Penetration of interplanetary electric field to the equatorial F region during the magnetic storm on November 20, 2003

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Abstract. Largest geomagnetic storm of the current solar cycle occurred on November 20, 2003. Multi-frequency HF Doppler radar made observation of the F region zonal electric field at *Trivandrum* during the period of the geomagnetic storm. The magnetic cloud that caused the storm had a high inclination to the ecliptic plane with the axial field pointing southward, and the magnitude of the magnetic field was the largest of the solar cycle. The interplanetary magnetic field (IMF) Bz was almost entirely due to the strong axial field, and hence very geo-effective. The storm started with the arrival of the shock at 07:28 UT on November 20 and reached a minimum Dst value of -472 nT at 20:00 UT followed by an extended recovery phase. These observations provide an opportunity to study the penetration of interplanetary electric field to the equatorial ionosphere. During this storm period, the Advanced Composition Explorer (ACE) satellite was at 240 R_E in the dayside of the magnetosphere and the WIND satellite was at the night side at a distance of 212 R_E, providing measurements of solar wind velocity and IMF at both locations. The Cluster satellite positioned in the polar region is used to provide the information about the penetration of interplanetary electric field (IEF) to the polar region. Two short period IMF Bz enhancement events and the following sharp change in Bz to southward direction in the interplanetary medium were observed by both ACE and WIND satellites, one after the other with a time delay of 75 minutes between them. The corresponding changes in the vertical plasma drift in the equatorial F region also show a time delay of 75 minutes with ACE observations. The polar geomagnetic field Z-component at two stations *Ny Alesund* and *Longyearbyen* in the IMAGE network recorded the same fluctuations in the Interplanetary Electric Field almost in unison with the observed vertical plasma drift. Since the time of southward turning of Bz coincided with the reversal time of the vertical plasma drift, there was an unprecedented downward plasma drift with a peak value 60 m/s. This depression in the vertical plasma drift is in phase with an increase in the duskward electric field in the magnetosphere observed by Cluster satellite, which provides an insight into the penetration of dawn-dusk electric field from polar to equatorial ionosphere.

Index Terms. Equatorial ionosphere, geomagnetic storm, penetration of electric fields, vertical plasma drift.

1. Introduction

Ionospheric measurements often indicate that during magnetically disturbed conditions the low latitude electric fields and currents undergo large departures from their quiet time averages (Fejer, 2002). The direct penetration (DP) of the high latitude electric field to lower latitudes and the ionospheric disturbance dynamo (DD) are the two significant contributors to the ionospheric electric field at low latitude during geomagnetic disturbances. The origin of these disturbance electric fields is at the magnetopause where solar wind meet the magnetic field of Earth. When IMF possess strong southward component, 'connection' of flux lines occur and the geomagnetic fields become open. Before the open field lines become closed at the magnetospheric tail through 'reconnection', the interplanetary electric field (IEF) can penetrate to polar ionosphere through magnetosphere.

During steady solar wind and magnetospheric conditions, pressure gradients near the inner edge of the plasma sheet act to shield the inner magnetosphere and low- and mid-latitude ionosphere from the effects of the general dawn-to-dusk convection electric field via production of field-aligned currents that couple the inner magnetosphere and underlying ionosphere. A sudden change in the cross polar cap potential drop, reflecting a change in the field-aligned currents that mediate the interaction between the solar wind and magnetosphere, destroys this shielding. The characteristic time scale for re-establishing shielding, controlled by several factors such as ionospheric conductivity and the temperature and density of the plasma sheet, was found to be less than one hour if the magnetospheric magnetic field remains constant. However changes in the magnetic field associated with changes in the polar cap potential were found to be causing increased shielding times and prolonged penetration electric fields (Maruyama *et al.*, 2005). A spectral study using electric field data from stations worldwide suggest that electric field fluctuations with periods less than 5 hours can be penetrated to equatorial latitudes (Earle and Kelley, 1987).

The horizontal dawn-to-dusk electric field when maps to equatorial ionosphere predominantly modify the zonal electric field. The vertical plasma drift measured by HF radar is indicative of this zonal electric field as the geomagnetic field lines are nearly horizontal above this region. This paper deals with events of prompt penetration of electric fields measured as vertical plasma drift variations by a multi-frequency HF Doppler radar system located at a magnetic equatorial station – Trivandrum (8.33°N, 77°E, dip 0.4°N), India during the super storm on November 20, 2003. The study of low-latitude impact of space weather phenomena is important in the perspective of providing early warnings and preventive measures for spacecrafts and space stations, which are orbiting above this region.

2. 2003 November 20 storm and database of the study

The largest geomagnetic storm of solar cycle 23 occurred on 2003 November 20 with a Dst index of –472 nT, due to a coronal mass ejection (CME) from active region 0501. The storm started with a shock at 07:28 UT on November 20 and reached a minimum Dst value –472 nT at 20:00 UT followed by an extended recovery phase. The magnetic cloud axis had a high inclination to the ecliptic plane with the axial field pointing southward and hence was very much geoeffective (Gopalswamy *et al.*, 2005).

The multi-frequency HF Doppler radar recorded vertical plasma drift data from 12:00 UT to 20:30 UT on this storm day. In local time, the data duration is from 17:30 LT on November 20 to 02:00 LT on November 21. Hence the radar data is conducive for a study of penetration of electric fields during evening to post-midnight sector of equatorial ionosphere. The radar was operated with two frequencies – 2.5 MHz and 3.5 MHz sequentially. Sounding is done first with 2.5 MHz and after 3 minutes with 3.5 MHz and this cycle continues such that data resolution for one particular frequency is six minutes. The detailed instrumentation of the radar system and the method of evaluation of the vertical plasma drift can be found in *Nayar and Sreehari*, (2004).

The incident solar wind and associated magnetic field information was derived from the data of Advanced Composition Explorer (ACE) satellite which was at a distance of 240 R_E from earth on the sunward direction. The WIND spacecraft was in the anti-sunward diection at distant magnetotail (-240 R_E) and measures exactly similar IMF Bz values as that ACE after appropriate time delay. This is a confirmation of the geo effectiveness of the incident magnetic cloud. The CLUSTER satellites measure magnetospheric electric field. The position of ACE-Wind-Cluster trio on this storm day provides a unique opportunity to understand the origin of some events of interplanetary electric field prompt penetration to low latitudes. The data from these satellites were taken from Coordinated Data Analysis (CDA) web. In addition high latitude geomagnetic field also exhibits some fluctuations corresponding to these electric field penetration. Data from two stations – Ny Alesund (78.92°N, 11.95°E) and Longyearbyen (78.20°N, 15.82°E) – in the IMAGE magnetometer network are also used for the present study.

3. Results

Fig. 1 shows the satellite and radar measurements during the evening sector of 20 November 2003. The top panel illustrates the IMF Bz measured by ACE satellite and this is time shifted appropriately. The ACE magnetic field is first time shifted by 40 min. in order to account for the time delay of propagation of the frozen-in IMF from first Lagrangian point (L1) to Earth's magnetosphere. Then the cross-correlation between this IMF component and vertical drift revealed a lag of 35 min. Thus the ACE magnetic field is time shifted by 75 min. so as to understand the penetration events clearly. This additional lag of 35 min. may correspond to the retardation of the solar wind by the bow shock and subsequent acceleration of the solar wind in the magnetosheath (Kelley *et al.*, 2003). The second row panel in Fig. 1 shows the magnetic field measured by the Wind satellite in the tail region. The bottom two panels illustrate the equatorial F-region vertical plasma drift measured by the radar during this storm time at 3.5 MHz and 2.5 MHz respectively.

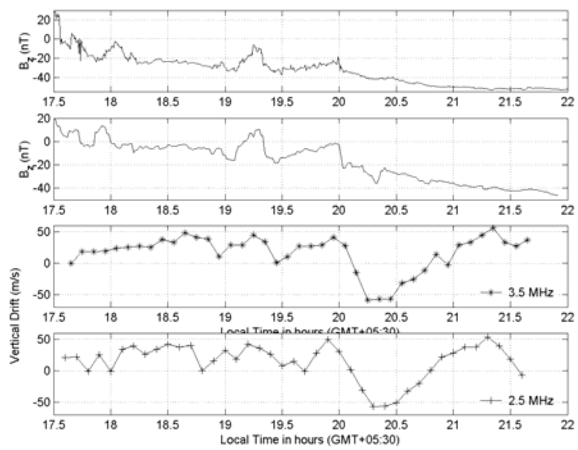

Fig. 1. IMF B_z (shifted 75 min.) observed by ACE satellite (top panel), IMF B_z measured by WIND at magnetotail (second row panel), and vertical plasma drift at equatorial ionosphere observed by HF Doppler radar at 3.5 MHz and 2.5 MHz respectively (bottom two panels).

One large fluctuation (of about 30 nT) in ACE Bz between 19:00 and 19:30 LT can be seen as clearly mapped to the equatorial ionosphere from the bottom panel. Similarly the sharp southward fall of IMF Bz at 20:00 LT causes a large westward electric field at equatorial region. Normally the low latitude zonal field become westward at this time causing a small downward drift of the order ~ -10 ms^{-1}. But the prompt penetration electric field seems to superpose with this westward field producing an unprecedented downward drift of the order of –60 ms^{-1}. Such magnitude of downward drift has never recorded by this radar in the evening/night time sector before or after this day. The vertical drift reaches this maximum value near 20:30 LT and returns to highly positive value (large upward drift) within an hour. This one hour long penetration event is exactly reflected in the CLUSTER measurements of dawn-to-dusk magnetospheric electric field seen in Fig. 2.

This one hour long electric filed penetration event and the event between 19 and 19:30 LT are also evident in high latitude geomagnetic field measurements from two stations in the IMAGE magnetometer network, *Ny Alesund* (78.92°N) and *Longyearbyen* (78.20°N), as seen in Fig. 3.

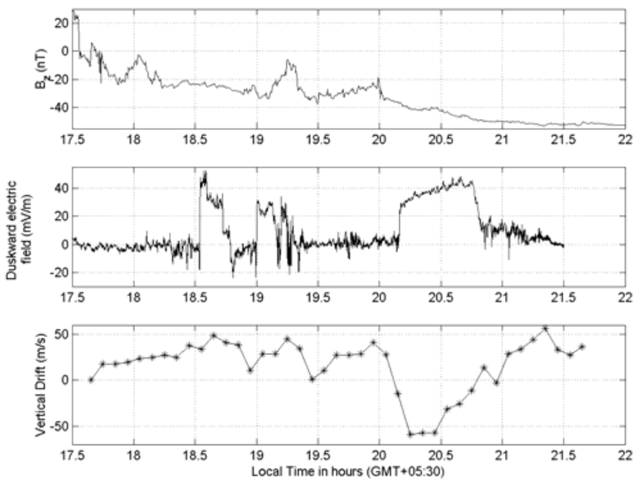

Fig. 2. IMF B_z (shifted by 75 min.) observed by ACE satellite (top panel), Dawn-to-dusk electric field measured by CLUSTER satellites (middle panel) and vertical plasma drift at equatorial ionosphere observed by HF Doppler radar at 3.5 MHz (bottom panel).

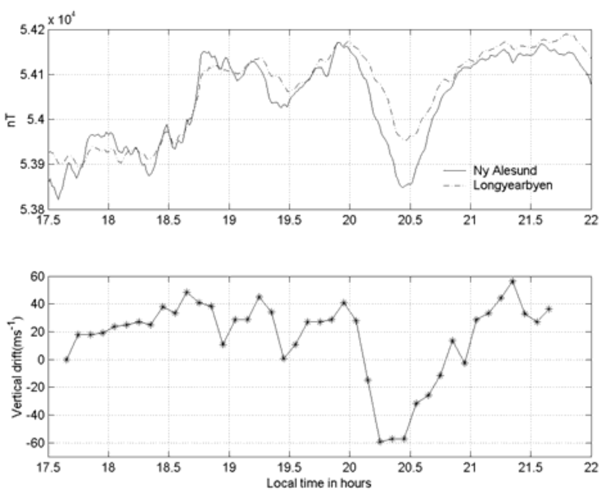

Fig. 3. Z-component of geomagnetic field at two high latitude stations (top panel) and vertical plasma drift at equatorial ionosphere radar at 3.5 MHz (bottom panel) during evening time.

Fig. 4 shows the high latitude geomagnetic field measurements and vertical plasma drift in the midnight sector, i.e. from 23:30 LT on November 20, 2003 to 02:00 LT on November 21, 2003. The fluctuations in high latitude magnetic field and equatorial vertical plasma drift are very similar in this time sector. This also corroborates the prompt penetration mechanism of electric field from polar to equatorial latitudes.

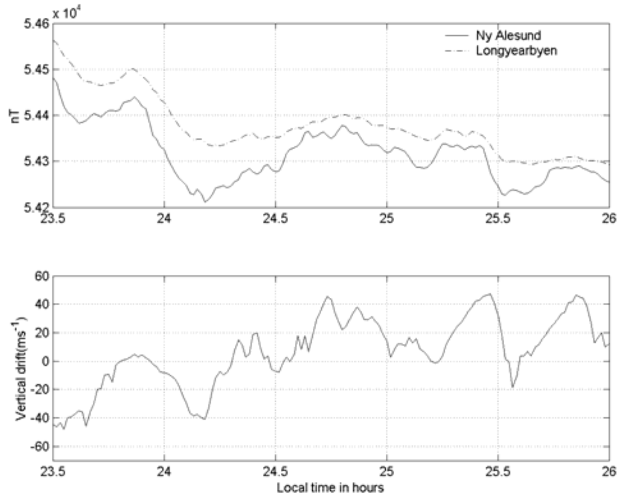

Fig. 4. Z-component of geomagnetic field at two high latitude stations (top panel) and vertical plasma drift from Radar at 3.5 MHz (bottom panel) during nighttime.

4. Discussion

Large geomagnetic storms (Dst < -100 nT) are generally caused by Earth-directed coronal mass ejections (CMEs) that evolve into interplanetary CMEs (ICMEs). The 2003 November 20 super magnetic storm, which was the largest in the current solar cycle 23, can be traced to a CME that erupted on November 18 (Gopalswamy *et al.*, 2005). The ICME was a magnetic cloud (MC) and was driving a shock, which was detected at L1 around 07:28 UT on November 20 by SOHO. The ACE observations revealed that the MC was an east-south-west cloud with its axis nearly perpendicular to the ecliptic. The axial field was strongly southward and hence the MC was very much geoeffective. The geomagnetic storm and the responsible MC were extreme events in their respective classes. Gopalswamy *et al.*, 2005 attributes the November 20 MC to the 08:50 UT CME on November 18.

The interplanetary magnetic field's southward component (B_z) introduce a dawn-to-dusk interplanetary electric field (IEF) at the magnetopause given by $E_{yy} = -V_{sw} \times B_z$. In the time interval between connection and reconnection, geomagnetic field lines are open and IEF can penetrate to the polar ionosphere causing sudden changes in cross polar cap potential. This electric field can be instantaneously mapped to low latitudes adopting a transverse magnetic (TM) mode of propagation through the Earth – Ionosphere waveguide (Kikuchi and Araki, 1978; Kikuchi, 1986; Kikuchi *et al.*, 1996). Kikuchi, 1986 has given a direct evidence of the equator ward transmission of the dawn-dusk polar electric field in the night-side hemisphere by using HF Doppler data at the equatorial station. Since the zeroth order TM mode has no lower cut-off frequency, both the transient and quasi-static electric fields are transmitted and cause geomagnetic disturbances (Kikuchi and Araki, 1978).

For a steady-state magnetosphere, the low-altitude region is shielded by the Alfven layer, a charge build-up at the inner edge of the ring current, which generates an electric field opposite in direction to the external electric field. This shielding effect is frequency dependent and rapid variations in the high-latitude electric field can penetrate to low-latitudes much more readily than the large-scale quasi-dc field. Earle and Kelley (1987) presented strong evidence that the shielding of magnetospheric sources from low latitudes is virtually non-existent for periods below 5 hours. Also, compressional hydromagnetic waves can pass through nightside magnetosphere and can modify equatorial ionospheric electric fields. The present work shows two events of such electric field penetration in the evening of a super magnetic storm day, 2003 November 20. The time-shifted ACE IMF B_z, the IMF B_z measured by WIND satellite situated at the magnetospheric tail and the HF Doppler radar at geomagnetic equator recorded identical fluctuations of very high magnitude between 19:00 LT and 19:30 LT and 20:00 and 21:00 LT. These two events can be clearly seen in Fig. 1. The magnetospheric electric field measurement by CLUSTER clearly depicts the 20.00 – 21.00 LT penetration event as seen in Fig. 2. Note that a dusk-ward electric field should produce a westward electric field perturbation at the equator.

The high latitude geomagnetic field measurements from two station - Ny Alesund and Longyearbyen - also exhibit the two fluctuations observed by satellites and HF Doppler radar on November 20, 2003 evening. The Z component of geomagnetic field at these two stations exhibit fluctuations in time sectors 19:00 - 19:30 LT and 20:00 – 21:00 LT exactly as observed by the radar, as evident from Fig. 3. This clearly points to the possibility of penetration of electric field from polar ionosphere to equatorial ionosphere. The polar ionospheric electric field in turn owes its origin to interplanetary electric field, which was mapped through magnetic field lines during the extreme space weather episodes of November 20, 2003. Also Fig. 4 shows one-to-one correspondence between high latitude geomagnetic field measurements and plasma drift measurements during the midnight sector of November 20-21, 2003. Hence, the simultaneous observations from different satellites along with the equatorial HF Doppler radar observation throws light on some aspects of penetration of interplanetary electric field from interplanetary medium to terrestrial equatorial ionosphere.

5. Conclusions

The 2003 November 20 storm provided an opportunity to study the penetration of IEF to the equatorial ionosphere. During 20 November 2003, associated with the CME, fluctuations in IMF Bz was observed by the ACE and WIND satellites with a time delay between them. The magnetospheric electric field observed by the CLUSTER satellite also observed this fluctuation, the electric field fluctuation observed by the HF Doppler radar is near simultaneous with the CLUSTER observation and the geomagnetic field at the high latitude stations. These observation reveals that the interplanetary electric field at the magnetopause can penetrate to the polar ionosphere causing sudden changes in cross polar cap potential. This electric field can be instantaneously mapped to the equatorial ionosphere.

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