VARIACIJE VREDNOSTI TEC NA OBMOČJU SRBIJE V OBDOBJU POVEČANE SONČEVE AKTIVNOSTI V LETIH 2013 IN 2014

VARIATIONS OF TOTAL ELECTRON CONTENT OVER SERBIA DURING THE INCREASED SOLAR ACTIVITY PERIOD IN 2013 AND 2014

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IZVLEČEK

Za razumevanje splošnih lastnosti ionosfere na območju Srbije smo opravili analizo časovnih in prostorskih sprememb vrednosti količine TEC (angl. total electron content). Osredotočili smo se na ugotavljanje dnevnih in letnih časovnih ter prostorskih sprememb razmer v ionosferi na podlagi vrednosti TEC, določenih z opazovanji GNSS oziroma GPS. Na podlagi opravljenih analiz smo skušali opredeliti lastnosti ionosfere na območju Srbije na lokalni in regionalni ravni. V obdobju intenzivne Sončeve aktivnosti so se dnevne vrednosti TEC spreminjale med 4 TECU (angl. total electron content unit) v nočnih urah in 55 TECU okrog poldneva. Te spremembe ustrezajo vrednostim zenitne ionosferske refrakcije od 0,6 metra ponoči do 8,8 metra podnevi. Sezonske spremembe vrednosti TEC se dobro ujemajo z običajno letno Sončevo aktivnostjo, kjer razlike v vrednosti TEC med letnimi časi dosežejo 45 TECU. Prostorska spremenljivost vrednosti TECU je opazna v vseh smereh, zato je ne moremo predstaviti s konstantnimi vrednostmi ali v obliki trenda.

ABSTRACT

To understand general ionosphere properties over Serbia, an analysis of temporal and spatial ionosphere Total Electron Content (TEC) over the region was performed. The present research focuses on daily, seasonal and spatial ionosphere variations, based on TEC series calculated from the GNSS ie. GPS measurements. This analysis provides for characterization of ionosphere nature and fine structure over Serbia, both locally and regionally. For the days with high solar activity changes of TEC values ranges from minimum 4 Total Electron Content Units (TECU), in night hours, up to 55 TECU around the noon. It is shown that that changes are equivalent to the to the delay of GPS signals approximately 8.8 m in in vertical direction during the (maximum) daily conditions and the delay of 0.6 m during the (minimum) night conditions. Also, it is shows that a seasonal TEC differences follows directly Son activity during the seasons, and maximal differences of TEC values between the seasons reaching values of 45 TECU, again in the years of high Son's activities. For spatial changes all gained results indicate that there exist changes in all directions which cannot be recognized as constant bias or a trend.

KLJUČNE BESEDE

GNSS, GPS, variacija ionosfere, skupna vsebnost elektronov (TEC)

KEY WORDS

GNSS; GPS; Ionosphere Variation; Total Electron Content (TEC)

1 INTRODUCTION

Global Navigation Satellite System (GNSS), such as Global Positioning System (GPS) or Globalnaya navigatsionnaya sputnikovaya sistema (GLONASS), application provides for accurate, three-dimensional positioning and navigation on the Earth's surface, being used in numerous civil and military applications. Although the GNSS techniques had been significantly improved over the past two decades, several sources of errors still remain, which may limit the accuracy, practical operation and performances of precise positioning. Ionosphere is the major source of errors for the GNSS positioning. Scope of ionosphere error may range from several meters (at night, during the minimum solar activity period, for the satellites in zenith), up to several tens of meters (mid-day, during the maximum solar activity period, for the satellites near the observer's horizon) (Hofmann-Wellenhof et al., 1992). Ionosphere is located approximately between 50 km and 1000 km above the Earth's surface. In this region, ionizing radiation from the Sun causes the existence of electrons, in the quantities influencing radio-waves propagation (Kleusberg &Teunissen, 1996). The number of electrons intercepted by the electro-magnetic waves traveling through ionosphere is known as the Total Electron Content – TEC. It represents an integral of electron density per unit of volume, along the signal path between the satellite and the GNSS receiver. It is noted in TECU, with 1 TECU being 10^{16} electrons per square meter of cylindrical cross-section. Ionosphere delay is nearly proportional to the Total Electron Content along the signal path and inverse proportional to the frequency squared. This dispersion property of ionosphere provides for dual frequency GNSS receivers to compensate for the errors of ionosphere delay and measure the TEC.

Ionosphere is a very dynamic environment, and the electron density may significantly vary in time (Wyllie, 2007) at the given location, which leads to temporal and spatial variations in the Total Electron Content. Temporal variation of TEC is the combination of regular and non-regular variations. Regular TEC variation is linked to daily and seasonal changes in the Earth-Sun geometry (or the solar zenith angle) and changes of solar ionizing radiation intensity considering Sun's eleven-year solar cycle (current solar cycle number is 24). Irregular (or non-repetitive) variation usually refer to the effects of Traveling Ionospheric Disturbances (TID) and ionospheric or geomagnetic storms.

Research related to the GNSS use for monitoring ionosphere had started in late 1980's. In these early researches, the focus was on improving ionospheric models for navigation, which would be capable of achieving better accuracy of ionospheric delay, or the Total Electron Content (TEC) modeling. In the past years, the ionosphere research using the GNSS is growing, predominantly focuses on three fields: global TEC distribution and changes (Komjathy et al., 1996; Hu et al., 2004; Hoque et al., 2007), ionospheric scintillations in various regions (Gherm, V.E et al., 2007; Béniguel et al., 2009; Abadi et al., 2014) and developing models for ionospheric research and satellite navigation (Skone, 1998; Gao, 2001).

Monitoring ionosphere at the global level by the means of GNSS was made possible by establishing the International Global Navigation Satellite System Service – IGS. This had provided for production of global TEC temporal changes maps. Since 1996, these maps are being regularly monitored by the IGS center (Schaer et al., 1996). However, due to the low density of the IGS GNSS network, spatial resolution of ionospheric observations is not sufficient for detailed ionosphere structure research. This also makes IGS data use for the real-time navigation more difficult.

In order to support regional navigation, survey and scientific research, a great number of regional GNSS permanent networks have been established in different parts of the world: Great Britain (Dodson et al., 2000), Spain (Talaya, 1999), Germany (Wanninger, 1999), Serbia (Odalovic and Aleksic, 2006; Odalovic et al., 2011). Establishing these regional GNSS networks with greater densities had provided for monitoring ionospheric activities with much greater accuracy and resolution that satisfy the needs of satellite navigation, survey and ionosphere research (Gao, 2002).

The TEC variations as per local weather, season and solar activities were intensively studied over the past several decades (Rastogi et al., 1971; Da Rosa et al., 1973; Rao et al., 2006; Wu et al., 2006; Oron et al., 2013). However, no such research had been performed over the territory of Serbia. Since the GNSS permanent stations network – AGROS (Active Geodetic Reference Base of Serbia) was established, the conditions were provided for researching daily, seasonal and spatial ionosphere variations. Therefore, in order to obtain better positioning accuracy, it is necessary to precisely know the particular value and variations of TEC over the various geographic locations and under the different conditions. Having in mind the above, this paper examines spatial-temporal TEC variations for the territory of Serbia. TEC values were calculated from dual frequency GPS measurements, for the period of increased solar activity. Since the ionosphere may show strong seasonal variations (Gorney, 1990), data were taken for the dates matching summer and winter solstice, and spring and autumn equinox in 2013 and 2014.

The TEC is also correlated to the solar flux, number of sun spots and the conditions of the geomagnetic field of the Earth. For example, solar flux F10.7 at a wavelength of 10.7 cm (2800 MHz) due to the relation to the X-ray, EUV and UV fluxes is one of the most commonly used indicators of solar activity. The F10.7 shows similar variations as the number of sun spots R. The value varies from the minimum of approximately 65 (for the number of sun spots equal to zero in the solar minimum) up to the maximum of approximately 200 for the number of sun spots ranging from 150 to 160 (Davies, 1989). Sun spots appear and disappear over time, and R indicates systemic variations that provide useful information about the Sun's state. The R value varies from zero to 200, within the period of approximately 11 years, being a so-called sun spots period or solar cycle (Memerzadeh, 2009). Parameters for the planetary *Ap* index are given as the daily global measure of geomagnetic activity. *Ap* index is defined throughout *Kp* index converted in the linear scale before it is averaged over the day, where *Kp* index is a global measure of the magnetic deviations from the regular daily variation during a 3-hour period (Schunk and Nagy, 2000).

2 TEC DETERMINATION USING GNSS TECHNOLOGY

A system of dual-frequency GPS receivers provides for monitoring ionosphere influence on the GPS signals. Therefore, it is possible to determine an integrated electron content between the satellite and the receiver, as well as the scintillations' effect on the L frequency band. To compensate ionospheric delay, dual-frequency GPS receivers use L1 (1575.42 MHz) and L2 (1227.60 MHz) frequencies. This removes such effects, using the dispersive ionosphere content, with the refraction index being a function of frequency.

Delay, $\Delta t = t2 - t1$, the measurement between L1 and L2 frequencies is used to calculate TEC along the signal path:

$$\Delta t = \left(\frac{40.3}{c}\right) \cdot \frac{\mathrm{TEC}}{\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right)} \tag{1}$$

where *c* is the speed of light in open space. Calculating TEC using exclusively pseudo-lengths data may produce the noise-encumbered results, while the phase differences provide a precise measure of relative TEC frequencies. The absolute TEC may be obtained only if pseudo-length are also being used.

Therefore, using pseudo-lengths provides absolute TEC, while using phase differences improves the accuracy. According to that, GPS data provides for the efficient method of estimating TEC values with greater spatial and temporal coverage (Davies and Hartmann, 1997; Hockeand Pavelyev, 2001). Having that the frequencies used by the GPS system are sufficiently high, the signals are minimally influenced by ionospheric absorption and Earth's magnetic field, both in short- and in long-term changes in the ionosphere structure.

Here, the values of vertical TEC were obtained as the sum of slanted TEC's, hardware satellite delay b_S and hardware receiver delay b_R. The b_S values as differential code discrepancies between the satellite can be taken over from the Data Centre of the Bern University (Switzerland), and b_R can be modeled as the minimized TEC value between 2:00 AM and 6:00 AM - local time. Thus, vertical TEC may be expressed as follows

$$\mathrm{VTEC} = \frac{(\mathrm{STEC} + b_S + b_R)}{S(e)} \tag{2}$$

where STEC is slanted TEC, *e* is the elevation angle of satellites in degrees, *S*(*e*) is the slant factor against the zenith angle z at the Ionospheric Pierce Point - IPP[1] and VTEC is vertical TEC in the IPP point. The slant factor, *S*(*e*) (or the mapping function) is defined as (Langley et al., 2002):

$$S(e) = \frac{1}{\cos(z)} = \left(1 - \frac{R_e \times \cos(e)}{R_e + h_i}\right)^{-0.5} \tag{3}$$

where *Re* is the average Earth's radius in km, and hi is the (effective) height of ionosphere over the Earth's surface. Vertical TEC (VTEC) determined in this manner was used in the present paper. Results are shown in the chapters below.

3 OBSERVATIONS, RESULTS AND DISCUSSION

A set of 30 AGROS stations distributed throughout the state had been used as the test polygon for this analysis. Data had been taken over for each base station from the archive, in the form of 30-second RINEX files. Data collected contain 72-hour observations from March, June, September and December of 2013 and 2014.

The temporal series of TEC measurements had been obtained using equation 2. "GPS TEC Analysis" software was used for processing, being developed at Boston University (Seemala, G. K., 2014). Phase

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[1] *Usual practice in the GNSS research community is to assume that, for the mapping purpose, ionosphere can be presented as the thin layer on the spherical shell at the altitude of 350 km above the Earth's surface. This represents a two-dimensional modelling approach.*

and code values on both frequencies had been used to eliminate clock and tropospheric effect errors, in order to calculate relative values of slanted TEC (Sardón and Zarraoa, 1997). Afterwards, absolute TEC values had been obtained by removing hardware delays, i.e. differential code discrepancies between the satellite and the receiver (Seemala, G.K., Valladares, C.E., 2011). Trigonometric single-layer mapping function (equation 3) was used to convert TEC to VTEC at AGROS stations and at the IPP point at the altitude of 350 km. Elevation angle was limited to the value of 20° to decrease a potential effect of multiple signal reflection during the tests. Data sampling was done at 30 seconds.

3.1 Solar Activity during the Testing Period

Solar activity during the testing period is shown in Figure 1 and 2. March 2013 was the period of moderate solar activity, with the exception of March 18th, when the solar flux had reached the value of 116, and the number of sun spots being 79. In June 2013, somewhat stronger geomagnetic activity is notable (*Ap* index reaching 18, with 95 sun spots and solar flux of 137.6). For the period of September 2013, there is a notable decrease of sun spots and solar flux. In December 2013, a low geomagnetic activity and increase in sun spots and solar flux is notable. 2014 was somewhat more turbulent than 2013, with February, March and December 2014 being prominent (*Ap* index reaching 19, number of sun spots equaling 80, and solar flux of 173.4).

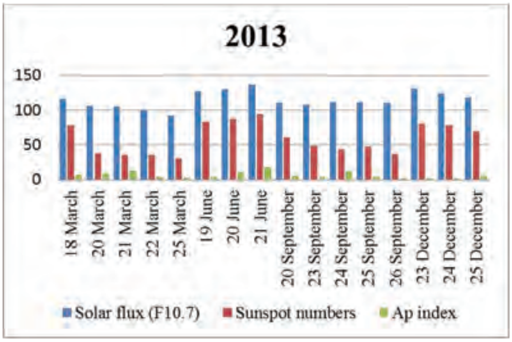

Figure 1: Solar flux, number of sun spots and ***Ap*** index in 2013

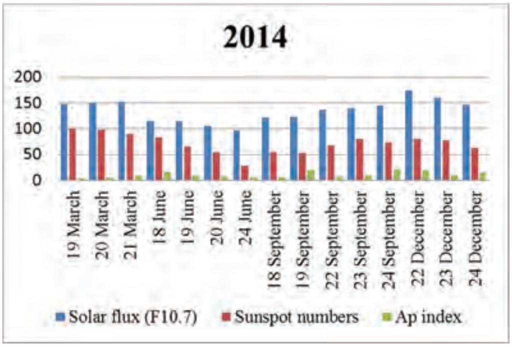

Figure 2: Solar flux, number of sun spots and ***Ap*** index in 2014

3.2 Daily and Seasonal TEC Variations

Grocka base station (44.64 N, 20.75 E) had been used for daily variations analysis. Figures 3 and 4 show daily and seasonal ionosphere variations over Grocka station during the characteristic period. Each figure shows 24-hour VTEC data for all visible satellites in four seasons in 2013 and 2014. X-axis shows the Coordinated Universal Time (UTC), and Y-axis the VTEC values. Minimal elevation angle for all satellites is 20 degrees.

For the purpose of this analysis, the assumption is made that the morning covers 4:00 – 9:00, day 9:00 – 17:00, dusk 17:00 – 21:00, and night covers 21:00 – 4:00 in Serbia local time.

Daily VTEC variations at Grocka station show numerous characteristics, typical for medium ionosphere widths, such as the occurrence of minimum values before dawn and gradual increase, with the maximum being reached around the noon, followed by a gradual decrease of values in the afternoon. The figure shows that the maximum VTEC values occur approximately around 11:00 UT, i.e. 12:00 to 14:00 local time, and the minimum VTEC values occur from 20:00 UT or 21:00 local time, to 4:00 UT or 5:00 local time. Therefore, it is notable that the VTEC values obtained during the day significantly exceeds the ones at night time.

However, occurrence of maximum and minimum ionospheric values varies with the season. It is also notable that there is a significant daily change in VTEC value during each season, even in June, when ionosphere is traditionally stable.

These daily VTEC variations, apart from the influence of Earth's magnetic field, could also be contributed to the changes in the Sun's activity and the intensity of incoming radiation, as well as the change of zenith angle under which the radiation breaches the Earth's atmosphere (Rao et al., 2006).

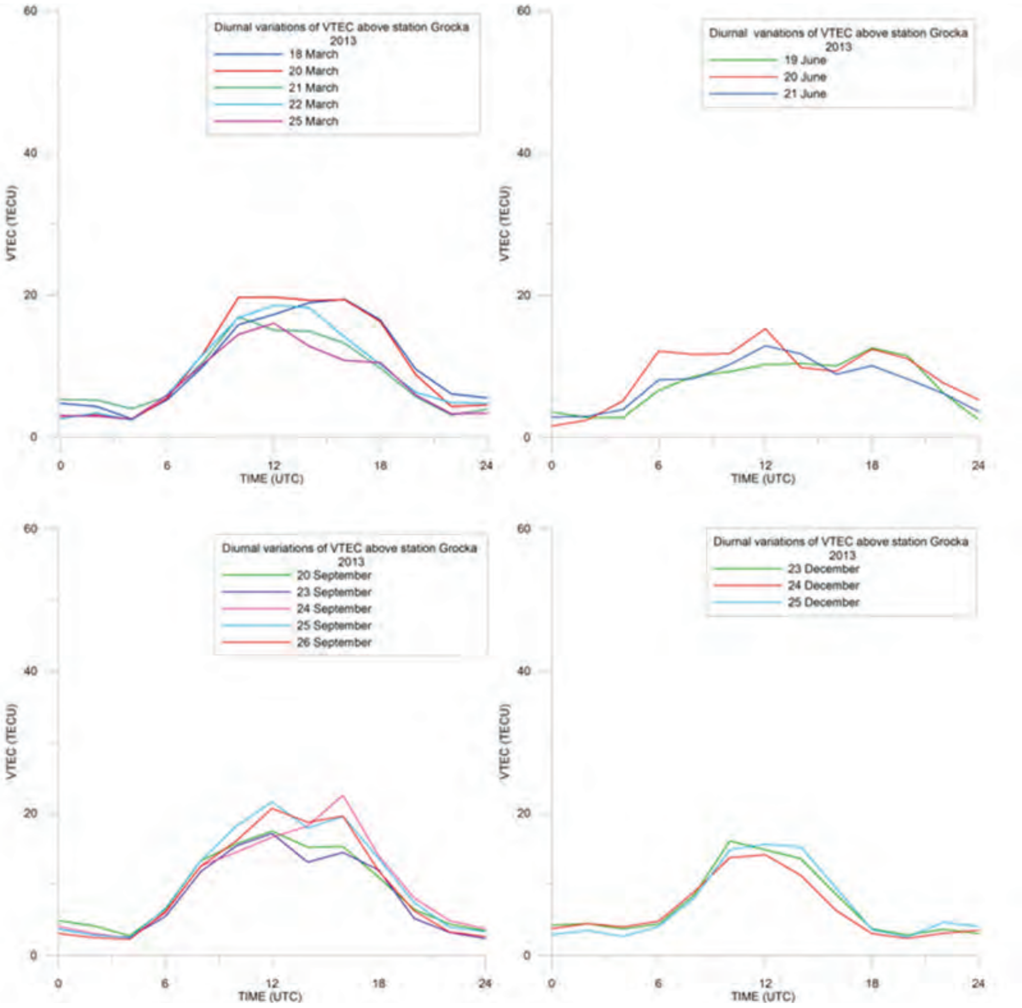

Figure 3: Daily and seasonal VTEC value variations over Grocka (AGROS) GPS base stations during 24 Hours (UTC), in 2013

Comparing the values on figures, significant differences in VTEC value are notable for different seasons in 2013 and 2014. The greatest values occur in March and December 2014, with the lowest ones being shown in June of both years. It can be noted that the daily VTEC values obtained in September (autumn) and March (spring) are generally greater than the values obtained in December (winter) and June (summer). This kind of gained results it in agreement with lot of other researches, for example (Wyllie, 2007) or (Leong, 2011).

However, during the period of December 2014, the VTEC values are higher, which may be due to the increased solar and geomagnetic activity (see Figures 2 and 4).

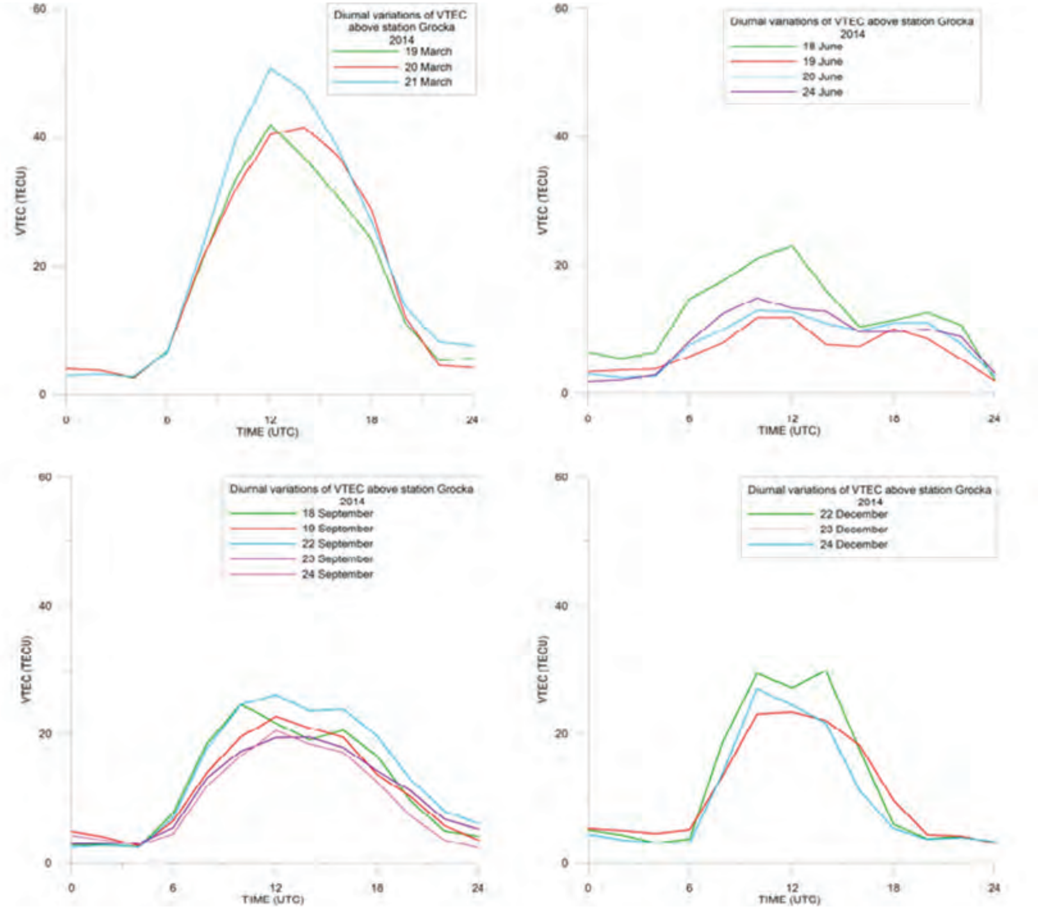

Figure 4: Daily and seasonal VTEC value variations over Grocka (AGROS) GPS base stations during 24 Hours (UTC), in 2014

Pursuant to these results, there is few evidence of consistency in observations among the seasons. While the general trend within each season is similar, modeled coefficients deducted from daily data are not sufficiently precise for the prediction of general ionosphere, day in, day out.

3.3 TEC Spatial Variations

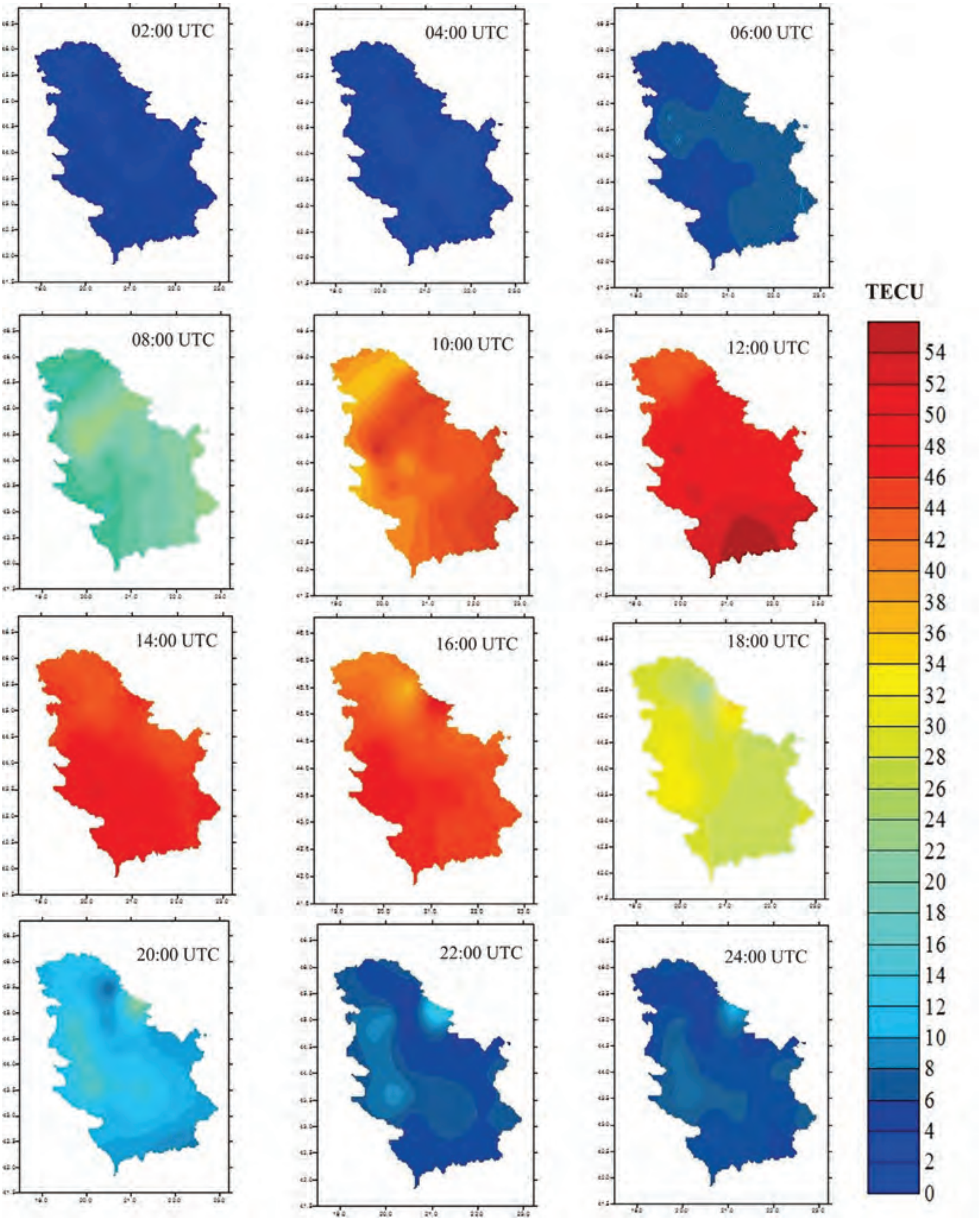

Figure 5: Overview of VTEC values over Serbia on March 21st, 2014 for 24 hours (units: TECU)

This section covers a broad, regional analysis of the ionosphere. Thirty AGROS stations, distributed over the territory of Serbia, had been used to determine VTEC value, using the procedure described above. Pursuant to the results obtained, a time series was calculated, consisting of 12 two-hour observations of VTEC over Serbia for four seasons in 2013 and 2014. The results are shown in Figure 5 with the values for March 21st, 2014, being the day when the greatest solar activity was noted. X and Y axis show longitude and latitude direction, respectively.

Figure 5 shows that the greatest VTEC values were registered from 12:00 UT to 14:00, reaching 55 TECU during the day, and the lowest values of 4 TECU were registered during the night, in March 2014. That is equal to the delay of approximately 8.8 m in vertical direction during the maximum daily conditions and the delay of 0.6 m during the minimum night conditions. As a general rule, the slant factor of 3 is applied to the low elevation angles of satellites. This ratio describes the factor by which the ionospheric delay is being increased against the delay in zenith, due to the ionospheric conditions and the satellite elevation angle. That would mean that during the maximum daily conditions in March 2014, satellites with low elevation angle had an ionospheric delay of 26.4 m.

Figure 5 shows that, apart from the fact that the VTEC values over the region vary during the day, they are also spatially correlated. These characteristics of spatial correlation provide for ionosphere modeling over the entire territory of Serbia. However, Figure 5 also shows that some data records indicate an obvious gradient from southwest towards northeast, while others indicate the inverse direction, while some even indicate perfectly homogeneous slope which can lead to difficulties in establishing a regular mathematical expression for VTEC modeling over Serbia. This is particularly important for the high precision, real-time positioning for instance (Wu et al., 2006).

4 CONCLUSIONS

Ionosphere varies regarding time, geographic location and some of solar and geomagnetic Earth-Sun geometry activities. Daily VTEC variation can be contributed to the changes in the Sun's activity. Apart from that, volatile Sun eruptions may cause an increase in ionospheric activity, correlated with the number of sun spots. This research covers the ionosphere changes at the daily level over the region of Serbia, in different seasons and considering the location in 2013 and 2014. These periods belong to the solar cycle number 24, and the period of increased solar activity. GPS observations from the AGROS permanent stations network were used to determine VTEC parameter and examine spatial and temporal ionosphere variation in Serbia. Data indicate that the daily variations show a consistent pattern throughout the seasons. VTEC shows the increase from 06:00 UT, with the maximum VTEC values being obtained around 12:00 UT, i.e. 13:00 to 14:00 local time; while the minimum VTEC values occur after the midnight. It is obvious, however, that there is a significant daily variation of the VTEC, thus the modeled coefficients deducted from daily data are not sufficiently precise to describe daily ionosphere changes. The value reached by the VTEC varies seasonally. Regarding seasonal variations, the greatest values occur in spring and autumn months, and the lowest ones in summer and winter period. However, some deviations are possible, which may be assigned to solar and geomagnetic activity (the period of December 2014). Spatial VTEC variations indicate that the values over the region are spatially correlated, thus providing for modeling of ionosphere over Serbia. However, a difficulty poses the lack of regularity in the daily VTEC values' variations against the geographic location. All showed results were in agreement with similar investigation around the world, but this kind of researches is the first detailed investigation of the ionosphere above the territory of the Serbia.

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