Spread F echoes variability along solar flux and seasonality conditions over the 50-MHz radar on Christmas Island

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This paper was prepared for presentation during the 14th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 3-6, 2015.

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Abstract

Perturbations in the amplitude (or phase) of radio signals are caused by irregularities in the ionospheric electron density. Ionospheric structures can disrupt the propagation of radio waves, and are commonly observed, for instance, by ionospheric vertical radio sounders (ionosondes). For historical reasons, the signatures of ionospheric irregularities in different types observations (optical, radio, *in-stu*) are referred to as equatorial spread F (ESF). Previous studies show that the occurrence rate can be greatly affected by solar and magnetic conditions. Observations during the period of 2003 to 2012 of nighttime echoes made from the 50-MHz radar on Christmas Island (2.0º N, 157.4º W) have revealed time and altitude pattern distribution along the descending phase of solar cycle 23 and the recent extended solar minimum phase. We present the study of spread F echoes as a function of solar flux conditions and seasonality in order to quantify their variability. Under higher solar flux conditions, echoes reach higher altitudes but decay earlier. Only during solar minimum conditions the echoes exist throughout the whole night, since the post- reversal anti- zonal background electric field is weaker. Thus, irregularities during solar maximum will be dominated by dynamics near the time of the PRE. Since the population of irregularities during solar minimum exists throughout the whole night, post- reversal ionospheric conditions may play a role in the morphology of plasma irregularities, especially with the coincidentally weaker PRE during solar minimum.

Peak time occurrence of echoes along the current period show a well defined pattern, meanwhile the peak altitude occurrence of echoes show a slight regular pattern.

Introduction

Perturbations in the amplitude (or phase) of radio signals caused by irregularities in the ionospheric electron density have been studied since the pioneer work of Booker and Wells (1938). Ionospheric structures can disrupt the propagation of radio waves, and are commonly observed, for instance, by ionospheric vertical radio sounders (ionosondes). For historical reasons, the signatures of ionospheric irregularities in different types observations (optical, radio, *in-stu*) are referred to as equatorial spread F (ESF).

ESF irregularities have a wide spectrum of scale sizes, ranging from a few centimeters to thousands of kilometers. The seminal ionospheric radar work of Woodman and LaHoz (1976) attributed the term “plumes” to describe radar echoes reaching the topside ionosphere. The echoes were caused by meter-scale irregularities developing in the west wall of large-scale ionospheric plasma depletions caused by an interchange plasma instability (Tsunoda, 1983). The observed tilt of the plumes was explained using numerical simulation by Ossakow (1981) and Zalesak et al. (1982).

Is well accepted that the most important mechanism for the generation of the F-region plasma irregularities is the generalized Rayleigh-taylor (RT) instability, which reaches greatest linear growth rates in the bottomside of the post-sunset equatorial F region (Fejer et al., 1999). Numerical simulations of the non-linear evolution of RT instability indicate that large-scale and amplitude plasma depletions start to develop in the bottomside and reach the topside F-region. These depletions create conditions favorable for the development of smaller (including meter) scale irregularities, which cause VHF radar echoes.

The RT instability (and ESF) is controlled by a number of parameters including the pre-reversal enhancement (PRE) of the zonal equatorial electric field, zonal and meridional neutral winds, longitudinal conductivity gradients, flux tube integrated conductivities, and, possibly, variations in initial (or seed) perturbations (Abdu, 2001). It has been noted that ESF bubbles at pre-midnight and post-midnight could be driven by different mechanisms (Dao et al., 2011; Yizengaw et al., 2013).

In this paper we present results of a comprehensive study of long-term observations of meter-scale F-region irregularities observed in the Pacific sector. The observations were made by a 50 MHz coherent backscatter radar between 2003 and 2012 years and including the study of seasonality of time and altitude of spread F echoes variations.

Measurements and Analyses

For this study, we used observations of meter-scale F-region irregularities made by a 50 MHz coherent backscatter radar located in Christmas Island (2.0º N, 157.4º W). The site is located near the magnetic equator, within a region of positive magnetic declination.

Measurements made between January 2003 and December 2012 were available for this study. The magnetic inclination (declination) at Christmas Island varied from 4.69º(9.36˚E) in 2003 to 4.61º(9.38ºE) in 2012.

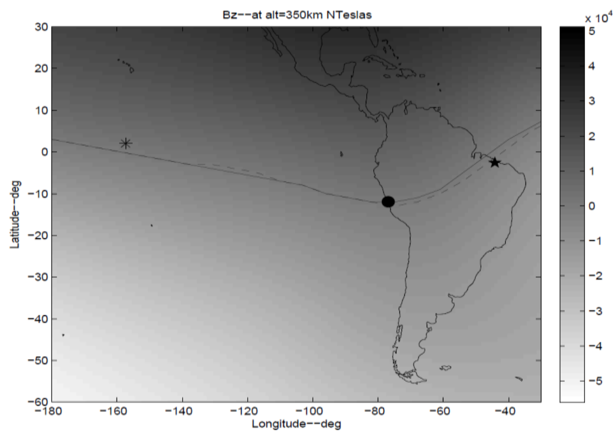


Figure 1 – Global map on which we show the location of the F-region (350 km altitude) magnetic equator 2003 (dashed line) and 2012 (solid line) according to the International Geomagnetic Reference Field (IGRF) model. The map also shows the location of the Christmas Island (CXI) radar (as asterisk) and the location of other radars used for ESF studies for reference like Jicamarca (as dot) and Sao Luis (as star) equatorial stations.

Figure 1 shows a map indicating the location of the F-region (350 km) magnetic equator (for 2003 and 2012) according to the International Geomagnetic Reference Field (IGRF) model. The map also shows the location of the Christmas Island (CXI) radar and the location of other radars used for ESF studies like Jicamarca and São Luís equatorial stations. The Christmas Island radar was, initially, operated by SRI International (2002-2007) and is now operated by the US Air Force Research Laboratory (AFRL). The system uses a 100 m x 100 m coaxial collinear (COCO) antenna array. Two stationary beams are used for measurements. One beam is pointed North (azimuth 0º and elevation 84.5º) and the other one is pointed to the east (azimuth 90º and elevation 60.5º). For this study, we will be using measurements made by the North beam only, which is nearly vertical. The beams have symmetric half-power beam widths of about 2.3º.

Figure 2 shows the variation of the solar flux index F10.7 between January 2003 and December 2013. We can see that the measurements available to this study cover solar conditions where F10.7 varied from 200 SFU (low solar flux conditions) to 66 SFU (high solar flux conditions).

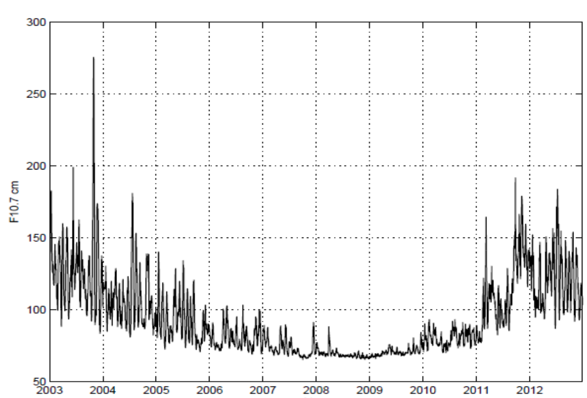


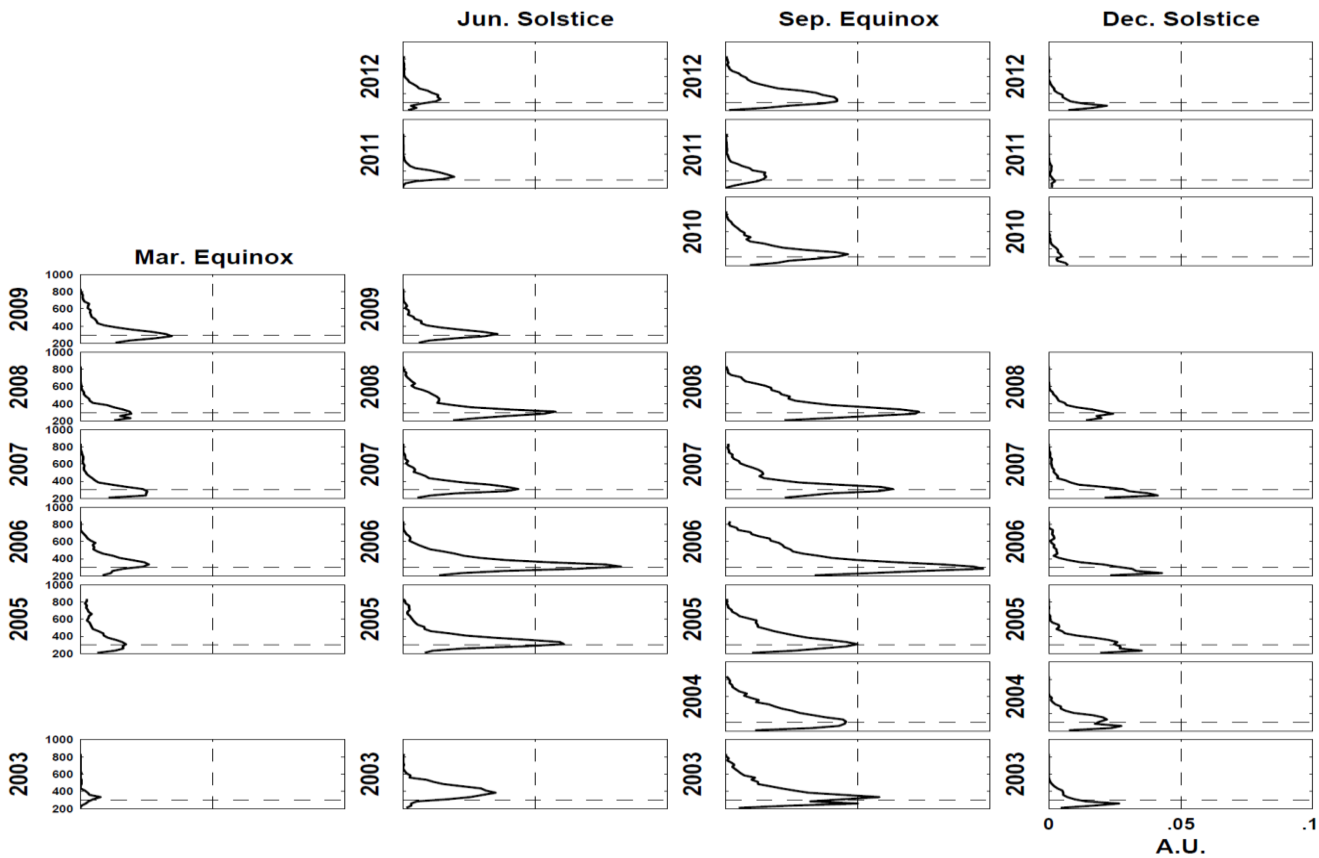
Figure 2 shows the variation of the solar flux index F10.7 between Janeiro 2003 and December 2012. The measurements (from 2003 to 2012) available for this study cover solar conditions where F10.7 varied from 200 SFU to 66 SFU.

We are interested in the occurrence of F-region echoes (meter-scale irregularities) as a function of local time and height for different seasonal and solar flux conditions. For this study, we limit our focus to quiet-time irregularities.

Geomagnetic activities can directly disturb the equatorial zonal electric field which affect the occurrence of F region irregularities. These effects on the occurrence rate of F region irregularities can be related to the eastward prompt penetration which act increasing the amplitude scintillation in VHF and GPS signals or the westward ionospheric disturbance dynamo electric fields which act decreasing the occurrence of irregularities and depletions. In order to classify the geomagnetic conditions of the measurements we used the 3-hour Planetary K index (Kp). Each radar measurements was tagged with the value of Kp for the time of the measurement plus the previous 3 Kp values. We considered quiet-time measurements to be those when none of the Kp values exceeded 3.

Then we grouped the data into seasons: Spring Equinox (March 21+/-45 days), Summer Solstice (June 21+/-45 days), Fall Equinox (September 21+/-45 days) and Winter Solstice (December 21+/-45 days). We used the quiet time echoes, for each season, to derive the occurrence rate of echoes. We found that, a good representation of irregularity occurrence is given by the number of echoes above 0 dB divided by the total number of observations. Our criterion is a good compromise between being able to identify the occurrence of spread F echoes and eliminate the effects of non-geophysical echoes caused by clutter.

The occurrence rate of irregularities is estimated for every 15-minute intervals starting at 18:00 LT, right before sunset until 05:00 LT near dawn. We also compute occurrence rates for every 15-km height intervals starting at 200 km up to 1000 km altitude. Therefore, this allows us to construct maps of the irregularity occurrence rate as a function of height and local time.



Results

Figure 3. Altitude Variations of spread F echoes observed over Christmas Island equatorial station for the period of 2003 to 2012, also separated by equinoxes and solstices. The horizontal line represent the threshold of 300 km, and the vertical line represent the 0.5 A.U. just for reference.

The results achieved in this report were expected since the evening upward drifts and layers heights increase noticeably with solar activity, and during nighttime, along solar maximum, the spread F occurs near the time when upward drift is large which is immediately after local sunset (Fejer et al., 1999). While during solar minimum when the upward drift is usually short the spread F exists throughout the whole night, and upward and downward ionospheric conditions may play a role in the morphology of irregularities.

The Figure 3 shows the solar cycle variation of height occurrence rate of meter-scale irregularities for March equinox, June Solstice, September equinox and December solstice in each column, from left to right. We can observe that higher echoes occurrence are around June and September months compared with March and December months, this observation is due to the peak occurrence of spread F for this region which occur around July-August months as represented by Cueva et al. (2013) and Niranjan et al. (2003).

Analysis of altitude profiles of Figure 3 along solar maximum and minimum conditions bring us a maximum peak occurrence of echoes in solar minimum period, and independent of season. During June solstice and September equinox occur a major increase in altitude profile when compared with March and December months. The horizontal line in the figure represents the threshold of 300 km in each altitude profile. Then we can observe that during June and September seasons the peak altitude was little over or on the threshold altitude, and during March and December seasons the peak altitude was below the threshold altitude. The peak altitude profile for each year occurs during September equinox, with minimum altitude profile during March Solstice.

The Figure 4 shows the solar cycle variation of time occurrence rate spread F echoes for March equinox, June Solstice, September equinox and December solstice in each column, from left to right.

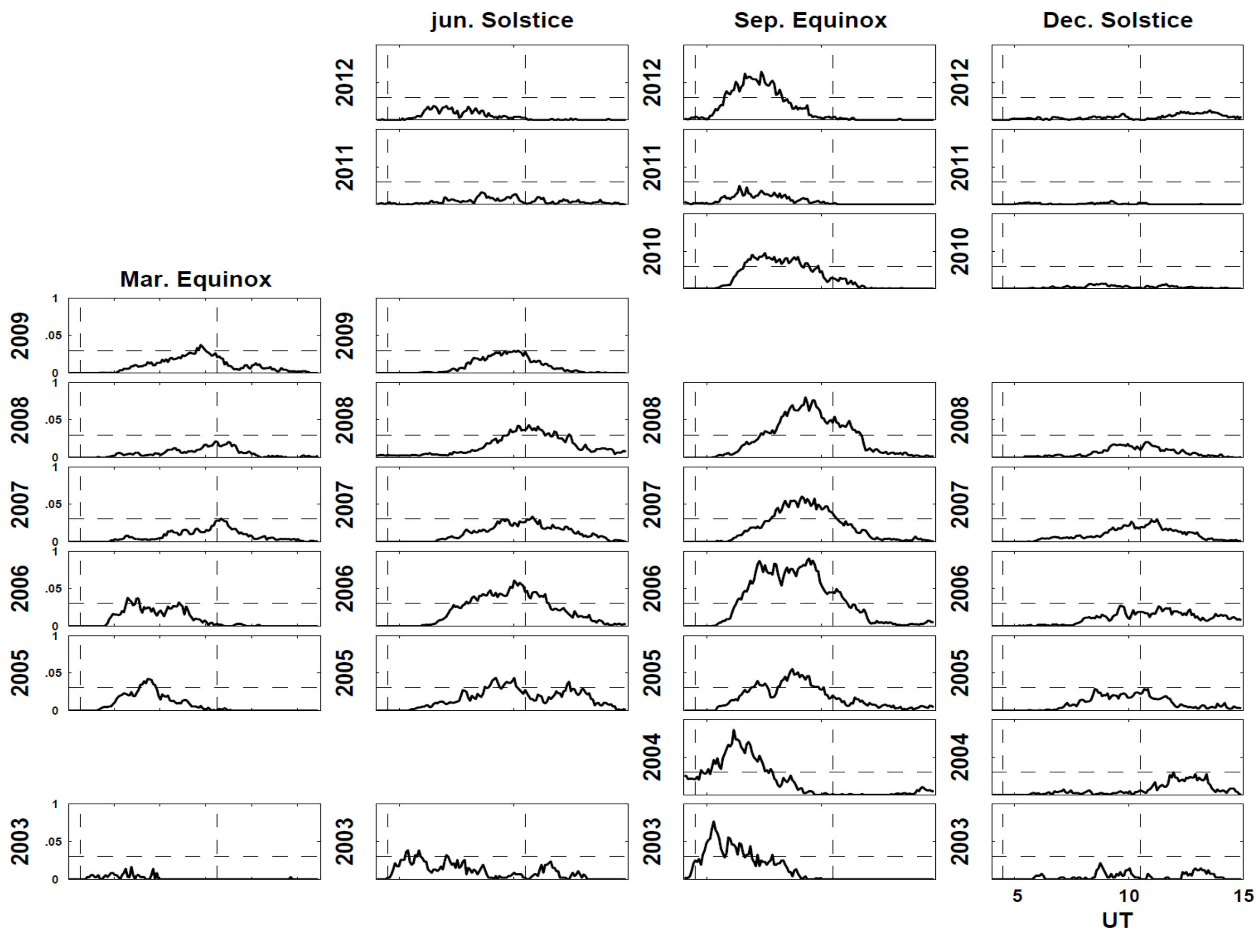


Figure 4. Time Variations of spread F echoes observed over Christmas Island equatorial station for the period of 2003 to 2012, also separated by equinoxes and solstices. The vertical lines represent the local sunset and local midnight respectively, and the horizontal line represent the 0.5 A.U. for reference.

The echoes occurrences from solar maximum to solar minimum has two main differences, during solar maximum they are confined in few hours and close to local sunset and during solar minimum periods the echoes are more spread out in time and can occur late on the night mainly well after sunset and more closely to midnight hours. As we get closer to solar minimum period the amplitude of echoes occurrence increases due to high probability to occur echoes along all night. This can be observed during years 2006 to 2010 with more amplitude than echoes observed during solar maximum.

Analyzing the echoes by each year we can observe that echoes amplitude increases from march equinox, June solstice, to September equinox then decreases to December solstice. This effect is due to the peak echoes occurrence is due to seasonal spread F occurrence over the Pacific region. It is observed that the post midnight spread F occurrence is maximum during the June solstice months (May-June-July) and December solstice months (November-December-January) of the low solar activity period (2006-2007 and 2008). This spread F occurrence for post-midnight events decrease from solar minimum to solar maximum. During March and September equinoxes is very rare to observe post-midnight spread F events for solar maximum conditions, and during solar minimum conditions is possible to observe some post-midnight events. During June and December solstice is possible to observe echoes occurring mostly after midnight hours. During solar maximum years the echoes are located between local sunset time and midnight (June solstice) with few events after midnight (December solstice), and during solar minimum years most of the echoes are located around (June solstice) and after midnight (December solstice) hours.

The spread F generation mechanism for solar minimum conditions seems to be unclear, due mainly that spread F during low solar conditions are distributed between pre-midnight and post-midnight occurrences. During solar minimum conditions pre- and post-midnight spread F events are more probable to occur, but along the seasonality we can observe that the pre-midnight events are mainly related to equinoxes and post-midnight events to solstices events.

Conclusions

These report brings out the seasonal variation of time and altitude peak echoes occurrences along solar maximum and recent extended solar minimum, over the Christmas Island equatorial station using the VHF-50 MHz coherent backscatter radar.

Under higher solar flux conditions, plumes reach higher altitudes but decay earlier. Only during solar minimum conditions do plumes exist throughout the whole night, since the post- reversal anti- zonal background electric field is weaker. During increased solar activity, the time frame during which irregularities can form is restricted to early evening and typically, they are completely suppressed before 22:00 local time. Hence, the typical irregularities formed during solar maximum predominantly are ones formed by the PRE, which is coincidentally stronger during higher solar conditions. Thus, irregularities during solar maximum will be dominated by dynamics near the time of the PRE. Since the population of irregularities during solar minimum exists throughout the whole night, post- reversal ionospheric conditions may play a role in the morphology of plasma irregularities, especially with the coincidentally weaker PRE during solar minimum.

As general rule we can say that the peak occurrence time of echoes shows a temporal variation as function of solar flux conditions being time close to local sunset during the period of high solar flux and time around local midnight during the period of the extended solar minimum. Furthermore, some alterations are observed when the analysis is made by seasonality.

From the peak occurrence altitude of echoes we can say that it is decreasing function from maximum to minimum solar conditions, and during solar minimum the peak altitude remains stable and low in altitude. Also few alterations can scape from the general rule when analysis is made by seasonality.

Acknowledgments

We thanks FAPESP under project 2012/25396-1 for supporting this research. We are very thankful to Christmas Island researchers and technical teams for providing the historical radar data needed for this study. The early Christmas Island radar data were collected by Roland Tsunoda with funds from National Science Foundation, ATM-0001678. More recent data were collected by Keith Groves with funds from AFRL.

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