JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, A00A01, doi:10.1029/2008JA013037, 2008

A statistical study of large-scale traveling ionospheric disturbances observed by GPS TEC during major magnetic storms over the years 2003–2005

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Received 15 January 2008; revised 19 March 2008; accepted 16 April 2008; published 4 July 2008.

[1] In this paper, we plot two-dimensional total electron content (TEC) perturbation maps and investigate the statistical characteristics of large-scale traveling ionospheric disturbances (LSTIDs) during major magnetic storms from 2003 to 2005. The TEC data were obtained from more than 600 GPS receivers in North America within the geographical latitudes of 25°N–55°N. We found a total of 135 cases of LSTIDs, with amplitudes of up to 3.5 TECU and a maximum front width of ~4000 km. The mean value of periods, horizontal velocities, and azimuths are 1.8 h, 300 m/s, and 187° (7° west of south), respectively. The mean velocity is obviously slower than that observed at lower latitudes such as Japan. Of all the 135 LSTID events, 35 cases (26%) occurred in the nighttime with their possible source within the region of North America, according to the variation of magnetic H component observed in this region. In addition, the occurrence of LSTIDs peaks at 1200 LT and at 1900 LT. It is also pointed out that the UT dependence of the occurrence of auroral geomagnetic disturbances plays a major role in the forming of UT and LT dependence of the occurrence of LSTIDs observed at midlatitudes.

Citation: Ding, F., W. Wan, L. Liu, E. L. Afraimovich, S. V. Voeykov, and N. P. Perevalova (2008), A statistical study of large-scale traveling ionospheric disturbances observed by GPS TEC during major magnetic storms over the years 2003–2005, *J. Geophys. Res.*, *113*, A00A01, doi:10.1029/2008JA013037.

1. Introduction

[2] Large-scale traveling ionospheric disturbances (LSTIDs) are now accepted as ionospheric manifestations of atmospheric gravity waves. The gravity waves are generated in the auroral or subauroral region during auroral substorms and geomagnetic storms, as a result of Joule heating and Lorentz forces caused by the enhancement of auroral electrojet and/or intense precipitation of charged particles. The gravity waves interact with the ionosphere and thus cause equatorward propagating LSTIDs. The stimulation of LSTIDs in the auroral region and their propagation from high to low latitudes have been studied by many authors.

[3] As LSTIDs are global in scale, scientists often use net instruments separated by a few hundred kilometers or less to detect their propagation properties. One of the typical early observations was conducted by *Hajkowicz* [1991], who used data from 46 ionosonde stations to observe the global propagation of LSTIDs during great substorms. *Rice et al.* [1988] instead used the combined observation of incoherent scatter radars, ionosondes, HF radars and optical measurements, to watch the global propagation of LSTIDs at midlatitudes. The observations of *Hajkowicz* [1991] and *Rice et al.* [1988] showed a sequential fluctuation of F_2-layer virtual height (h'F) and corresponding critical frequency (f_oF_2) from high to low latitudes.

[4] Previous researches reveal some basic features of LSTIDs. At high latitudes, as it is very close to the auroral source region, the occurrence of LSTIDs is always temporally and spatially well-correlated with that of auroral substorms. At midlatitudes, there is an obvious change of LSTIDs' periods, velocities, and amplitudes. When LSTIDs propagate equatorward from high latitudes to midlatitudes, they experience energy dissipation due to ion drag, molecular viscosity, and thermal conductivity. Meanwhile, the background ionosphere may change considerably due to such effects as the movement of the midlatitude trough and the poleward expansion of the ionosphere crest. And at low latitudes, the signature of LSTIDs is always mixed with ionospheric disturbances caused by other factors such as the equatorial eastward electrojets, the ionospheric irregularities, and the storm time penetration electric fields.

[5] Although many case studies have been made to investigate the stimulation and propagation process of LSTIDs, a statistical analysis has not frequently been seen in recent years. In order to obtain more reliable information of the geomagnetic control of LSTIDs, *Afraimovich et al.* [2001] conducted a 10-day statistical study using the global GPS network data and found that the total intensity of the spectrum of TIDs increases with the increase of geomagnetic disturbances, whose intensity highly correlated with

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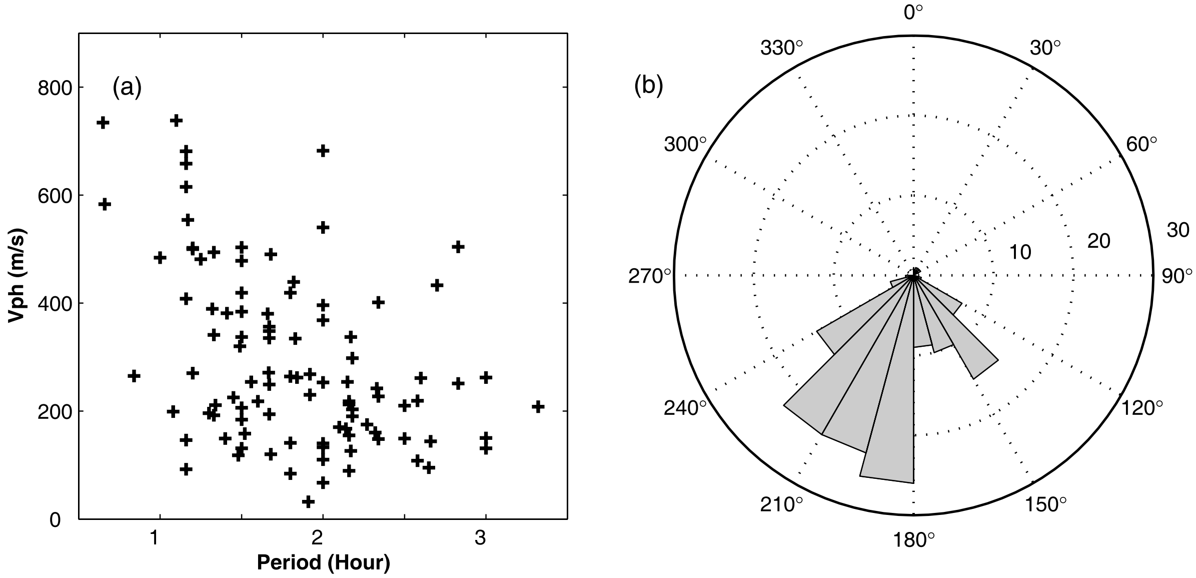

Figure 1. (a) A summary of the observed parameters of large-scale traveling ionospheric disturbances (LSTIDs) during the years 2003–2005 with horizontal velocities (V_{ph}) versus periods. (b) Occurrence histogram of propagation azimuths of LSTIDs. The azimuths were measured clockwise from north.

the time derivative of Dst index. Recently, *Tsugawa et al.* [2004] used GPS data from Japan's GEONET to analyze the morphology of LSTIDs during 1999–2002. They found that LSTIDs could be divided into the disturbed-time damping LSTIDs, the disturbed-time growing LSTIDs and the quiet time damping LSTIDs. Meanwhile, most of the disturbed-time LSTIDs propagated with damping amplitudes due mainly to ion drag. Such statistical analysis of LSTIDs via GPS network observations have yet to be performed at relatively high latitudes such as are available in North America.

[6] In this paper, we report the statistical characteristics of LSTIDs during major magnetic storms over the years 2003 to 2005. The total electron content (TEC) data were obtained from more than 600 GPS receivers in North America within the geographic latitudes of 25°N–55°N. We analyzed the propagation features of LSTIDs and their relation to auroral activities. We also discuss their local and universal time dependence.

2. Data Processing

[7] The International GNSS service (IGS) provides GPS RINEX files on the Internet, which were obtained from more than 1000 GPS receivers all around the world. Among them, more than 600 GPS receivers are in North America. The measurements of TEC from these GPS receivers provide a good opportunity to evaluate LSTID propagation features. We collected the RINEX data from 2003 to 2005 and converted them into slant TEC series.

[8] The method of determining the form of LSTIDs and their propagation parameters was introduced in detail by *Ding et al.* [2007]. First, we obtained the TEC perturbation series through excluding the background trends from original slant TEC time series observed by each GPS satellite-receiver pair. We designed the filtering method via expanding the background trends as one order function of local time and latitude. Then, we divided the area in the range of 25°N–55°N and 60°W–130°W into small pixels 0.5° latitude × 0.5° longitude in size. We obtained the TEC variation value at each pixel by averaging the TEC variations for all the GPS satellite-receiver paths whose ionospheric pierce points cross this pixel. Thus we obtained a sequence of two-dimensional TEC variation maps every 150 s. Finally, we checked the TEC variation maps to see if there were LSTIDs. The selection of LSTIDs was done through a visual examination of these sequences of maps. If there were LSTIDs passing by, there would be regularly moving band-like structures. On the basis of these maps, we then calculated the propagation parameters such as periods, phase velocities, azimuth angles, and amplitudes.

[9] For our statistical analysis, we choose GPS TEC data during the periods when major storms occurred throughout 2003–2005. Major storms here refer to magnetic storms with the value of minimum Dst less than −100 nT. We found a total of 28 cases of storms of this kind. We have evaluated the TEC variation maps for the time intervals during the occurrence of major storms.

3. Statistical Results

3.1. Parameters of LSTIDs

[10] We found a total of 135 LSTID events during 2003–2005. The periods of 99 events can be estimated. Figure 1 shows the values of azimuth angles, periods, and velocities. Among these LSTIDs, 80% have the horizontal wavelengths of more than 1000 km. The amplitudes of TEC variation caused by the LSTIDs are in the range ±3.5 TECU, peaking at 1.1 TECU. Their horizontal phase fronts can extend to 700–4000 km with an average width of ∼2000 km. These LSTIDs passed over USA and generally traveled 500–2000 km equatorward. The average period, phase velocity and azimuth are 1.8 h, 300 m/s, and 187 degrees (7° west of south), respectively. The mean velocity is

obviously slower than that observed over Japan (475 m/s) [*Tsugawa et al.*, 2004].

[11] Latitude difference between the United States and Japan is the main cause of the velocity difference of LSTIDs observed in these regions. According to the transfer function modeling results of *Mayr et al.* [1990], during the periods of auroral substorms, TIDs could be excited in auroral source regions with a wide range of period and velocity. During their propagation from high to middle latitudes, the wave energy dissipates considerably due to such effect as ion drag, molecular viscosity, and thermal diffusivity. Relatively small-scale TIDs dissipate more quickly than large-scale ones do. Accordingly, the energy attenuation prevents the slow-speed LSTIDs from arriving at lower latitudes. Hence slow-speed LSTIDs are more frequently observed in North America, as the region of Japan lies at a geomagnetic latitude range that is $\sim 15°$ lower than that of the United States. Different solar cycle phase of the data may be another possible cause, since *Tsugawa et al.* [2004] used the data observed during solar maximum (1999–2002), while ours are in the declining phase (2003–2005). However, in order to gain convincing results of this aspect, more work needs to be done in the future to analyze the data of a whole solar cycle.

[12] Slow-speed LSTIDs with velocities less than 300 m/s were previously observed in this region through GPS TEC, as introduced by *Afraimovich et al.* [2000, 2002, 2006] and *Ding et al.* [2007]. Similar small values of velocities of LSTIDs were also measured in other regions by the MU radar (averaging 240 m/s [*Oliver et al.*, 1997]), by SuperDARN (50–280 m/s [*Hall et al.*, 1999]), and EISCAT (180 m/s [*Ma et al.*, 1998]). Contrastingly, a recent study of *Tsugawa et al.* [2007] reported 2-D TEC perturbation maps of medium-scale traveling ionospheric disturbances (MSTIDs) during geomagnetically quiet times (Kp less than 2+) over the same region. Comparing the two results, the phase velocities of the MSTIDs (100–200 m/s [*Tsugawa et al.*, 2007]) and the extension width of their wavefronts are similar to those of the LSTIDs reported here. However, LSTIDs have much stronger amplitudes, longer periods, and longer wavelengths than MSTIDs. The difference between them may result from a different generation mechanism, as LSTIDs are always caused by auroral activities whereas the quiet-day MSTIDs may originate from many sources such as local meteorological process [*Wan et al.*, 1998] and electric field instability [*Kelley and Miller*, 1997].

[13] Among the 135 LSTID events, 79% (106 cases) belong to solitary waves, according to the shapes of time series of TEC variation recorded. The rest (29 cases) are periodic oscillations of more than one cycle. Examples of solitary TIDs are presented in Figure 2, which were observed on 21–22 January 2004. Clear wave-like structures are seen in the 2-D TEC variation maps (Figures 2a and 2b), reflecting the negative or positive phases. The wave-like structures passed over the United States and traveled southwestward with a front width of 4000 km and a living duration of several hours. The temporal variation of TEC, as seen in Figures 2c and 2d, shows that these TIDs are solitary waves characterized by approximately the same displacement of the TEC variation above or below the mean level. The LSTIDs traveled a long distance (more than 700 km) with little change to their shapes.

[14] The existence of solitary waves in the upper atmosphere was supported by some theoretical evidence [e.g., *Savina and Erukhimov*, 1981; *Francis*, 1974]. The LSTIDs associated with solitary waves have been observed by many researchers [*Richmond and Matsushita*, 1975; *Afraimovich et al.*, 2000, 2002, 2006; *Ding et al.*, 2007]. These authors found that ionospheric disturbances often have the form of an impulse for isolated substorms. The simulation of *Millward et al.* [1993] indicated that one electric field burst could cause a single perturbation pulse of the LSTID and not a continuous wave train. *Belashova et al.* [2007] suggested that the solitary gravity waves may have the shape of 2-D solitons with single or oscillating asymptotics depending on the dispersive characteristics of the media. Thus both the source property and the background upper atmosphere characteristics are responsible for the forming of solitary LSTIDs. Further study of them has to be performed. The present results indicate that most of the LSTIDs observed during major storms are solitary LSTIDs.

3.2. Auroral Activity Dependence

[15] It is known that the enhancement of auroral electrojets is one of the main causes of LSTIDs. The auroral electrojet index (AE index) is suitable to characterize auroral activities and measure the Joule heating in auroral source regions which are related to the generation of gravity waves and LSTIDs [*Hajkowicz*, 1991].

[16] Apart from the AE indices, we also used the LAE (i.e., local auroral electrojet) indices to approximately describe the local state of auroral electrojets over the region of North America. Similar to the calculation of the AE indices, the LAE indices were derived from geomagnetic variations in the horizontal component (B_h) observed at 11 geomagnetic stations in North America. The geographical locations of the selected observatories are listed in Table 1. Of the 11 observatories, the FCC, PBQ, and YKC are the contributing stations of the AE indices. These LAE observatories are located around the geomagnetic latitudes of 48°N–75°N. Of the variations of B_h from all the stations at each given time (UT), the largest and smallest values are selected. The LAU and LAL indices are defined by the largest and the smallest values thus selected, respectively. The difference, LAU minus LAL, defines the LAE index. Hence the LAU index and LAL index represent the strongest current intensity of the eastward and westward auroral electrojets over North America. The LAE index represents the overall activity of electrojets over this region. We used the term "LAE indices" to encompass all the indices (LAU, LAL, LAE).

[17] According to the power flux observation of the auroral particles via the POES satellite, the average equatorward boundary of the auroral oval can expand to the geomagnetic latitude of 50°N over North America (http://www.sel.noaa.gov/Aurora/index.html). Thus, the LAE indices can precisely describe the change of auroral electrojets in this region especially during major storms.

[18] Figure 3 plots a sample of the temporal variation of Dst, Kp, LAE, and AE indices on 21–22 January 2004. During this period, a major geomagnetic storm occurred with the value of Dst minimum dropping to -149 nT and the Kp value rising to 7 (Figures 3a and 3b). Two LSTID events were observed during this period. The spatial and

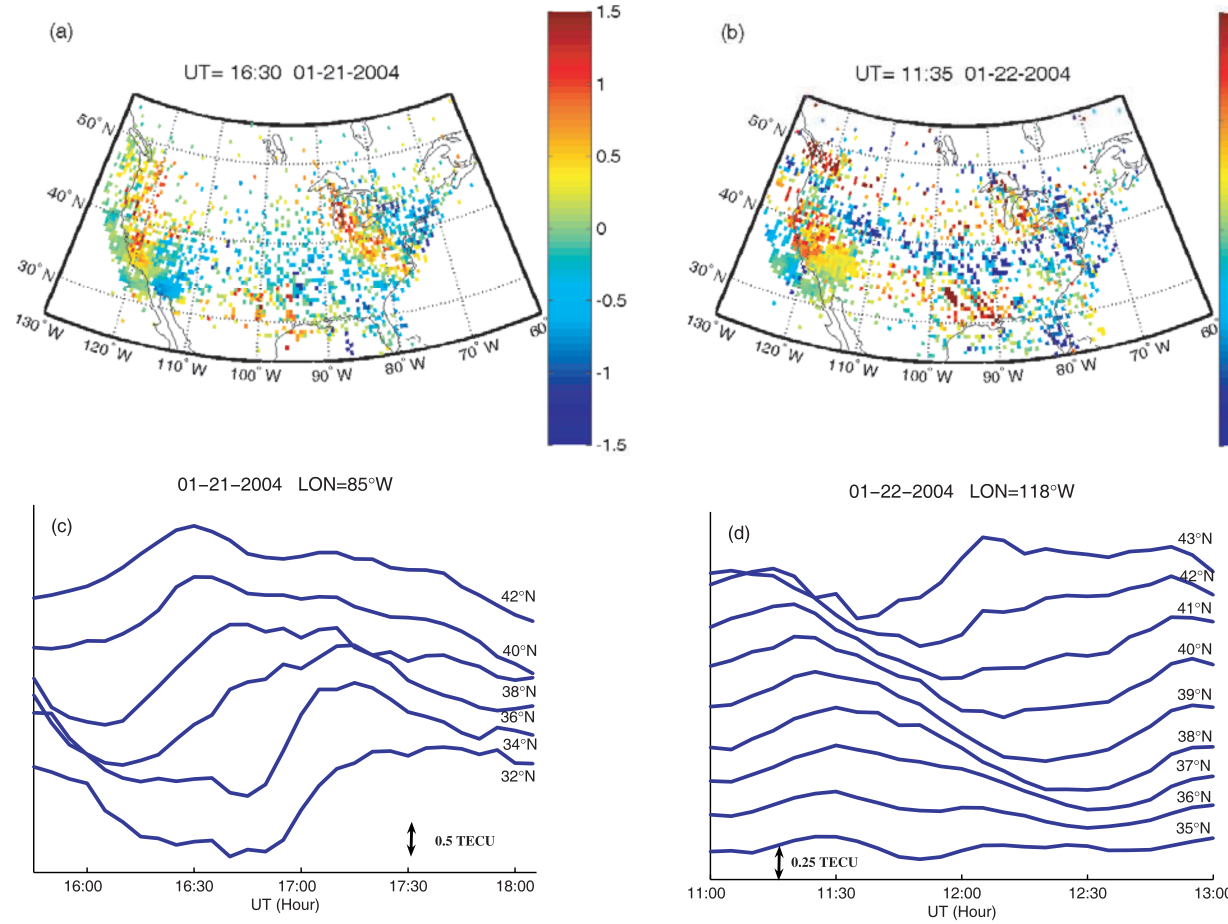

Figure 2. Example of solitary LSTID events on (a, c) 21 January 2004 and on (b, d) 22 January 2004. Figures 2a and 2b are samples of two-dimensional TEC variation maps during the passage of the LSTIDs on 21 January and 22 January. The value of the contours is the amplitudes of total electron content (TEC) variation in TECU. Figures 2c and 2d plot the temporal variations of TEC variation at some fixed grids along the longitude of 85°W on 21 January (Figure 2c) and along the longitude of 118°W on 22 January (Figure 2d). The latitudes of the grids are marked near each temporal variation curves.

temporal distribution of the LSTIDs is plotted in Figure 2. One occurred between 1545 UT and 1815 UT on 21 January following the drop of AL index at 1300–1400 UT. The other was observed at 1100–1300 UT on 22 January at the onset of a substorm at about 1100 UT (Figure 3c). The vertical dotted lines in Figure 3 mark the beginning time when two LSTIDs were registered.

[19] Before the registration of both cases, the AL index drops sharply. However, the LAL index did not suffer any noticeable change in the first case, while in the second case it evidently changed (Figure 3d). It could be inferred from Figure 3 that the source region for the TID event on 21 January is outside of North America, and the source region for the 22 January event is within the region of North America.

[20] A similar observation of LSTIDs originating from other time sectors has previously been reported by *Rice et al.* [1988], who found that a LSTID from the nighttime auroral oval of North Asia could propagate to distances of nearly 9000 km across the auroral oval and arrive at the midlatitude region of North America, which was then in the daytime sector.

[21] In the present results, of all the 135 LSTID events, 35 cases (26%) occurred in the nighttime with an evident increase of both the AE index and the LAE index. These LSTIDs mainly propagate southwestward with azimuth ranging between 190° and 240°. They were likely to be

Table 1. Geographic Locations of the Geomagnetic Observatories in North America[a]

Code	Geographical Latitude and Longitude	Geomagnetic Latitude and Longitude
FCC	58.8°N, 94.1°W	68.5°N, 33.9°W
PBQ	55.3°N, 77.7°W	66.2°N, 9.6°W
YKC	62.5°N, 114.5°W	69.1°N, 63.5°W
BOU	40.1°N, 105.2°W	48.9°N, 40.9°W
FRD	38.2°N, 77.4°W	49.1°N, 7.8°W
IQA	63.8°N, 68.5°W	74.8°N, 4.0°W
MEA	54.6°N, 113.3°W	61.9°N, 55.9°W
NEW	48.3°N, 117.1°W	55.1°N, 57.2°W
OTT	45.4°N, 75.6°W	56.4°N, 6.0°W
STJ	47.6°N, 52.7°W	57.9°N, 23.4°W
VIC	48.5°N, 123.4°W	54.3°N, 64.3°W

[a]We used their observation data of magnetic H component to calculate the local LAE indices.

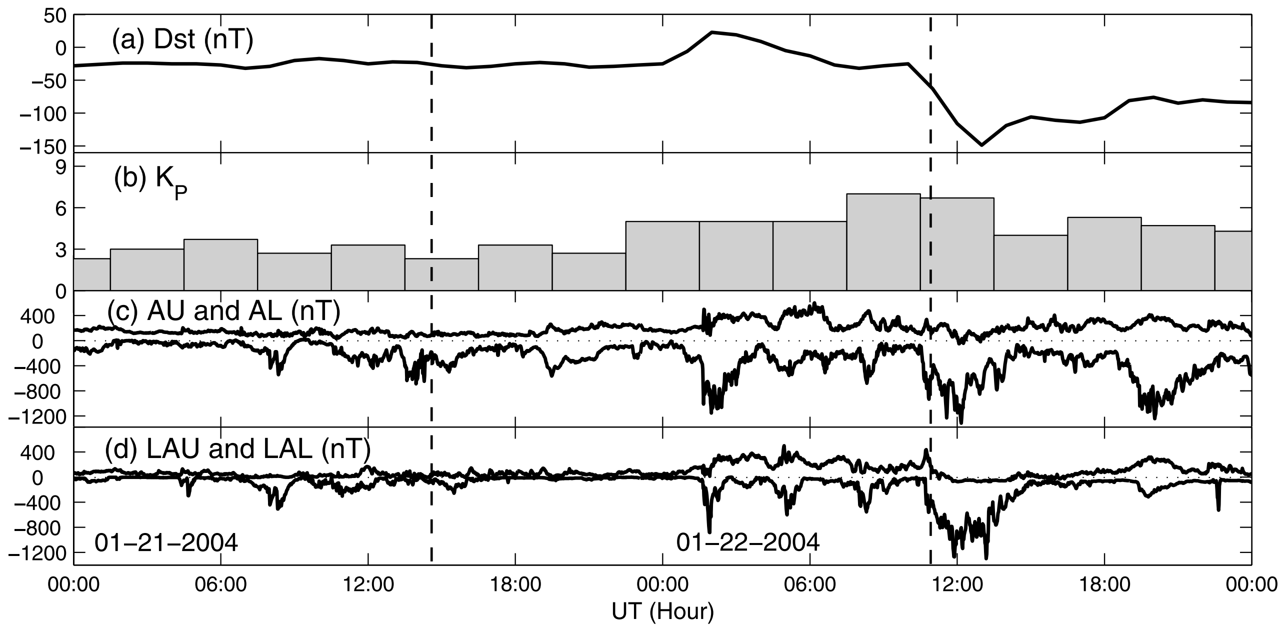

Figure 3. UT dependence of the indices (a) Dst, (b) Kp, (c) AU and AL, and (d) LAU and LAL on 21–22 January 2004. Two LSTID events are registered at 1545 UT on 21 January and 1100 on 22 January, respectively. The vertical thick dot lines mark the onset time. The spatial and temporal distribution of the two LSTIDs has been plotted in Figure 2.

excited in the auroral oval region in North America. One of the possible source region, as mentioned in our previous study [*Ding et al.*, 2007], may be located a few hundred kilometers north of 50°N near the geomagnetic observatory of PBQ (55°N, 78°W).

[22] Other 40 cases (30%) occurred with an evident increase of the AE index but an insignificant change of the LAE index. Further analysis indicates that they are mostly observed at local noon, and their propagation azimuths widely scatter between 130° and 230°. Provided that most enhancements of the auroral electrojets occur in the nighttime, we suggest that this part of LSTIDs were excited in other sectors outside of North America. The TIDs traveled long distances to arrive at the latitude of 30°N–50°N over North America. Detailed information of the source location in other sectors is still under investigation, due to the sparse distribution of geomagnetic observatories in some auroral or subauroral regions such as the north of Atlantic Ocean and North Asia.

[23] Figure 4 illustrates the variation of the number of LSTIDs (blue histograms) against the maximum AE index. We define the maximum AE index as the maximum of AE

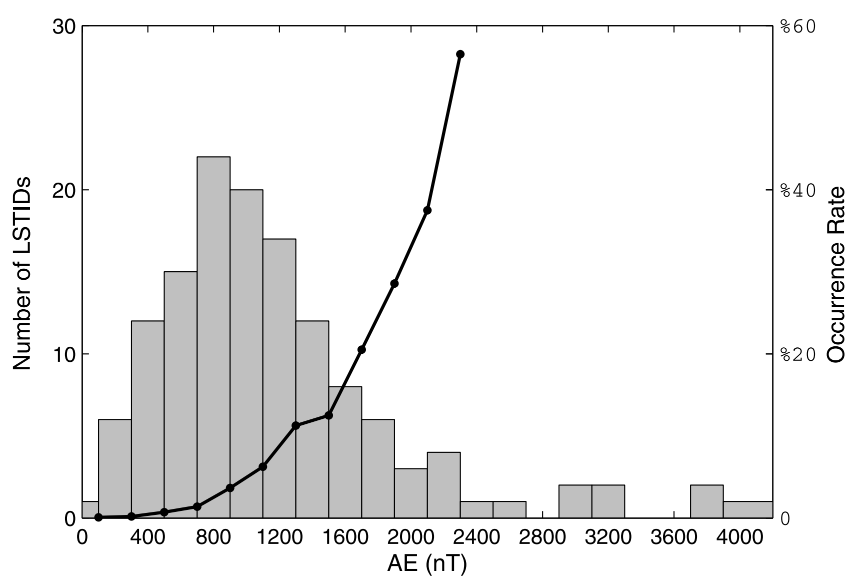

Figure 4. The histogram of the number of LSTID events against AE index (gray bars), and the change of occurrence rate with AE index (black curve).

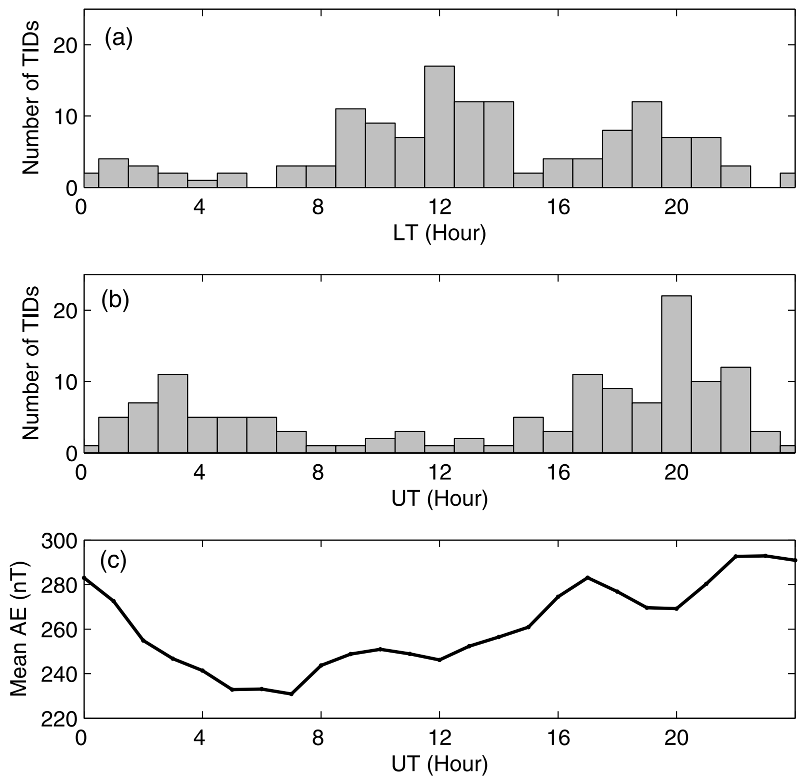

Figure 5. Statistical results of (a) local time dependence and (b) universal time dependence of the number of LSTIDs observed during 2003–2005. (c) The diurnal variation of the average AE index during these years.

index during a 3-h period prior to the arrival of the LSTIDs. Also plotted in Figure 4 is the variation of the occurrence rate against the maximum AE index (red curve). The occurrence rate was defined as the probability that one LSTID occurred during a 3-h period. It is shown in Figure 4 the number of LSTIDs peaks at the AE maximum value of 800 nT. The occurrence rate of the disturbed-time LSTIDs increases as the value of maximum AE index increases. This is good evidence that the occurrence of LSTIDs is highly correlated with enhancements of auroral electrojets during geomagnetic storms.

[24] Of all the LSTIDs, 10% (14 cases) occurred in a relatively quiet time. Quiet time here is assumed to be the time when the maximum AE index is less than 400 nT. These quiet time LSTIDs are always observed around noon time. Their mean period, phase velocity, and azimuth are 1.8 h, 233 m/s, and 152°. Comparing to the disturbed-time LSTIDs, they have relatively smaller phase velocities and more scattered propagation azimuth.

[25] Quiet time LSTIDs were previously observed by authors at mid and high latitudes. *Hocke et al.* [1996] found 45 quiet daytime LSTIDs from November 1987 to December 1991 using the EISCAT radar in Norway. *Maeda and Handa* [1980], using ionosonde array observations in Japan, found that the direction of LSTIDs during periods of low magnetic activity seemed to scatter considerably, due to variation of the east-west extent of the auroral current. An early theoretical study of *Francis* [1975] has shown that the average fluctuation of an auroral electrojet is sufficient to generate freely propagating gravity waves which should be detectable. This point was supported by *Mayr et al.* [1990], who suggested that excitation of LSTIDs is likely to occur under quiet geomagnetic conditions with relatively low energy contribution but optimal source properties.

[26] On the other hand, a large enhancement of auroral energy deposition into the ionosphere is often not accompanied by the excitation of LSTIDs. For example, we didn't observe any LSTIDs during 0140–0330 UT on 22 January, when an intense substorm occurred (Figure 3). So the occurrence of LSTIDs is not directly correlated with the intense of substorms. It may be more dependent on the spatial and temporal source properties [*Hocke et al.*, 1996].

3.3. LT and UT Dependence

[27] The histograms in Figures 5a–5b show the UT and LT dependences of the number of LSTID events over 2003–2005. It should be noted that the histogram of the LT dependence is not simply shifted a few hours relative to the histogram of the UT dependence, due to the fact that the mainland United States spans four time zones, and LSTIDs was observed at different zones. In some cases, LSTIDs were observed crossing more than one time zone. Hence we calculated the average local time for each case and then obtained a statistical histogram of the local time dependence of the occurrence number of LSTIDs.

[28] As is shown in Figure 5a, the occurrence of LSTIDs has a significant diurnal variation. They are more frequently observed around the local time of 1200 LT and 1900 LT than around other time. There are also occurrence peaks at the universal time of 2000 UT and 0300 UT, respectively (Figure 5b).

[29] It is interesting to find that the occurrence peaks both at night and noon, since the enhancements of auroral electrojets always happen in the nighttime. In order to compare the occurrence of LSTIDs with that of auroral disturbances, we drew in Figure 5c the diurnal variation of the mean value of AE index for the years 2003–2005. It can be seen that the majority of auroral disturbances in 2003–2005 occurred between 1700 UT and 0300 UT with a maximum at 2200 UT. The diurnal variation of LSTIDs' occurrence closely resembles the diurnal variation of 3-year mean AE (Figures 5b–5c). As the local time in North America is approximately 8 h behind universal time, LSTIDs' occurrence peak at 2000 UT corresponds to 1200 LT at noon (Figure 5a). It is inferred from above analysis that the UT dependence of the occurrence of auroral disturbances plays a major role in forming the UT and LT dependence of the occurrence of LSTIDs observed at midlatitudes.

[30] The peak of the occurrence of LSTIDs at noon was not seen by *Tsugawa et al.* [2004], who statistically analyzed LSTIDs over Japan and found they are more often observed at night than in the daytime. This can be explained by the difference in latitudes for North America and Japan, since North America is much closer to the auroral source region. Daytime LSTIDs suffer more energy dissipation from ion drag than do nighttime LSTIDs and thus may not easily propagate to relatively low latitudes. This was demonstrated by *Hajkowicz* [1991], who found through ionosonde observations that LSTIDs can be detected at high latitudes close to the source region in the daytime for strong auroral disturbances but not at lower latitudes.

4. Summary

[31] Using the GPS network data, we plotted two-dimensional TEC variation maps of North America and investigated the statistical characteristics of large-scale traveling ionospheric disturbances (LSTIDs) during major magnetic storms occurring in the period 2003–2005. The TEC data were obtained from more than 600 GPS receivers in North America, covering the geographical latitudes of 25°N–55°N (i.e., the geomagnetic latitudes of about 36°N–56°N).

[32] We found 135 cases of LSTIDs in total. Most of them (79%) are solitary waves. The amplitudes of TEC variation caused by these LSTIDs were in the range ±3.5 TECU. The mean value of periods, horizontal velocities, and azimuths are 1.8 h, 300 m/s, and 187° (7° west of south), respectively. The mean velocity is obviously slower than that observed at lower latitudes such as Japan [*Tsugawa et al.*, 2004]. This is consistent with the fact that slow-speed LSTIDs suffered more energy attenuation during their propagation from high latitudes to midlatitudes and thus cannot be frequently observed at lower latitudes.

[33] Of all the 135 LSTID events, 35 cases (26%) occurred in the nighttime with their possible source within the region of North America, according to the variation of magnetic H component observed in this region.

[34] The occurrence of LSTIDs peaks at the local time of 1200 LT and at 1900 LT and the universal time of 0300 UT and 2000 UT, respectively. The LSTIDs occurrence peak at noon was not reported before. It is found that the UT dependence of the occurrence of auroral disturbances plays a major role in the forming of the UT and LT dependence of the occurrence of LSTIDs observed at midlatitudes.

[35] **Acknowledgments.** We are grateful to the Scripps Orbit and Permanent Array Center (SOPAC) in the United States and Data Sharing Network of Earth System Science in China for providing GPS network data. We thank the Geological Survey of Canada for providing geomagnetic observation data over North America. This work was supported by the National Natural Science Foundation of China (grants 40774090 and 40636032), the KIP Pilot Project (KZCX-YW-123) of the Chinese Academy of Science, the National Important basic Research Project (2006CB806306), and RFBR grant N 06-05-39026.

[36] Zuyin Pu thanks Ken Lynn and Jan Lastovicka for their assistance in evaluating this paper.

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