Evolutionary phases of equatorial spread $F$ including L band scintillations and plumes in the context of GPS total electron content variability: A case study

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The evolution of large-scale (few kilometers), medium-scale (few hundreds of meters), and small-scale (meters) size plasma density irregularities in the post-sunset equatorial $F$ region, in the context of characteristic GPS total electron content (GTEC) variations, are reported from Indian longitudes. The ionograms and GTEC from a GPS receiver installed as a part of the GPS Aided Geo Augmentation Network (GAGAN) project for satellite-based navigation are obtained from an equatorial station at Trivandrum (8.5°N, 76.91°E, dip latitude 0.5°N). The variations in the GTEC with respect to TEC are considered to represent the seed perturbations for the plasma instability that results in the equatorial spread $F$ (ESF) irregularities and are treated as a perturbation factor ($P$). The VHF radar at Gadanki (13.5°N, 79.17°E, dip latitude 6.4°N) provided the small-scale structures of ESF. The background thermospheric conditions that affect the growth of the plasma instability through ion-neutral collision frequency ($\nu_{nm}$) are estimated using the $F$ region base height ($hF$) and the representative scale height of the neutral atmosphere and are represented by a growth factor ($G$). The present case study reveals a close coupling between the background ionospheric conditions and the baseline perturbations in deciding the evolutionary phases of ESF. It has been shown that although large-scale (kilometer scale) irregularities are formed without any constraints when the background ionospheric-thermospheric conditions are favorable in the presence of fluctuations in GTEC, consistently, the medium-scale and small-scale irregularities show remarkable similarity with the variations in the product of the perturbation and growth factors.


1. Introduction

[2] The phenomenon of equatorial spread $F$ (ESF) refers to, in the classical sense, the generation of plasma density irregularities spanning a wide range of scale sizes, from hundreds of kilometers to centimeters, in the post-sunset equatorial $F$ region. Very intense studies spanning over 6 decades, both experimental and theoretical have revealed the complexity of the phenomenon. It is widely accepted now, that it is a nonlinear plasma instability processes, primarily driven by the Rayleigh-Taylor (R-T) instability paving way for a hierarchy of instabilities, finally culminating in the generation of the wide ranging scale sizes of density irregularities referred above. This multidimensional phenomenon manifests in different ways, namely, as airglow intensity bite outs (scale sizes of hundreds of kilometers), spread in the $F$ region echoes as seen in the ionograms (kilometers), VHF and UHF scintillation of satellite to Earth communication signals (hundreds of meters) and plumes in the range-time-intensity (RTI) map of the backscatter echoes from coherent back scatter radars (meter to centimeter depending on the probing frequency). In addition, in situ measurements, whether by a satellite or by means of sounding rockets, see them as “plasma bubbles” or “ionization holes.” The plasma density irregularities associated with this phenomenon having a generic name of ESF, cause disruptions in the satellite to ground communication link and degrade the navigation signals. Since ESF shows large spatial (latitudinal and longitudinal) and temporal variability (day to day, seasonal, solar cycle), with our increasing dependence on satellite-based systems both for communication and navigation, understanding to what extent the latter would be affected by the former becomes imperative. The present paper attempts to address several of these aspects through case studies.

[3] The equatorial $F$ region base undergoes a steep rise in altitude in the post-sunset hours referred to prereversal enhancement (PRE). Further, because of the lack of ionizing solar radiation, the $E$ region decays fast. As a consequence, one is left with a very steep plasma density gradient in the
bottomside $F$ region which itself is lifted to great heights because of the PRE. Such a steep altitudinal gradient makes the situation analogous to a heavier fluid being supported by a lighter fluid in the presence of gravity. The situation is highly unstable. In the presence of any density perturbation in the bottomside ionosphere, the perturbation would grow in amplitude leading to the classical R-T instability. Any small perturbation in the form of depletion would grow through the $F$ region nonlinearly, as a bubble or as a density depleted region extending to the topside of ionosphere up to an altitude where the density inside the depletion (bubble) and outside were the same. This means that eventually the bubble would lose its identity. As the instability grows with time, the resultant large-scale irregularities provide the basic conditions for the secondary instabilities to operate resulting in the generation of the wide spectrum of irregularities referred to earlier. [4] A simplistic expression for the linear growth rate of the primary R-T instability can be given as [Haerendel, 1973; Ossakow et al., 1979]

$$\gamma = \frac{1}{L} g \nu_{in},$$

(1)

where $\nu_{in}$ is the ion-neutral collision frequency, $g$ is the acceleration due to gravity, and $L$ is the ambient plasma density scale length, which is inversely proportional to the plasma density gradient $dn_0/dz$ and is given by $L = (\frac{1}{n_0} \frac{dn_0}{dz})^{-1}$.

[5] Though the role of electric fields, zonal winds in the presence of zonal gradients, and vertical winds has been very well established by earlier workers [Hanson et al., 1986; Sekar and Raghavarao, 1987; Sekar and Kelley, 1998] in augmenting the primary R-T process, in the present exercise, we restrict ourselves only to the primary process and attempt to account for the primary factors only, as the purpose here is to investigate the various manifestations of the phenomenon on a given day rather than its day to day variability. In spite of the above restriction, it emerges that most of the observed variability could still be explained conceptually. The case study pertains to the equinoctial period of low solar activity when generally the base of the $F$ region is expected to reach nearly the same altitude levels during postsunset hours. As would be seen in section 4, the $F$ region base reached ~300 km on all the four occasions in the postsunset hours. This would imply that the plasma scale length $L$ would nearly be the same for all the cases. The other parameter would be the ion-neutral collision frequency $\nu_{in}$, the variability of which could be accounted for through $h'F$ variations. The perturbation grows nonlinearly essentially because of the altitude variations of $\nu_{in}$.

[6] As a phenomenon, the gross variability of ESF has been fairly understood but for its day to day variability making its prediction rather difficult. Several attempts have been made in the literature taking our understanding closer toward deterministic prediction [Raghavarao et al., 1988; Sridharan et al., 1994; Valladares et al., 2001; Mendillo et al., 2001; Devasia et al., 2002; Anderson et al., 2004; Thampi et al., 2006; Sreeja et al., 2009]. It is established now that large-scale wave structure (LSWS) most often precedes the ESF phenomenon [Tsunoda, 2005, 2008, 2009; Thampi et al., 2009; Tsunoda et al., 2010]. Recently, Tsunoda [2010a, 2010b] reported the possible lower atmospheric seeding for the ESF during solstices. It is important for us to have a comprehensive understanding of the various controlling factors to be able to eventually predict the phenomenon that too with minimum inputs on the background conditions so as to reach observational/operational deterministic forecasting capability. Though this would be our ultimate aim, in the present exercise, we restrict ourselves only to the evolutionary phases of the phenomenon with regard to large, medium and small-scale irregularities in the light of GPS total electron content (GTEC) variability.

2. Data Presentation

[7] The present case study has been carried out on four distinctly different ESF events during the equinoctial months (February–March) of 2007, a low solar activity period. Simultaneous measurements through ionograms, GTEC, L band scintillations on the GPS signals and RTI maps using the Indian MST radar operated in the ionospheric mode have been considered in the study. The digital ionosonde (KEL make, Model IPS-42) located at Trivandrum (8.5°N, 76.91°E, dip latitude 0.5°N) is used to monitor the basic ionospheric structure and also to monitor the movement of the base of the $F$ region ($h'F$) in the postsunset hours. The ESF initiation which is usually seen first in the ionosonde, indicates the evolution of kilometer-scale size irregularities. The dual-frequency GPS Ionospheric Scintillation and TEC Monitor (GISTM) system GSV 4000B colocated in Trivandrum as a part of the GPS Aided Geo Augmentation (GAGAN) project, mainly for the purpose of satellite-based navigation, provides the GTEC values in addition to the scintillation index (S4) for the L band GPS signals at an interval of 30 s. Both the GTEC variations and the S4 index are considered in the present study. The RTI maps are constructed using the coherent back scatter echoes from the field aligned irregularities, using the Indian MST radar located in Gadanki (13.5°N, 79.17°E, dip latitude 6.4°N) operated at 53 MHz with a power aperture product of $3 \times 10^8$ Wm$^{-2}$ and with a typical antenna beam width of 3°. The Indian MST radar when operated in the ionospheric mode (tilted northward by ~15° from zenith) scans the beam perpendicular to the geomagnetic field lines and enables the investigation of the phenomena dealing with field aligned irregularities [Rao et al., 1995]. The RTI maps give us clues on the evolution of the 3 m irregularities.

3. Approach

[8] As mentioned earlier, the aim of the present work to delineate the causative mechanisms that are responsible for the sort of variability exhibited by the ESF phenomenon during its evolutionary phase. The variability has to be necessarily dictated by the background ionospheric-thermospheric conditions like the $F$ region base height, the plasma scale length and the neutral atmospheric densities that control the ion-neutral collision frequencies at the base height. But there is an inherent assumption that, the initial perturbations are omnipresent. Though may be valid in a general sense, the perturbation amplitudes and periods need not be the same on all occasions and hence its variability would also modulate the evolution of the ESF. A similar line of thinking has been echoed by Tsunoda [2010a], who