IONOSPHERIC IRREGULARITIES MEASURED BY GROUND-BASED AND SATELLITE-EMBEDDED RECEIVERS: ANALYSIS OF S4 INDEX IN A LOW LATITUDE REGION

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ABSTRACT:

Ionosphere is an important layer of Earth's atmosphere which can interfere in the transmission of radio signals, affecting several activities, such as the ones related to global navigation satellite systems (GNSS) positioning. In this intend, many efforts have been made in the last decades in order to better understand and model this region of atmosphere. The observation of ionosphere and its irregularities can be performed by several techniques, including classic methods such as ionosondes. Besides that, the use of GNSS signals as source of atmospheric observations have allowed the development of different methodologies and techniques to obtain ionospheric information. Among those, the use of data collected by receivers embedded in low earth orbiting (LEO) satellites, such as the ones used in radio occultation (RO) missions can be relevant due to the amount and distribution of the data obtained. Besides that, GNSS receivers has also been used in ground stations networks to continuously monitor the ionosphere. In this sense, the present work aims to compare irregularities observed by two different techniques using data from ground-based (GNSS monitoring stations) and satellite-embedded (RO mission) receivers. The study is performed over one of the most challenging scenarios, the Brazilian region, considering seasonal variability in two months (low and high solar flux) from 2014 (solar cycle peak). The results obtained show agreement in the general behavior of the ionospheric irregularities observed by the two different techniques.

1. INTRODUCTION

Ionosphere has a significant influence in the activities related to radio signals, such as the global navigation satellite systems (GNSS) positioning. The influence of ionosphere is specially challenging due to the irregularity of the electron distribution in its composition. The electrons distribution is influenced by several factors, including anomalies, such as the equatorial ionization anomaly (EIA). When propagating thru small-scale plasma density irregularities regions in the ionosphere, the GNSS signal can suffer rapid fluctuations, the so-called ionospheric scintillation, which can degrade the signal. In order to quantify ionospheric irregularities, some parameters are normally used, for instance the S4 index, which is related to amplitude scintillation (Conker et al., 2003; Sreeja et al., 2012).

Considering the impacts of Earth's ionosphere, several techniques are currently used to investigate and monitor such important layer. Besides techniques such as the applied with ionosondes, which directly measures the behavior of the ionosphere, many other approaches use GNSS signals to study the ionosphere composition. Among those, it can be mentioned the ground-based receivers, such as monitoring stations networks, and low earth orbit (LEO) satellites with embedded receivers, such as some radio occultation (RO) missions.

As an example of ground-based monitoring stations, it can be mentioned the GNSS NavAer network, composed of high frequency GNSS receivers, which provides scintillation indices and metrics that can characterize the scintillation occurrence. The network is composed by GNSS receivers with high sampling rate (50 Hz), corresponding to 50 observations in one second. Figure 1 shows the active stations from the network. The network provides ionospheric information by means of the ISMR (Ionospheric Scintillation Monitor Receiver) Query Tool (Vani et al., 2017; Monico et al., 2022).

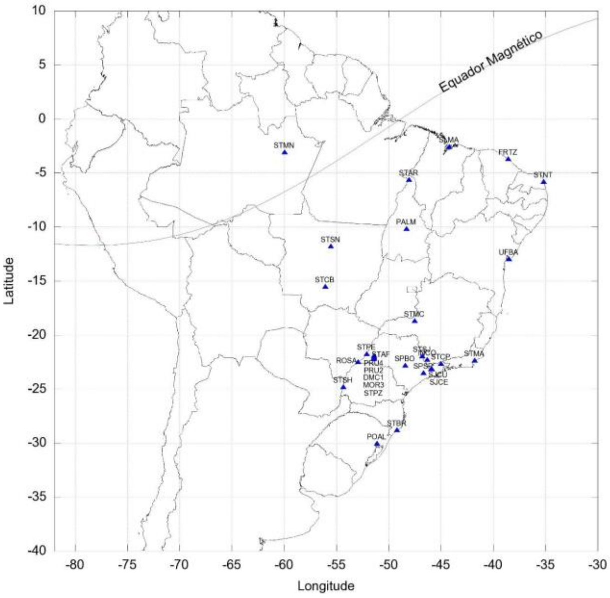

Figure 1. GNSS NavAer network active stations.
<https://inct-gnss-navaer.fct.unesp.br/>

S4 index can be obtained from observations of the signal intensity at high sampling rates as (DATTA-BARUA et al., 2003):

$$S4 = \sqrt{\frac{\langle SI^2 \rangle - \langle SI \rangle^2}{\langle SI \rangle^2}}, \qquad (1)$$

where *SI* is the signal intensity in a high-rate sampling, 50 Hz for instance, and the operator $\langle X \rangle$ indicates the expected or mean value for *X* in one minute interval. S4 index can be classified according to the intensity of ionospheric irregularities, Tiwari et al. (2011) present a classification divided in three levels as shown in Table 1.

Classification	S4 values
Strong scintillation	$S4 \geq 1$
Moderate scintillation	$0{,}5 < S4 < 1$
Weak scintillation	$S4 \leq 0{,}5$

Table 1. S4 index classification.
Tiwari, et. al. 2011.

Considering the satellite-embedded receivers, several missions with LEO satellites can be mentioned, such as the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), a RO mission with over 15 years of data, which has receivers specifically for S4 index. The COSMIC mission was composed of six satellites at approximated 800 km height (Anthes et al., 2008). One of the biggest advantages of the data from RO missions is the coverage area. Taking into account this type of data, the coverage area is related to the configuration of the satellite's orbits, in this sense there is no lack of information due to regions of difficult access, for instance. Figure 2 shows an example of the mean occurrence of S4 measurements for a day from 2014. The S4 profiles are made available by means of the products called scnLv1, which also provides auxiliary data. The files contain continuous S4 data (one value each second based on 50 Hz internal receiver sampling) from one GPS (Global Positioning System) satellite, only small data gaps are allowed (COSMIC, 2023).

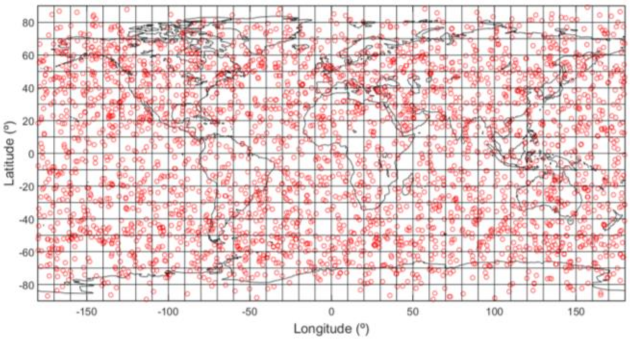

Figure 2. Occurrence of S4 profiles for a day in 2014 from COSMIC mission.

The S4 index from COSMIC data is calculated in a similar way than the presented in equation (1), the main difference is that the mean signal intensity is calculated for a one-second interval, i.e., using 50 observations (SYNDERGAARD, 2006).

Considering the influence of ionospheric irregularities and the different sources of information currently available, in this work, a comparison of the general behavior of S4 index obtained by ground-based and satellite-embedded receivers is performed. Data from NavAer network and COSMIC mission are used. The study takes into account two months of data (one with low and the other one with high solar flux) from 2014 in a low latitude area, the Brazilian region. In the second part of the study the impact of the ionospheric irregularities on electron density profiles obtained with the RO technique is briefly analysed. In this intend, a comparison of regular and irregular RO profiles and S4 values measured by a monitoring station close to the occurrence of the profiles is performed. The section 2 presents the methodology that is used in the study. Section 3 discusses the main findings and section 4 presents the conclusions.

2. METHODOLOGY

In this study, the S4 index obtained with data collected by ground-based and satellite-embedded receivers are compared. The ground-based receiver data is collected by PRU2 and POAL stations from the GNSS-NavAer network (INCT GNSS-NavAer, 2023; Vani, Shimabukuro and Monico, 2017). While the satellite-embedded data is from COSMIC mission (CDAAC, 2023). In order to perform this analysis, a search window of 20º x 20º (latitude x longitude) is used considering the position of PRU2 as reference. This way, all S4 profile, obtained with the COSMIC satellites, in which the mean value is inside the search window are considered in the analysis. For this approach, two months of data are used, corresponding to March and July of 2014. Then, all S4 values obtained are joined to represent the ionospheric irregularities of the region for each month. The selection of the region is based on the characteristics of the ionosphere, corresponding to a region with occurrence of intense irregularities. The selection of the months intends to comprise the ionospheric effects in different periods considering higher (March) and lower (July) intensity (Moraes et al., 2017). Figure 3 shows the calendar with the daily mean S4 value for stations PRU2 and POAL considering GPS data and 10° elevation mask.

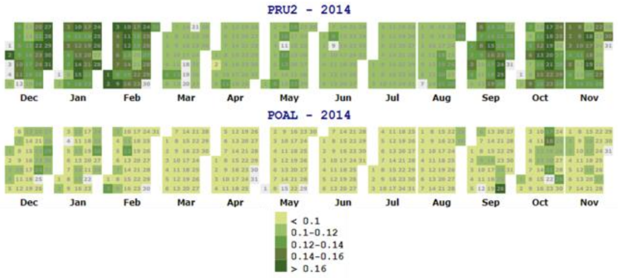

Figure 3. S4 calendar for stations PRU2 and POAL.

For the second part of the study the influence of the ionospheric irregularities is analysed directly in the electron density profiles obtained with the RO technique. In this case, search windows are once again applied considering the stations positions, and all the electron density profiles with electron density peak occurrence inside the search window are considered in the analysis. Then, the behavior of the profiles is compared with the corresponding time and region of occurrence of the S4 obtained with measurements from the monitoring stations PRU2 and POAL (located in regions with high and low influence of the ionosphere, respectively). For this part of the study, profiles from June (low solar flux); and March and October (high solar flux) are considered.

3. RESULTS

The main findings obtained so far in this study are addressed in this work. Even though the geometry involved in the acquisition of the data from ground-based and satellite-embedded receivers are different, the results obtained indicates correspondence between the behavior of S4 index values from the two different techniques used. Figures 4 and 5 present the general behavior of S4 index measured by PRU2 for March and July data, respectively, considering ground-based (a) and satellite-embedded (b) receivers. In general, S4 from COSMIC provides more sparse measurements (each occultation normally lasts up to 3 minutes), which is the main reason of the need of a month of data (Anthes et al., 2008).

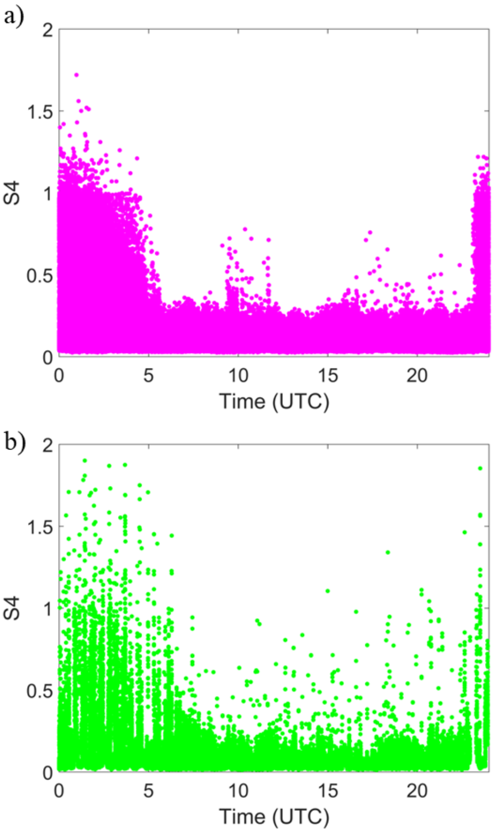

Figure 4. S4 values of March 2014 from PRU2 (a) and COSMIC (b).

It should be taken into account that COSMIC coverage in the equatorial region is limited, the current mission (COSMIC-2) provides a better coverage of this area, however, not all the products are already available, including the S4 profiles (scnLv1). The magnitude of the S4 obtained is also different for the two techniques, however there is compatibility between the results. For the month with high solar flux (March) larger indices are observed, especially considering the periods where irregularities, such as ionospheric scintillation, can be expected. Figure 4 clearly shows larger S4 values after 21h UTC up to 5 h UTC for ground-based and satellite embedded data. For the month with low solar flux (July) the general behavior is more regular during the day and the S4 values are smaller for both techniques. In both months it can be noticed that S4 from COSMIC presents more noisy data.

Figures 6 and 7 present the general behaviour of S4 index measured by POAL for March and July data, respectively. In general, it can be noticed that the behavior of S4 is smaller than in the PRU2 station.

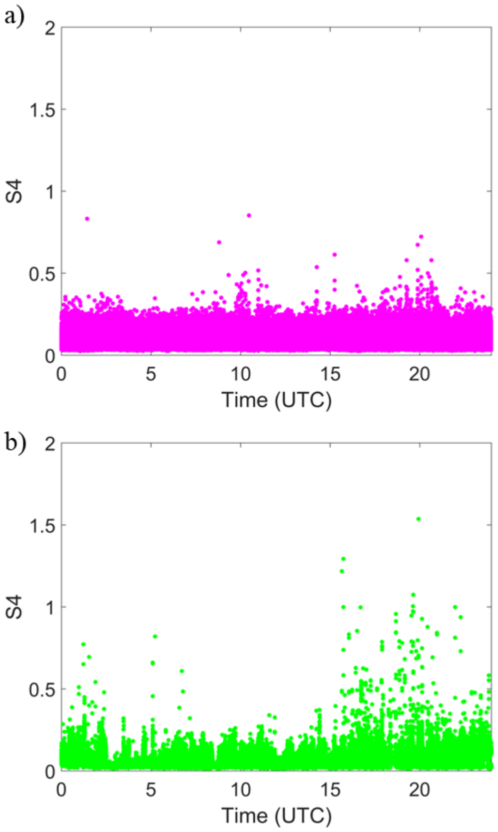

Figure 5. S4 values of July 2014 from PRU2 (a) and COSMIC (b).

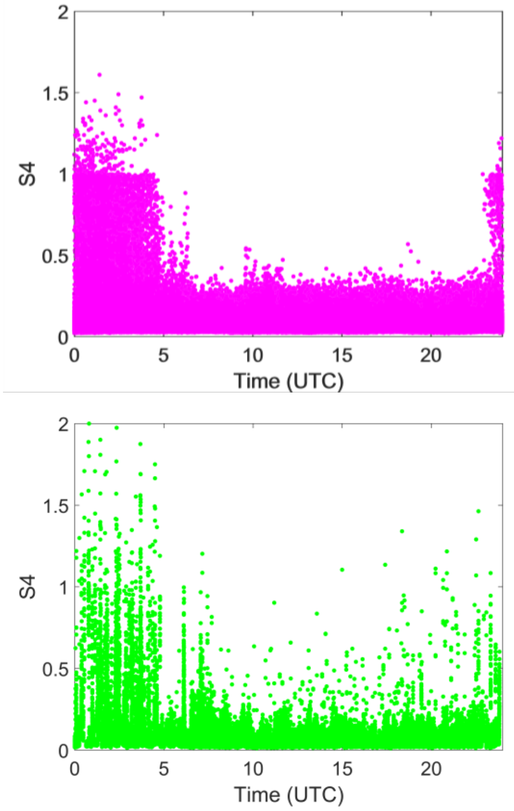

Figure 6. S4 values of March 2014 from POAL (a) and COSMIC (b).

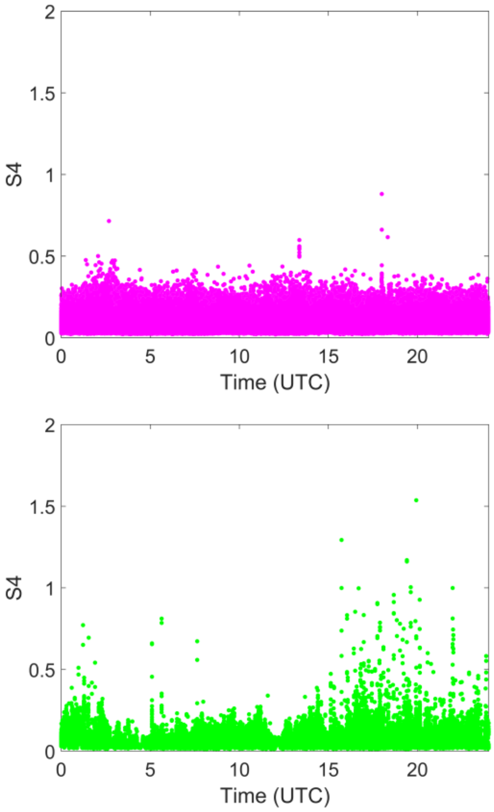

Figure 7. S4 values of July 2014 from POAL (a) and COSMIC (b).

In the second part of the study, RO electron density profiles with regular and irregular behaviour are examined and compared with S4 measurements from PRU2 station. Considering the general S4 values, there are some cases with correspondence in periods of irregularity observed in the RO profile and higher S4 values.

Figures 8 and 9 present data corresponding to June (low solar flux) for two occultations close to PRU2 and POAL. Figures 10 and 11 show results from October (high solar flux) also for two occultations close to PRU2 and POAL. Figures 12 shows results from March (also a period of high solar flux) for two occultations close to PRU2.

Analysing Figures 8 and 9 (low solar flux), as shown in graphs (c) from both stations, during this period no ionospheric scintillation is observed for both regions, corresponding to PRU2 and POAL (regions with higher and less ionospheric impacts, respectively). However, irregular RO ionospheric profiles can be observed, as presented in graphs (a), which can indicate the influence of other irregularities.

Considering Figures 10 and 11 (high solar flux), no strong scintillations can be observed in S4 indices from ground-based stations, as well as the RO electron density profiles observed are not so noisy. Trying to identify more noisy profiles in a high solar flux period, Figures 12 is analysed. But in this case, although more intense S4 values can be noted in the ground-based data, and there is occurrence of RO electron density profiles irregulars, those occurrences do not correspond to the time of ionospheric scintillation periods.

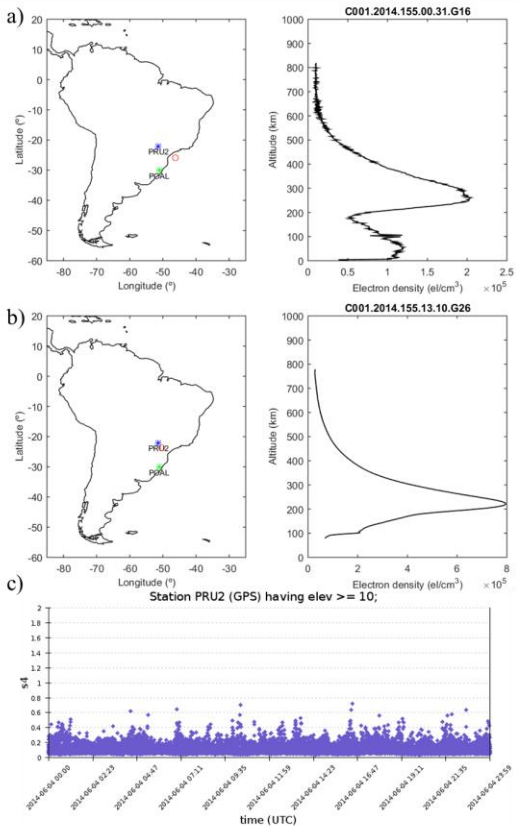

Figure 8. Location and behavior of noisy (a) and regular (b) COSMIC profiles in June (at 00h31 and 13h10) and S4 values from PRU2 (c).

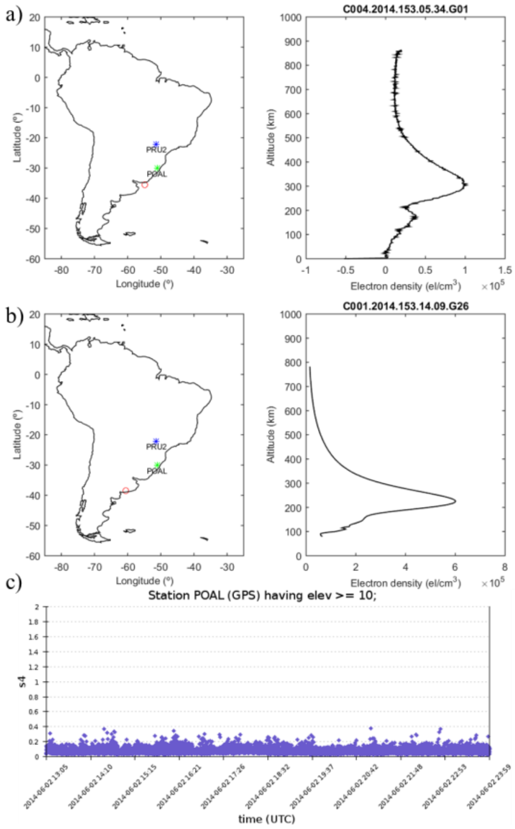

Figure 9. Location and behavior of noisy (a) and regular (b) COSMIC profiles in June (at 05h34 and 14h09) and S4 values from POAL (c).

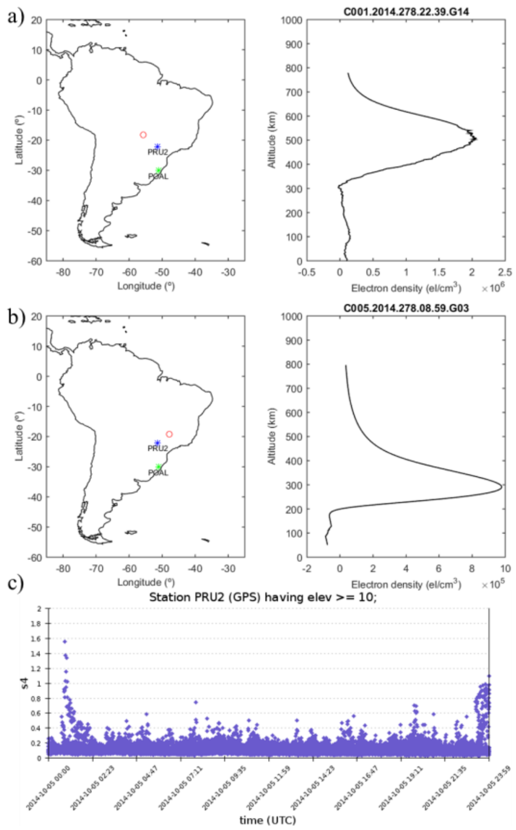

Figure 10. Location and behavior of noisy (a) and regular (b) COSMIC profiles in October (at 22h39 and 08h59) and S4 values from PRU2 (c).

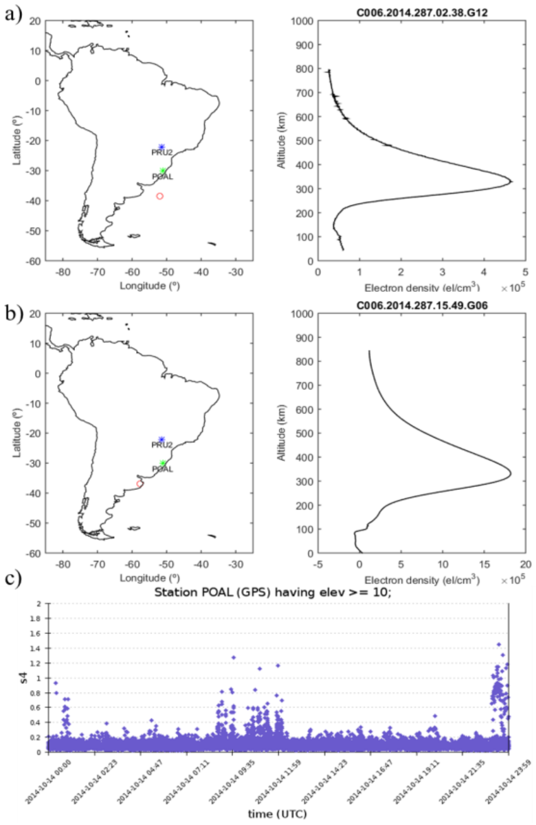

Figure 11. Location and behavior of noisy (a) and regular (b) COSMIC profiles in October (at 02h38 and 15h49) and S4 from POAL (c).

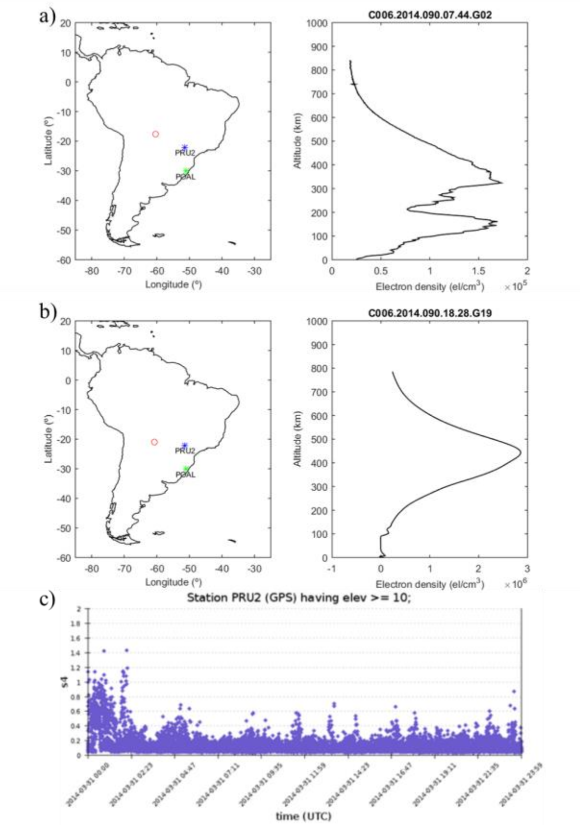

Figure 12. Location and behavior of noisy (a) and regular (b) COSMIC profiles in March (at 07h44 and 18h28) and S4 values from PRU2 (c).

To complement this last analysis, we took into account only S4 from the GPS satellites used in the occultations identified. However, the analysis with only S4 from the corresponding GPS satellite is not always possible due to the geometry involved. In the cases here investigated, it could be noticed that the time of the occultations corresponding to the profiles did not have simultaneous S4 data collected by the ground-based station. Further investigation should be performed in this case, aiming to find more examples of irregular RO profiles and S4 measurements. Also, this study should be extended to COSMIC-2 data, when all the products become available.

4. CONCLUSIONS

Considering the impact of ionospheric irregularities in several activities, in this work, a comparison of the general behavior of S4 index obtained by ground-based and satellite-embedded receivers is performed. For this study a two-month (one with low and the other one with high solar flux) dataset from 2014 is considered for a low latitude area, the Brazilian region. The direct impact of the ionospheric irregularities on electron density profiles obtained with the RO technique is also discussed.

For the general behavior in the two-month analysis, the agreement for S4 indices from ground-based and satellite-embedded receivers is clear. The values corresponding to both periods, with low and high solar flux, present more regular indices for the month with low solar flux (July), and more elevated indices after 21h UTC up to 05 h UT for the month with high solar flux (March). This behavior is compatible with the expected behavior in the region due to the occurrence of ionospheric irregularities, such as ionospheric scintillation.

Taking into account the analysis of RO electron density profiles with irregularities and the S4 observed by the ground stations, no clear correspondence can be made. There are irregular profiles observed in periods with no ionospheric scintillation and regular profiles in periods with high S4 measured by ground stations. There are periods of correspondence, but there is not a clear pattern, mainly due to the difference in the geometry of the signals observed by the ground-based and satellite-embedded receivers. Even the analysis of the S4 from the same satellite used for the occultation is not always possible because the availability of data collected is no coincident.

This is an initial study with many possibilities of further investigation. The next step is to analyse not only the S4 of one ground station corresponding to a close region of the occultation but try to identify pairs of stations in a similar alignment with the occultation. For the COSMIC mission this approach is not possible, due to the availability of data from ground-based stations. With the availability of all COSMIC-2 products and with the new stations from the NavAer GNSS network, more possibilities of analysis, including the use more recent data will be possible.

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