RADIO SCIENCE, VOL. 45, RS6001, doi:10.1029/2009RS004329, 2010

Characteristics of the equatorial ionization anomaly in relation to the day-to-day variability of ionospheric irregularities around the postsunset period

A. Paul[1,2] and A. DasGupta[2]

Received 17 November 2009; revised 18 May 2010; accepted 2 August 2010; published 2 November 2010.

[1] The equatorial ionosphere is characterized by the equatorial ionization anomaly (EIA) over a major part of the day, and ionospheric *F* region irregularities causing amplitude and phase scintillations on transionospheric satellite links during the postsunset period. Scintillations of transionospheric signals constitute one of the most intense Space Weather related propagation effects and exhibit extreme variability in space and time. The EIA exhibits an asymmetry in terms of the extents of the crests and peak ion densities on either side of the magnetic equator. It has been suggested that transequatorial winds cause significant redistribution of ionization with respect to the magnetic equator resulting in this asymmetry. The asymmetry in EIA between the two hemispheres has been suggested to influence growth of plasma instability and hence occurrence of scintillations. This paper presents some measures of EIA asymmetry derived from the latitudinal distribution of topside *F* region ionization density over the magnetic equator in the Indian longitude sector obtained from DMSP satellites and investigates their correspondence with the day-to-day variability of geostationary L band scintillations observed from Calcutta (latitude: 22.58°N; longitude: 88.38°E geographic; magnetic dip: 32°N) situated near the northern crest of the EIA during the high sunspot number years 2000–2001. A parameter combining the strength as well as the asymmetry of the EIA has been derived which shows good correlation with the occurrence of postsunset geostationary L band scintillations. These quantitative estimates may be used for forecasting occurrences of scintillations by system operators.

Citation: Paul, A., and A. DasGupta (2010), Characteristics of the equatorial ionization anomaly in relation to the day-to-day variability of ionospheric irregularities around the postsunset period, *Radio Sci.*, *45*, RS6001, doi:10.1029/2009RS004329.

1. Introduction

[2] Modern society is increasingly becoming dependent on space-based communication and navigation systems whose links operate through the ionosphere. The ionosphere is the main source of errors for users of satellite-based communication and navigation systems, with the equatorial region providing the worst-case figures. The equatorial ionosphere is characterized by the equatorial ionization anomaly (EIA) over a major part of the day, and ionospheric *F* region irregularities causing amplitude and phase scintillations on transionospheric satellite links during the postsunset period.

[3] Space Weather, a relatively new terminology, loosely defines the hierarchy of all phenomena within the Earth-Sun environment that may impact biology and systems that reside within that environment. Scintillations of transionospheric signals constitute one of the most intense Space Weather related propagation effects. The scintillation phenomenon has been studied for several decades and the climatology of scintillations, namely, its variation with latitude, season, local time, magnetic activity and solar cycle, is well documented. A robust climatological model, WBMOD, is also available [*Secan et al.*, 1995, 1997]. However, scintillations exhibit extreme variability in space and time. As such, climatological models are useful for planning purposes only. For the

[1]Institute of Radio Physics and Electronics, University of Calcutta, Calcutta, India.
[2]S. K. Mitra Center for Research in Space Environment, University of Calcutta, Calcutta, India.

0048-6604/10/2009RS004329

support of space-based communication and navigation systems, weather models are a necessity for real-time specification and forecasting. At equatorial latitudes, scintillation specification systems are a reality, primarily because the irregularity motion is very ordered, the irregularities are field-aligned and the lifetime of scintillation causing irregularities is long. Although theoretical studies, intensive observations and modeling have isolated the stabilizing [*Maruyama*, 1988; *Mendillo et al.*, 1992] and the destabilizing forces [*Basu et al.*, 1996; *Sultan*, 1996; *Fejer et al.*, 1999] in the equatorial ionosphere, the forecasting of equatorial scintillation still remains a challenging task.

[4] When a satellite-based communication or navigation system operates under intense scintillation activity, the resultant loss of signal is often attributed to interference or equipment malfunction. In addition to failure of vital communication and navigational links, which might jeopardize and endanger human lives, wastage of system resources during such periods is a matter of great concern for system managers. If forecasts with a realistic lead time or nowcasts are available, the system managers will not waste their resources and may instead evolve alternative techniques. This operational need could be addressed by assimilating satellite and ground-based measurements into physics-based space weather models. However, to meet the operational objective, scientific understanding about the origins and nature of the low latitude plasma turbulence that causes outage of communication and navigation systems has to be advanced. A major thrust area of several international scientific programs has been forecasting the behavior of different solar-terrestrial phenomena, which fall within the purview of Space Weather.

[5] Long-term predictions are necessary in HF broadcast planning and in other spectrum management activities where significant lead times are involved. They are also needed for planning both satellite and terrestrial systems. For example, advanced knowledge of scintillations in a particular operational area will allow satellite communication managers to develop mitigation strategies or provide alternate methods for data retrieval. Short-term predictions involve timescales from minutes to days. In the limit, a short-term forecast becomes a real-time ionospheric assessment or a nowcast. In the absence of established physics-based explanations of the day-to-day variability of occurrence of Equatorial Spread *F* (ESF), a statistical correlation between measurements of EIA parameters and ESF indices are important tools for possible use by satellite link designers.

[6] The postsunset occurrence of ESF is known to undergo variabilities at short-term, day-to-day, medium-term and long-term scales. The pattern and causes of the ESF short-term and day-to-day variabilities remain the least understood aspect of the phenomenon. The OH imagers routinely detect gravity wave type perturbations in the evening at mesospheric heights. However, these waves have not been tracked to the bottomside *F* region. *Hysell et al.* [2006] have established that large-scale seed waves that drive the Rayleigh-Taylor instability to cause scintillations are generated within the ionosphere system. These have been detected in the bottomside equatorial *F* region and are generated by the collisional shear instabilities during the postsunset hours. The wave structures may propagate obliquely through the base of the ionosphere to the topside and may have significant horizontal velocity component [*Vadas and Fritts*, 2006; *Vadas*, 2007]. However, the role of the gravity waves is believed to be merely to initiate ESF activity rather than sustaining it. Alternatively, *Tsunoda* [2007] have suggested that a polarization electric field, if generated by sporadic *E* layer instability should map to the base of the *F* layer and seed equatorial plasma irregularities. Electric field perturbations associated with the large-scale periodic structures over the magnetic equator may be coupled to off-equatorial ionospheric locations and vice versa along the highly conducting geomagnetic field lines [*Patra et al.*, 2005].

[7] A better understanding of the nature of short-term and day-to-day variabilities of ESF occurrence is an important requirement toward developing any predictive capability on the ESF occurrence conditions. On the basis of the presently known theoretical and model simulation studies [*Sultan*, 1996; *Keskinen et al.*, 2003] the following interdependent factors of the ambient ionosphere-thermosphere system control ESF development: (1) the evening *F* layer height and the vertical plasma drift due to the prereversal enhancement of the eastward electric field, (2) development of a steep density gradient at the *F* layer bottomside where instability is initiated by seed perturbations, and (3) the integrated Pedersen conductivity of the unstable flux tube which is controlled by thermospheric meridional/transequatorial winds and represented by the symmetry/asymmetry of the equatorial ionization anomaly. The complex and competing roles of the above mentioned factors play a crucial role in ESF development [*Abdu et al.*, 2009].

[8] An important source of the ESF variability resides in what appears to be inherent in the nature of the seeding mechanism. In this respect it is under debate whether the seeding mechanism originates from a remote gravity wave source and/or local instability growth by other processes such as, for example, the wind driven instability of the bottomside *F* layer to serve as seed perturbation to topside bubble development, as proposed by *Kudeki et al.* [2007], or the velocity shear mechanism at the *F* layer bottomside as proposed by *Hysell and Kudeki* [2004]. The possibility of ESF initiation by electric field perturbation due to gravity wave winds in the *E* region has been discussed by *Prakash* [1999]. Also under discussion is the possible role of a sporadic *E* layer instability mechanism for

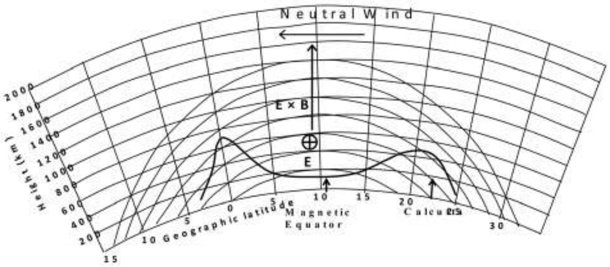

Figure 1. Schematic showing a typical plot of the latitudinal variation of ion density as obtained from DMSP superposed against the magnetic field lines with the locations of the magnetic equator and the present station Calcutta indicated. The directions of the eastward electric field, vertical drift over the magnetic equator in the postsunset hours, and direction of the meridional wind are also shown.

initiating the conditions for ESF development [*Tsunoda*, 2007; *Cosgrove and Tsunoda*, 2002]. More recently an important source of the ESF day-to-day variability has been shown to arise from planetary wave modulation of the evening prereversal enhancement in the zonal electric field (PRE)/vertical plasma drift [*Abdu et al.*, 2006]. Ionosphere-magnetosphere coupling processes under magnetically disturbed conditions are also known to be an important source of the ESF variability [*Sastri et al.*, 1997; *Abdu*, 1997; *Abdu et al.*, 2003]. A better understanding of the nature and causes of the variabilities in the ambient ionospheric electrodynamical parameters is a necessary requirement for further progress in this area. In the absence of any concrete physics-based explanation of the above issues, identification of precursors to occurrence of ESF has to be sought from statistical analysis of ground-based or in situ upper atmospheric data which may be of immense help to satellite link designers at times of severe outages. These analyses are most often based on statistical significance tests between two parameters whose theoretical relationships are established but no quantitative relation exists as yet, for example, correlating the latitudinal gradient of equatorial ionization anomaly (EIA) with the occurrence of ESF [*Ragahavarao et al.*, 1988; *Ray et al.*, 2006]. Similar studies aimed at identification of a threshold for the postsunset *F* region height rise over the magnetic equator with the occurrence of postsunset ESF have been attempted by *Anderson et al.* [2004].

[9] The EIA has been found to exhibit asymmetry, both in terms of the locations of the northern and the southern crests as well as the ionization densities at the crests. The influence of a transequatorial wind appears to depress the *F* layer in the lee side hemisphere and to raise it in the windward hemisphere [*Rishbeth*, 1972; *Bittencourt and Sahai*, 1978; *Mendillo et al.*, 2000]. Primarily, strong meridional winds are capable of creating this asymmetry in the EIA in the northern and southern hemispheres. It would also facilitate significant changes in the *E* region conductivities that could control the *F* region dynamics. This in turn would be reflected in the postsunset *F* region height rise and eventually in the occurrence of scintillations. The above mechanism suggested by *Maruyama and Matuura* [1984] would operate irrespective of the winds being northward or southward. A study of the ionization density distribution as a function of latitude from measurements by a low earth orbiting satellite like the Defense Meteorological Satellite Program (DMSP) of the U.S. Air Force may be used to understand the asymmetry, if any, of the EIA around the time of maximum ionization in the local afternoon hours. Parameters quantifying the asymmetry have to be developed and some threshold values/ranges identified vis-a-vis occurrence of postsunset scintillations. This may lead to an improved understanding of the day-to-day variability in the occurrence of ESF.

[10] Figure 1 shows the schematic diagram of an asymmetric EIA superposed against the magnetic field lines with the locations of the magnetic equator and the present station at Calcutta indicated. The direction of the meridional wind shown by the arrow has been assumed to be from the northern to the southern hemisphere. The directions of the eastward electric field E as well as the vertical upward drift E × B over the magnetic equator have been indicated by arrows.

[11] The amplitudes of the carriers from geostationary satellite beacons at VHF (FLEETSATCOM, 250 MHz) and L band (INMARSAT, 1.5 GHz) are routinely monitored from Calcutta. The present station at Calcutta is situated virtually under the northern crest of the equatorial ionization anomaly in the Indian longitude sector. The geostationary L band satellite link at Calcutta from INMARSAT is frequently disrupted by moderate to intense amplitude scintillations during the postsunset hours of equinoctial months of high sunspot number years. During these periods, the geostationary VHF link from the satellite FLEETSATCOM shows saturated and very fast scintillations. These scintillations are caused by ionospheric irregularities generated over the magnetic equator. On days when the prereversal enhancement of the eastward electric field forces the apex of the equatorial anomaly to rise to heights of 750 km or higher over the magnetic equator, the irregularities map to off-equatorial latitudes like Calcutta along the magnetic field lines in the postsunset hours. Polar orbiting DMSP satellites measure the latitudinal distribution of ionization density over the magnetic equator at 840 km altitude. The magnetic field line with the apex at 840 km above the magnetic equator maps down to 18°N magnetic latitude (23.8°N geographic latitude) at the mean ionospheric height 350 km. Thus a strong association may be expected between the latitudinal variation of the in situ ion density measurements of

DMSP around the magnetic equator and occurrence of L band scintillations near the northern crest of the equatorial anomaly at Calcutta. Locations near the anomaly crests experience worst-case disruptions in satellite based communication and navigation links and provide ideal test bed to check the reliability of operation of such services.

[12] The present paper explores the possibility of a relation between the asymmetry of the EIA, in terms of the latitudinal extent north and south of the magnetic equator and the maximum ionization densities at the two crests from the ion density measurements of DMSP in the local afternoon hours of the high sunspot number years 2000–2001, and the day-to-day variability in the occurrence of postsunset geostationary L band scintillations at Calcutta situated near the northern crest. A measure combining the strength and the asymmetry of the EIA has also been developed.

2. Data

[13] Latitudinal distribution of ionization density measured by polar orbiting DMSP satellites (F13) have been used to estimate different parameters related to the asymmetry. The spacecrafts are in near-polar and circular orbits at an altitude of 835 to 850 km. The orbital inclination of these spacecrafts is 96°, which results in a precession rate of the orbital plane of one rotation per year. This results in keeping the spacecraft's orbit roughly fixed in local time throughout the year. In general there are at least two operational DMSP spacecrafts at any given time, one in a dawn-dusk orientation and the other in an early evening–early morning orientation. The satellite DMSP F13 is in a roughly dawn-dusk orientation covering the magnetic latitude range ±30° once near local sunset at Calcutta (latitude: 22.58°N, longitude: 88.38°E geographic; magnetic dip: 32°N). The ion density data from DMSP at 4s resolution are available at http://cindispace.utdallas.edu/DMSP/. The asymmetry in EIA between the two hemispheres has been suggested to influence growth of plasma instability and hence occurrence of ESF.

[14] The strength of the EIA has been widely suggested to be indicated by the latitudinal gradient of the EIA between the trough and the crest [*Ragahavarao et al.*, 1988; *Valladares et al.*, 2001; *Ray et al.*, 2006]. A quantitative estimate of the same linking the gradient of the EIA with the occurrence of postsunset ESF has been obtained [*Ray et al.*, 2006]. Alternatively, it has been suggested [*Thampi et al.*, 2006] that a parameter combining the strength and the asymmetry of the EIA may provide a better correlation with the occurrence of scintillations. Daily ionization density-latitude data obtained from DMSP at 4s resolution have been utilized to understand the asymmetry of the EIA and to derive parameters quantifying the same.

[15] Amplitude of the L band carrier signal (1537.528 MHz) from INMARSAT (350 km subionospheric point 21.08°N, 86.59°E geographic; magnetic dip: 28.74°N) and VHF carrier signal (244.156 MHz) from FLEETSATCOM (350 km subionospheric point: 21.10°N, 87.25°E geographic; magnetic dip: 28.65°N) has been regularly recorded at Calcutta. ICOM wideband communication receivers are used to record the signals. The detected outputs are simultaneously recorded using PC-based data acquisition system and a strip chart recorder. The receivers are calibrated once a week using a HP signal generator (model: HP8648C) following *Basu and Basu* [1989]. The dynamic range of each receiver is ~25 dB. The scintillation data was scaled to obtain Scintillation Index [SI (dB)] and S_4 following *Whitney et al.* [1969]. The digital data has been recorded at a sampling frequency of 20 Hz. In the present paper, geostationary scintillations observed from Calcutta, a station located beneath the northern crest of the EIA, have been used to find correlation with the development of the equatorial anomaly during the equinoctial months August through October 2000, and February through April 2001. DMSP ion densities and amplitude scintillation records from geostationary INMARSAT observed at Calcutta were available on 80 days during August through October 2000 and for 83 days during February through April 2001. Since the VHF scintillation records during the period under consideration were mostly saturated with $S_4 \sim 1$, the maximum S_4 (S_{4max}) at L band for a particular night was used to study the day-to-day variability of the intensity of scintillations. The period of study, being equinoctial months of high sunspot number years, was chosen such that scintillation activities maximize in the equatorial region and present worst-case figures which may serve as a benchmark for the international Space Weather community.

3. Results

[16] Figure 2 shows the location of the present station at Calcutta on a map of India along with the subionospheric positions of the geostationary satellites FLEETSATCOM (250 MHz) and INMARSAT (1.5 GHz). It has been suggested [*Rishbeth*, 1972; *Maruyama and Matuura*, 1984] that a strong transequatorial neutral wind in the ionospheric *F* region will modify the electron density distribution to an asymmetric shape about the magnetic equator thereby producing an asymmetry in the equatorial ionization anomaly. In the present investigations, it was found from the plots of latitudinal distribution of ionization measured by DMSP F13 that the locations of the crests of ionization of the equatorial anomaly are generally not symmetric with respect to the magnetic equator. The differences between the northern and southern extent of the crests, referred to as the differential extent, was cal-

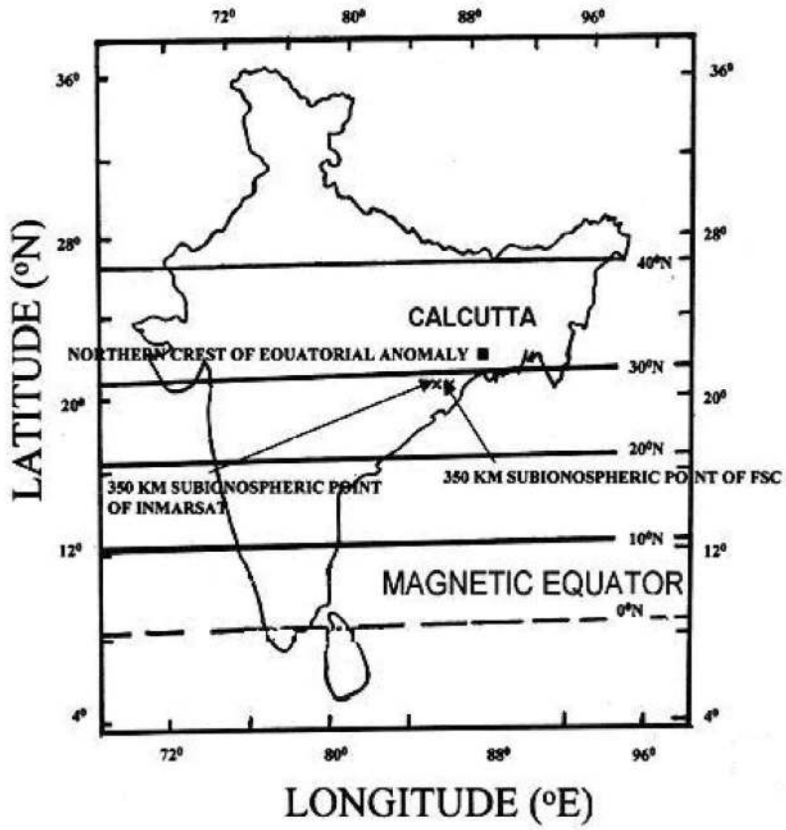

Figure 2. Map of India showing the location of Calcutta (latitude: 22.58°N longitude: 88.38°E geographic; magnetic dip: 32°N). The location of the magnetic equator and the northern crest of the equatorial anomaly around 30°N dip are also shown. Dip lines at 10^0 intervals from the magnetic equator to 40°N dip are included. The 350 km subionospheric points of the geostationary satellites FLEETSATCOM (71°E) (latitude: 21.10°N longitude: 87.25°E geographic; magnetic dip: 28.65°N) and INMARSAT (65°E) (latitude: 21.08°N longitude: 86.59°E geographic; magnetic dip: 28.74°N) from Calcutta are indicated by arrows.

culated during the equinox August through October 2000. Figure 3 shows the correlation between the differential extent and the occurrence of L band scintillations with $S_{4max} > 0.4$. A chi-square significance test was performed between the two by selecting a range of the differential extent from −2.5° to 0.05°. During August through October 2000, the differential extent showed an association at 2.5% significance level with the occurrence of L band scintillations.

[17] The area under the latitudinal distribution of ion density as obtained from DMSP on either side of the magnetic equator provides an idea about the ionization distribution. Because of the asymmetric nature of the equatorial anomaly with respect to the magnetic equator, the areas under the ion density-magnetic latitude curve are different in the two hemispheres. The asymmetry in equatorial ionization anomaly between the two hemispheres has been suggested to influence growth of plasma instability and hence occurrence of equatorial spread *F* [*Maruyama and Matuura*, 1984]. A difference between the areas north and south of the magnetic equator could provide insight into the effects of the meridional wind in creating the asymmetry, and hence could serve as a precursor for equatorial scintillations. Areas under the ion density-magnetic latitude plot on either side of the magnetic equator were calculated up to the crests of the EIA and their differences estimated. This difference was referred to as the differential area. It may be noted that the area under the ion density curve was calculated by estimating the areas of small polygons whose vertices were defined by the ion densities and the corresponding magnetic latitudes at 4s resolution. Areas

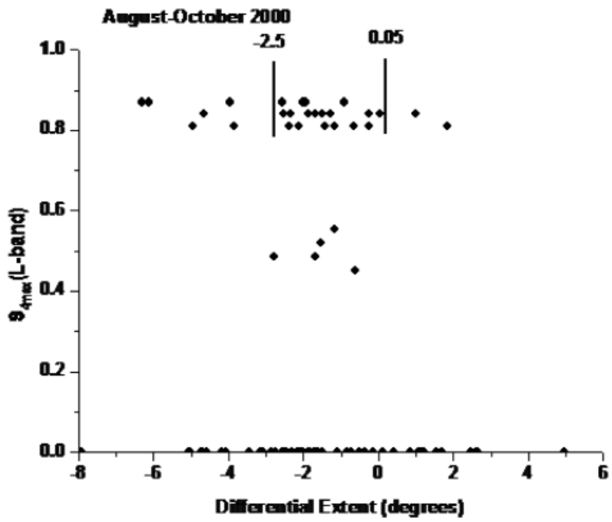

Figure 3. Differences in the extents of the northern and the southern crests of the equatorial ionization anomaly as obtained from the ion density-magnetic latitude plots of DMSP F13 during August through October 2000. The range of differential extents enclosed by the arrows correspond to values which show a significant association at 1% level with the occurrence of geostationary L band scintillations at Calcutta with $S_{4max} > 0.4$.

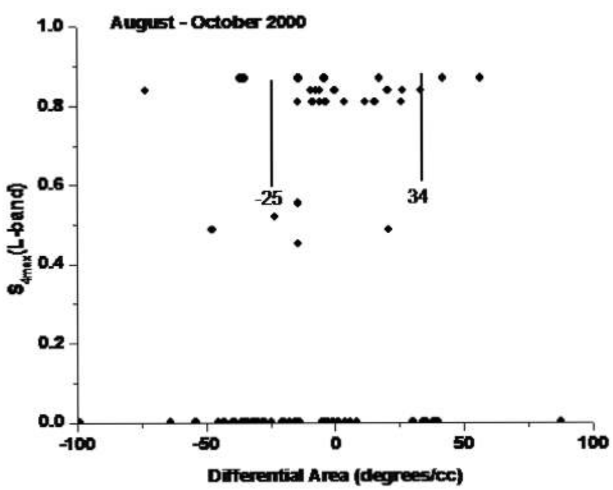

Figure 4. Difference between the areas measured under the ion density-magnetic latitude plots of DMSP F13 from the magnetic equator to the northern and southern crests of the EIA during August through October 2000. The range from −25 deg/cc to 34 deg/cc, bounded by arrows, shows a highly significant association with the occurrence of geostationary L band scintillations at Calcutta with $S_{4max} > 0.4$. Positive areas are taken north of the magnetic equator.

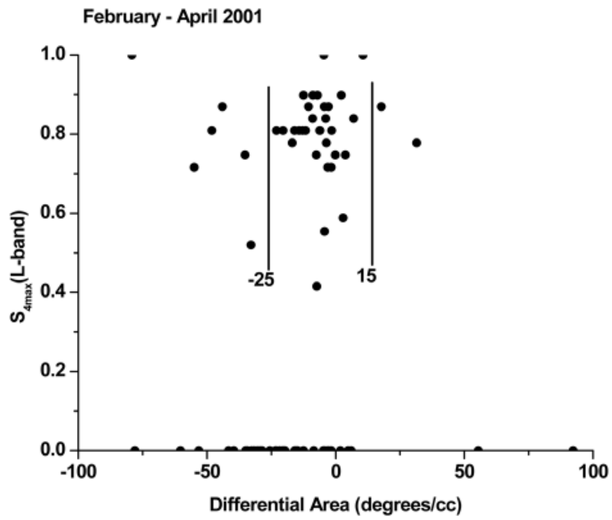

Figure 5. Difference between the areas measured under the ion density-magnetic latitude plots from DMSP F13 from the magnetic equator to the northern and southern crests of the EIA during February through April 2001. The range from −25 deg/cc to 15 deg/cc, bounded by arrows, shows a significant association with the occurrence of geostationary L band scintillations at Calcutta with $S_{4max} > 0.4$. Positive areas are taken north of the magnetic equator.

of these polygons were integrated to calculate the total area under the curve.

[18] Figures 4 and 5 show the plots of the differential areas as a function of the S_{4max} at L band for the equinoxes August through October 2000, and February through April 2001. The range of the differential area between −25 and 34 deg/cc was found to have a highly significant association at 1% level with the S_{4max} during August through October 2000 while the corresponding range for February through April 2001 was found to be from −25 to 15. The detailed values of the differential areas for these two equinoxes are presented in Tables 1 and 2, respectively. In the above analysis, positive areas are taken north of the magnetic equator.

[19] There has been a recent suggestion [*Thampi et al.*, 2006] that neither the strength nor the asymmetry of the equatorial ionization anomaly could completely address the day-to-day variability of the occurrence of scintillations. Instead these two factors should be combined together to provide a scintillation forecast parameter. Accordingly, the strengths of the EIA and the asymmetry have been defined following *Thampi et al.* [2006] and referred to as S and A, respectively.

Table 1. Detailed Values of the Differential Areas for the Equinox August–October 2000

	Differential Area Lies Within −25 deg/cc and 34 deg/cc	Differential Area Lies Outside −25 deg/cc and 34 deg/cc	Total
Occurrence of L band scintillations with $S_{4max} > 0.4$	25	6	31
Nonoccurrence of L band scintillations with $S_{4max} > 0.4$	21	28	49
	46	34	80

[20] The strength of the anomaly has been defined as

$$S = \frac{(A_1 + A_2)}{2}$$

and a measure of the asymmetry as

$$A = \frac{(A_1 - A_2)}{S}$$

where A_1 and A_2 are the areas calculated under the ion density-magnetic latitude plot on either side of the magnetic equator up to the crests of the EIA. Finally the measures of the anomaly and asymmetry of the EIA have been combined to produce the parameter C defined as

$$C = \frac{\sqrt{S}}{|A|}$$

Figures 6 and 7 show the results of the correlation between the combined parameter C and the occurrence of L band scintillations at Calcutta with $S_{4max} > 0.4$ for the two equinoctial periods August through October 2000, and February through April 2001. In Figure 6, the range of C from 4 to 80 was selected and a chi-square test was performed to estimate its level of association with the occurrence of L band scintillations. A highly significant

Table 2. Detailed Values of the Differential Areas for the Equinox February–April 2001

	Differential Area Lies Within −25 deg/cc and 15 deg/cc	Differential Area Lies Outside −25 deg/cc and 15 deg/cc	Total
Occurrence of L band scintillations with $S_{4max} > 0.4$	32	10	42
Nonoccurrence of L band scintillations with $S_{4max} > 0.4$	20	21	41
	52	31	83

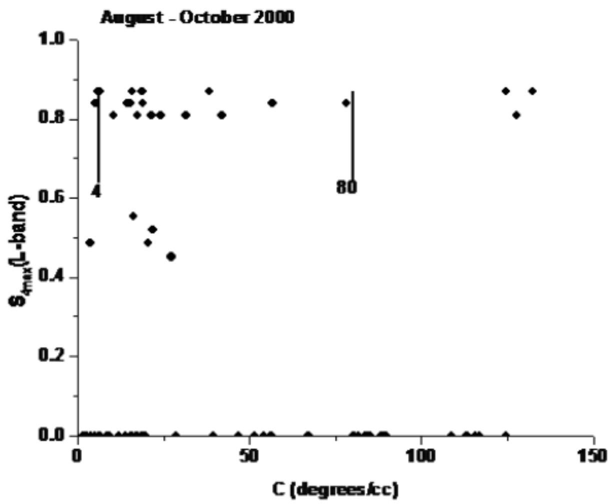

Figure 6. Parameter C (deg/cc) calculated by combining the strength and asymmetry of the EIA measured by DMSP during August through October 2000. The range of C shown within bounding arrows correspond to values for which a highly significant association is noted with the occurrence of L band scintillation at Calcutta with $S_{4max} > 0.4$.

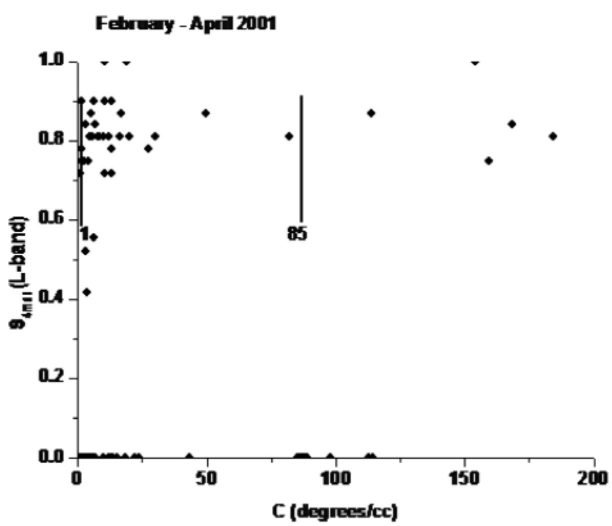

Figure 7. Parameter C (deg/cc) calculated by combining the strength and asymmetry of the EIA measured by DMSP during February through April 2001. The range of C shown within bounding arrows correspond to values for which a highly significant association is noted with the occurrence of L band scintillation at Calcutta with $S_{4max} > 0.4$.

Table 3. Results of Calculation of the Parameter *C* Over the Equinox August–October 2000

	C Lies Within 4 deg/cc and 80 deg/cc	*C* Lies Outside 4 deg/cc and 80 deg/cc	Total
Occurrence of L band scintillations with $S_{4max} > 0.4$	26	5	31
Nonoccurrence of L band scintillations with $S_{4max} > 0.4$	21	28	49
	47	33	80

correlation at 1% level was noted between the two. Similarly, during February through April 2001, the range of *C* between 1 and 85 showed significant association at 1% level with S_{4max} at L band. Tables 3 and 4 describe the results of calculation of the parameter *C* over the two equinoxes.

4. Discussions

[21] Present understanding of equatorial ionospheric dynamics does not provide answers to some outstanding issues related to day-to-day variability of occurrence of ESF. Recourse is often taken to statistical studies of some EIA parameters which are considered major drivers behind generation of ionospheric irregularities. The results presented in this paper assume importance from the point of view of applications to satellite-based systems.

[22] The equatorial electric field plays a dominant role in shaping the development of both daytime equatorial ionization anomaly and nighttime density irregularities. The field, which is eastward during the daytime reverses to the west around 2100 LT. Before reversal, at the time of sunset, a dramatic increase in the electric field known as the prereversal enhancement develops at *F* region heights. The increased electric field causes a redistribution of ionization leading to a secondary peak or a ledge in the ionization distribution [*Anderson and Klobuchar*, 1983; *DasGupta et al.*, 1985; *Huang et al.*, 1989]. Topside sounder [*King et al.*, 1967] and in situ observations have established that the equatorial anomaly is not confined to the height of maximum ionization only; it also extends to the topside. The separation between the crests decreases with increasing altitude, and the locus of the crest lies on a field line. A larger postsunset enhanced eastward electric field may raise the apex to heights above the nominal 840 km altitude of satellites like DMSP. On days when the electric field forces the apex of the EIA to rise to heights of 750 km or higher over the magnetic equator, the ionospheric irregularities developed over the magnetic equator in the postsunset hours may map to off-equatorial latitudes like Calcutta along the magnetic field lines.

[23] It has been suggested [*Maruyama and Matuura*, 1984] that transequatorial winds cause significant redistribution of ionization with respect to the magnetic equator resulting in an asymmetry of the extents of the crests of the equatorial ionization anomaly and peak ion densities in both the hemispheres. The asymmetry in EIA between the two hemispheres has been suggested to influence growth of plasma instability and hence occurrence of scintillations. Thus the ionization under the ion density plots obtained from DMSP reflects the asymmetry and hence acts as an effective precursor to equatorial scintillations.

[24] The percentage of correct forecasting of occurrence of scintillations using the differential area as a parameter was 81% and 76% during the two equinoxes of August through October 2000, and February through April 2001, respectively. When the parameter C derived combining the strength and the asymmetry of the EIA was used, the corresponding percentages of correct forecasting of the occurrence of scintillations for the two equinoxes were 84% and 81%, respectively, for the two equinoxes. The probability of misses using C, i.e., occurrence of geostationary L band scintillations with $S_{4max} > 0.4$ without a positive forecast, decreases to 16% and 19%, respectively, for the two equinoxes in comparison to 19% and 24% when using the differential area as a measure of asymmetry.

[25] As the level of precursors developed during a solar maximum study will not match with a moderate or low solar activity period, the results corresponding to the equinoctial months of high sunspot number years should be treated as the worst-case figures from a low-latitude station. However, suitable modification of the threshold level at other solar activity levels should be performed in order to minimize the cases of "errors" and "false alarms" both of which severely compromise the accuracy and integrity and leads to wastage of system resources in satellite-based communication and navigation systems. Analyses of DMSP ion density data during March 2004, a period of moderate sunspot number have been performed. During March 2004, only six cases of geostationary L band scintillations with $S_{4max} > 0.4$ were

Table 4. Results of Calculation of the Parameter *C* Over the Equinox February–April 2001

	C Lies Within 1 deg/cc and 85 deg/cc	*C* Lies Outside 1 deg/cc and 85 deg/cc	Total
Occurrence of L band scintillations with $S_{4max} > 0.4$	34	8	42
Nonoccurrence of L band scintillations with $S_{4max} > 0.4$	19	22	41
	53	30	83

recorded at Calcutta. It was noted that on 50% of the days of scintillations, the differential area was within a range of −11 and −1. The combined parameter C was found to lie within a range from 5 to 17 on 80% of the cases of scintillations. However, as the number of scintillation events were few in comparison to the solar maximum period and availability of DMSP data was limited, a more extensive study of the procedure presented in this paper may be attempted using other satellites for moderate and low sunspot number periods.

[26] A study of the results of the association between the strength and the asymmetry of the equatorial ionization anomaly using DMSP, and occurrence of geostationary L band scintillations from Calcutta, indicate that a single measure for the prediction of scintillations is indeed insufficient. When combined, the resultant parameter showed a better degree of association with the occurrence of scintillations. The selection of the range of values for the differential extent and differential area also indicate that very weak and very strong asymmetry inhibit ESF which is in conformity with the mechanism suggested by *Maruyama and Matuura* [1984]. It should be noted that the selection of the range of the different parameters have been done solely with the objective of attaining a high degree of association with the occurrence of postsunset scintillations. A reliable forecast of scintillations occurring during the postsunset hours in this geophysically sensitive region of the Earth would serve as a benchmark for the International Space Weather program and may address some of the outstanding issues related to the day-to-day variability of equatorial ionospheric irregularities. Parameters and thresholds detected using the DMSP satellites may be further refined during the upcoming solar maximum period using data from C/NOFS.

[27] **Acknowledgments.** The authors thank the reviewers for their careful study of the manuscript and suggestions helpful in improving the quality of the paper. A part of this research has been sponsored by the Indian Space Research Organization (ISRO) through projects at the S. K. Mitra Center for Research in Space Environment, University of Calcutta. The authors gratefully acknowledge the Center for Space Sciences at the University of Texas at Dallas and the U.S. Air Force for providing the DMSP thermal plasma data via the Web site http://cindispace.utdallas.edu/DMSP/.

References

Abdu, M. A. (1997), Major phenomena of the equatorial ionosphere thermosphere system under disturbed conditions, *J. Atmos. Sol. Terr. Phys.*, *59*(13), 1505–1519, doi:10.1016/S1364-6826(96)00152-6.

Abdu, M. A., I. S. Batista, H. Takahashi, J. MacDougall, J. H. Sobral, A. F. Medeiros, and N. B. Trivedi (2003), Magnetospheric disturbance induced equatorial plasma bubble development and dynamics: A case study in Brazilian sector, *J. Geophys. Res.*, *108*(A12), 1449, doi:10.1029/2002JA009721.

Abdu, M. A., P. P. Batista, I. S. Batista, C. G. M. Brum, A. Carrasco, and B. W. Reinisch (2006), Planetary wave oscillations in mesospheric winds, equatorial evening prereversal electric field and spread F, *Geophys. Res. Lett.*, *33*, L07107, doi:10.1029/2005GL024837.

Abdu, M. A., I. S. Batista, B. W. Reinisch, J. R. de Souza, J. H. A. Sobral, T. R. Pedersen, A. F. Madeiros, N. J. Schuch, E. R. de Paula, and K. M. Groves (2009), Conjugate Point Equatorial Experiment (COPEX) campaign in Brazil: Electrodynamics highlights on spread *F* developmeht conditions and day-to-day variability, *J. Geophys. Res.*, *114*, A04308, doi:10.1029/2008JA013749.

Anderson, D. N., and J. A. Klobuchar (1983), Modeling the total electron content observations above Ascension Island, *J. Geophys. Res.*, *88*(A10), 8020–8024.

Anderson, D. N., B. Reinisch, C. Valladare, J. Chau, and O. Veliz (2004), Forecasting the occurrence of ionospheric scintillation activity in the equatorial ionosphere on a day-to-day basis, *J. Atmos. Sol. Terr. Phys.*, *66*(17), 1567–1572.

Basu, S., and Su. Basu (1989), Scintillation technique for probing ionospheric irregularities, in *World Ionospheric Thermospheric Studies (WITS) Handbook*, vol. 2, edited by C. H. Liu, pp. 128–136, *Sci. Comm. on Sol.-Terr. Phys.*, Univ. of Ill., Urbana.

Basu, S., et al. (1996), Scintillations, plasma drifts, and neutral winds in the equatorial ionosphere after sunset, *J. Geophys. Res.*, *101*(A12), 26,795–26,809.

Bittencourt, J. A., and Y. Sahai (1978), *F*-region neutral winds from ionosonde measurements of *hmF2* at low latitude magnetic conjugate region, *J. Atmos. Terr. Phys.*, *40*(6), 669–676.

Cosgrove, R. B., and R. T. Tsunoda (2002), A direction-dependent instability of sporadic E layers in the nighttime midlatitude ionosphere, *Geophys. Res. Lett.*, *29*(18), 1864, doi:10.1029/2002GL014669.

DasGupta, A., D. N. Anderson, and J. A. Klobuchar (1985), Modeling the low latitude ionospheric total electron content, *J. Atmos. Terr. Phys.*, *47*(8–10), 917–924.

Fejer, B. G., L. Scherliess, and E. R. dePaula (1999), Effects of the vertical plasma drift velocity on the generation and evolution of equatorial spread *F*, *J. Geophys. Res.*, *104*(A9), 19,859–19,869.

Huang, Y., K. Cheng, and S. Chen (1989), On the equatorial anomaly of the ionospheric total electron content near the northern anomaly crest region, *J. Geophys. Res.*, *94*(A10), 13,515–13,525.

Hysell, D. L., and E. Kudeki (2004), Collisional shear instability in the equatorial *F* region ionosphere, *J. Geophys. Res.*, *109*, A11301, doi:10.1029/2004JA010636.

Hysell, D. L., M. F. Larsen, C. M. Swenson, and T. F. Wheeler (2006), Shear flow effects at the onset of equatorial spread *F*, *J. Geophys. Res.*, *111*, A11317, doi:10.1029/2006JA011963.

Keskinen, M. J., S. L. Ossakow, and B. G. Fejer (2003), Three-dimensional nonlinear evolution of equatorial ionospheric spread *F* bubbles, *Geophys. Res. Lett.*, *30*(16), 1855, doi:10.1029/2003GL017418.

King, J. W., K. C. Reed, E. O. Olatunji, and A. J. Legg (1967), The behavior of the topside ionosphere during storm conditions, *J. Atmos. Terr. Phys.*, *29*(11), 1355–1363.

Kudeki, E., A. Akgiray, M. Milla, J. L. Chau, and D. L. Hysell (2007), Equatorial spread-F initiation: Post-sunset vortex, thermospheric winds, gravity waves, *J. Atmos. Sol. Terr. Phys.*, *69*, 2416–2427, doi:10.1016/j.jastp.2007.04.012.

Maruyama, T. (1988), A diagnostic model for equatorial spread *F*: 1. Model description and application to electric field and neutral wind effects, *J. Geophys. Res.*, *93*(A12), 14,611–14,622.

Maruyama, T., and N. Matuura (1984), Longitudinal variability of annual changes in activity of equatorial spread *F* and plasma bubbles, *J. Geophys. Res.*, *89*(A12), 10,903–10,912.

Mendillo, M., J. Baumgardner, X. Pi, and P. J. Sultan (1992), Onset conditions for equatorial spread *F*, *J. Geophys. Res.*, *97*(A9), 13,865–13,876.

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

Patra, A. K., D. Tiwari, S. Sripathi, P. B. Rao, R. Sridharan, C. V. Devasia, K. S. Viswanathan, K. S. V. Subbarao, R. Sekar, and E. A. Kherani (2005), Simultaneous radar observations of meter-scale *F* region irregularities at and off the magnetic equator over India, *J. Geophys. Res.*, *110*, A02307, doi:10.1029/2004JA010565.

Prakash, S. (1999), Production of electric field perturbations by gravity wave winds in the *E* region suitable for initiating equatorial spread *F*, *J. Geophys. Res.*, *104*(A5), 10,051–10,069, doi:10.1029/1999JA900028.

Ragahavarao, R., M. Nageswararao, J. H. Sastri, G. D. Vyas, and M. Sriramarao (1988), Role of equatorial ionization anomaly in the initiation of equatorial spread *F*, *J. Geophys. Res.*, *93*(A6), 5959–5964.

Ray, S., A. Paul, and A. DasGupta (2006), Equatorial scintillations in relation to the development of ionization anomaly, *Ann. Geophys.*, *24*, 1429–1442.

Rishbeth, H. (1972), Thermospheric winds and the *F*-region: A review, *J. Atmos. Terr. Phys.*, *34*(1), 1–47.

Sastri, J. H., M. A. Abdu, I. S. Batista, and J. H. A. Sobral (1997), Onset conditions of equatorial (range) spread *F* at Fortaleza, Brazil, during the June solstice, *J. Geophys. Res.*, *102*(A11), 24,013–24,021, doi:10.1029/97JA02166.

Secan, J. A., R. M. Bussey, E. J. Fremouw, and S. Basu (1995), An improved model of equatorial scintillation, *Radio Sci.*, *30*(3), 607–617.

Secan, J. A., R. M. Bussey, E. J. Fremouw, and S. Basu (1997), High latitude upgrade to the Wideband ionospheric scintillation model, *Radio Sci.*, *32*(4), 1567–1574.

Sultan, P. J. (1996), Linear theory and modeling of the Rayleigh-Taylor instability leading to the occurrence of equatorial spread *F*, *J. Geophys. Res.*, *101*(A12), 26,875–26,892.

Thampi, S. V., S. Ravindran, T. K. Pant, C. V. Devasia, P. Sreelatha, and R. Sridharan (2006), Deterministic prediction of postsunset ESF based on the strength and asymmetry of EIA from ground based TEC measurements: Preliminary results, *Geophys. Res. Lett.*, *33*, L13103, doi:10.1029/2006GL026376.

Tsunoda, R. T. (2007), Seeding of equatorial plasma bubbles with electric fields from an E_s layer instability, *J. Geophys. Res.*, *112*, A06304, doi:10.1029/2006JA012103.

Vadas, S. L. (2007), Horizontal and vertical propagation and dissipation of gravity waves in the thermosphere from lower atmosphere and thermosphere sources, *J. Geophys. Res.*, *112*, A06305, doi:10.1029/2006JA011845.

Vadas, S. L., and D. C. Fritts (2006), Influence of solar variability on gravity wave structure and dissipation in the thermosphere from tropospheric convection, *J. Geophys. Res.*, *111*, A10S12, doi:10.1029/2005JA011510.

Valladares, C. E., S. Basu, K. Groves, M. P. Hagan, D. Hysell, A. J. Mazella Jr., and R. E. Sheehan (2001), Measurement of the latitudinal distribution of TEC during ESF events, *J. Geophys. Res.*, *106*(A12), 29,133–29,152.

Whitney, H. E., J. Aarons, and C. Malik (1969), A proposed index for measuring ionospheric scintillations, *Planet. Space Sci.*, *17*(5), 1069–1073.

A. DasGupta, S. K. Mitra Center for Research in Space Environment, University of Calcutta, Calcutta 700009, India.

A. Paul, Institute of Radio Physics and Electronics, University of Calcutta, Calcutta 700009, India. (ashik_paul@rediffmail.com)