Research Paper
J. Astron. Space Sci. 32(4), 335-340 (2015)
http://dx.doi.org/10.5140/JASS.2015.32.4.335

JASS Journal of Astronomy and Space Sciences

Statistics of Ionospheric Storms Using GPS TEC Measurements Between 2002 and 2014 in Jeju, Korea

Jong-Kyun Chung†, Byung-Kyu Choi
Korea Astronomy and Space Science Institute, Daejeon 34055, Korea

Using the Total Electron Content (TEC) data from the Global Navigation Service System (GNSS) site in Jeju, operated by the Korea Astronomy and Space Science Institute (geographic location: 33.3° N, 126.5° E; geomagnetic location: 23.6° N) for 2002–2014 in Korea, the results of the statistical analysis of positive and negative ionospheric storms are presented for the first time. In this paper, ionospheric storms are defined as turbulences that exceed 50% of the percentage differential Global Positioning System (GPS) TEC ratio (ΔTEC) with monthly median GPS TEC. During the period of observations, the total number of positive ionospheric storms (ΔTEC > 50%) was 170, which is greater than five times the number of negative ionospheric storms (ΔTEC < - 50%) of 33. The numbers of ionospheric storms recorded during solar cycles 23 and 24 were 134 and 69, respectively. Both positive and negative ionospheric storms showed yearly variation with solar activity during solar cycle 23, but during solar cycle 24, the occurrence of negative ionospheric storms did not show any particular trend with solar activity. This result indicates that the ionosphere is actively perturbed during solar cycle 23, whereas it is relatively quiet during solar cycle 24. The monthly variations of the ionospheric storms were not very clear although there seems to be stronger occurrence during solstice than during equinox. We also investigated the variations of GPS positioning accuracy caused by ionospheric storms during November 7–10, 2004. During this storm period, the GPS positioning accuracies from a single frequency receiver are 3.26 m and 2.97 m on November 8 and 10, respectively, which is much worse than the quiet conditions on November 7 and 9 with the accuracy of 1.54 m and 1.69 m, respectively.

Keywords: GPS TEC, ionospheric storm, GPS position accuracy

1. INTRODUCTION

Two radio frequencies (L1 = 1.57542 GHz and L2 = 1.22760 GHz) transmitted by Global Positioning System (GPS) satellites at an altitude of 20,200 km can be abnormally refracted or degraded by ionospheric scintillation, which is the sudden temporal and spatial variation of electron densities when radio signals pass through the Earth's ionosphere. The unusually enhanced electron densities in the ionosphere result in unexpected GPS time delay errors and they can cause fluctuations in the amplitudes and phases of L1 and L2 signals. These abnormal ionospheric variations finally result in low GPS positioning accuracy (Ledvina et al. 2002; Xu et al. 2007). Thus, understanding abnormal ionospheric variations can help in the practical estimation of GPS errors.

Ionospheric variations normally responding to solar and geomagnetic activities show latitudinal, seasonal, and local time characteristics (Lekshmi et al. 2011; Chen et al. 2012; Yun et al. 2013; Borries et al. 2015). The GPS Total Electron Content (TEC) often increases or decreases in response to geomagnetic storms and solar activities as compared to that during periods of normal ionospheric states or their monthly median values. These phenomena of increasing and decreasing TEC are commonly defined as positive and negative ionospheric storms, respectively. A well-known

Received Oct 27, 2015 **Revised** Nov 30, 2015 **Accepted** Nov 30, 2015
†**Corresponding Author**
E-mail: jkchung@kasi.re.kr, ORCID: 0000-0003-4493-8378
Tel: +82-42-865-3239, Fax: +82-42-861-5610

mechanism for the negative ionospheric storm phase is the change in neutral composition of the ionosphere. Enhanced neutral compositions, particularly molecular nitrogen, in the mid-latitudes by global neutral circulation during geomagnetic storms result in high loss rates of ionospheric electrons, leading to a significant decrease in GPS TEC. In contrast, the mechanisms of positive ionospheric storm phases remain poorly understood because of the extremely complicated mechanisms related to electromagnetic dynamics and thermodynamics between the ionosphere and magnetosphere/thermosphere and atmospheric wave propagation such as travelling ionospheric disturbances (Lekshmi et al. 2005; Heelis et al. 2009).

Studies on ionospheric storms have been mainly carried out for geomagnetic storm events in the low latitudes to understand their mechanisms and trends (Huang et al. 2005; Pedatella et al. 2009; Lekshmi et al. 2011; Park et al. 2013; Kuai et al. 2015). Here we present for the first time the results of a statistical analysis of ionospheric storms over Korea using GPS TEC measurements from the ground-based JEJU Global Navigation Service System (GNSS) site, which has been operated by the Korea Astronomy and Space Science Institute (KASI) since 2002. In this work, positive and negative ionospheric storm phases were analyzed according to their monthly and yearly occurrences, and the effects of the super geomagnetic storm, which occurred during November 8–10, 2004 in Korea, on GPS positioning accuracy are discussed.

2. GPS TEC MEASUREMENTS

GPS TEC is the column electron density (1 TEC unit = 10^{16} electrons/m^2) along the line of sight from a transmitter on a satellite at an altitude of 20,200 km to the receiver on the ground or satellite. GPS TEC variations generally represent ionospheric features although GPS radio signals propagate through the plasmasphere. GPS TEC plays a vital role in precise GPS positioning and navigation as it enables the correction of ionospheric time delay errors in single frequency GPS receivers and GPS augmentation systems under space environments.

Global TEC maps and GPS broadcast ionospheric correction parameters from the Klobuchar model generally have low temporal and spatial resolutions of several hours and degrees both latitudinally and longitudinally. Therefore, examination of the effects of ionospheric variations on GPS positioning accuracy in a local region using local ground-based GPS TEC measurements with a high temporal resolution is required. To this end, GPS TEC measurements with a consistently high resolution at a local ground-based site are very useful for developing ionospheric forecast models and real-time monitoring systems in a local area. Consequently, they may contribute to the development of more sophisticated global ionospheric models and monitoring systems.

To reveal abnormal ionospheric variations, GPS Median TEC (MTEC) values were computed with vertical TEC values and converted using slant TEC values, which were measured over a satellite elevation angle of 45° to reduce horizontal variations of electron densities. The schematic processes for MTEC calculation are described in Chung et al. (2011). Hereafter, the MTEC is referred to as the GPS TEC. We assumed an Ionospheric Pierce Point (IPP) height of 350 km. The IPP is the intersection of line of sight (between a satellite and ground-based GPS receivers), and the IPP height is generally the same as hmF2, which is the height of peak electron density in the ionosphere. Detailed computation processes for the TEC and its hardware bias are described in Choi et al. (2010, 2013).

Fig. 1 shows long-term GPS TEC values measured at the Jeju GNSS site (site name: "JEJU"; geographic location: 33.3°N, 126.5°E; geomagnetic location: 23.6°N) between 2002 and 2014. The GPS TEC values were averaged with

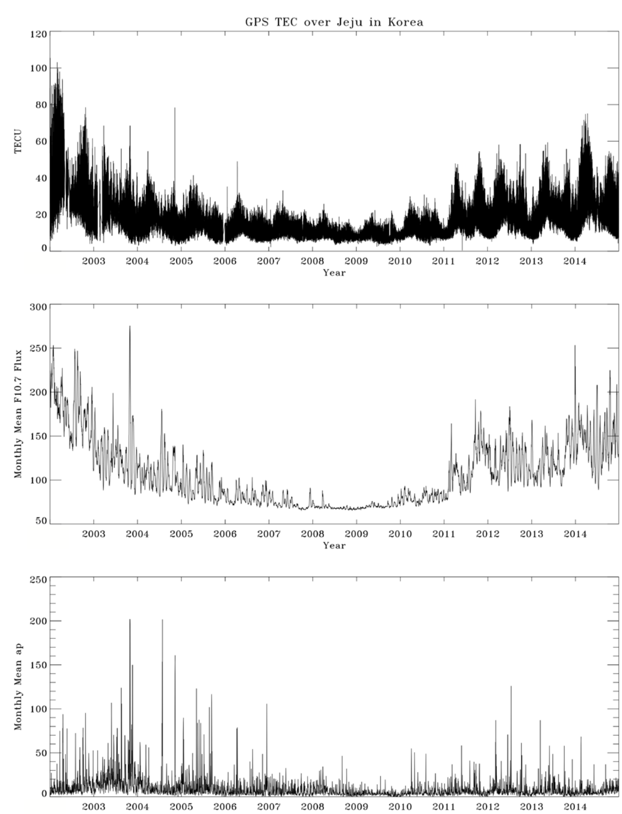

Fig. 1. GPS TEC values recorded at the KASI JEJU GPS site between 2002 and 2014.

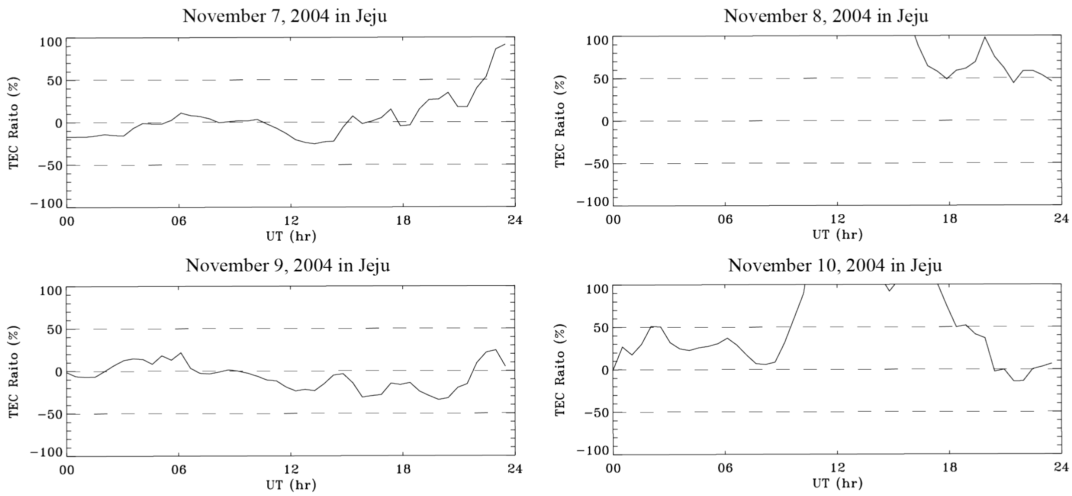

Fig. 2. Examples of positive ionospheric storms (TEC ratio > 50%) during November 7-10, 2004 in Jeju, except for November 9, 2004.

integration time of 30 min. These values cover the solar cycle 23 and also include solar cycle 24, which began in 2008. Therefore, the JEJU GPS TEC dataset is useful in examining ionospheric variations considering several geomagnetic storm events that occurred during periods of full solar activities.

Anomalous GPS TEC values compared with that during normal ionospheric states were simply calculated using the percentage differential TEC ratio, ΔTEC, as follows.

$$\Delta TEC = \frac{TEC_{obs} - TEC_{ref}}{TEC_{ref}} \times 100 \qquad (1)$$

where ΔTEC denotes the percentage of observed TEC (TEC_{obs}) values compared with the monthly median TEC of TEC_{ref} at a specific local time for each day. ΔTEC is a quantitative index for ionospheric storms and can be applied to monitor ionospheric perturbations in real-time. Fig. 2 shows examples of the diurnal behavior of differential TEC ratio during November 7–10, 2004 when the historic ionospheric storms were observed in Korea. A positive ΔTEC value indicates enhancement of GPS TEC and a high ΔTEC amplitude of more than 50% lasting for two hours indicates a positive ionospheric storm. In case of a negative ΔTEC value, GPS TEC decreases and GPS ionospheric time delay errors can be reduced but carries a possibility of irregularities in electron densities. A ΔTEC value of less than -50% lasting for two hours is defined as a negative ionospheric storm.

3. RESULTS AND DISCUSSION

Fig. 3 shows the yearly distribution of ionospheric storms between 2002 and 2014 in Jeju. The total number of positive ionospheric storms (170) was more than five times the number of negative ionospheric storms (33). During solar cycle 23 (between 2002 and 2007), the yearly distributions of positive and negative ionospheric storms have a trend corresponding to solar activities. In solar cycle 24 (during 2008–2014), only positive ionospheric storms showed a yearly distribution trend, and the negative ionospheric storms had no annual pattern. The numbers of occurrences of the positive and negative ionospheric storms were 134 and 69 in solar cycles 23 and 24, respectively. The results that the positive phase of ionospheric storms is much greater occurrences than the negative phase means that geomagnetic storm mostly causes the positive phase in the ionosphere because the positive ionospheric storms at low and mid latitudes mainly occur by thermospheric neutral winds and expansion of Equatorial Ionospheric Anomaly (EIA) during the period of geomagnetic storms (Lekshmi et al., 2011).

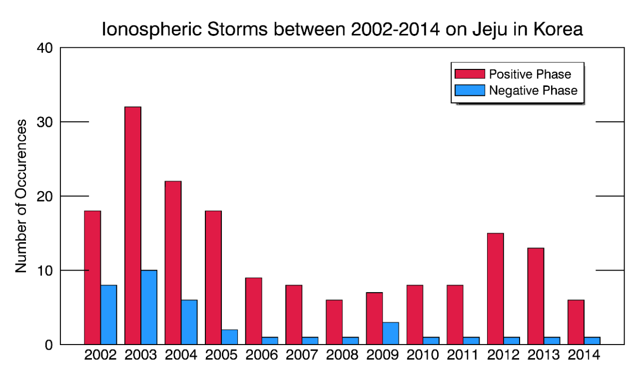

Fig. 3. Yearly trend of ionospheric storms between 2002 and 2014 in Jeju, Korea.

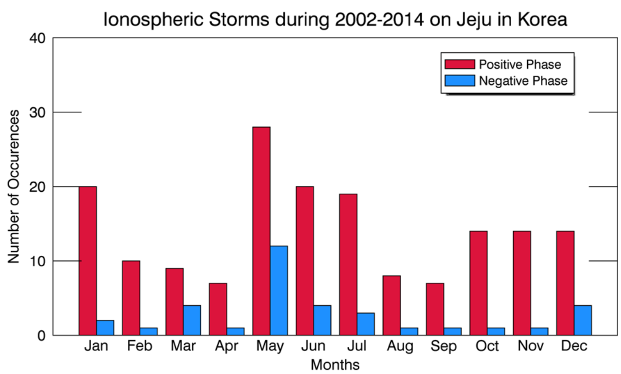

Fig. 4. Monthly trend of ionospheric storms between 2002 and 2014 in Jeju, Korea.

Fig. 4 shows the monthly distribution of the ionospheric storms between 2002 and 2014 in Jeju. The negative and positive phases of the ionospheric storms most commonly occurred during May to July. The occurrence trend of the negative ionospheric storm show the maximum in the summer. This result agrees with previous studies (Lekshmi et al., 2011; Mendillo et al., 2013). The physical mechanism of negative ionospheric storm has been discussed with the thermospheric composition changes that increase the loss rates of ionospheric electrons due to fast recombination during the period of geomagnetic storms (Buonsanto, 1999; Mendillo 2006; Lekshmi et al., 2011; Mendillo et al., 2013)

Lekshmi et al. (2011) present the seasonal occurrence trend of positive ionospheric storms using the peak electron density values from Kokubunji (35.7° N, 139.5° E; 26.8° N magnetic latitude) and Boulder (40.0° N, 254.7° E; 47.7° N magnetic latitude) between 1985 and 2005. They showed that the occurrences of the ionospheric storms have the significant seasonal trends of maximum in equinoxes and minimum in summer although the occurrence numbers in two locations are different. Mendillo (2006) discussed the seasonal effects of positive ionospheric storm with

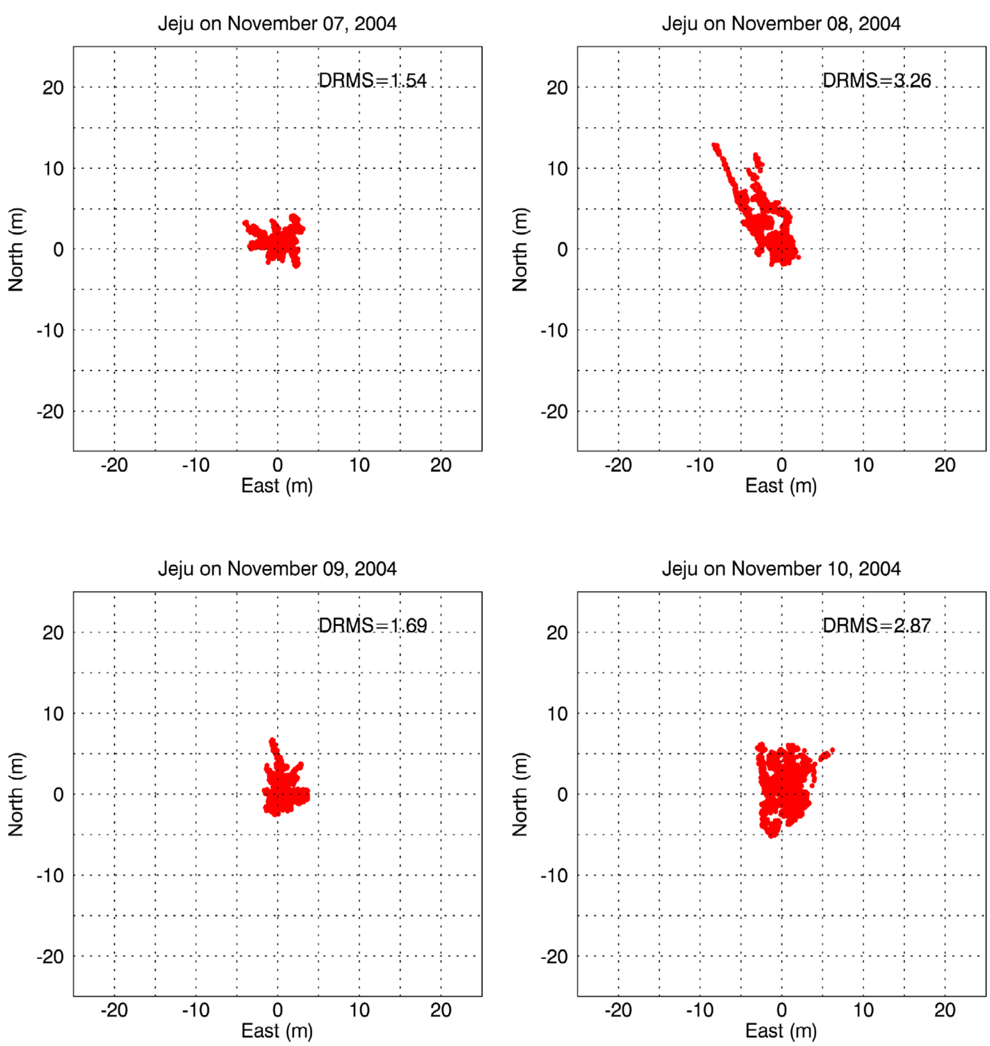

Fig. 5. GPS L1 positioning accuracy at the KASI JEJU GNSS permanent site in Korea during November 7–10, 2004.

http://dx.doi.org/10.5140/JASS.2015.32.4.335

seasonal anomaly when electron densities are higher in winter than in summer, and they also presented that the occurrence of positive ionospheric storm is higher in winter than in summer. However, the Fig. 4 shows the very different seasonal trend of the positive ionospheric storm: there are more storms during solstices than equinoxes. This result may be only a local characteristic in Jeju Island, Korea and further study is required.

Finally, we examined variations in GPS accuracy errors according to the positive ionospheric storms during November 7–10, as shown in Fig. 2, to evaluate GPS performance under the positive ionospheric storms. Fig. 5 shows the horizontal positioning accuracies computed by GPS L1 code at the KASI JEJU GNSS site. The distance root mean square (DRMS) of 2-D horizontal positioning errors on November 8 and 10, 2004, when the ionospheric storms (ΔTEC > 100%) occurred, were 3.26 m and 2.87 m, respectively. The errors on November 7 and 9, 2004 during quiet conditions were 1.54 m and 1.69 m, respectively. This shows the effect of positive ionospheric storms on the degradation of GPS positioning accuracy.

4. CONCLUSION

This work presents statistics of positive and negative ionospheric storms using GPS TEC data observed at the KASI JEJU GNSS site between 2002 and 2014. The number of positive ionospheric storms was 170, which is more than five times the number of negative ionospheric storms of 33. The trends of both positive and negative ionospheric storms seems to follow the solar activity during solar cycle 23, but only positive ionospheric storms show the solar activity variation during solar cycle 24. The number of positive and negative storms during solar cycles 23 and 24 were 134 and 69, respectively. This result indicates that the ionosphere was actively perturbed in solar cycle 23, whereas it was relatively quiet in solar cycle 24 in Korea.

Ionospheric storms frequently occurred during May to July. The occurrence of the negative ionospheric storms show the seasonal trend of the maximum in summer. The positive ionospheric storms show larger occurrence during solstices than equinoxes. We examined GPS positioning accuracy during the positive ionospheric storm on November 7–10, 2004. The DRMS values of GPS horizontal positioning on November 8 and 10 during the storm periods are 3.26 m and 2.97 m, respectively while the DRMS values on November 7 and 9 during the quiet periods are 1.54 m and 1.69 m, respectively.

ACKNOWLEDGMENTS

This work was supported by a research grant from the Korea Institute of Science and Technology Information.

REFERENCES

Borries C, Berdermann J, Jakowski N, Wilken V, Ionospheric storms—A challenge for empirical forecast of the total electron content, J. Geophys. Res. 120, 3175-3186 (2015). http://dx.doi.org/10.1002/2015JA020988

Buonsanto MJ, Ionospheric storms—A Review, Space Science Reviews, 88, 563-601 (1999). http://dx.doi.org/A:1005107532631

Chen CH, Saito A, Lin CH, Liu JY, Long-term variations of the nighttime electron density enhancement during the ionospheric midlatitude summer, J. Geophys. Res. 117, A07313 (2012). http://dx.doi.org/10.1029/2011JA017138

Choi BK, Chung JK, Cho JH, Receiver DCB Estimation and Analysis by Types of GPS Receiver, J. Astron. Space Sci. 27, 123-128 (2010). http://dx.doi.org/10.5140/JASS.2010.27.2.123

Choi BK, Yoo SM, Roh KM, Lee SJ, Real-time GPS Ionospheric TEC Estimation over South Korea, J. Astron. Space Sci. 30, 207-212 (2013). http://dx.doi.org/10.5140/JASS.2013.30.3.207

Chung JK, Jee GH, Lee CN, Global Positioning System Total Electron Content Variation over King Sejong Station in Antarctic under the Solar Minimum Condition Between 2005 and 2009, J. Astron. Space Sci. 28, 305-310 (2011). http://dx.doi.org/10.5140/JASS.2011.28.4.305

Heelis RA, Sojka JJ, David M, Schunk RW, Storm time density enhancements in the middle-latitude dayside ionosphere, J. Geophys. Res. 114, A03315 (2009). http://dx.doi.org/10.1029/2008JA013690

Huang CS, Foster JC, Goncharenko LP, Erickson PJ, Rideout W, et al., A strong positive phase of ionospheric storms observed by the Millstone Hill incoherent scatter radar and global GPS network, J. Geophys. Res. 110, A06303 (2005). http://dx.doi.org/10.1029/2004JA010865

Kuai J, Liu L, Liu J, Zhao B, Chen Y, et al., The long-duration positive storm effects in the equatorial ionosphere over Jicamarca, J. Geophys. Res. 120, 1311-1324 (2015). http://dx.doi.org/10.1002/2014JA020552

Ledvina BM, Makela JJ, Kintner PM, First observations of intense GPS L1 amplitude scintillations at midlatitude, Geophys. Res. Lett. 29, 1659 (2002). http://dx.doi.org/10.1029/2002GL014770

Lekshmi DV, Balan N, Ram ST, Liu JY, Statistics of geomagnetic storms and ionospheric storms at low and mid latitudes in two solar cycles, J. Geophys. Res. 116, A11328 (2011). http://dx.doi.org/10.1029/2011JA017042

Mendillo M, Storms in the ionosphere: Patterns and processes for total electron content, Reviews of Geophysics, 44, RG4001 (2006). http://dx.doi.org/10.1029/2005RG000193

Mendillo M, Narvaez C, Marusiak AG, Are ionospheric storms the same during different solar clycles?, J. Geophys. Res. 118, 6795-6805 (2013). http://dx.doi.org/10.1002/2013JA019102

Park YK, Kwak YS, Ahn BH, Seasonal and Latitudinal Variations of the F2-Layer during Magnetic Storms, J. Astron. Space Sci. 30, 231-239 (2013). http://dx.doi.org/10.5140/JASS.2013.30.4.231

Pedatella NM, Lei J, Larson, KM, Forbes JM, Observations of the ionospheric response to the 15 December 2006 geomagnetic storm: Long-duration positive storm effect, J. Geophys. Res. 114, A12313 (2009). http://dx.doi.org/10.1029/2009JA014568

Xu JS, Zhu J, Li L, Effects of a major storm on GPS amplitude scintillations and phase fluctuations at Wuhan in China, Adv. Space Res. 39, 1318-1324 (2007). http://dx.doi.org/10.1016/j.asr.2007.03.004

Yun J, Kim YH, Kim E, Kwak YS, Hong S, Unusual Enhancements of NmF2 in Anyang Ionosonde Data, J. Astron. Space Sci. 30, 223-230 (2013). http://dx.doi.org/10.5140/JASS.2013.30.4.223