Originally published as:


DOI: http://doi.org/10.1002/2017SW001710
The Response of Equatorial Ionization Anomaly in 120°E to the Geomagnetic Storm of 18 August 2003 at Different Altitudes From Multiple Satellite Observations

Weihua Luo1, Zhengping Zhu1, Chao Xiong2, and Shanshan Chang1

1College of Electronic Information and Engineer, South-Central University for Nationalities, Wuhan, China, 2Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany

Abstract In this paper, the variations of equatorial ionization anomaly (EIA) in 120°E region during the 17–20 August 2003 storm are investigated from measurements of satellites at different altitudes from Challenging Minisatellite Payload (CHAMP), Gravity Recovery and Climate Experiment (GRACE), scientific satellite of the Republic of China (ROCSAT-1), and Defense Meteorological Satellite Program missions. The results showed that (1) at CHAMP and GRACE altitudes, the EIA was inhibited before the storm sudden commencement (SSC) and also during the storm recovery phase, but it was enhanced significantly during the storm main phase of the storm. (2) The variations of EIA strength and interhemispheric density asymmetry of the two crests were similar at CHAMP and GRACE altitudes, while the location asymmetry of the two crests was different at CHAMP and GRACE altitudes. (3) The irregularities and long-duration scintillation were observed before the SSC of the storm, when the EIA was inhibited. The irregularities at different altitudes and short-duration scintillation were observed during the main phase of the storm, when the EIA was enhanced significantly. (4) The EIA enhancement can be attributed to the enhanced electric field due to prompt penetration interplanetary electric fields and the storm time neutral wind, while the suppression of EIA on 17 August can be attributed to the absence of the equatorward neutral wind, which varied with the altitudes. The EIA inhibition during the recovery phase may be caused mainly by the neutral wind. Our results suggest that the neutral wind is the crucial factor causing the variations in EIA and the occurrence of scintillation.

1. Introduction

An important structure of the low-latitude ionosphere is the equatorial ionization anomaly (EIA), exhibiting as two maximum electron densities (crests) at about ±15° on either side of the magnetic equator and a minimum (trough) above the magnetic equator, formed by the equatorial plasma fountain effect (Appleton, 1946; Kelly, 2009). The equatorial dynamo electric field is thought to be the main cause of the crest motion (Yeh et al., 2001), and the day-to-day variability of the EIA is controlled dominantly by the low-latitude ionospheric electrodynamics.

To quantify the characteristics of the EIA, the Crest-to-Trough Ratio (CTR) and latitudinal asymmetry of EIA two crests are usually used to represent the strength and interhemispheric asymmetry of EIA (Luo et al., 2016; Xiong & Lühr, 2013; Xiong et al., 2013). The CTR and locations of EIA crests can vary with various geophysical conditions, such as solar flux, local time, season, and longitudes. In general, CTR is around 1.6 in daytime peak electron density (Balan et al., 2017; Liu et al., 2007), and the CTR reaches the maximum around 2000 LT, with a value about 3 that almost twice the daytime value (Xiong et al., 2013). The interhemispheric asymmetry of EIA was also studied by previous studies, and the reason was mainly attributed to the asymmetric neutral composition and the summer-to-winter (transequatorial) neutral wind effects (Aydogdu, 1988; Ram et al., 2009; Walker, 1981). Considering that the background neutral and plasma density neutral wind vary with the altitudes, and the recombinating loss is smaller at higher altitude (Datta-Barua et al., 2009; Kelly, 2009; Lin et al., 2005; Pingree & Fejer, 1987), the EIA at different altitudes may have different performances. By comparing the long-term observations from Challenging Minisatellite Payload (CHAMP) (at about 400 km) with that from Gravity Recovery and Climate Experiment (GRACE) (at about 480 km), Xiong et al. (2013) found that the electron density of the EIA crest at CHAMP altitude is stronger in the winter hemisphere during morning to noontime hours, and it reverses after the noontime, while at GRACE altitude, the electron density of the EIA crest is always stronger in the summer hemisphere over the whole daytime.
Above mentioned characteristics of EIA are suitable during geomagnetic quiet periods. But during geomagnetic storms, the EIA morphology is easy to be disturbed due to the prompt penetration electric fields (PPEF) (e.g., Kikuchi et al., 2000) and ionospheric disturbance wind dynamo (e.g., Abdu et al., 1991; Blanc & Richmond, 1980; Mendillo, 2006). During the main phase of the storm, EIA is likely to expand poleward to even about ±30° and the density at the crests could increase significantly over 1,000%, due to the PPEF and fast Storm time Equatorward Winds, while during the recovery phase of the storm, EIA sometimes becomes to be suppressed with a maximum density at the dip equator which was suggested to be caused mainly by westward electric fields and an increase in O/N2 ratio around the equator (Balan et al., 2017, and references therein; Kassa et al., 2015).

The behavior of EIA during geomagnetic storms has been widely reported; however, there are few studies focusing on the variations of EIA at different altitudes during the disturbed period. Lei et al. (2014) investigated the ionospheric response to the October 2003 superstorm based on Jason, CHAMP, GRACE, and SAC-C satellite observations at different altitudes, and their result indicated that the relative stronger enhancement occurred was recorded by the Jason in the higher altitude, and the variations of vertical drifts played an important role in causing the main variations of the positive storm effects at low latitudes. By investigating the variations of EIA at different altitudes will help us to understand the physical process and major factors leading to the modifications in the equatorial and low-latitude ionosphere at different altitudes, especially during the disturbed period. The purpose of this paper is to study the response of EIA to the geomagnetic storm during 17–20 August 2003 at different altitudes based on different satellite observations, Challenging Minisatellite Payload (CHAMP), Gravity Recovery and Climate Experiment (GRACE), scientific satellite of the Republic of China (ROCSAT-1), and Defense Meteorological Satellite Program (DMSP), including the variations of the strength and asymmetry of EIA and the occurrence of irregularities and scintillation. The possible mechanism leading to the variations of EIA is discussed in the last.

2. Geophysical Conditions of the August 2003 Storm

Figure 1 shows the Dst index during 15–24 August 2003. The storm sudden commencement (SSC) of the intense geomagnetic storm during 17–20 August 2003 was at 1421 UT on 17 August, the minimum Dst index reached about −148 nT at 1600 UT on 18 August, and a regular recovery lasted approximately about 48 h on 19–20 August.

Interplanetary parameters during the storm period including solar wind speed ($V_{SW}$), the component of interplanetary magnetic field (IMF) $B_z$, and the derived interplanetary electric field (IEF) $E_y$ are displayed in Figure 2. $E_y$ is calculated as $E_y = V_{SW} \times B_z$.

In Figure 2, the IMF $B_z$ component was in southward direction since the main phase till about 0200 UT on 19 August, when rotated to northward for about 24 h. The solar wind speed started to increase about 1200 UT of 17 August, from about 440 to 600 km/s and it remained during the main phase and recovery phase of the storm. After the storm started, $E_y$ became westward and then turn to eastward from about 1800 UT of 17–19 August, which means that the $E_y$ was eastward during the main phase of the storm, with a maximum value of about 8 mV/m.

3. Data and Methodology

3.1. Satellite Observations

The CHAMP satellite was launched on 15 July 2000 into an almost circular, near-polar orbit, with an inclination of 87.3°. The initial altitude is about 454 km and the satellite decayed gradually to about 400 km after 3 years, and the orbit had decayed to 310 km by the end of 2009. The local time of the orbital plane changes by 1 h in 11 days, requiring about 130 days for covering all local times (Reigber et al., 2002). The Planar Langmuir Probe (PLP) on board the satellite was used to measure the in situ electron density and temperature every 15 s, the PLP electron density measurements have been validated by comparison with digisonde measurements at
Jicamarca, and the results indicated that the observations by PLP were consistent with the recordings by the digisonde (McNamara et al., 2007).

The GRACE mission, including two spacecraft GRACE-A and GRACE-B, was launched on 17 March 2002 into a near-circular, polar orbit (inclination: 89°) with an initial altitude of about 490 km. The altitude of the satellites is quite stable over the years, and now it stays around 480 km. The local time of the orbit changes by about 4.5 min/d, taking about 161 days to cover all local times (Tapley et al., 2004). The more detailed description of the electron density retrieval can be found in Xiong et al. (2010), and the derived electron density has been validated by ground-based radars of European Incoherent Scatter radar, Mill stole hill, and Arecibo (Xiong et al., 2015).

The ROCSAT-1 was launched in March 1999 to a circular orbit with a 35° inclination orbital plane at 600 km and a period of 97 min. ROCSAT-1 crosses a given longitudinal line 14 times per day and completes global coverage in local time and longitude every 52 days. The onboard Ionospheric and Plasma Electrodynamics Instrument (IPEI) operates at 100% duty cycle to take continuous data of ion density and ion composition in the low- to middle-latitude ionosphere (Yeh et al., 1999).

The DMSP is a series of satellites and orbits the Earth in 98.7° inclined polar and circular orbits at an altitude of about 840 km; the first DMSP spacecraft was launched in January 1965. Each satellite carries the Special Sensor-Ions, Electrons, and Scintillation package to measure the ion and electron densities, temperatures, and drifts. All DMSP satellites fly in Sun-synchronous orbits near either the 0600–1800 or the 0930–2130LT meridians, and there are at least two operational DMSP spacecraft at any given time (Rich & Hariston, 1994). The data used in this study are from the DMSP F15 satellite, whose orbit is on the 2100LT meridian.

### 3.2. EIA Parameters

To study the characteristics of the EIA, the parameters are defined to represent the strength and density asymmetry of EIA as below:

Figure 2. (a) The solar wind speed $V_{SW}$, (b) interplanetary magnetic field (IMF) $B_z$ component, and (c) interplanetary electric field $E_y$ from 12 to 22 August 2003.
CTR = \frac{N_n + S_n}{2T_n}, \quad (1)

ASY_D = \frac{N_n - S_n}{N_n + S_n}, \quad (2)

where \(N_n\), \(S_n\), and \(T_n\) represent the electron density at the north crest, south crest, and the trough, respectively. When the EIA is not well developed, with one peak above the magnetic equator, the CTR is set as 1 and the ASY_D is set as \(-1\).

And the interhemispheric asymmetry of the locations of the EIA crests is defined:

ASY_L = \frac{D_N - D_S}{D_N + D_S}, \quad (3)

where the \(D_N\) represents the distance between the north crest and the trough, and \(D_S\) represents the distance between the south crest and the trough. When the value of ASY_L is positive (negative), it means that the northern (southern) crest is farther away the geomagnetic equator.

Furthermore, considering that the EIA asymmetry includes the density asymmetry and location asymmetry between the two crests, the location-weighted asymmetry indices are defined as below:

ASY_{w_C} = \frac{N_n - S_n}{N_n + S_n} \times \frac{D_N - D_S}{D_N + D_S}, \quad (4)

ASY_{w_L} = \frac{N_n \times D_N - S_n \times D_S}{N_n \times D_N + S_n \times D_S}, \quad (5)

ASY_{w_E} = \frac{N_n / D_N - S_n / D_S}{N_n / D_N + S_n / D_S}, \quad (6)

4. Results

4.1. The Responses of EIA to the Storm

Figure 3 displays the variations of electron density in 120°E derived from GRACE (top) and CHAMP (bottom) from 16 to 20 August, respectively.

During 16–20 August, the EIA observed in these days showed a complicated process at CHAMP altitude. With respect to the day before the storm started (16 August), the EIA crests moved toward the equator on 17 August. The density at the south crest and the trough had an enhancement, while the density at the north crest decreased. On 1 day after the storm started day (18 August), during the main phase of the storm, the density both at the two crests and above the trough all increased significantly, and the crests moved toward the poles. The increase was about 49% at the south crest and 73.1% at the north crest relative to the values of 17 August, respectively.

During the recovery phase of the storm, EIA decreased sharply. The density on 19 August at the two crests decreased about 50.4% relative to the values of 18 August and about 26% at south crest relative to the value of 17 August, and the crests moved equatorward about 7° in latitude. On 20 August, the EIA crests moved to the poles and the density at the crests increased, which was still remarkable less than the value on quiet day (16 August) and the storm started day (17 August).

In GRACE altitude, it can be seen that the EIA was also inhibited on 17 August and enhanced significantly on 18 August. On the storm started day, the two crests moved toward the equator, and the density at the two crests had a difference variations. The density at the north crest decreased slightly, while the density at the south crest increased about 15% relative to the values on the quiet day (16 August). On 18 August, during the main phase of the storm, the density both at the two crests and at the trough had a remarkable enhancement, with a 77% increase at the south crest and 111.2% increase at the north crest relative...
to the value of 17 August, respectively. The crests moved poleward to about 13.2°S and 12.7°N, respectively. During the recovery phase of the storm, EIA was inhibited significantly. The EIA disappeared on 19–20 August.

Compared the density from GRACE (Figure 3a) with that from CHAMP (Figure 3b), it can be noticed that the EIA displayed different morphology at different altitudes during the storm period. During the recovery phase, the EIA was still observed at 400 km but disappeared at 480 km, which means that the duration of EIA was diminished.

Figure 4 displays the variations of the EIA strength in 120°E derived from GRACE (top) and CHAMP (bottom) from 12 to 23 August, respectively.

As shown in Figure 4, during 16–18 August, the CTR at 480 km had similar variations with that at 400 km, and the CTR was larger at 400 km than that at 480 km. The EIA strength decreased before the SSC and then increased after the storm started and reached the maximum on 18 August, with a value of 1.97 at 480 km and 2.78 at 400 km, which means that the EIA strength was suppressed before the SSC on the storm started day and enhanced during the main phase of storm. And at 400 km, during the recovery phase of the storm, the values of CTR decreased to 1.28 on 19 August and 1.38 on 20 August, respectively, which were smaller than that on the quiet day before the storm started.

Figure 5 presents the variations of the EIA density asymmetry (top) and location asymmetry (bottom) in 120°E derived from GRACE and CHAMP from 12 to 23 August, respectively. The values of $\text{ASY}_D$ are not shown in the figures.

In general, the variations of density asymmetry at different altitudes were similar during the storm period. The values of density asymmetry at higher altitude (480 km) were larger than that at lower altitude (400 km), which means that EIA became more asymmetric at higher altitude. $\text{ASY}_D$ decreased before the SSC and increased during the main phase. The value of $\text{ASY}_D$ on 17 August was very small and about half of that on 16 and 18 August, which represents that EIA was almost symmetric before the SSC.
The variations of the location asymmetry were different with the variations of density asymmetry. During 16–18 August, the density asymmetry decreased first and then increased. The location asymmetry at CHAMP altitude decreased gradually. The value of the location asymmetry index was negative on 17 August means that the distance between the north crest was smaller than that the distance between the south crest and the equator. At GRACE altitude, the location asymmetry increased first and then decreased. And in these days, the distance between the north crest and the equator was always larger than that between the south crest and the equator, which was different from the result derived from CHAMP.

Compared Figure 4 with Figure 3, the variations of CTR and density asymmetry at 400 km and 480 km were similar during the storm period, with a minimum before the SSC and a maximum during the main phase of the storm.

Figure 6 presents the variations of the three location-weighted asymmetry indices defined in section 3 in 120°E derived from GRACE and CHAMP from 12 to 23 August.

In Figure 6, it can be seen that the variations of three location-weighted asymmetry indices were different during the storm period. The index ASYwo had a similar variation with that of density asymmetry index ASYD, and the variations derived from different altitudes were similar. On 17 August, ASYwo and ASYD decreased, reached a minimum before the SSC, and increased during the main phase and recovery phase of the storm. The variations of ASYWT and ASYWE were different from that of ASYwo. For the index ASYWT, it increased and reached a maximum on 18 August and then increased during 19–20 August. For the index ASYWE, the absolute value reached a maximum on 17 August and decreased on 18 August, which was reverse with the variation of ASYwo, and the value of ASYWE increased during 19–20 August.

It can be noted that the values of the indices during the recovery phase (19–20 August) increased with respect to that during the main phase of the storm, which means that EIA became more asymmetric.
4.2. The Variations of EIA at Different Altitudes

Figure 7 shows the latitudinal variations of electron density from 16 to 20 August in EIA region in 120°E derived from CHAMP, GRACE, ROCSAT-1, and DMSP satellites, respectively. The time difference between the CHAMP pass and GRACE pass was about 1.5–2 h for the same longitude sector in these days. The variations of electron density from DMSP are the right y-axis, and the others are the left y-axis.

From Figure 7, it can be seen that the EIA structure was not observed by DMSP at 840 km in these days; it appeared at 400 km and 480 km and disappeared from 600 km on the quiet day before the storm started. On the storm day (before the SSC), the EIA was also seen only at 400 km and 480 km. The crests at higher altitudes expanded to the poles in these 2 days, and then the crests moved to the equator on 18 August.

During the main phase of the storm, on 18 August, the EIA was still developed at 600 km and disappeared at 840 km, which means that the EIA was enhanced. During the recovery phase of the storm, EIA was only formed at 400 km; it disappeared since 480 km which means that EIA was inhibited.

Moreover, it can be noticed that the density depletion or enhancement (irregularity) was observed in low-latitude region at 600 km on 17 August, but not be recorded by CHAMP at 400 km and by GRACE at 480 km, it may be interpreted that the irregularity had been moved upward to the topside ionosphere when the satellites passed the region.

DMSP recorded a density enhancement (plasma blob) in Northern Hemisphere. On 18 August, both ROCSAT-1 and DMSP observed a density enhancement in low-latitude region of Southern Hemisphere after local sunset, which was not observed by CHAMP and GRACE. On 20 August, ROCSAT-1 and DMSP also recorded the density depletion (plasma bubble) in Southern Hemisphere, while was not seen from CHAMP and GRACE. The ROCSAT-1 at lower orbit recorded more irregularities than that by the DMSP at higher altitude, which means that the irregularity moved upward and decayed with the height. It also can be noticed that the irregularity (density depletions) moved farther away from the equator on 18 August than that on 17 August.
August. On 17 August, the irregularities were observed in EIA region, and the irregularities were observed around the EIA south crest on 18 August.

4.3. Scintillation During the Storm Period

Figure 8 displays the S4 index derived from GPS observations from 15 to 22 August at Vanimo (−2.7°N, 141.3°E; Geom. Lat. −11.19°N).

It can be seen that there were obvious scintillation occurred during the main phase of the storm on 17 and 18 August. The scintillation occurred about 1100 UT on 17 August, before the SSC, lasted for about 3 h and decayed before the midnight. After the midnight, there were few weak scintillations. The maximum S4 reached about 0.62. On 18 August, there were short-duration enhanced scintillations before and after the midnight, which occurred at about 1400 UT and 1800 UT, respectively, which was later than that on 17 August. The value of S4 reached above 0.7, which was larger than that on 17 August. On the other days, before and after the storm started day, the occurrences of scintillation were not remarkable than that during the main phase of the storm, except some few weak scintillations.

Figure 6. Weighted asymmetry index of EIA derived from GRACE and CHAMP in 120°E during the August 2003 storm period, respectively.
Figure 7. Shows the variations of electron density from 16 to 20 August in EIA region in 120°E derived from CHAMP, GRACE, ROCSAT-1, and DMSP satellites, respectively. The variations of electron density from DMSP are the right $y$ axis, and the others are the left $y$ axis.
5. Discussions

The day-to-day variability of the EIA is controlled dominantly by the electrodynamics in the ionosphere, and the EIA may be suppressed or enhanced during the storm periods (Kassa et al., 2015; Mendillo, 2006).

As shown in Figures 3 and 4, EIA was inhibited before the SSC on the storm started day. The two crests moved toward the equator and the density decreased accordingly; the EIA strength representing by CTR also decreased at both CHAMP altitude and GRACE altitude on 17 August. In Figure 2, it can be seen that the IEF was westward before the storm started and reached a maximum around the SSC and then turned to eastward. The IEF could penetrate to the low-latitude ionosphere and the electric field in equatorial and low-latitude ionosphere decrease, resulting in a weaker fountain effect and EIA inhibition. But the westward IEF was very small before SSC on 17 August and its effect on the ionospheric electric field was also very weak, which can be ignored. Moreover, it also should be noted that the values of density asymmetry index shown in Figure 5 decreased at 400 km and 480 km, which means that EIA became more symmetric relative to the day before the storm started day. The major factor causing the asymmetry is the neutral wind (Aydogdu, 1988; Lin et al., 2005). The more symmetric EIA means that the weaker effect of the neutral wind. Furthermore, it can be seen that the scintillation on 17 August was the most remarkable during the storm periods from Figure 8. Some studies have shown that the meridional wind would suppress the occurrence of ionospheric irregularity and scintillation (e.g., Abdu et al., 2006; Krall et al., 2009; Mendillo et al., 2001). The strong occurrence of scintillation on 17 August represents that the meridional wind was weak or absent. Thus, it can be concluded that the neutral wind was very weak or absent before the SSC on 17 August, leading to the EIA suppression and the occurrence of scintillation.

During the main phase of the storm, EIA was enhanced significantly. The two crests moved to the poles and the density above the crests increased significantly, the EIA structure developed at higher altitude.
Generally, the eastward electric field may be enhanced due to the PPEF and a greatly enhanced equatorial plasma fountain is formed to produce a electron density enhancement in low and middle ionosphere (Balan et al., 2017, and references therein). As shown in Figure 2, the IEF was always eastward with a maximum of 8 mV/m during the main phase of the storm; the ionospheric electric field would be enhanced due to the PPEF. The density at the crests on 18 August increased more than 50% with respect to that on 17 August, and the density at higher altitude (GRACE) increased more than that at lower altitude (CHAMP), which could be reach about 110%. It also should be noted that the values of density asymmetry index at different heights during the main phase became larger than that on 17 August, which means that the EIA became more asymmetric during the main phase. In addition, the irregularity observed by ROCSAT-1 and DMSP shown in Figure 7 moved farther away from the equator on 18 August than that on 17 August, which means that the existence of the neutral wind. Some simulation results have shown that the meridional neutral wind also plays an important role in leading to the EIA enhancement in addition to the enhanced eastward electric field (Balan, Alleyne, et al., 2009; Balan, Shiokawa, et al., 2009; Lin et al., 2005). The equatorward neutral wind would reduce poleward plasma flow and raise the ionosphere to high altitudes of reduced chemical loss and cause a positive storm in low-latitude ionosphere, also resulting in the density asymmetry of the crests. It can be concluded that the neutral wind affected the development of EIA during the main phase of the storm; the enhancement of EIA on 18 August can be attributed to the effects of the enhanced electric field and neutral wind.

Moreover, the enhanced eastward electric field is favor to the development of Rayleigh-Taylor (R-T) instability in equatorial and low-latitude ionosphere, leading to the occurrence of the irregularity and scintillation (Luo et al., 2009; Sultan, 1996). The neutral wind also plays an important role in the initiation and evolution of irregularity, the meridional wind is thought to inhibit the growth of the R-T instability, and vertical wind promote the development of the R-T instability (Mendillo et al., 1992). As shown in Figures 7 and 8, on 17 August, the density disturbance in southern hemisphere was only observed by ROCSAT-1, and the scintillation was recorded at Vanimo, a low-latitude station in Southern Hemisphere. And the duration of the density disturbance observed by ROCSAT-1 was long, which means that the development and evolution of irregularity was enhanced. Thus, it can be seen that the scintillation at Vanimo was strong and long duration. On 18 August, both ROCSAT-1 and DMSP observed the plasma blob, leading to the scintillation observed by GPS. It should be noted that the scintillation observed by GPS was later than that on 17 August, and the satellite observations were consistent with it. It also can be noted that the scintillation on 18 August was weaker than that on 17 August. The results represent that the development of irregularity was promoted before the SSC and inhibited during the main phase, which may be related with the neutral wind. Before the SSC, due to the absence of the meridional wind, under the effect of electric field, the R-T instability was initiated and irregularity developed and moved into the topside ionosphere. During the main phase of the storm, though the ionospheric electric field was enhanced by the PPEF, the meridional neutral wind inhibited the growth of R-T instability, causing the slower development of the irregularity and helping the irregularity move to the higher-latitude region.

Compared the variations of EIA with the occurrence of scintillation during the storm period, it can be seen that the EIA enhancement may not result in the occurrence of scintillation. On 17 August, the EIA strength was weaker during the storm period, with a minimum value of CTR, the irregularity was observed at 600 km, and the scintillation was strong and long duration. The CTR reached a maximum on 18 August; the scintillation was short duration which was less remarkable than that on 17 August. Mendillo et al. (2001) and Thampi et al. (2008) indicated that the irregularities were likely to occur when the EIA strength was strong. That was not consistent with the results of Mendillo et al. (2001) and Thampi et al. (2008), which means that the electrodynamic in low-latitude ionosphere became complicated under the disturbed condition and the storm time neutral wind plays an important role in the variations of EIA and occurrence of irregularity and scintillation. Moreover, compared the results in Figure 4 with the occurrence of scintillation shown in Figure 8, it can be seen that when the EIA density is more symmetric, the scintillation is more likely to occur. The index ASYD representing EIA density asymmetry and the ASYW0 may be related with the occurrence of scintillation, while the variations of ASYW1 and ASYWc could not be related with the occurrence of scintillation. When the absolute value of ASYD is smaller, which means that the EIA is more symmetric, the occurrence of scintillation is higher. When the absolute value of ASYD is larger, which means that the EIA is more asymmetric, the occurrence of scintillation is lower.
During the recovery phase of the storm (19 and 20 August), the EIA was suppressed again, disappeared at GRACE altitude and the density above the crests decreased at CHAMP altitude, which means that the fountain effect was inhibited due to the westward electric field. The variations from satellite observations were different from the results about the August 2003 storm in 48.2°W reported by Sahai et al. (2007) and consistent with the results from Wen et al. (2007) in China region. Sahai et al. (2007) reported that the strong positive storm occurred during the main and recovery phase of the storm, and the density enhancement above the equatorial anomaly on the night of recovery phase was much stronger than that on the night of main phase. The different response to the storm during the recovery phase in different longitude sectors means that the storm effects on the ionosphere depend on the longitudes (Xu et al., 2008), especially during the recovery phase when the disturbance wind dynamo dominant the equatorial and low latitudes (Xiong et al., 2016). Furthermore, it can be noticed that the EIA density asymmetry and location asymmetry shown in Figures 5 and 6 increased with respect to the earlier several days, which means that the existence of the neutral wind and the effect of the neutral wind was remarkable. Moreover, it can be seen from Figure 8 that the occurrences of scintillation on 19 and 20 August were suppressed, which also means that the effect of meridional wind was remarkable. The IEF $E_y$ shown in Figure 2 was westward and reached a minimum about $-7.8$ mV/m around 1200 UT on 19 August. The zonal electric field in background ionosphere may be decreased due to this westward field, resulting in the suppression of EIA. The observations from CHAMP and GRACE were prior to 1200 UT; the effect of the penetrated westward electric field would be weak. And the IEF on 20 August was small, the effect of the westward electric field on the inhibition of EIA can be ignored. Thus, The EIA inhibitions during the recovery phase of the storm observed at 400 km and 480 km may be caused primarily by the meridional neutral wind, which also leading to inhibit the occurrence of irregularity and scintillation in low-latitude ionosphere. It is consistent with the reports reviewed by Balan et al. (2017); the major factor causing the inhibition of EIA is the storm time equatorward neutral wind during the recovery phase of the storm.

The variations of location asymmetry index shown in Figure 5 were different at 400 km and 480 km, which may be related with the neutral wind. The position of EIA crests is affected dominantly by the neutral wind, and the neutral wind varies with the altitudes. Thus, the positions of the crests were different at different altitudes, and the location asymmetry index displayed different variations. On the other hand, the recombination loss is smaller at higher height, which means that the recombination loss may be a factor to affect the asymmetry of EIA at different altitudes.

Above all, it can be concluded that the EIA was inhibited before the SSC on the storm started day (17 August), due to the penetration of westward IEF and the absence of the neutral wind; thus, the scintillation was strong and long duration. During the main phase of the storm, the EIA was enhanced significantly under the effect of the enhanced eastward electric field and meridional neutral wind, and the development of irregularity was inhibited, scintillation became weaker and short duration. During the recovery phase of the storm, the EIA was inhibited pronouncedly due to the storm time neutral wind, and the R-T instability was inhibited, leading to the absence of the scintillation.

6. Conclusions

In this paper, the variations at different altitudes in 120°E in EIA during the 17–20 August 2003 storm are investigated from CHAMP, GRACE, ROCSAT, and DMSP observations. The results can be concluded as below:

1. The EIA was suppressed before the SSC on the storm started day and during the recovery phase of the storm; EIA was enhanced significantly during the main phase of the storm.
2. The variations of EIA strength and density asymmetry during the storm period were similar at CHAMP and GRACE altitudes.
3. The variations of EIA location asymmetry were different at CHAMP and GRACE altitudes, which were different from that of EIA density asymmetry.
4. The irregularities at 600 km and long-duration scintillation were recorded before the SSC on storm started day, when the EIA was inhibited. The irregularities at different altitudes and short-duration scintillation were observed during the main phase of the storm, when the EIA was enhanced significantly. The results indicated that the EIA enhancement may not result in the occurrence of scintillation.
5. The EIA enhancement can be attributed to the enhanced electric field due to the prompt penetrated IEF and the storm time neutral wind, while the suppression of EIA on 17 August can be attributed to the absence of the equatorward neutral wind, which varied with the altitudes. The EIA inhibition during the recovery phase may be caused mainly by the neutral wind. The neutral wind is the crucial factor causing the variations in EIA and the occurrence of scintillation.

We only studied the response of EIA to the storm in one longitude sector in this paper; the global response should be studied in future work. Furthermore, the relationship between the variations of EIA and the occurrence of irregularity and scintillation needs to be investigated in more details.

References


