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MITIGATING GNSS POSITIONING ERRORS DUE TO ATMOSPHERIC SIGNAL DELAYS

There are some fundamental limitations on positioning accuracy using satellite navigation technique. Several sources of errors limit the accuracy of GNSS (Global Navigation Satellite System) positioning. The errors due to the earth's atmosphere have the largest value and must be significantly reduced in order to achieve more precise positioning results. The GNSS-based determination of the position is based on the very accurate measurement of the satellite radio signal propagation time between the satellite and the GNSS receiver aerials. GNSS signals change the propagation speed and direction as they pass through the atmosphere on their path from the satellite to the receiver, causing positioning errors. The article deals with the methods for reducing positioning errors due to the satellite signal propagation through the earth's atmosphere.

Key words: *GNSS, positioning error, ionospheric delay, tropospheric delay, delay correction models.*

1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) is the standard term for all satellite navigation systems that offer global coverage. GNSS includes the U.S. GPS system, the Russian GLONASS system, the future European Galileo system, as well as the future Chinese Compass system. All GNSS systems operate by the basic principle of calculating the user's position by establishing the distance relative to the satellites with known positions. The distance is calculated from the travel time of radio waves transmitted from the satellites. Satellites with a known position transmit regular time signals (ranging signals) at two different frequencies in the L band. Assuming that radio waves travel at the speed of light, the distances from satellites to the receiver are calculated by multiplying the travel time by the speed of light. Almost 95% of the travel time satellite signals pass through a vacuum with a constant speed. The last 5% of the path GNSS signals change the propagation speed as they pass through the earth's atmosphere. These signal delays through the atmosphere should be corrected to avoid errors in the calculated distances (pseudoranges) from the satellites to the receiver. The term pseudorange implies the measured raw range that should be corrected for different errors before calculating the position. Pseudorange errors and positioning errors are of the same order.

GNSS systems can provide positioning accuracy which ranges from a few millimetres to the tenth of meters, depending on the type of observables (code or phase measurements) and positioning mode (stand alone receiver or in augmented differential mode of operation). Most commercial GPS receivers use only code measurements, obtaining position accuracy of the tenth of meters. For obtaining centimetre accuracy, RF carrier phase measurements of GNSS signals are necessary as well as differential mode of operation. This is used in RTF (Real Time Kinematic) surveying with application in geodesy, cadastral, topographic and engineering survey. Millimetres accuracy is also possible for precise static measurements applications, however not in real-time but using post-processing of the observables.

The positioning performance of GNSS systems is also affected by the geometry of the satellite positions in respect to the receiver, affecting all types of measurements, which should also be considered. As the satellites move, the geometry varies with time. The DOP (Dilution of Precision) factor indicates the quality of satellites geometry. DOP only depends on the positions of the satellites relative to the receiver location. With optimal satellite allocation in respect to the receiver DOP factor is close to 1. While DOP factors of 2.5 are about the worldwide average, this factor can range up to 10 or more with poor satellite geometry. This means that the positioning error in the case of unfavourable satellite constellation would be 10 times higher than in optimal constellation. For optimum constellation the volume of the space comprising the point of the receiver position and the points of satellites positions should be as large as possible. As the satellite positions can be calculated in advance, the quality of the GPS position fix can also be calculated in advance, and precise positioning observations can be planned when the DOP is the most favourable.

The intention of this paper is to address the influence of the atmosphere on the GNSS signal propagation and compare different mitigation techniques to reduce or eliminate positioning errors due to the signal delay. Mitigation techniques depend on the type of application considered and required positioning accuracy.

Concerning the earth atmosphere, there are two layers affecting the radio propagation - the ionosphere and the troposphere, both having different properties, which will be described below. The propagation delay through these layers differs in several important aspects. During active space and tropospheric weather conditions, the refractivity of the ionosphere and troposphere can change drastically in time and space, causing significant degradation of the positioning accuracy under these conditions for any GNSS satellite navigation system. Describing and proper modelling of atmospheric signal delays under virtually all conditions should allow correcting the signal delay, and reducing the positioning error.

There are also other parameters degrading the positioning performance of any GNSS system. The error budget for the GNSS pseudorange observation can be expressed with:

$$P = R + c \cdot (\Delta T_s - \Delta t_r) + \Delta ion + \Delta trop + \Delta mult + n_r \tag{1}$$

where:

P - measured pseudorange,
R - geometrical range to the satellite,
c - speed of light in a vacuum,
ΔT_s and Δt_r - errors in the satellite and receiver clocks,
$\Delta\, ion$ and $\Delta\, trop$ - ionospheric and tropospheric signal delays,
$\Delta\, mult$ - errors introduced by the multipath propagation, and
n_r - receiver noise.

The GNSS positioning accuracy depends on how well all of the sources of error can be measured, estimated or eliminated [1, 2, 3]. In this article the ionospheric and tropospheric influences will be explained in more details.

Fig. 1 shows the structure of the atmosphere with ionospheric and tropospheric layers. Three different signal paths from satellites at low elevation to satellites in the zenith direction are shown. The values of the delay depend on the elevation angle to the satellite, as the length of the travelling path (slant path) is different for these cases. For the ionosphere the variation of the delay between the satellites with the elevation angle from 5° to the zenith direction is by the factor of about 3, and for the troposphere by the factor greater than 10 [1]. This is due to fact that the troposphere begins at the earth’s surface, and the ionosphere at the height of about 50 km.

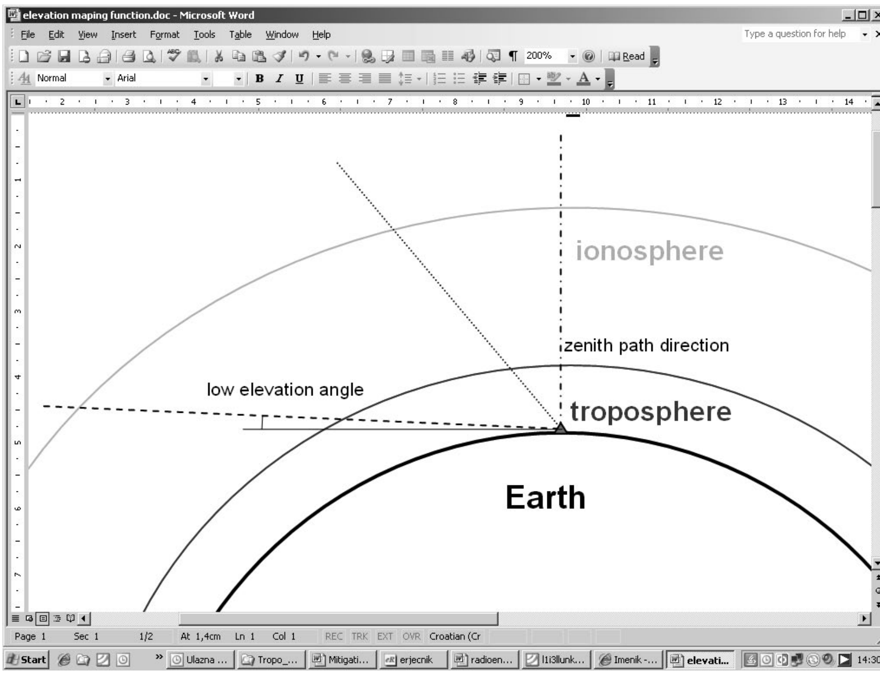

Figure 1. *Different slant paths through the atmosphere from low elevation satellites to the zenith path direction*

Source: Author

GPS offers two services for different categories of the users. PPS (Precise Positioning Service), offering better positioning performance, is intended for authorised users and SPS (Standard Positioning Service) is intended for all other GPS users. According to the SPS positioning and timing accuracy standard, the global average positioning domain accuracy horizontal error is ≤ 13 m for 95% of time, and vertical error ≤ 22 m for 95% of time if all satellites available are visible [15]. This does not imply that positioning error cannot be lower or higher in some percentage of time.

2. IONOSPHERIC INFLUENCE ON GNSS SIGNALS

The ionosphere is the space within the Earth's atmosphere, characterized by the increased number of ionized particles. The ionosphere is extending in various layers from about 50 km height to more than 1500 km above the earth surface. The GNSS ionospheric delay is originated by a complex dynamics of the space weather. Space weather is a common name for physical and chemical processes taking place in the space between the Sun and the Earth. The ionospheric delay of the satellite signal is caused by numerous processes both in the ionosphere and within the Sun-Earth system. Particles and radiations expelled from the Sun form the solar wind, which can cause disruption of the Earth's magnetic (geomagnetic) field and disturbance of the vertical distribution of ionised particles in the ionosphere. Stronger disturbances are expressed as ionospheric storms. Radiation from the Sun provokes ionization of the gas molecules, which releases free electrons. GNSS signals propagating through an ionized medium are affected by nonlinear dispersion characteristics of the medium.

The ionospheric delay is proportional to the total amount of free electrons - total electron content (TEC) encountered by the signal travelling from the GNSS satellite to the GNSS receiver. The TEC value directly determines the GNSS ionospheric delay, and delay *d* (usually expressed in metres) is described as:

$$d = \frac{40.3 \cdot TEC}{f^2} \tag{2}$$

where *f* is radio frequency (for single-frequency GPS receiver L1= 1575.42 MHz) and *TEC* is the Total Electron Content.

The total electron content between the satellite and the receiver can be expressed as:

$$TEC = \int_{satellite}^{receiver} N(h)dh \tag{3}$$

where *N(h)* is free electron density at the height *h* above the Earth's surface (the vertical profile of the ionosphere).

The TEC is the key parameter for the mitigation of the ionospheric error. The ionospheric delay causes ranging errors in the zenith direction that vary typically from 1-3 m at night to 5-15 m in the mid-afternoon [1, 2, 3, 11, 13]. For the satellites at low elevations the maximum delay can be even more than 100 m, depending mostly on the solar activity. The influence of the ionospheric layers on radio signal propagation is frequency dependent, and different frequencies have different signal delays, what is obvious from the equation (2). This characteristic of the ionosphere can be efficiently used to mitigate the signal delay.

GPS signals for the PPS service are transmitted at two different frequencies, to allow considerably reduction of the ionospheric delay error. Unfortunately, this service is not provided for commercial non-authorised users. All single frequency GNSS receivers need the real time mitigation of ionospheric delay effects for reducing the positioning error.

Ionospheric Errors Correction

Three different strategies can be used to correct the ionospheric delay:

- Measuring the difference of the GNSS signal delay at two transmitted frequencies and calculating the delay in real time
- Using mathematical models for the calculation of the GNSS signal delay
- Using additional information provided by ground and space-based augmentations - differential GPS/GNSS

1) As the ionospheric delay is frequency dependent, dual-frequency transmission allows eliminating the most of the ionospheric effects. The pseudorange *P* corrected for the ionospheric delay can be expressed with the equation:

$$P = \frac{P_2 - \left(f_1 / f_2 \right)^2 \cdot P_1}{1 - \left(f_1 / f_2 \right)^2} \tag{4}$$

where P_1 and P_2 are measured pseudoranges at two transmission frequencies f_1 and f_2 respectively [2, 3, 12]. Dual-frequency receivers are in this way capable of calculating the ionospheric delay in real time, significantly reducing the positioning error.

Commercial civil GPS receivers are typical single frequency units not capable of correcting the ionospheric delay with the dual-frequency technique.

2) The GPS system uses the broadcast ionospheric correction algorithm designed to correct the ionospheric delay. This is the standard correction used by almost all single-frequency GPS receivers. This model is usually named after its inventor John Klobuchar [2, 3], although it is a simplified version of the earlier more complex Bent model. The Klobuchar model provides two components in modelling the diurnal GPS ionospheric delay distribution - a constant component representing the night value, and a variable component expressed by cosine function representing the daily change of the GPS ionospheric error.

According to this simple analytical model the vertical ionospheric delay Δt for the zenith direction at L1 frequency is expressed by the equation:

$$\Delta t = A_1 + A_2 \cos\left(\frac{2\pi \left(t - A_3 \right)}{A_4} \right) \tag{5}$$

where A_1=5 x 10^{-9}seconds is a night-time DC value; $A_2 = \alpha_1 + \alpha_2\Phi + \alpha_3\Phi^2 + \alpha_4\Phi^3$ is amplitude; A_3=14:00 (local time) is phase; t is local time;

$A_4 = \beta_1 + \beta_2\Phi + \beta_3\Phi^2 + \beta_4\Phi^3$ is period; Φ is geomagnetic latitude; α and β represent eight ionospheric parameters transmitted to the users [2]. To estimate the actual ionospheric delay for any satellite elevation angle we must scale Δt by the obliquity factor.

GPS satellites send the values of these eight parameters of the Klobuchar model in the navigation message, so that single frequency receivers can compensate the ionospheric delay to a certain extent. These values are global ionospheric parameters and do not take into account possible regional ionospheric disturbances.

The Klobuchar model was a compromise between computational complexity and corrections accuracy, and provides successful correction of up to 60% of the positioning error caused by the ionospheric delay during stable ionospheric conditions [2]. This model responds very slowly to fast changing of the space weather condition and the ionospheric disturbances, which affects the overall GPS positioning performance considerably. Severe ionospheric disturbances reshape the daily ionospheric delay distribution significantly, making a destructive impact on the performance of the Klobuchar model and degrading the positioning performance of the single frequency GPS receivers. During severe space weather, geomagnetic and ionospheric disturbances, the Klobuchar model provides poor performance, even increasing the GPS ionospheric delay error instead of correcting it.

The availability of dual-frequency GPS pseudorange observations at the Dubrovnik site and the GPS satellite data (ephemeris and broadcast model parameter) for the time period in question provided the opportunity for analysing the performance of the standard Klobuchar model. Taken from our previous research paper [5] fig. 2 presents the curves for the measured and modelled ionospheric delay in the zenith direction using the Klobuchar model for a typical 24 hour period. The cosine shape of the modelled variable component is noticeably.

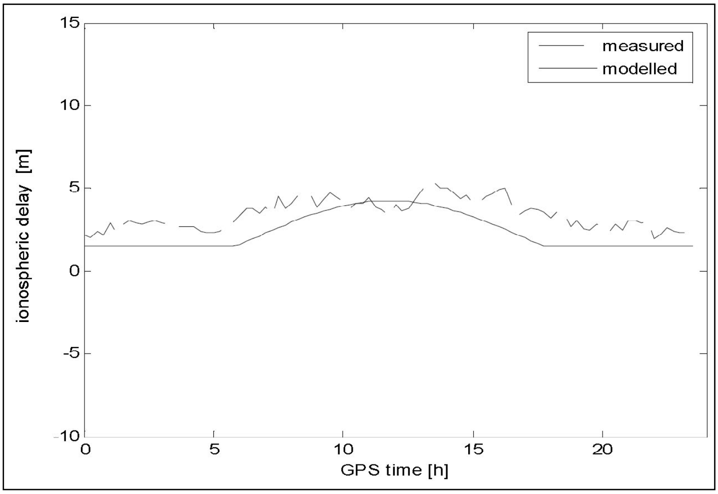

Figure 2. *Daily distribution of the zenith path ionospheric delay over Dubrovnik on 22nd September 2005 [5]*

As the Klobuchar model does not take into account local ionospheric conditions that significantly contribute to the general GPS ionospheric delay, many research activities conducted worldwide are analysing the observed GPS ionospheric delay dynamics and the relation to local ionosphere conditions. In our recent research we analysed daily GPS ionospheric delay dynamics observed along the Croatian coastal area of northern Adriatic in the periods of quiet space weather in 2007, and suggested some modifications of the Klobuchar model [6].

There are also some other versions of ionospheric delay models under research, performing much better than the mentioned Klobuchar model. A better correction of the ionospheric range delay can be obtained using a more sophisticated model requiring hundreds of coefficients. In the framework of the European positioning system Galileo, a quick-run empirical model NeQuick was chosen. NeQuick is a three-dimensional and time dependent ionospheric electron density model [6]. This global model provides monthly median electron density profiles for the given time, location and solar flux. It allows calculation of the electron concentration at any given location in the ionosphere. The total electron content can be computed by electron density integration along the satellite signal travelling paths. NeQuick is based on monthly median maps of ionosonde parameters.

3) The differential GPS offers the ability to reduce or eliminate many GPS measurement errors [2, 3, 14]. It involves the use of two receivers, one stationary at a reference station, and the other roving in the vicinity of the reference station. These receivers simultaneously track GPS signals from the same satellites.

By knowing the exact coordinates of the reference station, errors in the GPS measurements taken at the reference receiver can be estimated. The reference station estimates the error component of each satellite range measurement, and forms a correction for each satellite in view. As both the reference and the remote receivers track the same satellites, the errors estimated at the reference station can be used as real-time differential corrections for the measurements taken at the remote receivers locations. These corrections can be distributed to the users in many different ways, as radio signals and even through the internet. The positioning performance of the remote receivers in differential mode is more accurate than in the case of a single-point stand-alone positioning. The satellite clock error is totally eliminated, and ionospheric, tropospheric and orbital errors are also greatly reduced in differential mode of operation [2, 3, 14]. However, multipath and receiver noise are neither eliminated nor reduced with the DGPS corrections. Multipath is not receiver or satellite dependent, and receiver noise is not site-dependent. Over longer distances, DGPS corrections become less accurate causing degradation in the resulting positioning accuracy, because of the spatially decorrelation of errors. The expected accuracies with the DGPS corrections range from 1 to 5 m [2].

With the growing demand for an accurate and reliable worldwide differential GPS positioning, there has been a significant move towards the use of real-time GPS augmentation systems with wide area differential positioning capabilities. The U.S. Wide Area Augmentation System (WAAS) and the European Geostationary Navigation Overlay system (EGNOS) are good examples of such a move. The EGNOS is a satellite based augmentation system (SBAS) intended to supplement the GPS, GLONASS and Galileo systems. It consists of three geostationary satellites and a network of ground reference stations. Using corrections transmitted from these geostationary satellites the horizontal position accuracy can be at the metre level.

In the modernisation of the GPS system dual frequency transmission for civil users is planned, and in the near future the first method of mitigating the error will be available for them. To fully exploit the benefits of the modernised GPS system, a new generation of dual frequency receivers should be provided. This will solve the problem of ionospheric delay affecting positioning performance of a GPS system. But even after the modernisation of the GPS system, there will still be billions of GPS users all over the world having their old single frequency receivers, using the Klobuchar ionospheric model implemented in the receiver. They will benefit from using the DGPS differential corrections to achieve better positioning accuracy, within a few metres range.

The new European Galileo system will provide a wide range of improved and more reliable services to the users. Several types of signals will be provided, from one free to anyone signals for specific users such as safety of life and governmental users. Galileo satellites will transmit signals at several frequencies, to allow efficient mitigation of ionospheric errors in real time for several categories of users. Galileo will deliver positioning accuracy in the metre range with unrivalled integrity.

3. TROPOSPHERIC INFLUENCE ON GNSS SIGNALS

The troposphere is a lower part of the neutral atmosphere, extending from the earth's surface up to an altitude of approximately 16 km at the equator and 8 km at the poles, composed of dry gases and water vapour. The propagation speed of all radio signals below 30 GHz travelling through the neutral atmosphere is lower than in the free space, so all GNSS signals, regardless of frequency, are slowed equally. Since tropospheric delay is not frequency dependent, it cannot be estimated directly like the ionospheric delay, but must be modelled. Water vapour and dry gases found in the neutral atmosphere influence not only the propagation speed of the radio signal, but cause also bending the signal travelling path. The magnitude of the tropospheric delay depends on the refractive index of the atmosphere along the propagation path, which depends mainly on the atmospheric pressure, temperature and relative humidity (water vapour pressure).

3.1. Tropospheric Errors Correction

We can use several strategies to correct the errors caused by the tropospheric effects:

1) Ignore the tropospheric delay
2) Presume and use a constant value of the zenith path delay
3) Estimate the delay from the surface meteorological observation data
4) Predict the delay from empirically-derived climatologically data
5) Use additional information provided by a differential GPS station

1) The simplest strategy could be to ignore the tropospheric delay. This would cause an error in the calculated distance to the satellite varying between 2 m to more than 20 m [11, 14], depending on the elevation angle to the satellite. In the zenith direction the delay has the lowest magnitude, as the signal travelling path through the troposphere is the shortest. In the zenith direction there is no signal path bending, but for other elevation angles path bending causes additional ranging error.

2) As the tropospheric delay is rather constant, with the value for average tropospheric delay typically varying about ±5% from monthly average conditions, and by less than 20% over the entire earth, we can take an average value of the zenith path delay during all seasons and use it for reducing the ranging error. For mapping the zenith delay to other elevation angles a mapping function should be used.

3) The effect of the tropospheric delay on the GPS signal can be modelled using surface meteorological parameters, such as temperature, pressure and relative humidity. The tropospheric delay of the GPS satellite signal is caused by the refractivity gradients in the low atmosphere. The refractivity of the troposphere can be divided into hydrostatic and wet components. The refractive index can be expressed as the sum of the hydrostatic or 'dry' (ZHD) and non-hydrostatic or 'wet' refractivity (ZWD). The hydrostatic component contributes to approximately 90% of the total tropospheric delay, and can be modelled very accurately. A typically hydrostatic delay varies from 2m to 20m and represents about 90 percent of the total delay. The variation of water vapour in the atmosphere varies greatly with time and location, and the wet component is much more difficult to model efficiently. The wet component delay varies from 0.2m to 2m. Minimal values are obtained for the zenith path direction, and maximal values for low elevation signals when the satellite is near the horizon. For most GNSS applications accepting positioning error of several meters, the influence of the wet component to the total tropospheric delay is irrelevant, but for high precision positioning it is essential to calculate with both the tropospheric components. To estimate the combined tropospheric delay, a model of the standard atmosphere is usually used to determine the zenith path delay, and a mapping function should be used to determine the tropospheric delay for other satellite elevation angles. Mapping functions are usually not accurate for elevations <5°, which should not be a problem [11]. Low elevation satellites are not generally used for positioning, as in real environment obstacles like buildings, trees, vehicles, mountains and others can block signals from low elevation satellites.

A lot of researchers have examined the performance of currently available tropospheric delay models used in geodesy (Hopfield, Saastamoinen) and indicated that the zenith delay model of Saastamoinen is in general better than the others [8-12].

The total tropospheric delay *ZTD* using the Saastamoinen model comprising both the dry and the wet components, with incorporated mapping function [12] can be computed as:

$$ZTD_{Saas} = \frac{0.002277}{\cos z}\left[p + \left(\frac{1255}{T} + 0.05\right)\cdot e - B\tan^2 z\right] + \delta R \tag{6}$$

where p is the atmospheric pressure in hPa, e is the partial pressure of water vapor in hPa, T is the temperature in Kelvin, z is the zenith angle, and B is the correction term for the refined Saastamoinen model with values from the table (values are between 1.156 for the height 0 m and 1.079 for 500 m). δR is the correction term for the northern latitudes over 60°.

4) The strategy that does not require real-time meteorological input provides an estimate of the zenith tropospheric delay depending on the receiver's

height and empirical estimates of meteorological parameters – pressure, temperature, water vapor pressure, temperature lapse rate and water vapour lapse rate [8-12]. The values of each of these five meteorological parameters are computed from a table, using only the receiver height, latitude and day of the year as input. The values in the table are estimates of the yearly averages of the climatologic parameters and their associated seasonal variations, derived primarily from the North American meteorological data. The representative of this "navigation-type" model is the RTCA MOPS (Minimum Operational Performance Standard) or WAAS/EGNOS (Wide Area Augmentation System/European Geo-stationary Navigation Overlay System). The MOPS/WAAS/EGNOS model presumes constant values for all parameters in the region of ±15° around the equator, and symmetry between the northern and southern hemisphere. Each meteorological parameter ξ is computed using the following equation:

$$\xi(\phi, D) = \xi_0(\phi) - \Delta\xi(\phi) \cdot \cos\left(\frac{2\pi(D - D_{\min})}{365.25}\right) \tag{7}$$

where $D_{\min} = 28$ for northern latitudes, $D_{\min} = 211$ for southern latitudes, ξ_0 is the average value and $\Delta\xi$ seasonal variation for a particular parameter at the receiver latitude (obtained through linear interpolation). φ and D are the receiver latitude and day of year.

The zenith delay at a particular height H over the sea level is computed by summing up the hydrostatic and wet components given in equations (8) and (9):

$$d_{hyd} = \left(1 - \frac{\beta H}{T}\right)^{\frac{g}{R_d \beta}} \cdot \frac{10^{-6} k_1 R_d p}{g_m} \tag{8}$$

$$d_{wet} = \left(1 - \frac{\beta H}{T}\right)^{\frac{(\lambda+1)g}{R_d \beta} - 1} \cdot \frac{10^{-6} k_2 R_d}{g_m(\lambda + 1) - \beta R_d} \cdot \frac{e}{T} \tag{9}$$

where p, T, e are pressure (in mbar), temperature (in Kelvin) and vapour pressure at mean sea level (in mbar), λ and β water vapour lapse rate (dimensionless) and temperature lapse rate (in K/m) at the given latitude, $g = 9.80665$ m/s^2 and k_1, k_2, R_d, and g_m are constant coefficients.

Modifications of this kind of models are referred to as blind tropospheric correction models. Modifications include modelling of meteorological parameters by harmonically functions representing diurnal and seasonal variations. The coefficients of these harmonically functions can be derived by least-squares adjustment over a period of several years using world-wide numerical weather field data. This new correction approach is intended for the European satellite navigation system Galileo, and should offer a global accuracy improvement of about 25% in average in comparison to the MOPS/EGNOS model [13]. The advantage of this strategy is that no real-time measurements are needed, which is cost-effective and practical for a lot of applications.

5) In the differential mode of operation the GPS receiver can reduce or eliminate many GPS measurement errors, as mentioned in the previous chapter. Ionospheric, tropospheric and orbital errors are greatly reduced in the differential mode of operation [2, 3, 14].

Different strategies presented in this paper can be used for different applications, providing different positioning accuracy. Positioning accuracy is not the only criterion for selecting an error mitigation strategy. In order to check the efficiency of different types of tropospheric delay models, we compared it in our research.

3.2. Evaluation of Tropospheric Models Performance

As the thickness of the tropospheric layer is different from the equatorial region (up to 16 km) to the polar region (approximately 8 km), we selected three locations at different latitudes for our research:

Sodankyla, Finland at 67°25' N, 26°35' E, Altitude 179 m;

Zagreb, Croatia at 45°50' N, 15°59' E, Altitude 123 m and

Fortaleza, Brazil at 3°77' S, 38°57' E, Altitude 19 m, as shown on the world map on fig. 3.

Figure 3. *Locations of the measuring stations at a different latitude.*

Source: Author

This allows analysing the variation of tropospheric delay values at a different latitude. For these stations we calculated the zenith tropospheric delay using the Saastamoinen and MOPS/EGNOS model and compared the results with other strategies for correcting the tropospheric delay. In our previous research work [8, 9] the Saastamoinen model showed very good agreement with the measured zenith path tropospheric delay at different locations, with the largest differences of the measured and the calculated tropospheric delay values of less then 45 mm, and the mean value varying between 8 and 20 mm.

After successfully proofing the accuracy of the Saastamoinen model, our decision was to use it as a reference in our study, and compare it to other methods of mitigating the tropospheric delay. For the Saastamoinen model we used the archive of the measured meteorological parameters for particular locations available at the web site http://www.weatheronline.co.uk [16, 17]. Here are the results of our evaluation.

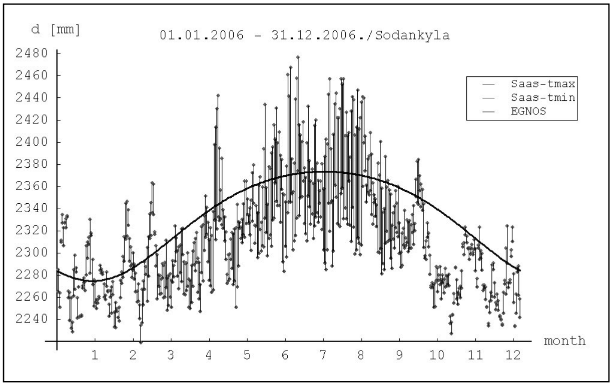

Figure 4. *Zenith tropospheric delay for Sodankyla, Finland, for the 12 month period*
Source: Author

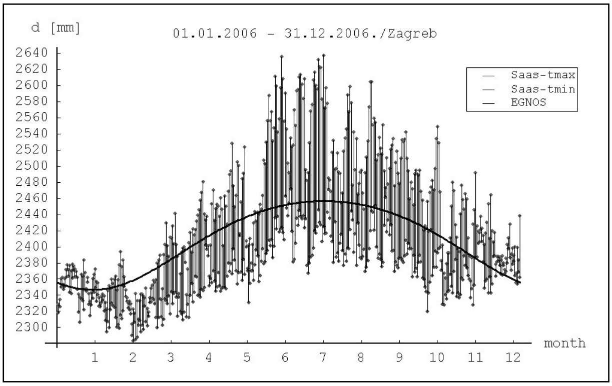

Figure 5. *Zenith tropospheric delay for Zagreb, Croatia, for the 12 month period*
Source: Author

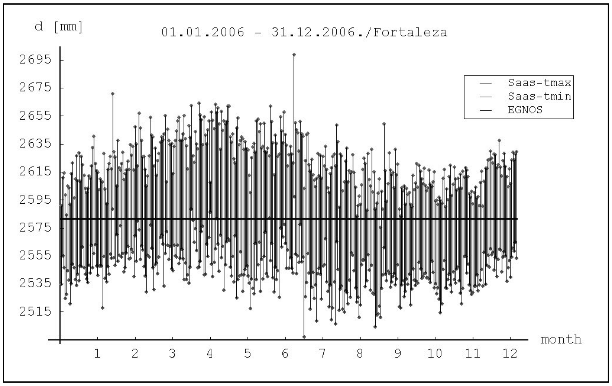

Figure 6. *Zenith tropospheric delay for Fortaleza, Brazil, for the 12 month period*
Source: Author

For the middle latitudes region the MOPS/EGNOS model presumes the seasonal variation of the zenith tropospheric delay of 110 mm. For higher latitudes like Sodankyla, Finland (67°25’ N), the seasonal variation is about 99 mm. In the equatorial region there is no seasonal variation according to the MOPS/EGNOS model.

As the used archive has available data for minimum and maximum daily temperatures, we calculated the total variations of the zenith tropospheric delay for every day using the Saastamoinen model. Taking into account the significant daily variation of the temperature, the Saastamoinen model shows considerably greater variation of the zenith tropospheric delay. For the year 2006, at the equatorial region the zenith tropospheric delay (ZTD) varied between 2515 and 2665 mm, at middle latitudes from 2280 to 2640 mm, and at higher latitudes from 2220 to 2480 mm over the whole year.

For the station Fortaleza, the maximal deviation between the MOPS/EGNOS and Saastamoinen model is 117.6 mm, and the mean value is 40.73 mm. For the station Sodankyla, the maximal deviation between these models is 104.8 mm, and the mean value is 40.70 mm. For Zagreb, the maximal deviation is 184.6 mm, and the mean value is 49.02 mm.

Table 1. shows the ranging errors due to the tropospheric delay for different mitigation scenarios.

***Table 1.** Tropospheric delay for the zenith direction and for low elevation satellites*

Strategy	Max. ZTD ranging error	Average ZTD ranging error	Low elevation ranging error (5°)
ignore the delay	2.6 m	2.4 m	26 m
use a constant value of 2.3 m	0.3 m	0.1 m	3 m
use the Saastamoinen model	0.05 m	0.02 m	0.5 m
use the MOPS/EGNOS model	0.18 m	0.05 m	1.8 m
use the differential GPS	0.2 m	0.1 m	>0.2 m

Source: Author

Analyzing the table 1 we can see different values of the ZTD ranging errors, from a few centimetres to a few meters.

If we ignore the tropospheric delay, we have a ranging error near the equatorial plane from 2.6 to 26 m depending on the elevation to the satellite. In the polar region the tropospheric delay is a little smaller. Such an error is not acceptable, and the tropospheric delay usually shouldn't be ignored.

Using the constant value of the zenith tropospheric delay could be the simplest acceptable solution. This method has the maximum ranging error of 3 m for low elevation satellites, which could be adequate for most applications.

Using the tropospheric model with available real-time, local meteorological parameters could be the best solution for users who require a top positioning performance. The ranging error is about 5 cm for the zenith direction, and less then 0.5 m for low elevation satellites. This should be adequate for most applications needing precise positioning with less than one meter error.

The use of the MOPS/EGNOS model, based on average meteorological conditions, has definitely the advantage that it does not require real-time meteorological measurements. It offers fairly satisfactory accuracy of less than 20 cm error for the zenith direction. The maximal error for low elevation satellites of less than 2 m in all seasons is also very acceptable.

Differential corrections offer the best positioning performance, but if the reference station and the user are at significantly different altitudes, variations in the tropospheric delay could be large. For low elevation satellites residual ranging error can be 2-7 mm per meter of altitude difference [4]. This method also requires transmission of real-time corrections.

4. CONCLUSIONS

The GNSS signal propagation velocity is affected by the Earth's atmosphere. The change of the signal travelling time through the atmospheric layers causes ranging errors. This article analyzes different strategies for mitigating

GNSS positioning errors due to atmospheric signal delays. Due to the ionospheric delay, the ranging error can vary from 5 to 15 m in the zenith direction, and up to 100 m for low elevation satellites. The ionospheric delay has high diurnal, seasonal and solar cycle variability, and must be corrected to achieve a better positioning performance. A permanent monitoring of the structure and dynamics of the ionosphere is necessary to reduce problems associated with the ionospheric impact on the GNSS performance. The ionospheric delay can be very efficiently mitigated using dual frequency measurements, but for civil users this technique is not available yet. For single frequency receivers GPS uses the Klobuchar ionospheric correction model for increasing the positioning accuracy of the system, allowing the reduction of errors by 60%. The values of the parameters for the Klobuchar model are specified in the navigation message broadcasted by GPS satellites. There are also other more sophisticated ionospheric delay models under research, performing much better than the Klobuchar model. One of them is the NeQuick model, adopted for single-frequency positioning applications in the European Galileo project.

The differential mode of operation allows the removal of a variety of positioning errors, and achieves positioning accuracy within a meter range. It is very efficient for the removal of ionospheric as well as tropospheric delay errors.

The tropospheric delay, although with a much lower seasonal variability, should also be considered to improve the positioning performance. The ranging error due to the tropospheric delay could vary from 2 m in the zenith direction to more than 25 m for low elevation satellites. Depending on the used method of mitigating the error, expected errors can be reduced to a few centimetres in the zenith direction and a few meters for low elevation satellites. Our experimental research analysing the efficiency of the MOPS/EGNOS model over a one year period at three different latitudes, showed a very acceptable performance of this model for most user's applications, with the greatest advantage that it does not require real-time meteorological measurements.

Mitigating the ionospheric as well as the tropospheric delay is essential for high precision positioning in geodesy, cadastral, topographic and engineering survey. Using efficient ionospheric delay mitigation and tropospheric delay models with real-time meteorological data, allows the most precise measurements and is unavoidable for getting centimetres level of precision.

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BIBLIOGRAPHY

[1] Klobuchar, J. A., J. M. Kunches, Comparative range delay and variability of the earth's troposphere and the ionosphere. GPS solutions 7, Eye on the Ionosphere, March 2003, 55 - 58.

[2] Parkinson, B. W., J. J. Spilker Jr, Global Positioning System: Theory and applications, Washington, American Institute of Aeronautics and Astronautics, Inc., 1996.

[3] Kaplan, E. D., Understanding GPS. Principles and Applications, Artech House, 1996.

[4] Misra, P., P. Enge, Global Positioning System - Signals, measurements and performance, Ganga-Jamuna Press 2001, 2004.

[5] Filjar, R., T. Kos, I. Markezic, GPS Ionospheric Error Correction Models, Proceedings of 48th International Symposium Elmar-2006, Zadar, Croatia, 2006., 215-217.

[6] Filjar, R., T. Kos, S. Kos, Klobuchar-Like Local Model of Quiet Space Weather GPS Ionospheric Delay for Northern Adriatic, The Journal of Navigation, 62 (2009), 3, 543–554.

[7] Nava, B., P. Coisson, S. M. Radicella, A new version of the NeQuick ionosphere electron density model, Journal of Atmospheric and Solar-Terrestrial Physics, 70 (2008), 1856–1862.

[8] Kos, T., M. Botincan, I. Markezic, Evaluation of EGNOS Tropospheric Delay Model in South-Eastern Europe. The Journal of Navigation, 62 (2009), 2, 341–349.

[9] Kos, T., M. Botincan, I. Markezic, Estimation of Tropospheric Delay Models compliance, Proceedings of 50th International Symposium Elmar-2008, Zadar, Croatia, 2008., 381-384.

[10] Penna, N., A. Dodson, W. Chen, Assessment of EGNOS Tropospheric Correction Model. The Journal of Navigation, 54 (2001), 37–55.

[11] Cove, K., Improvements in GPS Tropospheric Delay Estimation with Numerical Weather Prediction. Technical Report, 230, University of New Brunswick, Fredericton, New Brunswick, Canada, 2005.

[12] Ueno, M., /et al./, Assessment of Atmospheric Delay Correction Models for the Japanese MSAS, ION GPS 2001, Salt Lake City, UT, 2001, 2341-2350.

[13] Krueger, E., /et al./, Galileo Tropospheric Correction Approaches developed within GSTB-V1, Proc. of GNSS 2004 - European Navigation Conference, May 2004, Rotterdam, The Netherlands, 2004.

[14] Abousalem, M., /et al./, Performance Analysis of GPS Positioning using WAAS and EGNOS, GNSS 2000 Conference, Edinburgh, Scotland, UK, May 2000.

[15] Global Positioning System Standard Positioning Service Performance Standard, Assistant Secretary of Defense for Command, Control, Communications, and Intelligence, October, 2001

[16] http://www.weatheronline.co.uk/weather/maps/forecastmaps?LANG=en&CONT=euro&UP=0&R=150

[17] http://www.weatheronline.co.uk/weather/maps/forecastmaps?LANG=en&CONT=samk&UP=0&R=150

Sažetak

SMANJIVANJE POGREŠAKA ODREĐIVANJA POZICIJE USLIJED ATMOSFERSKOG KAŠNJENJA RADIOSIGNALA

Postoje temeljna ograničenja točnosti određivanja položaja korištenjem sustava satelitske navigacije. Različiti uzroci pogrešaka smanjuju točnost pozicioniranja GNSS (engl. Global Navigation Satellite System) sustava. Pogreške izazvane prolaskom radiosignala kroz Zemljinu atmosferu imaju najveći utjecaj te se moraju značajno umanjiti ako se želi ostvariti preciznije utvrđivanje pozicije. Određivanje položaja korištenjem GNSS sustava temelji se u osnovi na vrlo preciznom mjerenju vremena rasprostiranja radiosignala od satelita do GNSS prijamnika. Nailaskom na Zemljinu atmosferu GNSS radiosignali mijenjaju i brzinu rasprostiranja i smjer širenja, što ima kao posljedicu pogrešku u izračunavanju položaja. Članak obrađuje različite metode koje se koriste za smanjivanje pogreške u određivanju pozicije izazvane utjecajem Zemljine atmosfere na rasprostiranje radiosignala sa satelita.

Ključne riječi: *GNSS, pogreške pozicije, ionosfersko kašnjenje, troposfersko kašnjenje, modeli za korekciju kašnjenja*

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