INVESTIGATION OF IONOSPHERIC VARIATIONS AND SUDDEN DISTURBANCES, AS A SOURCE OF GNSS ERRORS AND EARTHQUAKE PRECURSOR

AUTHORS

Medžida Mulić
PhD, Assistant Professor
Faculty of Civil Engineering
Department of Geodesy and Geoinformatics
Sarajevo, Bosnia and Herzegovina
email: medzida.mulic@gf.unsa.ba

Randa Natraš
M.Sc., Research scholar
Vienna University of Technology
Department of Geodesy and Geoinformation
Vienna, Austria
email: randa.natras@geo.tuwien.ac.at

Džana Horozović
M.Sc., Project assistant
Vienna University of Technology
Department of Geodesy and Geoinformation
Vienna, Austria
email: dzana.horozovic@geo.tuwien.ac.at

Dževad Krdžalić
M. Sc., Advanced Assistant
Faculty of Civil Engineering
Department of Geodesy and Geoinformatics
Sarajevo, Bosnia and Herzegovina
email: krdzalic.dzevad@gf.unsa.ba

Ionosphere has significant impact on signals' propagation, which come from Global navigation satellite systems (GNSS). Consequently, it introduces the major part of errors in GNSS applications, such as positioning and navigation. One of the main parameters to describe state in ionosphere is Total Electron Content (TEC). Ionosphere is spatially and temporally highly variable. Sun is the primary source of its ionization. Activities on the Sun, such as solar flares, can cause abnormally high ionization in ionospheric D layer, known as sudden ionospheric disturbances. Geomagnetic storms can additionally disturbed conditions in ionosphere. Some studies, during last decades, showed that variations in ionosphere can also be seen in weeks before and after the earthquake´s occurrence, proposing the model of lithosphere-atmosphere-ionosphere (LAI) coupling. This paper briefly represents results of ionospheric investigation in Bosnia and Herzegovina (BiH). It was conducted using GNSS dual-frequency measurements for estimation of TEC values. Observations of SuperSID monitor were applied for detecting sudden ionospheric disturbances (SID). Some results of lithosphere-ionosphere investigation in 2015 were briefly mentioned as well. Study of TEC variations covered period from 2014 (year of solar maximum) to 2016. We discussed temporal ionospheric TEC variations, sudden ionospheric disturbances and their origin. Results show seasonal variability and solar cycle dependence of TEC values, as expected. Moderate to strong correlation between TEC variations and solar activities was observed. SuperSID monitor successfully detected sudden ionization in ionospheric D layer, due to solar flares from C 1.4 class to X 2.1 class. Geomagnetic disturbances produced the most of ionospheric anomalies observed prior and after moderate seismic activity.

Keywords: GNSS, Ionosphere, Total electron content (TEC), Sudden ionospheric disturbances, Solar activity, Litosphere-atmosphere-ionosphere coupling (LAI).

1. INTRODUCTION

The major errors in GNSS positioning and navigation are introduced by the upper part of atmosphere - ionosphere. This region contains free electrons in amount sufficient to influence propagation of radio signals [1], which consequently cause signal's delay or advance. Amount of free electrons along the GNSS signal's path in ionosphere, on this way from satellite to receiver on the Earth, can be presented by total electron contents (TEC).

High solar activity and space weather can produce significant variations in space environment between Sun and Earth, known as phenomena space weather. Consequently, it can severely disturb Earth's magnetic field (causing geomagnetic storms) and the state of ionosphere as well. The level of solar activity is usually presented by solar indices such as the sunspot Number (SSN) [2] and the solar radio flux at 10.7 cm (F10.7) [3].

Researches during the last decades [4-7] have reported a correlation between the state of the ionosphere and seismic activity of the lithosphere several days before devastating earthquakes. A model that combines different types of precursor is called the LAIC (Litosphere-Atmosphere-Ionosphere Coupling) model. This model combines changes from the Earth's interior to the magnetosphere [8]. The basic components of this model are: the earthquake preparation zone (EPZ), the radon emissions from the Earth and the air ionization caused by the anomalous electric field.

The concept is based on the assumption that changes in the ionosphere, associated with seismic activity, can be observed over the earthquake preparation zone, defined by the formula 1 [9]:

$$\rho = 10^{0.43M}\, km \qquad (1)$$

Where ρ is the radius of earthquake preparation zone in km (kilometers) and M is the earthquake magnitude on the Richter scale.

The LAIC model assumes that radon ionization from Earth increases in earthquake preparation zone, measured experimentally before earthquakes [10] and used as short-term precursor [11]. The ionization effects have electromagnetic and thermodynamic activity. Electromagnetic activity is reflected in creation of an anomalous electric field in the lower layers of the atmosphere, its penetration into the ionosphere and the formation of irregularities in the electrons' concentrations. Thermodynamic activity is reflected in changes in air temperature and relative humidity, through the process of condensation of water vapor, which may also lead to the modification of the ionosphere [8].

Previous research of ionosphere in Bosnia and Herzegovina (BiH) included study of GNSS-derived TEC variations at middle latitude [12-13], investigation of lithosphere-ionosphere coupling process before and after moderate seismic activity in BiH in 2015 [13-15], including few cases of stronger earthquakes in the world [16] and also in relation to severe space weather events [15]. Other studies of ionospheric state in BiH were carried out by investigation of sudden ionospheric disturbances (SID) by very low frequency (VLF) measurements as they bounce off the ionosphere [17-18].

The aim of this paper was to investigate regular and sudden variations in midlatitude ionosphere over Bosnia and Herzegovina, together with their sources. Variations were analyzed regarding solar activities, geomagnetic conditions and lithosphere-atmosphere-ionosphere coupling process. Investigation was carried out by studying GNSS-derived TEC, estimated from GNSS measurements of European Permanent Network (EPN) station SRJV (Sarajevo) at middle latitude (+43º52'04''). It covered the period from 2014 (period of intensive Sun's activity i.e. solar maximum) to 2016 (period of lower Sun's activity, i.e. decline phase of solar cycle 24). Monthly VTEC values were presented and discussed regarding their monthly, seasonal and solar cycle variations. They were compared to solar and their correlations were estimated. Next part of our study was conducted to detect sudden ionospheric disturbances in ionosphere, using observations from SuperSID monitor in Sarajevo and x-ray data flux data from Geostationary Operational Environmental Satellites (GEOS) from March to April 2015. In last part we presented some results from lithosphere-ionosphere coupling investigation before medium earthquakes (M > 4 Richters), in BiH, in April 2015 [14]. The aim of that study was to analyze total electron contents variations before and after seismic shock and determine whether they were caused by geomagnetic or solar activity, or were the consequence of earthquake.

2. MATERIALS AND METHODS

2.1 ESTIMATION OF TEC FROM GNSS – PRINCIPLES

TEC obtained from dual-frequency measurements is actually slant TEC (STEC), Value of STEC represents the total number of free electrons in the cylinder along the path of the electromagnetic wave from the satellite to the receiver. STEC value for a GNSS signal can be obtained from formula 2:

$$STEC = \int_{receiver}^{satellite} N ds \qquad (2)$$

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Where *N* represents the density of electrons along the line of sight *ds.*

The value of TEC depends on the frequency, so it can be estimated using two frequencies between receiver and satellite communication (formula 3), from [19]:

$$STEC = \frac{f_{l1}^2 \cdot f_{l2}^2}{40.3 \cdot (f_{l1}^2 - f_{l2}^2)} \cdot (\rho_{l2} - \rho_{l1}) + TEC_{CAL} \qquad (3)$$

Where f_1 is frequency on L1, f_2 is frequency on L2, ρ_1 is pseudo range on L1, ρ_2 is pseudo range on L2 and TEC_{CAL} is the bias error correction (receiver differential delay).

For full TEC modeling, using terrestrial GNSS data is necessary to use vertical TEC (VTEC). Thus it is needed to introduce a mapping function, which depends on elevation and describes the relationship between STEC and VTEC (formula 4):

$$F(z) = \frac{STEC}{VTEC} \qquad (4)$$

VTEC was estimated from dual-frequency measurements using approximations of single layer ionosphere model (SLM) [20], at height of 400 km. VTECs were calibrated by Ciraolo methodology [21], using program VShell GNSS 2017. Carrier phase GNSS measurements of GPS and GLONASS satellite systems were applied.

Correlation coefficient R between VTEC and solar indices (F10,7 and SN) were calculated by equation (formula 5):

$$R = \frac{\sum_{i=1}^{n} (x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \cdot \sum_{1=1}^{n} (y_i - \bar{y})^2}} \qquad (5)$$

Where x_i is VTEC value for specific day and y_i is solar index value (F10.7 or SN) for specific day. $\bar{x}$ and y represent average values for the entire study period (2014 - 2016) for VTEC and solar index, respectively.

2.2 OBSERVATION OF SUDDEN IONOSPHERIC DISTURBANCES (SID)

SuperSID monitor uses VLF (very low frequency) signals emitted from remote transmitters. Signal strength of VLF waves change as the Sun affects Earth's ionosphere and adds ionization. Such monitor is set up and currently active at the Faculty of Civil Engineering, Department for Geodesy (University in Sarajevo). Since July 2014, the monitor is officially registered in the database of University in Stanford under the name SRJV_ION 0436 [17-18]. It collects data from chosen VLF transmitters: DHO (Rhauderfehn, Germany), GBZ (Anthorn, UK) and NSC (Niscemi, Italy).

Data were registered every 5 seconds and for every new day at 00:00h in UTC time, in the SuperSID folder on the local computer daily excel files, which contains measured signal strength for each VLF transmitter separately. After collecting data of SuperSID monitor for period March-April 2014, the stored files were plotted in order to analyze the signal signatures. It is important to note that only the day time hours of the graphs can be analyzed since during the night time only cosmic radiation is affecting the Earth.

Larger spikes in graph could be caused by solar flare. Solar flares can be classified into 4 classes, from the weakest to the strongest: B, C, M and X, respectively. On the other hand, noise (interference from sources other than Sun) can appear in the data and look like a flare. Thus detected solar flare events were compared to data from GOES satellites, in order to determine if the peak came from solar flare or interference. Information about solar events was obtained from the catalogues.

2.3 DATA ACQUISITION

GNSS data from European Permanent Network were downloaded from: ftp://igs.bkg.bund.de/EUREF/.
GOES graphs and catalogues of solar events where found under the link: ftp://ftp.swpc.noaa.gov/pub/warehouse/.
Solar index F10.7cm solar radio flux was obtained from Canada, Department of Natural Resources. Space Weather Prediction Center: ftp://ftp.geolab.nrcan.gc.ca/data/solar_flux/daily_flux_values/fluxtable.txt.
Data of Sunspot numbers have been collected from Solar Influences Data Analysis Center (SILSO), of Royal Observatory of Belgium at: http://sidc.oma.be/silso/datafiles/.

3. ANALYSIS AND RESULTS

3.1 VTEC VARIATIONS

Variability of monthly VTEC values for the period 2014-2016 is shown on Fig. 1. The biggest VTEC values were observed in 2014, followed by VTEC decline, from 2015 to 2016.

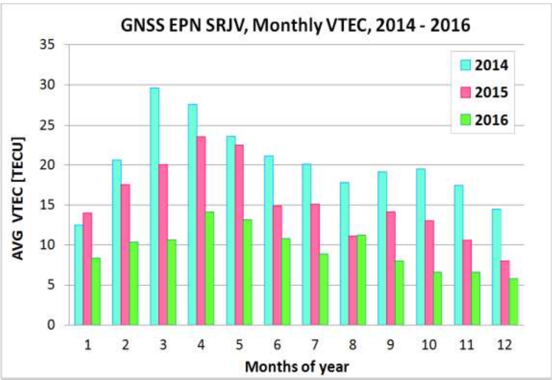


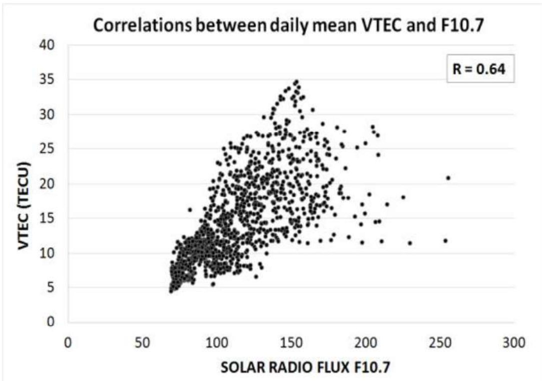
Figure 1: Variations of monthly VTEC at EPN station SRJV from 2014 to 2017, demonstrate seasonal and solar cycle variations. Highest TEC observed in the year of solar maximum (2014) and during spring equinoxes.

During one year the highest monthly values were usually during spring months (March-May). Afterwards, TEC gradually declined until the next peak, noticed in autumn months in 2014 and 2015 (September-October), while in 2016 it was in August. However, TEC values in autumn equinox were lower, than those observed in spring. The lowest TECs were recorded during winter (November-January).

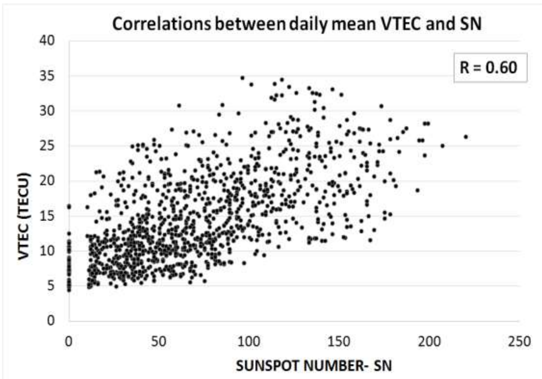
Concerning the entire period, the highest VTEC values and variations were seen in 2014, especially during months of spring equinoxes (March-April). It is period when Sun has reached its maximum activity level (in April 2014). With moving away from solar maximum, TEC variations become smaller and less expressive (especially in 2016). These results indicate seasonal TEC variability and solar cycle dependence

3.2 VTEC AND SOLAR ACTIVITY CORRELATION

Relationship between solar activity and VTEC variations was analyzed. Correlation coefficients between VTEC and solar indices: solar radio flux F10.7 and sunspot number (SN) were calculated for period 2014-2016 (fig. 2). Correlations between VTEC and solar indices from 2014 to 2016 can be described as moderate to strong positive relationship, with coefficient of 0.60 (VTEC and SN) and 0.64 (VTEC and F10.7). Correlation was slightly better between VTEC and solar flux F10.7.



a)



b)

Figure 2: Correlation between daily mean VTEC values and daily mean solar indices: a) solar radio flux F10.7, b) sunspot number (SN).

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3.3 SID DETECTION

Figure 3 shows comparison between graph from SuperSID monitor for 11 March 2015 and x-ray flux data from GEOS. Axis on the right hand side of the GOES graph is referring to the strength of a solar flare. Both graphs show similar signal signatures, so we can be sure that our monitor detected solar events. By analyzing DHO data, 4 visible spikes were observed, at around 7 AM, 8 AM, 11:30 AM and 4 PM (UT time). The first solar flare (M1.8) began at 7:10 and ended at 7:43, followed by the M2.6 flare which began at 7:51 and ended at 8:03. The third flare that we detected happened between 11:21 and 12:01 which was a C5.8 flare. Finally, an X-flare, X2.1 happened at 16:21 and was active until 16:29. The source of all flares was the sunspot region 2297, which is responsible for the coronal mass ejection that caused the strongest geomagnetic storm of Solar Cycle 24 (known as St. Patrick's Day geomagnetic storm) on 17.03.2015.

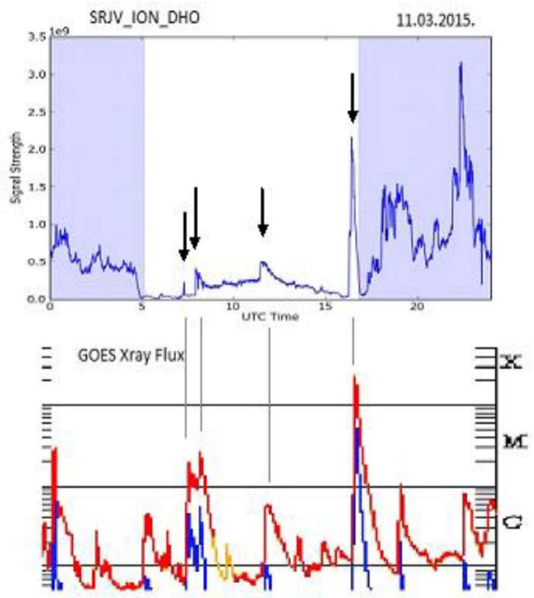


Figure 3: Direct comparison between the upper graph from SuperSID monitor with the lower graph representing x-ray data flux from GEOS. 4 spikes were detected originated from solar flare.

Information of solar event, such as exact time of occurrence, solar flare strength (Frq) and sunspot region (Reg#) that caused a particular solar event, was collected from catalogue of solar events (Tab. 1), for period March-April 2015. During March, stronger disturbances in the ionosphere were visible in the SuperSID graphs until the 16.03.2015. Afterwards, no significant spikes appeared in the graphs, nor a higher solar flare class happened in that time. Solar flares were B and C classes, which usually occur almost every day and have not indicated that solar radiation affected the ionosphere. April, opposite to March, showed in general less solar events, and also a less disturbed ionosphere. During the analyzed period in April, there were just two solar flares of class M detected, on 12.04.2015.

Table 1: List of events, detected by SuperSID monitor SRJV_ION 0436 in 2015. The first half of March showed significant ionospheric disturbances. On the other hand, April was more quiet, but still under influence of solar radiation.

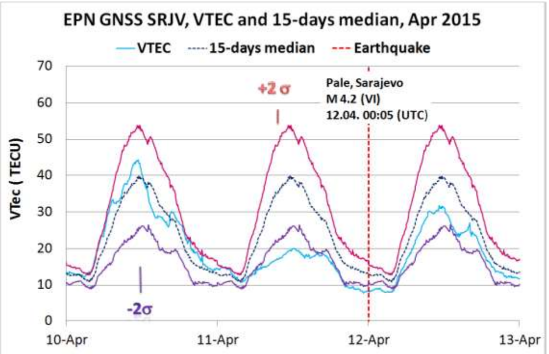
Date	Begin	Max	End	Loc/ Frq	Reg#
11.3.	0710	0718	0743	M1.8	2297
11.3.	0751	0757	0803	M2.6	2297
11.3.	1121	1134	1201	C5.8	2297
11.3.	1611	1622	1629	X2.1	2297
12.3.	1350	1408	1413	M4.2	2297
13.3.	0549	0607	0612	M1.8	2297
13.3.	1107	1123	1147	C1.9	2297
15.3.	0936	0940	0946	M1.0	2297
15.3.	1131	1203	1220	C6.8	2297
16.3.	1039	1058	1117	M1.6	2297
8.4.	1437	1443	1447	M1.4	2320
9.4.	1713	1729	1738	C5.9	2320
10.4.	0757	0803	806	C7.9	2320
10.4.	0933	0952	1000	C2.8	2320
12.4.	0811	0816	0827	C2.9	2321
12.4.	0851	0950	1044	M1.1	2321
13.4.	0821	0826	0828	C4.7	2322
13.4.	1314	1318	1321	C1.4	2320
16.4.	0900	0907	0914	C5.7	2324
16.4.	1117	1122	1130	C2.3	2321
16.4.	1616	1625	1637	C1.8	2321
18.4.	1403	1419	1439	C5.2	2321

3.4 LITOSPHERE-IONOSPHERE COUPLING

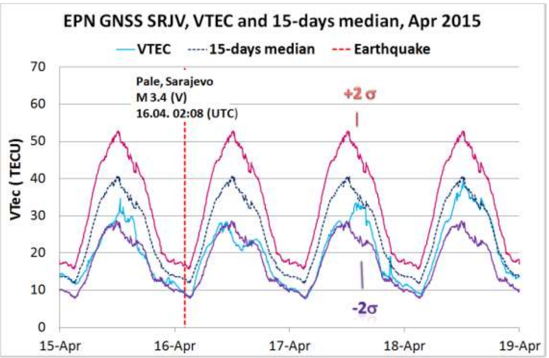
In April 2015, earthquake of magnitude greater than 4 Richter occurred near Sarajevo, followed by the earthquake of magnitude of 3 Richter, five days after. Epicenter of the both earthquakes was in Pale (12 April M=4.2 Richter, 16 April M=3.4 Richter), about 14 km far from Sarajevo [14].
GNSS observation data of EPN station SRJV (station inside earthquake preparation zone - EPZ) were used for TEC values estimation. In addition, data of EPN station ZADA in Zadar

(Croatia, +44^{0}06' 47.42" N, 15^0 13' 39.31" E) were introduced in statistical analysis, as the station outside EPZ [14]. Differences of observed VTEC from monthly median for station SJRV showed significant VTEC decreases shortly prior and after earthquakes' occurance [14].

VTEC variations were analyzed with 15-day median (which preceded the day of consideration) ± 2 * σ (standard deviations), in order to detect anomalies and determine if they were caused by seismic activity or space weather effect. Few significant anomalies in TEC variation were recorded, on 11-12 April and 15-17 April, when they reached lower bound or exceeded it (fig. 4).



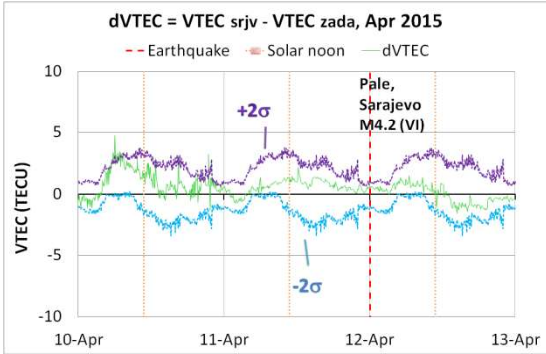
a)



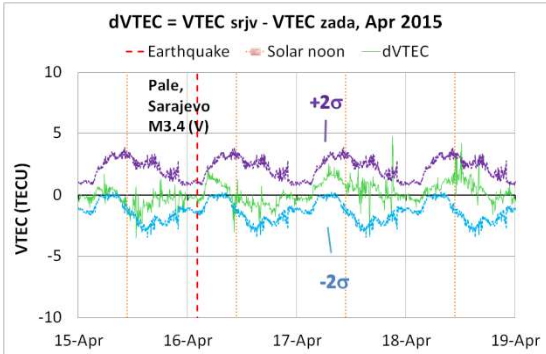
b)

Figure 4: Statistical analysis of VTEC variations at station SRJV, with 15-day median ± 2*σ. a) 10-12 Apr. b) 15-18 Apr. VTEC anomalies reached lower bound or exceeded it [14].

Comparison with data of station ZADA (Fig. 5) showed that the most of VTEC anomalies were also detected in VTEC signature of ZADA station. That implies that the most of anomalies were not produced from seismic activity, but probably from geomagnetic conditions, which was very active during that period, according to Kp and Ap geomagnetic indices [14].



a)



b)

Figure 5: VTEC difference between data of SRJV station (inside EPZ) and ZADA stations (otside (EPZ). a) 10-12 Apr b) 15-18 Apr. Similar variations at the both stations and most of the anomalies detected at the both stations [14].

4. CONCLUSION

Paper briefly showed investigation of the upper part of ionized atmosphere (ionosphere), that is responsible for the biggest errors in applications, which depend on Global Navigation Satellite Systems. Study was conducted for area of Bosnia and Herzegovina and wider region. State of ionosphere was presented with total electron contents along the satellite signal´s path in ionosphere, that comes from satellite (20 200 km above Earth) to receiver (located on the Earth´s surface).

Monthly TEC variability, solar cycle TEC dependence and seasonal TEC variation in mid-latitude ionosphere were studied for the period from 2014 to 2016. Increasing trend of VTEC as well as higher VTEC variations were observed during the months of equinoxes, while the decreasing trend of VTEC and lower variations were mostly seen during solstices. The most expressive TEC values and standard deviations occurred for the period of spring equinox, while the winter solstice caused the lowest. This implies strong influence of the period of a year on ionization in ionosphere. Variations of TEC followed the solar cycle's phases from solar maximum to descending phase of solar cycle 24. The highest values of TEC as well as the greatest standard deviations were recorded in the year of solar maximum (2014). Afterwards values and deviations decreased gradually through 2015, while significant decline was observed in 2016. To sum up, level of solar activity directly influenced the state in ionosphere over Bosnia and Herzegovina, as expected.

Correlation between VTEC values and solar indices solar radio flux F10.7 and sunspot number was medium to strong, during period 2014 to 2016. Correlation coefficients was slighlty better between VTEC and F10.7.

By monitoring the signal strength emitted by distant transmitters of very low frequency (VLF) waves, we detected sudden ionospheric disturbances during March – April 2015. SuperSID monitor successfully detected sudden ionization caused by solar flares, from C 1.4 class to X 2.1 class.

Study of lithosphere-ionosphere coupling process for few medium earthquakes in Bosnia and Herzegovina [14], showed that the most of the ionospheric anomalies, before and after seismic activity, were produced from geomagnetic disturbances.

In further work we are planning to investigate effects of severe solar events and space weather on the accuracy of coordinate estimation in Bosnia and Herzegovina.

Acknowledgements

Authors are sincerely grateful to International Center of Theoretical Physics – Abdus Salam in Trieste and dr. Luigi Ciraolo for providing program GNSS_VShell and to University in Stanford for providing software for SuperSID monitor, which enable us to conduct this research. Many thanks to the institutions and organizations, which kindly provide their data, solutions and files for scientific research: European Permanent Network (EPN); Department of Natural Resources - Space Weather Prediction Center Canada; Solar Influences Data Analysis Center (SILSO) of Royal Observatory of Belgium; National Oceanic and Atmospheric Administration, US Department of Commerce.

REFERENCES

[1] Richmond, A.D. (2007), Ionosphere. In: Gubbins D, Herrera-Bervera E (eds) Encyclopedia of geomagnetism and paleomagnetism. Springer, Heidelberg, pp 452-453.

[2] Covington, A.E. (1969), Solar Radio Emission at 10.7 cm, 1947–1968, J. R. Astron. Soc. Can., 63, pp 125–132.

[3] Wolf, R. (1851): Universal sunspot numbers: Sunspot observations in the second part of the year 1850. Mitteilungen der Naturforschenden Gesellschaft in Bern, 1, pp 89–95.

[4] Pulinets, S., Kotsarenko, A.N., Perez-Enfiquez, R., Ciraolo, L., Pulinets, I.A., (2006), New ionosphere variability index and its anomaly variation related to major earthquakes occurred in California, USA and Mexico

[5] Liu Z., Luo W., Ding X., Chen W., (2011), The new characteristics of ionospheric total electron content (TEC) disturbances prior to four large earthquakes, Department of Land surveying and Geo-informatics, the Hong Kong Polytechnic University

[6] Ouzounov, D.P., Pulinets, S.A., Davidenko, D.V., Kafatos, M., Taylor, P.G., (2013), Space-borne observations of atmospheric pre-earthquake signals in seismically active areas, Case study for Greece 2008–2009

[7] Pulinets, S., Davidenko, D., (2013), Ionospheric precursors of earthquakes and Global Electric Circuit, Advances in Space Research 53, 709-723

[8] Mubarak, M., Riaz, S., Awais, M., Jilani, Z., Ahmad, N., Irfan, M., Javed, F., Alam, A., Sultan, M. (2009), Earthquake prediction: a global review and local research, Center for Earthquake Studies (CES), National Center for Physics (NCP), Islamabad, ResearchGate, str. 233-246.

[9] Dobrovolsky, I.R., Zubkov, S.I., Myachkin. V.I. (1979), Estimation of the size of earthquake preparation zones. Pure Appl Geophys 117: pp 1025–1044

[10] Pulinets, S., Ouzounov, D. (2011), Lithosphere–Atmosphere–Ionosphere Coupling (LAIC) model – An unified concept for earthquake precursors validation, Journal of Asian Earth Sciences, Vol. 41, pp. 371-382.

[11] Pulinets, S. i Boyarchuk, K. (2004), Ionospheric Precursors of Earthquakes, Springer.

[12] Natras, R. (2016), Research of ionosphere with geodetic methods and estimation of TEC from GNSS observations, Master's thesis, Sarajevo: University of Sarajevo, Faculty of Civil Engineering.

[13] Sarvan, M. (2017), Analyses of the TEC GNSS at SRJV and selected BIHPOS stations. Master's thesis, Sarajevo: University of Sarajevo, Faculty of Civil Engineering.

[14] Mulic, M., Natras, R. (2017), Ionosphere TEC Variations Over Bosnia and Herzegovina Using GNSS Data. In: Cefalo R., Zieliński J., Barbarella M. (eds) New Advanced GNSS and 3D Spatial Techniques. Lecture Notes in Geoinformation and Cartography. Springer, Cham, pp 271-283, doi: https://doi.org/10.1007/978-3-319-56218-6_22.

[15] Natras, R., Mulic, M. (2017), Remote sensing of ionospheric TEC using GNSS data in relation to space weather effect and sesimic activity in Bosnia and Herzegovina, presented at Joint Scientific Asssembly IAG-IASPEI 2017, 30 July - 05 August 2017, Kobe, Japan.

[16] Zanacic, F. (2017), Earthquake prediction based on GNSS data, Master's thesis, Sarajevo: University of Sarajevo, Faculty of Civil Engineering

[17] Horozovic, Dz., Krdzalic, Dz., Mulic, M. (2015), Monitoring of ionosphere and space weather in Bosnia and Herzegovina, Geodetic courier, Union of Associations of Geodetic Professionals in Bosnia and Herzegovina, , Vol. 46, pp 111-131

[18] Behic, E. (2014), Investigation of ionosphere and space weather and use in positioning and navigation, Master's thesis, Sarajevo: University of Sarajevo, Faculty of Civil Engineering

[19] Bagiya, S. Mala, Joshi, H. P., Iyer, K. N., Aggarwal, M., Ravindran, S., & Pathan, B. M. (2009), TEC variations during low solar activity period (2005-2007) near the Equatorial Ionospheric Anomaly Crest Region in India. Annales Geophysicae, 27, pp.1047-1057. http://dx.doi.org/10.5194/angeo-27-1047-2009

[20] Schaer, S. (1999), Mapping and predicting the Earth's ionosphere using the Global Positioning System, PhD thesis, Bern University, Switzerland

[21] Ciraolo, L., Azpilicueta, F., Brunini, C., Mez,a A., Radicella, S.M. (2007), Calibration error on experimental slant total electron contents (TEC) determined with GPS, J. Geod., 81 (2), pp 111-120