TEC Response to Geomagnetic Storms and Solar Flares as Observed with SBAS L1/L5 Signals

G. A. Kurbatov[1], **V. E. Kunitsyn**[1], **A. M. Padokhin**[1], **and Yu. V. Yasyukevich**[2]

[1]Faculty of Physics, Lomonosov Moscow State University, Russia
[2]Institute of Solar-Terrestrial Physics SB RAS, Russia

Abstract— The development of Satellite Based Augmentation Systems (SBAS) provides the possibility to retrieve ionospheric Total Electron Content (TEC) from the dual frequency L1/L5 observations from a number of geostationary satellites using the same approach as for dual frequency GPS/GLONASS observations.

In this work we study L1/L5 signals of Indian GAGAN geostationary satellites observed with geodetic GNSS receivers at several stations at midlatitudes and estimate corresponding geostationary TEC variations. We present geostationary SBAS TEC response to X1.7 solar flare on October 25, 2013 showing good correlation between TEC and EUV flux for the stations at the sunlit hemisphere. We also present SBAS TEC response to geomagnetic field variations during moderate geomagnetic storm on June 1, 2013 showing examples of positive anomalies of order of tens TECU in TEC diurnal variations during main storm phase.

1. INTRODUCTION

Until recently the main approach for ionospheric TEC studies from geostationary orbits was based on Faraday rotation of polarization plane, which required additional information on Earths geomagnetic field. This method was used particularly for the studies of ionospheric effects of solar flares [1, 2], statistical characteristics of traveling ionospheric disturbances [3], acoustic gravity waves [4], etc.. With the development of SBAS systems it is now possible to use coherent dual frequency transmissions compatible with GPS L1 and L5 signals from geostationary SBAS satellites to estimate TEC along "receiver-satellite" line-of-sight using the same method as for GPS/GLONASS [6]. As it was shown in [6], SBAS TEC RMS could reach up to 1.5 TECU with typical values of 0.25–0.5 TECU which is up to one order greater than for common GPS/GLONASS observations. Such large values of SBAS TEC RMS are satellite dependent and not of ionospheric origin, so they could be easily filtered out without losing significant ionospheric information providing continous TEC datasets for selected satellite-receiver pairs instead of short 2–6 hours records as in GPS/GLONASS case. The purpose of this paper is to show the capabilities of SBAS TEC data for studying TEC anomalies during severe heliogeophysical disturbances, such as solar flares and geomagnetic storms.

2. OBSERVATIONS

Nowadays there are six SBAS satellites transmitting coherent GPS-like L1/L5 signals: SES-5, GSAT-8, GSAT-10, Intelsat Galaxy 15, TeleSat Anik F1R, Inmarsat 4-F3. As for groundbased receiving networks, the largest one was setup by International GNSS Service for The Multi-GNSS Experiment (MGEX) to track, collate and analyze all available GNSS (including SBAS L1/L5) signals [10].

For the purpose of the present work we used observations of GSAT-8 and GSAT-10 satellites from midlatitude MGEX TASH (41.33N, 69.30E) station and MSU (55.75N, 37.62E), ISTP (52.28N, 104.30E) and ORDA (52.75N, 103.66E) stations operated by Lomonosov Moscow State University and Institute of Solar-Terrestrial Physics.

Following [6], geostationary relative slant TEC can be estimated from the SBAS phase paths L_1 and L_5 at two coherent carrier frequencies $f_1 = 1575.42\,\text{MHz}$ and $f_5 = 1176.45\,\text{MHz}$ using the following relation:

$$TEC = \left(\frac{L_1}{f_1} - \frac{L_5}{f_5}\right) \frac{f_1^2 f_5^2}{f_1^2 - f_5^2} \frac{c}{K} + \text{const}, \tag{1}$$

where $K = 40.308\,\frac{\text{m}^3}{\text{sec}^2}$, c is the speed of light in vacuum. The carrier phase ambiguities (leading to undefined constant term in Eq. (1)) are not estimated here.

First example we present here is SBAS TEC variations during moderate (Kp$\sim$6) geomagnetic storm on June 1, 2013 (see Fig. 1). The Dst index reached the value $-119\,\text{nT}$ indicating moderate

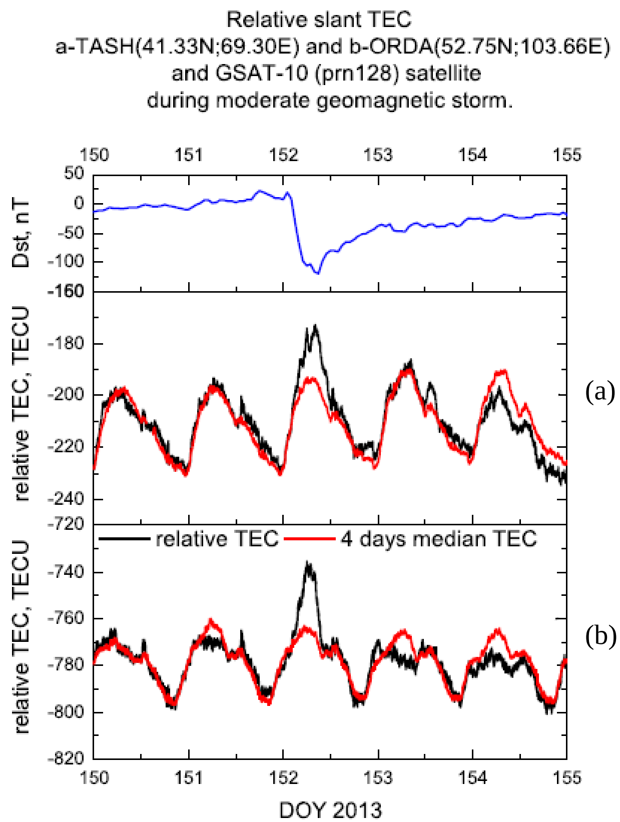

Figure 1: Dst index and relative slant SBAS TEC for GAGAN GSAT-10 satellite and ORDA and TASH receiving sites during moderate geomagnetic storm on June 1, 2013.

disturbances in midlatitude and near equatorial geomagnetic field. SBAS TEC variations during storm main and start of the recovery phases obtained at two midlatitude stations TASH and ORDA demonstrate strong positive anomaly up to 20–30 TECU compared to undisturbed 4-day median values. Two main mechanisms that can drive such positive storm are the penetration of magnetospheric electric field and the change in thermospheric circulation. In the first case, an enhanced eastward electric field induces a movement of ionospheric plasma in the direction perpendicular to the magnetic field lines (upward/poleward), whereas in the latter case the thermospheric equatorward neutral winds resulting from highlatitude energy injection drag the ionospheric plasma upward along the magnetic field lines. Rises in ionospheric height cause changes in the density and composition of the ambient atmosphere, and result in reductions in the molecular components of ionospheric plasma. Consequently, fewer O^+ ions are lost due to chemical reactions, thereby increasing the density [7]. Note also that according to [8] positive storm phases more frequently form under the winter conditions (negative storm phases tend to form during summer), while in our case positive storm was observed under summer conditions.

Finally let us demonstrate the capabilities of SBAS TEC observations in connection with ionospheric effects of solar flares. A chromospheric flare causes a sharp burst (by a few orders of magnitude) in the intensity of X-ray and EUV solar radiation, which results in the height-specific enhancement of electron density in the ionosphere of the Earth [5], and in the sudden increase in TEC, which can be detected using L1/L5 SBAS signals. Fig. 2 presents the example of processing the SBAS data recorded at MSU and ISTP stations during the X1.7-class flare on October 25, 2013. The maximum of the flare occurred at 8:01UT — at 12:01LT and 17:01LT at MSU and ISTP stations correspondingly. A sudden increase in TEC (SITEC) corresponding to variations in the X-ray and EUV radiation during the flare is observed at both stations: SITEC $\sim$4 TECU within 10 min is observed at MSU station, SITEC at ISTP station is $\sim$2.5TECU for prn 127 (GSAT-8) and less than 0.5TECU for prn 128 (GSAT-10) depending on the elevation angle of the Sun at the satellites ionospheric pierce points. The MSU station is in the noon sector while ISTP is in the evening one, so higher MSU TEC variations during this flare is what was expected. Note also that elevation angles of GAGAN satellites are low at both observation sites. It provides longer ray path in

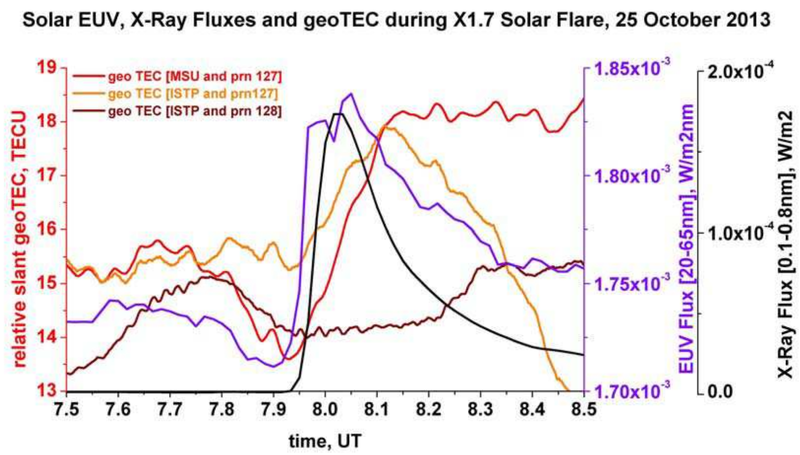

Figure 2: SBAS observation during X1.7-class Solar flare on October 25, 2013 [6].

ionosphere and thus larger SITEC values.

3. CONCLUSION

Our results show the capability of SBAS L1/L5 observations for continuous monitoring of ionospheric TEC in quite and disturbed geomagnetic conditions. Intensively growing networks of receivers capable to work with L1/L5 SBAS signals (for example MGEX network) and increasing number of dual-frequency satellites in SBAS constellation potentially make it a powerful instrument for TEC climatology. Note also that along with SBAS satellites, BeiDou/Compass geostationary satellites (currently 5 in orbit) can be used in the pretty same manner for continuous TEC monitoring [9], which doubles available constellation.

ACKNOWLEDGMENT

The authors are grateful to NGDC and IGS for the data used in presented research and to JAVAD GNSS for custom receiver firmware.

V. K. acknowledge the support of the Russian Scientific Foundation (grant 14-17-00637) in the part of analyzing geomagnetic storms effects, G. K. acknowledge the support of the Russian Foundation for Basic Research (grant 14-05-31445) in the part of studying SBAS signals, A. P. acknowledge grant of the President of Russian Federation (MK-2670.2014.5) in the part studying ionospheric effects of solar flares.

REFERENCES

1. Mendillo, M., J. A. Klobuchar, R. B. Fritz, A. V. da Rosa, L. Kersley, K. C. Yeh, B. J. Flaherty, S. Rangaswamy, P. E. Schmid, J. V. Evans, J. P. Schnödel, D. A. Matsoukas, J. R. Koster, A. R. Webster, and P. Chin, "Behavior of the ionospheric F region during the great solar flare of August 7, 1972," *Journal of Geophysical Research*, Vol. 79, No. 4, 665–672, 1974.
2. Davies, K., "Recent progress in satellite radio beacon studies with particular emphasis on the ATS-6 radio beacon experiment," *Space Science Review*, Vol. 25, No. 4, 357–430, 1980.
3. Katamzi, Z. T., N. D. Smith, C. N. Mitchell, P. Spalla, and M. Materassi, "Statistical analysis of travelling ionospheric disturbances using TEC observations from geostationary satellites," *Journal of Atmospheric and Solar-Terrestrial Physics*, Vol. 74, 64–80, 2011.
4. Dieminger, W., J. Schodel, G. Schmidt, and G. Hartmann, "Recording gravity waves by means of geostationary beacon-satellites," *Journal of Atmospheric and Terrestrial Physics*, Vol. 32, No. 9, 1615–1617, 1970.
5. Mitra, A. P., *Ionospheric Effects of Solar Flares*, D. Reidel, Norwell, MA, 1974.
6. Kunitsyn, V., G. Kurbatov, Y. Yasyukevich, and A. Padokhin, "Investigation of SBAS L1/L5 signals and their application to the ionospheric TEC studies," *IEEE Geoscience and Remote Sensing Lett.*, Vol. 12, No. 3, 547–551, 2015.
7. Prölss, G. W., "Ionospheric F-region storms," *Handbook of Atmospheric Electrodynamics*, Edited by H. Volland, CRC Press, Boca Raton, Fla, 1995.

8. Prölss, G. W., "Seasonal variation of atmospheric-ionospheric disturbances," *Journal of Geophysical Research*, Vol. 82, 1635–1640, 1977.
9. Jin, R., S. Jin, and X. Tao, "Ionospheric anomalies during the March 2013 geomagnetic storm from BeiDou navigation satellite system (BDS) observations," *China Satellite Navigation Conference (CSNC) 2014 Proceedings: Volume I, Lecture Notes in Electrical Engineering 303*, Springer-Verlag, Berlin, Heidelberg, 2014.
10. http://igs.org/mgex/.