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Extreme longitudinal variability of plasma structuring in the equatorial ionosphere on a magnetically quiet equinoctial day

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[1] We investigate the extreme longitudinal variability of equatorial scintillation under quiet magnetic conditions during 22–23 March 2002. Scintillation Network Decision Aid (SCINDA) observations show intense activity in the South American–Atlantic sector during local evening hours, whereas an absence of scintillation is seen in the far east Asian sector. Ground- and space-based measurements from SCINDA, the Global Ultraviolet Imager (GUVI), TOPEX, and a chain of GPS receivers are used in combination with the Utah State University Global Assimilation of Ionospheric Measurements (USU-GAIM) model to explore the relationship between the large-scale ionization distribution and small-scale irregularities at low latitudes in both the scintillating and nonscintillating longitude sectors. Our analysis shows that there are significant differences in the evolution of the ionization distributions during the evening hours, which are likely the result of differences in the daytime and postsunset vertical plasma drift in the two sectors. This study demonstrates the importance of USU-GAIM as a new tool for investigating longitudinal as well as day-to-day variability that is observed in the large-scale distribution of the ionosphere and how this relates to the occurrence of scintillation.


1. Introduction

[2] Plasma density irregularities in the ionosphere can lead to rapid fluctuation or scintillation of satellite radio communication signals at or near the Earth's surface. Scintillation affects radio signals up to a few GHz in frequency and can seriously degrade or disrupt satellite-based navigation and communication systems. This can be particularly severe at night at low latitudes. To understand the occurrence of scintillation it is important to understand the large-scale background ionospheric conditions on which plasma instabilities develop [Basu and Basu, 1985].

[3] Atmospheric motions within the low-latitude thermosphere contribute to the formation of instabilities in the ionosphere that lead to irregularities in the plasma distribution. One of the most important processes that control the large-scale distribution of plasma is the vertical plasma drift that is driven by the complex interaction of $E$ and $F$ region electrodynamic processes. During the day an eastward electric field generated by dynamo action in the $E$ region (90–120 km) causes a vertical $E \times B$ drift of $F$ region plasma at the equator. In the late afternoon, when the $E$ region density decreases, the $F$ region dynamo becomes more significant. The $F$ region dynamo, in conjunction with the conductivity gradient across the terminator, causes a postsunset enhancement of the electric field and thus of the vertical...
plasma drift. The plasma rises until the pressure gradients are large enough that it diffuses down the magnetic field lines, assisted by gravity, toward tropical latitudes. The postsetsun enhancement of the $E \times B$ drift has a significant effect since it causes the $F$ layer plasma at the equator to be driven to very high altitudes, typically 500 km, where recombination is slow. Regions of enhanced density, known collectively as the equatorial anomaly, form at roughly $\pm15^\circ$ of the magnetic equator and often persist into the postmidnight hours. In the absence of sunlight, the lower ionosphere rapidly decays and a steep density gradient develops on the bottomside of the raised $F$ region. This sets up the conditions for a gravitational Rayleigh-Taylor (R-T) instability to form. A small perturbation in the bottomside density can lead to growth of the instability, resulting in plasma irregularities and the formation of “bubbles” (structures with depleted density) [e.g., Kelley, 1989].

[4] There have been numerous studies that investigate the dependence of plasma irregularities on season, solar cycle, longitude, latitude and geomagnetic conditions and how they relate to ionospheric observables such as the postsetsun enhancement of the $E \times B$ drifts and the location, height, and electron content in the equatorial anomaly region. There is significant evidence for a close relationship between the vertical plasma drifts, the location of the anomaly crests, and the occurrence of equatorial spread $F$ (ESF) [Fejer et al., 1999; Whalen, 2001; Valladares et al., 2001; Hysell and Burcham, 2002]. Basu et al. [1996] conducted an equatorial campaign during 25 September to 7 October 1994 to investigate the day-to-day variability of the occurrence of ESF and found that during solar minimum a postsetsun enhancement of the upward plasma drift on the order of $\sim20$ m/s is necessary for the generation of irregularities. Recent results by Anderson et al. [2004] indicate that there indeed appears to be a threshold vertical velocity of $\sim20$ m/s for strong scintillation on the basis of observations carried out in 1998 and 1999 in the Peruvian/Chilean longitude sector. The climatology of scintillation indicates that it is generally expected to occur at all longitudes on geomagnetically quiet equinoctial days during solar maximum [e.g., Tsunoda, 1985; Basu and Basu, 1985]. Despite significant advances in understanding the climatology of plasma irregularities, there remains considerable day-to-day variability that tends to contradict the climatology [Tsunoda, 2005].

[5] The objective of this study is to make use of a diverse combination of space and ground-based data, along with a data assimilation model, to conduct a detailed investigation of the longitudinal variability in the occurrence of scintillation within a selected 24 hour period. With the combination of data and models, we are able to reconstruct the time evolution of the low-latitude plasma distributions in multiple longitude sectors in more detail than is possible with a single satellite or ground campaign. Though we are studying longitudinal variability of scintillation, we assume that it is more closely related to the day-to-day variability than to other longitudinal effects such as the displacement of the geographic and geomagnetic equators.

[6] We used UHF band scintillation measurements from AFRL’s Scintillation Network Decision Aid (SCINDA) [Groves et al., 1997] to determine locations where UHF scintillation occurred on the night of 22–23 March 2002. We then collected and analyzed far-ultraviolet radiances from the Global Ultraviolet Imager (GUVI) [Christensen et al., 2003] aboard the NASA Thermosphere Ionosphere Mesosphere Energy and Dynamics (TIMED) satellite. Vertically integrated total electron content (TEC) measurements were obtained from several sources including: the dual-frequency radar altimeter aboard the NASA/Center Nationale d’Etudes Spatiales TOPEX/Poseidon satellite [Janet, 1994], a chain of GPS receivers in South America [Valladares et al., 2001], and individual GPS stations. The Utah State University Global Assimilation of Ionospheric Measurements (USU-GAIM) model [Schunk et al., 2004] was used to assimilate TEC data derived from globally distributed GPS measurements.

2. Data and Models

[7] To find suitable days for the study, we used scintillation measurements obtained from the SCINDA system, which provides UHF band ($\sim250$ MHz) and L band frequency scintillation measurements from geostationary and GPS satellites at equatorial sites around the world [Groves et al., 1997; Caton et al., 2004]. We analyzed UHF band data from six stations; three in the far east Asian sector (Singapore, Manila, and Guam) and three in the South American–Atlantic sector (Ascension Island, Ancon, and Antofagasta). We chose 22–23 March 2002 because it was geomagnetically quiet and yet exhibited extreme differences in the occurrence of scintillation between the sectors. We were careful to select a period for the study with geomagnetically quiet conditions for at least 6 hours prior to dusk for each of the longitudes under investigation. The study spans from 0000 UT on 22 March to 0400 UT on 23 March 2002. During this time period the average 3-hour $Kp$ is 1.2 and reaches a maximum of 3 early on 22 March 2002. The 10.7 cm solar flux value ($F_{10.7}$) is 170 and the 81-day average $F_{10.7}$ is 186.7.

[8] Figure 1 shows the $S_4$ index of scintillation as a function of time derived from UHF links at the six SCINDA stations. Noise in the data, manifested as sharp spikes, has not been removed. Each of the figures is labeled with the 350 km intersection longitude, which is the longitude at which the station to satellite line of sight
intersects an altitude of 350 km, approximately the altitude of the peak of the F region. Time of sunset is marked with a red dashed line. Strong scintillation, starting after E region sunset and lasting well into the night, was detected at all three locations in the South American—Atlantic sector. No scintillation, however, was detected in Singapore or Manila, and only brief activity was detected in Guam. Though the Ancon and Antofagasta stations are at the same longitude, scintillation begins about 30 min earlier at Antofagasta because the observations are 6° east of the Ancon observations. Note that on average, scintillation is stronger in the equatorial anomaly region (Ascension Island, Antofagasta), where densities are enhanced, than at the magnetic equator (Ancon).

[9] We used space and ground-based measurements of the ionosphere to obtain the TEC for extended latitude regions at specific longitudes and local times. The TOPEX/Poseidon satellite, launched in August 1992 and operational until January 2006, flew at an altitude of 1336 km with a 66° inclination and carried a dual-frequency radar altimeter operating at 13.6 GHz and 5.6 GHz. Vertical TEC estimates are given by the ionospheric range correction computed from the differences in the altimeter measurements [Imel, 1994] of the sea surface height. For purposes of comparison with GAIM, the TOPEX TEC measurements are averaged over 2° in latitude.

[10] Additional space-based measurements were obtained from the GUVI instrument aboard the NASA TIMED satellite, which is in a 630-km circular polar orbit with a 74.1° inclination. GUVI collects spectral radiances of the Earth’s far-ultraviolet airglow in the spectral region from 120 to 180 nm using a cross-track scanning spectrometer [Christensen et al., 2003]; the scan begins on the antisunward limb and scans onto the disk, covering 140° every 15 s. The radiance is measured in five band-pass channels. In this study, we used the OI(135.6 nm) channel radiances from the disk observations. We estimated the nighttime TEC by first averaging the GUVI data within 30° of the nadir position. We then assumed that the 135.6 nm radiance is produced exclusively from the radiative recombination of O+ ions and that the ion and electron densities are equal. The TEC is then derived using a three parameter Chapman layer [Chamberlain and Hunten, 1987] with a constant O− scale height of 70 km.

[11] Ground-based TEC measurements were gathered from a chain of 11 dual-frequency GPS receivers located near the west coast of South America, which span latitudes from 9°N to 40°S. The TEC calculations are corrected for transmitter and receiver biases, multipaths, and cycle slips. Additionally, the data from all 11 stations were analyzed using a two-dimensional regression analysis to eliminate cases when cycle slips had not been corrected, or when unreasonably large values of TEC were obtained [Valladares et al., 2001].

[12] The data alone do not provide sufficient longitudinal or temporal coverage of the large-scale background ionospheric conditions that existed on 22–23 March 2002. To investigate the differences between the scintillating and nonscintillating longitude sectors, we use the USU-GAIM data assimilation model. The model uses a time-dependent physics-based model of the global ionosphere and a Gauss-Markov Kalman filter as a basis for assimilating diverse sets of observations [Schunk et al., 2004]. The physics-based model is the Ionospheric Forecast Model (IFM), which accounts for five ion...
species and covers the $E$ region, $F$ region, and the topside ionosphere over an altitude range from 90 to 1400 km. Within the Kalman filter, the IFM derived ionospheric densities constitute a background density field on which perturbations are superimposed. The USU-GAIM model was run for the 22–23 March 2002 time period; we assimilated slant GPS/TEC data from ~300 worldwide GPS receivers, bottomside electron density profiles from two ionosondes, and nighttime line-of-sight UV radiances from the low-resolution airglow and aurora spectrograph (LORAAS) aboard the Advanced Research and Global Observing Satellite (ARGOS) [McCoy et al., 1992].

3. Results and Discussion

[13] Figure 2 shows the composite GUVI disk scan images in the OI 135.6-nm band on the evening of 22–23 March 2002; the local time of the observations was 2330 LT. Time progresses from right to left, with the UT of the magnetic equator crossing of GUVI listed along the top of the image. Also indicated are the magnetic equator and SCINDA sites that are used in this study. The bright features on either side of the magnetic equator are the equatorial anomaly crests. The dark bands through these enhanced intensity regions are ionospheric depletions, or "bubbles," caused by plasma instabilities. Satellite signals crossing through these depleted regions will be significantly degraded. This composite image shows very clearly the longitudinal variability implied by the SCINDA data. The anomaly crests show no evidence of depletions in the far east Asian sectors (170°E to 80°E), but large-scale irregularities are present from the west coast of India to the American sector (50°E to 250°E).

[14] Next, we look more closely at the large-scale plasma distributions in the far east Asian and the South American–Atlantic sector. As mentioned in the previous section, the GUVI and TOPEX data alone cannot provide sufficient insight into the evolving postsunset ionosphere. The TOPEX and GUVI data (at 2240 LT and 2330 LT, respectively) provide only a snapshot of the ionosphere well after the conditions for scintillation are set. Ideally, we would use the GAIM model to provide the ionospheric specification at earlier times.

[15] In Figure 3 we show that GAIM reproduces the TOPEX and estimated GUVI disk scan TECs quite well in the far east Asian sector on 22 March 2002. Also shown in Figure 3 are the results for IFM, which are the model results obtained in the absence of data assimilation. Note that the "weather" results provided by GAIM are a significant improvement over the climatology predicted by IFM. In the South American–Atlantic sector the situation is different. Here, the GPS data are affected by the strong occurrence of bubbles during the evening hours of 22 March 2002. GAIM, in its current mode, uses a built-in GPS–TEC preprocessor that discards any GPS data that are affected by either ionospheric bubbles or large phase slips. This limitation of GAIM, which will be overcome in future versions of the model, prevents us from using the GAIM results in the South American–Atlantic sector during the evening hours of 22 March 2002. As an alternative, the GAIM results are used to provide TECs in the far east Asian sector, and the South American chain of GPS receivers are used to provide TECs at the times the GAIM results are unavailable. Because of the close proximity of the GPS chain receivers, additional processing is performed on this data set in order to remove the effects of the bubbles.

[16] Figure 4 shows a comparison of the TEC at two longitudes: one in the non-scintillating far east Asian sector (127°E) and the other in the scintillating South
Figure 3. Comparisons of GAIM to TOPEX and GUVI TECs on 22–23 March 2002. IFM model results are also shown. See color version of this figure in the HTML.

American sector (288°E). Figure 4a shows the evolution of the equatorial anomaly region from 1800 LT to midnight at 127°E longitude. From 1800 LT to 2000 LT, the crests move slightly poleward. Since the anomalies are already quite prominent before sunset the postsunset vertical plasma drift has little effect in the crest regions. The evolution of the TEC distributions at 288°E longitude, on the other hand, show the typical characteristics of a postsunset enhancement of the equatorial anomaly. The large ratio of TEC at the crests and trough probably arises from the action of the enhanced zonal electric field at the time of sunset that uplifting the plasma at the magnetic equator which then diffuses down the magnetic field lines. Between 1800 and 2000 LT, the anomaly crests increase in strength and move farther apart (Figure 4b). In fact, the anomaly crests do not begin to decay until nearly midnight.

The differences in the evolution of the TECs in the two longitude sectors are the result of differences in the strengths of the daytime and the postsunset vertical plasma drifts, as well as the duration of the upward drifts, at the two locations. In general, longitudinal variations in vertical drift velocities can be attributed to the differences in the alignment of the sunset terminator with the local magnetic meridian as a result of longitudinal changes in magnetic declination [Batista et al., 1986; Abdu et al., 1992]. However, various measurements have shown that the vertical drift velocities are largely independent of longitude near the equinoxes [e.g., Coley et al., 1990; Fejer et al., 1995, 1996]. On the other hand, ground and space-based measurements of vertical drifts indicate considerable day-to-day variability [e.g., Fejer et al., 1995; Fejer and Scherliess, 2001] that is likely due to meteorological influences from the lower atmosphere, such as upward propagating tides [Richmond, 1995]. More extensive studies are needed to better understand the coupling of the lower atmosphere to the variability observed at F region heights.

Certainly, the vertical plasma drifts in the South American sector had a greater effect on the early evening structure of the anomaly region than the drifts in the far east Asian sector. The fact that the anomaly crests decayed much more quickly in the far east Asian sector indicates that the drifts turned downward at an earlier time than in the South American sector. It is possible that a larger peak vertical drift velocity in the South American sector, along with a later reversal, led to the favorable conditions for scintillation, whereas a threshold velocity may not have been attained in the far east Asian sector. Fejer et al. [1999], for example, found that in the South American sector during solar maximum and low magnetic activity, strong equatorial spread F occurs when the peak vertical drift velocities exceed 55 m/s. Other results, however, indicate that a peak velocity of only 20 m/s is necessary [Basu et al., 1996; Anderson et al., 2004]. The need for seed perturbations at such times cannot be overlooked and clustered measurements may be necessary to resolve this issue [Tsunoda, 2005].

4. Conclusion

In this study we have shown that there exists significant longitudinal variability in the occurrence of scintillation over a 24 hour period under geomagnetically quiet conditions. Two sectors were analyzed in detail; one of the sectors exhibited strong equatorial scintillation (South American–Atlantic) and the other (far east Asian)
exhibited no scintillation. Together, the SCINDA and GUVI data show that the occurrence of ionospheric depletions or "bubbles" is correlated with strong scintillation activity.

[20] We have also shown that USU-GAIM data assimilation model is capable of reproducing the large-scale variability observed in the low-latitude plasma distribution provided that there is sufficient data coverage and that the data is not contaminated by ionospheric bubbles. The USU-GAIM model reproduced quite well the TECs observed by GUVI and TOPEX in the far east Asian sector. However, the model cannot be used to specify the background ionosphere in the South American–Atlantic sector after the onset of scintillation and occurrence of bubbles in this region.

[21] By comparing the TECs derived from the South American chain of GPS receivers to the USU-GAIM results in the far east Asian sector, we have shown that the combination of data and assimilation models can serve as a powerful tool for investigating the global time evolution of large-scale plasma distributions. Our analysis of the two sectors has shown that there were significant differences in the evolution of the TEC distributions from 1800 LT to 2400 LT, which were likely the result of differences in the daytime and post-sunset vertical plasma drifts in the two sectors. Previous studies have shown that such differences in plasma distributions are observed on a day-to-day basis in a single longitude sector [e.g., Valladares et al., 2001]. We have shown that similar differences are observed in different longitude sectors on the same day. The results of our study did not clearly indicate why scintillation was not observed in the far east Asian sector on 22 March 2002. Other processes not directly observable in the large-scale background ionosphere, such as perturbations on the bottomside F region, may play a significant role in the occurrence of scintillation [Tsunoda, 2005]. Additional measurement will need to be performed in order for this issue to be resolved. Our work raises additional questions concerning the scale lengths of ionospheric disturbances. In order for data assimilation forecasting models to be accurate, additional studies must be conducted to understand the scale lengths of the various physical processes that contribute to scintillation.

[22] Our limited study shows that USU-GAIM, with the additional assimilation of suitable data sets, will be an important tool for providing insight into the causes of the observed day-to-day and longitudinal variability of ionospheric weather. The ability of USU-GAIM to provide a specification of the background ionosphere that is far more accurate than that provided by current climatology models will prove useful to the Communications/Navigation Outage Forecasting System (C/NOFS) mission [de la Beaujardière et al., 2004], whose science objectives includes obtaining a better understanding of the equatorial ionosphere at all local times and, in particular, how plasma bubbles form.

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