All-sky imaging observations of conjugate medium-scale traveling ionospheric disturbances in the American sector

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Received 15 November 2010; revised 11 February 2011; accepted 25 February 2011; published 28 May 2011.

[1] All-sky imaging systems at Arecibo, Puerto Rico (18.3°N, 66.7°W, +28° mag. lat.), and Mercedes, Argentina (34.6°S, 59.4°W, −24.6° mag. lat.), are used to study ionospheric conjugate processes at lower midlatitudes. For the first time in the American sector the simultaneous occurrence in both hemispheres of medium-scale traveling ionospheric disturbances has been observed. The first year of observations yielded 43 nights (~40%) with simultaneous occurrence of airglow bands. Supporting information from GPS receivers indicate the presence of vertical total electron content variations that correlate with the airglow structures observed with the imagers. Weak phase fluctuations have been measured, indicating that these structures do not produce severe large-scale ionospheric irregularities.

Citation: Martinis, C., J. Baumgardner, J. Wroten, and M. Mendillo (2011), All-sky imaging observations of conjugate medium-scale traveling ionospheric disturbances in the American sector, *J. Geophys. Res.*, *116*, A05326, doi:10.1029/2010JA016264.

1. Introduction

[2] The midlatitude ionosphere is the region poleward from the location of the crests of the equatorial ionization anomaly (EIA), i.e., ≥15–20° mag. lat., and below the plasmapause/ionospheric trough at ~60° mag. lat. Satellite and ground-based observations at midlatitudes provided evidence for the occurrence of processes showing changes in total electron content (TEC), plasma instabilities and corrugations in ionospheric density with horizontal scale size of 100s of kilometers [*Behnke*, 1979]. These structured bands are loosely named medium-scale traveling ionospheric disturbances (MSTIDs), a term originally coined using ionosonde observations to describe midlatitude ionospheric structures with horizontal scale sizes of several 100s km [*Hunsucker*, 1982].

[3] The first optical studies of these midlatitude structures were carried out using an all-sky imager (ASI) at the Arecibo Observatory [*Mendillo et al.*, 1997; *Miller et al.*, 1997]. They observed the passage of band-like structures that were associated with vertical motions of the ionosphere. That study and a subsequent analysis by *Garcia et al.* [2000] showed that most of the airglow structures observed over Arecibo tended to move southwestward. During the SEEK (Sporadic E Experiment over Kyushu) campaign, *Taylor et al.* [1998] also observed wave-like structures in 630.0 nm nightglow emissions traveling southwestward. The results were compared with the ones observed at Arecibo and they concluded that the southwestward motion was in agreement with the hypothesis of gravity waves oriented in such a way to couple efficiently with the Perkins instability.

[4] In the southern hemisphere at American longitudes, the first observation of a band-like structure was at El Leoncito [*Martinis et al.*, 2006]. These features emerged from the southeast and moved northwestward. Studies in the Brazilian sector also showed the occurrence of band-like structures moving northwestward [*Pimenta et al.*, 2008]. High occurrence rate during June solstice, with very few observations during December solstice due to bad weather conditions were reported by *Candido et al.* [2008].

[5] Some of the bands observed by *Behnke* [1979] had poleward drifts as high as 400 m/s, indicating the presence of very strong electric fields. Subsequent studies showed that these corrugations were actually associated with electric field fluctuations. For example, *Saito et al.* [1995] using DE-2 satellite data showed the presence of electric field fluctuations in regions poleward from the locations of the crests of the EIA. These midlatitude electric field fluctuations (MEFs) were directed poleward in both hemispheres. *Saito et al.* [1998a] showed that MEFs observed with the Freja satellite were associated with peaks of traveling ionospheric disturbances (TIDs) observed with the MU radar in Japan; *Kelley et al.* [2000] showed that the presence of MEFs could be linked to the observations of MSTIDs. *Shiokawa et al.* [2003a] compared electric fields from a DMSP satellite with airglow bands observed with an all-sky imager and concluded that eastward (westward) electric fields correlated with the presence of dark (bright) bands.

[6] In addition to MSTIDs and MEFs, another process occurring at midlatitudes is related to the presence of ionospheric irregularities of large-scale size, typically known as Spread F. *Bowman* [2001] compared TID characteristics

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0148-0227/11/2010JA016264

between low-latitude and midlatitude regions and their relation with Spread F. He concluded that Spread F characteristics for the two regions were very similar with MSTIDs with enhanced amplitudes being responsible for the spread traces observed in ionograms. But *Shiokawa et al.* [2003b] showed in the Japanese sector that both processes (MSTIDs and Spread F) peaked during local summer, even though MSTIDs were not always accompanied by midlatitude Spread F. Only 10–15% of the cases analyzed using data from all-sky imagers and nearby ionosonde in the Japanese sector showed simultaneous occurrence.

[7] Although these three different processes, MEFs, MSTIDs and midlatitude Spread F, seem to follow similar geographical and seasonal distributions, it seems they do not always occur at the same time, with MSTIDs many times representing just an altitude modulation of the ionosphere, without significant irregularities embedded, i.e., no MEFs or midlatitude Spread F. This appears to be the case for the MSTID discovery images given by *Mendillo et al.* [1997]. Nevertheless, a recent study by *Lee et al.* [2008] showed the simultaneous occurrence of airglow bands, an indication of MSTIDs, and significant phase fluctuations from GPS receivers (TECU/min >0.45), an indication of ionospheric irregularities.

[8] Most of the midlatitude observations described above have been carried out in a single hemisphere, i.e., without considering effects or observations in the conjugate hemisphere. During a 10 day campaign in 1993, ionospheric measurements from both hemispheres used an ionosonde at Ramey and the incoherent scatter radar (ISR) at Arecibo, both in Puerto Rico, and an ionosonde in Puerto Madryn, Argentina, near the Arecibo magnetic conjugate point [*Scali et al.*, 1997]. Although the main conclusions were related to the comparisons between the plasma drifts obtained by the radar and ionosonde in Puerto Rico, the study discussed the effects of the conjugate hemisphere during sunrise and solstice conditions. Specifically, an increased westward component of the horizontal velocity measured at Arecibo and Ramey around 0330 LT (0730U T), was correlated with sunrise in the summer conjugate hemisphere. The study by *Saito et al.* [1995] showed the conjugate nature of MEFs, and the mapping of electric fields from one hemisphere to the other was assumed to be the main mechanism to explain the observations.

[9] Simultaneous optical observations in both hemispheres were carried out for the first time by *Otsuka et al.* [2004] and *Shiokawa et al.* [2005]. These studies showed cases of simultaneous occurrence of MSTIDs in the Japanese/Australian sector. Bands were seen at both hemispheres and the importance of interhemisphere electric field mapping was again stressed.

[10] We present here the first observations of simultaneous measurements of band-like structures at midlatitudes in the American sector using all-sky imaging and GPS data.

2. Data

2.1. All-Sky Imaging Data

[11] All-sky imaging systems with narrowband interference filters (FWHM ~ 1.2 nm) are typically used to measure emissions from mesospheric and thermospheric processes. For this study we focus on 630.0 nm airglow emissions to identify structures occurring in the midlatitude thermosphere-ionosphere in both hemispheres. This study uses imaging data from two sites in the American sector, Arecibo (PR) and Mercedes (Argentina). Quick-look images and movies from these and other all-sky imagers operated by Boston University can be found at www.buimaging.com. The Mercedes imager was installed in April 2009 with the specific purpose of studying conjugate processes occurring in the American sector. While the Arecibo geomagnetic conjugate point (AGCP) is ~300 km south from Mercedes, over the Atlantic Ocean, the Mercedes field of view (FOV) clearly covers most of the area corresponding to the Arecibo's conjugate FOV.

[12] Figure 1 shows a map with the local 160° FOV of the Arecibo (solid red) and Mercedes (solid blue) imagers, assuming an emission height of 250 km. The shadowed oval with dashed red borders in the southern hemisphere is the conjugate FOV of Arecibo, obtained by calculating the conjugate geomagnetic coordinates using quasidipolar coordinates [*Richmond*, 1995]. The Mercedes FOV mapped to the northern hemisphere is the shaded region outlined in blue. Notice how each circular FOV is distorted into an oval-shaped FOV, a result of the unusual behavior of the geomagnetic field in the region [*Martinis and Mendillo*, 2007]. Color-coded asterisks centered in each shaded FOV represent the geomagnetic conjugate locations of the two ASI zenith locations. Thick solid arcs at the south of each FOV, and their respective conjugate locations (thick dashed lines), are drawn to illustrate the mapping geometry. For example, the southern part of the circular FOV of Arecibo is mapped to the northern portion of the oval-shaped FOV in the southern hemisphere.

[13] Figure 2 shows examples of simultaneous detections of MSTIDs during three different nights. Images from Arecibo (Figure 2, top) show dark band structures aligned northwest-southeast that move (not shown) southwestward. At the bottom, Mercedes images show dark bands aligned northeast-southwest that move northwestward. The 21 September 2009 and 3 February 2010 cases showed structures occurring simultaneously at both hemispheres. The 3 June 2009 represents a case where structures seemed to be fully developed earlier at Arecibo.

[14] During the first year of joint observations the number of nights with sky conditions allowing the detection of 630.0 nm airglow structures was 170 at Arecibo and 139 at Mercedes. Of these, there were 104 photometric nights at Arecibo and 94 at Mercedes. A total of 43 nights showed simultaneous structures at both Observatories. Some nights had bands observed only at one site, while others showed time differences in their formation when compared to the conjugate site. The observation of simultaneous occurrence suggests that the physical drivers creating the MSTIDs can act in both hemispheres. If a time delay in the formation of MSTIDs at one hemisphere is observed, then local ionospheric conditions could be suppressing the effects of the polarization electric fields thought to generate the bands [*Yokoyama et al.*, 2009], and thus delaying the formation or evolution of the bands.

[15] To properly identify common features, the raw images from Mercedes and Arecibo were unwarped (i.e., converted into a latitude-longitude coordinate system using an orthographic projection) assuming an emission height of 250 km and a 160°FOV. Figure 3 shows an example on

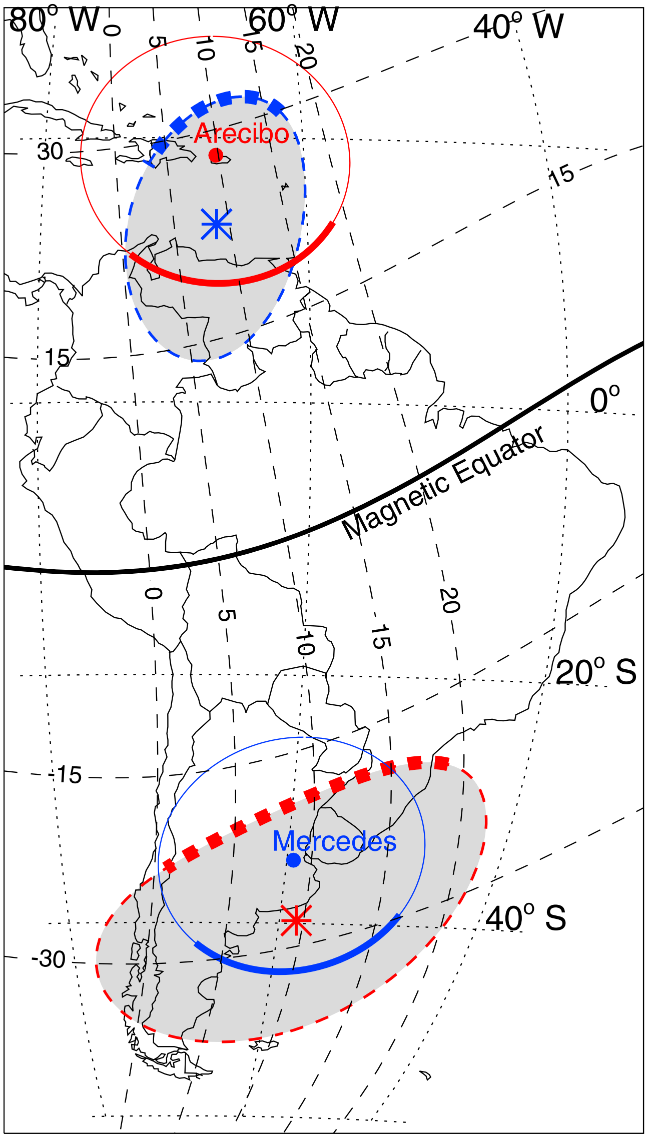

Figure 1. Map showing the 160° FOV of the imagers used in this study: Arecibo (solid red) and Mercedes (solid blue). Asterisks indicate the locations of the geomagnetically conjugate points. The gray-shadowed ovals are the FOV of the mapped Arecibo (dashed red) and Mercedes (dashed blue) circular FOV. Thick dashed-arcs to the south of each circular FOV and their conjugate locations are drawn to illustrate the mapping geometry. Thin dashed black lines represent magnetic latitudes and longitudes computed using quasidipolar coordinates.

9 February 2010 with 630.0 nm images from Arecibo at the top and images from Mercedes to the bottom. The asterisks drawn in each image represent the geomagnetic conjugate point of the zenith location of the imagers. There is a clear correlation between the structures seen at both hemispheres. For example, at 0550 UT, a dark band is seen overhead at Mercedes and the simultaneous image at Arecibo shows also a dark band to the south of zenith, above the asterisk (representing the conjugate location of Mercedes zenith). At 0655 UT, bright airglow can clearly be seen at Arecibo's zenith and at the location of Mercedes geomagnetic conjugate point (MGCP), while the corresponding image from Mercedes at 0659 UT shows a similar feature, i.e., bright airglow at Mercedes' zenith and above the Arecibo geomagnetic conjugate point (AGCP). Again, at 0732 UT Arecibo shows dark airglow at zenith and at the location of the MGCP, in agreement with the observations at Mercedes at 0733 UT. Although we can identify common features with wave-like behavior, it is clear that the patterns observed are more complicated. The structures at both sites propagate with a velocity of ~80 m/s and the average horizontal scale length is ~290 km. At Arecibo the direction of propagation was ~150° (measured counterclockwise from geographic north), while at Mercedes the direction was ~25°. The entire sequence can be viewed in Animation S1, where the images have been superposed on the map shown in Figure 1.[1]

[16] To illustrate a case with a more complex morphology, we analyze the night of 3 June 2009. Figure 4 shows again the unwarped images from both sites. Images from Mercedes have been processed in order to remove bright stars and the prominent Milky Way that make it difficult to identify airglow structures. Bands at Arecibo (top) were fully developed from the beginning of the observations (the phase of the moon allowed observations starting at 0618 UT at Arecibo and at 0656 UT at Mercedes). A movie showing the evolution of the structures in both hemispheres can be found in Animation S2. The general pattern observed at Arecibo is the presence of dark bands moving southwestward. By 0655 UT, two dark bands have passed the zenith of Arecibo and are followed by an extended bright area. The simultaneous image for Mercedes shows a single wide dark tilted region. At 0714 UT, the two dark bands at Arecibo seem to merge into a single dark band and are seen above the asterisk indicating the conjugate point of Mercedes' zenith. At Mercedes the elongated wide band is above its zenith. At 0742 UT, the leading part of the bright feature is approaching its conjugate location at Arecibo, while the trailing part is approaching Arecibo's zenith. Corresponding features are seen with the Mercedes imager, i.e., bright airglow at Arecibo's conjugate zenith and dark airglow reaching Mercedes' zenith. In general the structures do not look like typical wave-like bands: at Arecibo, the dark band to the western part of the FOV is more tilted than the one approaching zenith from the east. The bright area in-between looks like a funnel-shaped structure. The structures show a more pronounced westward propagation when compared to the 9 February 2010 case, with a wave vector of ~140° angle at Arecibo and ~45° at Mercedes, with comparable speeds of ~80 m/s.

[17] In summary, and as shown most clearly in Figure 4 (right), the key point of using conjugate images is to demonstrate the simultaneous occurrence of bands at both hemispheres, providing evidence of an electrodynamical mechanism responsible for their behavior.

2.2. Global Positioning System Data

[18] Global Positioning System (GPS) data from the International GNSS Service (IGS) network were available to

[1] Auxiliary materials are available in the HTML. doi:10.1029/2010ja016264.

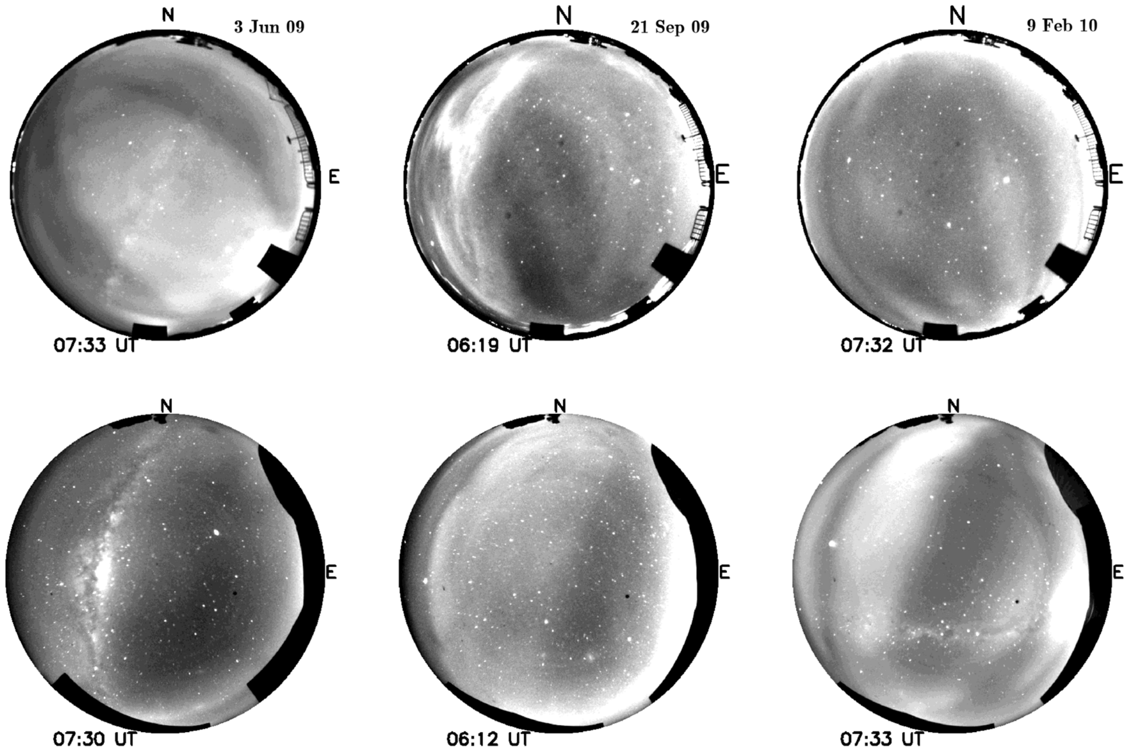

Figure 2. Three different nights with structures observed at both sites. (top) Arecibo images for 3 June 2009, 21 September 2009, and 9 February 2010. The corresponding images obtained within a few minutes at Mercedes are shown to the bottom. Fences, antenna, and light-blocking elements appear to the east in Arecibo's imager. The Mercedes imager also shows blocking elements added to avoid light contamination from the cities of Buenos Aires and Mercedes. These images show full 180°FOV data.

support the optical results. The stations used were Saint Croix (CRO1), located ~200 km to the east of Arecibo's ASI, and La Plata (LPGS), located ~150 km to the east of Mercedes imager. GPS data provide information on total electron content (TEC) and phase fluctuations, a measure of the presence of ionospheric irregularities with scale size of the order of several kilometers [*Aarons et al.*, 1996; *Mendillo et al.*, 2000]. The TEC values observed from the two stations analyzed, CRO1 and LGPS, were small (between 5 and 15 TECU, with 1 TECU = 1×10^{16} el/m^2), consistent with the geophysical conditions at the time of observations (low solar activity and early morning).

[19] For specific satellite passes with ionospheric piercing points traversing the region of depleted airglow, TEC decreases were observed. For example, Figure 5 shows to the left Arecibo data and to the right simultaneous data for Mercedes for the night of 9 February 2010. Imaging data are shown to the top with superposed ionospheric piercing points of GPS PRN 11 observed by CRO1 and GPS PRN 20 observed by LPGS. The arrows show the time along the trajectory when the image was taken. The time series of GPS TEC (center) and ΔTEC/min (bottom) are also shown. The vertical dashed line represents the time when the all-sky image was taken. It is clear that the bright (dark) bands are associated with increases (decreases) in TEC and that relatively weak phase fluctuations accompany both situations. Even though the satellites detect TEC structures not exactly at their conjugate locations, the undulations observed at both hemispheres are remarkable similar. The GPS analysis for the night of 3 June 2009 also showed phase fluctuations with negligible values, meaning that large-scale irregularities were not accompanying the band-like structures observed by the imagers on that night.

3. Discussion and Summary

[20] The structures observed with the ASIs and GPS receivers are common examples of processes occurring at midlatitudes, widely referred as MSTIDs. There is still no clear mechanism for the formation of these structures but the observation of simultaneous bands at both hemispheres provides further proof that these processes are not simply related to gravity waves occurring independently in each hemisphere. An electrodynamical coupling must exist and complete theories need to address interhemispheric coupling as a key (and perhaps the most important) process.

[21] When performing conjugate or interhemispheric studies of electrodynamics at midlatitudes in the American sector the presence of the south Atlantic magnetic anomaly (SAMA) will produce significant differences when compared to other longitudinal sectors. This anomaly affects the configuration of the magnetic field, especially in the southern hemisphere. In the Japanese-Australian sector, the geometry (dipole-like) dictates that mapping a circular FOV from one hemisphere to another results in another circular FOV [*Otsuka et al.*, 2004]. In the American-Atlantic sector, the SAMA distorts the dipolar geometry and, as a consequence, a circular FOV will not be mapped into another circle.

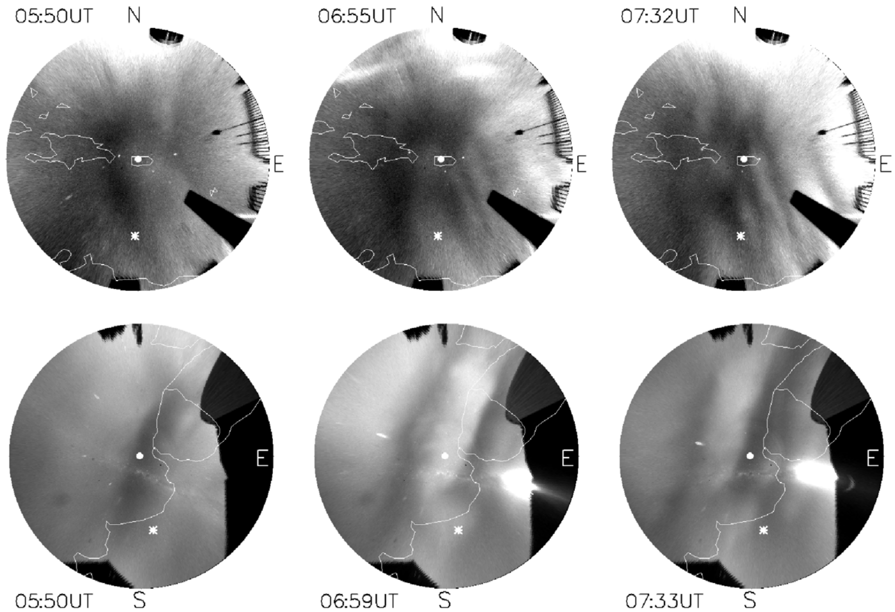

Figure 3. (top) Unwarped images (i.e., converted into geographical coordinates), indicated schematically by circles in Figure 1, for Arecibo images on the night of 9 February 2010. North is at the top of each image and east to the right. (bottom) Simultaneous images obtained with the Mercedes all-sky imager. Asterisks in each image represent the geomagnetically conjugate point of the opposite hemisphere imager's zenith location. Thus, structures observed at zenith with one imager are seen above the asterisk in the conjugate imager. The bright feature to the east at Mercedes is the Moon. These images use 160° FOV data, omitting the last 10° of zenith angle data shown in Figure 2.

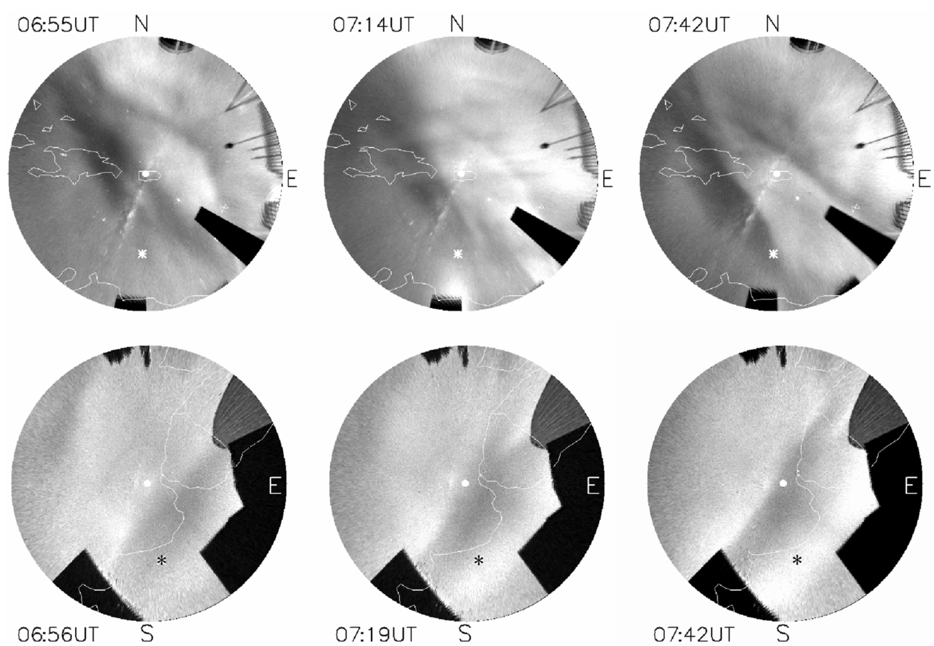

Figure 4. Same format as in Figure 3 but for the night of 3 June 2009. Images at Mercedes have been processed to subtract the Milky Way that is particularly prominent during this season. Notice that in each vertical pair of simultaneous images, if a bright or dark feature falls at one site's zenith (marked with white dots), the same feature is seen at its conjugate point (marked with white asterisks for Mercedes and black asterisks for Arecibo) in the other imager.

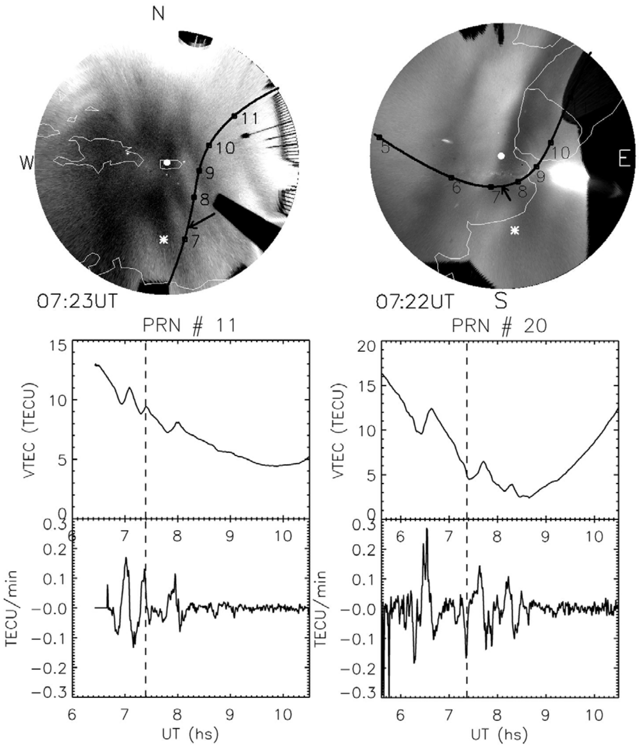

Figure 5. Imaging and GPS data showing airglow and TEC variations, respectively, on 9 February 2010. (top left) Unwarped Arecibo image; black line indicates the ionospheric piercing points of satellite 11 from CRO1 station. (bottom) Vertical TEC and phase fluctuations are shown, with a dashed line indicating the time where the image was taken. Increased airglow is associated with large TEC. (right) Similar results for Mercedes and satellite 20 from LPGS station. Dark airglow is associated with decreased TEC. In both cases, phase fluctuations (or rate of change of TEC) occur where the TEC and airglow vary (~6–8 UT). They are absent when TEC and airglow are structure-less (after ~0900 UT)

Structures seen in one hemisphere will be 'deformed' as they are mapped into the other hemisphere. This was shown by *Martinis and Mendillo* [2007] when studying the occurrence of equatorial Spread F airglow depletions over Arecibo and El Leoncito, a site located to the west from Mercedes, near the Andes mountain range. Also, the magnitudes of the magnetic field strength at both footprints are different: at 250 km at Arecibo's zenith the intensity of the magnetic field from the International Geomagnetic Reference Field (IGRF) model is 23,990 nT while at its conjugate location is only 16,595 nT. This could have consequences on the characteristics of structures mapped from one hemisphere to the other.

[22] The 9 February 2010 case gives a clear example of structures observed by different diagnostics, and behaving in a similar way, with simultaneous occurrence and similar propagation speed and horizontal wavelength. During the entire night, each band at one site has its 'mirrored band' in the opposite hemisphere. This result is in agreement with the observations made by *Otsuka et al.* [2004].

[23] The GPS data analyzed here show that phase fluctuations were very weak (i.e., less than 0.25 ΔTEC/min), in agreement with previous studies that indicated that MSTIDs, while large in amplitude (~20–25%) and extent (100s km), do not contain robust populations of large-scale (few km scale size) irregularities. For comparison, when equatorial Spread F is occurring, strong phase fluctuations (larger than 0.5–1 ΔTEC/min) are usually measured [*Mendillo et al.*, 2000]. Yet, a recent study by *Lee et al.* [2008] showed that rate of change of TEC could be large for some MSTIDs events. It is not clear under which circumstances MSTIDs can produce significant ΔTEC/min.

[24] The observations of 3 June 2009 (winter in the southern hemisphere) show similar features as the ones shown during 9 February 2010 (summer in the southern hemisphere). The observations at Mercedes show a dark elongated band extended NW-SE, while at the same time at Arecibo two distinct bands are observed. Later in time these two distinct bands seem to merge into a single wide one, similar to the observations at Mercedes (at 0742 UT in Figure 4). This could offer evidence of differences in the formation and evolution of dark bands associated with MSTIDs. When making interhemispheric comparisons, different background ionospheric parameters (conductivity, electron density, height of peak electron density, etc.) can occur, especially during solstice conditions when seasonal differences are more dramatic. These could contribute to less contrast in features observed at one site when compared with its conjugate location. The lack of simultaneity of the June pattern observed early at both sites could be related to the source electric field responsible for the motion of the bands. It is known that local summer is a period where the occurrence rate of MSTIDs is higher in all longitude sectors [*Shiokawa et al.*, 2003b; *Martinis et al.*, 2010]. For the 3 June 2009 case, the bands could have been generated first at Arecibo (local summer) by an electric field, perhaps the result of the coupling with *E* region structures. While the electrical potential associated with an electric field can map into the southern hemisphere almost instantaneously, the time scale for the generation of the bands could be different due to the different ionospheric conditions at Mercedes (local winter). This could point to a way to determine where the 'source' can be found, in this case, in the northern hemisphere. What needs to be understood is if this 'source' affecting the F region is really coming from the underlying E region or it is created in the F region. This is an area of active research through the development of 2D and 3D models of the coupling between these regions [*Yokoyama et al.*, 2009].

[25] Models of MSTIDs features do not yet include interhemispheric coupling. Attempts to analyze the influence of processes with scale size larger than 10 km occurring in the opposite hemisphere were made by *Saito et al.* [1998b]. They concluded that, in addition to local parameters, it was crucial to consider the behavior of neutral winds and ionospheric conductivities in the conjugate hemisphere. The need to include the influence of the conjugate F region has been addressed in the past [*Scali et al.*, 1997; *Otsuka et al.*, 2004]. With the set of optical instruments currently deployed in the American sector and the use of complementary information from in situ and remote instrumentation, it should be possible to address some of these issues.

In particular, it needs to be determined if the band-like structures always appear simultaneously in both hemispheres and under which conditions they show significant ionospheric irregularities. During the first year of observations most of the MSTIDs occurred simultaneously at both sites.

[26] A proper and complete understanding of ionospheric processes occurring at midlatitudes, such as MEFs, MSTIDs, and midlatitude spread F, will be obtained when observations, as well as modeling, from the conjugate hemisphere are carefully taken into account.

[27] **Acknowledgments.** This work was supported in part by grants from the Office of Naval Research, the National Science Foundation, and seed research funds from the Center for Space Physics at Boston University (BU). We thank Raul Garcia and Jonathan Friedman from the Arecibo Observatory for their continuous assistance in the operation of the imaging system. We acknowledge the collaboration of Miguel De Laurenti, director of the Mercedes Observatory, for his help in the installation and operation of the all-sky imager. Data analysis assistance was provided by BU undergraduate Paul Zablowski.

[28] Robert Lysak thanks the reviewer for their assistance in evaluating this paper.

References

Aarons, J., M. Mendillo, R. Yantosca, and E. Kudeki (1996), GPS phase fluctuations in the equatorial region during the MISETA 1994 campaign, *J. Geophys. Res.*, *101*(A12), 26,851–26,862, doi:10.1029/96JA00981.

Behnke, R. A. (1979), *F* layer height bands in the nocturnal ionosphere over Arecibo, *J. Geophys. Res.*, *84*(A3), 974–978, doi:10.1029/JA084iA03p00974.

Bowman, G. G. (2001), A comparison of nighttime TID characteristics between equatorial-ionospheric-anomaly crest and midlatitude regions, related to spread *F* occurrence, *J. Geophys. Res.*, *106*(A2), 1761–1769, doi:10.1029/2000JA900123.

Candido, C., A. A. Pimenta, J. A. Bittencourt, and F. Becker-Guedes (2008), Statistical analysis of the occurrence of medium-scale traveling ionospheric disturbances over Brazilian low latitudes using OI 630.0 nm emission all-sky images, *Geophys. Res. Lett.*, *35*, L17105, doi:10.1029/2008GL035043.

Garcia, F., M. Kelley, J. Makela, and C.-S. Huang (2000), Airglow observations of mesoscale low-velocity traveling ionospheric disturbances at midlatitudes, *J. Geophys. Res.*, *105*(A8), 18,407–18,415, doi:10.1029/1999JA000305.

Hunsucker, R. D. (1982), Atmospheric gravity waves generated in the high-latitude ionosphere: A review, *Rev. Geophys.*, *20*, 293–315, doi:10.1029/RG020i002p00293.

Kelley, M., J. Makela, A. Saito, N. Aponte, M. Sulzer, and S. Gonzalez (2000), On the electrical structure of airglow depletion/height layer bands over Arecibo, *Geophys. Res. Lett.*, *27*(18), 2837–2840, doi:10.1029/2000GL000024.

Lee, C. C., Y. A. Liou, Y. Otsuka, F. D. Chu, T. K. Yeh, K. Hoshinoo, and K. Matunaga (2008), Nighttime medium-scale traveling ionospheric disturbances detected by network GPS receivers in Taiwan, *J. Geophys. Res.*, *113*, A12316, doi:10.1029/2008JA013250.

Martinis, C., and M. Mendillo (2007), Equatorial spread F-related airglow depletions at Arecibo and conjugate observations, *J. Geophys. Res.*, *112*, A10310, doi:10.1029/2007JA012403.

Martinis, C., J. Baumgardner, S. M. Smith, M. Colerico, and M. Mendillo (2006), Imaging science at El Leoncito, Argentina, *Ann. Geophys.*, *24*, 1375–1385, doi:10.5194/angeo-24-1375-2006.

Martinis, C., J. Baumgardner, J. Wroten, and M. Mendillo (2010), Seasonal dependence of MSTIDs obtained from 630.0 nm airglow imaging at Arecibo, *Geophys. Res. Lett.*, *37*, L11103, doi:10.1029/2010GL043569.

Mendillo, M., et al. (1997), Investigations of thermospheric-ionospheric dynamics with 6300 Å images from the Arecibo Observatory, *J. Geophys. Res.*, *102*(A4), 7331–7343, doi:10.1029/96JA02786.

Mendillo, M., B. Lin, and J. Aarons (2000), The application of GPS observations to equatorial aeronomy, *Radio Sci.*, *35*(3), 885–904, doi:10.1029/1999RS002208.

Miller, C., W. Swartz, M. Kelley, M. Mendillo, D. Nottingham, J. Scali, and B. Reinisch (1997), Electrodynamics of midlatitude spread *F*: 1. Observations of unstable, gravity wave-induced ionospheric electric fields at tropical latitudes, *J. Geophys. Res.*, *102*(A6), 11,521–11,532, doi:10.1029/96JA03839.

Otsuka, Y., K. Shiokawa, T. Ogawa, and P. Wilkinson (2004), Geomagnetic conjugate observations of medium-scale traveling ionospheric disturbances at midlatitude using all-sky airglow imagers, *Geophys. Res. Lett.*, *31*, L15803, doi:10.1029/2004GL020262.

Pimenta, A. A., M. C. Kelley, Y. Sahai, J. A. Bittencourt, and P. R. Fagundes (2008), Thermospheric dark band structures observed in all-sky OI 630 nm emission images over the Brazilian low-latitude sector, *J. Geophys. Res.*, *113*, A01307, doi:10.1029/2007JA012444.

Richmond, A. D. (1995), Ionospheric electrodynamics using magnetic apex coordinates, *J. Geomag. Geoelectr.*, *47*, 191–212.

Saito, A., T. Iyemori, M. Sugiura, N. C. Maynard, T. L. Aggson, L. H. Brace, M. Takeda, and M. Yamamoto (1995), Conjugate occurrence of the electric field fluctuations in the nighttime midlatitude ionosphere, *J. Geophys. Res.*, *100*(A11), 21,439–21,451, doi:10.1029/95JA01505.

Saito, A., T. Iyemori, L. G. Blomberg, M. Yamamoto, and M. Takeda (1998a), Conjugate observations of the mid-latitude electric field fluctuations with the MU radar and the Freja satellite, *J. Atmos. Sol. Terr. Phys.*, *60*(1), 129–140, doi:10.1016/S1364-6826(97)00094-1.

Saito, A., T. Iyemori, and M. Takeda (1998b), Evolutionary process of 10 kilometer scale irregularities in the nighttime midlatitude ionosphere, *J. Geophys. Res.*, *103*(A3), 3993–4000, doi:10.1029/97JA02517.

Scali, J., B. Reinisch, M. Kelley, C. Miller, W. Swartz, Q. Zhou, and S. Radicella (1997), Incoherent scatter radar and Digisonde observations at tropical latitudes, including conjugate point studies, *J. Geophys. Res.*, *102*(A4), 7357–7367, doi:10.1029/96JA03519.

Shiokawa, K., Y. Otsuka, C. Ihara, T. Ogawa, and F. J. Rich (2003a), Ground and satellite observations of nighttime medium-scale traveling ionospheric disturbance at midlatitude, *J. Geophys. Res.*, *108*(A4), 1145, doi:10.1029/2002JA009639.

Shiokawa, K., C. Ihara, Y. Otsuka, and T. Ogawa (2003b), Statistical study of nighttime medium-scale traveling ionospheric disturbances using midlatitude airglow images, *J. Geophys. Res.*, *108*(A1), 1052, doi:10.1029/2002JA009491.

Shiokawa, K., et al. (2005), Geomagnetic conjugate observation of nighttime medium-scale and large-scale traveling ionospheric disturbances: FRONT3 campaign, *J. Geophys. Res.*, *110*, A05303, doi:10.1029/2004JA010845.

Taylor, M., J. M. John, S. Fukao, and A. Saito (1998), Possible evidence of gravity wave coupling into the midlatitude *F* region ionosphere during the SEEK campaign, *Geophys. Res. Lett.*, *25*, 1801–1804, doi:10.1029/97GL03448.

Yokoyama, T., D. L. Hysell, Y. Otsuka, and M. Yamamoto (2009), Three-dimensional simulation of the coupled Perkins and E_s-layer instabilities in the nighttime midlatitude ionosphere, *J. Geophys. Res.*, *114*, A03308, doi:10.1029/2008JA013789.

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