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ORIGINAL STUDY

Ionospheric irregularities at low latitude using VHF scintillations during extreme low solar activity period (2008–2010)

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Abstract In the present study, we have used 250 MHz radio signal radiated by geostationary satellite UFO-02 to study the occurrence characteristics of very high frequency scintillations associated with ionospheric irregularities during recent extreme low solar activity period from 2008 to 2010 at low latitude Indian station Varanasi (Geomag. latitude = 14°55′N, long. = 154°E, Dip angle = 37.3°, Sub-ionospheric dip = 34°). The impact of this recent extreme low solar activity period on ionosphere is investigated. It is observed that the scintillation occurrence is low having maximum percentage occurrence during pre-midnight periods. With increasing interest in understanding the behavior of ionospheric irregularities, an effort has been made to examine also the influence of solar and magnetic activity over the occurrence of scintillations. During the extreme low solar activity years the scintillation occurrences do not vary linearly with the sunspot number. The inhibition and generation of irregularities during enhanced magnetic activity period are explained by considering changes in the electric field. The spectral analysis provide spectral index for irregularities which varied between −1.5 and −8 and characteristic length of irregularities varied between 400 and 1200 m which confirms that 250 MHz scintillations observed over Varanasi were associated with intermediate scale irregularities.

Keywords Ionospheric irregularities · VHF scintillation · Wave propagation · Low solar activity

1 Introduction

Recent solar minimum between solar cycles 23 and 24 was unique amongst last several solar minima for two reasons: firstly the solar activity during this period was quietest during last 60 years and secondly, it prolonged for much more time than that of other solar

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minimum period. The impact of this extreme low solar activity period on Earth's environment especially on ionosphere is very interesting to be investigated. Ionospheric scintillation is a peculiar phenomenon that relates to fluctuations in the phase and amplitude of the radio signals from the satellites when they cross regions of electron density irregularities in the ionosphere (Kintner et al. 2001). The study of ionospheric scintillations is one of the important components of the space weather activities, because their observations have been used to identify and diagnose irregular structures in highly varied propagation medium and leads to contributions in ionospheric and magnetospheric physics (Abdu et al. 2003; Pedatella et al. 2009). The radio waves propagating through ionospheric irregularities experience scattering and diffraction, causing random fluctuations in amplitude and phase of the signal, known as amplitude and phase scintillations respectively (Aarons et al. 1980). The amplitude fluctuations may lead to data loss and cycle slips in Global Positioning System (GPS) and sudden phase changes may cause a loss of phase lock in GPS receivers (Basu et al. 1996). Hence, in order to provide support to operational communication/navigation systems, the magnitudes of amplitude and phase scintillations and the temporal structures of scintillations need to be specified.

The formation and dynamics of the plasma irregularities have been studied by many scientists (e.g., McClure et al. 1977; Aarons et al. 1980; Tsunoda et al. 1982; Basu et al. 1983; Chen et al. 1983; Singh et al. 2004, 2006) and it was concluded that after sunset these irregularities regions develop from the bottom side of the ionosphere probably due to Rayleigh–Taylor instabilities. Once these irregularities are triggered, they will cause a plasma depletion or depleted plasma bubble which rises into regions above the peak of F-layer extending to well over 1000 km in altitude (Huang 1970). These bubbles then move along the geomagnetic field lines to anomaly locations of 15°N and 15°S magnetic latitudes (Groves et al. 1997). The night-time scintillations are mainly attributed to spread-F, whereas daytime scintillations are linked to E-region irregularities (Anastassiadis et al. 1970; DasGupta and Kersley 1976; Rastogi and Iyer 1976; Basu et al. 1977; Ogawa et al. 1989; Hajkowicz and Minakoshi 2003; Patel et al. 2009).

The combined effects of gravity, eastward electric fields, and vertically downward neutral wind in association with vertically upward density gradient makes the plasma in the ionosphere unstable and generates density fluctuations over a wide range of scale sizes starting from a few centimetres to a few tens of kilometres (Haerendel 1974; Kelley 1989; Basu 1998). A single instability mechanism cannot account for such a wide range of scale sizes (Fejer and Kelley 1980). The generalized Rayleigh–Taylor instability (which includes cross field instability, neutral wind effects and various drift mode instabilities) can generate irregularities with longer as well as shorter wave lengths (Krishna Murthy 1993). Irregularities are broadly termed as large scale (>10 km), intermediate scale (10–0.1 km), transitional scale (100–10 m) and small scale (<10 m) (Kelley 1985).

The electric field at the site plays a dominant role in shaping the development of these irregularities. Any change in the electric field influences the occurrence of low-latitude scintillations (Fejer 1991, 1997). The influences of solar and magnetic activity over the occurrence of scintillation associated with ionospheric irregularities have been reported by many worker (Aarons et al. 1980; Rastogi et al. 1981; DasGupta et al. 1985; Dabas et al. 1989; Pathak et al. 1995; Chakraborty et al. 1999; Kumar and Gwal 2000; Banola et al. 2001; Basu et al. 2001a, b; Bhattacharya et al. 2002; Singh et al. 2004). Most of the studies are during solar active periods and study during extremely low solar activity period are lacking. The solar minimum between solar cycles 23 and 24 was unique because the solar activity during this period was quietest during last 60 years and it also prolonged for much more. The impact of this extreme low solar activity period on terrestrial environment especially on ionosphere is very interesting to be investigated. Hence, it is necessary to understand the occurrence of scintillations during this extremely low solar activity period.

The detailed study of the occurrence characteristics of very high frequency (VHF) scintillations associated with ionospheric irregularities during recent extremely low solar

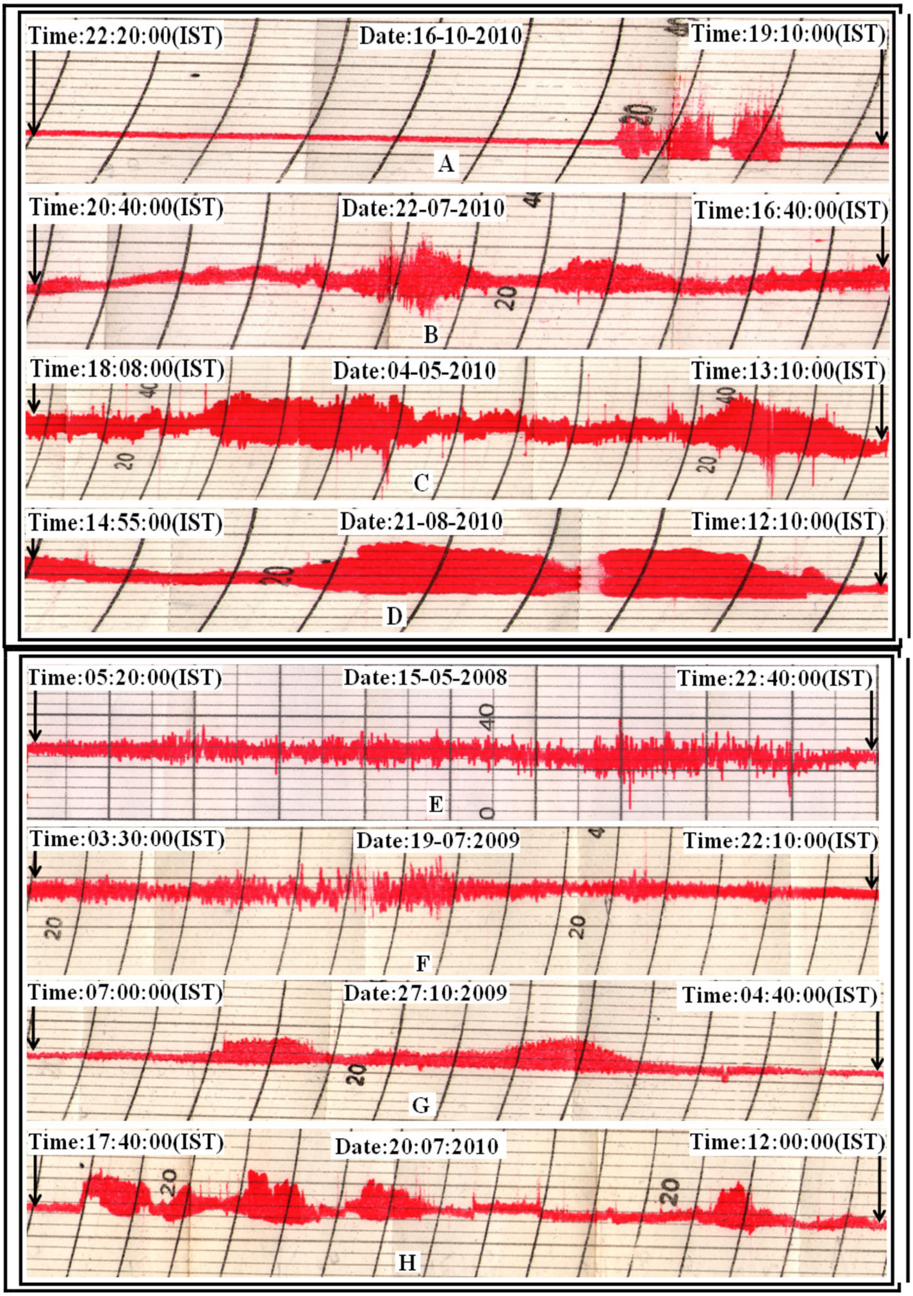

Fig. 1 Typical examples of different types of scintillations observed at Varanasi during 2008–2010

activity period of 3 years of 2008 (Rz = 2.9), 2009 (Rz = 3.1) and 2010 (Rz = 16.5) at our low latitude Indian station Varanasi (Geomag. latitude = 14°55′N, long. = 154°E, Dip angle = 37.3°, Sub-ionospheric dip = 34°) have been presented. The diurnal, monthly, seasonal, and annual occurrences of scintillations as well as effect of solar and geomagnetic activity on occurrence of scintillations have been carried out.

2 Data analysis

The experimental set up of receiving system installed at Banaras Hindu University, Varanasi consisted of an eleven element Yagi-Uda antenna, a super–heterodyne fixed frequency VHF receiver, 'Akash' and a signal channel strip chart recorder. The amplitude scintillations of the 250 MHz signal radiated from the geostationary satellite UFO-02 situated at 72°E longitude were continuously monitored at Varanasi (Singh et al. 2004). The receiver was calibrated using the method described by Basu and Basu (1989). The dynamic range of the receiver was about 20 dB. Most of our scintillation data were recorded on a strip chart which is calibrated as 1 cm equal to 2.54 dB (Singh et al. 2010). In addition to the normal chart recorder, data were also recorded digitally, at the sampling rate of 10 Hz, on a few nights. The amplitude fluctuations having peak to peak variations greater than 1 dB were included in the present analysis using the day and night time data. The scintillation index in dB has been scaled manually every 15 min by measuring peak-to-peak $P_{max} - P_{min}$ excursion in dB and using a calibration chart and a conversion chart (Whitney et al. 1969), where P_{max} is the power amplitude of the third peak down from the maximum excursion and P_{min} is the power amplitude of the third level up from the minimum excursion. The scintillation data are tabulated for each 15 min, to count the number of events per hour and hence to evaluate the occurrence rate. The percentage occurrence of scintillations has been calculated after dividing the number of the occurrence of scintillation data by total number of days of scintillation recorded and then multiplying by 100.

Some typical examples of different types of scintillations recorded on different dates and times at Varanasi during 2008–2010 are shown in the Fig. 1. At Varanasi VHF scintillation are predominantly produced after sunsets during evening and nighttimes (Singh et al. 2004). Figure 1 shows the events of different types of scintillations recorded (A) on 16-10-2010 having two small intense scintillation patches observed during 19:35–19:45 IST and 19:50–20:10 IST, (B) on 22-07-2010 having intense scintillation patches observed during 17:40–18:15 and 18:40–19:07 IST, (C) on 04-05-2010 having patches observed during 13:20–14:15 IST and 15:50–17:10 IST, (D) on 21-08-2010 having strong scintillation patches observed during 12:30–13:10 IST and 13:15–14:10 IST, (E) on 15-05-2008 having weak scintillation patches observed during 22:50–05:20 IST, (F) on 19-07-2009 having weak scintillation patches observed during 22:50–03:30 IST, (G) on 27-10-2009 having two scintillation patches during 05:15–05:50 IST and 06:10–06:30 IST and (H) on 20-07-2010 having patches observed during 12:50–13:14 IST. The scintillation index of the recorded different amplitude fluctuations varies between 1.27 and 5.08 dB. The scintillation index of the different scintillation patches of Fig. 1a is 2.54 dB, b is 3.55 and 2.03 dB, c is 4.57 and 5.08 dB, d is 3.55 and 3.04 dB, e is 1.52 dB, f is 1.54 dB, g is 1.27 and 1.42 dB, and h is 1.52 and 2.03 dB.

The seasonal variation of percentage occurrence of scintillation has been grouped in summer, equinox and winter months. The detailed analysis of occurrence characteristics of scintillations at Varanasi is explained in Sect. 3. The power spectral analysis and auto-correlation analysis of associated ionospheric irregularities are also presented.

3 Results and discussions

The diurnal, monthly, seasonal, and annual occurrence characteristics of scintillations as well as effect of solar and geomagnetic activity on occurrence of scintillations observed at low latitude station Varanasi during the lowest solar active period from 2008 to 2010 have been carried out.

3.1 Diurnal and annual variation

At Varanasi scintillations occur in small patches (Singh and Singh 1997). The duration of patches represents the East–West dimensions of the moving irregularity (Mathew et al. 1992). The mean value of patch duration at Varanasi is 30 min which is in good agreement with that of Rajkot (Mathew et al. 1992). The diurnal variation of percentage occurrence of scintillations during the period of 3 years from 2008 to 2010 is shown in the Fig. 2a. It is observed from Fig. 2a, that in general during 2008 and 2010, the scintillation occurrence is low having maximum percentage occurrence between 21:00 and 23:00 h IST during pre-midnight periods. The scintillation occurrence rate is comparatively high during the year 2008 in respect to 2009 and 2010. The peak occurrences are 11 % during 2008, 5 % during 2009 and 4 % during 2010. To compare the present results of extremely low solar activity

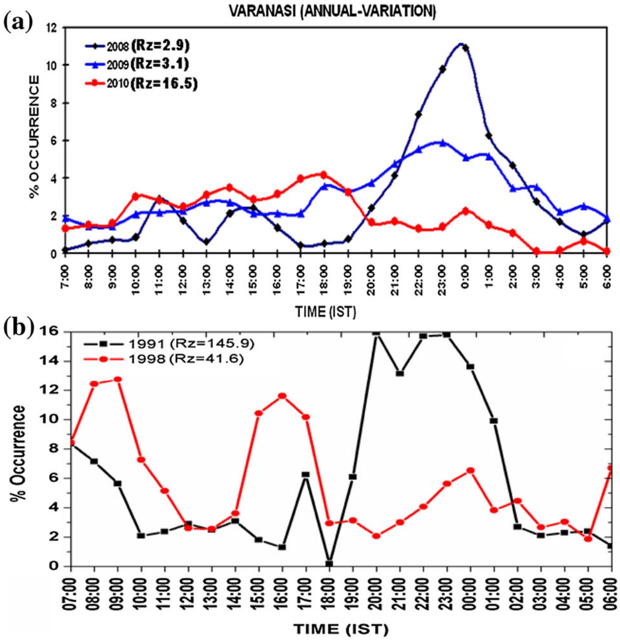

Fig. 2 Scintillation occurrence rate during **a** 2008–2010, and **b** 1991 and 1998 at low latitude station, Varanasi

periods with that of high solar activity period, we have analyzed the occurrence characteristics of VHF scintillations observed at Varanasi during complete year of a high solar activity period of 1991 (Rz = 145.9) which is shown in Fig. 2b. It is observed that the

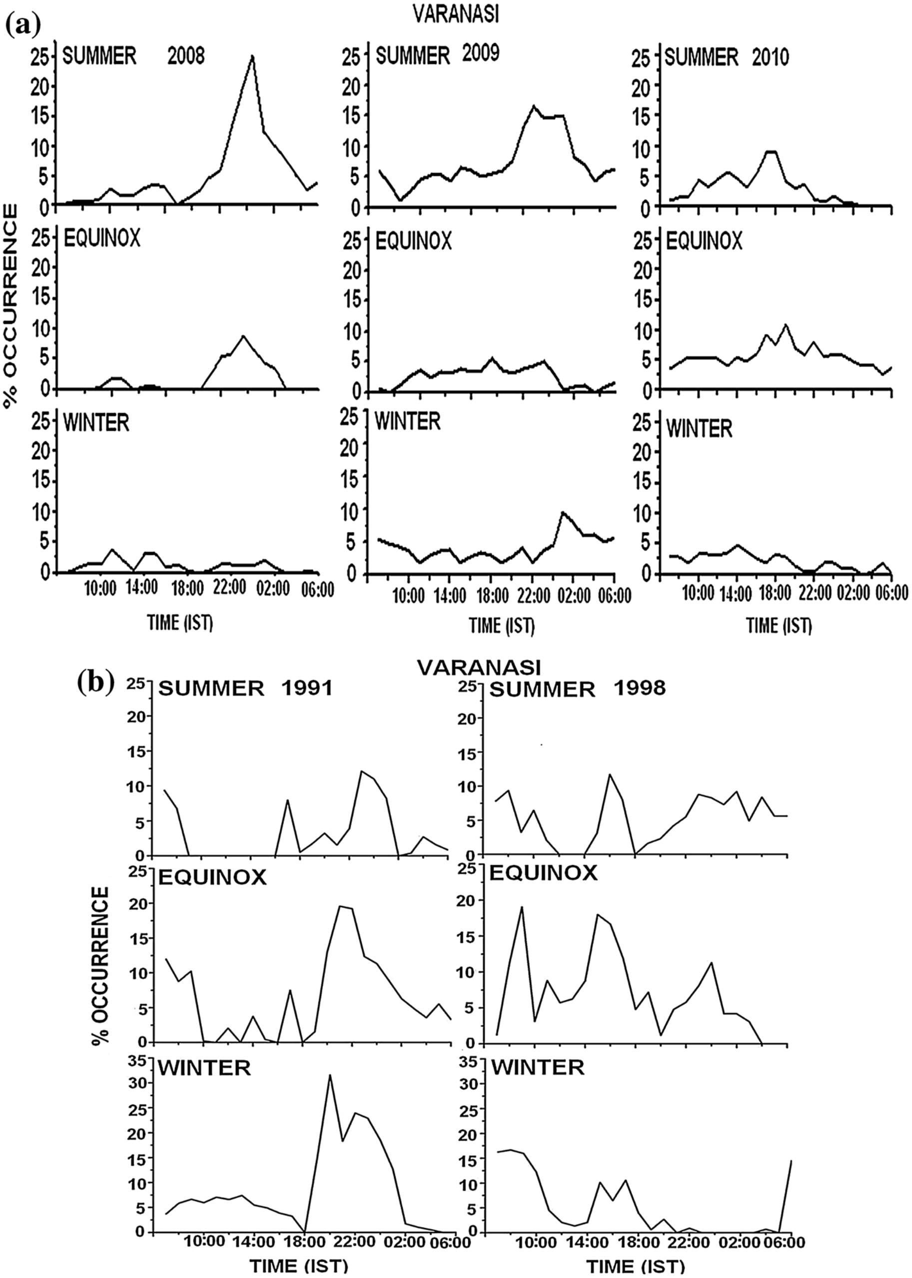

Fig. 3 Seasonal occurrence of scintillations during **a** 2008–2010 and **b** 1991 and 1998 at low latitude station, Varanasi

scintillation occurrence rate is comparatively high during the year 1991 having peak occurrence of 16 %. To compare our present results of extremely low solar activity periods with that of previous low solar activity period, we have analyzed the occurrence characteristics of VHF scintillations observed at Varanasi during complete year of a low solar activity period of 1998 (Rz = 41.6) which is also shown in Fig. 2b. It is observed that the scintillation occurrence rate is comparatively high during the year 1998 having peak occurrence of 12.8 % mainly during daytime.

Chandra et al. (1993) have analyzed scintillation data recorded at a chain of stations covering the whole of India and have shown that the scintillations become patchy and patch duration decreases as one move away from the equator. The relatively intense and faster fade rates observed before midnight at Varanasi could be of equatorial origin during winter and equinox seasons (Pathan et al. 1992; Kumar and Gwal 2000). Comparatively weak, slow and short duration scintillations seen during summer could have a local/mid latitude/equatorial origin (DasGupta et al. 1981; Chakraborty et al. 1999).

3.2 Seasonal variation

Seasonal variations of percentage occurrences of scintillations for three different seasons of summer, winter and equinox during the years 2008–2010 are presented in Fig. 3a. The percentage occurrence of scintillations is high in equinox and summer and low in the winter. During summer and equinox seasons the occurrence of scintillation events increases after one or two hours of local sunset time and attain a maximum percentage occurrences around mid-nighttime and then decreases from mid-nighttime to post-midnight time. Whereas in winter season the percentage occurrence of scintillation is comparatively low having maximum occurrence during daytime. To compare the present seasonal variations with that of a high solar activity period and a previous low solar activity period, we have analyzed the seasonal occurrence characteristics of VHF scintillations observed at Varanasi during a high solar activity period of 1991 (Rz = 145.9) and a low solar activity period of 1998 (Rz = 41.6) which is shown in Fig. 3b. It is observed that the scintillation occurrence rate is comparatively high during winter and equinox seasons but low during summer season during 1991 whereas scintillation occurrence rate is slightly large during 1998 mainly in daytime.

It is well recognized that the nighttime VHF scintillations are primarily produced due to presence of ionospheric F-region plasma density irregularities and daytime scintillations due to E-region irregularities (Rastogi and Iyer 1976; Hajkowicz and Minakoshi 2003; Patel et al. 2009). For identifications of various possible causes, origin and precursors for the onset time of VHF ionospheric scintillations occurrence, extensive experimental, modeling as well as theoretical work has been carried out in the recent past over equator and away from equator for understanding basic causes and precursors of VHF scintillations events with association of equatorial spread-F (ESF) phenomena (Rastogi and Woodman 1978; Rama Rao et al. 2004). Further a remarkable couplings in variations of VHF scintillation activity with maximum values of F-region electron density (NmF2) (Whalen 2009) and equatorial electrojet strength (EEJS) (Dabas, et al. 2003) have been observed. Several investigators have also demonstrated the association of scintillations events with the diurnal/seasonal behaviors of vertical drift velocity and with range spread-F before midnight and with frequency spread-F after midnight hours (Sreeja et al. 2009; Tulasi Ram et al. 2006).

3.3 Effect of solar activity

To study the effect of solar activity on occurrence of scintillations, the monthly variation of percentage occurrence of scintillations with mean sunspot numbers during the years 2008 (Rz = 2.9), 2009 (Rz = 3.1) and 2010 (Rz = 16.5) are shown in Fig. 4. The solar activity dependence is not clearly evident from the figure because these years are extreme lowest sunspot minimum years of several decades. The figure shows the maximum percentage occurrence in the equinox and winter months of each year in comparison to summer months. The solar activity effects reported here are not consistent with previous results reported from studies at anomaly crest stations (Pathak et al. 1995; Kumar and Gwal 2000; Singh et al. 2004) because the sunspot number variation is too low to show any effect. This may be due to extreme lowest solar activity years of our study period.

The equatorial plasma bubbles are incapable to rise over the magnetic equator above 800 km that diffuse downward along the geomagnetic field and scattered away from the equator and also not make the signature of scintillations activity over the edge of equatorial Appleton region during low solar activity periods due to the low occurrences and persistence of ESF, reduction of F-region height and vertical drift along with low ambient electron density in low solar activity period (Kumar and Gwal 2000; Dabas et al. 2003).

3.4 Effect of geomagnetic activity

To study the effect of geomagnetic activity on occurrence of scintillations we have chosen five most quiet days and five most disturb magnetic days from each month. The diurnal variations of percentage occurrence of scintillation during geomagnetic quiet and disturbed days during the years from 2008 to 2010 are shown in Fig. 5. The figure shows that in general the scintillation occurrence rate is high during quiet days in respect to disturbed days during the whole period from 2008 to 2010 except during daytime in 2010. This shows that in general the geomagnetic activity suppresses the occurrence scintillation.

The effects of geomagnetic disturbances on equatorial as well as low latitude ionospheric scintillations have been reported by several workers (Aarons et al. 1980; Rastogi et al. 1981; Vyas and Ayanandan 2011; Singh et al. 2010) who explained that with increase

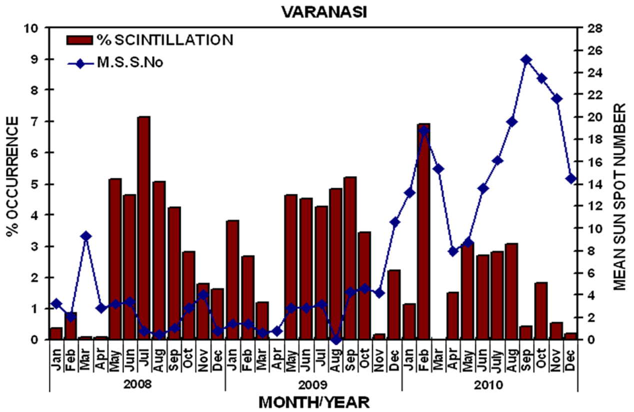

Fig. 4 Variation of scintillation occurrence with the mean sunspot number during 2008–2010 at low latitude station, Varanasi

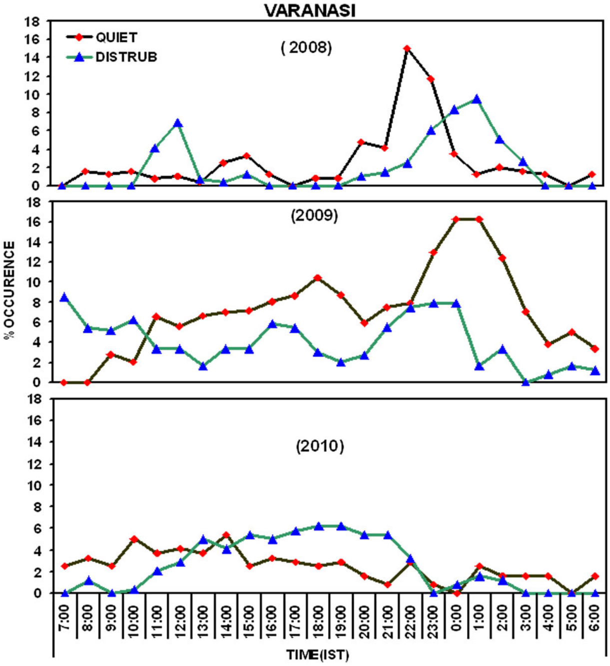

Fig. 5 Diurnal variation of scintillation occurrence during geomagnetic quiet and disturbed days for period of 2008–2010 at low latitude station, Varanasi

in the magnetic activity, the probability of occurrence of scintillation increases during the post-midnight periods in all longitude sectors, while the pre-midnight phenomenon depends on the season as well as on longitude. By comparing the percentage occurrence of scintillations during quiet and disturbed days, Rama Rao et al. (1996, 1997) and Prasad et al. (2004, 2012) have reported that the occurrence of nighttime scintillation is inhibited during disturbed days of higher solar activity period. Kumar et al. (1993) and Kumar and Gwal (2000) studied the effects of geomagnetic disturbances on scintillations at low latitudes and reported that the geomagnetic disturbances suppresses the scintillations throughout the night at Bhopal (23.2N, 77.6E), but at Varanasi (25.3N, 83E) the scintillations were inhibited in pre-midnight period and enhanced in the post-midnight period. Mathew et al. (1991) also studied the geomagnetic effect on the scintillation occurrence at equatorial and anomaly crest stations and reported that, there is a considerable suppression of scintillation activity in any season on disturbed days. The inhibition and enhancement of the irregularities during geomagnetic disturbances can be attributed to changes in ring current (Aarons 1991). During the pre-sunset period, the eastward electric field is increased, causing an increase in F-layer height (Fejer et al. 1999). Thus geomagnetic storm processes would lower the local eastward electric field and reduce the F-layer height. This effect may sometimes be large enough to reverse the upward movement of F-layer during the post-sunset period, thereby inhibiting the creation of irregularities. This may result in a suppression of pre-midnight scintillations over most longitudes during periods of intense magnetic activity.

3.5 Effect of geomagnetic storm

The geomagnetic storm is a temporary disturbance of the Earth's magnetosphere and caused by a solar wind shock wave and cloud of magnetic field which interacts with the Earth's magnetic field. During these disturbances ionosphere shows a variety of effects which may depend on season, geographic latitude, local time and the time of onset of the storm (Pedatella et al. 2009). These storms introduce dynamical and electro-dynamical changes in the ionosphere. The effect of geomagnetic storms on the occurrence of VHF scintillations have been observed by many scientists (Prasad et al. 2005; Singh et al. 2004) and their statistical results are explained relating to the average behavior of storm phenomena in the short term (transients) and long term (recurrent) effects during individual storm events (Abdu et al. 1995). These effects are known to differ from one storm to the other. Dynamic effects that can influence the ionosphere during geomagnetic disturbances to the upward or downward motion of the ionization caused, either by electric fields or neutral winds and field-aligned flow of ions between the ionosphere and magnetosphere (Fejer 1997).

Different phases of geomagnetic storms affect the generation and development of ionospheric irregularities differently. The Dst-index, which is a measure of the ring current is used to understand the effect on scintillations. The available theories which model the effect of ring currents on the generation of equatorial F-region irregularities depend on the timing of the maximum negative Dst excursion vis-a-vis local time (DasGupta et al. 1985; Aarons 1991; Basu et al. 2001a, b). In the present work storms for which Dst goes below −50 nT have been selected for study. A total of 12 moderate geomagnetic storms were seen during the observation period for which scintillations were recorded. The details of these 12 geomagnetic storms, their longevity and peak Dst-index along with the occurrence

Table 1 Details of geomagnetic storms and occurrence of scintillation during 2008–2010

S. no.	Storm day	Magnitude of storm (nT)	Longevity (h)	Occurrence of scintillations		
				Pre day	Occurrence day	Post day
1	28 February 2008	−52	230	No	No	No
2	9 March 2008	−86	261	No	No	No
3	27 March 2008	−56	138	No	No	No
4	11 October 2008	−54	155	No	No	No
5	22 July 2009	−83	200	Yes	No	No
6	15 February 2010	−58	81	No	No	No
7	6 April 2010	−73	138	No	No	No
8	12 April 2010	−51	25	No	Yes	No
9	2 May 2010	−66	201	Yes	No	Yes
10	29 May 2010	−85	209	No	No	Yes
11	4 August 2010	−67	123	No	No	No
12	11 October 2010	−80	64	Yes	Yes	No

of scintillations for next 3 days at Varanasi is shown in Table 1. Out of these 12 events scintillations were observed only in the case of five events. In the remaining seven storms no scintillations were observed. Thus no clear effect of moderate strength storms is seen on the occurrence of VHF scintillations over Varanasi.

3.6 Spectral analysis of ionospheric irregularities

For the spectral analysis of the amplitude scintillation index the auto-correlation function and power spectra are computed that gives the information about the relative power of irregularities in different temporal scales (Singh et al. 2004). Its significance is that, its measurements lies in the quantitative estimate of the fluctuations in the electron density where one needs the information of the power law index describing the irregularities.

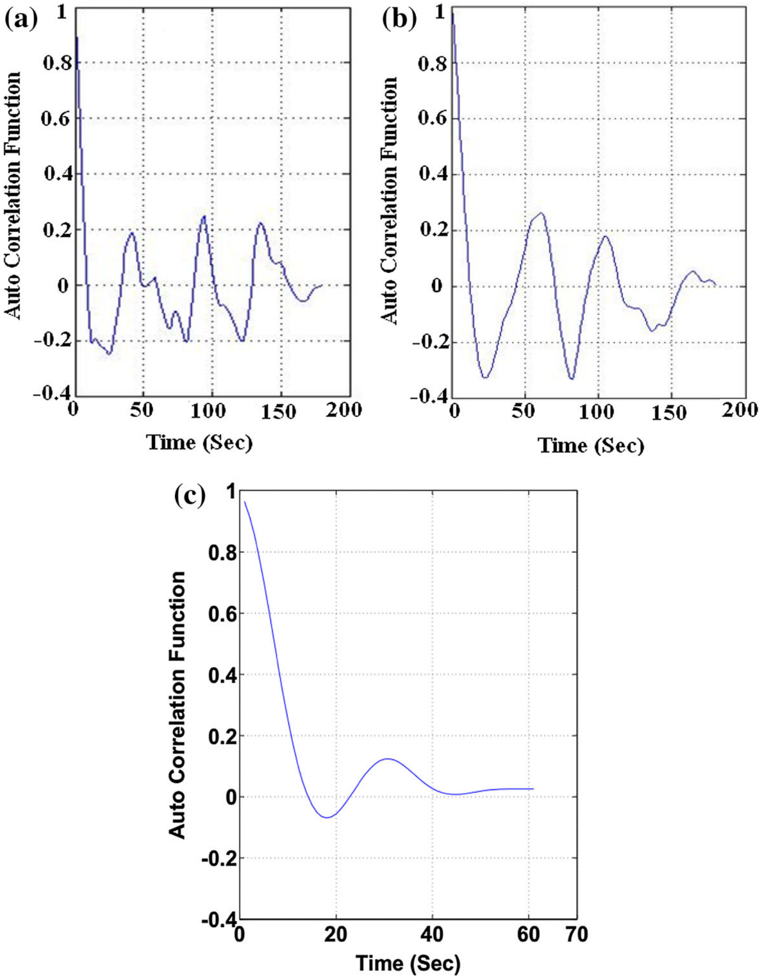

Fig. 6 Typical examples of auto-correlation function of VHF scintillations observed at Varanasi on **a** 21-07-2008, **b** 23-02-2008 and **c** 21-12-1992

3.6.1 Auto-correlation analysis

The auto-correlation function tells us about the correlation of the amplitude of scintillation within the same signal. This can be computed as (Muhtarov and Kutiev 1999)

$$\Gamma_k = \frac{\sum_{t=k+1}^{T} \{(X_t - \bar{X})(X_{t-k} - \bar{X})\}}{\sum_{t=1}^{T} (X_t - \bar{X})^2} \tag{1}$$

where X_t is the amplitude of the particular time and $\bar{X}$ is the average of the given data.

This function depicts the shape and scale size of the ionospheres irregularity. Typical examples of auto-correlation functions of VHF scintillations observed at Varanasi on (a) 21-07-2008 and (b) 23-02-2008 are shown in Fig. 6. From this the characteristic length of the irregularity can be determined according to its definition; the characteristic length of the irregularity is equal to the distance at which the auto-correlation function falls to 0.5 when the irregularity is moving with a known drift velocity (Khastgir and Singh 1960; Singh et al. 2006). The time at which the auto-correlation function falls to 0.5 is called as half-decorrelation time. From the figure, the half-decorrelation time is 6.67 and 9.7 s respectively. To determine the characteristic length of the irregularities at Varanasi, the average drift velocity is considered as 100 m/s (Singh et al. 2006). The product of the drift velocity and the half-decorrelation time gives the characteristic length of the corresponding irregularities as 667 and 970 m respectively. We have computed half-decorrelation time and characteristic lengths for 25 samples and observed that the corresponding length of irregularities varies between 400 and 1200 m which belongs to intermediate scale irregularities. To compare the auto-correlation functions of same strength scintillation patches with that of high solar activity period, we have included a typical example of auto-correlation function derived from scintillation data of high solar activity period observed on 21st December, 1992 at 1709–1710 h, IST which is also shown in Fig. 6 (Patel et al. 2009). From the Fig. 6c the half-decorrelation time is 4.9 s and the corresponding characteristic length of the irregularities is 490 m. Patel et al. (2009) and Singh et al. (2006) have shown that the characteristic lengths of irregularities over Varanasi varies between 100 and 3000 m which belongs to intermediate scale irregularities. Basu et al. (1977) have shown that irregularities for daytime scintillations cover the scale size range at least few meters to 1 km.

3.6.2 Power spectrum analysis

The power spectra of irregularities are derived from the analysis of the digital scintillation data. Due to the Fresnel filtering the spectral range is limited, for few hundred meters to tens of meters depending on the irregularity drift. However, from this, it is possible to cover large scale sizes. The amplitude scintillation data under strong scintillation conditions can be used to yield information about large irregularities with sizes greater than Fresnel zone dimension (Yeh and Liu 1982). For the analysis of scintillation through power spectrum which shows the relation between the power of the scintillation activity with respect to frequency.

Typical examples of power spectrum of VHF scintillations observed at Varanasi on (a) 21-07-2008 and (b) 23-02-2008 are shown in Fig. 7 which shows the flat portion towards the low frequency region, which is due to the effect of Fresnel filtering. The important features of interest are the slope of the high frequency portion of the scintillation spectra under consideration of weak scatter. The spectra from roll-off portion and onward can be approximated by a straight line. The spectral indices (slopes of the spectra) are computed between the frequency ranges of 0.1 to 0.5 Hz. The slopes of the corresponding spectra (Fig. 7) in the frequency range 0.1 Hz $\leq$ f $\leq$ 0.5 Hz are −6.97 and −1.98 respectively. The spectral slopes for 25 samples have been computed which determined that the spectral index of irregularities varies between −1.5 and −8 showing both transitional scale and intermediate scale irregularities over Varanasi. To compare the power spectrum of same strength scintillation patches with that of high solar activity period, we

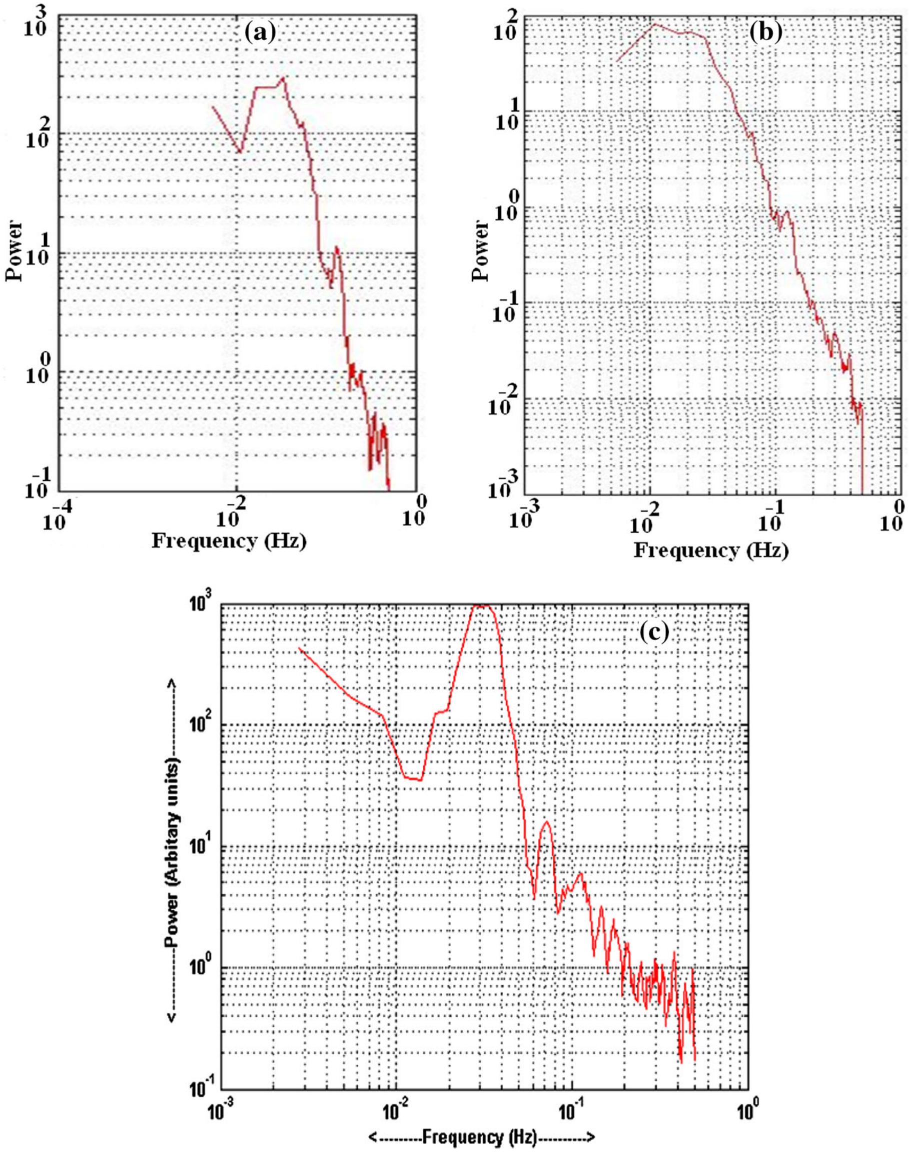

Fig. 7 Typical examples of power spectrum of VHF scintillations observed at Varanasi on **a** 21-07-2008, **b** 23-02-2008 and **c** 05-12-1992

have included a typical example of power spectra derived from scintillation data of high solar activity period observed on 5th December, 1992 at 1739–1745 Hrs IST which is also shown in Fig. 7 (Patel et al. 2009). The spectral index of the corresponding spectra (Fig. 7c) in the frequency range 0.1 Hz $\leq$ f $\leq$ 0.5 Hz is −6.5. Patel et al. (2009) and Singh et al. (2006) have shown that the spectral indices of irregularities over Varanasi range between −2 and −9 with a mean value of −4.

Spectral analysis of observed amplitude fluctuations have shown that the electron density irregularities in the ionosphere may be represented by a power law spectrum (Singleton 1974; Crane 1976). The derived power law index for irregularities lying overhead Varanasi varied between −1.5 and −8. This shows that the scale length of irregularities varied from event to event. Direct observations by rocket probes have confirmed the existence of different spectral slopes for different scale size ranges. Prakash et al. (1991) reported spectral index values ranging from −1.5 to −4.6 for one-dimensional power spectra of in situ electron density fluctuations measured by rocket-borne Langmuir probe flown from SHAR. Jahn and LaBelle (1998) derived spectral indices as −1.7 and −5 at frequencies less than 60 Hz and greater than 60 Hz from in situ rocket measurements of electron density and electric field. Analyzing about 100 scintillation events recorded at Ahmedabad, Vyas and Chandra (1994) reported spectral indices in the range −1 to −5. Basu et al. (1980) reported a spectral index value of 2.8 for scale sizes less than 1 km and of 1.5 for scale sizes greater than 1 km from in situ data obtained from AE-E satellite.

4 Conclusions

To understand the impact of the recent extreme low solar activity period on the occurrence of scintillations at low latitude, we analyzed the VHF scintillation observed at Varanasi during period of 2008–2010. At Varanasi scintillations occur in small patches having the mean value of patch duration of 30 min. The diurnal variation of percentage occurrence of scintillations during the extreme minimum solar activity period of 2008–2010 showed that the scintillation occurrence is low having maximum percentage occurrence between 21:00 and 23:00 h IST during pre-midnight periods. The peak occurrences are 11 % during 2008, 5 % during 2009 and 4 % during 2010. The seasonal percentage occurrence of scintillations is high in equinox and summer and low in the winter.

The occurrence of VHF scintillations at low latitude particularly in the late afternoon hours may be due to E-region irregularities and the nighttime scintillation maybe due to the F-region irregularities. During the extreme low solar activity years the scintillation occurrences do not vary linearly with the sunspot number. The inhibition and generation of irregularities during enhanced magnetic activity period are explained by considering changes in the electric field. The role of the storm time electric field is very complex. It appears that the magnetospheric electric field changes related to the ring current intensification are not sufficient to explain all of the observations of inhibition and the generation of low-latitude ionospheric irregularities during the night. Apart from the ring current, there are several other factors which shape the development of irregularities, such as the ion-neutral collision frequency, neutral wind, large scale plasma density gradient, gravity wave, etc. A magnetic storm enhances the interplay of these parameters and hence their contributions should be considered separately.

The spectral analysis of observed amplitude fluctuations have shown that the electron density irregularities in the ionosphere may be represented by a power law spectrum. The derived power law index for irregularities lying over head Varanasi varied between −1.5 and −8. This shows that the scale length of irregularities varied from event to event which correspond to intermediate scale irregularities. The auto-correlation analysis of amplitude scintillations showed that characteristic length of irregularities varies between 400 and 1200 m which confirms to the intermediate scale irregularities.

Effect of magnetic and solar activities on ionospheric irregularities are studied so as to ascertain their role in the space weather of the near-earth environment in space. Solar and geomagnetic activity are linked to the upper atmosphere and constituted one of the important links in understanding the complex solar terrestrial relations. The study of solar-terrestrial relation is also of practical importance because the trans-ionospheric radio communications and satellite ephemeris predictions are severally degraded during these activities.

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