Signatures of traveling convection vortices in ground magnetograms under the equatorial electrojet

N. B. Trivedi,[1] D. G. Sibeck,[2] E. Zesta,[3] J. C. Santos,[1] K. Yumoto,[5] T. Kitamura,[5] M. Shinohara,[6] and S. L. G. Dutra[4]

Received 31 May 2001; revised 20 November 2001; accepted 21 November 2001; published 29 June 2002.

[1] Traveling convection vortices (TCVs) are transient events in high-latitude ground magnetograms that can be interpreted as evidence for localized vortical flows in the high-latitude ionosphere. Their centers travel eastward or westward at geomagnetic latitudes near 72° to 74°. TCVs have been attributed to various transient interactions at the magnetopause but also to processes occurring deeper within the magnetosphere. Each interaction mechanism should launch shear Alfvén waves that produce high-latitude ground signatures but also compressional waves that should produce signatures at lower latitudes. *Zesta et al.* [1999], *Moretto et al.* [1997], *Ridley et al.* [1998], and *Lühr et al.* [1998] report detailed analyses for several high-latitude TCVs. In this paper, we present evidence for corresponding signatures at Belem, São Luis, and Teresina and other stations under or nearby the equatorial electrojet. The equatorial signatures are most pronounced when the high-latitude signatures are (1) longitudinally extended, (2) isolated, and (3) attain greatest amplitudes. *INDEX TERMS:* 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2736 Magnetospheric Physics: Magnetosphere/ionosphere interactions; 2760 Magnetospheric Physics: Plasma convection; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; *KEYWORDS:* traveling convection vortices, equatorial electrojet, magnetic impulse events

1. Introduction

[2] The magnetopause hosts a wide range of transient disturbances. The Kelvin-Helmholtz instability may drive quasiperiodic waves on the boundary during periods of enhanced solar wind velocities [*Southwood*, 1979]. Bursty merging may generate flux ropes of interconnected magnetospheric and magnetic field lines, known as flux transfer events (FTEs) [*Russell and Elphic*, 1978], on the equatorial magnetopause during periods of southward interplanetary magnetic field (IMF) orientation [*Rijnbeek et al.*, 1984]. Pressure pulses, whether of intrinsic solar wind origin or generated within the foreshock, may drive riplets on the magnetopause [*Sibeck et al.*, 1989]. Each disturbance should launch fast mode waves across magnetospheric magnetic field lines and parallel-propagating Alfvén mode waves along outer magnetospheric magnetic field lines [*Southwood and Kivelson*, 1990].

[3] The effects of the Alfvén mode waves (and corresponding field-aligned currents) should be observable at the ionospheric footprints of outer magnetospheric magnetic field lines. Magnetic impulse events (MIEs) with durations from 5 to 20 min and amplitudes greater than 40 nT are indeed common in the high-latitude dayside ionosphere. On average one occurs each day [*Sibeck and Korotova*, 1996], but repetitive sequences are not uncommon [*McHenry et al.*, 1990]. Efforts to identify the origin of the events have not met with great success. They show no tendency to occur for high solar wind velocities as predicted by the Kelvin-Helmholtz mechanism [*McHenry et al.*, 1990], for highly variable solar wind pressures as predicted for the pressure-pulse mechanism [*Konik et al.*, 1994], or for southward IMF orientations as predicted by the bursty merging mechanism [*Lanzerotti et al.*, 1990]. They may not even be associated with transient processes at the magnetopause [*Yahnin and Moretto*, 1996]. Efforts to identify corresponding signatures of the fast mode waves at geosynchronous orbit or at low latitudes on the ground have met with mixed success. While some case and statistical surveys report evidence for corresponding equatorial and geosynchronous signatures at the times of MIEs [*Sato*, 1964; *Sibeck*, 1993; *Korotova and Sibeck*, 1995; *Korotova et al.*, 1997], others do not [e.g., *Lanzerotti et al.*, 1990; *Konik et al.*, 1995].

[4] Perhaps each proposed mechanism, and still others yet unknown, can generate MIEs. If so, it may be necessary to survey only events with specific characteristics to obtain clear results. Of the various subcategories of MIEs, traveling convection vortices (TCVs) are the best known. With the help of observations from ground magnetometer arrays they can be identified on the basis of eastward or westward

[1]Centro Regional Sul de Pesquisas Espaciais-CRSPE/INPE, Santa Maria, Brazil.
[2]Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA.
[3]Department of Atmospheric Sciences, University of California, Los Angeles, California, USA.
[4]Instituto Nacional de Pesquisas Espaciais-INPE, Sao Jose dos Campos, São Paulo, Brazil.
[5]Department of Earth and Planetary Sciences, Kyushu University, Fukuoka, Japan.
[6]Solar Terrestrial Environment Laboratory, Nagoya University, Toyokawa, Japan.

0148-0227/02/2001JA000153

propagating ionospheric convection flows (magnetic field signatures) that reverse from westward (southward) to eastward (northward), or vice versa, with latitude. Since both azimuthally and latitudinally spaced networks of high-latitude ground magnetograms are needed to identify TCVs, only a few examples have appeared in the literature. The purpose of this paper is to examine high time and amplitude resolution low-latitude ground magnetograms for several well-documented TCVs recently reported by *Moretto et al.* [1997], *Ridley et al.* [1998], *Lühr et al.* [1998], and *Zesta et al.* [1999] and determine the conditions under which corresponding signatures can be seen under the equatorial electrojet.

[5] We choose to search for the signatures of TCVs at equatorial latitudes because we expect them to be greatly enhanced under the dip equator. As noted by *Hirono* [1950a, 1950b, 1952] and *Baker and Martyn* [1953], the magnetic and electric fields lie exactly perpendicular to one another along the dip equator. The former is horizontal and points northward, whereas the latter is part of the dayside *Sq* system and points eastward. The resulting upward plasma drift generates an upward polarization electric field between the upper and lower boundaries of the conducting *E* layer. In turn, this electric field drives a westward drift and additional eastward current thus enhancing the net eastward current within the dayside *E* region of equatorial ionosphere. The latter current is responsible for the large diurnal variation seen in the *H* component at equatorial stations like Huancayo. By analogy, the eastward and westward electric fields launched into the dayside magnetosphere by outward and inward magnetopause motion associated with transient events should also generate enhanced signatures in the *H* component of equatorial ground magnetograms.

2. Data and Methodology

[6] All of the TCVs studied in this paper were first identified by previous authors in high-latitude ground magnetograms. We present the observations at 5-s time resolution for events identified in the Magnetometer Array for Cusp and Cleft Studies (MACCS) array and 60-s time resolution for events identified in the Greenland ground magnetograms. For comparison, we will present observations from low-latitude stations at similar local times in Brazil. The National Institute of Space Research (INPE) in São Jose dos Campos, São Paulo, Brazil, and Kyushu University in Fukuoka, Japan, have jointly and intermittantly operated high time (3 s) and amplitude (0.05 nT) resolution, low-noise, three-component fluxgate magnetometers at three stations (Belem, São Luis, and Teresina) under the equatorial electrojet in Brazil since 1991 [*Tachihara et al.*, 1996; *Saka et al.*, 1996]. To determine the longitudinal extent of the low-latitude signatures, we will also present 3-s time resolution observations from Guam, Peradenia, Mokolo, Alcantara, and Ancon, all operated by K. Yumoto of the University of Kyushu in Japan. Table 1 and Figure 1 present the locations of all the stations used in this study. Finally, we present 1-min averages of GOES 6 and 7 geosynchronous magnetic field observations at LT = UT − 5 and − 7.5 hours, respectively. Whereas the total magnetic field strength is available from GOES 6, only the component parallel to the Earth's rotation axis is available from GOES 7.

Table 1. List of Magnetic Stations With Coordinates and Station Code

Station Name	Station Code	Geomagnetic		DIP Latitude	Time, LT
		Latitude	Longitude, E		
Alcântara	ALC	0.7°	29.3°	0.3°	UT − 3.0
Ancon	ANC	1.6°	354.6°	1.2°	UT − 5.1
Belém	BLM	2.8°	25.5°	6.0°	UT − 3.0
Cape Dorset	CDC	74.6°	1.2°	83.5°	UT − 4.75
Coral Harbour	CHC	74.8°	349.2°	84.4°	UT − 5.50
Godhavn	GDH	79.1°	34.6°	84.5°	UT − 2.40
Guam	GUA	4.7°	215.0°	9.5°	UT + 9.70
Igloolik	IGC	79.4°	351.5°	86.1°	UT − 5.33
Mokolo	MOK	1.9°	85.1°	1.5°	UT + 0.90
Narsarsuaq	NAQ	70.5°	38.7°	79.9°	UT − 2.10
Peradenia	PRD	0.1°	152.6°	2.8°	UT + 5.40
Santa Maria	SMA	18.9°	16.0°	32.5°	UT − 3.00
São Luis	SLZ	0.3°	29.2°	0.6°	UT − 3.00
Teresina	TER	2.8°	29.7°	6.6°	UT − 3.00
Thule	THL	88.3°	14.4°	89.2°	UT − 2.90

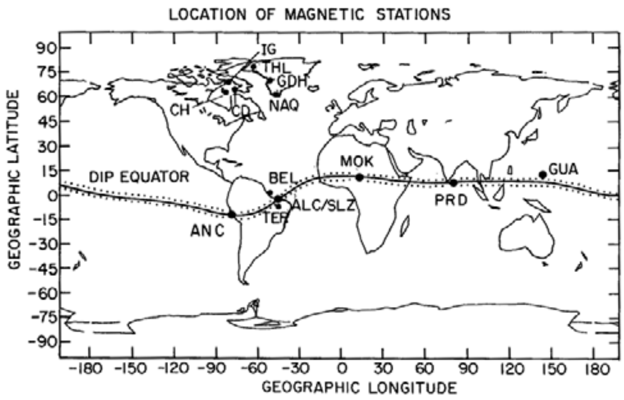

Figure 1. Locations of ground stations and the magnetic dip equator in geographic coordinates.

3. Events With Clear Equatorial Signatures

[7] As our reexamination of the previously reported events will show, TCVs exhibit a considerable range of signatures. Some are isolated, some repetitive, and the repetition times can vary. The signatures of some TCVs can be observed over a wide longitudinal range of high-latitude locations, while others cannot. Finally, amplitudes vary from less than 40 nT to greater than 200 nT. We begin by considering examples of isolated TCVs with widespread, large-amplitude, signatures.

3.1. Event 1715 UT on 9 November 1993

[8] Figure 2 (from top to bottom) presents GOES 6 and 7 geosynchronous magnetic field observations, the *H* component from three Greenland ground magnetograms, and the *X* component from three MACCS array ground magnetograms during the period from 1600 to 1800 UT on 9 November 1993. As indicated by the vertical lines in the lower panel, *Zesta et al.* [1999] identified four TCVs in the MACCS observations immediately after 1710 UT. Their amplitudes reached ∼300 nT at some of the MACCs

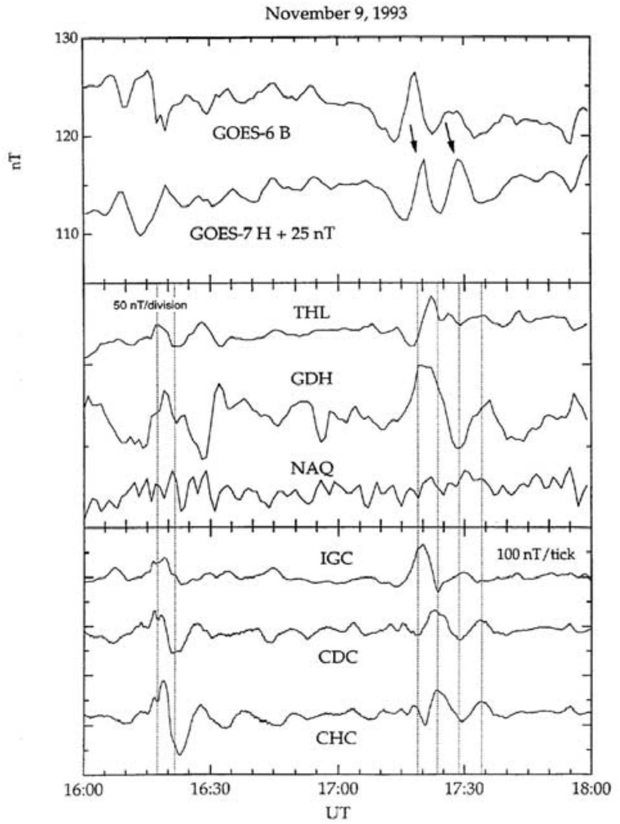

Figure 2. (top to bottom) GOES 6 and 7 geosynchronous magnetic field observations, the *H* component of Greenland ground magnetograms at THL, GDH, and NAQ, and the *X* component of Magnetometer Array for Cusp and Cleft Studies (MACCS) array stations IGC, CDC, and CHC from 1600 to 1800 UT on 9 November 1993. Vertical dashed lines after 1710 UT identify the times when *Zesta et al.* [1999] identified four TCVs in the ground observations. Vertical dashed lines prior to 1630 UT identify large-amplitude perturbations at CDC that cannot be interpreted as TCVs. See Table 1 for station names.

stations (not shown). As required for identification as TCVs, the sense of each *H* component perturbation reversed from low to high latitudes, so that positive (negative) perturbations in the *H* component at higher latitude (79.4°) IGC corresponded to negative (positive) perturbations in the *H* component at lower latitude CDC (74.6°) and CHC (74.8°). Corresponding events, with amplitudes reaching ~100 nT can also be seen in the Greenland ground magnetograms. However, the events cannot be classified as TCVs over Greenland because there is no clear reversal in the *H* component with latitude. The time between two peaks in the *H* component was ~11 min in the MACCS observations (e.g., CDC) but 16 min in the Greenland observations (GDH).

[9] Zesta et al. noted that a transient event in the MACCS array observations at 1615 UT exhibited equally strong amplitude perturbations but less clear TCV signatures. As indicated by the vertical lines, there was no reversal in the *H* component with latitude at either the Greenland or the MACCs stations for this event. There may have been other even weaker events between 1615 and 1700 UT.

[10] Zesta et al. associated the 1715 UT events with a sequence of transient pulses in which foreshock densities observed by IMP 8 varied by a factor of ~2 during an interval of northward IMF orientation. GOES 6 and 7 observations are consistent with this interpretation. As illustrated in the upper panel of Figure 2, the GOES 6 and 7 spacecraft observed a pair of compressional pulses moving westward from GOES 6 to 7 through the dayside prenoon geosynchronous magnetospheric magnetic field in conjunction with the ground events.

[11] For comparison, Figure 3 shows the high pass (30 min) filtered H components recorded at eight equatorial stations. The variations corresponding to the 1715 UT TCV event reached peak amplitudes (10 ~ 12 nT) at Ancon (1200 LT) and São Luis (1425 LT), both nearly directly under the dayside equatorial electrojet. The amplitudes were somewhat less (5 nT) at Teresina, Belem, and Santa Maria, all at local times similar that of São Luis, but well outside the equatorial electrojet. The perturbations reached still lower amplitudes (~3 nT) at Mokolo (1830 LT), Peradenia (2300 LT), and Guam (0300 LT), all on the nightside. Taken together, the observations indicate coherent variations whose amplitudes diminish with increasing local time from noon.

[12] Finally, note that both Ancon and São Luis recorded weaker and less prominent (i.e., less isolated) perturbations from 1610 to 1620 UT and 1645 to 1700 UT, perhaps corresponding to the weaker and less well defined high-latitude events at 1615 UT and from 1645 to 1700 UT. The examples below will provide further evidence that clear events under the equatorial electrojet correspond to strong and isolated TCV's at higher latitudes.

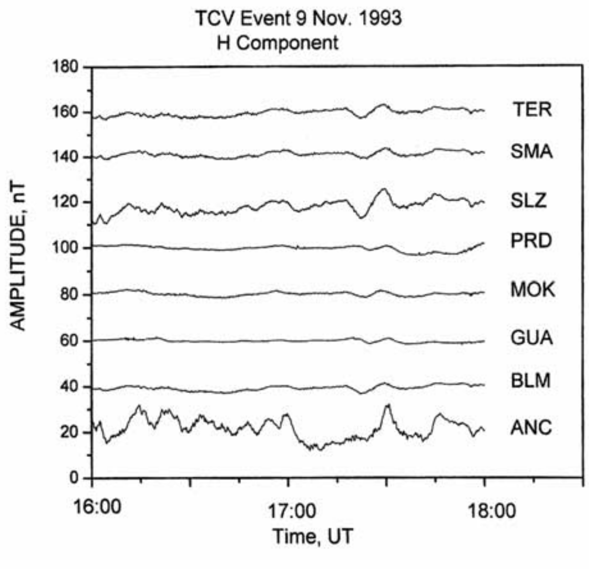

Figure 3. *H* component of ANC, GUA, MOK, PRD, BLM, SLZ, SMA, and TER ground magnetograms from 1600 to 1800 UT on 9 November 1993. See Table 1 for station names.

3.2. Event 1350 UT on 18 December 1993

[13] Figure 4 (bottom) presents the *H* components of Greenland ground magnetograms from 1300 to 1500 UT on 18 December 1993. As indicated by a vertical dashed line, *Moretto et al.* [1997] identified several TCVs near 1350 UT. The *H* component perturbations reversed from positive/negative at NAQ (where the amplitude approaches 200 nT) to negative/positive at GDH. THL observed a transient negative bay rather than a bipolar signature. *Moretto et al.* [1997] noted that this event could be interpreted as an isolated set of two or possibly three convection vortices moving eastward over the western coast of Greenland. *Moretto et al.* [1997] also reported that just prior to this event the Canadian and Scandinavian ground magnetograms provided evidence for a global change in convection patterns. Figure 4 (middle) provides *X* component observations from the three stations in the MACCS array whose longitudes are closest to those in the Greenland chain. While CDC and CHC observed bipolar positive/negative signatures, IGC recorded only a weak positive perturbation at 1350 UT.

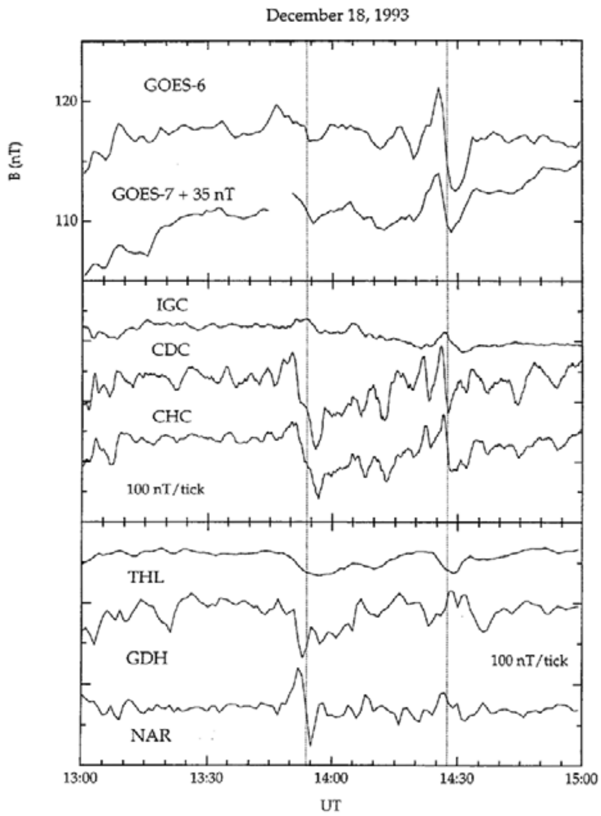

Figure 4. (top to bottom) GOES 6 and 7 geosynchronous magnetic field observations, the *X* component of MACCS array stations IGC, CDC, and CHC, and the *H* component of Greenland ground magnetograms at THL, GDH, and NAQ from 1600 to 1800 UT on 18 December 1993. A vertical dashed line at 1354 UT identifies the time when *Moretto et al.* [1997] identified a pair of TCVs in the ground observations. A vertical dashed line at 1427 UT identifies a second impulsive event in the MACCS array. See Table 1 for station names.

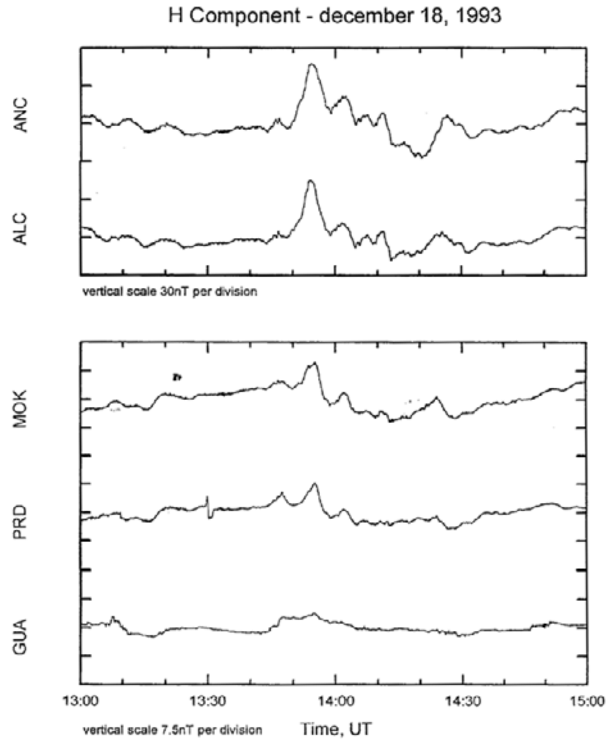

Figure 5. *H* component of ANC, ALC, MOK, PRD, and GUA ground magnetograms from 1600 to 1800 UT on 18 December 1993. See Table 1 for station names.

[14] The MACCS and Greenland observations provide evidence for a second impulsive event at 1427 UT on the same day. At CDC and CHC this event represents a significant ($\sim$200 nT) intensification of an ongoing pulsation with a period of $\sim$4 min. At IGC it can be identified as a slight increase in the *X* component. Positive perturbations mark the event at GDH and NAR, but a transient negative bay marks the event at THL.

[15] Figure 4 (top) presents GOES 6 and 7 geosynchronous magnetic field observations for the same time interval. Both GOES 6 and 7 observed only modest compressions at 1347 UT just prior to the 1350 UT event in Greenland, but the GOES spacecraft observed a particularly striking compression at 1425 UT followed by an equally transient rarefaction at 1429 UT, presumably corresponding to the 1427 UT ground event. No solar wind observations were available for either event.

[16] Figure 5 presents equatorial ground magnetograms for the same time interval. *H* component observations by the two stations located nearest local noon, ANC and ALC, indicate two pulsed increases at 1352 and 1428 UT, corresponding to both transient events at high latitudes on the ground. Dusk station MOK and nightside station PRD recorded similar signatures with much smaller amplitudes. Guam, located on the nightside and at higher latitudes, observed virtually no signatures corresponding to either event.

4. Less Successful Efforts

[17] Identifying signatures in the low-latitude ground magnetograms corresponding to the other TCV reported

by *Moretto et al.* [1997] and the events studied by *Ridley et al.* [1998] was not so simple. This may be due to the fact that their signatures were less isolated, exhibited lower amplitudes, or extended over a lesser range in local time.

4.1. Event 1300 UT on 14 October 1993

[18] Figure 6 (bottom) presents Greenland ground magnetograms observations from 1200 to 1400 UT on 14 October 1993. As illustrated by the vertical dashed lines, *Moretto et al.* [1997] identified a pair of TCVs near 1300 UT. The events reached a peak amplitude of ~150 nT at GDH. The MACCS observations shown in Figure 6 (middle) provide evidence for transient events with similar amplitudes shortly after 1300 UT. IMP 8 observations (not shown) provide no evidence for any solar wind pressure pulse, but they do indicate a highly variable IMF orientation with successive north/south turnings.

[19] As indicated in Figure 6 (top), there was a very prominent isolated compressional signature at both GOES 6 and 7 at the time of these events. However, as shown in Figure 7, signatures corresponding to these events are rather difficult to identify in the equatorial ground magnetograms. Duskside MOK (1400 LT) and PRD (1830 LT) recorded a weak increase in the *H* component at 1302 UT, whereas dawnside ANC (0800 LT) and ALC (1000 LT) recorded weak step function decreases starting at 1259 UT. Nightside GUA (2230 LT) recorded no signature at all. The weak and conflicting signatures at all the equatorial ground stations may be due to the fact that the high-latitude event attained lesser amplitudes than the others considered in this review, the fact that most of the ground stations were located far from local noon where the equatorial signatures are expected to reach peak amplitude, and the fact that the TCV signature was limited in local time extent. Indeed, one of the simpler and clearer signatures was seen at MOK, closest to local noon.

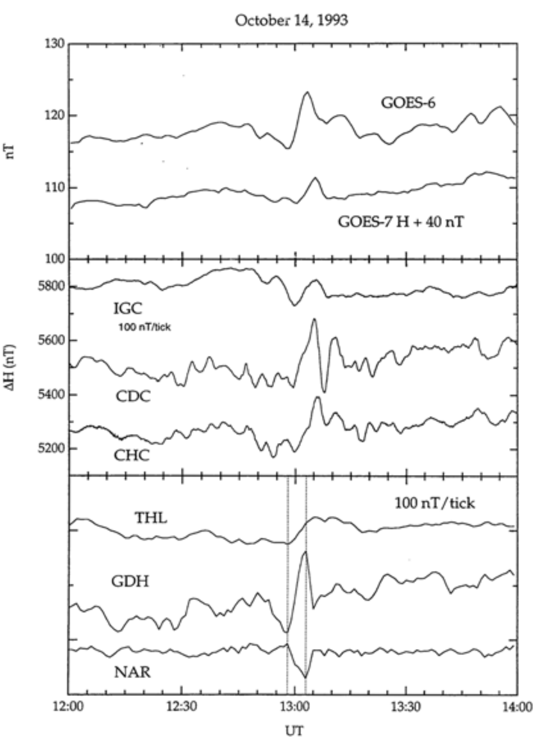

Figure 6. (top to bottom) GOES 6 and 7 geosynchronous magnetic field observations, the *X* component of MACCS array stations IGC, CDC, and CHC, and the *H* component of Greenland ground magnetograms at THL, GDH, and NAQ from 1200 to 1400 UT on 14 October 1993. Vertical dashed lines near 1300 UT indicate two TCVs identified in the Greenland observations by *Moretto et al.* [1997]. See Table 1 for station names.

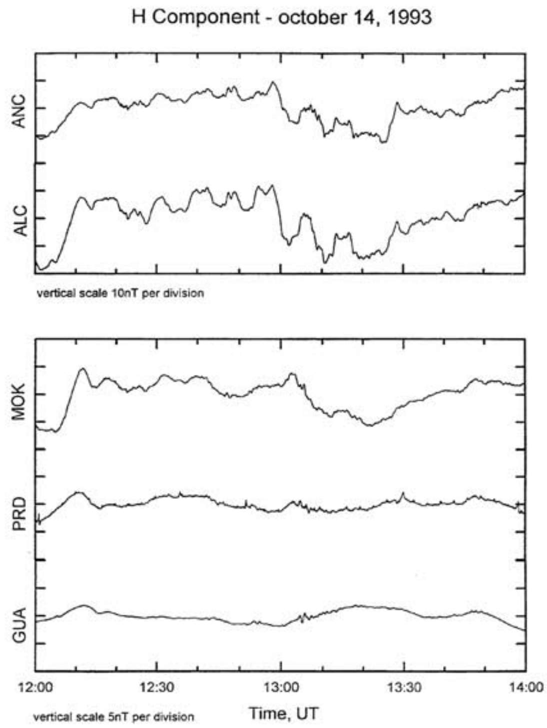

Figure 7. *H* component of ANC, ALC, MOK, PRD, and GUA ground magnetograms from 1200 to 1400 UT on 14 October 1993. See Table 1 for station names.

4.2. Event 1439 UT on 6 November 1993

[20] Figure 8 (bottom) presents the *H* components from three Greenland ground magnetograms (THL, GDH, and NAR) for the interval from 1400 to 1600 UT on 6 November 1993. *Ridley et al.* [1998] reported evidence for a pair of eastward moving vortices forming east and west of Greenland at 1439 UT. Ridley et al. reported that a third vortex formed west of Greenland after 1446 UT. Vertical dashed lines in Figure 8 indicate three times when negative *H* component perturbations at THL (85.4°) reversed to positive *H* component perturbations at NAQ (66.3°). Peak amplitudes reached 200 nT at NAQ but were only slightly larger than perturbations seen earlier and later during the time interval displayed in Figure 8. The time between two peaks in the *H* component was only 4 min. No corresponding signatures were seen in the MACCS observations.

[21] IMP 8 was located within the magnetosheath, where it observed a turbulent magnetic field (not shown) as is often the case. Figure 8 (top) presents GOES 6 and 7

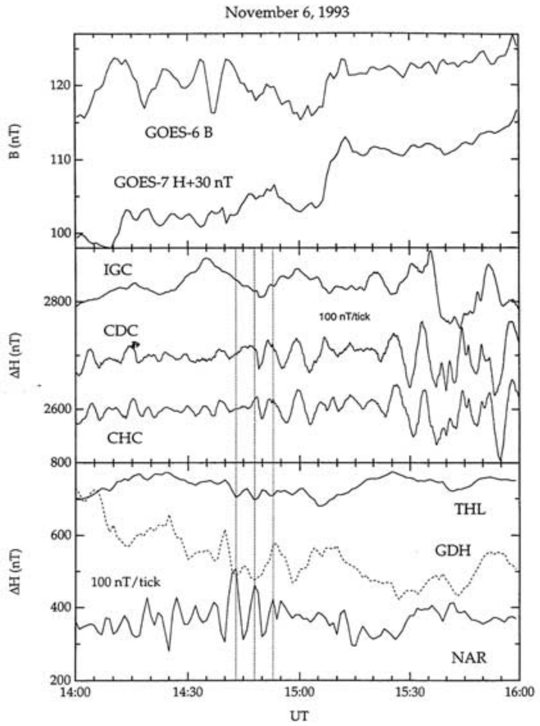

Figure 8. (top to bottom) GOES 6 and 7 geosynchronous magnetic field observations, the *X* component of MACCS array stations IGC, CDC, and CHC, and the *H* component of Greenland ground magnetograms at THL, GDH, and NAQ from 1400 to 1600 UT on 6 November 1993. Vertical dashed lines near 1300 UT indicate three TCVs identified in the Greenland observations by *Ridley et al.* [1998]. See Table 1 for station names.

geosynchronous magnetic field observations for the corresponding interval. Although GOES 6 recorded a pair of compressions at 1435 and 1440 UT, they were no greater than other variations at this spacecraft during the 2-hour interval and there were no corresponding signatures at GOES 7. Consequently, the events reported by Ridley et al. on 6 November 1993 exhibited a higher frequency, were less distinct from surrounding features, and were seen over a narrower range of longitudes than those reported by *Zesta et al.* [1999].

[22] Figure 9 compares the signature seen by ALC near local noon with those seen by equatorial stations at other local times. The *H* component at ALC exhibited an isolated pulsed increase at 1441 UT, the time when the TCVs began at higher latitudes. The *H* component at MOK, also on the dayside, observed a weaker pulsed increase at this time. By contrast, duskside PRD observed a strong negative peak at this time and nightside GUA observed a weak negative peak. We must conclude that the equatorial ground signatures for less prominent high-latitude events can depend strongly on local time, perhaps particularly when the high-latitude signatures are spatially limited, as in this case.

4.3. Multiple Events on 7 November 1993

[23] Figure 10 (bottom) presents Greenland ground magnetograms for the period from 1300 to 1500 UT on 7 November 1993. Vertical dashed lines at 1350, 1358, 1402, and 1405 UT mark the times when *Ridley et al.* [1998] identified four vortices over Greenland. Although perturbation amplitudes reached 150 nT, these events were much more poorly defined than those considered earlier in this paper. Because most cannot be associated within latitudinal transitions from northward to southward perturbations, it is not clear if they are TCVs. There were perturbations with equally large amplitudes earlier and later within the time interval shown. As indicated in the top panel, there were no corresponding features at geosynchronous orbit. As shown in Figure 11, there were no corresponding features at ALC, MOK, PRD, or GUA. BLM, SLZ, SMA, and TER in Brazil (not shown) all recorded the same pulsation sequence, with the greatest amplitudes occurring at ALC and SLZ, directly under the equatorial electrojet .

[24] Although no plasma data are available, the IMP 8 magnetometer recorded a sequence of bow shock crossings at 1354, 1357, 1401, and 1408 UT. During the period of this event, IMP 8 was located immediately outside the northern dawn bow shock, near GSE $(X, Y, Z) = (-15.6, -25.0, 17.7)$ R_E (Earth radii). We therefore suspect that the ground events were related to variations in the solar wind pressure, as was the case in a similar sequence of events reported by *Korotova et al.* [1997]. The IMF had a near equatorial orientation throughout these events.

4.4. Multiple Events on 5 November 1993

[25] Finally, Figure 12 (bottom) presents Greenland ground magnetograms for the period from 1300 to 1500

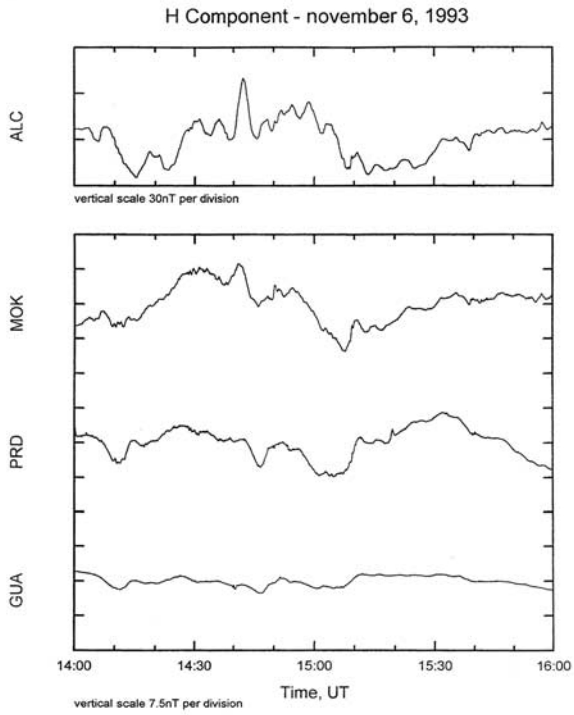

Figure 9. *H* component of ALC, MOK, PRD, and GUA ground magnetograms from 1400 to 1600 UT on 6 November 1993. See Table 1 for station names.

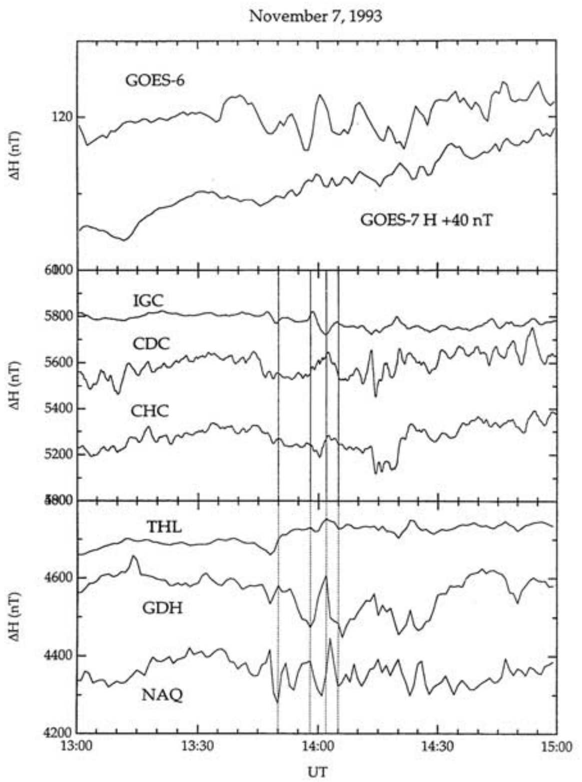

Figure 10. (top to bottom) GOES 6 and 7 geosynchronous magnetic field observations, the *X* component of MACCS array stations IGC, CDC, and CHC, and the *H* component of Greenland ground magnetograms at THL, GDH, and NAQ from 1300 to 1500 UT on 7 November 1993. Vertical dashed lines near 1300 UT indicate the times of four TCVs identified in the Greenland observations by *Ridley et al.* [1998]. See Table 1 for station names.

UT on 5 November 1993. Vertical dashed lines at 1358, 1401, 1405, and 1410 UT mark the times when *Ridley et al.* [1998] identified four vortices over Greenland. Although perturbation amplitudes once again reached 150 nT, these events were also more poorly defined than those considered earlier in this paper. The first two may be associated with reversals in the sense of H component perturbations from NAQ to GDH, but the latter two definitely cannot. Features with equal or greater amplitudes occur shortly prior to and after the events under consideration here. As indicated in Figure 12 (top), there were no corresponding events at geosynchronous orbit. As indicated in Figure 13, the events may be associated with abrupt step function changes in the ALC and ANC ground magnetograms at 1400 and 1408 UT. However, there are equally significant features in the equatorial ground magnetograms at earlier and later times. No IMP 8 observations were available for these events.

4.5. Other Events

[26] We sought to identify signatures in equatorial ground magnetograms for other previously published high-latitude TCVs. In particular, Brazilian ground magnetometer observations are available for the nineteen large amplitude (>100 nT) TCVs identified by *Lühr et al.* [1998] in IMAGE ground magnetograms from October 1993 to March 1994. Each IMAGE event exhibited a reversal in the *X* (north/south) component with latitude and propagated azimuthally.

[27] Table 2 lists the results of our survey. As *Lühr et al.* [1998] noted, IMP 8 solar wind/magnetotail observations were not available for most of the events. Nevertheless, the limited IMP 8 observations that were available indicate that the events occurred for all IMF orientations and were occassionally associated with solar wind pressure variations and brief compressions of the magnetotail.

[28] We were generally able to identify corresponding signatures in equatorial magnetograms at local times similar to those of the Scandinavian stations, but not in the Brazilian ground magnetograms. Brazil was located at early morning times for each of the IMAGE events. Since the equatorial electrojet is weak at early morning local times, we do not expect to see significant signatures in the Brazilian ground magnetograms. As these magnetograms constitute the focus of this study, we did not proceed further.

5. Discussion and Conclusions

[29] As summarized in Table 3, we obtained mixed results from our search for signatures in equatorial ground magnetograms corresponding to previously reported TCVs at higher latitudes. In part, this is due to the differing characteristics of the high-latitude events. We were unable to identify equatorial signatures for the events on 5 and 7 November that exhibited relatively weak (~100 nT) ampli-

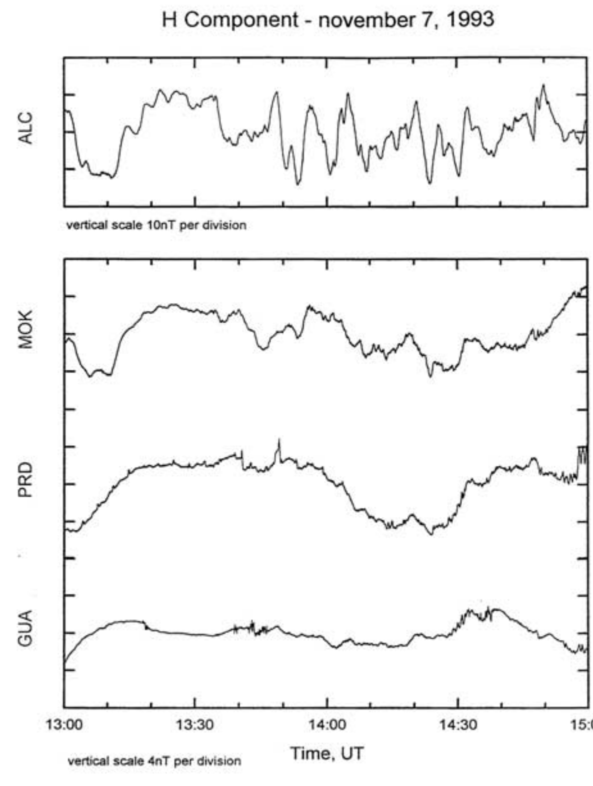

Figure 11. *H* component of ALC, MOK, PRD, and GUA ground magnetograms from 1300 to 1500 UT on 7 November 1993. See Table 1 for station names.

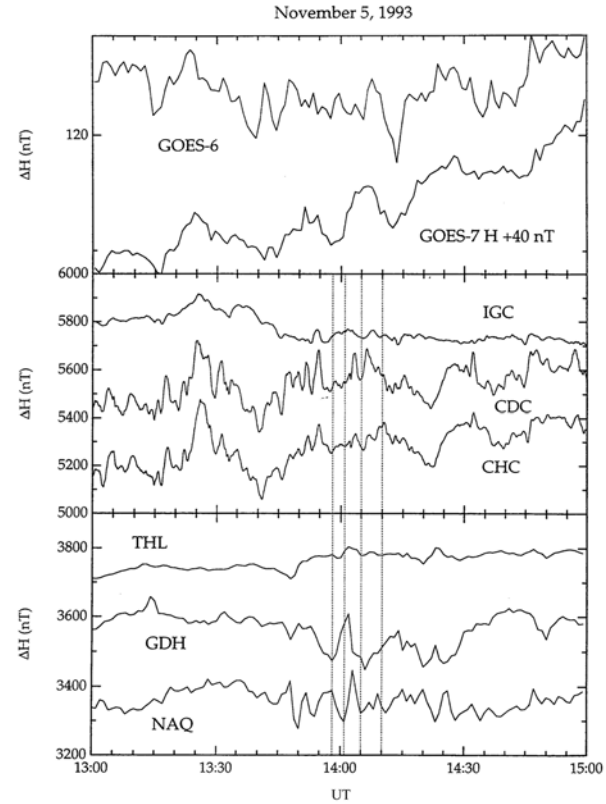

Figure 12. From top to bottom: GOES 6 and 7 geosynchronous magnetic field observations, the *X* component of MACCS array stations IGC, CDC, and CHC, and the *H* component of Greenland ground magnetograms at THL, GDH, and NAQ from 1300 to 1500 UT on 5 November 1993. Vertical dashed lines near 1300 UT indicate the times of four TCVs identified in the Greenland observations by *Ridley et al.* [1998]. See Table 1 for station names.

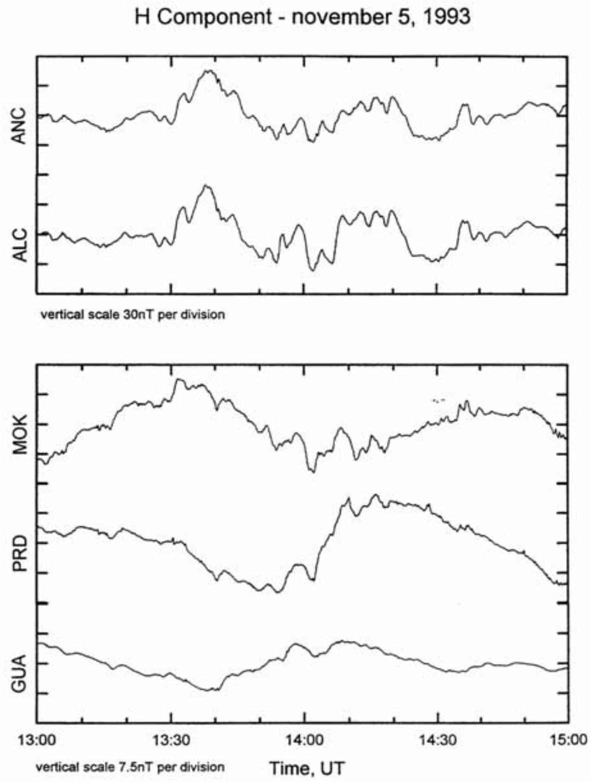

Figure 13. *H* component of ALC, MOK, PRD, and GUA ground magnetograms from 1300 to 1500 UT on 5 November 1993. See Table 1 for station names.

tudes, no *H* component reversal versus latitude, limited longitudinal extents, and quasiperiodic signatures. By contrast, we were able to identify an impulsive signature in the equatorial ground magnetograms for the event on 6 November that was also quasiperiodic with a limited longitudinal extent, but exhibited larger (~200 nT) *H* component amplitudes that clearly reversed with latitude.

[30] The event on 14 October was isolated and exhibited a strong (150 nT) bipolar signature in the *H* component that reversed with latitude. As might be expected, there were very clear corresponding signatures in the geosynchronous magnetic field measured by both GOES spacecraft. While there was a corresponding step function decrease in the dayside equatorial ground magnetograms, this decrease was only one of many quasi-periodic changes that occurred during the 2-hour period surrounding the high-latitude event. Because these other variations occurred at both ANC and ALC, but not PRD or GUA, their spatial extent was limited to the dayside equatorial ionosphere. As noted by *Trivedi et al.* [1997] and *Abdu et al.* [1998], the electric fields corresponding to long period geomagnetic pulsations travel equatorward through the ionosphere. Whatever their origin, such variations pose a difficulty in establishing a one-to-one correspondence between event signatures in high- and low-latitude ground magnetograms.

[31] By contrast, the relationships between the high- and low-latitude signatures on 9 November and 18 December 1993 were simpler to understand. The *H* component sig-

Table 2. Survey of *Luhr et al.* [1998] Event Occurrence Patterns

Date	Time, UT	Eq. Sig.?	SW Pressure	IMF *Bz*
12 Oct. 1993	0635	dayside	TLC	ND
13 Oct. 1993	0905	no	ND	ND
24 Oct. 1993	0743	dayside	slight TLC	ND
28 Oct. 1993	0748	dayside	ND	>0
8 Nov. 1993	0618	dayside	step decrease	<0
20 Nov. 1993	0721	?	ND	Near 0
23 Nov. 1993	0729	?	ND	ND
26 Nov. 1993	0716	dayside	ND	>0
6 Dec. 1993	0619	dayside	ND	ND
7 Dec. 1993	0636	dayside	ND	ND
21 Dec. 1993	0612	?	ND	ND
21 Dec. 1993	0727	dayside	ND	ND
22 Dec. 1993	0655	dayside	?	>0
16 Jan. 1994	0509	dayside	?	Mixed
18 Jan. 1994	0630	dayside	ND	ND
18 Jan. 1994	0732	dayside	ND	ND
2 Feb. 1994	0804	?	ND	ND
21 Feb. 1994	0726	dayside	ND	ND
14 March 1994	0637	dayside	?	<0

TLC, compression of the magnetotail lobe magnetic field; ND, no data. Question mark indicates insufficient time resolution to identify a corresponding feature.

Table 3. Description of the Equatorial Signatures of the Traveling Convection Vortices Events

Date	Time, UT	Equatorial Signature	SW Pressure	IMF, B_Z
9 November 1993	1715	clear	yes	>0
18 December 1993	1350	clear	no	no
14 October 1993	1300	poor	no data	variable
6 November 1993	1439–1446	poor	no	disturbed sheath
7 November 1993	1350–1405	poor	probable bs xings	~0
5 November 1993	1358–1440	poor	no	no

nature seen during the 1350 UT event on 18 December exceeded 200 nT, was bipolar, reversed with latitude over Greenland, and was seen in the MACCS array. A second event at 1425 UT exhibited an equally clear signature in the MACCS array observations, but a poor signature over Greenland. Both events were isolated and corresponded to clear compression/rarefactions at geosynchronous orbit and transient compressions in all the dayside equatorial ground magnetograms.

[32] The high-latitude events on 9 November were equally clear. Isolated impulsive H component signatures with amplitudes greater than 100 nT reversed with latitude over the MACCS array and were also detected by the Greenland ground magnetograms. The GOES spacecraft recorded transient disturbances that were particularly clear for the second set of events near 1730 UT. The same was true for stations within the Brazilian network of ground magnetograms (BLM, SLZ, SMA, and TER).

[33] It might also be supposed that the success rates in identifying equatorial signatures for the various high latitude events listed in Table 3 reflect the fact that the processes generating the events differed. Whereas *Zesta et al.* [1999] attributed their event to the effects of a solar wind pressure pulse, *Ridley et al.* [1998] attributed their events to variations in the reconnection rate at the sepatatrix. While the signatures of the high-latitude events certainly differ (those of Zesta et al. and Moretto et al. being much clearer), we have also noted that IMP 8 observations suggest that at least one sequence of events reported by Ridley et al. were associated with bow shock motion and, by inference, solar wind pressure variations.

[34] Even when signatures were observed in the equatorial ground magnetograms, they differed greatly from event to event. Considering only the two clearest events, those on 9 November and 18 October, we note that a sequence of several high-latitude events from 1720 to 1735 UT on 9 November corresponded to a sequence of several compressions/rarefactions in the GOES and ground magnetograms. The bipolar H signature seen at high latitudes at 1355 UT on 18 December indicates that a pair of TCVs corresponded to a bipolar compression/rarefaction at geosynchronous orbit, but a single strong compressional peak at the equatorial ground stations. The bipolar signature seen at 1300 UT on the same day in the high-latitude ground magnetograms also corresponded to a bipolar rarefaction/compression at the GOES spacecraft, but a step function decrease in the equatorial ground magnetograms.

[35] Since the signatures seen by the high- and low-latitude ground magnetometers differ in form, the equatorial signatures cannot be simply result from remote observations of the field aligned currents that generate the high-latitude signatures. Furthermore, signatures always reached greater amplitudes at stations under the dayside equatorial ionosphere than at midlatitude stations or on the nightside. This is to be expected, for the equatorial region where the strength of the equatorial electrojet and ionospheric densities reach greatest amplitudes [*Trivedi and Rastogi*, 1968; *Rastogi*, 1994]. Note that the aforementioned papers treat SI, which are seen globally, rather then TCV's which are generally localized.

[36] To summarize, we have inspected geosynchronous and equatorial ground magnetograms at the times of previously reported high-latitude transient events. When the high-latitude transient events exhibited clear, strong, isolated signatures corresponding to TCVs, we generally detected isolated bipolar compressional signatures at geosynchronous orbit and transient impulses in equatorial ground magnetograms. We had difficulty identifying corresponding equatorial signatures for high-latitude events that were quasiperiodic, weaker, spatially limited, or did not exhibit clear TCV signatures. On some occasions, equatorial signatures may be obscured by other phenomena, for example, the quasi-periodic variations seen throughout the interval shown on 14 October. Finally, efforts to identify equatorial signatures should focus on dayside stations, where amplitudes reach peak values.

[37] **Acknowledgments.** We thank H. J. Singer, NOAA, and NASA/GSFC SPDF for supplying the GOES geosynchronous magnetic field observations, The Danish Meteorological Institute for supplying the Greenland ground magnetograms, and M. Engebretson for supplying the MACCS ground magnetograms. Research at JHU/APL was supported by NSF grant ATM-9803800 with a supplement for joint work with Brazilian scientists. The Research in Brazil was supported by the Instituto Nacional de Pesquisas Espaciais–INPE/MCT and a grant from FAPESP 1998/15197-2.

[38] Janet G. Luhmann thanks Alexander Yahnin and another referee for their assistance in evaluating this paper.

References

Abdu, M. A., J. H. Sastri, H. Lühr, H. Tachihara, N. B. Trivedi, and J. H. A. Sobral, DP2 electric field fluctuations in the dusk-time dip equatorial ionosphere, *Geophys. Res. Lett.*, *25*, 1511–1514, 1998.

Baker, W. G., and D. F. Martyn, Conductivity of the ionosphere, *Philos. Trans. R. Soc. London, Ser. A*, *264*, 281–304, 1953.

Hirono, M., On the influence of the Hall current to the electrical conductivity of the ionosphere, I, *J. Geomagn. Geoelectr.*, *2*, 1–8, 1950a.

Hirono, M., On the influence of the hall current to the electrical conductivity of the ionosphere, II, *J. Geomagn. Geoelectr.*, *2*, 113–120, 1950b.

Hirono, M., A theory of diurnal magnetic variations in equatorial regions and conductivity of the ionosphere *E* region, *J. Geomagn. Geoelectr.*, *4*, 7–21, 1952.

Konik, R. M., L. J. Lanzerotti, A. Wolfe, C. G. Maclennan, and D. Venkatesan, Cusp latitude magnetic impulsive events, 2, Interplanetary magnetic field and solar wind conditions, *J. Geophys. Res.*, *99*, 14,831–14,853, 1994.

Konik, R. M., L. J. Lanzerotti, C. G. Maclennan, A. Wolfe, and D. Venkatesan, Cusp latitude magnetic impulse events, 3, Associated low-latitude signatures, *J. Geophys. Res.*, *100*, 7731–7743, 1995.

Korotova, G. I., and D. G. Sibeck, A case study of transient event motion in the magnetosphere and in the ionosphere, *J. Geophys. Res.*, *100*, 35–46, 1995.

Korotova, G. I., D. G. Sibeck, T. J. Rosenberg, C. T. Russell, and E. Friis Christensen, High latitude ionospheric transient events in a global context, *J. Geophys. Res.*, *102*, 17,499–17,508, 1997.

Lanzerotti, L. J., A. Wolfe, N. B. Trivedi, C. G. MacLennan, and L. V. Medford, Magnetic impulse events at high latitudes: Magnetopause and boundary layer plasma processes, *J. Geophys. Res.*, *95*, 97–107, 1990.

Lühr, H., M. Rother, T. Iyemori, T. L. Hansen, and R. P. Lepping, Superposed epoch analysis applied to large amplitude traveling convection vortices, *Ann. Geophys.*, *16*, 743–753, 1998.

McHenry, M. A., C. R. Clauer, and E. Friis-Christensen, Relationship of

solar wind parameters to continuous dayside high latitude traveling ionospheric convection vortices, *J. Geophys. Res.*, *95*, 15,007–15,022, 1990.
Moretto, T., E. Friis-Christensen, H. Lühr, and E. Zesta, Global perspective of ionospheric traveling convection vortices: Case studies of two Geospace Environmental Modeling events, *J. Geophys. Res.*, *102*, 11,597–11,610, 1997.
Rastogi, R. G., Ionospheric current system associated with the equatorial counterelectrojet, *J. Geophys. Res.*, *99*, 13,209–13,217, 1994.
Ridley, A. J., T. Moretto, P. Ernström, and C. R. Clauer, Global analysis of three traveling vortex events during the November 1993 storm using the assimilative mapping of ionospheric electrodynamics technique, *J. Geophys. Res.*, *103*, 26,349–26,358, 1998.
Rijnbeek, R. P., S. W. H. Cowley, D. J. Southwood, and C. T. Russell, A survey of dayside flux transfer events observed by ISEE-1 and 2 magnetometers, *J. Geophys. Res.*, *89*, 786, 1984.
Russell, C. T., and R. C. Elphic, Initial ISEE magnetometer results: Magnetopause observations, *Space Sci. Rev.*, *22*, 681–715, 1978.
Saka, O., M. Shinohara, H. Tachihara, H. Akaki, H. Inouye, T. Uozumi, and T. Kitamura, A time source for a data acquisition system designed for phase propagation study of magnetic pulsations, *J. Geomagn. Geoelectr.*, *48*, 1321–1326, 1996.
Sato, Y., Morphological study on Sudden Commencements of magnetic storms and Sudden Impulses (IV), *Mem. Kakioka Mag. Observ.*, *12*(1), 55–76, 1964.
Sibeck, D. G., Transient magnetic field signatures at high latitudes, *J. Geophys. Res.*, *98*, 243–256, 1993.
Sibeck, D. G., and G. I. Korotova, Occurrence patterns for transient magnetic field signatures at high latitudes, *J. Geophys. Res.*, *101*, 13,413–13,428, 1996.
Sibeck, D. G., et al., The magnetospheric response to 8 min. period strong amplitude upstream pressure variations, *J. Geophys. Res.*, *94*, 2505–2519, 1989.
Southwood, D. J., Magnetopause Kelvin Helmholtz instability, in *Magnetospheric Boundary Layers*, edited by B. Battrick, *Eur. Space Agency Spec. Publ., SP-148*, 357–364, 1979.
Southwood, D. J., and M. G. Kivelson, The magnetohydrodynamic response of the magnetospheric cavity to changes in solar wind pressure, *J. Geophys. Res.*, *95*, 2301–2310, 1990.
Tachihara, H., and M. Shinohara, Magnetometer system for studies of the equatorial electrojet and micropulsations in equatorial regions, *J. Geomagn. Geoelectr.*, *48*, 1311–1320, 1996.
Tachihara, H., M. Shinohara, M. Simoizumi, O. Saka, and T. Kitamura, Magnetometer system for studies of the equatorial electrojet and micropulsations in the equatorial regions, *J. Geomagn. Geoelectr.*, *48*, 1311–1319, 1996.
Trivedi, N. B., and R. G. Rastogi, Studies of sudden changes in *H* and *Z* at equatorial stations in the Indian Zone, *Ann. Geophys.*, *24*, 1037–1046, 1968.
Trivedi, N. B., B. R. Arora, A. L. Padilha, J. M. da Costa, S. L. G. Dutra, F. H. Chamalaun, and A. Rigoti, Global Pc5 geomagnetic pulsations of March 24, 1991 as observed along the American sector, *Geophy. Res. Lett.*, *24*, 1683–1686, 1997.
Yahnin, A., and T. Moretto, Travelling convection vortices in the ionosphere map to the central plasma sheet, *Ann. Geophys.*, *14*, 1025–1031, 1996.
Zesta, E., W. J. Hughes, M. J. Engebretson, T. J. Hughes, A. J. Lazarus, and K. I. Paularena, The November 9, 1993, traveling convection vortex event: A case study, *J. Geophys. Res.*, *104*, 28,041–28,058, 1999.

S. L. G. Dutra, Instituto Nacional de Pesquisas Espaciais-INPE, Sao Jose dos Campos, 515, SP, Brazil.

T. Kitamura and K. Yumoto, Department of Earth and Planetary Sciences, Kyushu University, Fukuoka, Japan.

J. C. Santos and N. B. Trivedi, Centro Regional Sul de Pesquisas Espaciais-CRSPE/INPE, Santa Maria, RS 97105-900, Brazil. (trivedi@dge.inpe.br)

M. Shinohara, Solar Terrestrial Environment Laboratory, Nagoya University, Toyokawa 442, Japan.

D. G. Sibeck, Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723-6099, USA.

E. Zesta, Department of Atmospheric Sciences, University of California, Los Angeles, CA 90095, USA.