Modeling of VHF Scintillation Observed at Low Latitude

S B Singh\textsuperscript{1}, K Patel\textsuperscript{2}, R P Patel\textsuperscript{3}, A K Singh\textsuperscript{2,4} and R P Singh\textsuperscript{4}

\textsuperscript{1}Department of Physics, Maharaja College, V.K.S. University, Ara-802301, India
\textsuperscript{2}Physics Department, Banaras Hindu University, Varanasi-221005
\textsuperscript{3}Department of Physics, M. M. H. P. G. College, Ghaziabad.
\textsuperscript{4}Vice-Chancellor, V. K. S. University, Ara,Bihar,India.

Abstract. The VHF amplitude scintillations recorded during the period from January 1991 to December 1993 in the declining phase of a solar cycle and April 1998 to December 1999 in the ascending phase of the next solar cycle and from January 2008 to July, 2008 at low latitude station Varanasi (geomag. lat. = 14\textdegree 55’ N, long. = 154\textdegree E, Dip angle = 37.3\textdegree, Sub-ionospheric dip = 34\textdegree) have been analyzed to study the characteristics of ionospheric irregularities during the active solar and magnetic periods. In this paper, the expression for flux tube integrated linear growth rate of irregularities supposed to be produced through generalized Rayleigh-Taylor instability (GRTI) have been derived. Realistic atmospheric and ionospheric density model inputs are used to compute R-T growth rates for a range of geophysical conditions. The derived parameters of irregularities from scintillation data observed at low latitude are compared with computed values. An attempt is made to produce a model for ionospheric low latitude irregularities.

1 Introduction
The space-time variability of ionospheric irregularities is of serious concern to radio communications because these irregularities affect the amplitude and phase of satellite signals. Amplitude variations may induce signal fading, and when depth of fading exceeds the fade margin of a receiving system, message errors are encountered. If navigation is dependent on the Global Positioning System (GPS), then amplitude fluctuations may lead to data loss and cycle slips [1]. Sudden phase changes may cause a loss of phase lock in GPS receivers [2]. Equatorial scintillations during a high solar activity period have been found to be sufficiently intense to disable many communication and navigation systems [3]. Hence, it is necessary to understand the role of space weather events on scintillations.

The fluctuations in the ionospheric electron density, commonly known as irregularities, are generated on the bottom side of the post sunset F-region over the magnetic equator by the nonlinear Rayleigh Taylor instability mechanism. Irregularities are of two types, namely those related to plasma bubbles [4] and those known as bottom side sinusoidal irregularities [5]. The plasma bubbles become highly structured as

\textsuperscript{3}To whom any correspondence should be addressed.
they rise to higher altitudes above the magnetic equator. These bubbles then move along the geomagnetic field line to anomaly locations of $15^0$ N and $15^0$ S magnetic latitudes [3]. The electric field at the site plays a dominant role in shaping the development of these irregularities. The field is eastward during the day and westward after sunset. Before this direction reversal, there is a sudden enhancement of the eastward electric field [6]. The field and its variation are seasonally depending with solar activity.

Any change in the electric field influences the occurrence of low latitude scintillations. With increasing interest in understanding the behavior of ionospheric irregularities near the magnetic equator, efforts have been made to examine the influence of solar and magnetic activity over the occurrence of scintillations associated with ionospheric irregularities [7-12]. An enhancement in the eastward electric field raises the F-layer at the magnetic equator to higher altitudes where conditions more favorable for the generation of irregularities may be obtained [13-14].

In this paper, we present some results of 244MHz amplitude scintillation measurements during the period January 1991 to December 1993 in the declining phase of the solar cycle, April 1998 to December 1999 in the ascending phase of the succeeding solar cycle and Jan 2008 to July 2008 again the descending phase of the solar cycle at Varanasi, which is situated near the northern crest of the equatorial anomaly zone. We have examined the seasonal variation of the scintillation activity and showed that both the seasonal pattern and the level of scintillations are controlled by solar activity. The effect of magnetic activity on the occurrence of scintillations is also studied.

2. Data Analysis

The amplitude scintillations of the 244MHz signal radiated from the geostationary satellite FLEETSAT situated at $73^0$ E longitudes were continuously monitored at Varanasi using a fixed frequency VHF receiver and strip chart recorder. The receiver was calibrated using the method described by Basu and Basu [15]. 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. 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 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.

3. Observational Results

Using the data of the years 1991-1993, 1998-1999 and from Jan - July 2008, the month-to-month variation of the percentage occurrence of the scintillation and the mean sunspot number of the respective years is shown in figure 1. No data was available for the period of Jan.1994-March1998 and Jan. 2000- Dec. 2007. The figure shows the maximum percentage occurrence in the winter and equinox months of each year in comparison to summer months. Figure 1 shows that the scintillation occurrence is varying linearly with the sunspot number except in summer months which does not show any significant change. Our results are very much agreeable with those of the previous results [10,16,17].

The day and nighttime variation of occurrence scintillation are shown in figure 2(a,b). From the figures we observe that daytime scintillation activity is less than the nighttime scintillation activity. Figure 2(a) represents that scintillation occurrence decreases with the decrease of mean sunspot number (solar activity). The maximum scintillation occurrence is ~17% in 1991 ($R_z = 145$), 10% in 1992 ($R_z = 95$) and in the year 1993 ($R_z = 55$) it is ~7%. Figure 2(b) shows that the scintillation occurrence in 1998 ($R_z = 64$) with maximum scintillation occurrence ~ 10% and in the year 1999 ($R_z = 94$) with maximum occurrence of ~14% but in 2008 ($R_z = 4$) there is again increase of scintillation occurrence with the decrease of the mean.
Figure 1. The month-to-month variation of the mean percentage occurrence of scintillations and sunspot numbers for the years Jan. 1991-Dec. 1993, April 1998-Dec. 1999 and Jan 2008- July 2008.

sunspot number with maximum occurrence of ~17%, which may be due to only six months data analyzed in the whole year. Figure 3 shows the magnetic effect on the scintillation occurrence indicating that the

Figure 2. The day and night time variation of the scintillation occurrence rate along with mean sunspot number as a function of time (a) for the year 1991, 1992,1993 (b) for the year 1998, 1999, 2008.
scintillation occurrence rate is suppressed during magnetic disturbed days. This trend is throughout the years for both day and night time scintillations.

4. Theoretical Formulation

The Collisional plasma instability in the nighttime equatorial ionosphere is described by the particle conservation equation

$$\frac{dn_j}{dt} + \nabla \cdot (n_j \cdot V_j) = 0$$

(1)

and the charge conservation equation

$$\nabla \cdot \vec{J} = 0$$

(2)

where, $n$ is the particle density, $\vec{J} = n e (V_e - V_i)$ is the current density, and the quasi neutrality condition ($n_e = n_i = n$) is assumed. Here $j = e$ for electron and $i$ for ions. The steady state momentum equations for cold plasma are

$$0 = n_j m_j g + q_j n_j (\vec{E} + V_j \times \vec{B}) - n_j m_j V_j (V_j - \vec{u})$$

(3)

where, $\vec{u}$ is the neutral wind, $g$ is gravitational acceleration, $q$ is charge and $\vec{E}$ and $\vec{B}$ are the ambient electric and magnetic fields. Here, the effects of chemical recombination of the plasma components are not included. The inertia terms in the momentum equatorials have been ignored.

Following Haerendel [18] and Haerendel et al. [19], the equations for the flux tubes integrated current ($J$) and ion flux ($F$) components are expressed in the two-dimensions ($L$, $\phi$) coordinate system, where $L$ is the McIlwain parameter and $\phi$ is the geomagnetic longitude of the field line

$$J_L = \sum_p (E_L + \frac{B_L}{L^2} U_{\phi}^p) - \sum_H (E_\phi + \frac{B_\phi}{L^2} U_L^H)$$

(4)
The individual flux tube integrated quantities for total flux tube electron content \( N \), Pedersen conductivity \( \Sigma_P \), and Pedersen conductivity weighted neutral wind in the L direction \( U^P_L \) are defined by Haerendel et al. [19]. Separating out the density and conductivity contributions from the E and F- regions and taking the case of a longitudinal uniform E-region, the growth rate is obtained as Sultan [20]

\[
\gamma = \frac{-\Sigma_{F,0}^E - \Sigma_{P,0}^F}{\Sigma_{P,0}^E + \Sigma_{P,0}^F} \frac{g_e}{L^3} K^F
\]

when the flux tube integrated quantity \( V^{\text{eff}}_F \) is an effective F-region collision frequency weighted by number density along the flux tube, \( \Sigma_{F,0}^F = m_i L^3 N^F F^{\text{eff}}_F / B_0^2 \) is integrated F- region Pederson conductivity, \( K^F = \frac{1}{R_e L^3 N_0^F} \frac{\partial}{\partial L} (L^3 N_0^{F}) \) is the F-region flux tube electron content height gradient and \( g_e = g_0 / L^3 \).

The R-T linear instability growth rate, considering the effects of chemical recombination (\( R_T \)), neutral winds (\( U^P_L \)) and ambient electric fields (\( E_\phi \)) and neglecting the effects of E-region horizontal density gradients, can now be summarized by Sultan [20]

\[
\gamma = \frac{\Sigma_{P,0}^F}{\Sigma_{P,0}^E + \Sigma_{P,0}^F} (V_p - U^P_L - \frac{g_e}{V^{\text{eff}}_F}) K^F - R_T
\]

The \( V_p \) is the flux tube integrated plasma velocity perpendicular to B, which is equivalent to the zonal electric field term \( E_\phi L^3 / B_0 \).

### 5. Computation of Growth rates

The R-T linear growth rate of the irregularities have been numerically evaluated using the above equation (7). In the computation, the Parameterized Ionospheric Model (PIM) [21] and the Mass spectrometer Incoherent Scatter (MSIS) thermospheric model [22] has been used to obtain the ambient electron density and neutral densities as a function of altitude and latitude. Vertical winds (\( U^P_L \)) in the range of 10-25 ms\(^{-1}\) have been observed over SHAR [23] and hence a vertical wind of 20 ms\(^{-1}\) has been used. The corresponding westward electric field is \( \sim 0.8 \text{ mV/m} \) [24]. The flux tube integrated R-T instability growth rate as a function of the apex altitude is plotted in Fig. 4. The figure shows that the largest growth rates are at the lower altitude, however, indicating that the bottom side is still the most likely place for plume events to begin.
6. Validity of the Model
Instability growth rate patterns over a seasonal time frame can be found using the flux tube model by calculating $\gamma$ altitude profiles as a function of both of local time and time of year. The maximum value of each profile is shown in Fig. 5 (a) for solar maximum conditions. These seasonal patterns are calculated for the equatorial region [20]. Here average geophysical conditions are used throughout. The occurrence patterns for VHF scintillation contours of 250 MHz frequency observed at low latitude station Varanasi for the years 1991-92 are plotted in Fig. 5 (b) for comparison with the calculated patterns of instability growth rate. These data does not correspond one-to-one correlation with computed values. However, there is a striking agreement in morphology between the model and data occurrence patterns. Observed occurrence peaks and computed growth rate maxima centered on the Equinox months and seen to match up well and both plots shows deep minima near the Summer months.
7. Conclusions
The study revealed that daytime VHF scintillations particularly in the late afternoon hours may be due to E-region irregularities and the night time scintillation may be due to the F-region irregularities. The irregularities observed during summer months are relatively weak as compared to those recorded during winter and equinox months. Weak scintillations observed during the recovery phase in some magnetic storms are attributed to freshly generated irregularities caused by disturbance dynamo electric fields. The increase in solar activity normally increases the occurrence of scintillation but also decreases with the decrease of solar activity. The enhancement in magnetic activity leads to a suppression of occurrence of scintillation. The inhibition and generation of irregularities during enhanced magnetic activity period are explained by considering changes in the electric field.

In this paper we have tried for further understanding of the geophysical conditions that lead to initiation of ESF events. The resulting form of γ extended the results of previous work by including direct dependencies on trans-equatorial neutral winds, zonal electric fields, vertical and horizontal ionospheric density gradients and chemical recombination. When growth rates are computed over a climatologically times scale, the local time/time of year pattern of growth rate determined for the equatorial region is found to have the same overall morphology as patterns of scintillation occurrence at Varanasi. Thus it is concluded that the magnetic flux tube formalism well duplicates the physics of the low latitude/equatorial ionosphere. Since the plasma instability and its consequences are usually observed in the fully developed nonlinear state, hence an accurate non-linear theory is to be developed to explain the observations of irregularities.

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References
[1] Aarons J and Basu S 1994 Ionospheric amplitude and phase fluctuations at the GPS frequencies In Proceeding of ION GPS-94 Inst.of Navig., Arlington Va. 1569–1578
[2] Basu S, Groves K M, Basu Su and Sultan P J 2002 Specification and forecasting of scintillations in communication / navigation links: current status and future planes J. Atm Solar Terr. Phys. 64 1745-1754
[3] Groves K M, Basu S, Weber E J, Smithan M, Kuenzler H, Valladares C E, Sheehan R, Mackenzie E, Secan J A, Ning P, McNeill W J, Moonan DW, and Kendra M J 1997 Equatorial scintillation and system support Radio Science 32 2047–2064
[4] KelleyM C 1989 The Earth’s ionosphere Plasma Physics and Electrodynamics Academic Press San Diego, Calif
[5] Valladares C E, Hanson W B, McClure J P, and Cragin B L 1983 Bottom side sinusoidal irregularities in the equatorial F-region J. Geophys. Res. 88 8025–8042
[6] Fejer B G 1997 The electrodynamics of the low latitude ionosphere: Recent results and future challenges J. Atmos. Solar Terr. Phys. 59 1465–1482
[7] Aarons J, Mullen J P, Koster J R, daSilva R F, Madeiros J R, Medeiros R T, Bushby A, Pantoja J, Lanat J, and Paulson M R 1980 Seasonal and geomagnetic control of equatorial scintillations in two longitudinal sectors J. Atmos. Terr. Phys. 42 861–866
[8] Rastogi R G, Mullen J P, and Mackenzie E 1981 Effect of geomagnetic activity on equatorial VHF
scintillations and spread F. *J. Geophy. Res.* **86** 3661

[9] DasGupta A, Maitra A, and Das S K 1985 Post-midnight scintillation activity in relation to geomagnetic disturbances *J. Atmos. Terr. Phys.* **47** 911–916

[10] Pathak K N, Jivrajani R D, Joshi H P, and Iyer K N 1995 Characteristics of VHF scintillations in the equatorial anomaly crest region in India *Ann. Geophys.* **13** 730–739

[11] Chakraborty S K, DasGupta A, Ray S, and Banerjee S 1999 Long term observations of VHF scintillation and total electron content near the crest of the equatorial anomaly in the Indian longitude zone *Radio Science* **34** 241–255

[12] Basu B 2002 On the linear theory of equatorial plasma instability: comparison of different descriptions *J. Geophys. Res.* **107** A8, 10.1029/2001JA000317

[13] Haerendel G 1974 Theory of equatorial spread-F, Rep. Max Planck- Institut f’ur Phys. and Astrophys. Garching Germany

[14] Woodman R F and LaHoz C 1976 Radar observations of equatorial F-region irregularities *J. Geophys. Res.* **81** 5447–5466

[15] Basu S and Basu Su 1989 Scintillation technique for probing ionospheric irregularities, in World Ionospheric/Thermospheric Studies(WITS) Handbook, vol 2, edited by Liu C H, SCOSTEP, University of Ill., Urbana 128–130

[16] Kumar S and Gwal AK 2000 VHF ionospheric scintillations near the equatorial anomaly crest: solar and magnetic activity effect *J. Atoms. solar Terr phis* **62** 157-169

[17] Singh R P, Patel R P, Singh A K 2004 Effect of solar and magnetic activity on VHF scintillations near the equatorial anomaly crest *Ann. Geophys.* **22** 2849-2860

[18] Haerendel G 1973 Theory of equatorial spread F, Report Max-Planck Institute Fur. *Phys. Und. Astrophys. Garchin* West Germany

[19] Haerendel G, Eccles J V and Cakir S 1992 Theory for modeling the equatorial evening ionosphere and the origin of the shear in the horizontal plasma flow *J. Geophys. Res.* **97** 1209-1223

[20] Sultan P J 1996 Linear theory and modeling of the Rayligh-Taylor instability leading to the occurrence of equatorial spread F *J. Geophys. Res.* **101** A12 26875-26891

[21] Daniell R E, Brown Jr L D, Anderson D N, Fox M W, Doherty P H, Decker D T, Sojka J J and Schunk R W 1995 Parameterized ionospheric model: a global ionospheric parameterization based on first principle *Radio Science* **30** 1499-1510

[22] Hedin A E, 1987MSIS-86 thermospheric model *J. Geophys. Res.* **92** 4649-4662

[23] Raghavarao R, Gupta S P, Sekar R, Narayanan R, Desai J N, Sridharan R, Babu V V and Sudhakar V 1987 In-situ measurements of wind, electric fields and electron densities at on the set of equatorial spread F *J. Atmos. Terr. Phys.* **49** 485-492

[24] Raizada S and Sinha H S S 2000 Some new features of electron density irregularities over SHAR during strong spread F *Ann. Geophys.* **18** 141-151