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A comparison of the equatorial spread *F* derived by the International Reference Ionosphere and the S_4 index observed by FORMOSAT-3/COSMIC during the solar minimum period of 2007–2009

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The latest version of the International Reference Ionosphere (IRI-2007) model includes an option for spread-*F* occurrence prediction for the first-time. The IRI-2007 spread-*F* occurrence is a function of solar 10.7 cm radiation flux, $F_{10.7}$. In this paper, an attempt is made to cross-examine the spread-*F* occurrence derived by the IRI-2007 and the ionospheric scintillations in terms of the maximum value of the S_4 index ($S_{4\max}$) between 150–350-km altitudes, calculated from fluctuations of the signal-to-noise ratio (SNR) intensity in the L1 channel of GPS radio occultation signals using FORMOSAT-3/COSMIC (F3/C) satellites during the low solar activity years 2007–2009. It is found that $S_{4\max}$ maintains a fairly good consistency with spread-*F* occurrence simulated by IRI-2007 in the Brazilian region. Thus, the global S_4 index statistics can be considered as a viable source of database to be incorporated into the global IRI spread-*F* prediction scheme owing to fact that the F3/C satellites can provide an unprecedented global database including the S_4 index.
Key words: GPS RO technique, S_4 index, IRI-2007, spread-*F*.

1. Introduction

The International Reference Ionosphere (IRI) model is one of most comprehensive empirical models to describe global ionospheric behaviour and variation up to several hundred kilometers (∼1500 km). The IRI project was initiated by the Committee on Space Research (COSPAR) and by the International Union of Radio Science (URSI) in the late sixties with the goal of establishing an international standard (empirical model) for the specification of ionospheric parameters based on all worldwide available data from ground-based, as well as satellite, observations (Bilitza and Reinisch, 2008). The IRI model has been steadily improved with newer data and with better mathematical descriptions of global and temporal variation patterns since its inception (Bilitza and Reinisch, 2008). In the latest version of IRI—IRI-2007—several new options are introduced, including a first-time model for the spread-*F* occurrence probability, which is a regional model for the Brazilian longitude sector/region (Fig. 1) based on the work of Abdu *et al.* (2003) using ionosonde observations in Brazil. The model describes the variations of the occurrence probability with latitude, local time, day of year, and solar activity (Bilitza and Reinisch, 2008).

The Earth's ionosphere often becomes turbulent and develops electron density irregularities which manifest themselves as spread-*F* on ionograms, plume-like structures in the range-time-intensity images of HF radars, intensity bite-outs in airglow intensity measurements and scintillations on amplitude, as well as the phase of VHF and UHF signals from satellites, and are commonly referred as equatorial spread-*F* irregularities (ESF), spanning scale sizes from 10s of centimeters to 100s of kilometers.

There have been many studies on the occurrence characteristics of ionospheric density irregularities using ground-based measurements (Rastogi, 1980; Abdu, 2001), satellite-based in situ measurements (Watanabe and Oya, 1986; Huang *et al.*, 2002; Burke *et al.*, 2004), and topside sounders (Maruyama and Matuura, 1984), and many important features of these have been reported including temporal variations (Sahai *et al.*, 2000; Huang *et al.*, 2002), seasonal-longitudinal variability (Burke *et al.*, 2004), several-day variation, and day-to-day variation (Basu *et al.*, 1996) though several enigmatic features of them are yet to be revealed (Thampi *et al.*, 2009). However, studies on continuous and global characteristic features of ionospheric plasma irregularities are very scanty due to the fact that the global coverage is difficult to obtain from ground-based observations. Moreover, the observational locations are limited around the world and though satellite measurements can cover all longitudes, observational areas are fixed in geographic latitude and the satellite altitudes.

On the other hand, with the aid of low earth orbit

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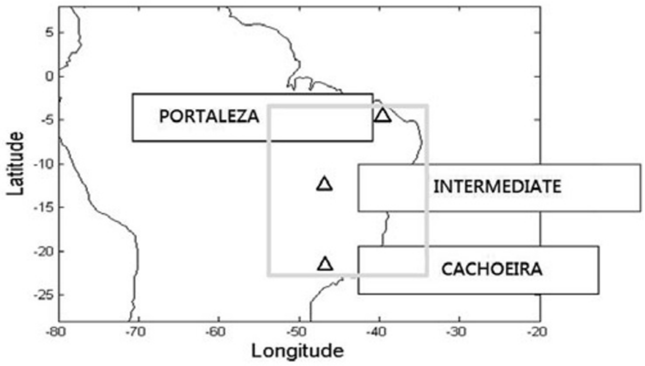

Fig. 1. Locations of 3 ionosondes constructing the IRI Spread-F and an area of $S_{4\max}$ isolated. The triangle symbols denote the 3 ionosonde stations at Fortaleza (3.88°S, 38.43°W), Cachoeira Paulista (22.6°S, 45°W), and Intermediate (13°S, 45°W). The area (within 22.5°S, 55°W to 2.5°S, 35°W) for isolating F3/C $S_{4\max}$ is denoted by a gray frame.

(LEO) satellites performing GPS radio occultation (RO) observations, it is possible to obtain global soundings of the atmospheric profiles in three dimensions from the Earth's surface to the topside of the satellite altitude with a higher vertical resolution (Schreiner *et al.*, 2007). For a better understanding of the global phenomena of ionospheric irregularities, a RO technique using multiple satellites that can provide dense spatial coverage of the world such as FORMOSAT-3/COSMIC (F3/C) is essential. The F3/C configuration consists of six microsatellites at about 800-km altitude which are placed in 72° inclination circular orbits with a separation angle between neighboring orbital planes of 30° longitude. In principle, an occultation takes place when a GPS sets or rises behind the Earth's atmosphere as seen by the LEO satellite, then the GPS radio signals are received by a receiver on the LEO satellite and such an occultation lasts a few minutes. Once the GPS signal is received at LEO during an occultation, the on-board algorithm, which was implemented into the GPS RO receiver software by the Jet Propulsion Laboratory (JPL) (http://cosmic-io.cosmic.ucar.edu/cdaac/doc/documents/s4_description.pdf), computes an average of the intensity fluctuations from the raw 50-Hz L1 amplitude measurements and records it at a 1-Hz rate. A low-pass filter is further applied to a time series of those averages to obtain a new average of the intensity each second. Based on the filtered average (FA), the RMS (root mean square) and S_4 (=RMS/FA) index are obtained. On average, nearly 6000 to 7000 S_4 index profiles are derived by F3/C per day covering an altitude range from the Earth's surface to 800 km. For scintillation studies, the F3/C dataset specifically denotes the maximum value and associated location (altitude, latitude, longitude) of each S_4 profile (hereafter denoted $S_{4\max}$). In this paper, to help understand the three-dimensional structure of the equatorial F-layer scintillation, spread-F occurrence percentages, derived from IRI-2007, and concurrent F3/C $S_{4\max}$, in the Brazilian region, during the low solar activity years 2007–2009, are investigated.

2. IRI Spread-F Occurrence and F3/C S_4 Index at the Brazilian Sector

Figure 1 depicts 3 ionosonde locations for IRI-2007 computing spread-F occurrence probabilities and the area of F3/C $S_{4\max}$ isolated in the Brazilian region. Figure 2 compares the $F_{10.7}$ index and the nocturnal variation of spread-F occurrence probabilities in the Brazilian region between the years 2000 and 2009. Several interesting features can be noted from this figure: the spread-F occurrence probability decreases with a decrease in solar flux; the occurrence probabilities attain larger values from around September to March (spread-F season) of each year; and the onset time of this activity seems to start at around 1830 LT and continues until 0600 LT the following day. Figure 3 illustrates the spread-F occurrence percentage derived by IRI-2007 (Fig. 3(a)) and the $S_{4\max}$ observed by F3/C (Fig. 3(b)) between 150–350 km altitudes in the Brazilian region from 2007 to 2009. A one-to-one correspondence exists between the spread-F occurrence percentage and the $S_{4\max}$ in the seasonal variation (correlation coefficient 0.55). Higher percentages are noted during the spread-F season (between September–March) and less, or completely diminished, percentages during the non-spread-F season (between April–August) in each year. It is found that a considerable difference in the onset time is found in the spread-F (1830–1930 LT) and the $S_{4\max}$ (1930–2000 LT).

3. Global $S_{4\max}$ Map

As discussed before, the F3/C GPS RO technique enabled us to study the global morphology of ionospheric irregularities causing a scintillation effect (in terms of the S_4 index). Figure 4(a) depicts the global variation of $S_{4\max}$ from noon to noon in local time (LT) from 150 to 450 km during the M-month (March 21 ±1.5 month) between 2007–2009. It is clear that the equatorial scintillations become more prominent from post-sunset hours and often persist till post-midnight hours (i.e. from 1900 to 0300 LT) mainly at the bottom side of the F-region (150–350 km). Though the $S_{4\max}$ increases with increasing altitude up to a 250–300-km bin, its latitudinal decreases, however, and fixes to the equatorial regions particularly between 150 and 450 km, finally disappearing beyond 450 km altitude. $S_{4\max}$ in the S-

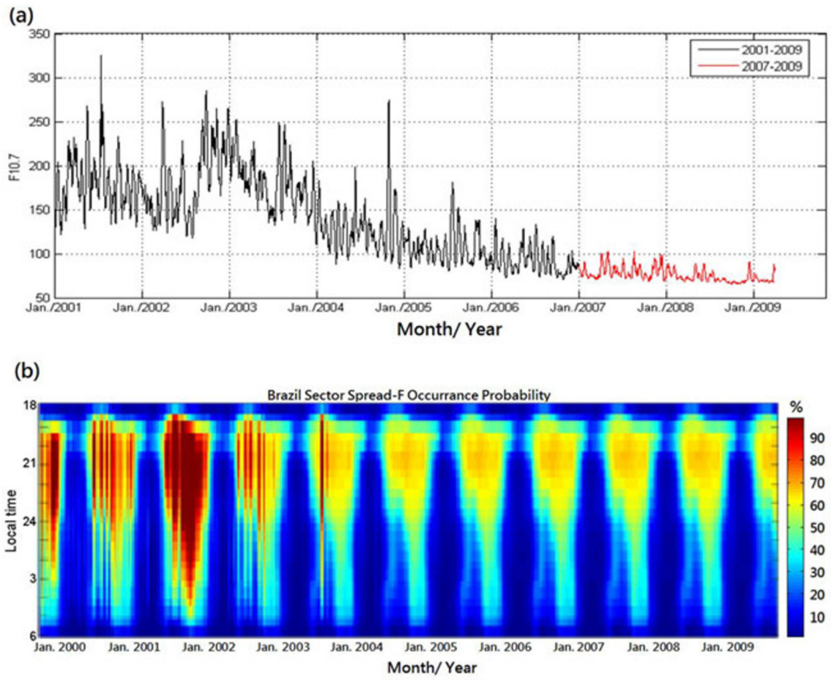

Fig. 2. Variations of the $F_{10.7}$ and the Spread-F occurrence probability in the Brazilian region during 2000–2009. (a) $F_{10.7}$ solar radio flux (b) Spread-F occurrence probability derived from IRI-2007. $F_{10.7}$ shows that it is solar minimum during 2007–2009 (denoted by the red curve).

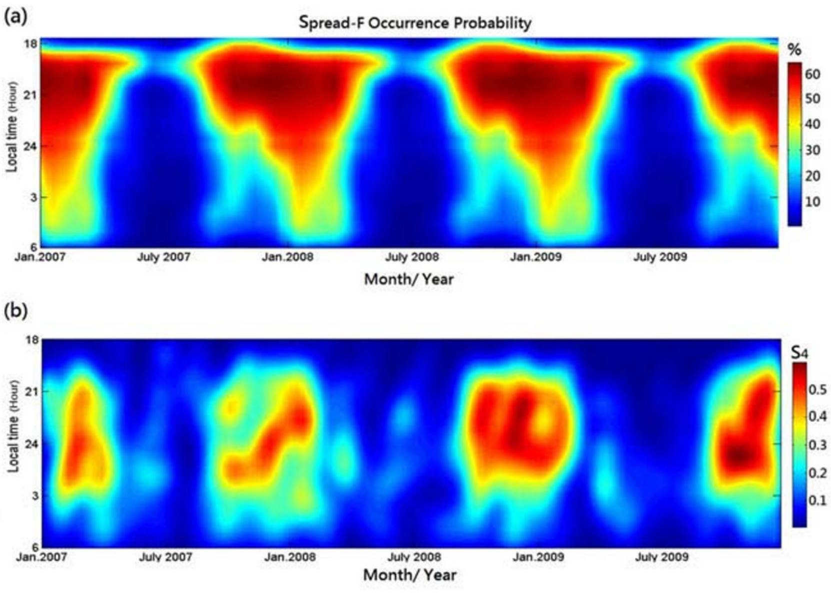

Fig. 3. Spread-F occurrence percentage and $S_{4\max}$ at 150–350 km altitude during 2007–2009. (a) The occurrence percentage of IRI Spread-F and (b) the $S_{4\max}$ (values 0–1.0).

month (September 21 $\pm$1.5 month) shows that the intense scintillation activity appears near the equator and low latitudes in the F-region similar to the M-month as can be seen in Fig. 4(a). Figure 4(d) shows during the D-month (December 21 $\pm$1.5 month) that the scintillation activity becomes less intense and asymmetric. The $S_{4\max}$ in the southern/summer hemisphere is slightly greater than that in the northern/winter one. By contrast, Fig. 4(b) reveals that during the J-month (June 21 $\pm$1.5 month), the intensity of the scintillation activity becomes much less compared to other seasons, and in the F-region it almost disappears beyond the 300–350-km altitude bin. In general, $S_{4\max}$ yields the greatest value and the highest altitude during the M-month, followed by the S-, D-, and J-months.

4. Discussion and Summary

It is generally accepted that the generalized Rayleigh-Taylor instability (RTI) mechanism is responsible for the generation and growth of equatorial spread-F irregularities (Zalesak and Ossakow, 1980; Kelley, 1989; Sultan, 1996), which occur over a wide range of scale sizes, as has been established from various diagnostic techniques. The occur-

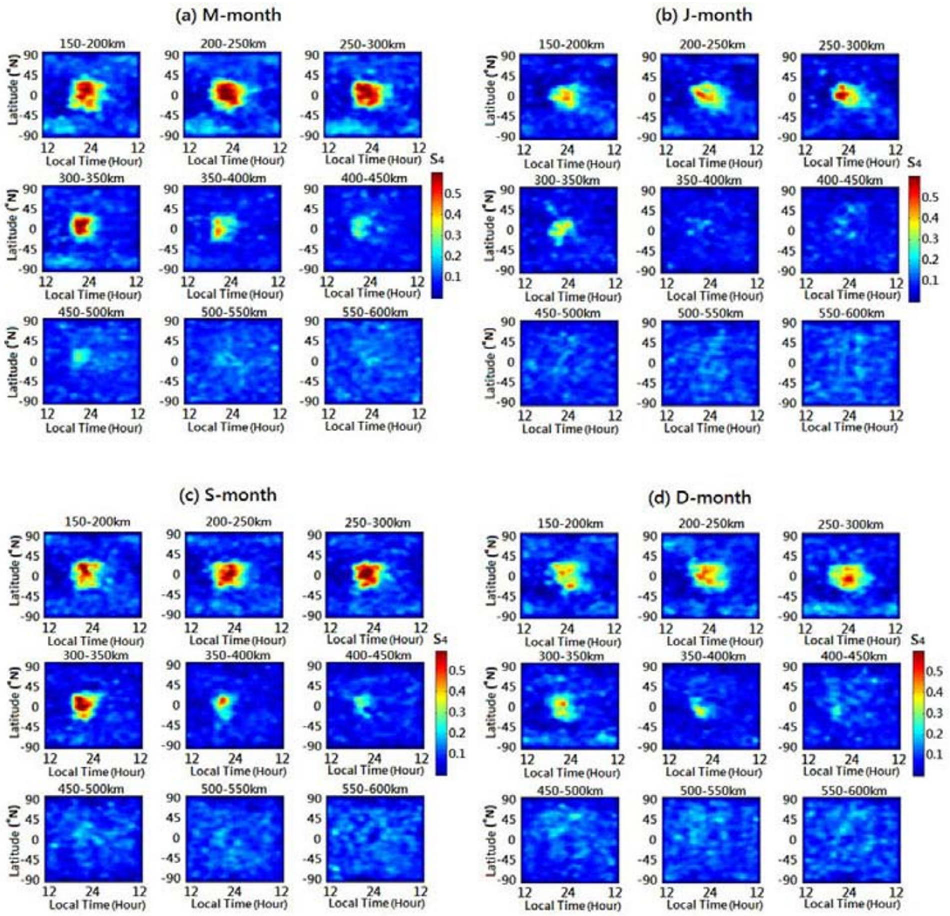

Fig. 4. Global $S_{4\max}$ from noon to noon at various altitudes observed by F3/C during 2007–2009. Each subplot shows $S_{4\max}$ data integrated with a 50-km-altitude bin interval from 150–600 km. (a) M-month, (b) J-month, (c) S-month, and (d) D-month.

rence of spread-F irregularities is associated with post sunset height rise in the F-region (Chandra and Rastogi, 1972) which is highly affected by the upward $E \times B$ drifts in pre-reversal enhancement (PRE), and is strongly dependent on the solar activity level and season (Fejer *et al.*, 1991, 2008; Scherliess and Fejer, 1999). Thus, it is conceivable to expect higher spread-F occurrence percentages by IRI during the sunspot maximum, which, in general, establishes a positive correlation between them (Fig. 2) (Abdu *et al.*, 1992; Subba Rao and Krishna Murthy, 1994).

Tsunoda (1985) shows that the ionospheric irregularity occurrence is a maximum when sunsets in the conjugate E-region are simultaneous. Simultaneous sunset is expected to intensify the so-called PRE (Abdu *et al.*, 1981, 1992, 2010; Batista *et al.*, 1986), a favorable and sufficient condition for the initiation of RTI. The angle between the geomagnetic meridian and the sunset terminator line was introduced as a proxy of the simultaneous sunset in the conjugate points (Burke *et al.*, 2004). Since, in the Brazilian longitude sector, the angle tends to be much closer during November–February than March–September, higher occurrence probabilities and greater $S_{4\max}$ are more expected during the November–February (see Figs. 2 and 3).

The time lag in onset timings between spread-F and $S_{4\max}$ (Fig. 3) is primarily due to the physical processes involved in the generation of different scale sizes of the irregularities responsible for producing spread-F and scintillation effects. It is recognized that the spread-F in ionograms is associated with large scale (100s of km) plasma depletions, that originate initially at the F-layer bottomside (by the RTI mechanism) and, in turn, rise nonlinearly to the topside. These rising bubbles with the passage of time can bifurcate to form small-scale irregularities by cascade, or two step, mechanisms (Ossakow, 1981). Such smaller-scale irregularities effectively produce scintillations at the L-band (Basu *et al.*, 1978; DasGupta *et al.*, 1982).

In summary, it is shown that the IRI-2007 spread-F prediction model based on the Brazilian region data reflects well the temporal, diurnal and seasonal variations, and such variations are also found in the S_4 index data. Therefore, the global S_4 index data obtained by the F3/C GPS RO technique might be usefully incorporated into the global IRI spread-F prediction scheme.

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