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Research paper

TROPOSPHERIC INFLUENCE IN GNSS POSITIONING

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Abstract

Atmospheric influences, mainly caused by ionospheric and tropospheric conditions, lead to delays and distortions of GNSS signals that travel from satellites to receivers on Earth. This impact must be considered for projects that require high positioning and navigation accuracy. The troposphere dominates in areas with a large amount of water vapour and can also cause measurement errors due to changes in signal propagation speed. In this work, the tropospheric influence on GNSS positioning was analysed. The focus is on their cause, how they affect the accuracy of GNSS measurements, and the methods and technologies used to reduce or eliminate this influence. A 3D geodetic network of permanent stations was levelled using different empirical tropospheric models. Understanding and correcting these factors are important for improving GNSS technology's accuracy, reliability and practical use in modern geodetic and scientific research. The tropospheric delay is usually modelled in the zenith direction and is called the zenith tropospheric delay. As the zenith angle increases, the delay itself increases. So-called reduction functions obtain the relationship between the zenith and oblique delays. The GNSS-Lab Tool software and data collection and processing methods were used to calculate and obtain the zenith tropospheric delay (ZTK) value.

Keywords: *global navigation satellite system, the network of permanent stations, atmosphere, troposphere, tropospheric models, mapping functions*

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1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) are a collective name for all systems that deal with positioning and navigation using artificial satellites. GNSS are based on a technique called trilateration, which is the determination of the position of an unknown point based on measuring its distance to points with known positions, or coordinates. The atmosphere is defined as the region that surrounds the Earth from sea level to about 1000 km in altitude, with different physical and chemical properties. The atmosphere has various effects on our planet: on the shape, rotation and gravitational field of the Earth [1]. When considering the influence of the atmosphere on the measurement results in satellite geodesy, the atmosphere is divided into two basic layers, the troposphere and the ionosphere. The troposphere is the lower part of the Earth's atmosphere, which extends to a height of about 15 km (depending on geographical location). This part of the atmosphere consists of dry gases and water vapour [2], which can cause measurement errors due to changes in signal propagation speed. The stratosphere is much more stable and less turbulent, and therefore, the electromagnetic waves of GNSS signals experience practically no significant delays or changes as they pass through this layer of the atmosphere [3-5].

Among the many sources of errors affecting and reducing GNSS measurements' accuracy, tropospheric refraction is considered one of the most significant. GNSS signal propagation errors occurred amid ionospheric influences, eliminating the use of dual-frequency transmissions. Being a refractive layer, the troposphere delays the GNSS signal. Its temperature decreases with altitude, its thickness also varies with latitude, and it contains 90% of the atmospheric mass. The troposphere is an environment that is not dispersive for the frequencies used in the GNSS system (<30 GHz) and is made up of neutral atoms and molecules [6], which is why tropospheric refraction, unlike ionospheric influences, cannot be eliminated using dual-frequency receivers. The delay value caused by the troposphere during signal propagation is identical at all frequencies and all types of measurement. Tropospheric delay is characterised by a refractive index that can be divided into two parts, i.e. are a dry and a wet component.

Many studies have been carried out to create and test tropospheric refraction models for calculating the refractivity along the signal propagation path. Saastamoinen (Saastamoinen, 1972), Hopfield (Hopfield, 1969), Goud and Goodman (1974) and Black (1978) stand out as the most significant researchers and originators of the theory of empirical tropospheric modelling, of which the Saastamoinen and Hopfield model stands out as the most commonly used in practice. These models typically calculate the zenith delay (for elevation angle = 0) and then use a mapping function to obtain the total tilt delay, depending on the satellite elevation angle [7].

The permanent GNSS network of Bosnia and Herzegovina, BiHPOS, consists of two subnetworks: SRPOS (managed by the Republic Administration for Geodetic and Property-Legal Affairs of the Republic of Srpska) and FBiHPOS (managed by the Federal Administration for Geodetic and Property-Legal Affairs of the Federation of BiH). Both permanent GNSS networks of BiHPOS have been active and available to users since 27.09.2011. They are based on the same hardware and software solutions, which enable full system compatibility and data exchange. The networks of permanent GNSS stations enable fast and reliable determination of point coordinates for geodetic positioning, surveying, establishment and reflection of the real estate cadastre, and other applications in engineering geodesy [8].

The subject of the work is to perform an analysis of a levelled 3D geodetic network of permanent stations using different empirical tropospheric models. Despite the well-documented impact of the troposphere on GNSS signals and the existence of various correction models, there is a research gap regarding a comprehensive comparison of different empirical models (Hopfield, modified Hopfield, and Saastamoinen) and their specific influence on the levelling of a 3D geodetic network of permanent stations in a particular geographical area like Bosnia and Herzegovina's BiHPOS network. Furthermore, a detailed analysis of how geographical location and altitude directly affect the values of the zenith tropospheric delay (ZTD) using data from local networks such as SRPOS has not been sufficiently explored. Based on these considerations, the main hypothesis of this work is that the application of empirical tropospheric models significantly improves the accuracy of coordinates, especially the height component, compared to levelling without any model, with the greatest differences observed over longer baselines. The secondary hypothesis is that the value of the zenith tropospheric delay (ZTD) is directly dependent on the altitude of the permanent station: with increasing altitude, the ZTD values decrease proportionally.

Alignment will be done in the global WGS84 system, with subsequent transformation of the aligned coordinates into the national coordinate system (DKS) with special emphasis on applying the same observation plan when processing vectors with different tropospheric models.

The tropospheric delay is usually modelled in the direction of the zenith and is called the zenith tropospheric delay. As the zenith angle increases, the delay itself increases. The Niell Mapping reduction function is used to obtain the relationship between the zenith delay and the slant delay. The paper will also calculate the zenith tropospheric delay for three stations of the SRPOS network of permanent stations for a multi-day observation period, with the help of the appropriate gLAB software.

2. MATERIALS AND METHODOLOGY

2.1. Study of the area

In the Republic of Srpska, the SRPOS network of permanent stations is active, consisting of 23 permanent stations, evenly distributed at distances of 35-50 km from each other. To ensure better network geometry, the SRPOS network also receives data from 12 stations of the FBiHPOS network and 9 stations from surrounding countries (Croatia, Serbia and Montenegro). Also, in addition to SRPOS, there is the newly established GiCORS network of permanent stations, which was installed in 2022. Three permanent stations of the SRPOS network were used in the work: Banja Luka, Teslić and Derventa (Figure 1) and three stations of the GiCORS network: GIBL (Banja Luka), GIDE (Derventa) and GITE (Teslić).

Figure 1. Locations of SRPOS permanent stations within the BiHPOS network [9]

2.2. Input data

The precise positioning method (PPP) was used for data processing. RINEX raw observations for individual stations, SP3 files with precise ephemeris for the corresponding day and ANTEX files with data on the deviations of the phase centres of receiver and satellite antennas are used as input data for the mentioned type of processing.

RINEX raw observations were taken from the Republic Administration for Geodetic and Property Legal Affairs in Banja Luka, for SRPOS permanent stations Banja Luka, Derventa and Teslić. The data referred to the measurement period of five consecutive days, from August 8, 2020, to August 12, 2020. The length of the measurement session at the mentioned stations was 24 hours, for a data registration interval of 15" and a limiting vertical angle of 10°. Observations were also taken from the stations of the GiCORS network, i.e. GIBL (Banja Luka), GIDE (Derventa) and GITE (Teslić). The observations refer to a twenty-four-hour period, from 00:59:45 hours on August 9 until 00:59:30 on August 10, 2020.

To examine the influence of geographical location and altitude, raw data were downloaded for SRPOS permanent stations Banja Luka (214 m a.s.l.), Teslić (270 m a.s.l.), Brod (150 m a.s.l.), Gacko (1016 m a.s.l.) and Sokolac (944 m a.s.l.). Data were taken for one measurement day, April 23, 2015.

Precise ephemerides are downloaded in standard SP3 format. The download was made from the official website of the International GNSS Service (IGS) for the necessary periods for which the observations are analysed. A separate, corresponding SP3 file is loaded for each measurement day.

ANTEX files provide data on antennas, that is, on deviations of the phase centres of receiver and satellite antennas, and were downloaded from the official website of the National Geodetic Survey (NGS) belonging to the American National Oceanic and Atmospheric Administration (NOAA).

For the given task, 5 independent vectors were formed between six permanent stations (Figure 2).

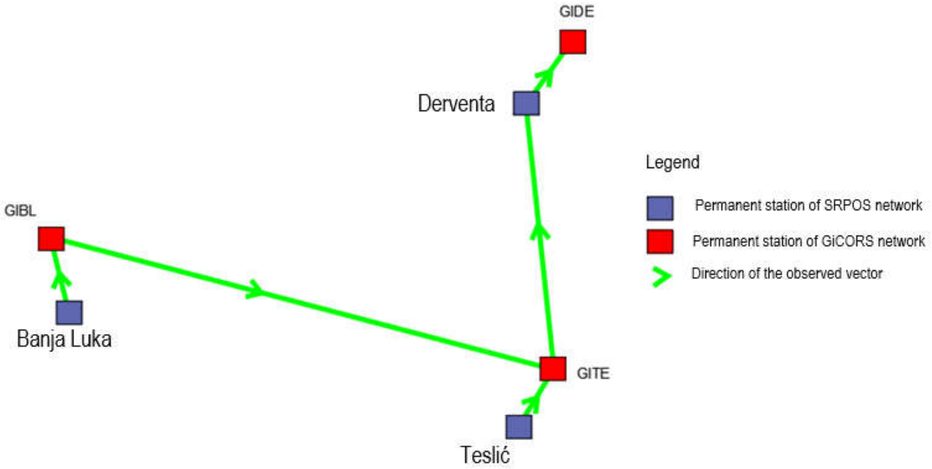

Figure 2. Representation of GNSS vectors selected for basic mathematical processing

2.3. Tropospheric refraction of GNSS signals

Tropospheric refraction parameters are evaluated during GPS positioning according to:

$$\mathrm{ZTD}=\mathrm{ZHD}+\mathrm{ZWD} \tag{1}$$

which contains the following members: ZTD is Zenith Total Delay, ZHD is Zenith Hydrostatic Delay, and ZWD is Zenith Wet Delay. The dry component or hydrostatic part has a slow time variation, so it is modelled and used as an a-priori value while the wet component or ZWD is evaluated in the parameter estimation procedure. The most commonly used models for the ZHD component are the ECMWF (European Centre for Medium-Range Weather Forecasts) or the GPT (Global Pressure Temperature) model [10].

2.3.1. Models for correcting hydrostatic tropospheric delay

The hydrostatic (dry) zenith delay can be accurately calculated a priori from the surface pressure and the station latitude and altitude [11], using the Saastamoinen and Hopfield model [4, 5]. If meteorological data are not available, values derived from the standard atmosphere are used instead. The hydrostatic component of the delay accounts for about 90% of the total delay. For smaller wet zenith delays, there is no exact model to obtain an a priori value. Therefore, this component is usually included as an unknown parameter in the observation equations and is estimated as such in the PPP processing. This parameterisation can be further improved by including horizontal gradients [12-15], which primarily improves the latitudinal component at the millimetre level [16].

Saastamoinen developed a model based on surface pressure measurements and the latitude and altitude of the station. In his model, he adopts the Essen and Froome (1951) refractive constant. The expression for calculating the hydrostatic zenith delay is:

$$ZHD_{[m]} = \frac{0.0022768 * \rho_{0[mbar]}}{1-0.00266 * cos\varphi - 0.00028 * H_{[km]}} \tag{2}$$

where: ρ_0, total pressure at the station; φ, latitude of the station, and и H, orthometric height of the station.

Hopfield uses a quartic model based on temperature and altitude, representing the hydrostatic refractivity by a fourth-degree curve, and the Smith and Weintraub (1953) refractive constant:

$$ZHD = \frac{10^{-6}}{5} \; N_H \, h_H \tag{3}$$

where: N_H, hydrostatic refractivity and h_H, temperature-dependent hydrostatic height (h_H=40082-0.14898*(T -273.16)).

In addition to the basic Hopfield model, there is a modified version of it, where the lengths of the position vectors are introduced instead of heights, and the expression is obtained:

$$N_d(r) = N_{ds} * \left(\frac{r_d - r}{r_d - Rz}\right)^4 \tag{4}$$

where: Rz is the radius of the Earth, and the lengths r_d and r can be obtained as the sum of the radius and the corresponding heights, *H* (the height corresponding to the humid part of the atmosphere) and *Hd* (the height corresponding to the dry part of the atmosphere):

$$r_d = Rz + Hd \tag{5}$$

$$r = Rz + H \tag{6}$$

2.3.2. Models for correcting wet tropospheric delay

Moist delay models have lower accuracy than hydrostatic delay models. This is since the characteristics of water vapour vary greatly in time and space, which significantly complicates the modelling of the moist component of refraction. Therefore, detailed research has been conducted to define an a-priori value of the moist zenith delay, but it has been determined that an accuracy of determination better than a few centimetres cannot be achieved. [17].

Saastamoinen's model assumes that temperature and water vapour decrease linearly with increasing altitude. He uses the same refractive constant as in the hydrostatic delay model. Therefore, Saastamoinen's expression for calculating the wet delay model is:

$$ZWD = 0.002277 * \left(\frac{1255}{T_s} + 0.05\right) * e_s \tag{7}$$

where: T_s, the temperature at the Earth's surface and e_s, the water vapour pressure at the Earth's surface.

Hopfield gives an expression using the wet component Nws from Smith and Weintraub (1953):

$$d_w^z = 10^{-6} N_{ws} \frac{H_w^e}{5} \tag{8}$$

2.4. Neill mapping reduction function (NMF) for tropospheric modelling

Tropospheric delay is the smallest in the zenith direction. With increasing zenith angle, the tropospheric delay itself increases. Reduction functions serve to give the relationship between zenith delay and oblique delay.

Due to the lower accuracy of determining a-priori wet delay models compared to dry delay models, the same principle is applied to reduction functions. That is, determining the total reduction function would not satisfy the needs of precise positioning, and therefore, the wet delay reduction functions and the hydrostatic delay reduction functions are most often studied separately. The Niell reduction function was used in the paper. Although it was defined in 1996, the Niell reduction function is still used today in many GNSS software because it is independent of atmospheric parameter measurements. The advantage of this function over others is that it provides accurate positioning results for receivers located between 43° and 75° north latitude, for a minimum elevation angle of 3°.

The Niell reduction function is [18]:

$$m(E) = \frac{1+\frac{a_i}{1+\frac{b_i}{1+c_i}}}{sinE+\frac{a_i}{sinE+\frac{b_i}{sinE+c_i}}} + \left(\frac{1}{sinE} - \frac{1+\frac{a_{ht}}{1+\frac{b_{ht}}{1+c_{ht}}}}{sinE+\frac{a_{ht}}{sinE+\frac{b_{ht}}{sinE+c_{ht}}}}\right) * \frac{H}{1000} \tag{9}$$

where a_i, b_i and c_i are the parameters of the hydrostatic or wet reduction function. a_{ht}, b_{ht} and c_{ht} are the constant values of the height correction, and are $a_{ht} = 2{,}53 * 10^{-5}$, $b_{ht} = 5{,}49 * 10^{-3}$ and $c_{ht} = 1{,}14 * 10^{-3}$. *H* is the orthometric height of the receiver in meters. The height correction is applied only to the hydrostatic NMF, and the values of the coefficients a_i, b_i and c_i are shown in Tables 1 and 2 [18].

Table 1. Coefficients of the hydrostatic mapping function

Coefficient	Latitude				
	15°	30°	45°	60°	75°
a	0	$1.271*10^{-5}$	$2.652*10^{-5}$	$3.400*10^{-5}$	$4.120*10^{-5}$
b	0	$2.142*10^{-5}$	$3.016*10^{-5}$	$7.256*10^{-5}$	$11.723*10^{-5}$
c	0	$9.013*10^{-5}$	$4.350*10^{-5}$	$84.795*10^{-5}$	$170.372*10^{-5}$

Table 2. Coefficients of the wet mapping function

Coefficient	Latitude				
	15°	30°	45°	60°	75°
a	$5.802*10^{-4}$	$5.679*10^{-4}$	$5.812*10^{-4}$	$5.973*10^{-4}$	$6.164*10^{-4}$
b	$1.428*10^{-3}$	$1.514*10^{-3}$	$1.457*10^{-3}$	$1.457*10^{-3}$	$1.457*10^{-3}$
c	$4.347*10^{-2}$	$4.347*10^{-2}$	$4.391*10^{-2}$	$4.453*10^{-2}$	$5.474*10^{-2}$

3. RESULTS

3.1. 3D levelling using various tropospheric models

In the first practical part of the work, data from six permanent stations were processed using the commercial software package Leica Geo Office (LGO). Three permanent stations are related to the SRPOS network of permanent stations, and three to the GiCORS network. The adjustment is performed using the least squares method using a mathematical model that implies a functional and stochastic model and a network datum. The network datum is defined by the coordinates of the SRPOS permanent station Banja Luka, fixing its given values.

The adjustment of the appropriate tropospheric model, without a tropospheric model, the Hopfield model, the modified Hopfield model and the Saastamoinen model, is performed before the processing of each vector. To ensure the validity of the obtained results, 3D adjustment was performed for all tropospheric models according to the same observation plan.

As a result of processing, individual reports are obtained for each vector. The reports include basic data on the processing performed, such as data on observed points, processing parameters, observation quality ratings, approximate coordinates, etc. After alignment, the final coordinates were transformed from the WGS84 system to the State Coordinate System (DKS), i.e. the sixth zone of the Gauss-Krüger projection, using the seven-parameter Helmert transformation model (Tables 3, 4, 5, and 6). Given that the subject permanent stations are located at three separate “microlocations” (the city of Banja Luka, the municipality of Teslić, and Derventa), transformation parameters were created for each of these locations.

Table 3. Coordinates of permanent stations without an applied tropospheric model

Station	Y [m]	X [m]	H [m]
Banja Luka	6438923.345	4959040.676	168.936
GIBL	6437304.537	4961077.384	175.015
Derventa	6493077.446	4981380.852	171.753
GIDE	6493110.139	4981501.583	158.070
GITE	6489304.095	4939854.012	217.911
Teslic	6489078.093	4939593.253	224.797

Table 4. Coordinates of permanent stations with the applied Hopfield model

Station	Y [m]	X [m]	H [m]
Banja Luka	6438923.345	4959040.676	168.936
GIBL	6437304.540	4961077.382	175.025
Derventa	6493077.388	4981380.818	171.771
GIDE	6493110.081	4981501.549	158.077
GITE	6489304.040	4939854.034	217.981
Teslic	6489078.039	4939593.274	224.874

Table 5. Coordinates of permanent stations with the modified Hopfield model applied

Station	Y [m]	X [m]	H [m]
Banja Luka	6438923.345	4959040.676	168.936
GIBL	6437304.540	4961077.382	175.026
Derventa	6493077.389	4981380.818	171.770
GIDE	6493110.082	4981501.549	158.074
GITE	6489304.041	4939854.033	217.988
Teslic	6489078.040	4939593.273	224.881

Table 6. Coordinates of permanent stations with the Saastamoinen model applied

Station	Y [m]	X [m]	H [m]
Banja Luka	6438923.345	4959040.676	168.936
GIBL	6437304.540	4961077.382	175.025
Derventa	6493077.389	4981380.818	171.771
GIDE	6493110.082	4981501.549	158.077
GITE	6489304.040	4939854.034	217.981
Teslic	6489078.039	4939593.274	224.874

The values obtained with the different tropospheric models applied were first compared with those obtained without using the tropospheric model, and then a mutual comparison of the results obtained from the different models was performed (Tables 7 and 8).

Table 7. Differences in coordinates obtained by comparing coordinates without models with different models

	Without troposphere-Hopfield			Without troposphere-modified Hopfield			Without troposphere-Saastamoinen		
Station	Y [cm]	X [cm]	H [cm]	Y [cm]	X [cm]	H [cm]	Y [cm]	X [cm]	H [cm]
Banja Luka	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GIBL	-0.3	0.2	-1.0	-0.3	0.2	-1.1	-0.3	0.2	-1.0
Derventa	5.7	3.4	-1.8	5.7	3.4	-1.8	5.7	3.4	-1.8
GIDE	5.7	3.4	-0.6	5.7	3.4	-0.4	5.7	3.4	-0.6
GITE	5.5	-2.2	-6.9	5.5	-2.2	-7.6	5.5	-2.2	-7.0
Teslic	5.4	-2.1	-7.7	5.3	-2.0	-8.3	5.4	-2.1	-7.7

Table 8. Differences in coordinates obtained by comparing the coordinates different models

	Hopfield - modified Hopfield			Hopfield - Saastamoinen			Saastamoinen - modified Hopfield		
Station	Y [cm]	X [cm]	H [cm]	Y [cm]	X [cm]	H [cm]	Y [cm]	X [cm]	H [cm]
Banja Luka	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GIBL	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	-0.1
Derventa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
GIDE	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.2
GITE	0.0	0.1	-0.7	0.0	0.0	-0.1	0.0	0.1	-0.6
Teslic	-0.1	0.1	-0.7	0.0	0.0	-0.1	-0.1	0.1	-0.6

3.2. Determination of zenith tropospheric delay

In the second part of the paper, the zenith tropospheric delay (ZTD) was calculated for the permanent stations of Banja Luka, Teslić and Derventa, during a measurement period of 5 days. The dependence of ZTD on the geographical position, i.e. the altitude of the measuring station, was also examined. ZTD was determined for the permanent stations of Banja Luka (214 m a.s.l.), Teslić (270 m a.s.l.), Brod (150 m a.s.l.), Gacko (1016 m a.s.l.) and Sokolac (944 m a.s.l.). The calculation was performed using the specialised GNSS-Lab Tool, abbreviated as gLAB.

This software package is used for precise modelling of GNSS observations. Observations of the SRPOS network stations were performed using the PPP method. The software used consists of five basic modules that are passed through to obtain the desired final results: Input, Preprocess, Modelling, Filter and Output. The corresponding RINEX, SP3 and ANTEX files are imported. The loading is done separately for each measurement day, with the selection of the appropriate precise ephemeris, while ANTEX is the same for all permanent stations in question.

In the Modelling module, the Simple Nominal option with the Niell reduction function is selected because, in this case, the tropospheric correction is significant. The Simple Nominal model is a global tropospheric model that does not require meteorological data for modelling.

Table 9 shows the averaged values of the tropospheric zenith delay for the permanent stations Banja Luka, Teslić and Derventa.

Table 9. ZTD values for the period 08.08.2020-12.08.2020. year

Date →	08.08.2020.	09.08.2020.	10.08.2020.	11.08.2020.	12.08.2020.
Station	Average ZTD [m]	Average ZTD [m]	Average ZTD [m]	Average ZTD [m]	Average ZTD [m]
Banja Luka	2.494	2.465	2.461	2.506	2.476
Derventa	2.486	2.455	2.459	2.495	2.461
Teslic	2.480	2.453	2.453	2.447	2.472

To determine the dependence of ZTD and altitude, the same methods described above were used to calculate ZTD for the lowest permanent station in the SRPOS network (Brod – 150 m a.s.l.), as well as the two highest permanent stations (Sokolac – 944 m a.s.l. and Gacko 1016 m a.s.l.). Given that, based on previous data, it was determined that there were no significant deviations in determining ZTD on consecutive measurement days, the data were taken and the analysis was carried out for one measurement day, 23.04.2015. Table 10 presents the obtained results of determining ZTD for the permanent stations Banja Luka, Teslić, Gacko, Brod and Sokolac. There are no measurement data for the permanent station Derventa for the specified day.

Table 10. ZTD values on April 23, 2015. year

Station	Station altitude [m]	Average ZTD [m]
Banja Luka	214	2.408
Brod	150	2.418
Teslic	270	2.367
Gacko	1016	2.145
Sokolac	944	2.187

4. DISCUSSION

The GNSS network consisted of six permanent stations, three belonging to the SRPOS network of permanent stations of the Republic of Srpska and three belonging to the private GiCors network of permanent stations. Raw observations in RINEX format were downloaded for the above stations. The downloaded observations refer to a twenty-four-hour period during August 8 and 9, 2020.

Based on the results in Table 7, it is visible that there is a significant difference in the calculation of coordinates without tropospheric corrections and using tropospheric models. The application of tropospheric models led to a significant improvement in the accuracy of coordinates, especially for the height component, compared to processing without a model. For longer baselines (over 50 km from the reference station), these differences reached up to 5.7 cm along the positional axes and 8.3 cm for the height component. In contrast, for the GIBL station, located only 2.6 km from the Banja Luka station, the differences were minimal, measuring up to 0.3 cm on the positional axes and 1.1 cm in height. The difference is especially pronounced for permanent stations located at greater distances from the permanent station Banja Luka, whose values were taken as known (fixed) in the smoothing. The permanent station GIBL, located 2.6 km from the Banja Luka station, did not show significant deviations with and without the use of tropospheric corrections (up to 0.3 cm along the positional coordinate axes and up to 1.1 cm along the height). The remaining permanent stations are located at distances greater than 50 km from the Banja Luka station, and their coordinates change significantly with the use of tropospheric models, in the range of 2.2 cm - 5.7 cm along the coordinate axes and from 0.6 cm - 8.3 cm along the height. The values in Table 8 show the mutual relationships of the coordinates obtained by using different tropospheric models. From the obtained results, it is evident that all models give approximately the same results, with special emphasis on the Hopfield and Saastamoinen models, where differences were obtained only for two permanent stations, in the value of 0.1 cm. On the other hand, the modified Hopfield model shows slightly larger deviations than the other two models, especially in terms of height for the permanent stations Teslic and GITE, where differences of 0.6 cm and 0.7 cm were obtained.

From the results presented in Table 9, it can be seen that the ZTD values for all stations vary in the range from 2,447 m to 2,507 m, with a maximum change of 4.5 cm for an individual station. The similarity of the ZTD values can be associated with a similar geographical location and altitude (the lowest station is Banja Luka with 214 m a.s.l., and the highest is Teslić with 270 m a.s.l.).

From Table 10, it is visible that the zenith tropospheric delay is noticeably different for permanent stations located at altitudes of approximately 1000 m and those located in lower areas. Our results unambiguously indicate a direct dependence of the zenith tropospheric delay (ZTD) values on the geographical location and altitude of the station, with ZTD values decreasing proportionally as altitude increases. For example, the average ZTD for the highest stations (Gacko at 1016 m a.s.l. and Sokolac at 944 m a.s.l.) were 2.145 m and 2.187 m, respectively. In comparison, lower-altitude stations like Brod (150 m a.s.l.) and Banja Luka (214 m a.s.l.) had higher average ZTD values of 2.418 m and 2.408 m, respectively.

First, the altitude of the permanent stations is compared with the lowest (Brod) and then the obtained ZTD values are compared in the same way. There is a clear direct connection and proportionality between the geographical location, i.e. the altitude of the permanent station, and the values of the zenith tropospheric delay for the same. With increasing altitude, the ZTD decreases and vice versa.

5. CONCLUSION

In GNSS receivers for civil use, tropospheric delay is determined using developed models that estimate the delay based on surface meteorological parameters. In the last few decades, models have been developed in such a way that models for zenith tropospheric delay (the satellite is at an elevation angle of 90˚) and models for a functional delay function that judges the delay at a certain angle have been developed. The most famous model of the function that maps the zenith tropospheric delay to the angular delay is the Niell function. A. Niell in 1996, in his work, gave an expression for the Niell function and showed that it gives satisfactory accuracy for elevation angles greater than or equal to 3˚. The Niell function is written in the form of continued fractions. J. V. Marini, in 1972, first expressed the function that maps the zenith delay to the angular delay in the form of continued fractions. Since then, it has been most commonly used because it has proven to be better than the others for small elevation angles.

The research presented in this paper aimed to address a specific research gap by comparing the effectiveness of various empirical tropospheric models on GNSS network adjustment and by analyzing the relationship between station altitude and Zenith Tropospheric Delay (ZTD) values within the context of the BiHPOS network. The findings confirmed our initial hypothesis that the application of tropospheric models leads to a significant improvement in the accuracy of coordinates.

The analysis of the obtained results showed that, depending on the length of the baselines, the application of tropospheric models yields time coordinates of grid points that differ significantly from those obtained without the model in tropical models. These differences reach values of up to 5.7 cm along the position axes and 8.3 cm along the height. For this reason, the permanent station GIBL, located 2.6 km from the Banja Luka station, shows only 0.3 cm along the position coordinate axes and 1.1 cm along the height. The modified Hopfield model does not take into account the station's sea level in its calculation, which shows slightly larger deviations than the other two models, especially in terms of altitude for the permanent stations Teslić and GITE, where 06 cm were obtained.

The second task in the work was related to the calculation of the values of the zenith tropospheric delay (ZTD) and the examination of the dependence of the station altitude on these values. For the first measurement period of five consecutive days (08.08.2020 - 12.08.2020), the obtained ZTD values for the SRPOS permanent stations Banja Luka, Derventa and Teslić were in the interval from 2447 m to 2507 m, with a maximum daily change of 4.5 cm for an individual station. Given that the obtained results showed similar values, both for different permanent stations and for different measurement days, a similar procedure was repeated for the one-day measurement period. For the second measurement period, data were taken for the Banja Luka and Teslić stations as common stations with the previous procedure, as well as Gacko and Sokolac as stations located at a significantly higher altitude, and the Brod station, which is located at a significantly lower altitude than all stations from the SRPOS network.

The average ZTD values for the stations Brod, Banja Luka, Teslić, Sokolac and Gacko were 2418 m, 2408 m, 2467 m, 2187 m and 2145 m, respectively, which confirmed the above assumptions.

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