Long-term control of solar activity on equatorial scintillations

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Abstract. The Sun has a tremendous influence on the Earth's upper atmosphere. It is not only a source of ionizing radiation but also produces severe disturbances like geomagnetic storms. The 11-year cycle in the variation of behavior and energy output of the Sun influences the generation of equatorial *F*-region irregularities, which produce scintillations of satellite signals. The phenomenon of scintillations particularly in the L-band has received considerable attention in recent years because of its detrimental effects on communication and navigational systems like GPS. Amplitude scintillations induce signal fading and when the depth of fading exceeds the fade margin of a receiving system, message errors in satellite communication systems are introduced. In GPS, amplitude scintillation may cause degradation of position fixing by standalone GPS receivers, data loss and cycle slips. Severe phase scintillations may stress phase-locked loops in GPS receivers and give rise to loss of phase lock. Scintillation is not a transient phenomenon like the geomagnetic storms but is prevalent mostly during magnetically quiet periods in the pre-midnight hours of equinoctial months of high sunspot number years for a station like Calcutta located near the northern crest of the equatorial anomaly. Amplitude scintillations at L-band (1.5 GHz) and VHF (244 MHz) have been recorded at Calcutta (22.58^{o}N, 88.38^{o}E geographic; 32^{o}N magnetic dip) for more than a solar cycle from geostationary satellites INMARSAT and FLEETSATCOM respectively. The signal-to-noise ratios of GPS L1 (1575.42 MHz) have also been recorded at the same station since 1994. This paper presents a study of L-band scintillations for nearly half a solar cycle (1996-2000) from Calcutta, which is located under the northern anomaly crest in the Indian longitude sector. The variations of occurrence with local time, season, solar and magnetic activity have been discussed to show that solar activity has a very prominent control over development of ionospheric *F*-region irregularities unlike the transient phenomenon associated with disturbed Sun and geomagnetic storms.

Index Terms. Equatorial anomaly crest, equatorial plasma bubbles, L-band scintillations, solar activity dependence**.**

1. Introduction

The phenomenon of scintillations, i.e., amplitude and phase fluctuations of satellite signals propagating through the ionosphere particularly in the lower microwave band has received considerable attention in recent years because of its detrimental effects on communication and navigational systems like Global Positioning System. Amplitude scintillations induce signal fading and when the depth of fading exceeds the fade margin of a receiving system, message errors in satellite communication systems are introduced. In GPS, amplitude scintillation may cause degradation of position fixing by standalone GPS receivers (Bandyopadhyay et al., 1997; DasGupta et al., 2004), data loss and cycle slips (Kelly et al., 1996). Severe phase scintillations may stress phase-lock loops in GPS receivers and give rise to loss of phase lock.

During scintillations, irregular phase fluctuations are imposed on a transionospheric radio wave and amplitude fluctuations are developed by a diffraction process as the wave propagates in the free space beneath the ionosphere. The magnitude of the random phase perturbations depends on the integrated electron density deviation, $\int \Delta N\, dl$, along the ray path. This parameter is controlled by the irregularity amplitude ($\Delta N/N$) and the background electron density, N, and its distribution in the ionosphere. Satellite *in situ* measurements have shown that though the irregularity amplitude remains nearly constant, the background density in some regions undergoes a drastic variation with the sunspot cycle. This in turn affects the magnitude of amplitude and phase scintillations as a function of sunspot cycle at any point on the globe (Basu et al., 1988).

The morphology of L-band scintillations during solar maximum and minimum years were reported by Basu et al. (1988). It has been found that L-band scintillations are most intense in the equatorial region, moderate at high latitudes and generally absent at mid-latitudes. At high latitudes, scintillations are associated with large-scale plasma structures and are mainly controlled by the Interplanetary Magnetic Field (IMF) from the Sun. At low latitudes, scintillations are not fully controlled by solar transients such as magnetic storms - intense scintillations have been observed during magnetically quiet periods. For all latitude regions,

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scintillation occurrence is maximum during high sunspot number period when *F*-region ionization density increases and the irregularities occur in a background of high ionization density.

The equatorial *F* -region possesses two unique features: (1) the equatorial or Appleton anomaly, which is the latitudinal variation of electron density with a trough at the magnetic dip equator and two crests at 15^o–20^o north and south dip latitudes, and (2) intense irregularities in electron density distribution. The equatorial electric field plays a dominant role in shaping the development of both daytime equatorial anomaly and nighttime density irregularities. The field is eastward during the day and reverses to the west after sunset, at about 2100LT. Before reversal, at the time of sunset, a dramatic increase in the electric field, known as pre-reversal enhancement develops at *F* region heights (Fejer, 1991). The effect of pre-reversal enhancement on the eastward electric field is two-fold and has both seasonal and solar activity dependences. The increased electric field causes a redistribution of ionization by a fountain-like effect, thereby increasing the ionization density near the crests at the expense of that at the trough over the magnetic equator. At the anomaly crests, fresh influx of ionization combined with the neutral wind counteracts the normal decay of ionization and produces a secondary peak or a ledge in the ionization distribution (Anderson and Klobuchar, 1983; DasGupta et al., 1985; Huang et al., 1989). Further, the pre-reversal enhancement of the eastward electric field raises the *F* layer at the magnetic equator to high altitudes, where recombination effects are negligible and conditions favorable for the generation of irregularities may be obtained (Haerendel, 1974; Woodman and LaHoz, 1976). Through the Rayleigh-Taylor mechanism, the irregularities then develop into plasma-depleted bubbles and are upwelled to the topside of the ionosphere. The polarization electric field within the bubbles is higher, and as a result, the bubbles rise to the topside at a velocity much greater than the ambient *F* region plasma drift (Anderson and Haerendel, 1979). Steep gradients on the edges of the depletions (Haerendel, 1974; Costa and Kelly, 1978) help to generate small-scale irregularities as the bubbles rise to great heights, sometimes exceeding 1000 km above the magnetic equator. These are widely recognized as plumes on radar backscatter maps (Woodman and LaHoz, 1976). The bubbles extended in altitude map down along the magnetic field line to anomaly locations of about 15^oN and 15^oS magnetic latitudes. The above effect is most pronounced during the equinoctial months of sunspot number maximum years. Persistence of high ambient ionization and injection of equatorial irregularities result in severe scintillation effects near the anomaly crest in the post-sunset period.

During geomagnetic storms, the ionospheric electric fields, plasma drifts, plasma density distribution and onset of plasma instabilities in the equatorial *F*-region giving rise to scintillations differ from their quiet day pattern. Two major sources of storm time electric field perturbations have been identified. They are the magnetospheric and ionospheric disturbance dynamos. For the past four decades, extensive work has been carried out to find a correlation between geomagnetic activity and occurrence of small-scale irregularities causing scintillations. Aarons (1991) showed the presence or absence of irregularities versus longitude and storm time by considering the Universal Time (UT) of the storm's peak effect (Dst). The use of a geomagnetic index to designate peak storm time can identify the longitude sector most susceptible to irregularity generation. Su. Basu et al. (2001) related the occurrence of strong irregularities with rate of change of Dst (dDst/dt), which is a measure of the particle injection rate, greater that –50 nT/hr. They reported that equatorial irregularities occur in the specific longitude sector for which early evening period corresponds to the time of rapid Dst variation and strong negative Dst values.

A robust climatological model of scintillations WBMOD, which is useful for planning purposes, is now available (Secan et al., 1995, 1997). The model uses VHF scintillation data collected from Wideband Satellite at Ancon, Peru and Kwajalein Island and VHF and L-band data from MARISAT satellite recorded at Manila, Phillipines (VHF), Huancayo, Peru (VHF) and Ascension Island (L-band). Scintillation is a phenomenon exhibiting extreme variability in space and time. Thus climatological models are unsuitable for supporting space-based communication and navigation systems and weather models, which can provide real-time specification and forecasting, are required. Such a system, known as Scintillation Network Decision Aid (SCINDA) has been developed for the American sector (Groves et al., 1997). The system combines scintillation magnitude and zonal drift measurements made at two sites, Ancon, Peru near the magnetic equator and Antofagasta, Chile at 11^oS magnetic latitude by using transmissions from two geostationary satellites, one to the east and the other to the west of the stations. The data drives the equatorial scintillation model, which uses upwelling and zonal motion to produce three-dimensional scintillation structures. The latitude variation of *in situ* electron density at 840 km by the polar orbiting DMSP satellites measured at 18h local time at the equator gives an indication of the pre-reversal enhancement of the eastward electric field one and a half hour prior to sunset on a particular day. The DMSP data has been incorporated in the SCINDA system to provide actual forecast of scintillation to be observed one hour later at the longitude of DMSP transit on the same day (Basu et al., 2002). To specify and forecast scintillations, the Communication Navigation Outage Forecasting System (C/NOFS) Satellite, a joint initiative of the U.S. Air Force Research Laboratory, NASA and Naval Research Laboratory, is to be launched in February 2006. The satellite will be placed in an elliptical (375 kmX710 km) orbit with 13^o inclination and will measure the ionospheric parameters such as ambient and fluctuating electron density as well as the drivers such as the electric and magnetic field and neutral wind (de La Beaujardiére et al., 2003). These data will drive an equatorial ionospheric model, which will be able to forecast the onset of plasma instability.

The occurrence statistics of L-band scintillations reported so far are from the American longitude sector (Basu Su. et al., 1980; Livingston, 1980; Aarons et al., 1981; Basu and Basu, 1981; Aarons et al., 1983; Basu Su. and Basu, 1985; Basu et al., 1988; Groves et al., 1997; Basu et al., 2002); no such statistics have been reported from other longitudes. In fact, Calcutta is one of the very few stations outside the American zone having a continuous database of L-band scintillations for over a solar cycle (1990 to date). This paper presents a study of L-band scintillations for half a solar cycle (1996-2000) from Calcutta, which is located under the northern anomaly crest in the Indian longitude sector. The year 1996 corresponds to sunspot number minimum (8.6) and 2000 to sunspot number maximum (119.6). The variations of occurrence with local time, season, solar and magnetic activity have been discussed. The L-band scintillation statistics of Calcutta presented in this paper can provide useful inputs from the Indian sector to global climatological and weather models of scintillations to be developed in the future.

2. Data

Amplitude of the L-band carrier signal (1537.528 MHz) from INMARSAT (350 km-subionospheric point 21.08^{o}N, 86.59^{o}E geographic; 28.74^{o}N magnetic dip, 15.33^{o}N dip latitude) and VHF carrier signal (244.156 MHz) from FLEETSATCOM (350 km-subionospheric point: 21.10^{o}N, 87.25^{o}E geographic; 28.65^{o}N magnetic dip, 15.28^{o}N dip latitude) has regularly been recorded at Calcutta since 1990 and 1981 respectively. The receivers used are ICOM Wideband Communication Receivers. The detected outputs are simultaneously recorded on a PC-based Data Acquisition System and a strip chart recorder. The receivers are calibrated once a week by a HP Signal Generator (model: HP8648C) following Basu and Basu (1989). The dynamic range of each receiver is ~25 dB and the sampling frequency is 20 Hz. The Scintillation Index S_4 has been computed at 15minutes interval from the digitally sampled signal power data. The corresponding SI (dB) is obtained using the third peak method of Whitney et al. (1969). Following scattering theory, the signal fade depths in dB, which is more useful for communication engineers, have been computed for the SI (dB) levels. The 350 km subionospheric points of INMARSAT and FSC map up along the field line to a height of 700 km above the magnetic equator. Scintillations observed at Calcutta thus correspond to equatorial bubbles at or above this altitude over the magnetic equator.

Geomagnetic storms can be classified as intense, moderate or small (substorm) according to minimum Dst value, and duration and magnitude of southward component of Bz. A geomagnetic storm is said to be intense if minimum Dst < -100 nT; Bz < -10 nT for at least 3 hours. It is moderate if minimum Dst < -50 nT; Bz < -5 nT for at least 2 hours. The storm is small if minimum Dst < -30 nT; Bz < -3 nT for at least 1 hour (Gonzalez et al., 1994). During the period of study covering half a solar cycle from solar minimum (1996) through maximum (2000) years, 40 moderate storms with sudden commencement were observed, out of which scintillations, at least in VHF link were present in 9 storms and absent in 31. Restricting our study to intense magnetic storms with sudden commencement, it is observed that 17 such storms occurred during 1996-2000 of which 4 showed scintillation activity.

The storms under study have been ordered both with respect to the maximum negative dDst/dt and AE maximum. The Dst and AE indices have been obtained from the World Data Center for Geomagnetism, Kyoto (URL address: http://swdcwww.kugi.kyoto-u.ac.jp/) and the IMF Bz and Solar Wind Speed from Advanced Composition Explorer (ACE) data (URL: http://www.srl.caltech.edu/ACE/).

3. Results

Fig. 1 shows the hourly percentage occurrences of L-band (1.5 GHz) scintillations with SI ≥ 10 and 20 dB respectively during 1996-2000. Saturated VHF (244 MHz) scintillation occurrence is also shown in the same figure for comparison. It is observed that scintillations at L-band essentially occur between local sunset and midnight with a maximum in the local time interval 19-20. On the contrary, at VHF, it extends well beyond midnight; the maximum occurring around 20LT. Fig. 1 also shows two clear seasonal maxima corresponding to the two equinoxes namely, February-April and August–October. The solar activity dependence is also evident. Scintillations at L-band are practically absent during 1996-1997 for SI ≥ 10dB and 1996-1998 for SI ≥ 20 dB respectively, which are years of low sunspot number. The maximum hourly percentage occurrences are 39% for S I≥10 dB and 37% for SI ≥ 20dB respectively in March 2000, the period of sunspot number maximum. For saturated VHF scintillations, the solar activity dependence is similar; with little or no scintillations during 1996-1997 and the maximum hourly percentage occurrence is 45% in March 2000. It should however be noted that during low sunspot number years, there are individual occasions of scintillations at both VHF and L-band frequencies at the latitude of Calcutta caused by high altitude equatorial bubbles. Their occurrence frequency is no doubt less but they are occasionally observed.

A distribution of monthly percentage occurrence during 20-24 LT over the rising solar epoch 1996-2000 with smoothed monthly mean sunspot number has been found for fade depth levels 6, 10 and 20 dB, shown in Fig. 2. The increase in both percentage occurrence and intensity of scintillations with sunspot number is very much evident with a maximum occurrence ~ 30 % for fade depth > 10 dB in March 2000.

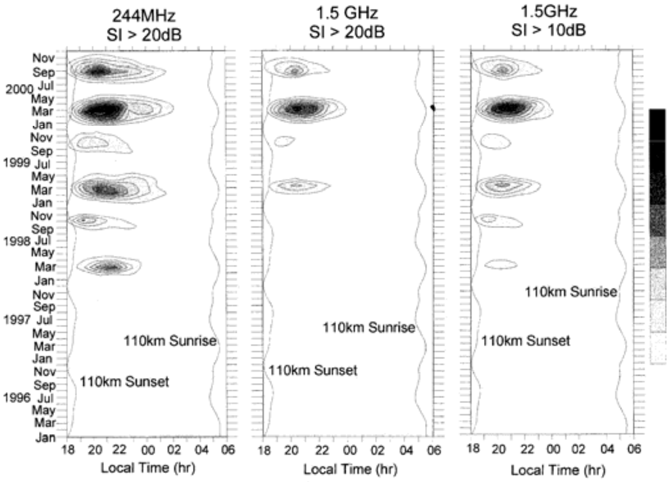


Fig. 1. Hourly percentage occurrence contours of VHF (244MHz) for SI > 20dB and L-band (1.5GHz) for SI > 10 and 20dB for 1996-2000. The E-region sunrise and sunset lines are also shown.

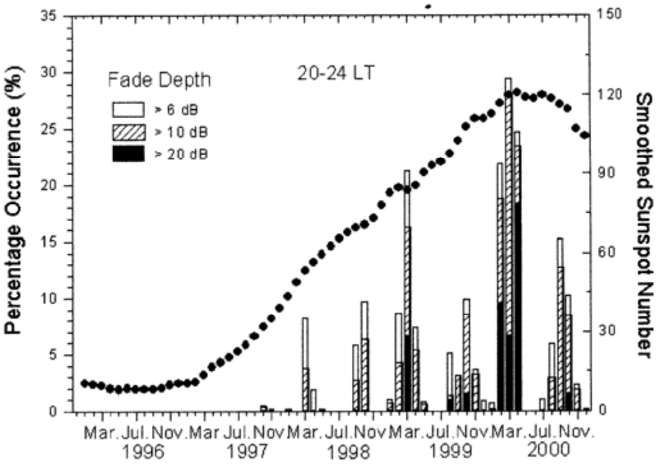


Fig. 2. Monthly Percentage Occurrence over 20-24 LT for Fade Depth > 6, 10 and 20 dB with smoothed sunspot numbers for the rising solar epoch 1996-2000.

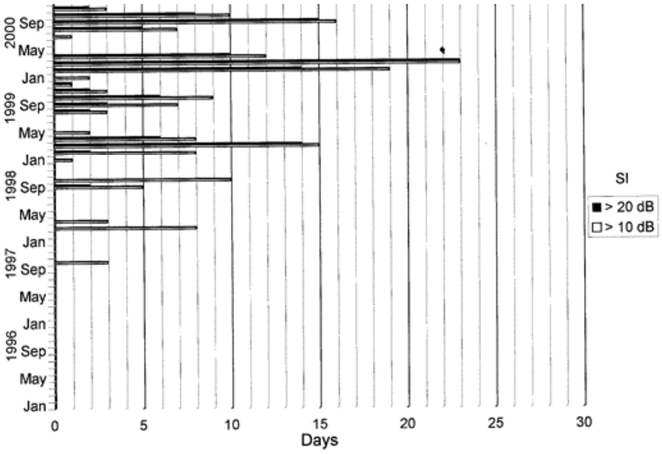


Fig. 3. No. of Days of Scintillation Occurrence for SI > 10 and 20 dB during 1996-2000.

Although the maximum hourly percentage occurrence of scintillations at L-band is in the range 35-40 (Fig. 1) during the sunspot maximum years, it is more or less a daily feature in the equinoctial months of high sunspot number years. For example, in March 2000, out of 31 nights, scintillations were observed on 23 nights (Fig. 3). The apparently small percentage occurrence is due to the fact that scintillations do not occur continuously but occurs in well-defined patches with clear gaps in between. In other words, the irregularities causing scintillations drift across the line of sight of the satellite in the form of clouds.

Figs. 4(a) and (b) show the monthly occurrence of scintillations for magnetically quiet (Kp = 0 - 3) and disturbed (Kp = 3+ - 9). It has also been found that, during the equinoctial months of August-October and February-April, occurrence of scintillations is less during magnetically active periods than during quiet periods except in April 2000. In the local summer months of May-July (for example: May 1998, May 1999, July 2000), occurrence of scintillations is more in the magnetically active period than during the quiet periods.

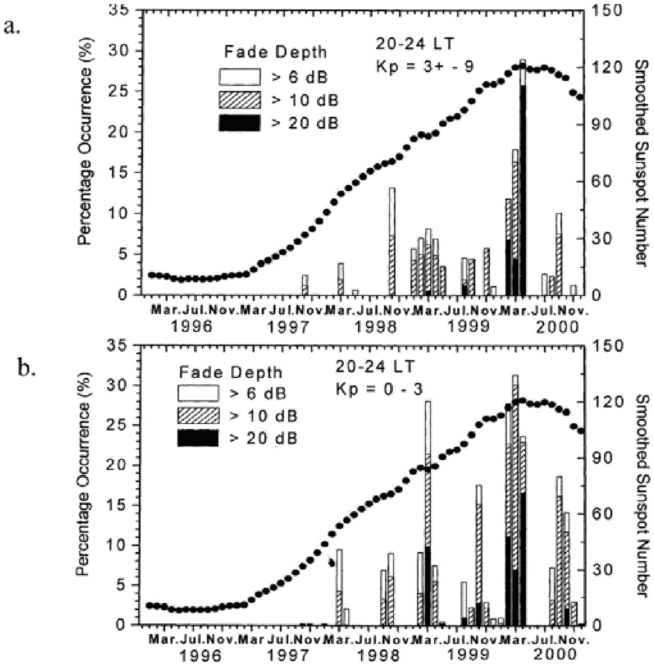


Fig. 4. Monthly Percentage Occurrence over 20-24 LT for Fade Depth > 6, 10 and 20 dB with smoothed sunspot numbers for the rising solar epoch 1996-2000 for a) Magnetically Active Period Kp = 3+ - 9 and b) Magnetically Quiet Period Kp = 0 - 3.

The L-band scintillation occurrence at Calcutta during the solar epoch 1996-2000 is compared with L-band scintillation occurrence distribution in the same local time interval and magnetic activity conditions but for a different solar epoch 1986-1989 observed at Ascension Island (7.4^{o}S, 14.4^{o}W geographic; 17^{o}S dip latitude) (Fig. 5) situated near the southern anomaly crest in the American-Atlantic longitude sector (Basu et al., 2002). The occurrence statistics more or less follows the same pattern as that observed from Calcutta. It has also been found that occurrence of scintillations at

Ascension Island is less during magnetically active periods than during quiet periods.

To examine the nature of scintillation occurrence during magnetically active periods, the 17 intense geomagnetic storms with sudden commencement that occurred during the period of observation 1996-2000 have been selected. Table I shows the seasonal distribution of 17 intense geomagnetic storms observed during 1996-2000 and the presence/absence of scintillations during these storms. Scintillations were recorded in 4 out of 17 storms (23.53%) and absent in 13 (76.47%). It is observed that during the equinoctial months of February-April and August-October, out of a total of 10 storms, 9 (90%) did not show any scintillation activity. In the local summer months of May-July, 50% of the storms showed scintillation activity while for the local winter months of November-January scintillations were present in 66.67% storms.

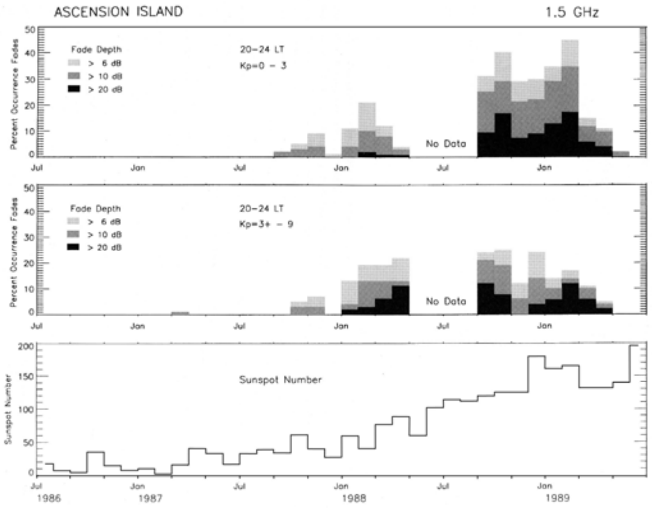
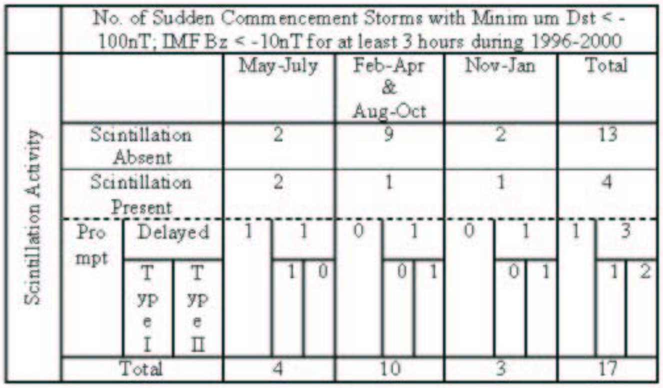


Fig. 5. Variation of occurrence of 1.5GHz scintillation with sunspot number observed at Ascension Island, near the crest of the equatorial anomaly, during pre-midnight period (From Basu et al., 2002).

Table 1. Distribution of Scintillation Activity with Magnetic Storms



	No. of Sudden Commencement Storms with Minimum Dst < -100nT; IMF Bz < -10nT for at least 3 hours during 1996-2000				
		May-July	Feb-Apr & Aug-Oct	Nov-Jan	Total
Scintillation Activity	Scintillation Absent	2	9	2	13
	Scintillation Present	2	1	1	4
	Prompt	1	0	0	1
	Delayed	1	1	1	3
	Delayed Type I	1	0	0	1
	Delayed Type II	0	1	1	2
Total		4	10	3	17

In the present study, the delay of scintillation onset from the time of occurrence of maximum AE, maximum negative dDst/dt and minimum Dst respectively have been calculated. The response is said to be "prompt" when the offset in time from AE maximum and dDst/dt maximum is ~3hours or less and it is "delayed" when this time difference is greater than 3 hours. The delayed response has been classified as Type I and II. For the Type I delay, the difference in time is greater than 3 hours but less than 12 hours and for the Type II delay it is more than 12 hours but less than 30 hours. The scintillation response of storms under study has been classified into Prompt, Delayed Type I and Delayed Type II as shown in Table I.

4. Summary and discussions

The confinement of the occurrence of L-band scintillations to pre-midnight hours and extension of VHF scintillations to post-midnight hours has been explained by DasGupta et al. (1982). L-band scintillations are effectively caused by irregularities of scale size of a few hundreds of meters and VHF scintillations by irregularities in the scale size range of one kilometer. During the initial phase of development in the post sunset hours, irregularities of different scale sizes coexist and scintillations in excess of 20dB are present in both L-band and VHF. In the later phase, during post-midnight hours, the overall strength of the irregularities is eroded, the smaller scale irregularities decaying earlier (Basu et al., 1978; Basu et al., 1980) and hence scintillations at 1.5GHz are practically absent after local midnight. The continuation of VHF scintillations beyond midnight is due to the longer lifetimes of the km-scale irregularities.

The season and solar activity dependences of equatorial scintillations can be explained in terms of the effect of variation of pre-reversal enhancement of the eastward electric field with season and solar activity. Fejer et al. (1979) have shown from incoherent scatter radar measurements of *F* region vertical drift at Jicamarca Observatory, Peru that during solar maximum years, the evening pre-reversal enhancement is observed throughout the year but its amplitude is smallest from May to August. For solar minimum years, the amplitude of pre-reversal enhancement is much less compared to the solar maximum years. Also during low solar activity years, the height of the *F* region decreases resulting in sparse scintillation occurrence.

In the present paper, the response of scintillations observed at Calcutta during seventeen intense (Gonzalez et al., 1994) storms with sudden commencement during 1996-2000 has also been studied. An examination of Table I show that the probability of scintillation occurrence is enhanced on disturbed days in the May-July months and may be attributed to the storm time disturbed electric field and plasma drifts leading to the development of equatorial irregularities. Scintillations were observed on two occasions out of four magnetic disturbance cases studied in this season of generally scarce scintillation activity. Mullen's (1973) observations may also be seen in conformity with the present inferences. During the equinoctial months of August-October and February-April, when scintillations are normally more frequent, the generation of equatorial irregularities is in general suppressed by magnetic disturbance. Of the ten storms analyzed, on nine occasions no scintillations were recorded.

The magnetospheric dynamo converts the solar wind energy into electromagnetic energy in the magnetosphere through reconnection process between the solar wind and the Earth's magnetic field. This reconnection is favored when the direction of the Interplanetary Magnetic Field (IMF) is southward and is opposed when the direction of the IMF is northward. The magnetosphere intercepts the solar wind voltage and this magnetospheric potential is impressed upon the ionosphere as high latitude polar cap potential (Φ_{pc}) that generates field aligned region 1 currents (higher latitude current systems in the auroral region). Prompt penetration of electric field is caused by rapid changes in Φ_{pc} that produce sudden region 1 current variations. Region 2 currents (the lower latitude current system in the auroral zone) cannot change at the same rate and there is an "undershielding" condition whereby the high latitude electric field can penetrate to much lower latitudes (Kikuchi et al., 2000). Magnetospheric dynamo process generates short-term ("prompt") electric field perturbations with time scales ~2hours or less (Jaggi and Wolf, 1973; Senior and Blanc, 1984). The penetration electric fields are eastward during the day and westward at night (Nopper and Carovillano, 1978) producing equatorial perturbation plasma drifts, which are upward during the day and downward at night. The drift pattern is in good agreement with the Rice Convection Model (RCM) (Spiro et al., 1988; Fejer et al., 1990) and other global convection models (Senior and Blanc, 1984).

A few hours after the onset of geomagnetic activity, when Φ_{pc} suddenly decreases, region 2 currents remain large and electric field of opposite polarity can propagate to lower latitude. This "overshielding" condition drives in low latitude westward electric field during the day and eastward fields at night, which result in upward drifts at night and downward during the day. Theory suggests that the disturbance drifts result from the dynamo action of storm time winds driven by enhanced energy deposition into the high latitude ionosphere during geomagnetically active periods. The effect is thus delayed and longer lasting (Blanc and Richmond, 1980).

Scherliess and Fejer (1997) showed that there is also a long-term disturbance dynamo component with time delays of about 20-30 hour, which generates relatively large upward perturbations at night and small downward drifts during the day. These long term disturbance dynamo drifts maximize during geomagnetically quiet times preceded by strongly disturbed conditions, and are probably due to disturbance electric fields resulting from storm-induced composition changes, which alter the magnetic field line integrated conductivities.

The prompt penetration of high latitude electric field to the equatorial locations in an "undershielding" environment occurs within three hours of dDst/dt maximum or AE maximum and much enhanced eastward electric field develops in the equatorial region during the post-sunset hours. Such electric fields form equatorial irregularities by plasma instability processes that cause scintillations of satellite radio signals. Since the present study is based on observations at a particular location, the UT corresponding to the prompt phase of the storm does not correspond to the post-sunset time but it may be detected at other favorable locations. During November – January, when occurrence of scintillations is not as high as in the equinoctial months, subsequent to magnetic storms, scintillations were observed on one occasion. A long-term analysis of this feature at other longitudes may establish if there is any longitudinal asymmetry in this response to magnetic disturbance from the global perspective.

This paper presents a study of equatorial scintillations particularly at L-band from geostationary satellites observed at Calcutta. Calcutta is located near the crest of the equatorial anomaly and severe scintillations at both VHF and L-band are frequently observed at this station in the post-sunset hours of equinoctial months of high sunspot number years, predominantly in magnetically quiet conditions. The essential difference between equatorial scintillations and scintillations at higher latitudes is that the latter is mainly controlled by transient phenomena of the Sun like the solar wind, the IMF components and geomagnetic storm while the former is primarily controlled by the Sun's 11-year cycle. Intense equatorial scintillations may disable satellite-based communication and navigation systems like GPS and SBAS for a considerable period of time resulting in position errors and loss of data. The study of the dependence of such worst-case scintillation events on local time, season, solar and magnetic activity is required in order to provide a complete characterization of equatorial scintillations observed from the crest of the equatorial anomaly.

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References

J. Aarons, "The role of ring current in the generation or inhibition of equatorial *F* layer irregularities during magnetic storms," *Radio Sci.,* vol. 26, pp. 1131-1149, 1991.

J. Aarons, H. E. Whitney, E. MacKenzie and S. Basu, "Microwave equatorial scintillation intensity during solar maximum," *Radio Sci.,* vol. 16, pp. 939-945, 1981.

J. Aarons, J. A. Klobuchar, H. E. Whitney, J. Austen, A. L. Johnson and C. L. Rino, "Gigahertz scintillations associated with equatorial patches," *Radio Sci.,* vol.18, pp. 421-434, 1983.

D. N. Anderson and G. Haerendel, "The motion of depleted plasma regions in the equatorial ionosphere," *J. Geophys. Res.,* vol. 84, pp. 4251-4256, 1979.

D. N. Anderson and J. A. Klobuchar, "Modeling the total electron content observations above Ascension Island", *J. Geophys. Res.,* vol. 88, pp. 8020-8024, 1983.

T. Bandyopadhyay, A. Guha, A. DasGupta, P. Banerjee and A. Bose, "Degradation of navigational accuracy with Global Positioning System during periods of scintillation at equatorial latitudes," *Elect. Lett.,* vol. 33, pp. 1010-1011, 1997.

S. Basu, Su. Basu, J. Aarons, J. P. McClure and M. D. Cousins, “On the coexistence of kilometer- and meter-scale irregularities in the nighttime equatorial *F* region,” *J. Geophys. Res.*, vol. 83, pp. 4219-4226, 1978.

S. Basu, J. P. McClure, Su. Basu, W. B. Hanson and J. Aarons, “Coordinated study of equatorial scintillation and *in situ* and radar observations of nighttime *F* region irregularities,” *J. Geophys. Res.*, vol. 85, pp. 5119-5130, 1980.

S. Basu and Su. Basu, “Equatorial scintillations – a review,” *J. Atmos Terr. Phys.*, vol. 43, pp. 473-489, 1981.

S. Basu, E. MacKenzie and Su. Basu, “Ionospheric constraints on VHF/UHF communications links during solar maximum and minimum periods,” *Radio Sci.*, vol. 23, pp. 363-378, 1988.

S. Basu and Su. Basu, “Scintillation Technique for Probing Ionospheric Irregularities,” in *WITS Handbook*, vol. 2 ed. by C.H. Liu, pp. 128-136, SCOSTEP, Univ. of Ill., Urbana, 1989.

S. Basu, K. M.Groves, Su. Basu and P. J. Sultan, “Specification and forecasting of scintillations in communication/navigation links: current status and future plans,” *J. Atmos. Sol. Terr. Phys.*, vol. 64, pp. 1745-1754, 2002.

Su. Basu, S. Basu, J. P. Mullen and A. Bushby, “Long-term 1.5GHz amplitude scintillation measurements at the magnetic equator,” *Geophys. Res. Lett.*, vol. 7, pp. 259-262, 1980.

Su. Basu and S. Basu, “Equatorial scintillations: advances since ISEA-6,” *J. Atmos. Terr. Phys.*, vol. 47, pp. 753-768, 1985.

Su. Basu, S. Basu, C. E. Valladares, H.–C. Yeh, S.–Y. Su, E. MacKenzie, P. J. Sultan, J. Aarons, F. J. Rich, P. Doherty, K. M. Groves and T. W. Bullett, “Ionospheric effects of major magnetic storms during the International Space Weather Period of September and October 1999: GPS observations, VHF/UHF scintillations, and in situ density structures at middle and equatorial latitudes,” *J. Geophys. Res.*, vol. 106, pp. 30389-30414, 2001.

M. Blanc and A. D. Richmond, “The ionospheric disturbance dynamo,” *J. Geophys. Res.*, vol.85, pp. 1669-1686, 1980.

E. Costa and M.C. Kelley, “On the role of steepened structures and drift waves in equatorial spread F,” *J. Geophys. Res.*, vol. 83, pp. 4359-4364, 1978.

A. DasGupta, J. Aarons, J. A. Klobuchar, S. Basu and A. Bushby, “Ionospheric electron content depletions associated with amplitude scintillations in the equatorial region,” *Geophys. Res. Lett.*, vol. 9, pp. 147-150, 1982.

A. DasGupta, D. N. Anderson and J. A. Klobuchar, “Modeling of low latitude ionospheric total electron content,” *J. Atmos. Terr. Phys.*, vol. 47, pp. 917-925, 1985.

A. DasGupta, S. Ray, A. Paul, P. Banerjee and A. Bose, “Errors in position-fixing by GPS in an environment of strong equatorial scintillations in the Indian zone,” *Radio Sci.*, vol. 39, RS1S30, doi:10.1029/2002RS002822, 2004.

O. de La Beaujardiére, L. Jeong, B. Basu, S. Basu, T. Beach, P. Bernhardt, W. Burke, K. Groves, R. Heelis, R. Holzworth, C. Huang, D. Hunton, M. Kelley, R. Pfaff, J. Retterer, F. Rich, M. Starks, P. Straus and C. Valladares, “C/NOFS: a Mission to Forecast Scintillations,” *J. Atmos. Sol. Terr. Phys.*, vol. 66, pp. 1573-1591, 2003.

B. G. Fejer, “Low latitude electrodynamic plasma drifts: A review”, *J. Atmos. Sol. Terr. Phys.*, vol. 53, pp. 677-693, 1991.

B. G. Fejer, D. T. Farley, R. F. Woodman and C. Calderon, “Dependence of equatorial *F* region vertical drifts on season and solar cycle,” *J. Geophys. Res.*, vol. 84, pp. 5792-5796, 1979.

B. G. Fejer, R. A. Wolf, R. W. Spiro and J. C. Foster, “Latitudinal variation of perturbation electric fields during geomagnetically disturbed periods: 1986 SUNDIAL observations and model results,” *Ann. Geophysicae*, vol. 8, pp. 441-454, 1990.

K. M. Groves, S. Basu, E. J. Weber, M. Smitham, H. Kuenzler, C. E. Valladares, R. Sheehan, E. MacKenzie, J. A. Secan, P. Ning, W. J. McNeill, D. W. Moonan and M. J. Kendra, “Equatorial scintillation and systems support,” *Radio Sci.*, vol. 32, pp. 2047-2064, 1997.

W. D. Gonzalez, J. A. Joselyn, Y. Kamide, H. W. Kroehl, G. Rostoker, B. T. Tsurutani and V. M. Vasyliunas, “What is a geomagnetic storm?” *J. Geophys. Res.*, vol. 99, pp. 5771-5792, 1994.

G. Haerendel, “Theory of equatorial spread *F*,” report Max-Planck-Inst. fur Phys. Und Astrophys., Garching, Germany.

Y.-N., Huang, K. Cheng and S.–W. Chen, “On the equatorial anomaly of the ionospheric total electron content near the northern anomaly crest region,” *J. Geophys. Res.*, vol. 94, pp. 13515-13525, 1989.

R. Jaggi and R. Wolf, “Self-consistent calculation of the motion of a sheet of ions in the magnetosphere,” *J. Geophys. Res.*, vol. 78, pp. 2852-2866, 1973.

M. C. Kelly, D. Kotsikopoulos, T. Beach, D. Hysell and S. Musman, “Simultaneous Global Positioning System and radar observations of equatorial spread *F* at Kwajalein,” *J. Geophys. Res.*, vol. 101, pp. 2333-2341, 1996.

T. Kikuchi, H. Lühr, K. Schlegel, H. Tachihara, M. Shinohara and T.-I. Kitamura, “Penetration of auroral electric fields to the equator during a substorm,” *J. Geophys. Res.*, vol. 105, pp. 23251-23262, 2000.

R. C. Livingston, “Comparison of multifrequency equatorial scintillation: American and Pacific sectors,” *Radio Sci.*, vol. 15, pp. 801-814, 1980.

J. P. Mullen, “Sensitivity of equatorial scintillation to magnetic activity,” *J. Atmos. Terr. Phys.*, vol. 35, pp. 1187-1194, 1973.

R. W. Nopper and R. L. Carovillano, “Polar-equatorial coupling during magnetically active periods,” *J. Geophys. Res.*, vol. 83, pp. 699-702, 1978.

L. Scherliess and B. G. Fejer, “Storm time dependence of equatorial disturbance dynamo zonal electric fields,” *J. Geophys. Res.*, vol. 102, pp. 24037-24046, 1997.

J. A. Secan, R. M. Bussey, E. J. Fremouw and S. Basu, “An improved model of equatorial scintillation,” *Radio Sci.*, vol. 30, pp. 607-617, 1995.

J. A. Secan, R. M. Bussey, E. J. Fremouw and S. Basu, “High latitude upgrade to the Wideband ionospheric scintillation model,” *Radio Sci.*, vol. 32, pp. 1567-1574, 1997.

C. Senior and M. Blanc, “On the control of magnetospheric convection by the spatial distribution of ionospheric conductivities,” *J. Geophys. Res.*, vol. 89, pp. 231-234, 1984.

R. W. Spiro, R. A. Wolf and B. G. Fejer, “Penetration of high-latitude electric field effects to low latitudes during SUNDIAL 1984,” *Ann. Geophysicae*, vol. 6, p. 39, 1988.

H. E. Whitney, J. Aarons and C. Malik, “A proposed index for measuring ionospheric scintillations,” *Planet. Space Sci.*, vol. 17, pp. 1069-1073, 1969.

R. F. Woodman and C. La Hoz, “Radar observations of *F* region equatorial irregularities,” *J. Geophys. Res.*, vol. 81, pp. 5447-5466, 1976.