Statistical analysis and modelling of equatorial spread F parameters obtained from VHF radar at three longitudinal sectors

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Abstract

Equatorial Spread F (ESF) is a manifestation of ionospheric interchange instabilities in the nighttime equatorial F region. These instabilities generate plasma density irregularities with scale sizes ranging from kilometers to thousands of kilometers. In the present study, statistics of various aspects of spread F occurrence are presented from HF/VHF radar located at three equatorial stations: Christmas Island (2^{o}N, 202.6^{o}E, 2.9^{o}N dip latitude, VHF radar), São Luís (2.59^{o}S, 315.8^{o}E, 0.5^{o}S dip latitude, HF radar) and Jicamarca (12^{o}S, 283.1^{o}E, 0.6^{o}N dip latitude). The spread F parameters presented here are the onset altitude and onset time (onset refers to first appearance of signal in the radar field of view) of the bottom-type and plume, and the peak altitude of the plume which are known to be associated with the spread F occurrence characteristics. The study reveals novel features namely, seasonal and solar flux dependence of spread F occurrence over Christmas island /São Luís, and longitudinal dependence of spread F occurrence characteristics from these three stations based on the chosen parameters. The importance of this work lies in the spread F parameter empirical model developed combining statistical analysis of three equatorial and longitudinally separated stations, which is important to study evolution of irregularities in different longitudinal sectors for space weather forecasting and nowcasting programs, and improving scintillation warning models. These parameters show generally linear correlation with solar flux index (F10.7 cm) and variation with season and magnetic declination angle. The fit correlation with F10.7cm is shown as useful information to implement one spread-F development empirical model based on small scale irregularities detected by VHF radars.

Introduction

Upward developing plumes from upwelling of the bottomside F layer associated with equatorial spread F (ESF) events have been studied with VHF/UHF/L-band backscatter radars located near the geomagnetic equator [e.g. Woodman and LaHoz, 1976; Tsunoda et al., 1979; Tsunoda 1980a, Tsunoda 1980b; Hysell and Burcham, 1998; de Paula et al., 2004a; Kudeki et al., 2008]. ESF is formed by the Rayleigh-Taylor instability in the bottomside F layer above the geomagnetic equator and it grows nonlinearly to the topside [e.g. Ossakow, 1981]. Related to initiation of ESF, the eastward electric field in the dayside equatorial ionosphere is sharply intensified just before it reverses to the nightside westward direction. This intensification gives origin to the so-called evening plasma prereversal enhancement [e.g. Rishbeth, 1971; Farley et al, 1986; Haerendel et al., 1992; Abdu, 2005] which is responsible for the initiation of the Rayleigh-Taylor instability by increasing both the gravitational and electrodynamic terms of the growth rate [e.g. Fejer et al, 1999; Abdu, 2001]. It has been established that the height of the post-sunset F layer is the most important parameter controlling the generation of equatorial spread F [e.g. Farley et al., 1970; Abdu et al., 1983; Jayachandran et al., 1993; Fejer et al., 1999].

Much of the advances in studying the equatorial spread-F phenomena resulted from VHF backscatter radar measurements [e.g., Farley et al., 1970; Woodman and La Hoz, 1976; Kudeki et al., 2007; Rodrigues et al., 2004]. The ESF phenomenon occurrence covers a wide spectrum of scale sizes ranging from few centimeters to hundreds of kilometers, and varies with longitude, local time, season and solar and geomagnetic activity. The irregularities can be detected by coherent and incoherent scatter radars, in situ space probes, radio propagation, and airglow detectors in addition to ionosondes. Although the irregularities represent a continuum of scales, most remote techniques for observing them are sensitive to particular scale sizes (Basu et al., 1978).

A series of papers had discussed the occurrence patterns of bottom-type, bottomside, and topside echoes [e.g. Hysell and Farley, 1996; Hysell and Burcham, 1998; Hysell, 2000; Hysell and Burcham, 2002]. Bottom-type and bottomside spread F layers are both scattering layers that exist in the bottom side of the F region. Bottomside layers frequently appear subsequent to bottom-type layers, the reverse does not happen. Bottom-type layers are narrowed and confined to an small range of altitudes under the action of a still westward zonal electric field. They do not present much vertical development. This layer cause very less spreading in the ionograms. The bottomside layer is considerably more intense and structured broad scattering layer than the bottom-type layer and occasionally gave rise to small plumes penetration into the topside. Bottomside layers are those that emerge in regions of the ionosphere controlled by the F region dynamo [Hysell and Farley, 1996; Hysell and Burcham, 1998]. This layers drift eastward. Radar plumes are evidence of deep plasma depletions rising up through the F peak under the influence of well-developed instabilities and entering to the topside. Large-scale radar plumes seem to occur frequently in the time interval of transition from bottom-type to bottomside layers, where the F region flow changes from westward to eastward.

Instrumentation

This work presents results of observations made by three radars. Coherent scatter VHF radar observations at São Luís (SLZ), Christmas Island (ROJ) and Jicamarca (ROJ) were analyzed. The geographic and geomagnetic coordinates of these equatorial stations are presented at Table 1, and geographic positions of these equatorial stations in stars over geomagnetic field lines (Bz) are presented in Figure 1. Figure 1 represents the variation of the magnetic declination angle at each equatorial station. The declination is represented as the angle between the perpendicular line to the geomagnetic equator (blue line) and the true north (black line).

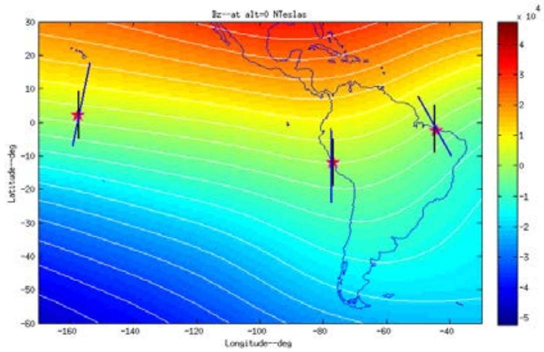

Figure 1. The geographic position of the three equatorial stations are plotted in stars over the geomagnetic field lines (Bz). Modified code of magnetic field lines from Copyright (c) 2010, Charles Rino.

Station	Geo. Lat.	Geog. Long.
SLZ	2.59° S	44.2° W
ROJ	12.0° S	76.9° W
CXI	2.0° N	157.4° W

Table 1. Geographic and geomagnetic coordinates of the equatorial ionospheric stations.

VHF radar specifications and parameters for the three equatorial stations are shown in Table 2. Details of operational and experimental issues for São Luís radar can be found in de Paula and Hysell (2004), de Paula et al. (2004b), Rodrigues et al. (2004), and Rodrigues et al. (2008); in Woodman and Hagfors, 1969; Kudeki and Bhattacharyya, 1999, for Jicamarca radar; and Tsunoda et al., 1995; Miller et al., 2009; Miller et al., 2010 and Makela et al., 2009, for Christmas Island radar.

	São Luís	Jicamarca (2003-2006 / 2007-2013)	Christmas Island
Antenna half-power-full-beam-width	10°	1°	2.3°
Inter-pulse-period (IPP)	1400 km (9.34 ms)	2000 km (13.33 ms) / 937.5 km (6.25 ms)	782 km (2.6 ms)
Altitude coverage	87.5-1267.5 km	79.95-1961.85 km / 0 – 926.25 km	83.9-865.96 km
Altitude resolution	2.5 km	2.55 km / 3.75 km	8.75 Km
Velocity coverage	±250 m/s	±112 m/s / ±240 m/s	±250 m/s
Peak Power	4 kW	1.5 MW	16 kW
Frequency	30 MHz	50 MHz	50 MHz
Small-scale irregularities	5 m	3 m	3 m
Noise Band	120 KHz	120 KHz	100 KHz

Width			

Table 2. VHF Radar specifications/parameters for the three equatorial stations in use.

Method

In the present work we use coherent scatter radar measurements over Christmas Island, São Luís and Jicamarca, located at equatorial regions in different longitudinal sectors. Christmas Island data are from 2003 to 2009, period that corresponds from the descending phase to extended minimum phase of the last solar cycle. São Luís data covers period from 2001 to 2008, and Jicamarca data covers period from 2001 to 2009 covering from solar maximum to solar minimum periods.

Coherent scatter radar observations of the ionospheric plasma irregularities are usually displayed in range time intensity (RTI) format, in which the backscatter power is plotted against altitude and time. The structures presented in the RTI plots show high day-to-day variability in the equatorial spread F occurrence. This high variability of the structures, observed in the RTI plots, may be sorted into few main categories. These are bottom-type layers, bottomside layers, topside layers (radar plumes), and post midnight irregularities.

Figure 2 depicts an ESF event at São Luís radar on December 1, 2002. The figure shows the backscatter signal-to-noise ratio in dB versus altitude (in km) and time (in UT). The color bar shows S/N index from -5 to 20 dB units. Intense backscatter indicates the presence of strong plasma irregularities with 5 m wavelength. Indicated in black lines and labels are the spread F parameters used. This image is a classic representation of spread F observed over São Luís station during high spread F activity.

The present statistical study is based on identifying spread F parameters which are related to bottom-type, bottomside and plumes structures. This study adopts the methodolgy of climatological/statistical study of series of papers from Fejer et al. (1999), Hysell and Burcham (2002), Chapagain et al. (2009) and de Paula et al. (2011). These authors had stated climatological study of the ESF characteristics using the altitude and time parameters of spread F observed with VHF radar, in function of solar flux-dependence in order to state forecasting strategies. These parameters are shown in RTI plots in Figure 2. These parameters are labeled as onset time (**Ti**) and height (**Hi**) of initial spread F which is the time and altitude of the first appearance of bottom-type, and onset time (**Tp**) and height (**Hp**) of plumes which is the time and altitude of the first appearance of the plume, as well as the peak altitude (**Hpk**) of the radar plume. The peak altitude parameter can only be determined when radar plume is present in the RTI plots. The onset time and altitude stand for the time and altitude, when/where the back scattered signal first appear in the radar field of view. The identification of parameters are based on RTI map where (S-N)/N is plotted. (S-N)/N greater than -10 dB are considered for the estimations of these parameters. Therefore, the estimated parameters are subjected to change depends on noise level and the chosen criteria.

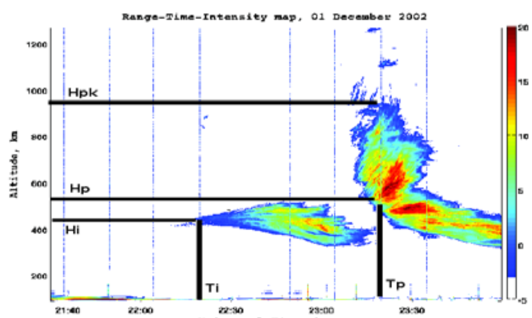

Figure 2. Plume characteristics observed at São Luís station on 01 December, 2002. The VHF radar parameters are highlighted in black label.

Results

In this section we show the season- and solar flux-dependence of the onset times and heights of spread F parameters as seen in the VHF radar RTI maps over Christmas Island, São Luís, and Jicamarca stations. We present all available observations and do not separate by geomagnetic activity, since no much good statistical representation was obtained with our database. Even though during 2001 to 2003 there was fair amount of magnetic activity, which correspond to solar maximum, there were no enough data for geomagnetic activity statistical purposes. At the same time we present the climatological behavior of the radar data showing the F region irregularity activity in function of solar flux, season and magnetic declination.

We separated the measurements in three seasons representing equinox (March-April and September-October), December solstice (November-February) and June solstice (May-August) for São Luís and Jicamarca. For Christmas Island, that is located in the northern hemisphere the solstice seasons are the opposite. In order to not confuse the reader with northern and southern seasonal nomenclature we use nov-feb and may-aug referring to the months of each solstice. Moreover, measurements have been binned by data-points to represent seasonal and solar flux dependence. Results for may-aug (souther winter) solstice are not present for São Luís neither for Jicamarca due to lack of data resulting in no statistical representation for this analysis.

Abdu et al. (1981) found that magnetic declination plays a significant tole in the amplitude and duration of vertical F layer movement during the pre-reversal enhancement of the eastward electric field. The F region vertical peak velocity depends directly of the conductivity variation of the E magnetically conjugate regions. The sunset time in each of the E conjugate regions has a particular seasonal variation, occasioned by the magnetic declination angle. So, whether one of the E conjugate regions remains illuminated by the sun during the sunset period a closed partial circuit through the E and F regions still exists. Tsunoda (1985), Farley et al. (1986) Abdu et al (1982) and Batista et al. (1986) described that the seasonal dependence of sunset vertical drift and spread F (and scintillation) occurrence at a given longitude are controlled by the magnetic declination angle, and high occurrence is expected during the months when the conjugate E layers enter darkness at the same time with a consequent integrated Pedersen conductivity decrease. This confirms that the alignment might be necessary, although insufficient, condition for irregularity growth (Tsunoda et al., 1982, Tsunoda, 1985). The thermospheric wind seasonal variations also affects the ESF occurrence.

The seasonal difference in maximum occurrence over São Luís and Christmas Island/Jicamarca is owing to the finite magnetic declination angle effect as explained by de Paula et al (2011). Magnetic declination control of topside SF was reported by Maruyama and Matuura (1980). Tsunoda (1985) showed that seasonal variation in the scintillation occurrence and its longitude dependence could indeed be explained by the longitude dependent magnetic declination angle. Thus, the spread F maximum season in Brazil which present a westward declination (with declination angle ~20^o W at São Luís) is centered in the solstitial months, whereas at Jicamarca with almost zero declination (declination angle being ~0^o W) are present two maximal centered in the equinoctial months of September and March. Meanwhile, in Christmas Island with slow eastward declination (declination angle of 8.55^{o}W) the spread F maximum season is around the winter (summer) solstice for southern (northern) hemisphere.

Spread F parameters in function of Solar Flux during different seasons

For each season the spread F parameters for selected solar flux bins were calculated and then plotted the modelled results in Figures 3 and 4, that show these parameters for Christmas Island, Jicamarca and São Luís stations for 3 seasons (equinox and nov-feb and may-aug solstices). It is observed a linear correlation of the VHF radar spread F parameters with the solar flux. As a general finding, for seasonality and for each equatorial stations, the onset altitude of bottom-type (Hi), plume (Hp) and peak altitude (Hpk) of the topside plume increase as the solar flux increases and the onset time of bottom-type (Ti) and plume (Tp) decrease as solar flux increases.

Observing the linear fits we can observe that, for Christmas Island station, the time parameters has a strong decrease as the solar flux increases while altitude parameters has a tendency to increase with solar flux. For São Luís, the altitude parameters have a stronger increase with the solar flux in nov-feb than in equinox. The onset time (Ti) of bottom-type has an small decrease tendency as the solar flux decreases during equinoctial and nov-feb solstice seasons for São Luís. For Jicamarca the altitude parameters have a stronger increase with the solar flux in equinox than in nov-feb. The onset time (Ti) of bottom-type has an small decrease tendency as the solar flux decreases during equinoctial and nov-feb solstice seasons for São Luís and Jicamarca. The results obtained for Jicamarca are already known characteristic (Chapagain et al, 2009). However, for Christmas island and São Luis, these characteristics are not known and present study bring out these results for the first time as seasonal, longitudinal and solar flux dependence.

Even with the poor statistical representation for nov-feb solstice for CXI we were able to represent the same general VHF parameters trend, but however due to scarce data the standard deviations in nov-feb solstice are large. It is good to highlight that the period covered for CXI is mostly for solar minimum then the x-axes goes up to 150 sfu instead of 300 sfu as in SLZ and ROJ stations.

From the scatter bars (standard deviations) analysis (not shown here) is revealed that in radar observations, in particular, the occurrence and morphology of ESF is highly variable on day-to-day basis [Woodman and La Hoz, 1976; Tsunoda et al., 1982]. The high variability of spread F irregularities occurrence in altitude and time are being investigated by different authors and recently published by Valladares et al. (2004), Miller et al. (2010), Kherani et al. (2012), Seemala et al. (2011) and de Paula et al. (2012). They stated that spread F high day-to-day variability occurrence and longitudinal behavior depends on the onset conditions as onset altitude, onset time and velocity of the prereversal vertical drift, wave-like seeding and its solar flux dependence.

Is important to mention that in Jicamarca and São Luís stations at approximately ~180 sfu for equinox and ~200 sfu for nov-feb solstice was observed an apparent saturation of the altitude parameters (onset altitude and peak altitude of the plume). Same finding was previously indicated by Chapagain et al. (2009) using Jicamarca plume parameters, but no clear reason for this behavior was mentioned. More effort needs to be done from data coming from one more solar cycle to improve this observation.

The present work confirms the results obtained by Hysell and Burcham (2002), that indicates that during high solar flux activity the magnitude of the plasma prereversal enhancement is larger, causing rapid movement of the F layer to higher altitudes and consequently the frequency of the irregularities are also higher in solar maximum than in solar minimum. This is observed during the high solar flux when plumes onset and peak altitude reach higher altitudes than during low solar flux conditions.

Longitudinal effect of spread F parameters

It is well established that different longitudinal regions have different annual or seasonal patterns in ESF occurrence and intensity. Years of high solar flux bring about both higher occurrence of equatorial irregularities and higher intensities. However the longitudinal pattern remains approximately the same even when solar flux changes from solar maximum to solar minimum (Aarons, 1993).

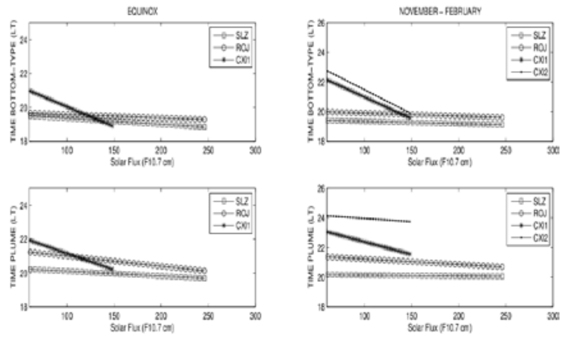

Figure 3. Seasonal/Longitudinal comparison of Time VHF radar parameters. The line values (CXI2) represent may-aug season.

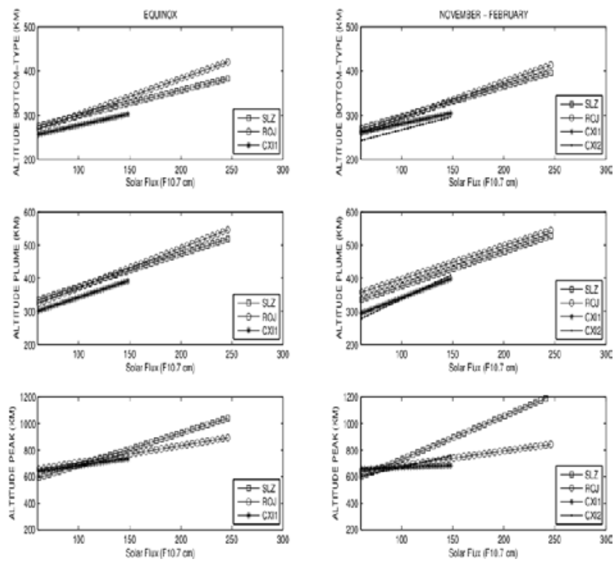

Figure 4. Seasonal/Longitudinal comparison of Altitude VHF radar parameters. The line values (CXI2) represent may-aug season.

A defining cause for the seasonal difference in the maximum occurrence over São Luis and CXI/JRO is the finite declination angle effect over São Luis. This aspect is discussed at the beginning. In order to analyze the longitudinal difference of occurrence characteristics among these three stations, we develop a empirical model based on empirical relations. The empirical relations in each station by season/VHF radar parameter allows to develop an empirical model which is important to study the evolution of irregularities in different longitudinal sectors, for space weather forecasting and nowcasting programs, and improving scintillation warning models. Figure 3 and 4 show the seasonal behavior/radar parameters empirical model for nov-feb solstice and equinox for SLZ and ROJ, and equinox, nov-feb and may-aug solstices for CXI. These Figures present time and altitude parameters in function of solar flux. Each station is named as SLZ, ROJ and CXI1 and CXI2. CXI1 is related to nov-feb solstice and CXI2 to may-aug solstice when presented as solstices.

The similar slope in the altitude parameters characterize the increase gradient from low to high solar flux which is almost the same for the three stations (even in seasonality), but differing just in nov-feb solstice for the peak altitude parameter. In the time parameter for SLZ and ROJ are mostly horizontal which means no much solar flux dependence, but in CXI the time parameters show high solar flux dependence with exception of may-aug solstice (CXI2) for onset time of the plume which seems to be also horizontal.

During solstices Ti and Tp parameters from CXI are later than the southern stations, moreover may-aug solstice being later than nov-feb solstice. In the Tp parameter for may-aug solstice there is no appreciable time variation.

The time variation for Ti and Tp parameters with season and solar flux dependence was also studied and an interesting feature was observe in the time occurrence of the irregularities (being bottom-type or plume structure) along the years from solar maximum to solar minimum.

Conclusions

This work presents several interesting conclusions regarding the climatology of the VHF radar parameters during the course of the solar cycle, in three longitudinal spaced stations. Time and altitude parameters were analyzed as solar flux dependence, and studied in function of seasonality and longitude.

A linear correlation of the VHF radar spread F parameters in the three longitudinally separated stations when plotted against the F10.7 solar flux was found. For the three radar sites, and for all seasons the onset altitude of bottom-type (Hi), plume (Hp) and peak of the topside plume (Hpk) increase as the solar flux increase. The onset time of bottom-type (Ti) and plume (Tp) decrease as solar flux increase. The onset time (Tp) and onset altitude (Hp) of plume parameters are highly important from scintillation point of view, because scintillation at GPS/VHF frequencies are observed when plume formation starts. Therefore, during high solar flux, the scintillations should occur early and at higher altitude, in comparison to that during low solar-flux.

It was observed that for solar fluxes larger than 180 units for equinox and 200 units for nov-feb solstice there is a saturation in the irregularity onset and plume peak altitudes.

The linear fits and mainly the slope corresponding to each station, for each season and for each parameter are presented in this paper. The development of a radar parameter empirical model results of combining statistical analysis of VHF radar parameters of three equatorial and longitudinally separated stations. These contributions about plasma bubbles evolution in time and altitude (controlled by background ionospheric conditions) in function of longitude and season might be useful to understand the evolution and structuring of ESF and also for satellite (like C/NOFS) orbit planning.

Was found a similar slope in the altitude parameters which characterize the increase gradient from low to high solar flux that is almost the same for the three stations (even in seasonality), but differing in nov-feb solstice (for the peak altitude parameter).

Acknowledgments

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