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Multi-scale ionospheric irregularities occurrence over South America during the St. Patrick's day storm on March 17, 2015

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A B S T R A C T

During the solar cycle 24 there was a very intense geomagnetic storm due to the St. Patrick's day storm and the effects of this storm on ionosphere has become a topic of extensive space weather investigation. Up to now several aspects of the St. Patrick's ionospheric storm have been study such as the prompt penetration electric fields (PPEFs), TEC changes, electron density disturbances, plasma drift, O+ concentration modification, hemispherical asymmetry developments, equatorial ionization anomaly (EIA) modification, and ionospheric irregularities. Besides all these important studies, there are some essential aspects, which have not been addressed yet, related to the occurrence of multi-scale ionospheric irregularities. In this paper, we present and discuss the generation and suppression of multi-scale ionospheric irregularities, using the observations conducted in the Latin American Sector from 4 ionosondes, 20 dual frequency GPS stations, and JULIA radar observations during the month of March 2015, which includes the St. Patrick's day geomagnetic storm period. Suppression of large-small scales ionospheric irregularities has occurred during the main and second night of the recovery phases. However, during the first night of recovery phase there was post-midnight ionospheric irregularities.

1. Introduction

Ionospheric storm is a term to describe global disturbances on ionosphere during geomagnetic disturbed periods (Astafyeva et al., 2015). However, it is well known that, during the geomagnetic disturbed periods the high latitude ionosphere experiences the initial impact and the consequent disturbance fields are mapped/penetrated to the equatorial and low latitudes through magnetic field lines and/or travelling ionospheric disturbances (TIDs), which propagate from high latitude towards the equatorial region (Denardini et al., 2011; Venkatesh et al., 2017). Although the high latitude ionosphere experiences the first impact of geomagnetic disturbances and it is the source of TIDs, the influence of disturbed fields is more intense at the equatorial and low-latitude regions due to the presence of strong electrodynamics and ionospheric variability. Therefore, the equatorial and low-latitude region is one of the most interesting and challenging regions of the Earth's upper atmosphere to study the ionospheric disturbances during extreme space weather conditions. The main possible sources of the equatorial and low-latitude ionospheric storm include prompt penetration of electric fields (PPEFs), disturbed dynamo effects, TIDs, and neutral composition changes (Fejer, 2011; Fagundes et al., 2016; Venkatesh et al., 2017).

During the solar cycle 24 there was a very intense geomagnetic storm, called the St. Patrick's day storm and the effects of this storm on ionosphere has become a topic of extensive space weather investigation. The Dst during this storm reached −223 nT on March 17, 2015 at 23:00 UT. A halo coronal mass ejection (CME) associated with a C9.1 flare at 02:00 UT on March 15, 2015 was the main driver of the St. Patrick's day storm (Kataoka et al., 2015; Nayak et al., 2016).

Special efforts have been devoted so far to investigate many aspects of the St. Patrick's day ionospheric storm such as the prompt penetration electric fields (PPEFs), GPS-TEC (total electron content) changes, electron density disturbances, plasma drift, O+ concentration modification, hemispherical asymmetry developments, equatorial ionization anomaly (EIA) modification, and ionospheric irregularities (Ramsingh et al., 2015; Carter et al., 2016; Cherniak and Zakharenkova,

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2016; De Michelis et al., 2016; Fagundes et al., 2016; Huang et al., 2016; Joshi et al., 2016; Kakad et al., 2016; Kuai et al., 2016; Nava et al., 2016; Nayak et al., 2016; Spogli et al., 2016; Zhou et al., 2016; Dmitriev et al., 2017; Figueiredo et al., 2017; Venkatesh et al., 2017; Zakharenkova et al., 2018). It is important to mention that Fagundes et al. (2016), Venkatesh et al. (2017), and Figueiredo et al. (2017) have studied different features of the ionospheric disturbances in the American sector due to the St. Patrick's day storm. Using GPS-TEC, Fagundes et al. (2016) investigated the positive and negative ionospheric storm effects during the main and recovery phases, respectively. Venkatesh et al. (2017) studied the storm induced daytime zonal electric field variations, equatorial F-layer disturbances, EIA modifications, and consequent spatial-temporal changes in the electron density during this ionospheric storm. In addition, Figueiredo et al. (2017) investigated the propagation of large-scale travelling ionospheric disturbances over North and South American sectors. Besides all these studies, there are some important aspects, which have not been addressed yet, such as the equatorial large-medium-small scale ionospheric irregularities in the South American sector during this intense geomagnetic storm. Carter et al. (2016) and Zakharenkova et al. (2018) investigated the global occurrence of F-region ionospheric irregularities and over Russia during the St. Patrick's day storm, respectively.

Plasma bubbles are known to be one of the largest ionospheric irregularities and it is well known that, these structures are aligned to magnetic flux tubes with east-west and north-south dimensions of hundreds and thousands of kilometers, respectively (e.g., Fejer and Kelley, 1980). These large-scale structures are generated at equatorial region and extend towards low-latitudes in both hemispheres. Large-scale irregularities are characterized by having a lower electron density than the ambient plasma density while the medium and small scales irregularities can be generated inside them. Therefore, using different optical or radio-waves instruments, it is possible to investigate large-medium-small scale irregularities (Sahai et al., 2004; Becker-Guedes et al., 2004). These equatorial ionospheric irregularities can be observed using different instruments such as ionosondes (spread-F), GPS receivers (S4 and ROT), and All-Sky imager systems (using OI 630.0 nm oxygen emission). However, each instrument observes irregularities with different scale-size, based on a different technique. Therefore, combinations of 2 or more instruments provide a better understanding of the irregularity characteristics. It is well known that the equatorial spread-F (ESF) and plasma bubbles have higher frequency of occurrence from November to March and low frequency of occurrence from June to August in the South American sector. In addition, the months of April, May, September and October are transition periods (Sahai et al., 1999, 2000; Pimenta et al., 2001). It has been further understood that the geomagnetic storms and solar activity significantly affect the rate of occurrence and morphology of ESF (Bowman, 1982; Aarons, 1991; Sahai et al., 1998, 2004; Fejer et al., 1999).

In this paper, we present and discuss the generation and suppression of multi-scale ionospheric irregularities, using the observations from 20 dual frequency GPS stations (ROT phase fluctuation), 4 ionosondes (ESF), and JULIA radar observations in the Latin American Sector during March 2015, which includes St. Patrick's day geomagnetic storm period. It is important to emphasize the significance of performing ionospheric studies using a network of observatories and experimental data from different instruments. Using this strategy, it is possible to study the ionosphere in much more detail and thus to advance the current knowledge of ionosphere physics.

2. Results and discussion

The GPS receiver and ionosonde data are used to investigate multi-scale ionospheric irregularities. These data were recorded in the equatorial and low-latitudes over South American. More details about geographic coordinates and dip-latitudes of these stations are given in Table 1 and the locations are indicated in Fig. 1. We also present measurements of 3-m spread F irregularities obtained using a low power 50 MHz JULIA (Jicamarca Unattended Long-term Investigations of the Ionosphere and Atmosphere) system at the Jicamarca Radio Observatory, Peru (Hysell and Burcham, 1998, 2002). The main purpose of this study is to investigate the generation and inhibition of ionospheric irregularities during March 2015 which includes the St. Patrick's storm period. In this study, 20 GPS receivers and 4 ionosondes stations are used among which, 10 GPS stations and 2 ionosondes are located in the eastern sector and remaining stations in the western sector. Fagundes et al. (2016) showed VETC and EIA longitudinal differences in the Brazilian sector during St. Patrick's day storm. Thus, in this paper, we explore ionospheric irregularities (Spread-F and ROT phase fluctuations) variability and their longitudinal differences (see Fig. 1).

Fig. 1 show the South American map and locations of all stations used in this investigation. The red and blue icons present GPS stations located in the equatorial and low-latitude region, respectively. The yellow icons show the ionosondes locations. Notice that the left yellow icon refers to Jicamarca where ionosonde and JULIA radar operated simultaneously. The black and yellow colored curves indicate the geomagnetic and geographic equators. It is interesting to note here that the distance between the east and west sectors is about 17.5° (~1900 km) and in the west sector the distance between magnetic and geographic equators is about 9.4° (~1000 km).

2.1. Rates of change of TEC (ROT) During March 2015

In this paper the rates of change of TEC (ROT) are calculated using the same methodology used by Sahai et al. (2004). In addition, using the same methodology the ROT has been used to study ionospheric irregularities during quiet and disturbed time (de Jesus et al., 2010, 2016, de Abreu et al., 2010, 2014, 2017). According to Aarons et al. (1996) and Aarons (1997) the phase fluctuation is obtained by examining the total electron content variation. Therefore, the rates of change of TEC are obtained as follow:

$$ROT = \frac{\Delta \text{TEC}}{\Delta \text{t}} \tag{1}$$

where ΔTEC is the difference between consecutive TEC (TECt + 1–TECt) and Δt ((t + 1) – t) in seconds. The ROT can be used to study ionospheric irregularities of order of several kilometers (small scale irregularities). When there are ROT random fluctuations it is an indication of the occurrence of ionospheric irregularities. Basu et al., 1988 mentioned that the magnitude of random phase perturbations imposed on a transionospheric communication link depends on the integrated electron density deviation $\int \frac{\Delta N}{N} dl$, along the ray path. This parameter is controlled by the irregularity amplitude (ΔN/N) and the background electron density (N). In addition, during the initial stages the large and small scale ionospheric irregularities coexist. However, the small scale irregularities disappear earlier than the large scale irregularities due to recombination process (Buhari et al., 2014, 2017).

Fig. 2 shows ROT over an equatorial region SALU (Dip-latitude 3.7° S) on March 01–02, 2015 for several satellites (indicating by the numbers on the left Y-axis). Each horizontal line shows the ROT for an individual satellite, the length of the line indicates the time duration, which the satellite was in the field of view of the GPS receiver. When there is no presence of irregularities the ROT phase fluctuation shows a nearly straight and horizontal line, on the other hand when there is presence of irregularities the ROT present phase fluctuations. Therefore, the ROT phase fluctuations are seen when there is an ionospheric irregularity between the GPS receiver and satellite signal path. It can be noticed from Fig. 2 that the start and end of the ROT phase fluctuations for each satellite is different. Since the ionospheric irregularity does not fill the entire field of view of the GPS receiver, at a specific time, some satellite signals of the GPS constellation are affected by the irregularities and others are not (Fig. 2). Therefore, we assume that the