STATISTICAL PROPERTIES OF QUIET SPACE WEATHER NORTHERN ADRIATIC RESIDUAL GPS IONOSPHERIC DELAY

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Recent developments in understanding behaviour of the GPS ionospheric delay time series in Northern Adriatic during quiet space weather conditions led to introduction of Klobuchar-like Northern Adriatic quiet space weather (NA-QSW) GPS ionospheric delay model. It provides improvement over the standard (Klobuchar) global GPS ionospheric delay model by taking into account the local patterns of ionospheric dynamics.

The residual quiet space weather Northern Adriatic GPS ionospheric delay are obtained from the real (actual) GPS ionospheric delay observables after subtracting the estimates given by quiet space weather Northern Adriatic GPS ionospheric delay model. The values of the residual GPS ionospheric delay taken during quiet space weather conditions in Northern Adriatic account for as a very small portion of the actual GPS ionospheric delay, proving the correctness of developed model, especially in winter.

In this article, the analysis results of statistical properties of the quiet space weather Northern Adriatic residual GPS ionospheric delay time series are presented with the aim to describe the nature of the residual GPS ionospheric delay and thus provide a foundation for improvements of previously established Klobuchar-like NA-QSW model. In addition, performance of the NA-QSW model is compared with the performance of the European NeQuick model. A case study of quiet space weather and general ionospheric conditions in Summer 2007 has been chosen for a comparative analysis.

The results of the analysis show a fair performance of Klobuchar-like NA-QSW model. Statistical analysis of residual GPS ionospheric delays reveals the NA-QSW model performs even better than the standard European NeQuick model. In addition, it suggests several improvements of the NA-QSW model to be made in order to achieve the normal distribution of the residual GPS ionospheric delays.

This will eventually lead towards establishment of a three-component (linear night-time, cosine day-time and stochastic with known statistical distribution) GPS ionospheric model for the Adriatic Sea are. Establishment of this expanded and improved model with extended geographical coverage will be in focus of future developments.

KEY WORDS

1. GPS ionospheric delay 2. space weather 3. normal distribution 4. error correction model

1 INTRODUCTION. Performance of satellite navigation system such as GPS greatly relies upon the state of the ionosphere. Numerous studies show that the GPS ionospheric delay act as the major single cause of GPS positioning error (Davis, 1990, Parkinson, Spilker, 1996, Sandford, 1999, Misra and Enge, 2004, Samama, 2008). Standard GPS ionospheric correction model (usually referred to as the Klobuchar model, after his developer) (Klobuchar, 1987, Parkinson and Spilker, 1996, Misra and Enge, 2004), although an elegant attempt to tackle the ionospheric effects on global scale, does not provide acceptable solution for the combat of the ionospheric delay effects on satellite navigation during disturbed space weather conditions and in local ionospheric disturbance conditions (Parkinson and Spilker, 1996, Misra and Enge, 2004, Filjar, 2008). Attempts to improve understanding of space weather and ionospheric effects on satellite navigation systems have lead to

important achievements and development of various regional models, among them the NeQuick (Coisson, Radicella and Nava, 2002, ITU-R, 2008), recently adopted as the standard ionospheric correction model for European satellite navigation system Galileo. With satellite navigation systems' importance steadily growing in various areas of modern systems (from economy and infrastructure, through science and sustainable development to everyday life), the motivation for understanding of space weather and ionospheric effects on satellite navigation performance remains a very important research challenge.

Increasing importance of satellite navigation systems on the territory of Republic of Croatia causes more and more technical, economic and social systems rely upon sustained performance of the systems like GPS. Growing traffic (air, marine and road), impose of the EU regulations in the field of transport, new governmental and regulatory services and a huge increase in utilisation of personal navigation systems (in cars and on mobile phones) have triggered a systematic research with the aim to establish accurate and reliable GPS ionospheric correction model for Croatia, the Adriatic Sea and surrounding areas. As a result of recent research activities, a Klobuchar-like model of GPS ionospheric delay in quit space weather conditions (NA-QSW model) has been developed for the Northern Adriatic area, based on the archived experimental observation of real GPS ionospheric delay (Filjar, Kos and Kos, 2008).

This paper presents a case-study analysis of NA-QSW performance, along with a comparative performance analysis with European NeQuick model. Statistical analysis of residual GPS ionospheric delay provides suggestions for NA-QSW model improvements, which will ultimately lead to enhanced quiet space weather model to be applied in the Adriatic Sea area.

2 THE NATURE OF GPS IONOSPHERIC DELAY. The GPS ionospheric delay is caused by satellite signals' encounter with charged particles on its path through the ionosphere (Davis, 1990, Parkinson and Spilker, 1996, Misra and Enge 2004). Presuming the vertical profile of the ionosphere is known, it can be presented by the vertical charged particle density N(h), which generally varies with height h above the Earth's surface. Considerable variations of the vertical ionospheric profile N(h) are caused by various effects related too the solar activity, geomagnetic conditions (both commonly known as space weather) and local effects affecting the state of the ionosphere. There several observed patterns of ionospheric dynamics (Davis, 1990, Parkinson and Spilker, 1996), among them:

- daily variations (due to differences in ionisation processes)
- season variations (due to changing intensity of solar energy involved in ionisation process and free electron transport processes)
- geographical variations (polar, mid-latitude, equatorial)
- presence of scintillation effects.

The impact of ionosphere on travelling satellite radio signal is expressed by a separate parameter called the Total Electron Content (*TEC*), encountered by satellite ray during the flight from satellite to satellite navigation receiver (Parkinson and Spilker, 1996, Misra and Enge, 2004). The relation between *TEC* and the vertical ionospheric profile is expressed as follows:

$$TEC = \int_{h1}^{h2} N(h) \cdot dh \quad (1)$$

The GPS ionospheric delay can be directly obtained from the known value of TEC, as follows:

$$d = \frac{40.3 \cdot TEC}{f^2} \quad (2)$$

where: d ... equivalent GPS ionospheric time delay in [m], TEC ... Total Electron Content in [m^{-2}], f ... frequency of radio wave (for single-frequency GPS, $f = L_1 = 1547.42$ Mhz).

Expressions (1) and (2) are valid regardless of relative position of GPS satellite and GPS user equipment. In order to normalise *TEC* value for the purpose of comparative analysis, the so-called Vertical Total Electron Content (*VTEC*) parameter can be used. The *VTEC* is a projection of the TEC to the plane perpendicular to the Earth's surface. In simple terms, the *VTEC* is vertical component of *TEC*. If satellite ray enters the ionosphere under the elevation angle e, the relation with *TEC* and *VTEC* can be expressed as follows:

$$VTEC = TEC \cdot \sin(e) \tag{3}$$

Using the *VTEC*, it is possible to determine the Vertical GPS ionospheric delay (Vd). Standard GPS service offers an opportunity to tackle the effects of the ionosphere using so-called Klobuchar model (Klobuchar, 1987, Parkinson and Spilker, 1996, Misra and Enge, 2004, Samama, 2008). Klobuchar model is a global GPS ionospheric model providing estimates of GPS ionospheric delay based on the knowledge of the current space weather conditions, and average global geomagnetic and ionospheric conditions. GPS ionospheric delay referred to in the rest of the paper is assumed to be the Vertical GPS ionospheric delay.
Model assumes that daily variations of GPS ionospheric delay follow common pattern (Fig 1), as described below:

- Night-time GPS ionospheric delay has a constant value
- Daily variations of the GPS ionospheric delay follow the half-cosine law, with the peak GPS ionospheric delay observed at 14.00 h local time

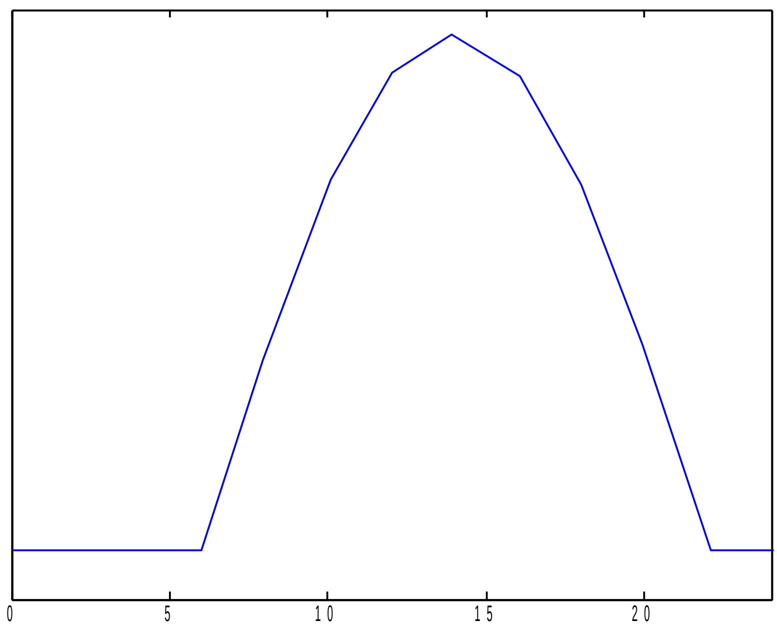

Fig 1 Common pattern of TEC/GPS ionospheric delay daily variations (y-axis: *VTEC* or Vd, respectively, x-axis: local time)

Elegantly developed to provide a compromise between prediction accuracy and computational complexity, Klobuchar model is capable of correcting up to 70% of actual GPS ionospheric delay. It is especially accurate in quiet space weather conditions (Klobuchar, 1987, Parkinson and Spilker, 1996), but fails to provide needed accuracy in disturbed and severe space weather conditions, and in situation when local ionospheric disturbances emerge without following the characteristic pattern of ionospheric behaviour (Filjar, 2008).
In a relatively recent attempt to combat regional patterns of space weather and ionospheric behaviour, European community has developed the NeQuick model, which has recently been

appointed as an official model of ionospheric corrections for the European satellite navigation system Galileo. NeQuick model is based on archived observables of space weather and ionospheric dynamics over Europe. Publicly available version of the NeQuick ionospheric model has been used in this comparative study.

3 QUIET SPACE WEATHER NORTHERN ADRIATIC GPS IONOSPHERIC MODEL. Daily GPS ionospheric delay dynamics as observed in Northern Adriatic region has been investigated by our team, using the archived TEC data (University of Bern, 2008) for a reference site φ = 45°N, λ = 15°E, which corresponds to a place in Kvarner Bay area.
A Klobuchar-like local model of the GPS ionospheric delay for Northern Adriatic in quiet space weather conditions (NA-QSW model) has been developed as the result of the analysis of local dynamics of daily GPS ionospheric delay (Filjar, Kos and Kos, 2008). The NA-QSW model consists of two expressions, each relating to specific season (summer and winter, respectively), as presented in Table 1.

Table 1 The NA-QSW model version 1.0

	SUMMER		**WINTER**	
	Night-time	Day-time	Night-time	Day-time
Expression	$d = a_0$	$d = a_0 + a_1*cos(2*\pi*(t-14)/32)$	$d = a_0$	$d = a_0 + a_1*cos(2*\pi*(t-14)/24)$
Parameter values	$a_0 = 0.982$	$a_0 = 0.982$ $a_1 = 0.877$	$a_0 = 1.003$	$a_0 = 1.003$ $a_1 = 0.557$
Time interval of validity in [h], local time	$<0, 6> U <22, 24>$	$[6, 22]$	$<0, 8> U <20, 24>$	$[8, 20]$

Current version (1.0) of the NA-QSW model is developed under the same presumptions as it is developed the Klobuchar model.
During the NA-QSW model development, certain patterns of local *TEC* behaviour has been observed, among the others:

- Linear decline of the night-time GPS ionospheric delay is especially pronounced in Winter
- Two daily maxima of the GPS ionospheric delay variations (especially pronounced in Summer), instead of the only one as assumed by Klobuchar model

The observation of local patterns are to be deployed in the version 2.0 of the NQ-QSW model. In due course, certain inaccuracy can be observed in the NA-QSW version 1 model. The NQ-QSW version 1.0 model has been used in the analysis presented in this paper.

4 PROPERTIES OF RESIDUAL GPS IONOSPHERIC DELAY. Validation of the NA-QSW model has been performed through the comparative study of several test-cases. Here we present one of them, related to the period of quite space weather in Summer 2007 (8 – 17 September 2007, days 251 - 260).
Space weather indices (sunspot number, solar flux, and global *Ap* index) for the period in question confirm the assumption of quiet space weather conditions prevailing through the observed period, as shown on Fig 2. Sunspot number and *Ap* index show no activity, 10.7 cm solar flux is at a very low level, and the value of *Kp* index is not exceeded the value of 2, all of them presenting entirely quiet space weather conditions.

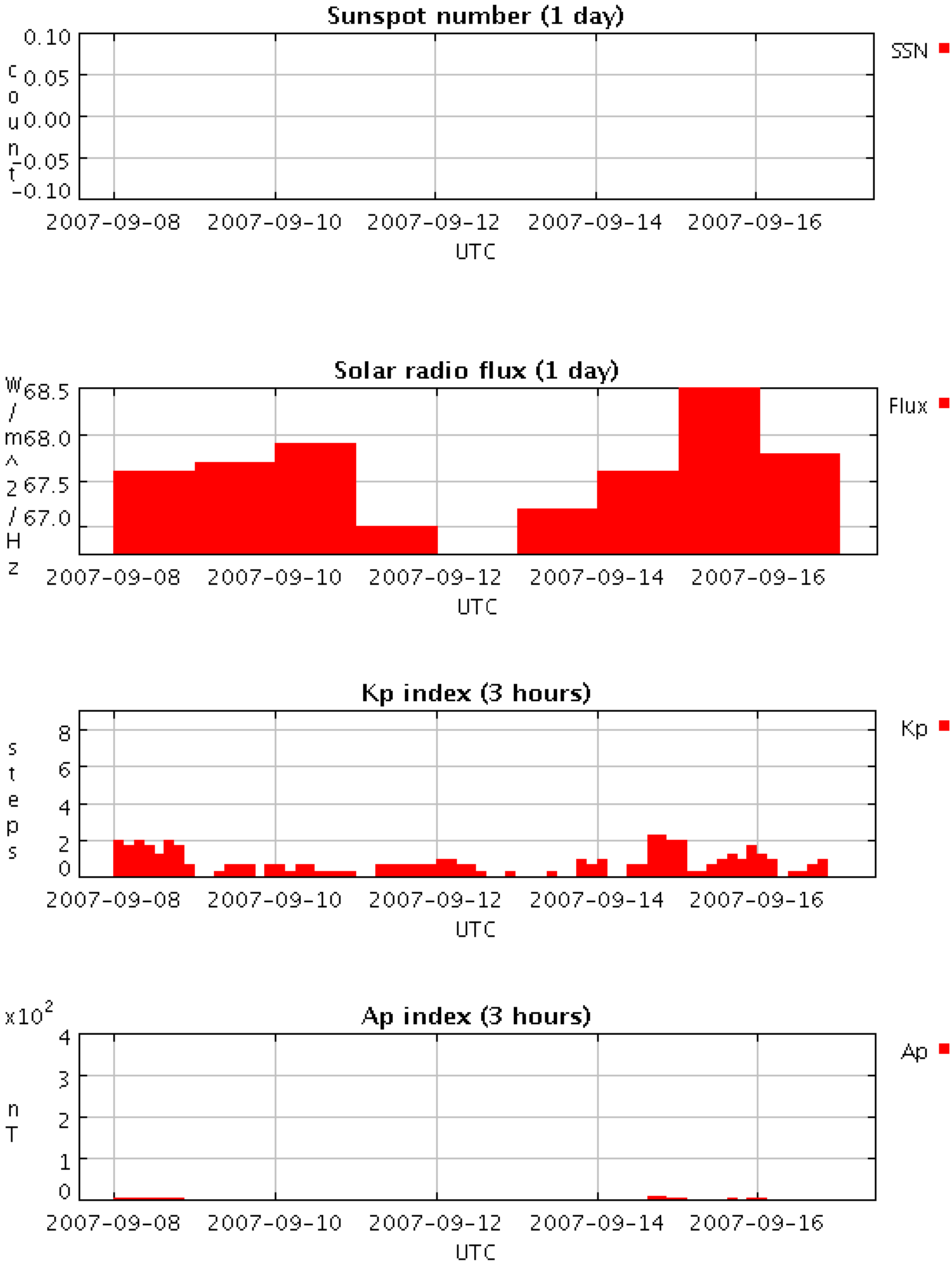

Fig 2 Space weather indices in quiet space weather period 2007 (top-to-bottom: sunspot number, 10.7-cm solar flux, *Kp* index, *Ap* index) (Data and plots courtesy NASA - SPIDR)

For the time period in question, the values of the actual GPS ionospheric delay have been derived from the internet archive data (University of Bern, 2008). Additionally, a time series have been derived using the NeQuick model software (ITU-R, 2008). Time series modelled by NA-QSW and NeQuick have been compared with the actual GPS ionospheric delay data (University of Bern, 2008) in order to conduct a comparative analysis. Time series of data for the period in question are presented on Fig 3.

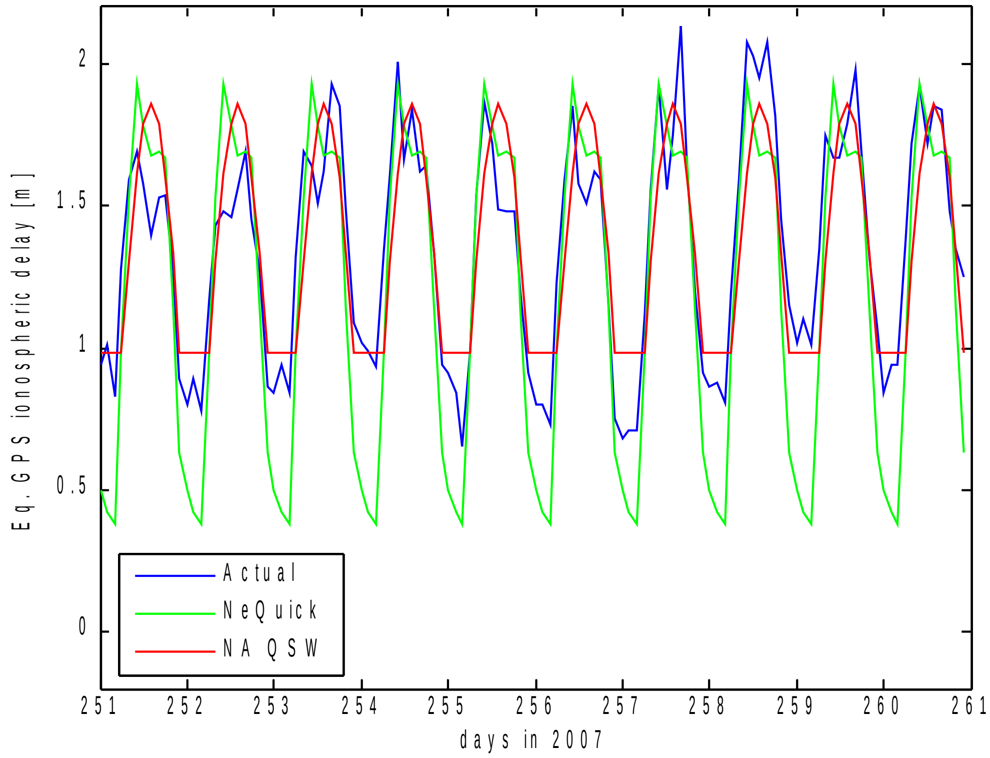

Fig 3 Time series of GPS ionospheric delays (actual – blue, NeQuick – green, NA-QSW – red) in quiet space weather period 2007

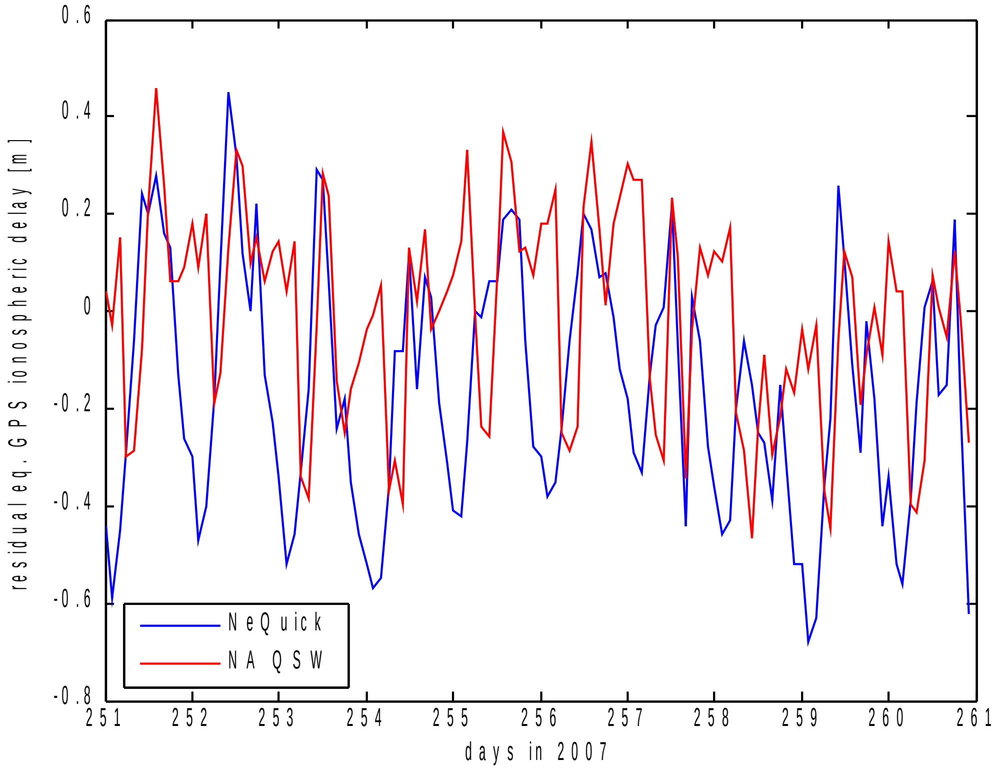

Fig 4 Residual NeQuick (blue) and NA-QSW (red) GPS ionospheric delays in observed period of quiet space weather (8 – 17 September 2007)

Residual GPS ionospheric delay has been obtained both for NeQuick and NA-QSW models as a difference between a model output and actual GPS ionospheric delays, as follows:

$$\delta d = d_{model} - d_{actual} \quad (4)$$

Time series of both residuals are presented on Fig 4. Statistical parameters of the residual GPS ionospheric delay determined by (4) are presented in Table 2. Fig 5 shows histograms of both residuals (NeQuick and NA-QSW). Histograms of residual GPS ionospheric delays during the period of quiet space weather are presented on Fig 4.

Table 2 Statistical parameters of residual GPS ionospheric delay

	NeQuick model	**NA-QSW model**
Mean [m]	-0.1617	-0.0069
Median [m]	-0.1800	0.0420
Standard deviation [m]	0.2525	0.2113
Skewness	-30.56	4.82
Kurtosis	168.21	23.6

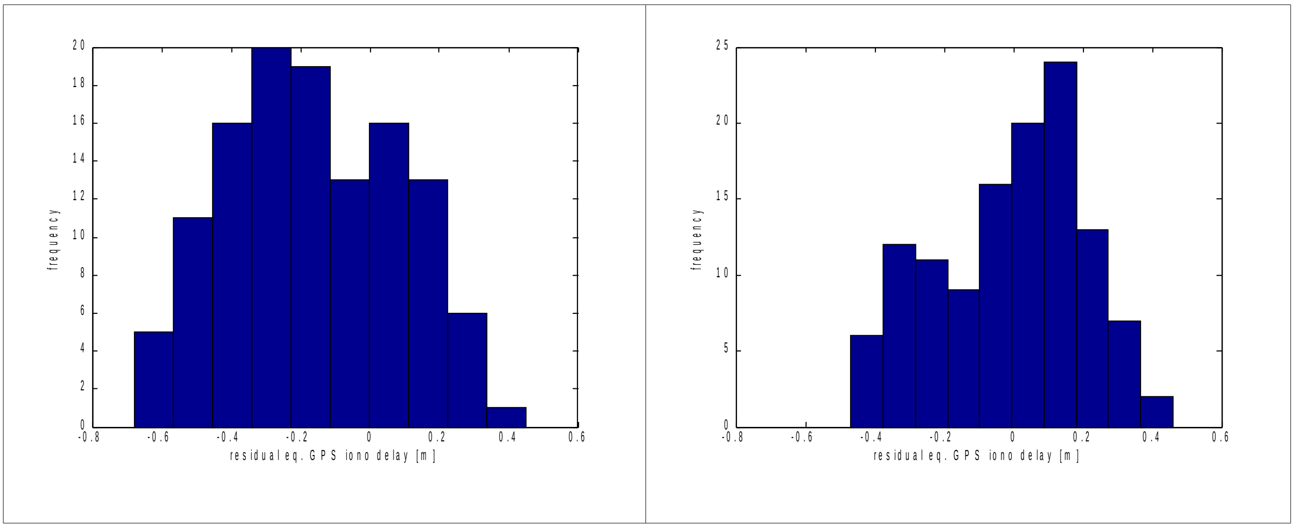

Fig 5 Histograms of NeQuick and NA-QSW residual GPS ionospheric delay, respectively, in period 2007

5 DISCUSSION. Fig 3 shows good correlation between actual GPS ionospheric delay observed in Northern Adriatic during the period of quiet space weather in 2007 and GPS ionospheric delay modelled by NA-QSW model. Statistical analysis (Table 2) reveals the mean equivalent error of the NA-QSW model of -0.0069 m, with standard deviation of 0.2113 m.

Furthermore, the histogram of residual GPS ionospheric delay show better compliance with normal (Gaussian) distribution of errors than it is a case with standard NeQuick model.. This leads to conclusion that actual GPS ionospheric delay in Northern Adriatic in quiet space weather conditions can be described as a combination of night-time linear value, day-time half-cosine function, and a stochastic component with normal (Gaussian) distribution, as shown in the equation (5).

$$d = a_0 + a_1 \cdot \cos\left(\frac{2 \cdot \pi \cdot (t - t_0)}{P}\right) + a_3 \cdot N(0, \sigma) \quad (5)$$

where: *d* ... GPS ionospheric delay, a_0 ... night time value (assumed to be constant by Klobuchar), a_1 ... amplitude of the half-cosine component, t_0 ... time of the maximum daily GPS ionospheric delay (14.00 local time, as assumed by Klobuchar), *a3* … scaling factor of stochastic component, $N(0, \sigma)$ ... stochastic component with normal (Gaussian) distribution.
Observed declinations from the normal (Gaussian) distribution in NA-QSW data are caused by following the initial presumptions of the Klobuchar model, and the negligence of the local patterns of daily GPS ionospheric delay dynamics.

6 CONCLUSION AND FUTURE WORK. The first version of the local NA-QSW model of GPS ionospheric delay shows better performance during quiet space weather condition in Northern Adriatic than the standard European NeQuick model, as presented in 2007 case study.
Statistical analysis of residual GPS ionospheric delays reveals good compliance with normal (Gaussian) distribution. It is expected that correlation with normal distribution of residuals will be further improved after eventual transition of the NA-QSW model towards the three-component Adriatic Quiet Space Weather (A-QSW) model.
Further work will focus on development of the NA-QSW model version 2, which will encompass the stochastic component and assume the linear decline of night-time GPS ionospheric delay, as well as two-maxima daily variations of the GPS ionospheric delay.

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