Multi-instrument observations of winter solstice F-region irregularities during the low solar activity

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Received October 2011; accepted 2 April 2012

Coordinated observations of the nighttime ionosphere in the Indian low-latitude zone were conducted during the winter of 2008-2009 using GPS TEC/Scintillation receiver, radar, ionosonde, and airglow photometer. It has been noted that out of ten nights of observations from 19 January to 27 January 2009, F-region irregularities were observed on six nights. Three distinctly different case studies have been presented to characterize the plasma irregularities observed during the extremely low solar activity condition. Specifically, the focus is on: (i) space-time evolution of plasma bubbles, (ii) zonal drift of the depleted regions, (iii) absence of sub-kilometer scale irregularities in the presence of its higher and lower scale irregularities, and (iv) characteristics of the post-midnight F-region irregularities. It has been found that rate of change of TEC index (ROTI) and derivative of ROTI (DROTI) increase with TEC depletions, but no correlation was found between DROTI and S4 index. These observations are discussed in the light of current understanding on the plasma irregularity processes with due importance to TEC variation and scintillation, which are detrimental for GPS based communication navigation applications.

Keywords: F-region irregularities, Equatorial plasma bubbles, Plasma irregularities, Low solar activity condition, TEC depletions, Airglow depletion

PACS Nos: 94.20.dj; 94.20.Vv; 96.60.Q-

1 Introduction

Equatorial F-region plasma irregularities, especially those associated with the equatorial plasma bubble (EPB), are of renewed scientific interest since they cause random range error and severe scintillation for the satellite signals which result in communication/navigation outages. The EPBs are low plasma density regions surrounded by high density plasma in the F-region and above. EPB is believed to be generated by the non-linear evolution of the Generalized Rayleigh-Taylor (GRT) instability, which eventually results in plasma irregularities encompassing a wide range of scale sizes, which are detected by different ground based and in situ sensors. It is also believed that the GRT instability needs a triggering mechanism, such as those generated by gravity waves or the counter streaming at the bottom of the F-region. A well developed EPB over the equator when moves upward extend along the magnetic field lines that appear like a plasma depleted flux tube. These EPBs while rise and evolve with time, they also drift horizontally and are detected at locations other than where they were originally generated. The fate (lifetime) of the EPBs and associated irregularities depends upon several background ionospheric parameters and before an EPB is completely diminished and dissolved in the background, it may thus traverse multiple longitudes changing its shape and strength of the irregularities. It is also known that while the occurrence of EPB varies on a day-to-day basis and also with season and solar activity, it remarkably varies from one longitude to another. These factors make the forecast extremely difficult, which however, is important for all practical purposes, viz. the GPS based navigation applications.

While most of the EPBs are known to occur soon after sunset, observations have also shown that they occur more frequently in the post-midnight sector during the low solar activity period. Further, the post-sunset occurrence of EPBs is found to maximize in the equinoxes. In contrast, the post-midnight occurrence is found to maximize in the summer solstices. While there exists enough observational results in the literature on the equinoxial and summer time features of the F-region irregularities from the Asian sector, there is nearly no information on
these corresponding to the winter solstice. It is worth mentioning that during the winter solstice, the background ionospheric conditions are different from those of equinoxes and summer solstice. For example, the zonal electric fields during the day and during the period of pre-reversal enhancement as well as during the midnight-temperature-maximum (MTM) activity are much weaker in winter than those in equinoxes and summer.

In this paper, the characteristics of F-region plasma irregularities observed during the winter solstice of 2008-2009, which happened to be part of the low solar activity period, have been presented. Importantly, these observations were made using a network of closely separated GPS receivers, MST radar, ionosonde and airglow photometer, which allowed to characterize different domain of the irregularities and their spatial and temporal evolution including their movement. Localizing the irregularities and estimations of their zonal drift has important implications with regard to such studies. The results obtained during the winter solstice of low solar activity are presented and discussed in the light of current understanding of the low latitude F-region response and plasma irregularities.

2 Experiments and Data

Observations used for the present study were made using a GPS receiver, an airglow photometer, ionosonde and MST radar all located at Gadanki and three more GPS receivers, two from Bangalore and one from Hyderabad. The multi-instrument observations used here were made on 23 December 2008, 21 January 2009, and 24 January 2009. Geomagnetic conditions were quiet as characterized by Kp values less than 2 and Dst values not less than -13 nT.

2.1 Ground based GPS for TEC and Scintillation observations

TEC observations were made using four GPS receivers, one located at Gadanki (GADK), one in Hyderabad (HYDE) and two in Bangalore (BAN2 and IISC). The receivers at Hyderabad and Bangalore are part of International GNSS service (IGS) network. Receiver specific information and RINEX data for these locations are available at IGS website (www.igs.org). The receiver at Gadanki was installed in October 2008 and is a specialized ionospheric TEC and scintillation monitor GSV4004B. This receiver provides amplitude scintillation index (S4 index) corresponding to L1 frequency (1575.42 MHz) of the signal. Thus, scintillation observations were made only from Gadanki. The coordinates of these receivers (GADK (13.45°N, 79.12°E); HYDE (17.41°N, 78.55°E); BAN2 (13.03°N, 77.51°E); and IISC (13.02°N, 77.57°E) are shown in Fig. 1(a). Figure 1(b) shows the geomagnetic field lines, based on IGRF-2011 model, with apex altitudes in northern hemisphere and the corresponding geomagnetic locations of the stations along abscissa.
RINEX data, which gives code and phase ranges, has been used to estimate TEC following Dashora\textsuperscript{16}. The line-of-sight slant TEC for elevation angle greater than 30° has been converted to vertical TEC (VTEC) assuming the ionospheric shell height to be at 300 km. A sudden decrement in VTEC (vertical TEC) and subsequent recovery to the background level is defined as depletion in VTEC\textsuperscript{17-18}. The level of depletion has been obtained by subtracting VTEC values corresponding to the night of no depletion (any of the previous/subsequent night) from those observed on the night of depletion. These depletions in TEC have been considered to be due to EPBs.

For the stations other than GADK, where scintillation observations are not available, rate of change of TEC index (ROTI) and derivative of ROTI (DROTI) have been used as proxy of the scintillation\textsuperscript{19-20}.

2.2 The 630 nm nightglow measurements

For the present study, a Mesosphere Lower Thermosphere Photometer (MLTP) (Taori \textit{et al.}\textsuperscript{21}) was operated from Gadanki to measure thermospheric emission at 630 nm O($^1$D). The governing process for this emission during nighttime is dissociative recombination between O$_2$ and electrons. Hence, the variations of nightglow intensities are considered as imprints of electron density variations\textsuperscript{22} occurring at the peak emission altitudes (250 ± 25 km) of O($^1$D) emissions. Therefore, this emission has been used as a proxy of electron density variability at an altitude of ~250 km.

2.3 MST Radar observations

The radar observations were made using the Gadanki MST radar in a similar way as that done by Patra & Phanikumar\textsuperscript{23}. Radar observations were made with range and time resolutions of 24 km and 30 s, respectively and with an unambiguous Doppler window of ±283 m s\textsuperscript{-1}. Signal-to-noise ratio (SNR), mean Doppler velocity, and spectral width (2\textsigma, where, \textsigma, is the standard deviation of the velocity distribution), which are presented here, were obtained from the low order moments of the Doppler power spectrum.

2.4 Ionosonde observations

Ionosonde observations were made using an IPS-42 digital ionosonde installed at Gadanki. Ionograms were recorded quarter hourly, which were scaled to obtain critical frequency of the F-layer (foF2) and the virtual base height of the F-region (h'F).

3 Observations

3.1 Observations on 24 January 2009

Figure 2(a-d) shows observations from GPS receivers at BAN2, IISC, HYDE and GADK.
respectively. Top panels in each figure show VTEC differenced with respect to previous quiet day for PRN 16 and bottom panels show ROTI (blue line) and DROTI (magenta line). The S4 index (red line) is only available from GADK and is shown in Fig. 2(d). PRN 16 was selected owing to longitudinal alignment of its pass and the duration of interest (post-sunset) for coordinated measurements from other instruments. The top panels show three distinct depletions from IISC (during 20:40-21:30; 21:55-22:40 and 22:45-23:20 hrs IST), a series of depletions from HYDE during 20:40-22:40 hrs IST and three separate depletions from GADK (during 19:50-20:40, 20:40-22:10 hrs IST and 22:10 hrs IST-end of pass). From BAN2, due to a data gap during 22:00-23:00 hrs IST, two depletions (during 20:40-21:30 and 22:45-22:20 hrs IST) were noticed. The ROTI and DROTI indices increased corresponding to the depletions. Both the indices showed higher peak values (0.5-0.6) from HYDE and GADK than from IISC (0.3) indicating that the associated EPB developed further after passing over IISC. The S4 index obtained from GADK remained well below 0.1 throughout, indicating subdued amplitude scintillation. The variation in shape of TEC depletions and in associated indices observed from different stations show that the irregularities underwent remarkable restructuring within a zonal distance of about 200 km.

Figure 3 presents the variation of 630.0 nm airglow intensity on the night of 24 January 2009. It shows features of large and small scale variations, indicating the presence of large depletions and fine scale structures embedded in them. Major depletions are obvious during 20:20-20:40, 20:40-21:40 and 22:00-23:00 hrs IST along with the smaller scale perturbations running throughout the period of observation.

Figure 4 shows the height-time-SNR plot of radar backscatter from the field-aligned irregularities (FAI) for the same night. The SNR map is characterized by multiple plumes occurring between 20:40 hrs IST and midnight. One can clearly note three pairs of plumes with temporal separation of ~40 min. But, within each pair, there exist two plumes, for which the average separation is ~15 min. At the later stage of the plume events, the structures are seen to descend. The above observations clearly show that the noticed depletions in TEC and in airglow intensity variations agree extremely well with the radar plume structures, suggesting that the manifestations in the three diagnostics represent basically the same phenomenon.

3.1.1 Localizing EPBs using multiple instruments

To ascertain the observations from each instrument and to use them for collective interpretation, localization of EPBs is very important. Also, the plasma bubbles can be tracked in several longitudes using this approach. By integrating all these observations at a particular time over a particular space, one can localize the EPBs.

Figure 5 shows the space-time history of depletions in terms of differenced VTEC as observed using the GPS network. The satellite moved towards north as time progressed which means that the previous depletions would have drifted when newer ones are observed during the later time of the satellite pass. Therefore, one must follow the time-annotations when tracing any feature in the differenced VTEC from different stations. The observations are arranged.
from east to west as obtained from different instruments for the night of 24 January and check temporal variation of the structures. Thus, it was found that the irregularities were first seen from IISC (as TEC depletions), then from HYDE, then from Gadanki by both the radar (as plumes) and by MLTP (as nightglow depletions), and finally from GADK (as TEC depletions). It was noted earlier that a single depletion was observed during 20:40-21:30 hrs IST from IISC and GADK but, for the same duration from the same PRN, multiple smaller depletions were observed from HYDE. It may be noted that the IPP latitudes are 10-11° for IISC and GADK, and 14-15° for HYDE (Fig. 5). Hence, it was observed that when the same satellites is viewed from different stations at the same time, the difference in latitude and longitude of IPP marks the variation in depletions structures, which is worth noticing. The implication of this is evident from the plume structures in the radar observation before 22:00 hrs IST, which agree well with the multiple temporal structures of TEC depletion observed from HYDE. This is because both were seeing the same volume of space at that latitude (~14°) and at almost the same time. Also, the depletions seen in the airglow intensity from Gadanki are found to be of similar type.

Coming to the observations made after 22:00 hrs IST, it may be noted that the PRN 16 moved towards north. At this time a depletion seen from IISC between 22:00 and 23:00 hrs IST falls in close proximity of Gadanki in terms of latitude and longitude (Fig. 5). The airglow intensity showed a declining pattern starting at 22:00 hrs IST and ending at 23:00 hrs IST. During the same time, a plume structure started appearing in the radar field of view. However, when the VTEC was examined from GADK and HYDE, it was found that the VTEC depletions started from 22:20 hrs IST. It may be noted that the IPPs seen by the GPS receivers from GADK and HYDE were east of that seen by IISC and those regions probed by the airglow photometer and the radar. This exercise reveals the spatio-temporal structure and evolution of depletion and proves their close association with other plasma irregularities.

3.1.2 Drift estimated using TEC depletions

The GPS receiver at IISC is 0.06° east of BAN2, which correspond to horizontal separation of 6 km. The specific locations of these two GPS receivers are used to correlate the VTEC variations. Using cross-correlation analysis, for the VTEC-depletion that occurred during 20:40-21:30 hrs IST, time offset of 2 points was obtained (with cross-correlation coefficient = 0.99). The drift velocity is estimated through \( V_d = D/(j/R) \), where, \( V_d \) is the apparent drift velocity; \( D \), the eastward distance between the initial point of the IPP of the GPS line of sight and Gadanki; \( j \), the offset number of time lag; and \( R \), the sampling rate (one per minute for both data sets). Thus, time lag of 60 s (sampling interval=30 s) with respect to IPPs difference resulted in ~86 m s\(^{-1}\) eastward drift.

3.2 Observations on 23 December 2008

Figure 6(a-d) presents GPS-TEC observations made during 20:00-23:00 hrs IST from BAN2, IISC, HYDE and GADK stations in the similar form as that of Fig. 2. Two depletions were observed from BAN2 and IISC, the first depletion (DEP1) during 20:50-21:40 hrs IST with a reduction of 1-2 TECU and the second depletion (DEP2) during 21:50-22:30 hrs IST with a reduction of 4-6 TECU. When the same PRN 31 observed from HYDE (north-east to Bangalore) and GADK (east of Bangalore), DEP1 and DEP2 appear with time delays of ~20 min and ~35 min, respectively. It may be noted that while the depth of DEP1 is increased by 2 TECU and that of DEP2 is decreased by 2 TECU when observed from HYDE, observations from GADK show further

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**Fig. 5** — Differenced VTEC mapped on trajectories of PRN16 in color scale, as seen from IISC, HYDE and GADK stations on night of 24 January 2009 (IST annotated over the trajectory)
increase of 2 TECU and further decrease of 2 TECU for the two depletions, respectively. Considering that the longitude of HYDE falls in between those of BAN2/IISC and GADK, the above observations imply that plasma depletions evolved as they moved eastward. As far as scintillation indices are concerned, increments in ROTI index estimated at about 21:25, 21:35, 22:30 and 23:10 hrs IST correlate well with those depletions. Similar variations are present in the DROTI index also. The S4 index as observed from GADK station [Fig. 6(d)], however, remained below 0.1 without any significant increments during the occurrence of TEC depletions, except a small peak at about 22:40 hrs IST.

Figure 7(a) shows variation in 630 nm airglow intensity observed on the same night. It shows large variability with a small increase at around 21:30 hrs IST followed by a significant decrease much alike the TEC depletions observed during 21:50-22:30 hrs IST. Again after 22:30 hrs IST, depleted intensity is seen during 22:45-23:30 hrs IST. After this epoch, intensity shows a steady increase until midnight. Unfortunately, the radar observations on this night are not there to supplement that they were indeed linked with plasma bubble.

Figure 7(b) shows virtual height of the bottommost echo trace (h'F) (red curve with its axis on right ordinate) and foF2 (blue curve with its axis on the left ordinate) obtained during 19:00-24:00 hrs IST on 23 December 2008. In this case, h'F represents for both non-spread F and spread F echoes. It was noted that subsequent to an anomalous rise in h'F, the first range-type spread-F was observed at 21:00 hrs IST which continued till 21:30 hrs IST (shown by a gray block). Then, the range spread disappeared in two successive ionograms at 21:45 and 22:00 hrs IST. It reappeared during 22:15-23:00 hrs IST with large range and frequency spread. This shows two separate instances of range type spread-F in the post-sunset hours, which are likely related to two well separated plasma bubbles, which are consistent with the depletions observed in 630.0 nm airglow intensity.

3.2.1 Localizing EPBs using multiple instruments

Figure 8 shows the differenced VTEC as observed from BAN2, HYDE and GADK for PRN 31. The trajectories clearly show DEP1 and DEP2 as a function of latitude and longitude. The time of first appearance of DEP1 as observed from BAN2 is delayed at HYDE and GADK as expected from
eastward motion of plasma drift. The time of occurrence of DEP1 and DEP2 as observed from GADK agrees well with those observed using airglow and ionosonde from Gadanki. It may be noted that while the first depletion observed by the GADK-GPS was right over Gadanki; the second one slightly differs in latitude, indicating the field aligned nature of the depletions and directly relate them to EPB.

3.2.2 Drift derived from TEC and airglow observations

Considering that the 630.0 nm nightglow intensity is a function of the base height of the F-region, it is possible to estimate drift by correlating GPS-TEC variations with those of airglow intensity. Existence of remarkable correlation between the two quantities has been reported earlier by Weber et al.\textsuperscript{25}, Kelley et al.\textsuperscript{26} and Ogawa et al.\textsuperscript{27}. Cross-correlation of these two parameters shows correlation coefficient of 0.732 at a time lag of 18 minutes. Figure 9 presents the variation of original VTEC along airglow intensity advanced by 18 minutes. As evident, the features of TEC depletions are well captured in the nightglow data. The apparent drift velocity estimated is 44 ms\textsuperscript{-1} eastward. It is important to note that the estimated drift is remarkably small when compared to those reported in the literature\textsuperscript{15}.

3.2.3 Drift estimation using TEC depletions

As noted in previous case, cross-correlation analysis has been used for VTEC from 21:40 to 22:10 hrs IST for PRN 31. Time lag of 3 points was obtained (with cross-correlation coefficient = 0.99). The corresponding drift (with respect to IPPs) resulted to be ~67 m s\textsuperscript{-1}. When compared to the zonal drift using airglow-VTEC correlation (44ms\textsuperscript{-1} for DEP1 from Gadanki), this value is higher (~67ms\textsuperscript{-1} for DEP2 from Bangalore) for the same night. The difference in two values is not unexpected and could be due to various reasons, e.g. the difference in technique of measurement and accuracy; and not the least, the dynamics of bubbles, i.e. whether they were in diffusing or growing stage. However, the drift values obtained above are lower when compared to high
solar activity periods for the same local time as reported by Yao & Makela\textsuperscript{15} using data during 2001-2005 from North American sector. The very low values of zonal drifts have been associated with lowest solar activity during 2008-09.

3.3 Observations on 21 January 2009

Figures 10(a), (b) and (c), respectively, show mean VTEC, airglow intensity and foF2 and h’F observations during 19:00-02:00 hrs IST on the night of 21 January 2009. The mean VTEC is obtained by averaging VTEC for elevations angle >50°. The decreasing trend in VTEC observed from 19:00 to 21:00 hrs IST for all stations is an oft-occurring phenomenon during quiet time. In absence of irregularities, such trend continues for the rest of the night, finally settling into a late night minimum level of VTEC. But, on this night, an enhancement in VTEC is noted during 21:30-24:00 hrs IST from all the stations nearly simultaneously, except from HYDE. Mean VTEC peaked at around 23:00 hrs IST and decreased thereafter.

Evidently, the nightglow intensity rapidly decayed until 20:00 hrs IST and reached to its minimum just before 21:00 hrs IST. Thereafter, a build-up in intensity is seen with a small peak at 21:45 hrs IST, followed by another minima at about 23:00 hrs IST. The intensity exhibited fluctuations throughout the night indicating large electron density perturbations.

The foF2 exhibited post-sunset rapid fall from about 7 MHz at 19:00 hrs IST to about 4.3 MHz at 21:30 hrs IST. Thereafter, it gradually increased peaking at about 22:30 hrs IST with a noticeable plateau at 4.5 MHz and then decreased for the rest of the night. The h’F variations exhibited very peculiar double hump structure as obvious from the figure. It followed a reverse pattern as compared to foF2 variations. The h’F increased from 210 km after sunset to 260 km at 21:30 hrs IST and fall back to 220 km by 22:45 hrs IST. An anomalous rise of 140 km occurred in h’F during 23:00-24:00 hrs IST, accompanied with range-type spread-F starting at 23:30 hrs IST and lasting by 01:15 hrs IST. But h’F decreased after 24:15 hrs IST, thus forming a peak around mid-night. Thereafter, no observations could be made till morning because very faint traces were received by the ionosonde.

Apart from the enhancement in VTEC, depletions of ~1-1.5 TECU in post midnight sector were also observed from PRNs 19, 20 and 23. These depletions resembled small scale perturbations in VTEC. These were averaged out in mean VTEC and hence, no trace was seen in Fig. 10(a). Hence, PRN 19 was selected in this case and the differenced VTEC has been shown from all four stations in Figs 11(a-d). The depletions are visible during 01:15-02:20 hrs IST from IISC and BAN2, and during 01:00-02:40 hrs IST from HYDE and GADK. The ROTI, DROTI and S4 indices have remained well below 0.1 and showed no increase from any of the station.

Figure 12 shows the height-time-SNR plot of FAI on the night of 21 January 2009. Till midnight, there was no trace of irregularity but at about 24:15 hrs IST, a small structure was observed around 150 km altitude. After this blob of irregularity, a plume like structure is discernible starting from 01:00 hrs IST and lasting till 02:45 hrs IST. Within this duration, the plot shows three detached high altitude structures looking like striations. The first one crossed the radar beam at about 01:15 hrs IST with an altitude of ~275-300 km. This structure remained detached from the second and larger structure that appeared at about 01:15 hrs IST with peak altitude of ~425 km. It descended continuously till 02:15 hrs IST. A third detached small structure is seen at around 02:45 hrs IST at ~250 km altitude.
and lasted for few minutes. Evidently, the second plume like structure exhibited greater variability than the first and the third.

### 3.3.1 Tracking and localization of EPBs/FAIs

From the observations presented in this case above, the plume reached very high altitude of about 425 km, but the local time of its occurrence and preceding enhancements in 630 nm nightglow intensity and VTEC makes this case more intriguing. The perturbations (depletions) in the differenced VTEC were of the order of 1 TECU, which made it difficult to track them. However, the tracking scenario has been shown in Fig. 13 for differenced VTEC obtained for PRN 19. The coverage through this PRN show a long stretch of depletion within ~80°-81°E longitude sector from all the stations except from HYDE that shows a small recovery in depletion at about 01:30 hrs IST within a larger depletion. Though, the depth of

![Fig. 11 — TEC observations on night of 21 January 2009 for PRN 19 from: (a) BAN2, (b) IISC, (c) HYDE, and (d) GADK [upper panels show differenced VTEC & lower panels show ROTI (blue) & DORTI (magenta) indices for each station, respectively; variations in S4 index are shown in lower panel of (d) for GADK in red color]

![Fig. 12 — Height-time-SNR plot for night of 21 January 2009 as obtained from MST radar, Gadanki]
depletion was small, notably it has grown. As seen from IISC and BAN2, the depth was about 0.5 TECU and it looked like a perturbation. This structure deepened to about 0.7 TECU and also showed a definite shape of depletion as seen from HYDE. The same structure when seen from GADK showed about 1-1.5 TECU depth. Spread-F was observed in ionograms during 11:30-01:15 hrs IST over Gadanki and plume in radar echoes was observed during 01:15-03:00 hrs IST. The depletions were observed in the eastern side of Gadanki at the time when plume was observed from radar. This grossly indicates that the irregularity was drifting towards east in post-midnight sector.

4 Discussion

Multi-technique observations corresponding to the winter of 2008-2009 presented above have revealed: (i) space-time evolution of plasma bubbles, (ii) zonal drift of the depleted regions, (iii) absence of sub-kilometer scale irregularities in the presence of its higher and lower scale irregularities, and (iv) characteristics of the post midnight F-region irregularities.

Using the cross-correlation method, the zonal drifts have been estimated from TEC depletions, which are found to be 65-85 m s\(^{-1}\) eastward during the pre-midnight hours. These estimates agree quite well with those reported earlier\(^{25}\) from the Indian sector and also those reported by Yao & Makela\(^{15}\) from the American sector.

Multi-instrumented observations also have clearly revealed the occurrence of various scale sizes of irregularities associated with EPB. For example, while hundred km-scale irregularities were observed in the form of TEC and airglow depletions and also in the form of radar plume structures, the radar echoes themselves indicated the presence of meter-scale irregularities. Also, range spread-F has been observed in the ionosonde observations, which can be attributed to the irregularities with scales sizes of few tens of meters. On the other hand, significant value in the ROTI has been noted, which can be viewed as 3-4 km scale sizes\(^{19}\) assuming that the zonal drifts are 65-75 m s\(^{-1}\). The noticeable values of the DROTI have also been observed, which indicates the possibility of occurrence of L band scintillation. However, no L band scintillation have been observed, which could be related to irregularities with scale sizes of 370-400 m. It may also be mentioned that L band scintillations were not observed even for the post-sunset spread-F events. Thus, it is quite intriguing that while the ROTI clearly indicated the presence of 3-4 km scale irregularities and the radar/ionosonde detected the presence of meter-decimeter scale irregularities, why the intermediate scales were not detected in the form of S4 index.

As far as L band scintillation is concerned, adequate background density and density structures with horizontal scales corresponding to the Fresnel dimension (370-400 m for the L1 band) would be required. The background TEC (just prior to depletion) in most of the cases presented here, however, is below 12 TECU and the perturbation (difference) in TEC is about 3-5 TECU. Earlier observations (of 2005) from Bangalore\(^{29}\), showed higher S4 index (reaching up to 0.6-0.8) than those presented here, were found to have higher background TEC values (not less than 20 TECU) and higher perturbation amplitudes in TEC depletions. Thus, lower background TEC and perturbation amplitudes appear to be the cause behind the subdued S4 index associated with the observations presented here. It may also be possible that intermediate scale irregularities, especially 300-400 m scales, were not excited sufficiently to cause scintillation. One of the reasons of inhibition of intermediate scale irregularities is the lack of electron density gradients associated with the EPB. In fact, recent observations from C/NOFS satellite\(^{30}\) made during the low solar activity period of 2008 showed spectral break in density power spectra observed at an altitude of
450 km. The spectral break occurred at ~100 m scale. Thus, in the present case, it is quite likely that either the inertial regime was broken at much higher scale length than 370-400 m so that these irregularities were not triggered (as secondary wave) or the irregularities may be present at this scale but were too weak to cause scintillations.

Statistically, however, it has been found that L band scintillation occur more frequently in high solar activity period when the background electron density is higher than that of low solar activity. Also, during the high solar activity period, EPB is known to occur at an earlier local time than that during low solar activity period. Thus, the frequent occurrence of L band scintillation in the high solar activity when EPB occurs early in the sunset period is consistent with the high background density. In the present observations, it has been found that the EPB occurred rather late, corroborating the role of background density in the L band scintillation. Although, it is very apparent that the C/NOFS observations correspond to low solar activity when the L band scintillation is known to be weak, the reason for the observed break at the intermediate scale in the density power spectrum, however, is not clear.

Coming to the observations of post-midnight F-region irregularities, neither significant depletion nor L band scintillation has been found to be present simultaneously. Further, the Doppler velocities associated with the F-region FAI were found to be predominantly downward with values limited to 20 m s\(^{-1}\) (Fig. 14). Also, spectral widths (2\(\sigma\)), which can be viewed as a measure of plasma turbulence, were also mostly confined to 30 m s\(^{-1}\), whereas their counterpart in pre-midnight hours were as high as 80 m s\(^{-1}\). These indicate that the plasma irregularities observed in the post-midnight hours were in the decay phase. Plasma irregularities observed on 21 January, however, were confined to 01:00-03:00 hrs IST and in all probability they were associated with fossil structures similar to those reported earlier by Sekar et al.\(^{31}\) The origin of the meter scale irregularities in the absence of intermediate scale and km-scale irregularities, however, has not been fully understood. In the above context, it may be worth discussing the enhancement in the TEC observed during 21:30-23:30 hrs IST on 21 January. This enhancement was also observed from Bangalore, indicating that the region located just west of Gadanki was basically devoid of

![Fig. 14 — Height-time-doppler velocity (upper panels) and height-time-spectral width (lower panels) plots for night of 24 January 2009 (left panels) and for night of 21 January 2009 (right panels), respectively as obtained from MST radar, Gadanki](image)
any depletion that could give rise to plasma irregularities. It may be recalled that on this night, weak plasma irregularities were detected by the MST radar only after 01:00 hrs IST. Assuming that the background plasma was moving at 70 m s\(^{-1}\) eastward, the observed fossil-type plasma irregularities may be linked to a depleted region originally formed soon after the sunset at a location far west of Gadanki. So far, as the enhancement in the TEC is considered, any such feature from Hyderabad has not been observed. The origin of the enhanced TEC region is not clear from the present dataset. This is an aspect of further investigation and it is planned under next observational campaigns.

Acknowledgments
The authors acknowledge the effort of NARL technical staff for carrying out MST radar observations used in the present investigation. The data from three IGS sites BAN2, IISC and HYDE has been obtained from http://igscb.jpl.nasa.gov/ and efforts of the contributing agencies are appreciated.

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