



1 Application of Fengyun 3-C GNSS occultation sounder for 2 assessing global ionospheric response to magnetic storm event

3

4 Weihua Bai^{1,2,3}, Guojun Wang^{1,4}, Yueqiang Sun^{1,2,3}, Jiankui Shi^{1,3,4}, Xiangguang Meng^{1,2},
5 Dongwei Wang^{1,2}, Qifei Du^{1,2}, Xianyi Wang^{1,2}, Junming Xia^{1,2}, Yuerong Cai^{1,2}, Congliang
6 Liu^{1,2}, Wei Li^{1,2}, Chunjun Wu^{1,2}, Danyang Zhao^{1,2}, Di Wu^{1,2}, Cheng Liu^{1,2}

7

8 ¹National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China

9 ²Beijing Key Laboratory of Space Environment, Beijing 100190, China

10 ³University of Chinese Academy of Sciences, Beijing 100049, China

11 ⁴State Key Laboratory of Space Weather, Beijing 100190, China

12 Correspondence to: Guojun Wang (gjwang@nssc.ac.cn)

13

14 Abstract.

15 The rapid advancement of global navigation satellite system (GNSS) occultation technology in recent years has
16 made it one of the most advanced space detection technologies of the 21st century. GNSS radio occultation has
17 many advantages, including all-weather operation, global coverage, high vertical resolution, high precision,
18 long-term stability, and self-calibration. Data products from GNSS occultation sounding can greatly enhance
19 ionospheric observations and contribute to space weather monitoring, forecasting, modeling, and research. In this
20 study, GNSS occultation sounder (GNOS) results from a radio occultation sounding payload aboard the Fengyun
21 3-C (FY3-C) satellite were compared with ground-based ionosonde observations. Correlation coefficients for
22 peak electron density (NmF2) derived from GNOS Global Position System (GPS) and Beidou navigation system
23 (BDS) products with ionosonde data were higher than 0.9, and standard deviations were less than 20 %. Global
24 ionospheric effects of the strong magnetic storm event in March 2015 were analyzed using GNOS results
25 supported by ionosonde observations. The magnetic storm caused a significant disturbance in NmF2 and hmF2
26 levels. Suppressed daytime and nighttime NmF2 levels indicated mainly negative storm conditions. In the zone
27 of geomagnetic inclination between 40–80°, average NmF2 during the geomagnetic storm showed the same
28 basic trends in GNOS measurements, and in observations from 17 ground-based ionosonde stations, and
29 confirmed the negative effect of the event on the ionosphere. The analysis demonstrates the reliability of the
30 GNSS radio occultation sounding instrument GNOS aboard the FY3-C satellite, and confirms the utility of
31 ionosphere products from GNOS for statistical and event-specific ionospheric physical analyses. Future FY3



series satellites, and increasing numbers of Beidou navigation satellites, will provide increasing GNOS occultation data on the ionosphere, which will contribute to ionosphere research and forecasting applications.

1 Introduction

Global navigation satellite system (GNSS) occultation detection uses occultation receivers mounted on low earth orbit (LEO) satellites to collect GNSS signals that are refracted and delayed by the atmosphere and ionosphere. The excess phase due to the atmosphere and ionosphere is determined from measurements of the delayed carrier phase, and the precise positions and velocities of the LEO and GNSS satellites. An inverse Abel transform method is used to derive electron density of the ionosphere, the refraction index, temperature, humidity, and atmospheric pressure data, as shown in Fig. 1.

GNSS radio occultation technology makes global scale measurements of the atmosphere and ionosphere possible. It has the advantages of high precision, high vertical resolution, long-term stability, global coverage, all-weather operation, and a relatively low-cost, which can compensate for some of the shortcomings of conventional atmospheric and ionospheric sounding tools (e.g., Fu et al., 2007). The global scale data obtained has important scientific potential for improving the accuracy of numerical weather prediction, near space environment monitoring research, global climate change research, atmospheric modeling research, and data assimilation. Radio occultation technology has significant scientific value and a broad array of potential practical applications in climatology, meteorology, ionospheric studies, and geodesy.

Radio occultation is extremely useful and important in ionosphere research, monitoring ionospheric anomalies, investigating ionospheric scintillation, and forecasting space weather. It also has a broad range of potential applications in communications, space operations, and national defense. Zhao et al. (2013) used ionosonde and radio occultation data to analyze differences in the ionosphere in eastern and western China, including the origins of ionospheric changes and latitudinal and longitudinal changes in structural layers of the ionosphere. Liu et al. (2008, 2009, 2010, 2011) used COSMIC radio occultation data to study seasonal changes in the electron density of the ionosphere, characteristics of the low latitude ionosphere, and the scale height of the ionospheric peak. In addition, many researchers have used ionospheric occultation data to search for ionospheric anomalies prior to earthquakes (Yang, et al., 2008; Zhang, et al., 2008). As well as using GNSS radio occultation data to obtain ionospheric electron density profiles, new and innovative exploratory studies continue to emerge; for example, using amplitude and signal-to-noise ratio data from radio occultation to detect the Es layer (Hocke, et al., 2001), and spread F (Lu, et al., 2011).

The GNSS radio occultation sounder (GNOS) instrument (Fig. 2), developed by the National Space Science Center of the Chinese Academy of Sciences (NSSC, CAS), has accumulated large amounts of radio occultation data since it was launched into orbit aboard the Fengyun 3 C (FY3-C) satellite on September 23, 2013. It was the first GNOS instrument compatible with both Beidou navigation satellite system (BDS) and Global Positioning System (GPS) technology. FY3-C is in a sun-synchronous polar orbit, at an altitude of 836 km, inclination of 98.8°, and has an orbital period of 101.5 minutes. The atmospheric refractivity profile of GNOS has a precision of less than 1 % in 5–25 km (Bai, et al., 2014; Liao, et al., 2016; Wang, et al., 2015). Peak electron density in the ionosphere can be detected to within 20 % of ionosonde measurements (Wang, et al., 2015; Yang, 2015).



1 The purpose of this study is to explore applications of FY3-C GNOS ionospheric data products in space weather
 2 research, specifically in the analysis of ionospheric NmF2 patterns during the magnetic storm of March 2015.
 3 Results of the study lay the foundation for the use of GNOS in space weather research, including magnetic and
 4 ionospheric storms.

5 **2 Instrument performance and data validation**

6 The GNOS aboard the FY3-C satellite is composed of two fixed occultation antennas, one forward and one aft.
 7 The electronic unit is located in the cabin. The forward and aft occultation antennae are each electrically split
 8 into atmospheric and ionospheric components (Bai, et al., 2014). The ionospheric occultation antennas are single
 9 unit, micro-strip, dual-mode, and dual-frequency, and they can simultaneously receive BDS dual-frequency (B1
 10 and B2) and GPS dual frequency (L1 and L2) ionospheric occultation signals. The maximum gain of each
 11 antenna is 5 dB, and the half power beam width of the ionospheric occultation antenna is $\pm 40^\circ$. The forward
 12 ionospheric occultation antenna is oriented normal to the +X axis of the satellite, i.e., the direction in which the
 13 satellite is moving. The aft ionospheric occultation antenna is oriented normal to the -X axis of the satellite. The
 14 objective of this design is to make the beam of the ionospheric occultation antenna with maximum gain cover the
 15 ionospheric occultation target region, in order to obtain a high signal-to-noise-ratio (SNR), and high quality
 16 occultation signal.

17 Within the power consumption limits aboard the FY3-C satellite, GNOS is equipped with six dual-frequency
 18 GPS occultation channels, which are able to simultaneously track dual-frequency signals from six GPS satellites
 19 (including atmospheric and ionospheric occultation signals). It also has four dual-frequency BDS occultation
 20 channels, which can simultaneously track four dual-frequency BDS satellite signals (including atmospheric and
 21 ionospheric occultation signals). The GNOS ionospheric occultation data mainly includes dual-system, dual-
 22 frequency carrier phase and SNR information, with a sampling rate of 1 Hz. Since the primary mission is
 23 atmospheric occultation sounding, this is given priority, so that when there are no free channels, a new
 24 atmospheric occultation event occupies an ionospheric occultation channel. Under these limited channel
 25 conditions, the actual number of complete ionospheric occultation profiles that can be produced daily is around
 26 220 from the GPS and around 130 from the BDS.

27 GNSS signals transmitted through the ionosphere and received by LEO satellites are bent and delayed by
 28 refraction in the ionosphere. Using dual-frequency phase observations, the corresponding total electron content
 29 (TEC) of the ionosphere can be obtained:

$$30 \quad TEC = \frac{f_1^2 f_2^2}{C(f_1^2 - f_2^2)} (L_1 - L_2) \quad (1)$$

31 where L_1 and L_2 are the dual-frequency carrier phase observations, $C=40.3082 \text{ m}^3 \text{ s}^{-2}$ is a constant, and f_1 and f_2
 32 indicate the two frequencies. This type of dual frequency TEC inversion method (Syndergaard, et al., 2000;
 33 Datta-Barua, et al., 2008) eliminates clock differences and other instrumental biases, and also allows information
 34 on bending angle and impact height to be obtained. Equation (2) uses an inverse Abel transformation to obtain
 35 the refraction index, then electron density in the ionosphere is derived from the A-H formula (Hartree, 1931;
 36 Appleton, 1932).



$$n(a) = \exp\left(\frac{1}{\pi} \int_a^\infty \frac{\alpha(x)dx}{\sqrt{x^2 - a^2}}\right) \quad (2)$$

where n is the ionosphere refraction index, α the bending angle, and a the impact height.

We evaluated the GNOS ionosphere electron density profiles through statistical comparison with ionosonde data. Electron density profile data were collected from GNOS, covering a 365-day period between October 1, 2013 and September 30, 2014, giving 81,215 occultation profiles from the GPS and 50,356 from the BDS. We also collected ionosphere observation data taken from ground ionosonde stations, which mainly comprised two parameters: maximum electron density in the F2 layer of the ionosphere (NmF2); and the altitude of the maximum electron density (hmF2). Ionosonde data were obtained from 69 ionosonde stations of the U.S. Space Weather Prediction Center (SWPC) (as shown in Fig. 3). The criteria used for matching GNOS and ionosonde data were a time interval within ± 1 hour, and geographic latitude and longitude within $\pm 2^\circ$. For every matching pair of data, the relative error (R) in the GNOS NmF2 was calculated using Eq. (3):

$$R = \frac{NmF2_{GNOS} - NmF2_{IONO}}{NmF2_{IONO}} \times 100\% \quad (3)$$

where the subscript $IONO$ represents ionosonde.

Figure 4 compares NmF2 measurements from the GNOS GPS occultation and the ionosondes. Over the course of the year, a total of 547 matching pairs of data were collected. Since the FY3-C satellite is in a sun-synchronous polar orbit, it passes ground stations at around 10:00 and 22:00 (LT), hence, occultation events are mainly concentrated in the two local time periods between 09:00–12:00 and 21:00–24:00. Linear regression of absolute NmF2 values derived from each methods (Fig. 4), gives a correlation coefficient of 0.95, statistical bias of 3.00 %, and standard deviation of 17.93 %. Figure 5 is similar to Fig. 4, but with GNOS BDS occultation profiles rather than GPS products, and shows most occultation events also occurred at local times of 9:00–12:00 and 21:00–24:00. The correlation coefficient of the fitted regression is 0.95, statistical bias is 4.67 %, and standard deviation is 19.19 %.

Global electron density profiles have been successfully probed in several previous GNSS radio occultation missions, including GPS/MET, CHAMP, and COSMIC. Using ionosonde data for verification, their reported precisions are: NmF2 average bias 1 %, and standard deviation 20 % for GPS/MET (Hajj et al., 1998); NmF2 average bias -1.7 %, and standard deviation 17.8 % for CHAMP (Jakowski et al., 2002); insignificant mean differences for COSMIC, with 22–30 % for NmF2 and 10–15 % for hmF2 (Limberger, et al., 2015). GNOS GPS and BDS occultation NmF2 observations reported in this study have a slightly higher average bias than the other systems, but their good correlation coefficients and standard deviations demonstrate the overall reliability of the results.



3 Analysis of GNOS results during the magnetic storm of March 2015

3.1 Characteristics of the magnetic storm

Solar activity in 2015 was at a moderate level, and there were several large geomagnetic storm events. This study focuses on the magnetic storm event that occurred between March 11 and March 31, 2015, peaking at 05:22 UT on March 17. Changes in magnetic indices during the storm are shown in Fig. 6. The geomagnetic activity index K_p , which characterizes global geomagnetic activity, was generally below 3 before March 17, then it increased significantly, with large perturbations continuing until March 26, after which it returned to pre-storm levels. The Dst index, which is an index of geomagnetic activity used to assess the severity of magnetic storms, was relatively stable before March 17, hovering around zero. The index suddenly increased between 04:00–06:00 UT on the 17th, marking the initial phase of the magnetic storm, and then dropped rapidly during the main phase to a minimum of -223 nT at 23:00 UT. A rapid recovery phase followed, from 23:00 UT on March 17 until 18:00 UT on March 18, then a slower recovery until around 10:00 UT on March 25, when it returned to pre-storm levels. The auroral electrojet (AE) index mainly reflects polar substorm intensity, with variations closely related to the quantity of particles injected into polar regions. The AL and AU indices reflect westward and eastward electrojet conditions, and the AE index is the absolute difference between them. During the main phase of the magnetic storm, the magnitude of AE index perturbations reached around 1500, with frequent lower magnitude perturbations during the recovery phase. Overall, this magnetic storm event caused severe geomagnetic disturbances on a global scale. As plasma in the ionosphere is controlled by the earth's magnetic field, the global ionosphere was also affected by the magnetic storm.

3.2 Global GNOS results during the magnetic storm

Figure 7 shows global daytime (07:00–17:00 LT, Fig. 7a) and nighttime (19:00–05:00 LT, Fig. 7b) occultation event distributions for March 14, 2015 (pre-storm calm), March 17 (main phase), March 18 (rapid recovery phase), and March 22 (recovery phase). Around 350 ionosphere occultation profiles were recorded daily (220 GPS + 130 BDS). Although the quantity of data is limited due to the rather high inclination polar orbit of FY3-C, recorded occultation events are distributed across the globe, with a relative concentration at higher latitudes. Fig. 7a shows that, before the magnetic storm, the highest daytime NmF2 values were mostly distributed around the magnetic equator, with relatively low electron densities in high magnetic latitudes. During the magnetic storm, NmF2 perturbations were significant, with especially large increases in the South Atlantic region. In the southeastern Pacific, NmF2 decreased during the main storm phase, and increased during the recovery phase, returning to pre-storm levels by March 22. Nighttime GNOS soundings (Fig. 7b) show suppressed NmF2 values in East Asia and Australia during the main phase and start of the recovery phase of the storm. NmF2 values had returned to pre-storm levels by March 22. These results demonstrate the capability of FY3-C GNOS for characterizing global NmF2 response to magnetic storm events.

3.3 Statistical analysis of GNOS ionosphere products during the magnetic storm period

The daily GNOS ionosphere profiles are relatively sparse, and unevenly distributed around the globe. Therefore, it is difficult to quantitatively analyze the response of a specific location during a magnetic storm event. However, as most occultation events are distributed in mid and high latitudes, it is possible to analyze changes in average NmF2 and hmF2 values during a magnetic storm. Figure 8 plots changes in average daytime and



nighttime NmF2 and hmF2 values as determined by GNOS, in the zone of geomagnetic inclinations between 40–80°, in both the northern and southern hemispheres. Samples from geomagnetic inclinations outside this zone were excluded as there were insufficient radio occultation events for statistical analysis. Figure 8 shows the following trends:

(1) Nighttime average NmF2 levels were much lower in the main phase (March 17) and at the start of the recovery phase (March 18–20) than before the storm, reaching a minimum on March 18.

(2) In the northern hemisphere, nighttime average hmF2 increased rapidly during the main phase of the storm, reaching a maximum on March 17, decreased to a minimum on March 20, and slowly increased again after. However, in the southern hemisphere, average hmF2 was only slightly higher on the 17th than on the 16th. It reached a minimum on the 18th, after which it slowly rose again. This pattern is essentially in accord with the NmF2 trends.

(3) Daytime average NmF2 in the northern hemisphere reached a maximum during the main phase of the magnetic storm on March 17, falling to a minimum on the 19th, after which it slowly increased. In the southern hemisphere, daytime average NmF2 began to fall on the 15th, reached a minimum on the 18th, and then slowly recovered.

(4) Daytime average hmF2 results were similar for both the northern and southern hemispheres, reaching a maximum on March 17, and rapidly dropping to a minimum on the 18th, before gradually recovering.

Overall, the magnetic storm caused significant disturbances in global NmF2 and hmF2 values in the region of magnetic inclinations between 40–80°, in both the northern and southern hemispheres. Both daytime and nighttime NmF2 values showed mainly negative storm characteristics, while hmF2 increased significantly during the main phase of the storm, and was suppressed at the start of the recovery phase.

3.4 Comparisons with ionosonde observations

In previous sections, analysis of the effects of the magnetic storm event on FY3-C satellite GNOS results showed that it caused significant perturbations in global NmF2 levels. In this section, we compare GNOS measurements with ionosonde data from the SWPC worldwide stations. As there are very few ionosonde stations located at magnetic inclinations of 40–80° in the southern hemisphere, we focused on NmF2 data from the 15 ground stations in the northern hemisphere, in the period March 14–22, 2015. The geographic distribution of these 15 stations is shown in Fig. 9. We also included NmF2 data from two China Meridian Project stations in the analysis (shown as red stars in Fig. 9). Figures 10 and 11 plot NmF2 variations at each station. Perhaps the most outstanding feature is a surge in NmF2 values at individual stations on March 17, during the main phase of the magnetic storm (e.g., around 12:00 UT at Moscow), with a decrease after 16:00 at many stations. Almost all the stations show a significant decrease in NmF2 measurements during the beginning of the recovery phase, on March 18 and 19, except for a few western European stations (e.g., Rome). After March 19, NmF2 patterns become more complex, with some stations (e.g., Mohe) showing values below pre-storm levels, and others (e.g., Okinawa) about the same as pre-storm levels. Overall, ionospheric perturbations during the magnetic storm were mainly negative.



Figure 12 compares average NmF2 values from the 17 ionosonde stations with those from the GNOS occultation products for different time periods in the magnetic storm event, including all day (24 h), 9:00–12:00 LT, and 21:00–24:00 LT (in Figs. 4 and 5 most of the GNOS occultation events were concentrated around these times). In these plots, NmF2 trends are very similar for the two observation methods, with the negative storm effects of the recovery phase quite clear. However, GNOS measurements, especially in the 21:00–24:00 time block, show larger perturbations than those of the ionosonde stations, indicating significant differences still exist between the two measurement techniques.

4 Discussion

The GNSS radio occultation allows monitoring of electron density in the ionosphere at a global scale. It has the advantages of high accuracy, good vertical resolution, global coverage, and all-weather capability. However, an important constraint in applications of the occultation electron density products is the assumption of a symmetrical ionosphere in the inverse Abel transformation calculations. In reality, it is very difficult to guarantee symmetrical distribution of electron density in the ionosphere, especially near anomalies at the magnetic equator. Nevertheless, comparison of the GNOS probe results with ionosonde measurements provided a correlation coefficient of 0.95, and standard deviation less than 20 %. Therefore, in the majority of cases, GNOS results may be considered to be reliable and reasonable.

The study analyzed the effect of the March 2015 magnetic storm on the global ionosphere, using data from FY3-C GNOS and from ground-based ionosonde stations. In terms of spatial distribution, Figs. 7a and 7b showed that daytime NmF2 values in the southern Atlantic region were elevated throughout the course of the storm. In the southeastern Pacific, NmF2 values first decreased at the beginning of the main phase of the magnetic storm, and then increased in the recovery phase. Nighttime NmF2 values around East Asia and Australia were mainly suppressed during the main phase, and at the start of the recovery phase, and returned to pre-storm levels by March 22. In terms of different geomagnetic inclination zones (Fig. 8), the magnetic storm had a significant effect on NmF2 and hmF2 values. Both daytime and nighttime average NmF2 values showed negative storm effects. It was not possible to perform long-term continuous comparison between ionosonde and GNOS data, as the number of occultation events recorded by GNOS was insufficient. Hence, the results from two geomagnetic inclination zones were averaged to enable a quantitative comparison. Besides, the statistical significance of this method is based on the assumption that the effects of the magnetic storm are basically consistent throughout the ionosphere in each magnetic latitudinal zone. The statistical comparison of the averaged data showed similar general trends in measurements from the 17 ionosonde stations and GNOS during the March 2015 magnetic storm. The comparison further confirmed the nature of the magnetic storm, and the negative effects of the storm on the ionosphere.

The way in which the global ionosphere responds to magnetic storms is extremely complicated. From Fig. 7a, we can see that this particular magnetic storm caused varying responses in the ionosphere at different times and locations. Many physical factors influence the ionosphere, such as electric fields, and neutral winds. For a specific magnetic storm, corresponding ionospheric perturbations also depend on the season, solar activity, local time of magnetic storm occurrence, and the latitude and longitude. Therefore, ionospheric storms are extremely complex; no two storms are precisely alike, and the mechanisms that generate them also vary (Balan, et al., 1990;



1 Fuller-Rowell, et al., 1996; Danilov, et al., 2001; Mendilo, et al., 2006). In addition, the type and form of a
2 magnetic storm also makes a difference in the way that it affects the ionosphere (Zhang, et al., 1995). Future
3 analysis incorporating assimilation with other data sources and models may allow the precise mechanisms
4 responsible for ionospheric effects of the March 2015 magnetic storm to be determined.

5 **5 Conclusions**

6 The comparison of ionosonde data and FY3-C GNOS radio occultation products presented in this study shows
7 that, in the majority of cases, GNOS data is reliable and reasonable. Based on ionosphere data from the FY3-C
8 GNOS payload combined with those from ground-based ionosonde, this study analyzed the characteristics of
9 global ionosphere response to the magnetic storm event in March 2015. Daytime NmF2 values increased in the
10 South Atlantic region, and first decreased and then increased in the southeast Pacific region. In East Asia and
11 Australia, nighttime NmF2 values were mainly suppressed, but recovered to pre-storm levels around March 22.
12 In the region of higher magnetic inclinations, NmF2 and hmF2 levels were clearly affected by the storm.
13 Daytime and nighttime NmF2 levels mainly indicated a negative storm response. Overall, the trend detected by
14 GNOS during the magnetic storm event in the zone of magnetic inclinations between 40–80° in the northern
15 hemisphere was similar to the trend detected by the 17 ground-based ionosonde stations in that region. This
16 further confirmed the negative response of the ionosphere to the March 2015 magnetic storm event. The study
17 demonstrates the reliability of FY3-C GNOS radio occultation measurements for analyzing statistical and event-
18 specific physical characteristics of the ionosphere. More Beidou navigation satellites, and other FY3 series
19 satellites (FY3-D, E, F, G, and H), are planned in the future, and their GNOS payloads offer the potential for
20 generation of significantly more data in support of ionospheric physics research and forecasting applications.

21 **Acknowledgments**

22 We thank UML GIRO for providing the ionosonde data. We also acknowledge the use of data from the Chinese
23 meridian Project. This research was supported jointly by National Science Fund (41505030, 41405039,
24 41405040 and 41574150 and 41606206) and Scientific Research Project of Chinese Academy of Sciences
25 (YZ201129).

26



1 References

- 2 Appleton, E. V.: Wireless studies of the ionosphere. *J. Inst. Elec. Engrs*, 71(430): 642-650, 1932.
- 3 Balan, N., Rao, P. B.: Dependence of ionospheric response on the local time of sudden commencement and the
4 intensity of geomagnetic storms. *J. Atmos. Terr. Phys.*, 52(4): 269-275, 1990.
- 5 Bai, W. H., Sun, Y. Q., et al.: An introduction to the FY3 GNOS instrument and mountain-top tests. *Atmos. Meas.*
6 *Tech.*, 7, 1817–1823, 2014.
- 7 Datta-Barua, S., Walter, T., Blanch, J., et al.: Bounding Higher Order Ionosphere Errors for the Dual Frequency
8 GPS User. *Radio Sci.*, 43(5): 1429-1443, 2008.
- 9 Danilov, A. D.: F2-region response to geomagnetic disturbances. *J. Atmos. Solar-Terr. Phys*, 63(5), 441-449,
10 2001.
- 11 Fu, E., Zhang, K., Wu, F., et al.: An Evaluation of GNSS Radio Occultation Technology for Australian
12 Meteorology. *Positioning*, 6(1):74-79, 2007.
- 13 Fuller-Rowell, T. J., Codrescu, M. V., Rishbeth, H., et al.: On the seasonal response of thermosphere and
14 ionosphere to magnetic storms. *J. Geophys. Res.*, 101(A2), 2343-2353, 1996.
- 15 Hartree, D. R.: The propagation of electromagnetic waves in a refracting medium in a magnetic field, *Proc.*
16 *Cambridge Phil. Soc.*, 27, 143, 1931.
- 17 Hajj, G. A., Remans, L.: Ionospheric electron density profiles obtained with the global positioning system:
18 Results from the GPS/MET experiment. *Radio Science*, 33(1):175-190, 1998.
- 19 Hocke, K., Lgarashi, K., Nakamura, M., et al.: Global sounding of sporadic E layers by the GPS / MET radio
20 occultation experiment. *Journal of Atmospheric and Solar-Terrestrial Physics*, 63(18): 1973-1980, 2001.
- 21 Jakowski, N., A., Wehrenpfennig, S., Heise, et al.: GPS radio occultation measurements of the ionosphere from
22 CHAMP: Early results. *Geophysical Research Letters*, 29(10): 2-4, 2002.
- 23 Liu, L., Le, H., Chen, Y., et al.: Features of the middle- and low-latitude ionosphere during solar minimum as
24 revealed from COSMIC radio occultation measurements. *Journal of Geophysical Research-Space Physics*,
25 116(A09): 1161-1166, 2011.
- 26 Liu, L., He, M., Ning, B., et al.: Ionosphere around equinoxes during low solar activity. *Journal of Geophysical*
27 *Research-Space Physics*, 115(A09), 307, 2010.
- 28 Liu, L., Zhao, B., Wan, W., et al.: Seasonal variations of the ionospheric electron densities retrieved from
29 Constellation Observing System for Meteorology, Ionosphere, and Climate mission radio occultation
30 measurements. *Journal of Geophysical Research-Space Physics*, 114(A02), 302, 2009.
- 31 Liu, L., He, M., Wan, W., et al.: Topside ionospheric scale heights retrieved from Constellation Observing
32 System for Meteorology, Ionosphere, and Climate radio occultation measurements. *Journal of Geophysical*
33 *Research-Space Physics*, 113(A10): 1429-1443, 2008.



- 1 Limberger, M., Hernández-Pajares, M., Aragón-Ángel, A., Altadill, D., and Dettmering, D.: Long-term
2 comparison of the ionospheric F2 layer electron density peak derived from ionosonde data and Formosat-
3 3/COSMIC occultations. *J. Space Weather Space Clim.*, 5, A21, 2015.
- 4 Lu, H., Zou, Y.: Research on the global morphological features of spread F based on GPS occultation
5 observation. *Journal of Guilin University of Electronic Technology*, 31(6): 508-512, 2011.
- 6 Liao, M., Zhang, P., Yang, G. L., Bi, Y. M., Y., Liu, Bai, W. H., Meng, X. G., Du, Q. F., and Sun, Y. Q.:
7 Preliminary validation of refractivity from a new radio occultation sounder GNOS/FY-3C. *AMT*, 9, 781-792,
8 2016.
- 9 Mendilo, M.: Storms in the ionosphere: patterns and processes for total electron content. *Rev. Geophys.*, 44(4):
10 335-360, 2006.
- 11 Syndergaard, S.: On the ionosphere calibration in GPS radio occultation measurements. *Radio Sci.*, 35(3) 865-883,
12 2000.
- 13 Wang, S. Z., Zhu, G. W., Bai, W. H., et al.: For the first time fengyun3 C satellite-global navigation satellite
14 system occultation sounder achieved spaceborne Bei Dou system radio occultation. *Acta Phys.*
15 *Sin.*, 64(08), 089301, 2015.
- 16 Yang, G. L.: Ionospheric Radio Occultation by GNOS, Phd. thesis, University of Chinese Academy of Science,
17 Beijing, 2015.
- 18 Yang, J., Wu, Y., Zhou, Y.: Research on Seismo-Ionospheric Anomalies Using GPS Radio Occultation Data.
19 *Journal of Geodesy and Geodynamics*, 28(01): 16-22, 2008.
- 20 Zhao, B., Wang, M., Wang, Y., et al.: East-West Differences in F-region Electron Density at Midlatitude:
21 Evidence from the Far East Region. *J. Geophys. Res.*, 118(1): 542-553, 2013.
- 22 Zhang, X., Hu, X., Zhang, C.: Ionospheric Response with Wenchuan Big Earthquake by Occulted Data, 5(10): 1-
23 5, GNSS World of China, 2008.
- 24 Zhang, Q. W., Guo, J. S., Zhang, G. L., et al.: Mid-and low-latitude ionospheric responses to different type of
25 magnetic storm. *Chinese J. Geophys.*, 38(5): 581-589, 1995.
- 26 Zhao, B., Wan, W., Yue, X., et al.: Global characteristics of occurrence of an additional layer in the ionosphere
27 observed by COSMIC/FORMOSAT-3. *Geophys. Res. Lett.*, 38(2): 622-635, 2012.

28

29 **Figure captions**

30 Figure 1: Sketch of GNSS radio occultation sounding technology (using China's FY3-C satellite as an example).

31 Figure 2: The FY3-C GNSS occultation sounder GNOS.

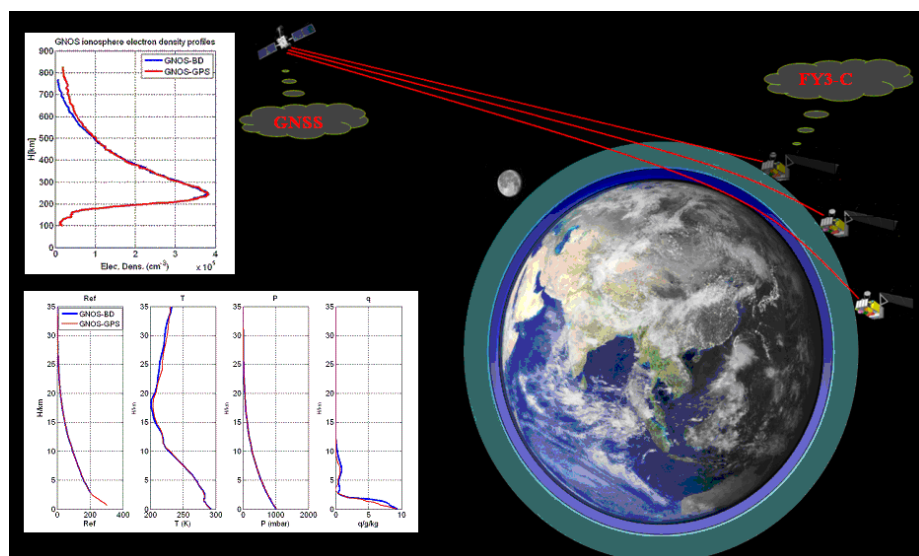
32 Figure 3: The distribution of ionosonde stations. The data of 69 ionosonde stations can be obtain from the US
33 Space Weather Prediction Center



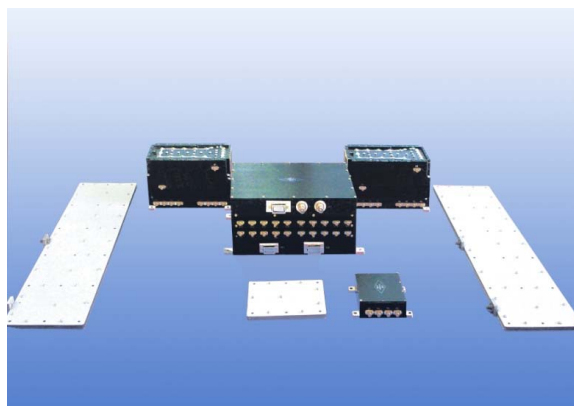
- 1 Figure 4. Comparison of NmF2 measurements from GNOS GPS occultation and ionosondes. The left panel is a
- 2 histogram of 547 occultation events in local time (LT). The right panel is a linear regression of the absolute
- 3 NmF2 values measured using the two methods. The black line is $y=x$, the red line is the fitted regression,
- 4 Corr. Coef. is the correlation coefficient, Bias is the statistical bias, Std is the standard deviation.
- 5 Figure 5: Same as Fig.4, but for GNOS Beidou navigation system (BDS). Comparison of NmF2 measurements
- 6 from GNOS BDS occultation and ionosondes. The left panel is a histogram of 376 occultation events in the local
- 7 time (LT), the right panel is a linear regression fit between the two sets of measurements.
- 8 Figure 6: Variations of geomagnetic indices (Kp, ap, Dst, AE, AU, AL, and AO) during the magnetic storm of
- 9 March 2015 (data from the International Service of Geomagnetic Indices (ISGI) website:
- 10 <http://isgi.latmos.ipsl.fr/>)
- 11 Figure 7a: NmF2 values detected by GNOS in all daytime (07:00–17:00 LT) occultation events on typical
- 12 representative days (March 14 quiet, March 17 magnetic storm main phase, March 18 rapid recovery phase, and
- 13 March 22 steady recovery phase). Squares represent the geographic location of GNOS GPS occultation events.
- 14 Diamonds represent the geographic location of GNOS BDS occultation events. The color of each square or
- 15 diamond represents NmF2 magnitude for that occultation event. Black contours represent geomagnetic
- 16 inclination isolines.
- 17 Figure 7b: Same as Fig.7a, but for the NmF2 values detected by GNOS in all nighttime (19:00–5:00 LT)
- 18 occultation events.
- 19 Figure 8. Average daytime and nighttime NmF2 and hmF2 values as detected by GNOS in the zone of
- 20 geomagnetic inclinations between 40–80° in the northern and southern hemispheres. Blue lines with circle
- 21 markers represent average daily NmF2, and green lines with square markers average daily hmF2. Black and red
- 22 figures denote the number of GNOS BDS and GPS occultation events, respectively.
- 23 Figure 9: Distribution of ionosonde stations located in the zone of geomagnetic inclinations between 40–80°.
- 24 Black squares represent SWPC stations, and red stars represent China Meridian Project stations.
- 25 Figure 10: Variations in NmF2 at 15 ground ionosonde stations located in the zone of geomagnetic inclinations
- 26 between 40–80° during the magnetic storm of March 2015. Ionosonde data were obtained from SWPC.
- 27 Figure 11: Variations in NmF2 at two ground ionosonde stations located in the zone of geomagnetic inclinations
- 28 between 40–80° during the magnetic storm of March 2015. Ionosonde data obtained from China Meridian
- 29 Project.
- 30 Figure 12: Comparison of average NmF2 values from the 17 ionosonde stations and GNOS in the region of
- 31 magnetic inclinations between 40–80° in the northern hemisphere.

32

33

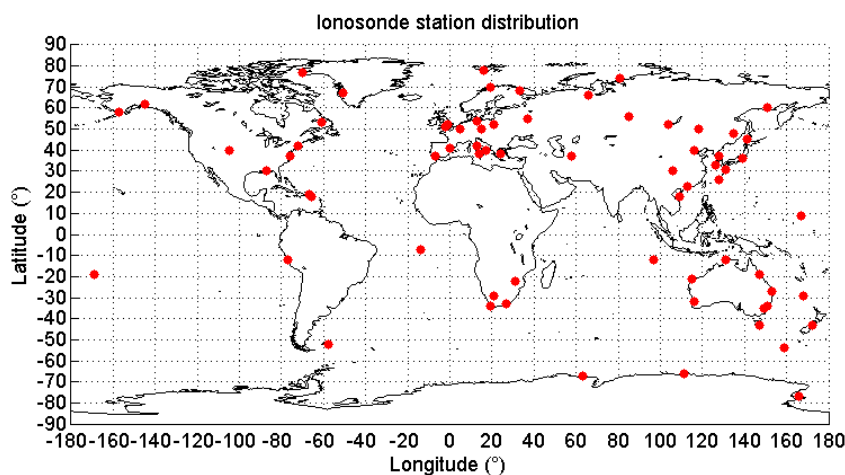


1
 2 Figure 1. Sketch of GNSS radio occultation sounding technology (using China's FY3-C satellite as an example).

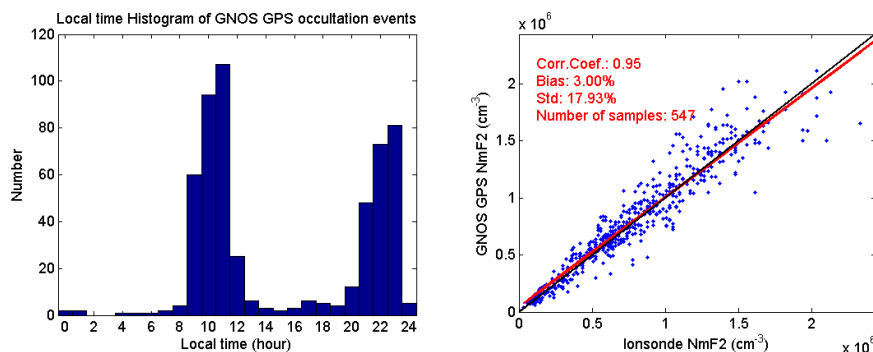


3
 4 Figure 2. The FY3-C GNSS occultation sounder GNOS.

5



1
 2 Figure 3. The distribution of ionosonde stations. The data of 69 ionosonde stations can be obtain from the US
 3 Space Weather Prediction Center



4
 5 Figure 4. Comparison of NmF2 measurements from GNOS GPS occultation and ionosondes. The left panel is a
 6 histogram of 547 occultation events in local time (LT). The right panel is a linear regression of the absolute
 7 NmF2 values measured using the two methods. The black line is $y=x$, the red line is the fitted regression,
 8 Corr. Coef. is the correlation coefficient, Bias is the statistical bias, Std is the standard deviation.

9

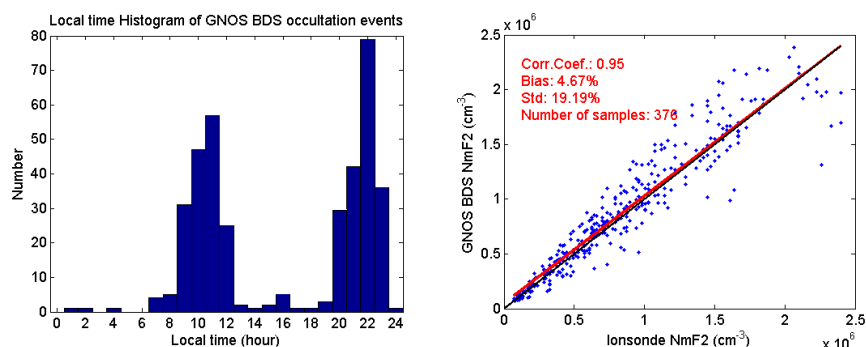


Figure 5. Same as Fig.4, but for GNOS Beidou navigation system (BDS). Comparison of NmF2 measurements from GNOS BDS occultation and ionosondes. The left panel is a histogram of 376 occultation events in the local time (LT), the right panel is a linear regression fit between the two sets of measurements.

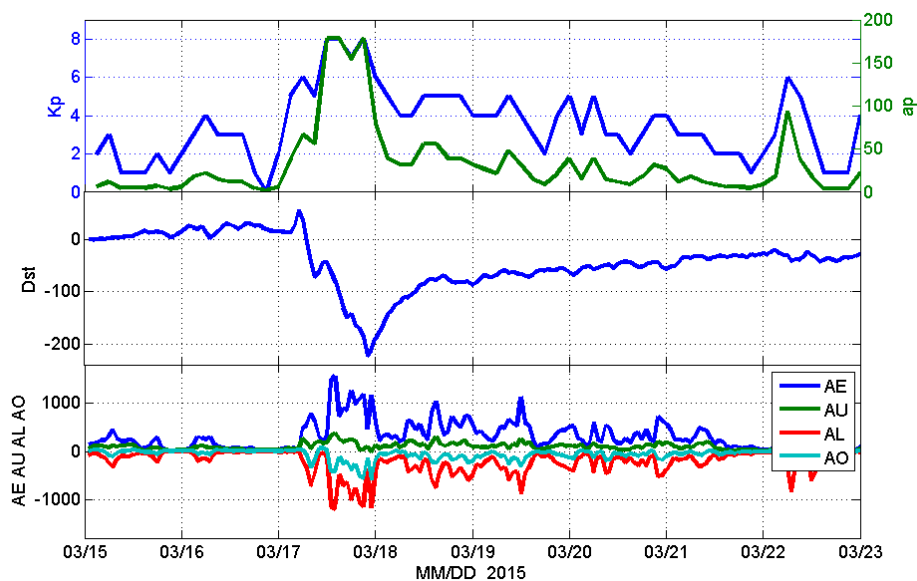
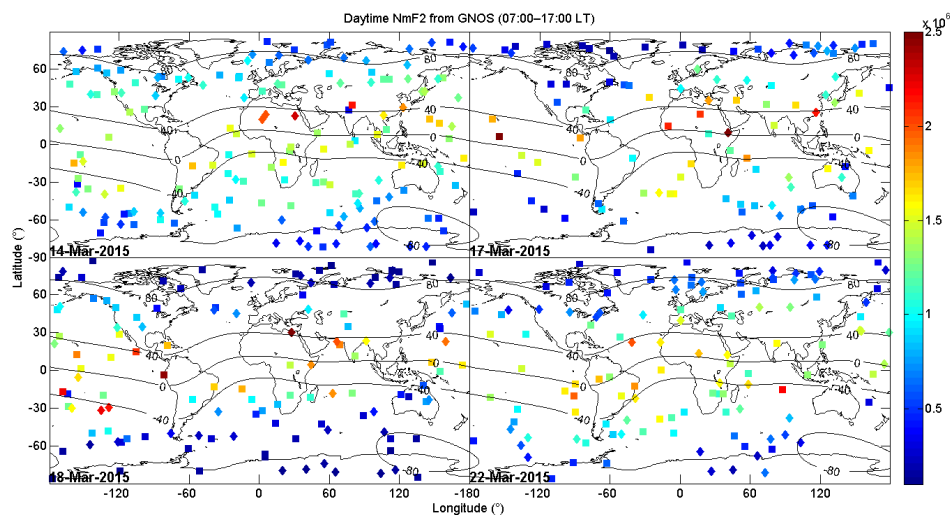


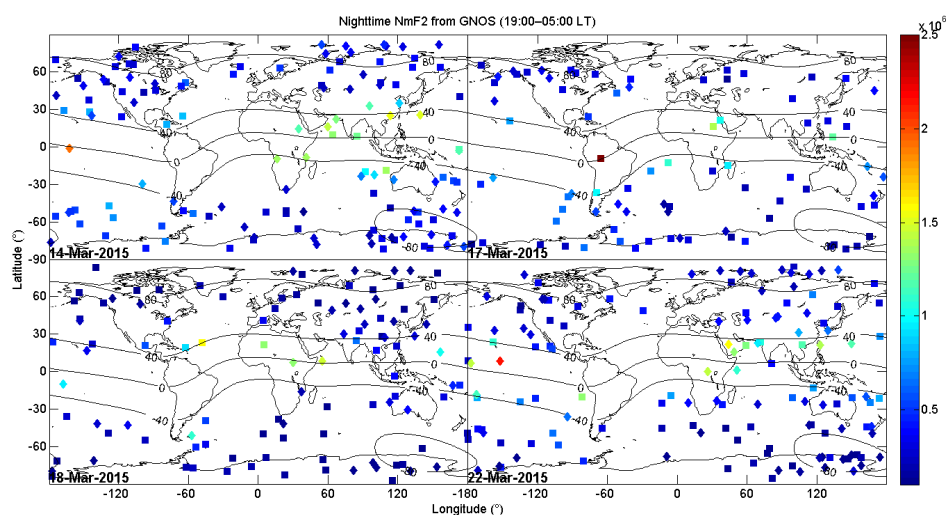
Figure 6. Variations of geomagnetic indices (Kp, ap, Dst, AE, AU, AL, and AO) during the magnetic storm of March 2015 (data from the International Service of Geomagnetic Indices (ISGI) website: <http://isgi.latmos.ipsl.fr/>)



1

2 Figure 7a. NmF2 values detected by GNOS in all daytime (07:00–17:00 LT) occultation events on typical
 3 representative days (March 14 quiet, March 17 magnetic storm main phase, March 18 rapid recovery phase, and
 4 March 22 steady recovery phase). Squares represent the geographic location of GNOS GPS occultation events.
 5 Diamonds represent the geographic location of GNOS BDS occultation events. The color of each square or
 6 diamond represents NmF2 magnitude for that occultation event. Black contours represent geomagnetic
 7 inclination isolines.

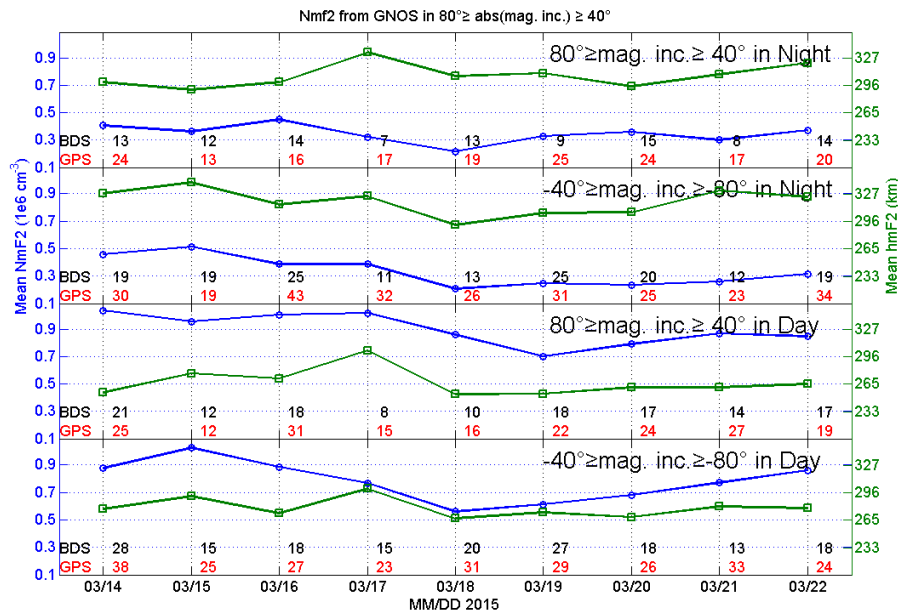
8



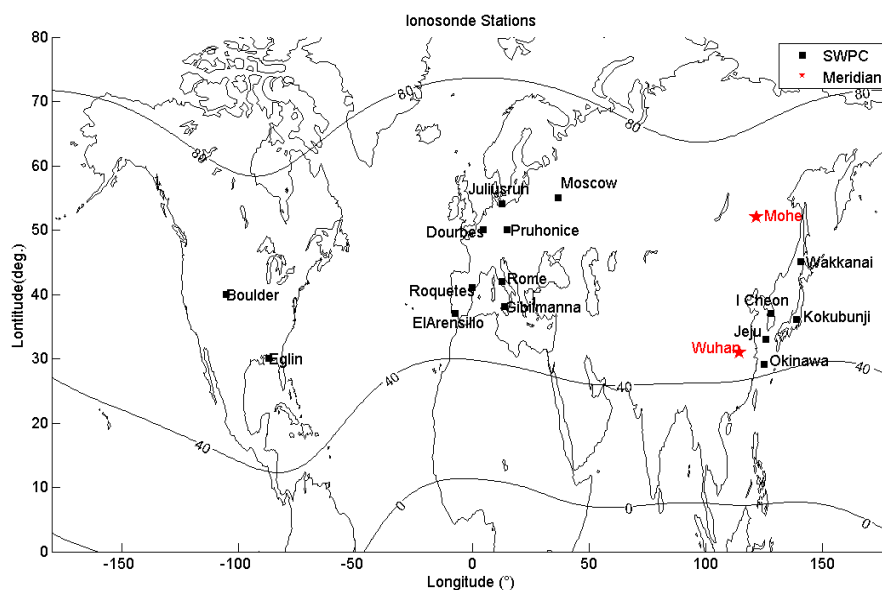
9



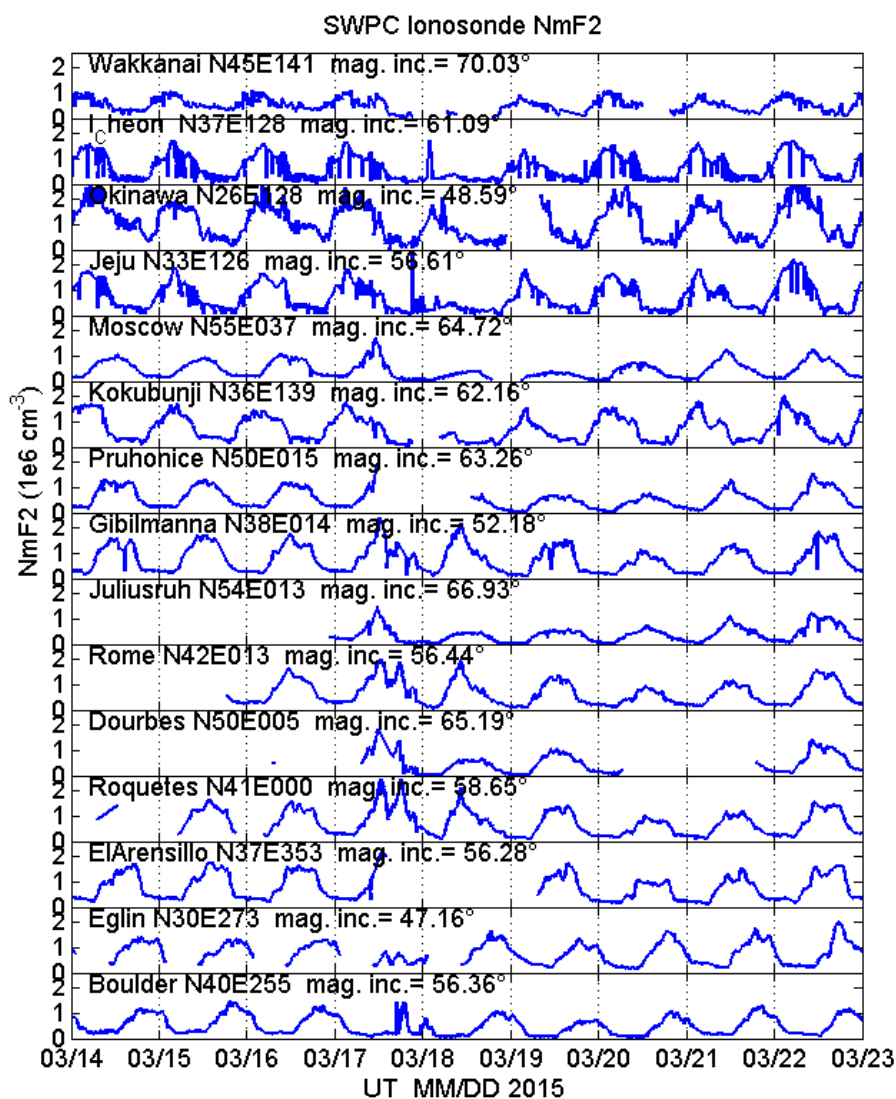
1 Figure 7b. Same as Fig.7a, but for the NmF2 values detected by GNOS in all nighttime (19:00–5:00 LT)
2 occultation events.



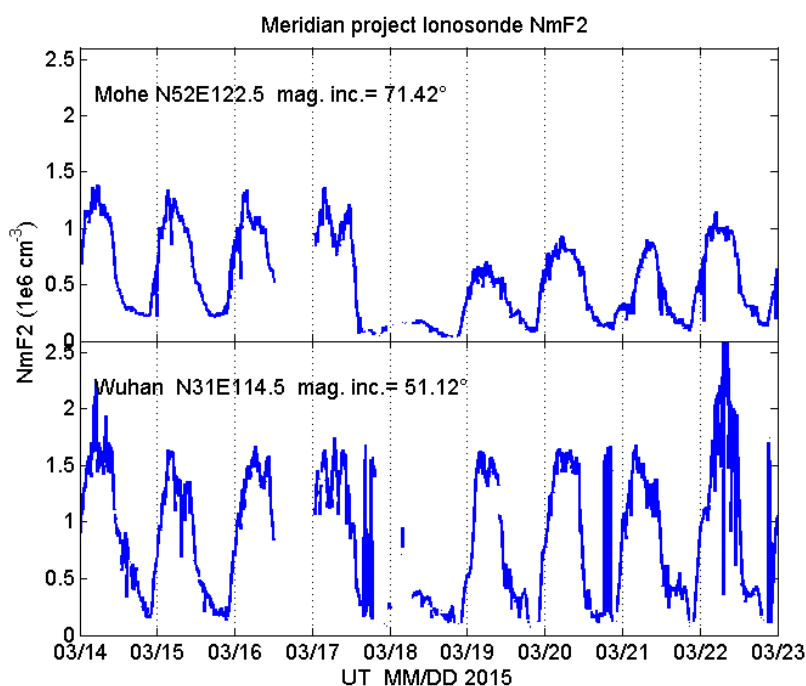
3
4 Figure 8. Average daytime and nighttime NmF2 and hmF2 values as detected by GNOS in the zone of
5 geomagnetic inclinations between 40–80° in the northern and southern hemispheres. Blue lines with circle
6 markers represent average daily NmF2, and green lines with square markers average daily hmF2. Black and red
7 figures denote the number of GNOS BDS and GPS occultation events, respectively.
8



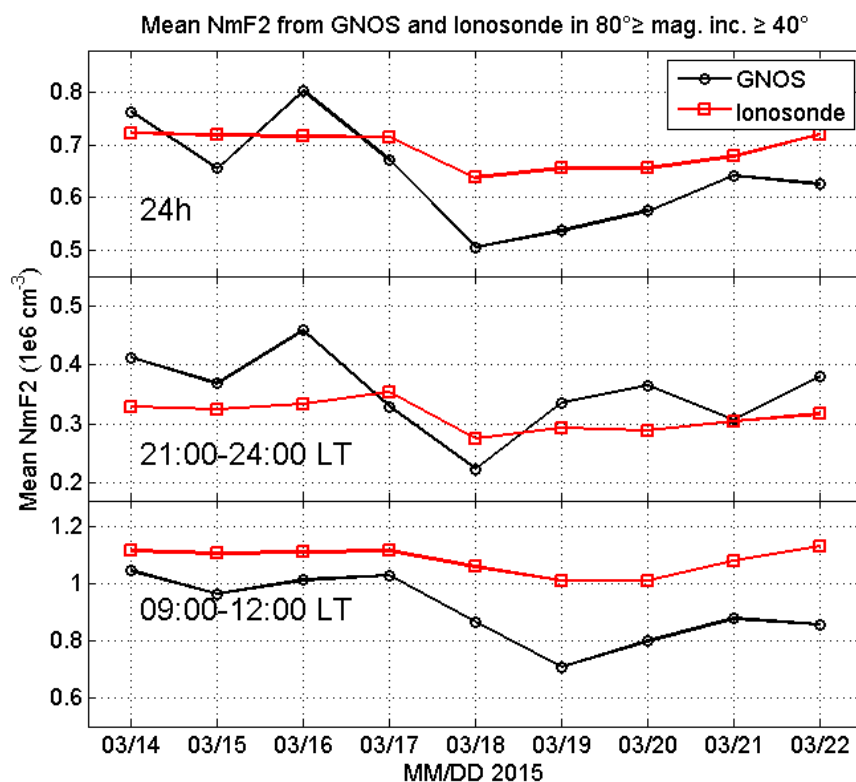
1
 2 Figure 9. Distribution of ionosonde stations located in the zone of geomagnetic inclinations between 40–80°.
 3 Black squares represent SWPC stations, and red stars represent China Meridian Project stations.



1
 2 Figure 10. Variations in NmF2 at 15 ground ionosonde stations located in the zone of geomagnetic inclinations
 3 between 40–80° during the magnetic storm of March 2015. Ionosonde data were obtained from SWPC.



1
 2 Figure 11. Variations in NmF2 at two ground ionosonde stations located in the zone of geomagnetic inclinations
 3 between 40–80° during the magnetic storm of March 2015. Ionosonde data obtained from China Meridian
 4 Project.



1
 2 Figure 12. Comparison of average NmF2 values from the 17 ionosonde stations and GNOS in the region of
 3 magnetic inclinations between 40° – 80° in the northern hemisphere.
 4