Structures of Multiple Large-Scale Traveling Ionospheric Disturbances Observed by Dense Global Navigation Satellite System Networks in China

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Abstract The propagation features of three groups of multiple large-scale traveling ionospheric disturbances (LSTIDs), which formed on 22 June 2015 during the passage of LSTIDs that propagated in different directions simultaneously over China, were investigated using the total electron content data from 341 Global Navigation Satellite System stations. The ranges of the periods and horizontal phase velocities of the LSTIDs were ~40–120 min and ~209–750 m/s, respectively. The first two groups were observed during 0700–1400 UT. The meeting of LSTIDs propagating in opposite directions yielded a differential of total electron content (DTEC) variation net structure, where the enhancement and reduction of DTEC amplitude appeared successively and reached a maximum amplitude of ~16% in the overlapping areas. DTEC series based on the observations of geostationary satellites from China’s BeiDou Navigation Satellite System addressed the propagation and meeting of fronts. The third group contained two southward propagating LSTIDs, a northward LSTID, and a northwestward one. The joint propagation of the northward LSTID and northwestern LSTID led to a large-amplitude mixed front, which was broadened both in latitudinal and meridional range. The mixed front moved northward at a distance of ~1,500 km until it separated into two fronts, due to the difference in propagation velocities and directions. After separation, the northward LSTID continued to propagate and encountered a southward LSTID. The northwestward LSTID dissipated within 30 min in the northwest of China. Such multi-LSTIDs have mainly been observed previously in equatorial regions, and our observations imply that the propagation of LSTIDs in the mid and low latitudes is more complicated than previously reported.

1. Introduction

Large-scale traveling ionospheric disturbances (LSTIDs) are an important dynamic mechanism in the ionosphere that transfers energy and momentum vertically and horizontally. Previously, many works have reported observations and simulations of the equatorward propagation of LSTIDs. Some activities in the auroral region (e.g., the enhancement of auroral electrojets, particle precipitation, and moving supersonic auroral arcs) are the basic sources of LSTIDs (Hunsucker, 1982). Chimonas and Hines (1970) presented at least two mechanisms whereby auroral electrojet currents may affect the neutral atmospheric gas and excite LSTIDs. One mechanism is through the Lorentz force and the other is Joule heating. At midlatitude and high latitude, equatorward LSTIDs from high latitudes are frequently observed by Global Navigation Satellite System (GNSS) networks, such as those located in North America (Ding et al., 2007) and Europe (Nykiel et al., 2017). With combined observations from incoherent scatter radar and a GNSS network, Nicolls et al. (2004) presented the three-dimensional structures of LSTIDs over North America. Williams et al. (1988) observed the excitation and propagation of LSTIDs over northern Europe and the UK with a combination of European Incoherent Scatter Scientific Association (EISCAT) incoherent scatter radar, HF Doppler, and a chain of ionosonde data. Lyons et al. (2019) observed several LSTIDs over North America relating to different types of identified auroral oval disturbances based on all-sky imaging data and Global Positioning System (GPS) total electron content (TEC) data. Shiokawa et al. (2002) observed an equatorward LSTID over Japan based on airglow data and a north-south chain of ionosondes and analyzed the
relationship between LSTIDs and poleward wind pulses. Tsugawa et al. (2004) carried out a statistical study of LSTIDs using TEC data from the GPS Earth Observation Network (GEONET) in Japan and found the occurrence of LSTIDs to be related to the seasonal variation of geomagnetic disturbances. In the middle and low latitudes, Ding et al. (2012) observed several LSTIDs with GPS network and ionosonde data over China, and discussed the effect of dissipative factors of atmospheric gravity waves on LSTIDs.

Compared with southward LSTIDs, the occurrence of northward LSTIDs has been less reported. Lei et al. (2008) used the Coupled Magnetosphere Ionosphere Thermosphere 2.0 model to simulate and compare with observations of LSTID events by GEONET over Japan, revealing an obvious hemispheric asymmetry in the propagation of traveling atmospheric disturbances. Hayashi et al. (2010) studied northward LSTIDs across the equator, moving from the Southern Hemisphere to the Northern Hemisphere, based on SuperDARN Hokkaido HF radar and GEONET observations. Cai et al. (2011) described LSTIDs propagating across the northern polar cap using EISCAT Svalbard Radar data. Ding et al. (2013) observed two northward LSTIDs over China. These northward LSTIDs exhibit narrower phase fronts and smaller amplitude compared to southward ones in the same region. The statistical analysis of Ding et al. (2014) indicated that the occurrence of northward LSTIDs is greater in China than in North America. China's magnetic latitude is lower than North America's by ~20°. For some northward LSTIDs that are excited in the Southern Hemisphere auroral oval and propagate across the equatorial area, their amplitude tends to decrease because of dissipation while propagating.

Previous studies have mainly discussed southward LSTIDs or northward ones separately, with few having reported situations where LSTIDs exist simultaneously or encounter one another. Wan et al. (1996) analyzed data from a HF Doppler array and found multi-TIDs events. Guo et al. (2014) reported constructive interference between two large-scale gravity waves that were excited in southern and northern auroral regions and observed an enhancement of neutral density of the nightside equatorial area because of interference. Pradipta et al. (2016) presented observations of two LSTIDs propagating from opposite hemispheres and interacting near the geomagnetic equator and found that these LSTIDs propagated continuously with an unchanged speed after their interaction.

Previous observations indicate an occurrence rate of 26.4% for southward LSTIDs and 7.4% for northward ones during the geomagnetically disturbed time (Ding et al., 2014). Therefore, it should be possible to observe the simultaneous propagation of both southward and northward LSTIDs over China. In this paper, we present observations of multi-LSTIDs on 22 June 2015 during a severe geomagnetic storm, based on dense GNSS networks in China. Combined with geostationary (GEO) satellite results from China's BeiDou Navigation Satellite System, we discuss the impact of multi-LSTIDs events on the ionosphere and the possible source of each LSTID.

2. Data and Methods

The TEC data were collected from 341 GNSS stations in the Crustal Movement Observation Network of China (CMONOC) and the International GNSS Service (IGS). Moreover, we also utilized GEO satellite data from five receiving stations of China’s BeiDou Navigation Satellite System—namely, Beijing (116.38°E, 39.98°N), Wuhan (114.39°E, 30.50°N), Hanshou (112.21°E, 28.70°N), Shaoyang (111.46°E, 26.89°N), and Sanya (109.62°E, 18.35°N). These stations belong to the Beijing National Observatory of Space Environment, IGGCAS (Institute of Geology and Geophysics, Chinese Academy of Sciences). Figure 1 shows the locations of the GNSS receiving stations in China and surrounding regions. For more information on CMONOC, readers are referred to Ding et al. (2013).

Based on these observation data, we constructed two-dimensional differential-of-TEC (2D DTEC) maps to monitor LSTIDs over China. First, we calculated all ionospheric pierce points along all paths between the GNSS satellites and the ground receivers, based on the single-layer model of the ionosphere, and filtered the TEC background trends from the original series to obtain the TEC perturbation. Specifically, the TEC background trend was expressed as a second-order function of latitude, as well as a one-order function of coordinated universal time (Ding et al., 2012). Second, we divided the region (70–170°E, 10–60°N) into pixels of 1° longitude × 1° latitude in size and obtained the amplitude of TEC variation in each pixel by taking the median of the TEC variations of all ionospheric pierce points crossing this pixel during the observation. Third, we obtained a sequence of 2D DTEC maps with a temporal resolution of 5 min. If LSTIDs passed...
through, we would find their moving band-like structures on the map. By analyzing these structures, we were able to gain several basic physical parameters of the LSTIDs, such as their periods, horizontal phase velocities, azimuthal angles, and amplitudes.

This method alone, however, is insufficient for the analysis of multi-LSTIDs. As the structures of the fronts of multi-LSTIDs mix together, it is difficult to distinguish each specific wave front from a 2D DTEC map clearly. Therefore, to analyze the structures of multi-LSTIDs precisely, we needed to set some slices along meridional and zonal lines and then calculate the spatial and temporal variations of the DTEC amplitude along each slice. In this way, we were able to separate each LSTID from the mixed state effectively and track the propagation features of multi-LSTIDs.

3. Observations

Observations were conducted during a severe geomagnetic storm, with the maximum Kp index exceeding 8+, from 21 to 26 June 2015. Figure 2a shows the temporal variation of the SYM-H index during this storm, as well as the AU and AL indices during 21–22 June 2015. The sudden commencement of the storm took place at ~1800 UT 21 June, when the SYM-H value increased to 46 nT. Then, the value dropped to the minimum of ~208 nT on 23 June and recovered later. On 22 June, two sets of multicycle substorms occurred during the main phase of the storm (Partamies et al., 2013). The first occurred at 0600 UT. During the expansion phase of the first cycle, the peak value of the AU index rose to a maximum of 655 nT, and the value of the AL index fell to a minimum of ~695 nT. The second set started at 1400 UT. The peak value of the AU index rose to 1473 nT, and the value of the AL index fell to a minimum of ~1508 nT. During the main phase of the magnetic storm, a slight SYM-H peak of 38 nT and relatively large peak of 88 nT occurred at 0550 and 1837 UT on 22 June, respectively.

Three groups of multi-LSTIDs events were observed on 22 June 2015 during the initial and main phases of the storm. The first two were observed after the growth phase of the first set of substorms, whereas the third was during the expansion and recovery phase of the second set (three black arrows in Figure 2b). Next, we present in detail the observations of the three groups separately.
3.1. First and Second Groups of Multi-LSTIDs

Figure 3a is a snapshot of the 2D DTEC map at 0730 UT with four slices set along the meridional and zonal lines as 110°E, 43°N, 36°N, and 30°N. The DTEC variations in the UT-distance plane along each slice are presented in Figures 3b–3e. The southward and northward LSTID fronts are marked as red and black.

Figure 2. Temporal variations of (a) SYM-H index, (b) provisional AU and AL indices, and (c) Kp index. The red bars represent Kp ≥ 4, and the yellow ones represent Kp < 4. The data have a temporal resolution of 1 min and are available from OMNIWeb data services (http://omniweb.gsfc.nasa.gov) and WDC for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html) (World Data Center for Geomagnetism, Kyoto et al., 2015a, 2015b). The three black arrows in Figure 2(b) represent the start times of three multi-LSTIDs events.

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Figure 3. (a) Slices set on the 2D DTEC map. (b–e) DTEC variations along each slice in the UT-distance plane on 22 June 2015. (f) Calculation of the TID horizontal phase velocity based on the speed results along the meridional and zonal slices. The color map indicates the DTEC value, with contours of red representing positive DTEC and blue representing negative DTEC. The letters S and N represent the southward and northward LSTIDs, respectively, with the red and black dashed lines representing the southward and northward LSTID fronts, respectively.
dashed lines, respectively. Two groups of LSTIDs were observed. One appeared during ~0700–0900 UT and the other during ~0900–1400 UT. We describe them separately as follows.

The first group of multi-LSTIDs comprised a southward LSTID and a northward one. As shown in Figure 3b, two LSTIDs occurred simultaneously at ~0700 UT and lasted until ~0900 UT. Their initial amplitudes were 0.6 TECU and 0.3 TECU, respectively. They propagated with a period of 75 and 90 min, respectively. The two LSTIDs encountered one another around the north of China, and their fronts with the same polarity met in area 1 and area 2. The variation of DTEC in area 1 was faint, but the DTEC in area 2 had a negative enhancement of −0.7 TECU.

Figures 3c–3e show the zonal structures of multi-LSTIDs. Figure 3c shows two southward propagating fronts; the northward LSTID did not reach slice c. As the phase fronts were nearly vertical to the UT axis during 0700–0900 UT (Figure 3c), these fronts propagated southward almost without a zonal velocity component. Then, both slice d and slice e observed an eastward propagating positive front, indicating that the northward LSTID propagated with an eastward velocity component.

Note that the velocity measured from the slope of the phase fronts in Figures 3b–3e was not the actual velocity of the movement of fronts along meridional or zonal lines. The actual LSTID velocity \( V_{ph} \) and azimuthal angle \( \theta \) (clockwise from north) were calculated according to the geometry drawn in Figure 3f:

\[
\begin{align*}
V_{ph} &= \frac{v_1 v_2}{\sqrt{v_1^2 + v_2^2}} \\
\theta &= \arctan \left( \frac{v_2}{v_1} \right)
\end{align*}
\]

where \( v_1 \) is the phase front velocity measured along the zonal slice and \( v_2 \) is the velocity measured along the meridional slice. Using this method, we computed the propagation of the LSTIDs. The southward LSTID propagated at a velocity of 476 m/s and an azimuth of ~180°. The northward LSTID's velocity was 354 m/s and propagated with an azimuth of 25°.

The second group of multi-LSTIDs was observed during 0900–1400 UT. As shown in Figure 3b, a northward LSTID and a southward one had periods of 112 and 120 min, respectively. Both exhibited a larger amplitude and longer period than the first group. The fronts of the two LSTIDs met within ~25°N–37°N, over Central China. This yielded several enhancements or reductions of DTEC, with the maximum exceeding 0.64 TECU. Figure 3c shows the zonal structures of the LSTIDs crossing the latitude of 43°. Three positive phase fronts were observed in slice c during 0900–1200 UT (Figure 3c). Since slice c was ~6°N north of the range in which the two LSTIDs encountered one another, these fronts should belong to the southward LSTID. According to equation 1, the southward LSTID's phase velocity \( V_{ph} \) and azimuthal angle \( \theta \) were 366 m/s and ~180°.

Slice d was located 7° south of slice c and was situated within the latitudinal range where the LSTIDs encountered one another. During 0930–1130 UT, three fronts—marked with red dashed lines in Figure 3d—exhibited the same period and velocity as those of the southward LSTID (Figure 3c). Moreover, the propagation time and velocity of these fronts were consistent with the distance between slices c and d. Therefore, these fronts belonged to the southward LSTID. For the two fronts marked with black dashed lines during 1100–1300 UT in Figure 3d, they should belong to the northward LSTID. As we can see, the fronts of the two LSTIDs met with each other at 1100 and 1200 UT, respectively (area 4 in Figure 3d). Based on equation 1, the northward LSTID's velocity and azimuthal angle were 209 m/s and −17° (clockwise from north).

The southernmost slice (slice e) was still within the range in which the LSTIDs encountered one another. Three clear fronts were observed in slice e during 1100–1300 UT (Figure 3e). They had the same period and direction as the fronts of the northward LSTID in Figure 3d. Therefore, these fronts belonged to the northward LSTID. Despite the southward LSTID propagating to the latitude of slice e (30°N) in Figure 3b, the fronts of the southward LSTID are not clear in Figure 3e. This may be related to the dissipation and interference of the northward LSTID.

### 3.2. Third Group of Multi-LSTIDs

The third group of multi-LSTIDs is shown in Figure 4. This event was observed during 2100–2400 UT. Figure 4a is a snapshot of the 2D DTEC map at 2215 UT over China. Five slices (black lines with arrows)
are set in Figure 4a, and then the spatial and temporal variations of DTEC along each slice in UT-distance planes are plotted in Figures 4b–4f.

Figures 4b and 4c show the propagation of LSTIDs along two meridional slices (slices b and c). Both southward and northward LSTIDs were observed in slice b (Figure 4b). Five fronts of southward LSTIDs appeared

Figure 4. (a) Slices set on the 2D DTEC map. (b–f) DTEC variations in the UT-distance plane along each slice on 22 June 2015. The slices are along the meridional and zonal lines of 120°E, 110°E, 25°N, 37°N, and 46°N.
during 2030–2300 UT, which are marked with red dashed lines. Given the time intervals among fronts, we found these fronts to belong to two southward LSTIDs with periods of 80 and 40 min, respectively. Despite the clear appearance of fronts in slice b, the fronts of the southward LSTIDs were not noticeable in slice c (Figure 4c). Note that slice c was located ~1,000 km west of slice b. This indicates there is a limit to the propagation of these southward LSTIDs in west China.

Figures 4d–4f show the propagation of LSTIDs along three zonal slices (slice d [25°N], slice e [37°N], and slice f [46°N]). Given the time intervals among fronts and the occurrence time, five fronts of southward LSTIDs can be clearly seen in two slices in the north—namely, slices e and f (Figures 4e and 4f, red dashed lines). The fronts appeared first in slice f and then in slice e, indicating the meridional propagation velocities of two southward LSTIDs of ~500 and 750 m/s. This is consistent with the velocity measured from Figure 4b. In addition, the fronts were almost perpendicular to the UT axis, which means that both the azimuthal angle of two southward LSTIDs were ~180° (clockwise from north). However, these fronts could not be seen in slice d. This implies two southward LSTIDs did not reach 25°N.

The propagation process of northward LSTID was more complex than the southward ones. Three fronts of northward LSTID were observed in slice b (Figure 4b, black dashed lines). Besides, an obvious distortion of the fronts could be seen during 2200–2300 UT, indicating a change in meridional velocity from ~1,000 m/s to ~490 m/s. The distortion could also be seen in slice c (Figure 4c).

The distortion of fronts could also be observed in the southernmost zonal slice (slice d). As shown in Figure 4d, we observed two phase fronts (black dashed lines) with the same duration when the northward LSTID appeared in Figures 4b and 4c. The distortion of the fronts in slice d indicates a change in propagation direction from northward to northwestward. However, this distortion was not seen in the other two zonal slices (slices e and f). As shown in Figures 4e and 4f, two northward fronts appeared in slices e and f (black dashed lines), indicating a northward propagation. As the fronts were nearly vertical to the UT axis, these phase fronts in Figures 4e and 4f belonged to an LSTID that propagated northward with few zonal velocity components.

Based on the analysis above, the propagation structures of the northward LSTIDs in Figure 4 can be summarized as follows. In southern China, the northward wave structure was initially made up of a northward LSTID and a northwestward LSTID. During 2100–2230 UT, their phase fronts were mixed. This yielded a front with broadened width and enhanced perturbation amplitude in area 1 in Figures 4b–4d. The mixed fronts moved northward at a distance of ~1,500 km until they arrived in Central China at ~2230 UT, where the fronts of the two northward LSTIDs separated because of their different zonal velocity components. According to equation 1, the northwestward LSTID propagated with a velocity, period, and azimuth of 300 m/s, 76 min, and −41° (clockwise from north). The northward LSTID moved with a velocity, period, and azimuth of 700 m/s, 70 min, and 0°.

After the two LSTIDs separated, their phase fronts became narrower (area 2, Figures 4b–4d). According to Figure 4c, the northwestward LSTID continued to propagate a short distance of ~400 km until it was not observable owing to dissipation. Hence, the northward LSTID did not reach the latitudes of slices e and f (Figures 4e and 4f). Given the occurrence time, the fronts marked with black lines in Figures 4b, 4e, and 4f after 2230 UT belonged to the northward LSTID. According to these figures, the northward LSTID continued to propagate to the latitude of 46°N after separation and then encountered the southward LSTID. Thereafter, this northward LSTID continued to travel until it was not observable at the latitude of ~48°N.

### 3.3. BeiDou GEO Observations

Three groups of multi-LSTIDs were also observed in BeiDou GEO data. Figure 5 depicts five time series of DTEC from the BeiDou GEO-01 observation chain. We band-pass filtered the data and set the top and bottom bounds of the period as 130 and 30 min, respectively. We can see all three groups of LSTIDs in Figure 5. Red frames mark the time ranges when the three groups were observed.

During 0600–0900 UT, a northward LSTID appeared clearly in the BeiDou observations (Figure 5). This was not consistent with the GNSS observations, in which a northward LSTID and a southward one were observed simultaneously (Figure 3b). We found that the latitudinal range where we could observe the
southward LSTID in the GNSS data was beyond the observational ranges of the IGGCAS BeiDou stations we
used. Hence, the southward LSTID was not found in the BeiDou GEO observations.

In the second frame, an obvious southward positive front and a northward positive front could be observed
during 0900–1400 UT. The fronts moved toward one another and met around Shaoyang station. This yielded
an enhancement of DTEC at that location. This enhancement can also be observed at the latitude of ~25°N
in Figure 3b during 1030–1100 UT.

In the third frame, a southward positive front and a large-amplitude northward positive front were observed
during 2100–0000 UT. They propagated in an opposite direction and met around Shaoyang station. The
northward front with large amplitude overlapped the southward front from Hanshou station to Shaoyang
station during 2200–2300 UT. This was consistent with the result from the GNSS observations in that the
northward LSTID covered the first southward LSTID after they encountered one another during 2200–
2300 UT (Figure 4b). Nevertheless, the other two LSTIDs in the third group cannot be observed in
Figure 5. We estimated that the observation of DTEC series from some single stations was not enough to pre-
sent the whole status of multi-LSTIDs events, due to a wide propagation range of LSTIDs.

Note that a large-amplitude (~2 TECU) disturbance was observed at all BeiDou receivers during ~1930–2000
UT (Figure 5). This was an isolated LSTID event. Because its time of appearance was outside that of the 2D
DTEC maps’ observation time, it was not observed in the 2D DTEC maps (Figures 3 and 4).

4. Discussion

This paper has analyzed the wave structures of multi-LSTIDs over China during a severe magnetic storm.
Multi-LSTIDs events were observed three times over China on 22 June 2015. Previous studies have shown
that such multi-LSTIDs events are mainly observed in the equatorial area rather than in the mid-low
latitudes (Guo et al., 2014; Pradipta et al., 2016). It is inferred, therefore, that the propagation of LSTIDs during storms at middle and low latitudes is more complicated and occurs more frequently than previously reported.

The first two groups of multi-LSTIDs were observed during the initial phase of the storm, and the third group was shown during the main phase of the storm (Figure 2a). A large number of observations of LSTIDs were presented during storm (Afraimovich et al., 2000; Ding et al., 2007; Shiokawa et al., 2002; Zakharenkova et al., 2016). Many of them were observed during the main phase and recovery phase of storm. As shown in Figures 3 and 4, the mean amplitude of the third group was larger than the former two groups. Afraimovich et al. (2001) found that the intensity of TIDs was highly correlated with the time derivative of Dst index. But the direct correlation between the amplitude of LSTID and the step of storm has not been presented yet.

The sources of multi-LSTIDs are also more complicated than single LSTID events. It has been widely accepted that the auroral zone is the most usual source region in storm time (Guo et al., 2014; Hunsucker, 1982; Pradipta et al., 2016). Hereafter, we discuss the possible sources of multi-LSTIDs and their relationships with activities in the auroral oval.

Based on the auroral oval images from DMSP/SSUSI on 22 June 2015, we show the position of the auroral oval equatorward boundaries on this day. The auroral oval images we used were obtained from http://ssusi.jhuapl.edu/, and the data are available from the website of DMSP SSJ (http://sd-www.jhuapl.edu/auroral/) (Newell et al., 1996a, 1996b). According to the location, time, and phase velocity of LSTIDs observed in China, we calculated the virtual excitation time of each LSTID near the auroral oval equatorward boundaries and estimated the possibility of each LSTID coming from the auroral oval. For example, the southward LSTID in the first group was observed at 0700 UT at around 46°N. Its propagation velocity was 476 m/s. If this southward LSTID had been excited at ~0448 UT at around ~80°N, it should have been excited in the auroral oval of the Northern Hemisphere. This agrees well with the position of the auroral oval equatorward boundaries at 0400–0600 UT in Figure 6a. Similarly, we analyzed other southward LSTIDs in the three groups and found the times and locations corresponded well to those of the auroral oval in the Northern Hemisphere (Figure 6). For northward LSTIDs, only the northward LSTID in the third group had a good agreement with the Southern Hemisphere auroral oval equatorward boundaries. Other northward LSTIDs seemed not to be excited near the auroral oval and propagate to the China region, as their virtual excitation area did not match the location of auroral oval boundaries owing to their slow propagation velocity.

The above analysis reveals that all the southward LSTIDs in our study were likely to have been excited in the auroral oval and indeed traveled to the China region. Temporally, the first two groups of multi-LSTIDs occurred in the dayside ionosphere and the third group was in the nightside (three black arrows in Figure 2b). As substorm activities were mainly nightside processes, they may be not associated directly with the excitation of the first and second groups. Karpachev et al. (2010) presented that the excitation sources of dayside LSTIDs have many candidates like auroral thermospheric heating, intense particle precipitation, and ionospheric convection. As for the northward LSTIDs, only the one in the third group was likely to have been excited in the Southern Hemisphere auroral oval and propagated to the China area across the equatorial zone. Other northward LSTIDs did not. A conspicuous feature of the auroral-origin northward LSTID that differed from the other northward LSTIDs was that it propagated much faster (700 m/s) than the other northward LSTIDs (288 m/s on the average). The velocity of this northward LSTID we observed was close to the auroral-origin poleward LSTID’s velocity observed by Pradipta et al. (2016). Other slower northward LSTIDs were not excited in the auroral oval directly. We do not have direct observational data relating to the auroral oval equatorward boundaries at 0400–0600 UT in Figure 6a. Similarly, we analyzed other southward LSTIDs in the three groups and found the times and locations corresponded well to those of the auroral oval in the Northern Hemisphere (Figure 6). For northward LSTIDs, only the northward LSTID in the third group had a good agreement with the Southern Hemisphere auroral oval equatorward boundaries. Other northward LSTIDs seemed not to be excited near the auroral oval and propagate to the China region, as their virtual excitation area did not match the location of auroral oval boundaries owing to their slow propagation velocity.

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Figure 6. Position of the auroral oval equatorial border in the two hemispheres during 0400–0600 UT (lacking data in the Southern Hemisphere), 0600–0900 UT, and 1800–2200 UT, 22 June 2015. Different colors represent the three time periods. F16-F19 are the satellite numbers in the DMSP data.
the sources of these northward LSTIDs at present. Previous studies have suggested some possible sources of these northward LSTID, such as equatorial electrodynamics (Habarulema et al., 2015), localized sources (Ding et al., 2013), secondary excitation (Jonah et al., 2018), or background winds (Ding et al., 2014).

5. Conclusions

This paper presents the spatial and temporal propagations of multi-LSTIDs over China during a severe geomagnetic storm on 22 June 2015. TEC data were used, which were collected from 341 GNSS stations (CMONOC and IGS combined). We also used TEC data from five IGGCAS BeiDou GEO-01 receivers. Through constructing 2D DTEC maps and setting multiple slices over the maps, we analyzed the propagating processes of multi-LSTIDs that formed during the passage of LSTIDs that propagated in different directions simultaneously over China.

We observed three groups of multi-LSTIDs during the occurrence of two sets of multicycle substorms. The first two groups were observed in the first set of multicycle substorms, and the third group appeared in the second set. The period and horizontal phase velocity ranges of these LSTIDs were ~40–120 min and ~209–750 m/s, respectively. The results can be summarized as follows:

1. The first and second group of multi-LSTIDs were composed of a southward propagation LSTID and a northeastward one that occurred simultaneously during 0700–1400 UT. The LSTIDs propagated in opposite directions and encountered one another between ~25°N and 40°N. The propagation yielded a net structure of DTEC variation, where the amplitude of DTEC enhanced and reduced successively and reached a maximum of ~16% in the fronts’ overlapping areas.

2. The third group was observed during 2100–2400 UT. It consisted of two southward LSTIDs, a northward LSTID, and a northwestward one. The fronts of the northward LSTID and the northwestward one were mixed initially in South China and then moved northward together during 2100–2230 UT. This led to broadening band-like structures and an enhancement of the DTEC amplitude of the mixed fronts. The mixed fronts propagated northward at a distance of ~1,500 km and separated because of their different propagation velocities. After the two LSTIDs separated, their phase fronts became narrower. The northward LSTID continued to propagate to the latitude of 46°N and encountered the second southward LSTID.

3. The time series of five BeiDou GEO-01 receivers captured the structures of three groups of multi-LSTIDs. Most of the propagation and encountering processes of the LSTIDs were consistent with the results from the GNSS observations. Nevertheless, as the range of the BeiDou chain we used was limited, a southward LSTID in the first and third groups and a northward LSTID in the third group were not observed. We estimated that the series observations from some single stations were insufficient to exhibit the overall features of multi-LSTIDs.

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