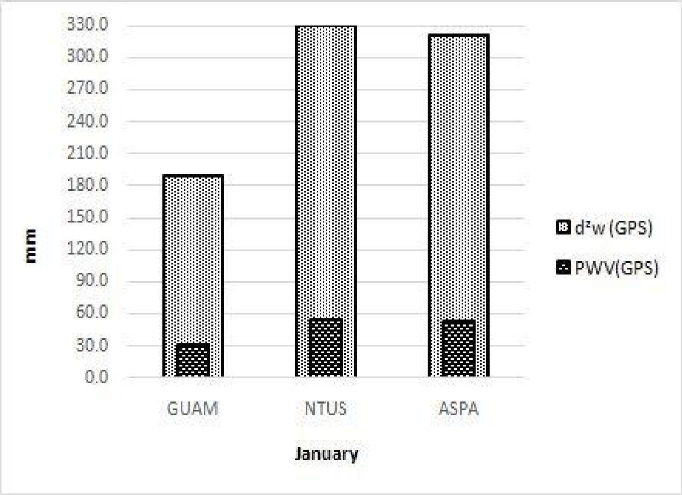

Fig. 3. The averaged values of $d^{z}_{w(GPS)}$ *and* $PWV_{(GPS)}$ *according to the data of the tropical latitudes stations in January*

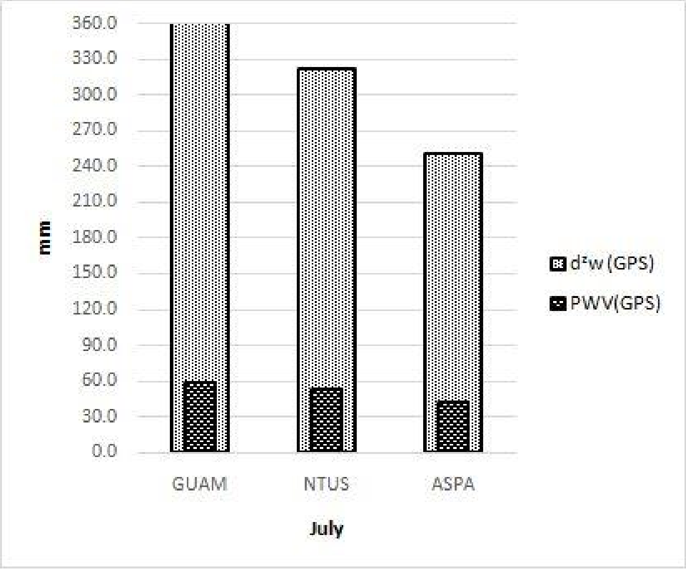

Fig. 4. The averaged values of $d^{z}_{w(GPS)}$ *and* $PWV_{(GPS)}$ *according to the data of the tropical latitudes in July*

It is clear from Fig. 3 and 4 that the values $d^{z}_{w(GPS)}$ and $PWV_{(GPS)}$ are much larger in the tropical latitudes, than in the middle ones (except for the GUAM station), and the scaling relations, both in summer and in winter, are practically the same and equal on average to 6.08. It should be noted that, according to the soundings results, an anomalous distribution of relative humidity with the height was observed at the Guam aerological station in January, first of all, in the lower 5 km layer, which dramatically reduces the content of water vapour in the atmosphere, and, accordingly, the wet component of the zenith tropospheric delay. Unlike in January, a uniform fall in relative humidity with the height is observed in July. As a result, at almost the same ground air temperatures (both in January and in July, t > 25 °C), the wet component value is different. It is seen from Figures that the wet component $d^{z}_{w(GPS)}$ is twice less in January, than in July.

By analysing the above presented figures, it can be said that the PWV values vary by analogy to the values of, $d^{z}_{w(GPS)}$. In Tabl. 3, the statistical characteristics of the differences of hydrostatic and wet components of the zenith tropospheric delay are given, as well as the differences of the precipitable water vapour ΔPWV.

Table 3

Statistical characteristics of differences

Stations' *Charac-teristics*	*Middle latitudes*					*Tropical latitudes*		
	Praha GOPE	Kyiv GLSV	Legionowo BOGI	Beauvecchain BRUX	Poprad GANP	Guam GUAM	Singapore NTUS	Pago Pago ASPA
1	2	3	4	5	6	8	9	10
	January, 2018							
min $\Delta d^{z}_{h(SA)}$	-1.2	6.0	2.1	-2.2	-4.7	-8.4	-8.7	-8.7
max $\Delta d^{z}_{h(SA)}$	7.9	11.7	7.6	16.5	1.4	-6.9	-5.6	-5.9
M	2.7	8.9	4.3	7.3	2.5	7.7	7.2	8.2
Σ	2.8	1.7	1.5	5.6	1.6	0.4	1.0	0.9
min $\Delta d^{z}_{w(GPS)}$	-13.6	-15.7	-8.2	-21.2	-8.3	-28.8	-2.3	-48.8
max $\Delta d^{z}_{w(GPS)}$	5.7	13.1	3.1	28.5	-2.7	11.5	12.5	1.5
M	7.6	8.0	3.6	13.9	5.7	15.4	9.4	35.3
Σ	6.1	7.9	3.8	13.8	1.8	11.7	5.2	19.1
min ΔPWV	-2.10	-2.40	-1.27	-3.30	-1.28	-4.73	-0.38	-8.77
max ΔPWV	0.88	1.49	0.64	4.41	-0.41	1.90	2.05	0.24
M	1.16	1.21	0.55	2.16	0.87	2.54	1.53	5.84
Σ	0.94	1.20	0.58	2.15	0.28	1.93	0.85	3.16
	July, 2018							
min $\Delta d^{z}_{h(SA)}$	-6.1	-12.9	-4.0	-15.0	-6.5	-9.9	-10.0	-9.6
max $\Delta d^{z}_{h(SA)}$	-3.2	-3.8	0.7	-5.6	-3.3	-7.9	-6.9	-7.4
M	4.3	7.8	2.4	9.9	5.3	9.1	8.2	8.7
Σ	1.0	3.2	1.6	3.4	1.0	0.6	1.0	0.8
min $\Delta d^{z}_{w(GPS)}$	-34.7	-29.8	-8.7	-47.6	-19.2	-56.4	-10.8	-41.3
max $\Delta d^{z}_{w(GPS)}$	12.4	10.7	10.4	2.7	10.7	-1.6	14.1	-12.8
M	17.3	19.9	5.2	27.9	10.7	26.1	10.8	23.8
Σ	12.7	11.3	5.5	16.3	9.7	16.2	8.9	9.8

Continuation of Table 3

1	2	3	4	5	6	7	8	9
min ΔPWV	-5.59	-4.81	-1.40	-7.71	-3.07	-9.29	-1.79	-6.82
max ΔPWV	1.98	1.73	1.68	0.44	1.72	-0.26	2.50	-2.11
M	2.79	3.21	0.84	4.54	1.71	4.29	1.78	3.92
Σ	2.05	1.82	0.88	2.66	1.55	2.68	1.46	1.61

The following symbols are given in Table 3: min and max respectively are the minimum and maximum values of the indicated differences, m – is a mean square error, σ – is a standard deviation. Having analysed the table, it is stated that the extreme deviations for differences $\Delta d^{z}_{h(SA)}$ both in winter and in summer do not exceed 10 mm, which confirms the exact definition of the hydrostatic component by the model of Saastamoinen. An exception is several Beauvecchain stations – BRUX, where the extreme deviation is 18.7 mm in January, and the standard deviation is σ = 5.6 mm, which is 2–3 times higher, than the corresponding characteristics of other stations. This can be explained by the fact that, the heights of the soundings did not exceed 17 km on average at the Beauvecchain station in January, which is almost twice less than the generally accepted sounding heights – 35 km, and this, in its turn, directly reduces the accuracy of the hydrostatic component determination.

Concerning the peculiarities of the spread of wet components differences $\Delta d^{z}_{w(GPS)}$, it is almost twice less in winter, than in summer period, for temperate latitudes, except for Beauvecchain stations – BRUX, where such a spread reaches 50 mm. This is to some extent due to the geographical location of the stations, the relative humidity of the air here, both in winter and in summer, is quite high, because of the proximity of the Atlantic Ocean.

As for the spread of differences ΔPWV, according to the data of both European and tropical stations, the given values do not exceed 10 mm during the winter and summer seasons.

Novelty and practical significance

For the first time, simultaneous studies of the ZTD and its components and the water vapor content at five stations in the middle latitudes and three stations of the tropical zone were conducted. The obtained results can further be used in the studies of changes in climatic processes.

Conclusions

In the process of the conducted research, a comparative characteristics of hydrostatic and wet components values of the zenith tropospheric delay and the precipitable water vapour was carried out, which were determined according to the data of the aerological and GNSS stations, located both in temperate and tropical latitudes. Generally, the accuracy of the hydrostatic component of the zenith tropospheric delay determination is about 10 mm, and the accuracy of the wet component definition of zenith tropospheric delay, deducted from GNSS measurements, is approximately 20 mm. The PWV values mainly vary by analogy to the values $d^{z}_{w(GPS)}$, and the accuracy of its definition reaches ≈3 mm.

As it was already stated, by the results of the soundings, there was the abnormal distribution of relative humidity of air with the height at Guam station in January, therefore, in order to clarify the reason for such anomaly, it is expedient to increase a number of experimental data by developing and analyzing monthly soundings for the Guam station during the year in the future.

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ВИЗНАЧЕННЯ ОСАДЖУВАНОЇ ВОДЯНОЇ ПАРИ ЗА ДАНИМИ АЕРОЛОГІЧНИХ ТА ГНСС-ВИМІРЮВАНЬ НА ЄВРОПЕЙСЬКИХ І ТРОПІЧНИХ СТАНЦІЯХ

Мета роботи полягає в дослідженні атмосферної випадаючої водяної пари (PWV), що ґрунтується на опрацюванні аерологічних та ГНСС-вимірювань, а також порівнянні величин PWV, визначених за даними аерологічних і ГНСС-станцій, розміщених і в помірних, і тропічних широтах. **Методика.** Алгоритм визначення осаджуваної водяної пари на основі ГНСС-спостережень поділяється на кілька етапів: 1) за основним рівнянням кодових або фазових псевдовідстаней ГНСС-вимірювань визначають повну тропосферну затримку; 2) вибирають величини ZTD на момент ГНСС-спостережень [ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/new/]; 3) за аналітичною моделлю Saastamoinen обчислюють гідростатичну складову зенітної тропосферної затримки; 4) за величинами ЗТЗ і гідростатичною складовою отримують величини вологої складової ЗТЗ; 5) за вологою складовою ЗТЗ обчислюють величини інтегрованої IWV та осаджуваної водяної пари PWV. Величини IWV і PWV визначають також і за даними аерологічного зондування. **Результати.** В ході виконаних досліджень визначено складові ЗТЗ та величини PWV. Проведено порівняльну характеристику цих величин, визначених за даними і аерологічних, і ГНСС-станцій. Загалом точність визначення гідростатичної складової ЗТЗ становить близько 10 мм, а точність визначення вологої складової ЗТЗ, виведеної із ГНСС-вимірювань, приблизно 20 мм. Величини PWV, переважно, змінюються за аналогією до величин вологої складової ЗТЗ, а точність їх визначення досягає 3 мм. **Новизна та практична значущість.** Вперше виконано одночасні дослідження тропосферної затримки та її складових і вмісту водяної пари на п’яти станціях середніх широт та трьох станціях тропічної зони. Отримані результати надалі можна використали під час дослідження змін кліматичних процесів.

Ключові слова: ГНСС-вимірювання; волога складова зенітної тропосферної затримки; аерологічне зондування; водяна пара.

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