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Ionosphere redistribution during strong geomagnetic storms as detected by the CHAMP, SAC-C, TOPEX and Jason-1 satellites

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Ionosphere response to severe geomagnetic storms that occurred in 2001-2003 was analyzed using data of global ionosphere maps (GIM), altimeter data from the Jason-1 and TOPEX satellites, and data of GPS receivers onboard CHAMP and SAC-C satellites. This allowed us to study in detail ionosphere redistribution due to geomagnetic storms, dayside ionospheric uplift and overall dayside TEC increase. It is shown that after the interplanetary magnetic field turns southward and intensifies, the crests of the equatorial ionization anomaly (EIA) travel poleward and the TEC value within the EIA area increases significantly (up to ~50%). GPS data from the SAC-C satellite show that during the main phase of geomagnetic storms TEC values above the altitude of 715 km are 2-3 times higher than during undisturbed conditions. These effects of dayside ionospheric uplift occur owing to the «super-fountain effect» and last few hours while the enhanced interplanetary electric field impinged on the magnetopause.

1. Introduction

The ionosphere response to geomagnetic storms has been a subject of numerous studies for several decades (Abdu et al., 1991; Foster and Rideout, 2005; Huang et al., 2005; Mannucci et al., 2005; Zhao et al., 2005; Astafyeva et al., 2007; Basu et al., 2007). Ionospheric effects are known to be wide-ranging in their manifestations. One of the most outstanding modifications is alterations in ionospheric total electron content at equatorial and middle latitudes. The equatorial ionosphere represents perhaps the most persistent manifestation of ionosphere-thermosphere coupling at equatorial latitudes and serves as an indicator of the electric coupling status in the solar wind-magnetosphere-ionosphere system.

The equatorial plasma distribution is controlled by the neutral winds and electric fields. The neutral winds induce the hemispheric asymmetry of the ionosphere with respect to the magnetic equator, with large plasma flow (toward the hemisphere of stronger poleward wind) and a stronger anomaly crest occurring in opposite hemispheres. The electric field or the **E**x**B** drift creates the ionization trough at the magnetic equator and plasma density enhancements, EIA, at ±12-15° magnetic latitudes during geomagnetically quiet conditions (Abdu et al., 1990; Fejer, 1991; Balan and Bailey, 1995).

During the main phase of geomagnetic storms, when the interplanetary magnetic field (IMF) turns southward and intensifies, the interplanetary electric field can penetrate to the low-latitude ionosphere for many hours without decay (Gonzalez and Tsurutani, 1987; Gonzalez et al., 1994; Huang et al., 2005). The interconnection between southward IMF and the Earth's magnetic field leads to a strong dawn-to-dusk electric field which moves the equatorial F-region plasma upward enhancing the fountain effect: the fountain rises up to 800-1000 km altitude at the equator and covers about ±30° magnetic latitude. Solar photoionization replaces the uplifted plasma at lower altitudes, leading to an overall increase in ionosphere TEC (e.g., Vlasov et al., 2003; Tsurutani et al., 2004; Mannucci et al., 2005; Astafyeva et al., 2007; Basu et al., 2007). The phenomenon of the ionosphere dayside uplift due to "super fountain effect" (SFE) has been described and shown in detail for the geomagnetic storm on 5-6 November 2001 (Tsurutani et al., 2004). Then, the dayside SFE was observed during the "Halloween storms" of October 2003 (Mannucci et al., 2005, Basu et al., 2007; Tsurutani et al., 2007, 2008). In this paper we will present observations of the ionosphere dayside uplift due to the SFE during strong geomagnetic storms on 21-22 October 2001, 7-8 September 2002, 20-21 November 2003, using TEC

measurements of the satellite altimeters TOPEX and Jason-1, CHAMP and SAC-C GPS data, as well as data of vertical TEC from global ionosphere maps.

2. Methods of data analyses

Figure 1 illustrates the scheme of the TEC measurements. For this analysis, simultaneous observations of TEC by the CHAMP, SAC-C, TOPEX/Jason-1 satellites were combined with the modeled global ionospheric maps (GIM) produced by the different IGS modeling centers. Each of these is described in more detail.

2.1. Global Ionosphere Maps (GIM)

Global ionosphere maps are generated using data from about 150 GPS sites of the IGS and other institutions. The vertical total electron content (VTEC) is modeled in a solar-geomagnetic reference frame, the technology of VTEC reconstruction was described in detail by Schaer et al. (1998) and Mannucci et al. (1998). The output files contain values of VTEC with spatial resolution of 2.5º of latitude and 5º of longitude, and a time resolution of 2 hours. In this paper we used data of CODE (http://www.aiub.unibe.ch/ionosphere.html) and by Jet Propulsion Laboratory of California Institute of Technology (JPL, http://www.jpl.nasa.gov/).

2.2. Satellite altimeters TOPEX/Jason-1

The dual-frequency satellite altimeters TOPEX and Jason-1 perform 1-sec measurements of VTEC beneath the satellites, i.e. between the water surface and the orbit height of about of 1335 km (Fu et al., 1994; http://www.aviso.oceanobs.com/html/missions/welcome_uk.html). The orbit parameters are presented in Figure 1. The TOPEX/Poseidon satellite was launched on 10 August 1992 into a circular orbit at about 1300 km with an inclination 66.5°, an orbital period of 112 minutes and a repeat cycle of 10 days. Jason-1 is a follow-on mission of the TOPEX/Poseidon mission; it was launched on 7 December 2001. The Jason-1 satellite flies the same ground-track as TOPEX.

Satellite altimeter observations of ice and sea surface heights are affected by the retardation/refraction of the altimeter signal in the ionospheric plasma. By measuring the heights above the Earth surface at two frequencies the ionosphere electron content between the ground and the satellite can be determined. Thus, dual-frequency altimeters provide TEC measurements as a byproduct of the sea surface height observations.

The data of satellite altimeters are very helpful in making observations in areas that lack ground-based instruments for observing the ionosphere, e.g., above oceans (Bilitza et al., 1996). However, since the altimeters were designed to measure only ocean heights, there are data gaps over landmasses.

To analyze the ionosphere response to geomagnetic storms on 21-22 October 2001 and on 20-21 November 2003 we used data of TOPEX altimeter and we used data of Jason-1 for geomagnetic storm on 7-8 September 2002.

2.3. CHAMP data

CHAMP is a project of the Potsdam Geophysical Observatory GFZ (http://op.gfz-potsdam.de/champ). CHAMP has a polar orbit (87º inclination) and its orbital period is about 91 min (Figure 1). The orbit altitude changed from ~450 km in 2001 to ~350 km in 2005; thus, CHAMP passes are close to the height of the F2 layer peak density in a meridional direction allowing us to estimate the contribution of the upper ionosphere to TEC.

From the whole set of CHAMP TEC measurements we selected data those GPS satellites that had the maximum elevation angles at the time of observations. The disadvantage of this method is that TEC value may change by jumps at the points of changing a satellite with the maximum elevation angle. However, such approach provides reliable information about changes of the vertical TEC. The method of TEC retrieval from the data of on-board GPS receivers was described by Afraimovich et al. (2005)

2.4. SAC-C data

SAC-C is a joint project of the USA, Argentina, Brazil, Denmark, Italy and France (http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/spacesci/sac-c.html). The altitude of SAC-C satellite orbit is 715 km (Figure 1), so data from SAC-C allow us to estimate TEC within the range of latitudes from 715 km to 20,200 km. The SAC-C data were selected and processed in a manner similar to that of CHAMP.

3. Observations

3.1. Storm of 21-22 October 2001

Fig. 2a shows variations of the index of geomagnetic activity Dst and of IMF B_z on 21-22 October. The B_z sharply turns southward and attains its maximum negative value of -16.4 nT at 18 UT. Then, the Dst value went sharply down from 17 UT and reached its maximum negative value of -187 nT by 21 UT.

2-3 hours after the sudden changes of B_z IMF, at the main phase of geomagnetic storm, TEC increased within the area of the EIA up to 140-160 TECU in the noon-early afternoon sector, according to GIM (Fig.3 b, c). There also is a displacement of the EIA crests by about 5-10° of latitude from the geomagnetic equator (Fig. 3b).

The CHAMP satellite, passing near the dusk sector (~19:30 LT), showed poleward displacement of the EIA crests by ~10-15° of latitude with concurrent TEC increases to 160 TECU above ~400 km. Apart from that, from CHAMP observations we can see a very large value of the ratio of TEC crest to the equatorial trough, which is the result of the penetration of the eastward electric field at middle and low latitudes that enhances the fountain effect (Vlasov et al., 2003). Note, that similar TEC changes are obvious from GIM data, so one can see good agreement between GIM data and satellite observations.

The TOPEX satellite passed over the Atlantic Ocean in the evening sector (~18 LT) and recorded TEC levels of about 120-140 TECU below ~1336 km in the EIA crests which were located at about ±10º magnetic latitude. In this longitude sector the ratio crest-to-trough of the EIA is close to normal and the location of the EIA crests is close to the usual position (Fig. 3 b, f). The TEC response in this longitudinal sector differs from that in the dusk sector (CHAMP observations). A similar effect was observed during the Bastille Day storm of July 2000 and was explained by different longitudinal conditions in the afternoon and evening sectors (Vlasov et al., 2003). The SAC-C data in the forenoon sector (~10:30 LT) show a fourfold increase in TEC to ~80 TECU (Figs. 3a, 4a, 5a) in the near-equatorial region (Fig. 3 b, f). By 22 UT, the TEC value in the dusk sector decreases to ~130 TECU and the ratio crest-to-through becomes close to normal (CHAMP TEC measurements, Fig. 3 c, g). The TEC above ~715 km decreased to ~40 TECU. Unfortunately, the geometry of the TOPEX pass did not allow monitoring further TEC changes during the geomagnetic storm on 21-22 October 2001 (Fig. 3 c, g).

The subsequent sudden decrease of B_z IMF down to -15.4 nT at 23 UT on 21 October 2001 caused recurring TEC enhancement up to 150-160 TECU below 1336 km, up to 140-150 TECU above ~400 km, and up to 50 TECU above 715 km (Fig. 3 d, h). It should be noted that this time period does not correspond to the sudden drop of Dst but to the sudden drop of B_z IMF, so significant TEC increase has strong dependence on B_z variations..

Satellite measurements allowed us to measure TEC enhancements caused by the geomagnetic storm of 21-22 October 2001 in different longitudinal sectors from ~10:30 LT to ~19 LT. TEC enhancements in the afternoon sector correspond to a positive ionospheric disturbance produced by either a southward wind or an eastward electric field coupled with a small enhanced fountain effect. More significant TEC changes occurred in the dusk sector since at dusk the eastward penetration electric field may add to the eastward electric field because of the neutral dynamo (Basu et al., 2007).

3.2. Storm of 7-8 September 2002

The abrupt change of B_z IMF to -22 nT at 17 UT on 7 September 2002 caused an intense geomagnetic storm and the following decrease of Dst to -160 nT at 18 UT. Further variations of B_z at 22 UT (-15 nT) lead to a subsequent Dst decrease down to -187 nT at 24 UT (Fig. 2b). In this paper we will discuss TEC changes from 17 to 23 UT.

As a response to the southward IMF B_z event, the dayside near-noon TEC increased up to 140 TECU by 19 UT within the northern EIA crest, and up to 110 TECU within the southern crest (GIM data, Fig. 4b), i.e., the northern crest appeared to be more pronounced than the southern one. Similar north-south asymmetry was observed by the satellite altimeter Jason-1 that passed near the local time ~13 LT and showed TEC maxima of 189 TECU (northern crest) and 154 TECU (southern crest). Concurrently, the crests moved to ±21º MLAT from their normal position, and the TEC over the equator was reduced, increasing the ratio of the equatorial crest-to-trough TEC. All these observations are evidence of an enhanced fountain effect.

CHAMP passed near local time ~15 LT and detected that TEC above ~400 km increased from ~90 TECU (Fig. 4 a, e) to 120 TECU, and two well pronounced peaks of the EIA were formed (Fig. 4 b, h). At the same time, according to SAC-C observations (~10:30 LT), the TEC value above 715 km altitude increased to 60 TECU (Fig. 4 b, f), i.e., 2-2.5 times the value before the storm (Fig. 2 a, e).

From 21 UT the TEC value within the EIA crests started to decrease , and so did the ratio of crest-to-through TEC (Fig. 4c, g). However, the TEC value above ~400 km appeared to increase further to ~170 TECU (northern anomaly) and to ~140 TECU (southern anomaly). By 23 UT the crests of the EIA moved farther equatorward combining into a singular equatorial peak with a concurrent decrease of TEC value to ~100 TECU (CHAMP and Jason-1 measurements, Fig. 4 d, h).

Thus, the satellite TEC measurements revealed large dayside TEC enhancements during the geomagnetic storm on 7-8 September 2002 in the forenoon-early afternoon sectors (from 10:30 LT to 15 LT). Dayside TEC increased after B_z turned southward. At the main phase of the storm the two EIA crests appeared and further traveled poleward by ~7 º of latitude. TEC above ~400 km remained enhanced for about 5-6 hours after the southward IMF B_z event started. The observed north-south asymmetry seems to be a result of the influence of neutral winds, since they are known to produce hemispheric asymmetry of the ionosphere with respect to the magnetic equator.

3.3. Storm of 20-21 November 2003

The sudden IMF negative B_z increase to -24 nT at 12 UT on 20 November 2003 caused a sharp decrease in the Dst value down to -229 nT by 15 UT. Further steady decreasing of B_z to a minimum value of -51 nT at 15-16 UT provoked an extreme excursion of the Dst index to -422 nT by 20-21 UT (Fig. 2c). During the main phase of the geomagnetic storm TEC increased to 170-180 TECU with the EIA crests displaced poleward by about 5-10º of latitude from their regular position (from GIM, Fig.5 b, c).

CHAMP observed TEC enhancements to 140-150 TECU in the forenoon sector (~11 LT). Both northern and southern crests of the anomaly are well pronounced (compared to the time of the storm initial phase, Fig. 5 a, e) and have their maximums at ~±20° MLT. TEC measurements performed by TOPEX showed no less than 100 TECU around the evening sector (~19 UT, Fig.5 b, f). TEC within the southern crest of the EIA reached ~150 TECU by 20-21 UT (Fig. 5 c, g). The SAC-C pass occurred close to ~10:30 LT and recorded TEC increases of up to 60 TECU for altitudes above ~715 km. This effect of the ionosphere uplift lasted for 2-4 hours (Fig. 5c, g), in response to the long-term impact of the negative B_z IMF.

For these times one can notice a substantial error in the estimation of vertical TEC in GIM: according to the simultaneous satellite observations, the storm-enhanced TEC area was much more elongated along the geomagnetic equator, from the forenoon to the dusk sector (Fig.5 b, c). Starting at 24 UT, B_z turns northward (Fig. 2c) and the CHAMP and TOPEX measurements show only a single equatorial peak (Fig.5 d, h). The dayside TEC level did not exceed 80-90 TECU, i.e., it stayed close to the "quiet-time" TEC level, although the Dst level was still extremely low (-309 nT).

The dayside ionospheric uplift seems to have a strong dependence on IMF B_z variations. From Fig. 3-5 one can see that even when the character of TEC changes due to geomagnetic storms is similar, TEC values for h > 715 km may be different. During the geomagnetic storm of 20 November 2003 TEC remained significantly enhanced for more than 3-4 hours, whereas for the storms of October 2001 and September 2002 the SFE lasted for ~1-2 hours. Apparently, this was caused by the fact that B_z IMF had values less than -25 nT for more than 8 hours, reaching the extreme value of -51 nT at 15-16 UT on 20 November 2003. TEC returns to its "quiet-time" level after B_z turns northward (Figs. 4d, 5d).

Unfortunately, the geometry of the SAC-C passes did not allow us to see the ionosphere uplift above 715 km during the storm on 7 November 2004. However, we derived analogous results from CHAMP and Jason-1 TEC measurements for this event: at the main phase of the geomagnetic storm the EIA crests moved poleward and the equatorial TEC value increased, and the ratio crest-to-trough TEC went up. All these effects appear to be strong evidences of the SFE (Vlasov et al., 2003; Mannucci et al., 2005; Basu et al., 2007).

4. Conclusions and discussions

Simultaneous use of data of satellite altimeters TOPEX and Jason-1, and measurements from GPS-receivers onboard CHAMP and SAC-C satellites allowed us to assess the dayside redistribution of ionospheric plasma during intense geomagnetic storms. Since the satellites passed over different longitudinal sectors and measured TEC in different range of altitudes we could obtain information about altitude and longitudinal ionosphere effects. The principal results from the investigation areas follows:

1. During strong geomagnetic storms on 21-22 October 2001, 7-8 September 2002, and 20-21 November 2003 we observed extreme TEC enhancements in the equatorial region (up to ~50%) with concurrent poleward traveling of the EIA crests for a distance of 5-15° of latitude. At the same time, TEC above 715 km increased to 2-3 times the quiet-time TEC level. Such phenomenon, known as the daytime “super-fountain” effect, occurred after sudden decreases in IMF B_z and consequent penetration of electric fields to the low-latitude ionosphere. The SFE weakened after the B_z value increased and turned northward. Our results on the SFE are in good agreement with previous observations (Vlasov et al., 2003; Tsurutani et al., 2004, 2008; Mannucci et al., 2005; Basu et al., 2007).

2. Significant dayside TEC changes seem to have strong dependence on IMF B_z variations. From Fig. 3-5 one can see that even if the character of TEC changes due to geomagnetic storms is similar, TEC above ~715 km on 20 November 2003 remained severely enhanced much longer than during the storms of October 2001 and of September 2002. Apparently, this effect was caused by the fact that B_z IMF remained below -25 nT for more than 8 hours, reaching the extreme value of -51 nT at 15-16 UT.

3. In general, GIM show a good agreement with satellite observations: the maps reflect very well the dynamics of the TEC redistribution during geomagnetic storms. However, at equatorial latitudes noticeable differences in the VTEC values estimated by GIM and those measured by the satellites were observed times (e.g., Fig. 5).

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Figures

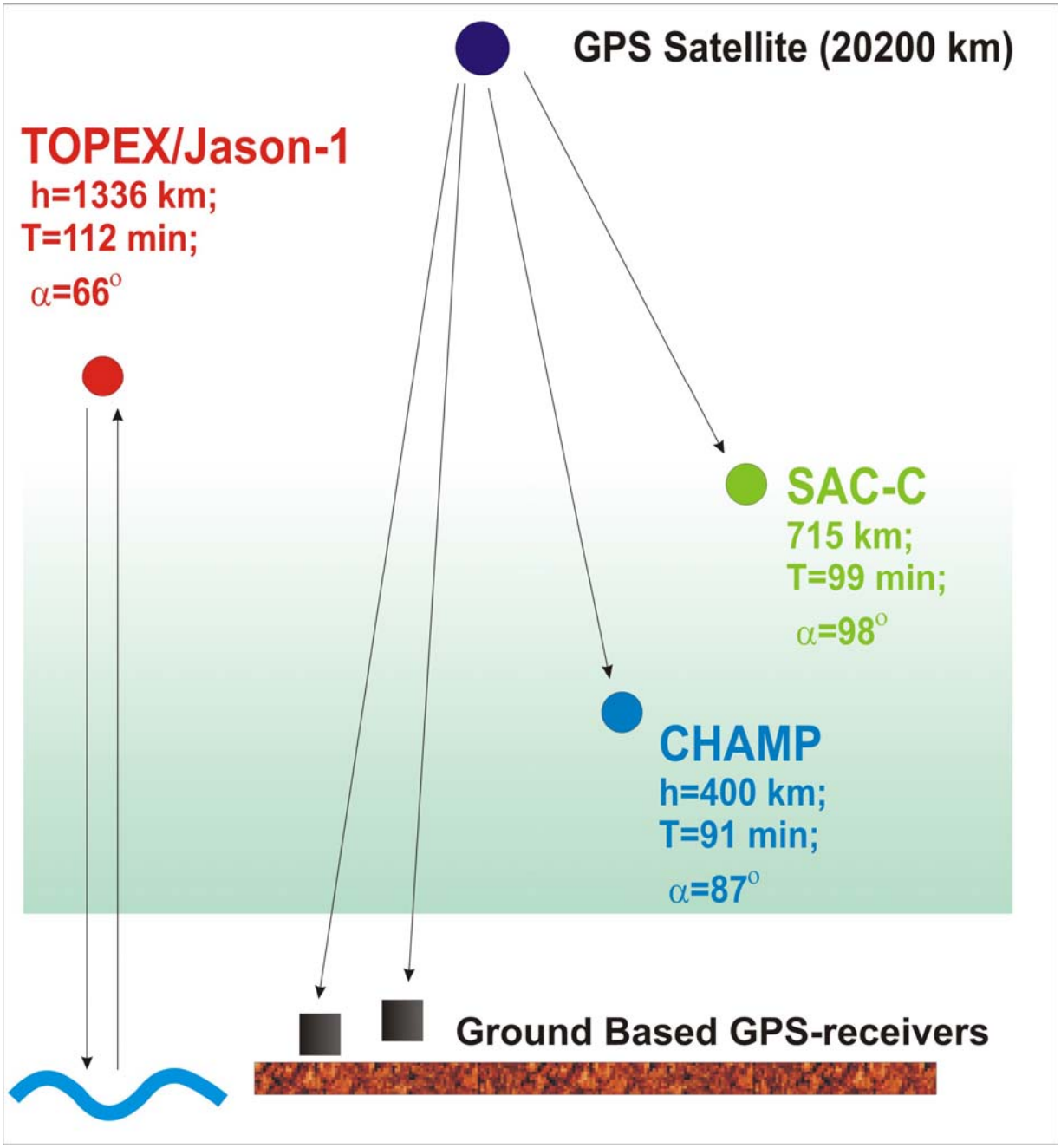


Figure 1. A scheme of ionosphere observations performed by GPS receivers on-board CHAMP and SAC-C satellites and by altimeters carried by the TOPEX and Jason-1 satellites. The satellites orbital parameters are indicated on the panel.

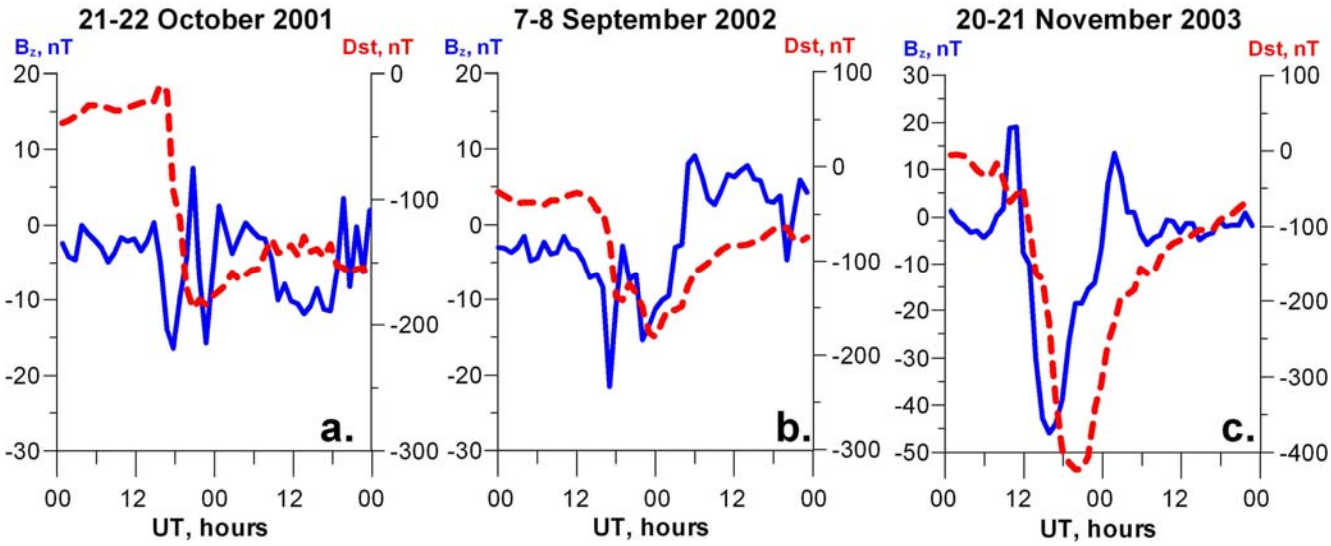


Figure 2. Variations of B_z component of the IMF (blue continuous curves) and of index of geomagnetic activity Dst (red dotted curves).

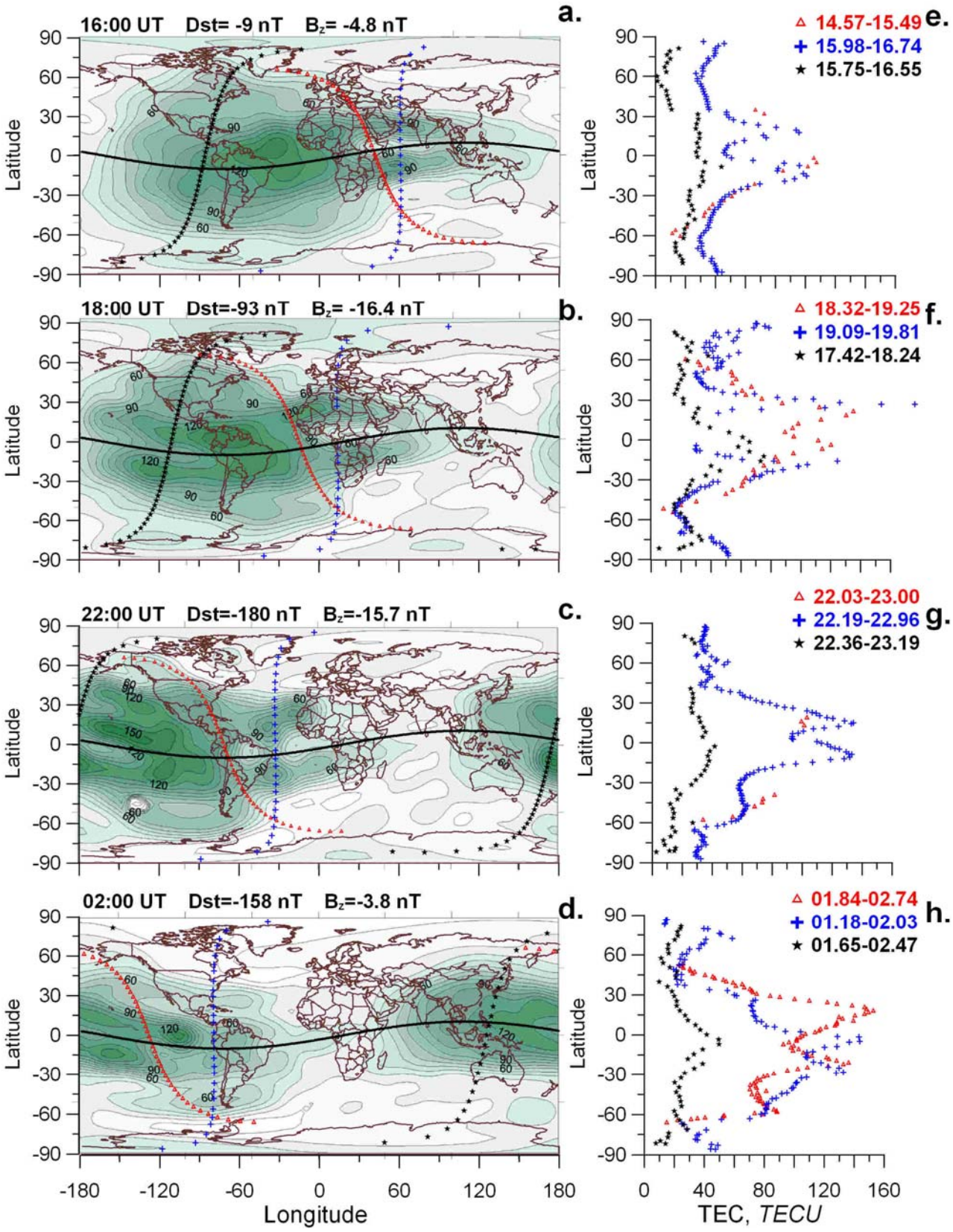


Figure 3. TEC changes during the geomagnetic storm on 21-22 October 2001 (from 16 UT on 21 October to 02 UT on 22 October). Maps of vertical TEC (GIM results) are presented in panels (**a-d**), TEC isolines are indicated by thin black lines, numbers show TEC values in TECU. TEC measurements performed by TOPEX (below 1336 km, triangles), CHAMP (above 350 km, crosses) and SAC-C satellites (above 715 km, stars) are shown on panels **e-h**. The trajectories of the satellites are indicated on panels (**a-d**) in triangles, crosses, and stars, respectively. UT of the satellites flights is written on panels **e-h.** Dst and B_z values for 16, 18, 22, and 02 UT are given on panels **a-d**.

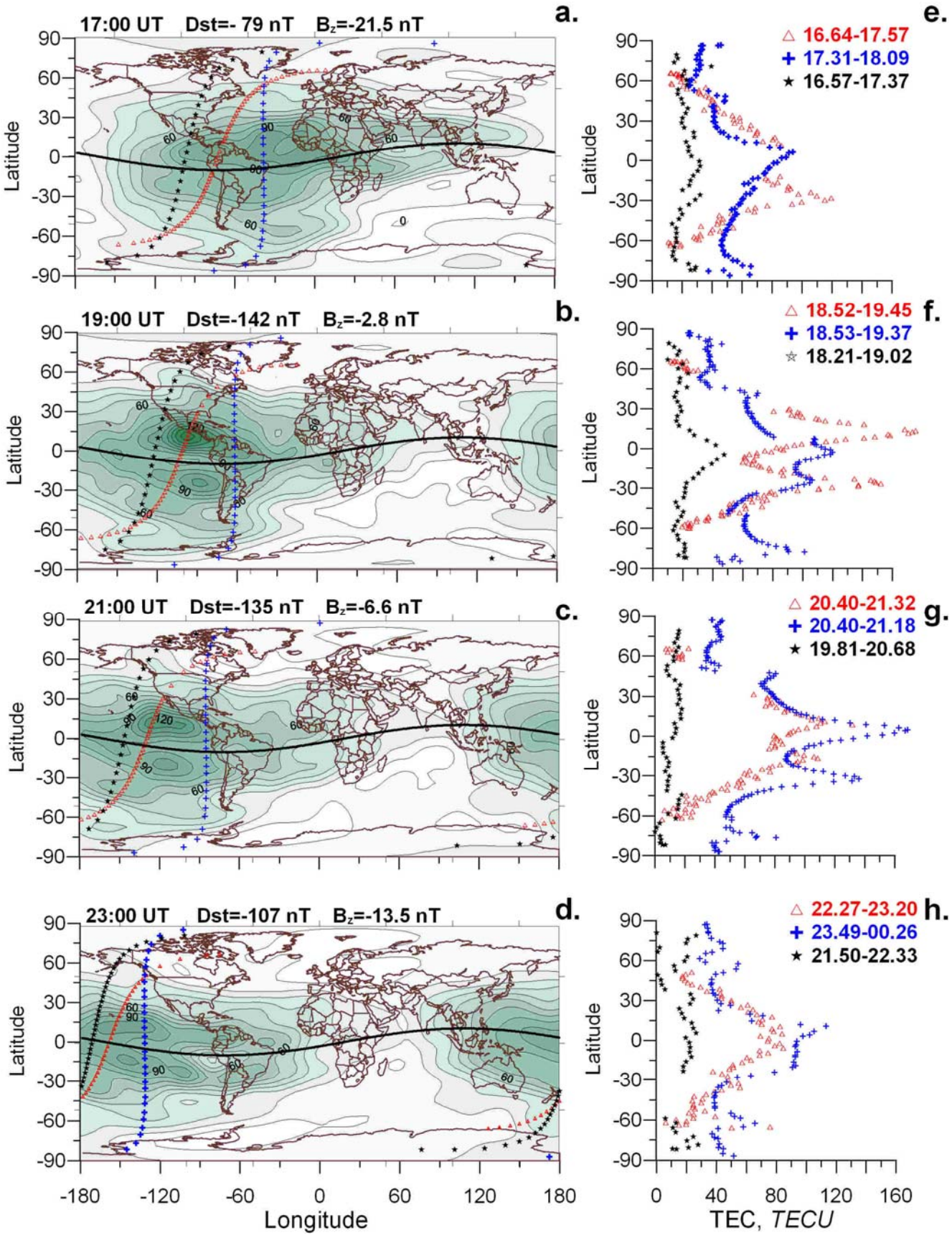


Figure 4. The same as in Figure 3 but for the geomagnetic storm on 7 September 2002 and Jason-1 measurements (triangles), from 17:00 to 23:00 UT.

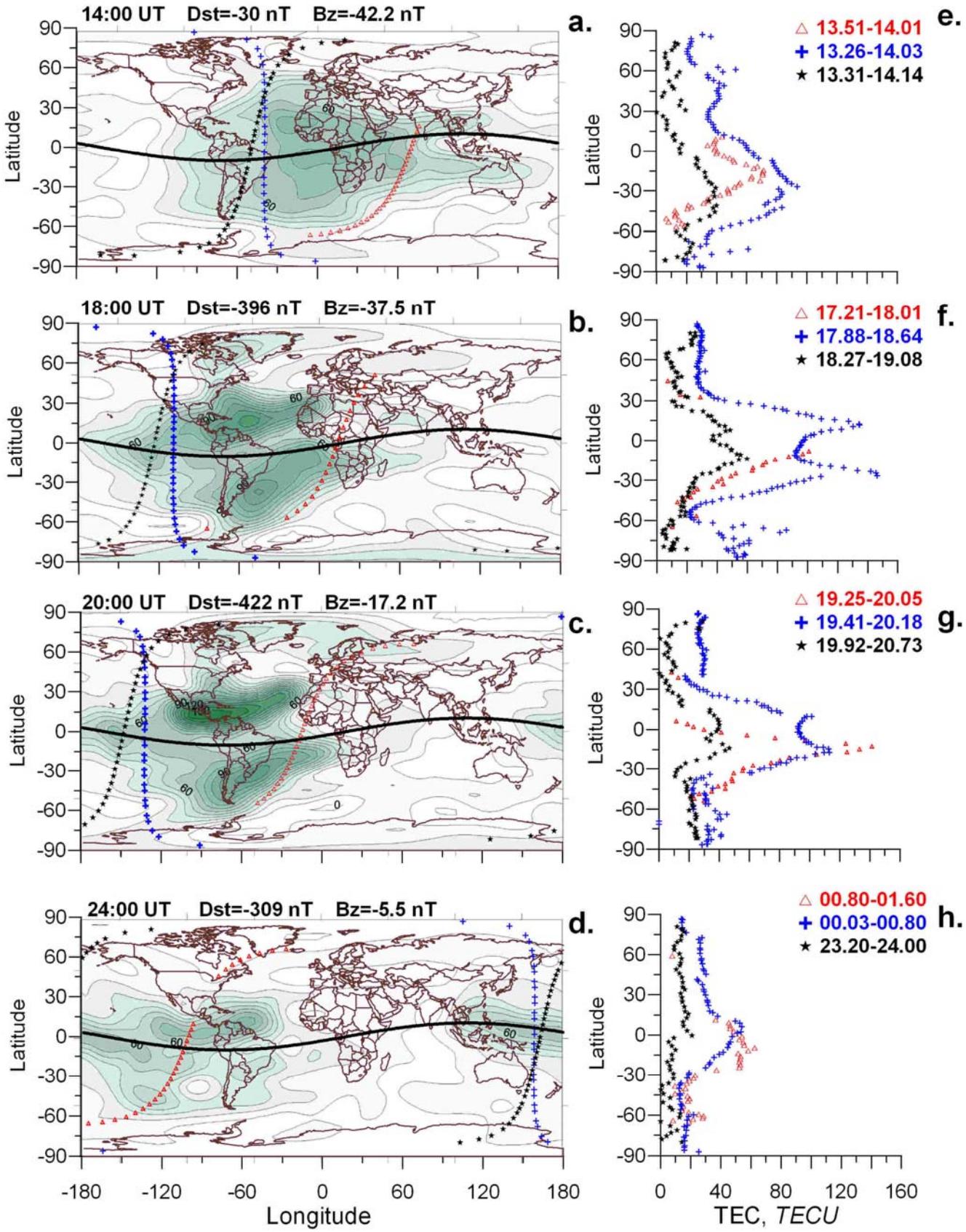


Figure 5. The same as in Figure 3 but for the geomagnetic storm on 20 November 2003, from 14:00 to 24:00 UT.