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On Global Ionospheric Maps based winter-time GPS ionospheric delay with reference to the Klobuchar model: Case study of the Northern Adriatic

David Brčić[1], Renato Filjar[2], Serdjo Kos[1], Marko Valčić[3]

[1] University of Rijeka, Faculty of Maritime Studies, Studentska 2, 51000 Rijeka, Croatia, e-mail: brcic@pfri.hr
[2] Zagreb University of Applied Sciences, Vrbik, 10000 Zagreb, Croatia
[3] University of Rijeka, Faculty of Engineering, Vukovarska 58, 51000 Rijeka, Croatia

ABSTRACT

Modelling of the ionospheric Total Electron Content (TEC) represents a challenging and demanding task in Global Navigation Satellite Systems (GNSS) positioning performance. In terms of satellite Positioning, Navigation and Timing (PNT), TEC represents a significant cause of the satellite signal ionospheric delay. There are several approaches to TEC estimation. The Standard (Klobuchar) ionospheric delay correction model is the most common model for Global Positioning System (GPS) single-frequency (L1) receivers. The development of International GNSS Service (IGS) Global Ionospheric Maps (GIM) has enabled the insight into global TEC dynamics. GIM analyses in the Northern Adriatic area have shown that, under specific conditions, local ionospheric delay patterns differ from the one defined in the Klobuchar model. This has been the motivation for the presented research, with the aim to develop a rudimentary model of the TEC estimation, with emphasis on areas where ground truth data are not available. The local pattern of the ionospheric delay has been modelled with wave functions based on the similarity of waveforms, considering diurnal differences in TEC behavior from defined TEC patterns. The model represents a spatiotemporal winter-time ionospheric delay correction with the Klobuchar model as a basis. The evaluation results have shown accurate approximation of the local pattern of the ionospheric delay. The model was verified in the same seasonal period in 2007, revealing it successfulness under pre-defined conditions. The presented approach represents a basis for the further work on the local ionospheric delay modelling, considering local ionospheric and space weather conditions, thus improving the satellite positioning performance for single-frequency GNSS receivers.

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1 Introduction

Single-frequency satellite positioning accuracy depends, among other, on conditions between the space segment and the ground receivers. Ionospheric layers are situated at heights up to 2000 km above the surface of the Earth. Solar activity accumulates the free electrons and ions of various elements, mostly oxygen and nitrogen in ionospheric layers, causing refractions and delays of satellite positioning signals. Various ionospheric correction models have been developed so far. The most common model is the standard Global Positioning System (GPS) ionospheric delay correction (Klobuchar) model, a composite model compiled of nighttime constant values and daytime cosine function [16]. Empirically determined model coefficients are incorporated in the satellite signal navigational message. Given that the model operates on a global basis, it does not consider local patterns of ionospheric dynamics, potentially leading to inadequate estimation of the ionospheric delay.

The aim of the research is to present possibilities of a model creation of seasonal local ionospheric delay as observed in the Northern Adriatic area. Annual Global Ionospheric Maps (GIM) data, provided by the International GNSS Service (IGS) at a single position, have been collected and analysed to detect and identify the appearance of daily local ionospheric delay patterns. The results have shown both continuous and individual periods where this pattern differed from the one defined in the Klobuchar model. It has opened the possibility for determining the local ionospheric delay regularities. The local pattern has been modelled with wave functions based on the similarity of waveforms. The introduced model has been discussed in terms of local ionospheric delay approximation and accuracy with reference to GIM observations during winter days, the pattern description successfulness and, ultimately, with the model verification during the same period in 2007. Seasonal characteristics have been discussed further, in terms of future work on the model development and analyses of ionospheric data. The proposed research, together with the accompanying results presents an introduction to local ionospheric delay modeling and to the standard ionospheric model modification as well. The modelling approach offers the basis for the creation of the improved GPS single frequency ionospheric model on a wider area, adapted to local ionospheric delay dynamics.

2 Background

Given that the position determined by the GPS system is based on the exact time measurement for the signal to reach the receiver antenna, the propagation speed implies as a constant. The small deviation in time delay will produce considerable errors in the GPS derived position. The relation between the satellite positioning signal ionospheric delay and the number of free electrons can be described as follows [17, 15]:

$$\Delta t = \frac{40.3}{c \cdot f^2} TEC \tag{1}$$

where Δt... ionospheric delay, c... signal propagation speed, f... operating frequency, and TEC... Total Electron Content, which can be described as number of free electrons encountered along an equivalent column having a cross section of one square meter from the satellite to the receiver [17, 15].

The Slant TEC (STEC) represents the total electron content encountered at different satellite signal reception elevation angles χ [25]:

$$STEC = \int N(s) ds \tag{2}$$

where N... distribution of the electron density along the ray path s, implying that $\chi \neq 0^0$.

Observed STEC values are reduced to reference vertical values (VTEC), where the following relation can be given [25]:

$$N(s)ds = N(h) \sec \chi_s dh \tag{3}$$

where χ_s... the ray path zenith angle at the reference ionospheric height and $N(h)$... vertical electron density distribution over the height h above the Earth's surface.

The Total Electron Content is expressed in TEC Units (TECU), where [21]:

$$1\, TECU = \frac{10^{16} e^-}{m^2}. \tag{4}$$

The behavior of VTEC is subject to geographical, daily, seasonal, solar cycle and storm-time variations [25]. Each of the mentioned factors affects the ionospheric dynamics behaviour in specific manner, and they have been considered during the research.

The 1 TECU represents an equivalent ranging error of 0.1624 m at GPS L1 frequency or 0.542 ns of the time delay [21]. The direct TEC determination method employs dual-frequency (L1 and L2) GPS code and phase observations, frequencies being placed far enough that the ionospheric delay can be determined by the differential calculations [19, 15, 24]. This process is presented on Figure 1. The indirect method implies the usage of differential GPS stations and the fact that influences error causes are approximately equal for the specific area. Local values of ionospheric delay can be derived by comparing determined pseudoranges [14]. Despite its accuracy, the ionospheric error – except the multipath – cannot be distinguished among all other components [15], meaning that TEC cannot be exactly determined.

The estimation method employs various physical and empirical models which are describing the daily TEC pattern and mitigating the ionospheric delay in single frequency GNSS receivers [3, 16, 12]. Because of complex algorithms and powerful computer requirements, physical models are less frequent. The empirical models are based on the existing ionospheric data and spatial TEC distribution [9].

The Klobuchar Single Layer Model (SLM) is the most common ionospheric delay model used in GPS and Beidou. The model is based on the following regularities [16, 24]:

- The electron content is concentrated in a single (reference) layer at 350 kilometers in height; the slant delay is computed from the vertical delay at the intersection of the signal ray with the ionospheric reference layer (the Ionospheric Pierce Point – IPP);
- The dark side of the Earth is not influenced by ionospheric changes. Therefore, the night value of GPS daily ionospheric delay is taken as a constant;
- The ionospheric delay is directly related to the daily path of the Sun moving above the horizon; the daily value of GPS ionospheric delay changes by the cosine law, reaching its maximum at 1400 user Local Time (LT);
- The model is most applicable in quiet space weather conditions.

The model is capable eliminating 50-70 % off the ionospheric error [7, 10]. It will be successful in extent in which the real pattern of daily ionospheric delay follows the cosine curve/law. The model can be described as follows [24]:

$$I = \begin{cases} F\left[5 \cdot 10^{-9} + \left(\sum_{n=0}^{3} \alpha_n \phi_m^n\right)\left(1 - \frac{X^2}{2} + \frac{X^4}{24}\right)\right], & \text{for } |X| \geq 1.57 \\ F \cdot 5 \cdot 10^{-9}, & \text{for } |X| < 1.57 \end{cases} \tag{5}$$

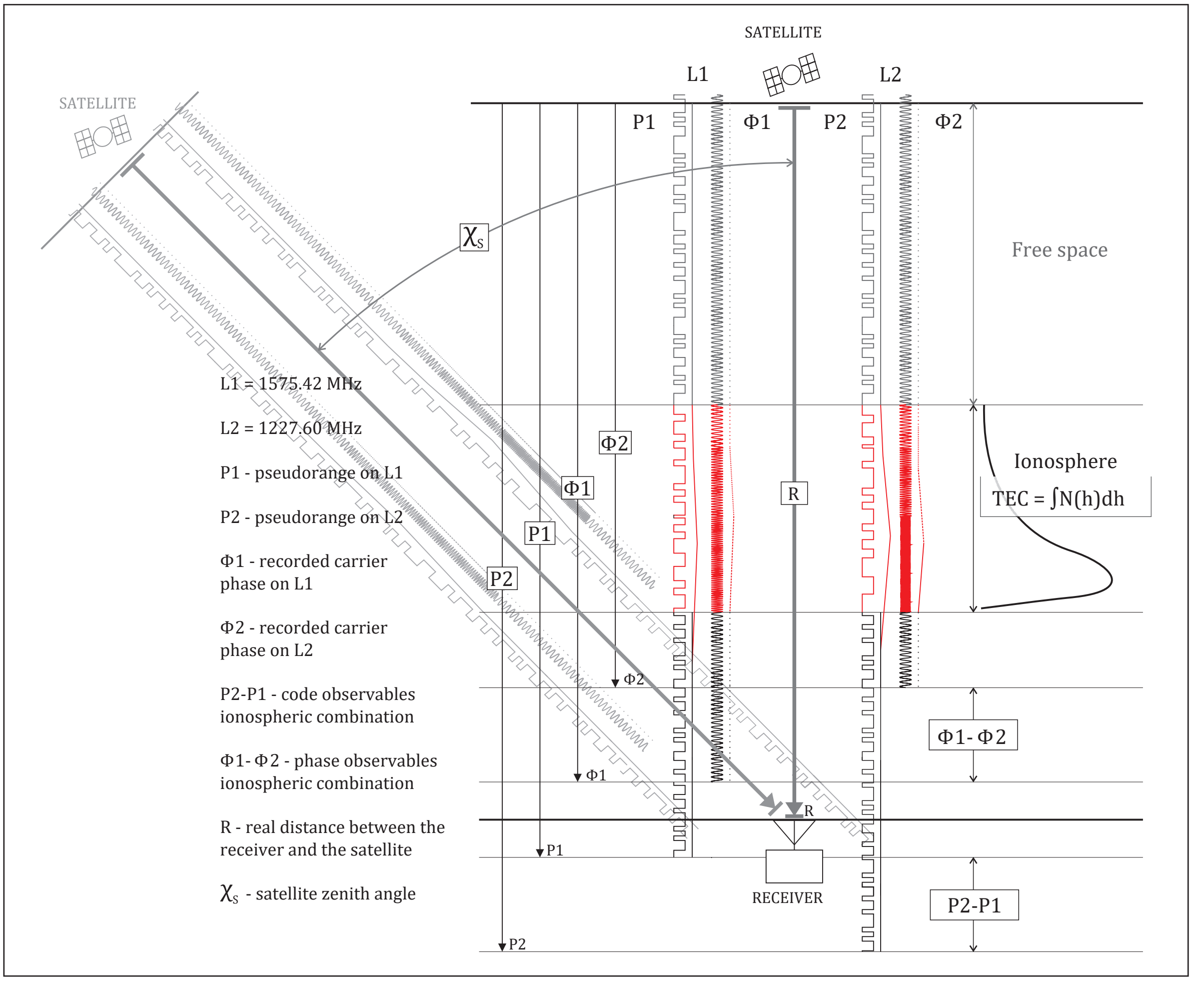

Figure 1 A simplified representation of the TEC determination method based on ionospheric combinations of GPS dual-frequency code and phase measurements. Parts of signals marked red indicate the ionospheric (code-carrier) divergence.

Source: Authors

where: *I*... ionospheric delay at the GPS L1 frequency, *F*... slant factor, ϕ_m geomagnetic latitude of the IPP, *X*... phase of the ionospheric delay.

In the standard GPS navigational message frame, eight parameters related to the amplitude and the period of the delay are sent to the receivers (coefficients α, β). Simplified in great extent (according to the time and the technology when it was developed), the standard model represents the compromise between the correction accuracies and the simplicity of the model [10]. It explains why there are only eight coefficients in the navigational message, updated approximately once a day [7]. For these reasons, the model shows certain deficiencies:

- In cases of severe/disturbed space weather, the model responds with delay (up to several days) – position determined in such conditions will notably deviate from the actual one;
- Estimated values of GPS ionospheric delay are noticeably higher than the real values – in cases of space weather disturbances and/or geomagnetic storms, instead of positioning error elimination, an additional error can be generated;
- The model response to short-term disturbances has a pronounced and sustained impact long after the triggering disturbances fades away – the predicted/employed correction does not follow the real-time;
- The model does not consider local ionospheric dynamics and TEC behaviour.

Several ionospheric delay-based studies have been conducted in the Northern Adriatic area. Klobuchar-like seasonal models during quiet space weather conditions have been introduced in [10]. In [4], the local ionospheric pattern has been analysed by deriving the TEC from GPS observables. During 2012, three types of prevailing TEC patterns in the area were categorised [18] (Figure 2): one-peak, two-peak and three-peak pattern.

Non-Klobuchar patterns were found to be present through several years [22]. The ionospheric maps analysed in [18] have been used for the same single point in this study.

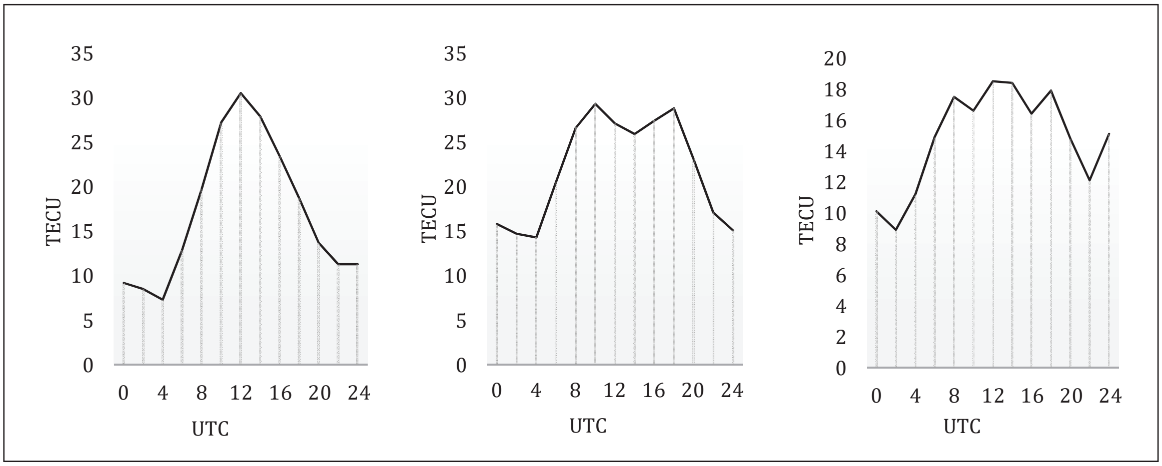

Figure 2 Three types of daily ionospheric delay pattern as observed in the Northern Adriatic area. Adopted from [18]

The GIM data have been also used for the modifications of the Klobuchar model on a wider scale. In [22], the Klobuchar correction model based on the *k*-means clustering of ionospheric daily variations has been presented for midlatitude regions. In [8], an empirical TEC model has been proposed, based on GIM observables distributed globally. The GIM data availability has allowed for the insight into the behavior of ionospheric dynamics on a global basis, but also for the definition of local ionospheric delay patterns. The identification of local patterns of daily ionospheric delay which differ from the pattern defined in the Klobuchar model has been a motivation for this research.

3 GIM based ionospheric delay modelling

3.1 TEC data sources

Mapping of the ionosphere represents an empirical approach for the interpolation of TEC values. GIMs are gener-

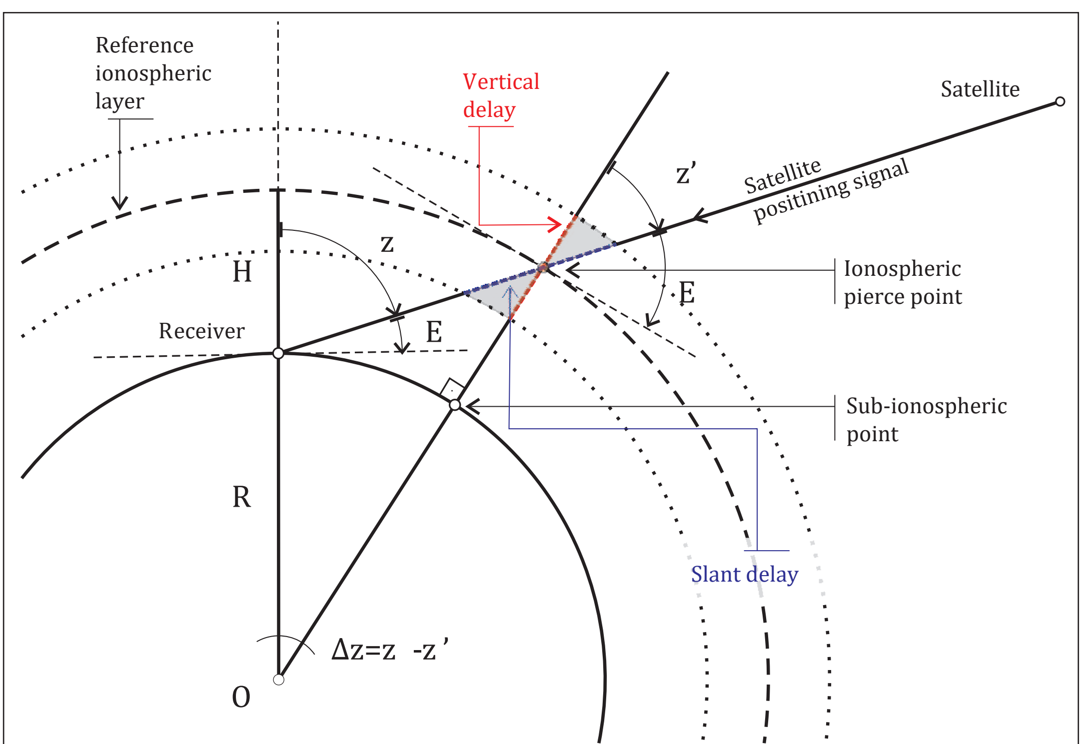

Figure 3 Dependance of TEC on the relative position of the satellite and receiver antenna.

Source: Authors

ated as spatial and temporal VTEC distributions, based on daily observables from global IGS network [11]. The GIM spatial resolution is φ=2.5°/λ=5°, while the values were provided every two hours until the year 2014, and every two years afterwards, respectively. The VTEC is modeled in a solar-geomagnetic reference frame using a spherical harmonics expansion. Satellite and receiver instrumental biases (Differential Code Biases – DCB) are estimated as constant values for each day.

The STEC – VTEC conversion has been made with a Modified Single-Layer Model (MSLM) mapping function [2], referring to IPP on the SLM reference ionospheric layer (Figure 3):

$$F(z) = \frac{1}{\cos z'}, \quad (6)$$

$$\sin z' = \frac{R}{R+H} \sin(\alpha z). \quad (7)$$

where z'... zenith distance between satellite and IPP, z... zenith distance between satellite and receiver, R... Earth radius, α... 0.9872, H... height of the reference layer.

The elaborated GIM data produced by the Center for Orbit Determination in Europe (CODE) were analysed during the year 2006 and 2007 [1], characterised by solar cycle declining. The obtained data refer to the single GIM position at φ=45° N, λ=15° E, representing a mid-latitude region (Figure 4).

The maps have been obtained in a standardised IONEX format [23]. The geomagnetic (Kp and Dst) and solar (SSN) indices have been analysed in order to define periods with quiet space weather and Solar Terrestrial Environment (STE) conditions. Winter-time and summer-time periods have been analysed with the aim to identify seasonal variations and their impact on the model development and its features. The data have been retrieved from NOAA's Space Physics Interactive Data Resource (SPIDR) [20].

Quiet space weather conditions have been set as the criteria for the selection of periods which will be considered for further analyses. During these periods, ionospheric delay patterns, as obtained from GIM data, have been analysed further, with TECU values converted to meters, as defined previously. The patterns have been modelled with wave functions based on the similarity of waveforms, representing a spatiotemporal ionospheric delay correction. The Klobuchar algorithm has been used as a basis for the proposed model. The nighttime values have been kept during the model development as marginal values, while the daily values have been modified according to the observed regularities in the area.

3.2 Space weather conditions

GIM analyses have shown a recurring appearance of the local ionospheric delay pattern during both years. The period of 6 consecutive days (10 – 15 February 2006; DOY 41 – 46) has been selected for the model development. The part of the same period in 2007 (days which satisfied the quiet conditions of the space weather) has been used for the model verification. In Figure 5, space weather conditions during the period used for model building are presented.

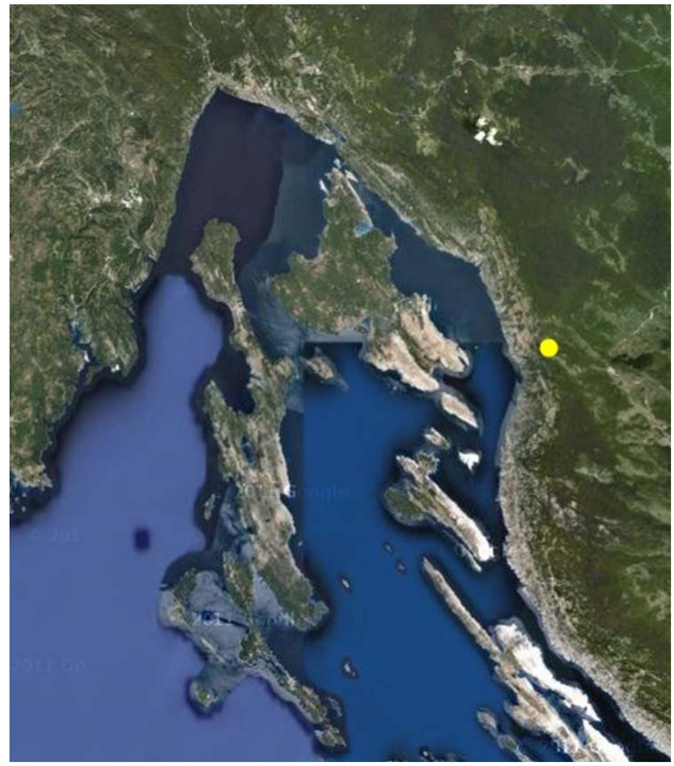

Figure 4 Northern Adriatic GIM point (φ=45°N, λ=15°E) (dotted yellow). Courtesy ©Google Earth

The planetary Kp index is a compiled index derived from the K indexes from various reference stations distributed around the globe, representing the intensity of the geomagnetic disturbance. The values of Kp in the observed period (max. 3) indicate quiet space weather conditions. The constant value of the Disturbance Storm Time (Dst) index confirms unchanging and low geomagnetic activity [13]. The sunspot number average value for February was 4.9, with maximum SSN of 15 on DOY 46.

3.3 TEC modelling

The elaborated GIM point daily ionospheric delay pattern through the elaborated period is shown in the following figure. Superimposed daily patterns of the ionospheric delay have been presented together with the calculated average value.

The diurnal pattern follows the same characteristic path. Speaking of daytime, the curve in the Klobuchar model has, cosine-likely, one maximum at approximately 1400 LT. The observed data can be seen as a combination of two maxima, representing identified regularities.

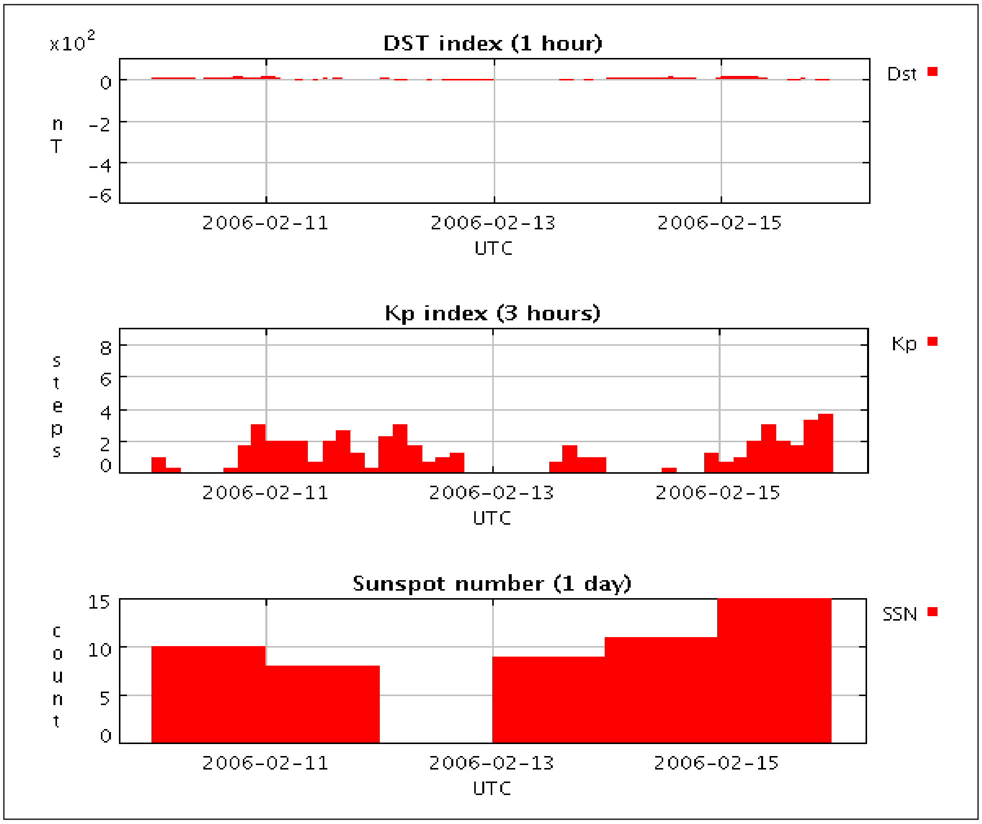

Figure 5 Space weather conditions during the observed period in 2006, DOY 41 – 46 [20]

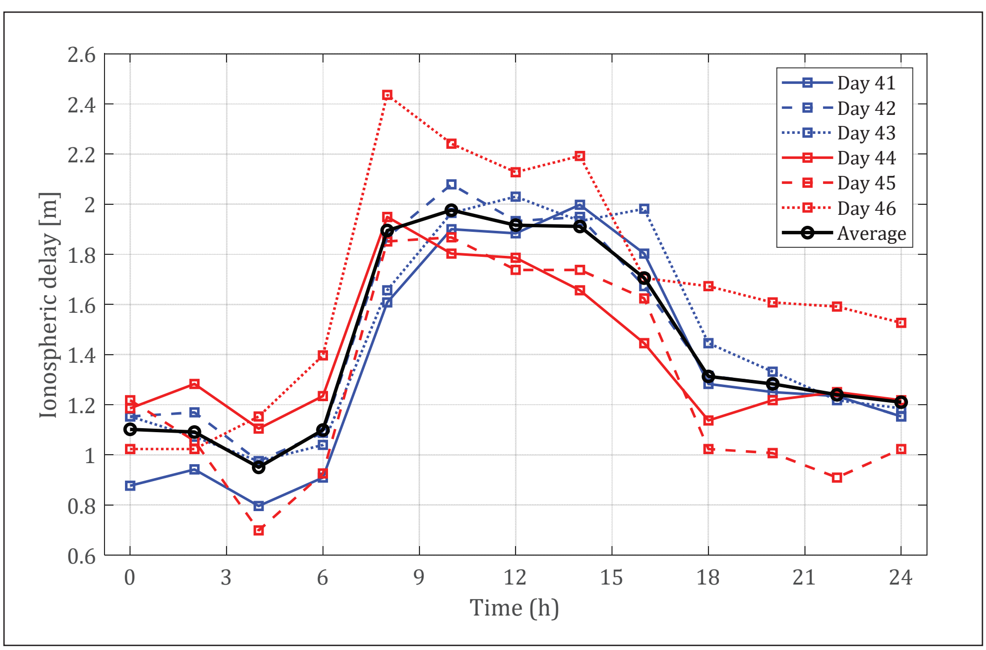

Figure 6 GIM data of daily ionospheric delay patterns through DOY 41 – 46 in 2006.

Source: Authors

Nighttime observations/values have not been considered, and they have been managed as constants, depending on marginal values of the ionospheric delay. The estimated daily variations are described using the following terms:

$$\hat{f}(t)=\begin{cases}\hat{f}(6), & \text{for } t \in [0,6\rangle \\ \hat{a}_1\cdot\dfrac{\sin[\hat{k}_1(t-\hat{t}_1)]}{\hat{k}_1(t-\hat{t}_1)}+\hat{a}_2\cdot\dfrac{\sin[\hat{k}_2(t-\hat{t}_2)]}{\hat{k}_2(t-\hat{t}_2)}, & \text{for } t \in [6,18] \\ \hat{f}(18), & \text{for } t \in \langle 18,24] \end{cases} \tag{8}$$

where *t*... time for which the ionospheric delay is calculated in seconds, $\hat{a}_1$, $\hat{a}_2$ ... local maximum values optimisation coefficients, $\hat{k}_1$, $\hat{k}_2$ ... local maxima period coefficients, $\hat{t}_1$, $\hat{t}_2$... phases of peak values of the local maxima.

The estimation of parameters $\hat{a}_1$, $\hat{k}_1$, $\hat{t}_1$, $\hat{a}_2$, $\hat{k}_2$ and $\hat{t}_2$ in (8), for which the obtained values are shown in Table 1, was performed using the nonlinear least squares estimation (NLSE) method [6] with trust-region optimization algorithm [5].

Table 1 Estimated coefficients for the local ionospheric delay pattern model

Day	Estimated coefficients (with 95 % confidence bounds)					
	$\hat{a}_1$	$\hat{k}_1$	$\hat{t}_1$	$\hat{a}_2$	$\hat{k}_2$	$\hat{t}_2$
DOY 41	2.010	-0.274	12.64	2.795	-0.992	-11.70
DOY 42	2.026	-0.221	11.20	-0.594	-1.165	5.27
DOY 43	2.085	0.313	11.91	0.481	0.971	17.07
DOY 44	2.341	0.567	9.40	1.876	0.645	16.48
DOY 45	2.385	0.653	9.67	2.124	0.752	15.90
DOY 46	2.397	1.104	1.36	2.287	0.235	10.75
Average	1.987	-0.223	11.63	-0.700	-1.025	4.25

Estimated modelling coefficients are given for each of the observed days, including average (6-day period) coefficients' values. The assessment of the model performance in terms of pattern description and its validation is presented further, together with the discussion on limitations and possibilities for a further improvement.

4 Model performance evaluation

The modelled values are presented in Figure 7. When compared with the actual data, the model accurately describes the observed daily patterns of the ionospheric delay. The proposed equation does not use external data or coefficients as in the Klobuchar model.

In Table 2, goodness of fit is given for each modelled day, including the average (6-day) model test.

Table 2 Goodness of fit for the local ionospheric delay pattern model

Day in 2006	Goodness of fit			
	SSE	R^2	R^2_{adj}	*RMSE*
DOY 41	0.0002908	0.9997	0.9981	0.01705
DOY 42	0.0001525	0.9998	0.9989	0.01235
DOY 43	0.0050680	0.9938	0.9626	0.07119
DOY 44	0.0267000	0.9530	0.7178	0.16340
DOY 45	0.0033430	0.9964	0.9785	0.05782
DOY 46	0.0039330	0.9968	0.9807	0.06271
Average	0.0009678	0.9986	0.9919	0.03111

Residuals of GPS ionospheric delay data are presented in Figure 8. During the daytime period, residual values are varying to a minimum extent with tolerant deviations, which is best seen on the daily average residual value. The residuals are highest in the nighttime period, where the function in the model is taken as a constant one.

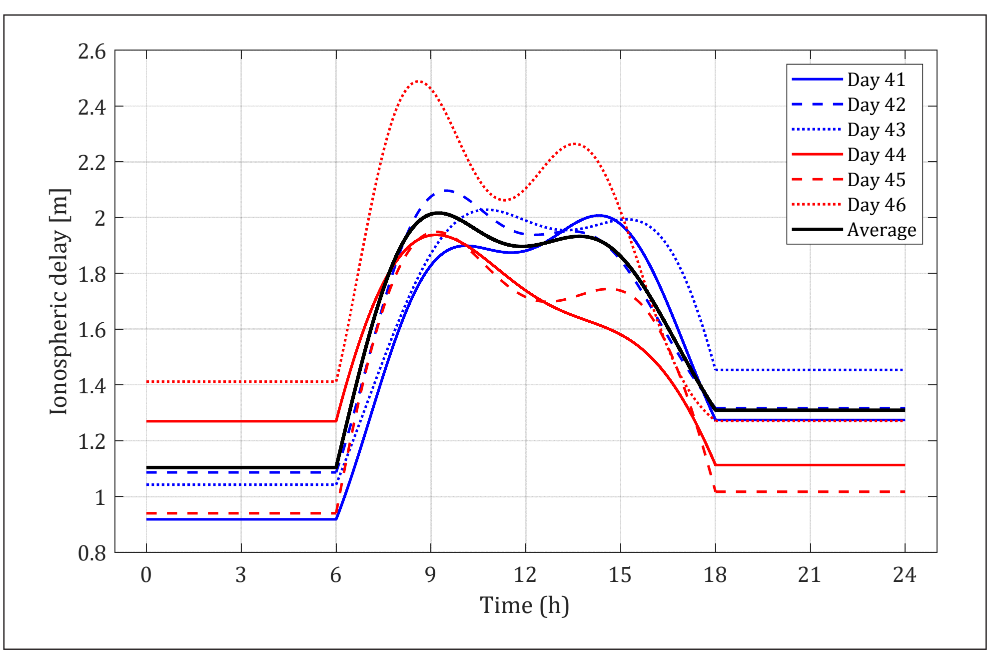

Figure 7 Models of daily ionospheric dynamics for the observed period, including the average value.

Source: Authors

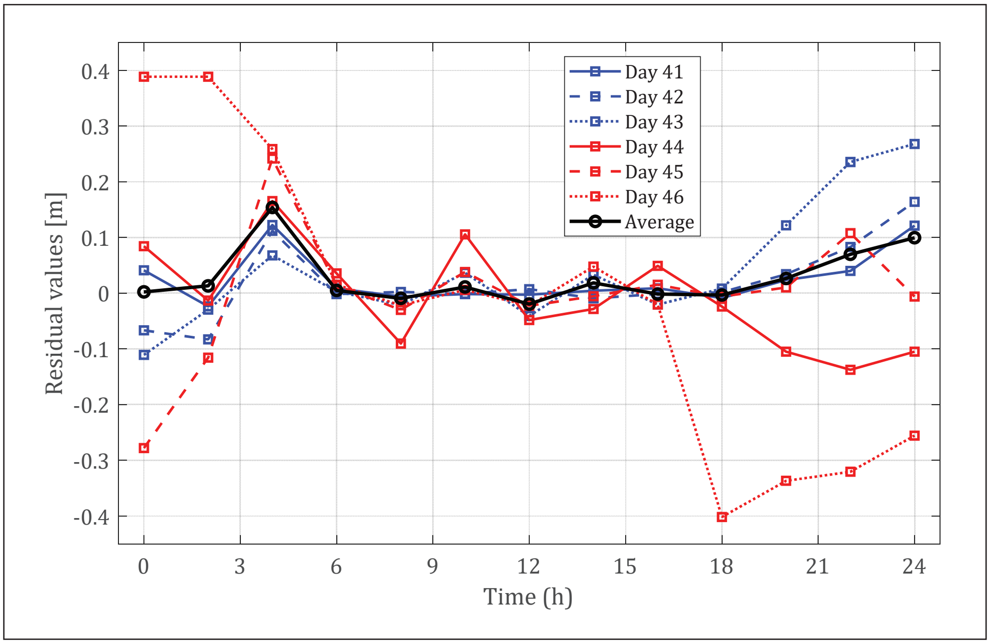

Figure 8 Residuals between measured and modelled values, DOY 41 – 46 in 2006.

Source: Authors

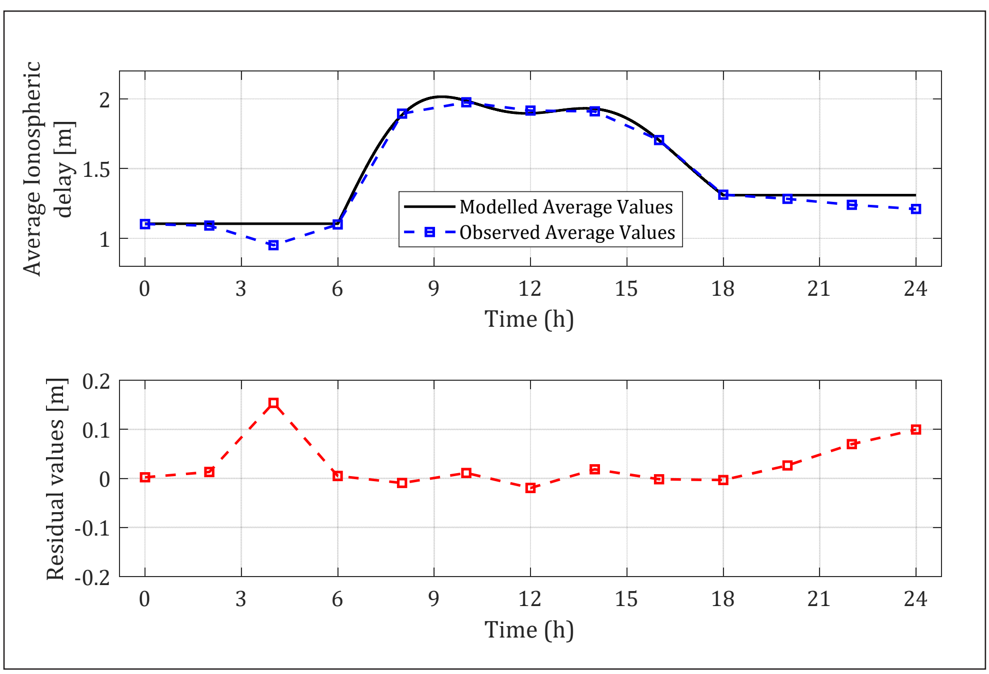

Figure 9 Modelled and observed (upper image) and residual (lower image) average values of ionospheric delay, DOY 41 – 46 in 2006.

Source: Authors

Figure 9 shows the average residual daily values between the model and the observed data through the period.

There are two observed curves of TEC enhancement and depletion, peaks of which are placed apart for approximately 4 hours. The saddle between the peaks represents a basic difference from the standard model – appearance of decreased TEC, while for this local time the TEC is expected to be at its highest in the Klobuchar model.

The model was validated on DOY 41-43 in 2007, which was characterised with quiet space weather conditions, similar as during the period based on which the model was developed. The daily ionospheric delay patterns together with average values during the validation period are shown in Figure 10.

The average residual daily values between the proposed model and the observed data are shown in Figure 11.

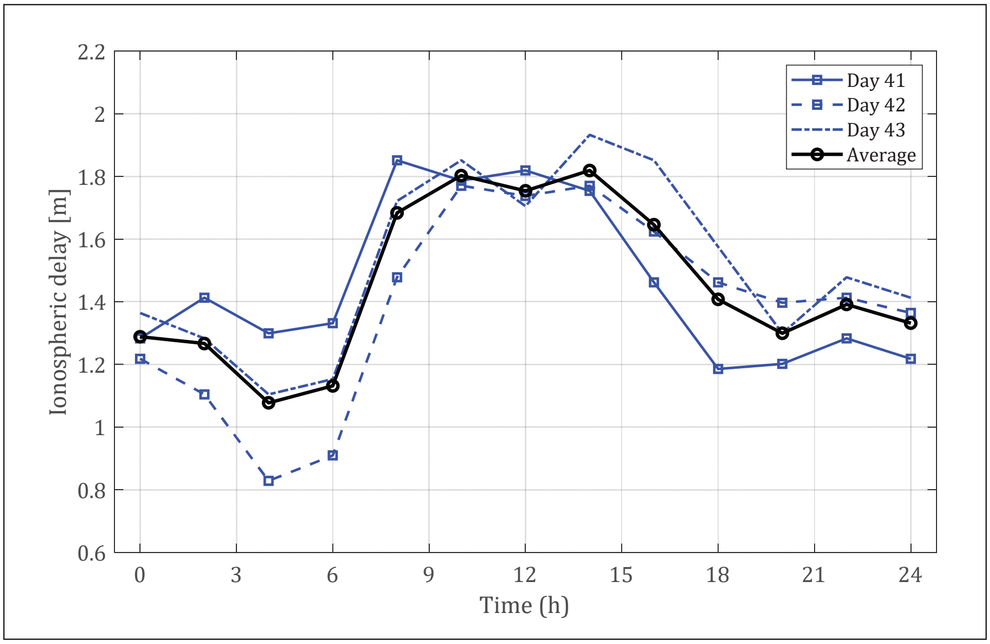

Figure 10 GIM data of daily ionospheric delay patterns through DOY 41 – 43 in 2007.

Source: Authors

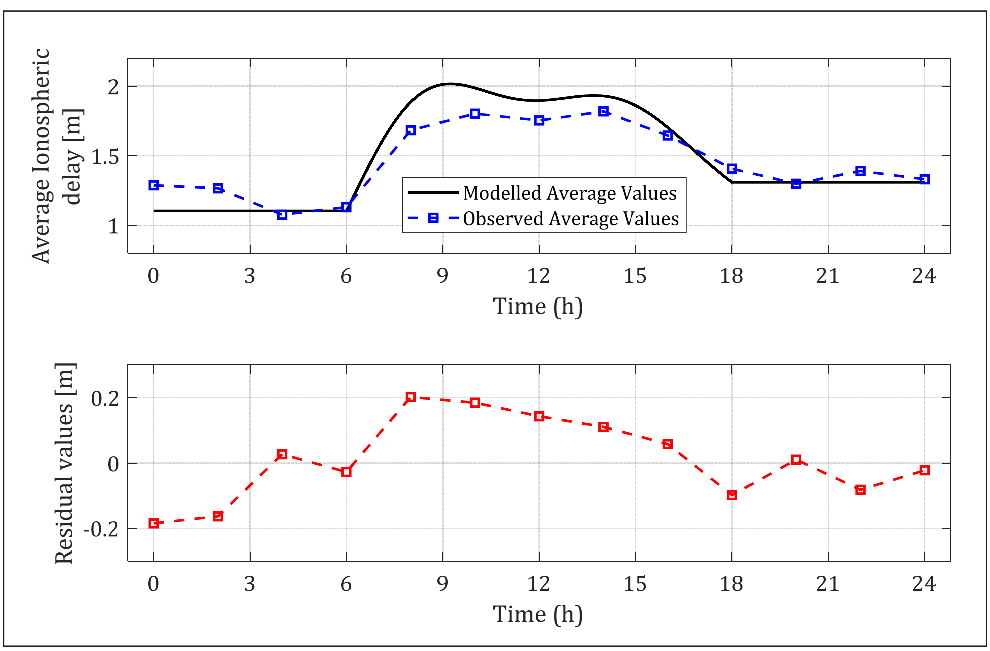

Figure 11 Modelled and observed (upper image) and residual (lower image) average values of ionospheric delay, DOY 41 – 43 in 2007.

Source: Authors

During the testing period, the model performed successfully in terms of the ionospheric delay modelling and the pattern description. It can be seen as the presentation of remaining averages during the daytime hours of the ionospheric delay.

The model was validated in different seasons as well. In Figure 12, daily ionospheric dynamics during summer days (DOY 175-178 in 2006) are presented. Seasonal variations led to a higher difference between the observed and modelled data. One of the reasons is due to longer daytime period directly affecting the TEC behavior, as well as the higher amount of VTEC. The differences between the observed and modelled values of the ionospheric delay can be seen in Figure 13.

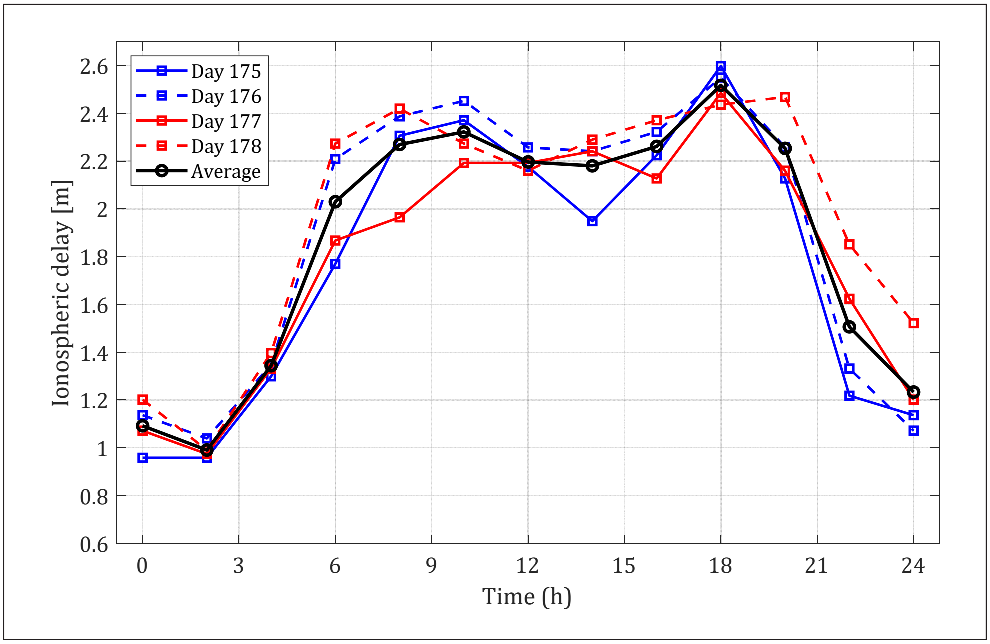

Figure 12 GIM data of daily ionospheric delay patterns through DOY 175 – 178 in 2006.

Source: Authors

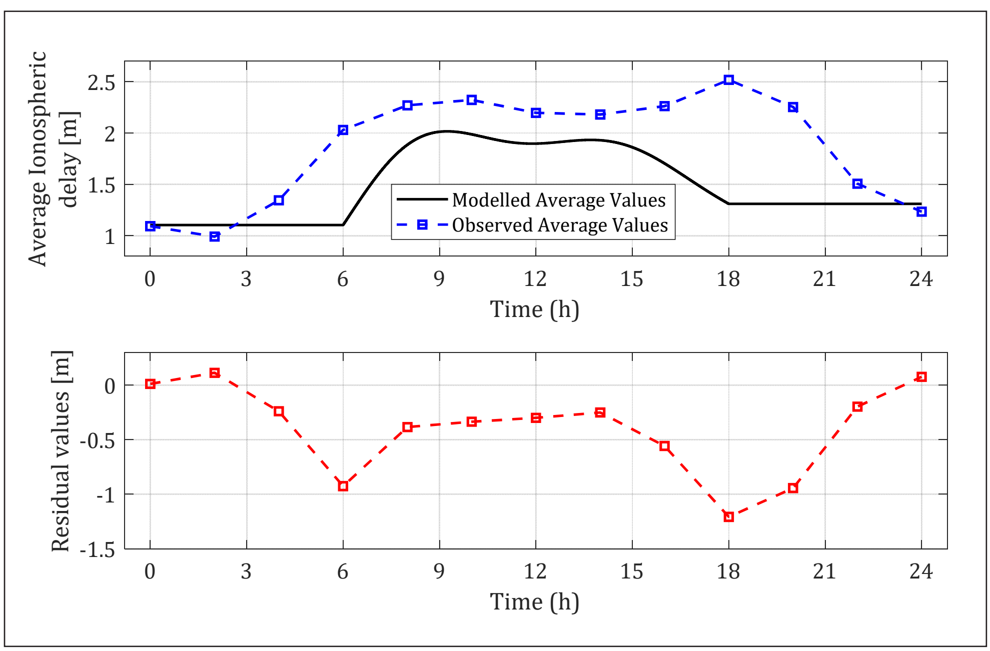

Figure 13 Modelled and observed (upper image) and residual (lower image) average values of ionospheric delay, DOY 175 – 178 in 2006.

Source: Authors

To summarise the results, it can be stated that, in this phase, the proposed model has shown its best performance during winter. Although the model has described the ionospheric delay pattern well, the residual values have remained too high for the model to be considered for different seasons. The modelling of nighttime ionospheric delay values, and steering of coefficients towards different seasons' application, remains a task for the further work.

An accurate description of the ionospheric delay based on GIM data can be achieved with the proposed approach, modifying the basic pattern of the ionospheric delay without the use of additional data inputs. Further modifications are required in order to achieve even higher accuracy of the single-frequency satellite positioning in the area.

7 Conclusion and further work

The Klobuchar-like ionospheric delay modelling based on GIM data has been presented in the paper. The model has been developed for mid-latitude region, during the solar minimum, in quiet space weather conditions, in a winter season and for the daytime period. Data from global ionospheric maps have been analysed in order to define local patterns of the ionospheric delay for the Northern Adriatic GIM point, where ground truth data from IGS reference stations are not available. The model was based on the data compiled for the 6-day period during February 2006, while the model was tested during the same period in 2007. The daily local pattern has been characterised by two curves representing TEC maxima, in contrast to the Klobuchar model, where daytime ionospheric delay follows a single curve. This characteristic pattern has been presented through the whole year, recurring mainly in conditions of low solar and geomagnetic activity. The model testing has shown that accurate description of the local diurnal ionospheric delay pattern has been achieved and verified on independent GIM data. The presented research contributes to local understanding of the ionospheric dynamics and improved ionospheric delay modelling. Future activities will be focused on the origins of different types of local ionospheric delay patterns. The quiet space weather conditions have served as an input criterion for the research. This has also been the reason for analysing the years of the Solar cycle minimum. The nighttime values of the ionospheric delay have been the subject of the further modifications as well, together with the proposed model development in terms of seasonal ionospheric delay dynamics. The analyses of other GIM data in the region are necessary to detect the areas of similar TEC behaviour, in order to develop an ionospheric delay correction model on a regional basis. For this purpose, ground truth observables from IGS reference stations are required besides GIM data, as well as other networks providing GNSS observables.

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