Records of the Geomagnetic Storm of March 17, 2015 in the Brazilian Equatorial Region

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***Abstract*: Using data from geomagnetic-sensitive instruments, this article analyzes the geomagnetic storm that occurred on March 17, 2015, characterized as intense and associated with a eruption of filaments and a solar flare of class C9.1 occurred on March 15, 2015. These solar events triggered a halo-type geo-effective CME, which generated a severe geomagnetic storm on March 17, 2015 (the minimum Dst -223 nT at 23 UT). The results showed that the strong geomagnetic storm produced a great impact on the ionosphere. The effects of the storm show changes in the ionospheric parameters measured in the Brazilian stations of Boa Vista (2.82° N, 60.7° W), Campo Grande (20.50° S, 54.70° W), Fortaleza (3.70° S, 38.5° W) 2.53° S, 44.30° W). The results showed that foF2 and TEC did not show important changes during the main phase. But changes in foF2 and TEC were observed at all seasons during the storm recovery period, which contributed to significant changes occurred in the ionosphere (SF) thickness. Another important phenomenon that arose with the geomagnetic tempest was the formation of ionospheric F3 layer.**

Keywords: Geomagnetic storm; foF2; layer F3; terrestrial ionosphere; ionosphere thickness.

I. INTRODUCTION

Geomagnetic storms generated by solar activities can contribute to ionospheric disturbances due to the huge energetic particle, momentum and energy injected into the Earth's atmosphere. disturbances in the ionosphere due to geomagnetic storms can have important effects capable of altering the position accuracy and performance of satellite tracking, damage to the energetic sectors, changes in HF communications (3-30 MHz), loss of navigation signal. A series of studies on the effects of the geomagnetic storms in the ionosphere have been realized in the last two decades [2], [12], [1], [5], [10]. The authors reveal a common feature that the ionosphere response during the geomagnetic storm. The nature of many mechanisms of a geo-magnetic storm is not yet sufficiently clear. The ionospheric effects of storms are vary from season to season, such as solar activity, storm start time, storm intensity, storm duration, station, local time and many other factors [3].

Geomagnetic storms occur on Earth in response to different forms of manifestation of solar activity, which can cause disturbances in the interplanetary environment and even affect the space environment near the Earth. A geomagnetic storm is the result of the energy transfer from the solar wind to the Earth's magnetosphere, causing additional changes in the Earth's magnetic field [6], [13]. These variations can be observed in the different components of the Earth's magnetic field, and are represented by magnetic indexes [8]. The most used indexes are: Disturbance Storm Time (DST) and Planetarische Kennziffer (Kp); the DST index is the measurement e of the magnetic field strength, near the earth's magnetic equator, resulting in a measure of the intensity of the ring current's equatorial symmetry. The Kp index is obtained from a weighted average of K indexes from a network of geomagnetic observatories in middle latitudes. The K index is related to the maximum variations of the horizontal components observed in a magnetometer in relation to a calm day, during a 3-hour interval [7], [13]. Geomagnetic storms can cause changes in the electron composition found in the ionosphere so that if the electron density of the ionosphere increases as a result of storm dynamics, this effect is called a positive ionospheric storm, and if the density decays, it is called a negative ionospheric storm [14]. Chemical effects increase enriches the process of increasing nitrogen, in the lower layers of the F region [21]. In this way, the chemical recombination becomes faster than normal [17], which increases the rate of electron loss in the F2 layer, leading to a decrease in NmF2 and foF2. Therefore, the decrease of the O / N2 ratio results in the reduction of the electron density, which drives a negative response of the ionosphere [18].

Ionospheric parameters are susceptible to changes due to alterations in the electron composition of the ionosphere such as in the Total Electron Content (TEC) and in the critical frequency of the ordinary wave of the ionosphere layer F2 ($foF2$). Thus, when these two parameters vary, other dependent parameters can be changed, as for example, the ionosphere thickness (SF), which is defined from the TEC and foF2 by the following expression: $SF = TEC/1.24\,10^{10}\,(foF2)^2$. TEC is measured in $electrons/m^2$ whereas the denominator that is the electron density (NmF2) is measured with units $elétrons/m^3$. Therefore, SF's unity is measured in Km [4]. The SF is a representation of the equivalent thickness of the ionosphere and is generally "idealized" as containing the same electron content of the "real" ionosphere, but with uniform electron density equal to

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 09, September - 2017

the maximum electronic density at the peak of the F region [15]. Changes in the interplanetary magnetic field (IMF) resulted in a decrease of foF2 at the equator and the formation of an additional F layer above the F2 peak. For this phenomenon, it received sufficient attention information and the nomenclature F3 layer [20] for the densities improved above the F2 layer, which is related to strengthening of the equatorial region, caused by the combination of plasma drift $\boldsymbol{ExB}$ and modulation of the neutral wind [19]. When observing the evolution of SF, there is a tendency for the formation of the ionospheric layer F3 in the equatorial region. The F3 layer forms during the morning-noon period in the equatorial region where the combined effect of the upward $\boldsymbol{ExB}$ drift, and neutral wind provides vertically upward plasma velocity at altitudes near and above the F2 peak. The vertical velocity causes the F2 peak to drift upward and form the F3 layer while the normal F2 layer develops at lower altitudes through the usual photochemical and dynamical processes of the equatorial region. The density of the F3 layer can exceed that, of the F2 layer. The layer is predicted to be distinct, and frequent on the summer side of the geomagnetic equator and to become less distinct, with increasing solar activity. The latitudinal extent of the layer may extend to the winter side of the geomagnetic equator if there is a strong ascending $\boldsymbol{E\,x\,B}$ drift, or a weak wind of the pole, or a combination of the two.

Thus, this work besides addressing variances in the ionospheric parameters (foF2, TEC and SF) also identifies the ionospheric F3 layer formation during the geomagnetic storm of March 17, 2015, with data from GPS receivers (Global Positioning System) and digison at the Boa Vista and Campo Grande stations located on the crest of the equatorial ionization anomaly (EIA), and, Fortaleza and São Luís, located near the magnetic equator.

II MATERIALS AND METHODS

To identify the geomagnetic storm, observations were made in the DST index by using magnetometer data. Figure 1 shows the variation of the intensity of this index for the month of March, 2015. The daily variation characteristic of Dst index illustrates that this geomagnetic storm is almost the most intense storm since year 2010 in the 24th solar cycle. The DST index shows a slight increase, which is associated with the compression of the magnetic field lines (initial phase) from 08:00 UT on March 17th. This intensity decreases to a minimum value close to -223 nT (main phase) at 23:00 UT in the same day, which is associated with the generated magnetic field, opposite to the terrestrial magnetic field. Then, lasting several days, the intensity measurement shows a slow recovery (recovery phase).

The methodology for the study of the geomagnetic storm was to choose magnetically calm days before and after the event. Thus, the days 15 to 20 of March 2015 were chosen for the analysis of the TEC obtained from GPS measurements and $foF2$ extracted from digisonde data. Figure 2 illustrates *FoF2*, TEC, SF and the DST index. Figure 3 shows the variation of the Kp index, DST, Protons density and electric field in station Boa Vista. Then an average for March 2015 of each parameter was calculated and compared with values for the day of the storm (Figures 4,5 and 6). In figures 7 and 8 are contained images of ionograms of the stations Boa Vista and Campo Grande pointing to layer F3.

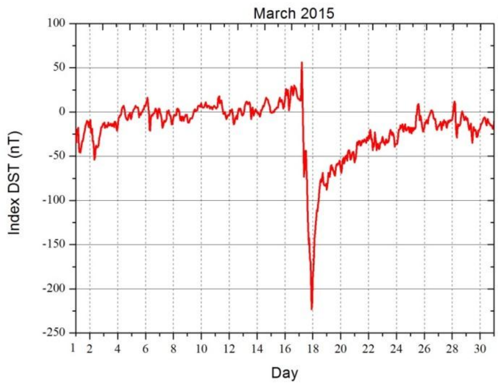

Figure 1. Identification of geomagnetic storm on March 17, 2015 through variation of the DST index.

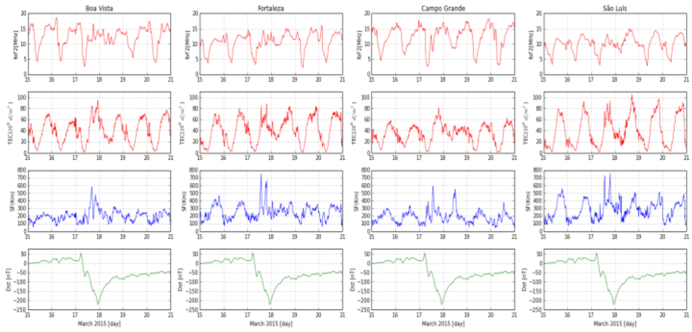

Figure 2. Variation of the DST index and ionospheric parameters ($foF2$, TEC and SF) between March 15 and 21, 2015, at the stations Boa Vista, Campo Grande, Fortaleza and São Luís.

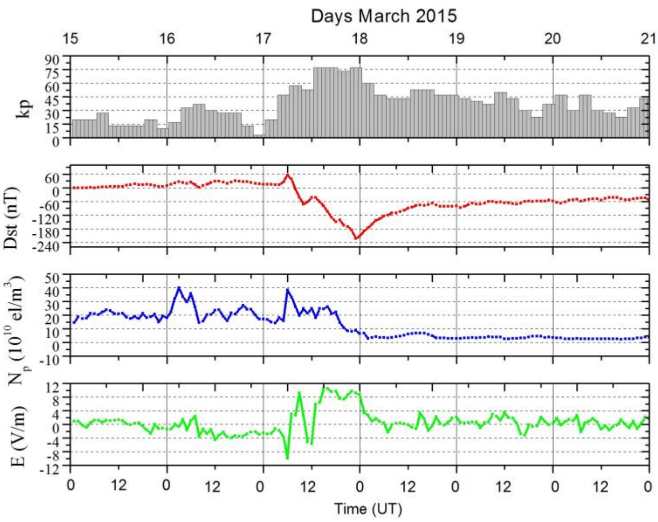

Figure 3. Variation of the Kp and DST index, Protons density and electric field between March 15 and 20, 2015, at the station Boa Vista.

III EFFECTS ON TERRESTRIAL IONOSPHERE

Figure 2 shows that during the main phase of the geomagnetic storm, identified by the DST index, the parameters$foF2$, TEC and SF had changes in daily behavior with values usually perceived during magnetically calm days in all monitoring stations. Figure 4 shows the 24-hour monthly average of $foF2$ for the month of March 2015 and the variation of this parameter on the day of the storm. In general, when the monthly average is compared to the values on March 17, it is seen that, as of 12:00 UT, $foF2$ increased on the day of the storm in Boa Vista and Campo Grande, because the stations are located in the crests of the EIA, while in São Luis and Fortaleza there was a reduction of the observed values, due to their proximity to the magnetic equator.

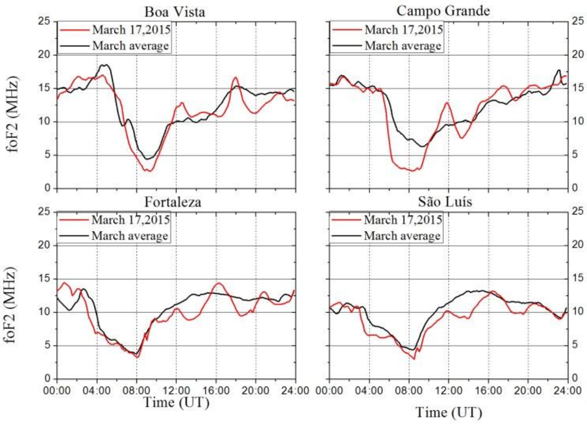

Figure 4. Average of $foF2$ for March 2015 and values for the day of the storm in Boa Vista, Campo Grande, Fortaleza and São Luís.

From the TEC graphs, Figure 5, by analyzing the graphs for each of the stations, it can be observed that there was an increase in the electron content in the regions of the crest of EIA (Boa Vista and Campo Grande), whereas in the stations closest to the geomagnetic equator (São Luís and Fortaleza) the negative effect on the TEC was more prominent on the day of the storm, for the period from 12:00 UT; however, the maximum value of the TEC was above 80 10^{16} el/m^3 in all seasons. In percentage terms, the TEC increase observed in each season on the day of the storm set up the following values: in Boa Vista there was a 90% increase, in Campo Grande 60%, Fortaleza 12% and São Luís 34%. Therefore, it is noted for all seasons that the daily variability of the TEC is considerable because of the changes in certain regions of the ionosphere, caused by the storm of March 17, in which ionization changes occurred in the ionosphere during the disturbed period. Thus, from the TEC and $foF2$ it was observed that SF increased in all seasons on March 17, due to the variation of the $foF2$ and to the more prominent increase in TEC.

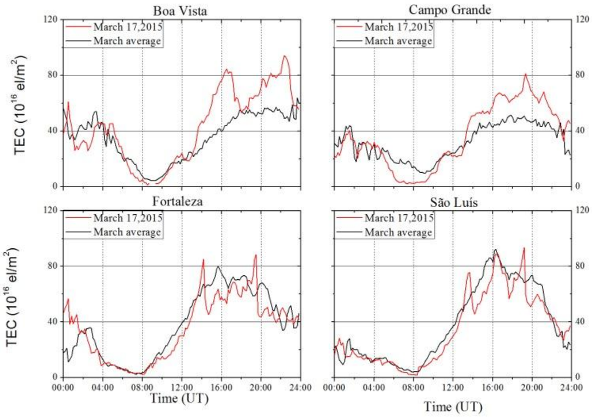

Figure 5 Average of TEC for March 2015 and values for the day of the storm in Boa Vista, Campo Grande, Fortaleza and São Luís.

Figure 6 shows the monthly average for the month of March 2015 and the SF variation for March 17. In São Luís, which is located on the magnetic equator, the thickness of the ionosphere increases from 200 km to 680 km, representing an increase of 340%, shortly after the initial phase of the storm. This effect was also noticed in other stations, in Boa Vista there was an increase of 80 km (60%) and in Campo Grande of 150 km (66%) for the same period as observed in São Luís. At Fortaleza station, however, there was no notice of alteration of SF. After 12:00 UT, the scenery becomes more uniform, in all the stations were observed two maxima that characterize increase in the ionosphere thickness; the first maximum occurs around 14:00 UT (except in Boa Vista, which occurs by around 16:00 UT). The second maximum is observed before 20:00 UT in São Luís, Fortaleza and Campo Grande, while in Boa Vista the second maximum occurs after 20:00 UT.

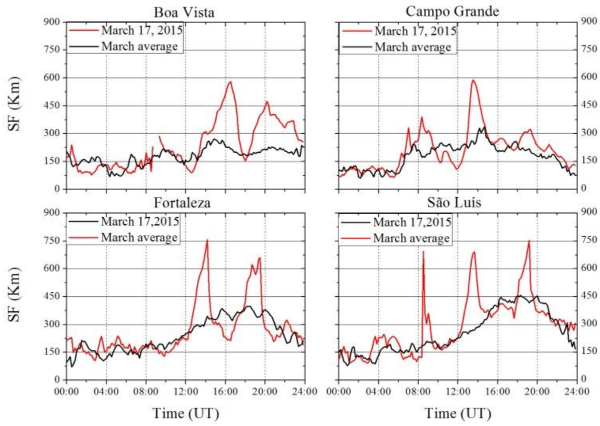

Figure 6. Average of SF for March 2015 and values for the day of the storm in Boa Vista, Campo Grande, Fortaleza and São Luís.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 09, September - 2017

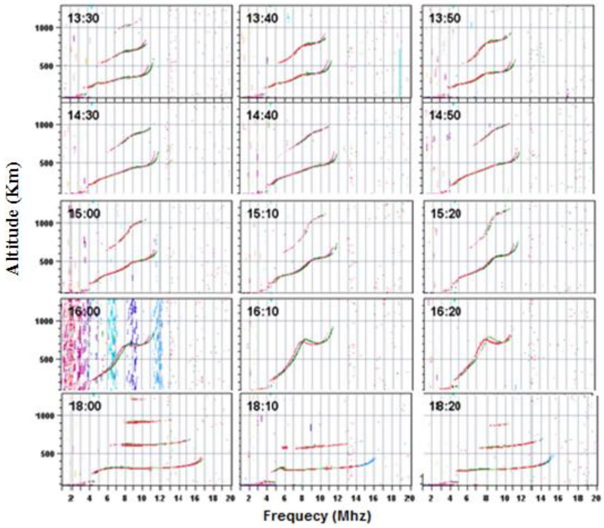

Figura 7. Ionograms of digissonde observed in Boa Vista on March 17, 2015.

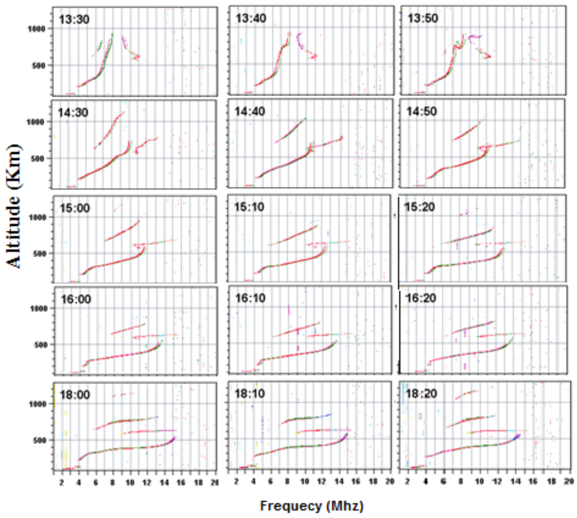

Figura 8. Ionograms of digissonde observed in Campo Grande on March 17, 2015.

Beginning around 13:30 UT, the lower F2 the layer plasma changed very slowly to larger heights maintaining the frequencies. Therefore at 14:30 UT, the echoes above 500 km (F2> 10 MHz), where the F3 layer begins to form on the Boa Vista station (Figure 7). The ionosgrams later show the formation of F3 and, around of 16:00 UT has the fully evolved F3 layer. In Campo Grande (Figure 8) the beginning of the formation of the F3 layer takes place at 13:30 UT where the height reaches 700 Km at a frequency of 8 MHz. At around 14:00 UT the ionograms show the Fico in the SF value and the formation of the F3 layer. Note that the apparent echo propagation in the F3 trace at 13:50 UT did not spread, but is an artifact of digital processing caused by signal saturation.
The ionosgrams generated by the digissondas show the rising steady F2 stable layer increased rapidly associated with the magnetic storm, important factor that contributes to decreases the peak density of layer F3 during the event can be understood as a result of this expansion. An aligned flux in the field, whereby plasma is deposited in the higher latitude ionosphere, further reducing equatorial density, may not be essential.

IV. CONCLUSION

The characteristic daily variation of the Dst index illustrates that this The geomagnetic storm is almost the most intense storm since the year 2010 in the 24th solar cycle. Figure 3 shows the variations of the parameters of the geomagnetic storm for the period from March 15 to 20. On March 15 and 16, the interplanetary environment presented some north-south disturbances from 03:00 to 09:00 UT, the Kp and Dst index of 3 hours revealed a relative level of calm geomagnetic conditions. However The geomagnetic parameters occurred obvious oscillation on March 17, 2015. The Dst shift reveals that there was a short and moderate geomagnetic storm occurred at about 04 UT and ended at about 09:00 UT before the arrival of the strongest storm. From 04:00 UT to 09:00 UT, the field was intensified causing a sudden increase and then decreased dramatically after the spin South, however, the Kp and Dst indexes showed a gradual reinforcement indicating that the energy was injected continuously and accumulated during this period, as to show the positive variation of the proton density.

The results showed changes in the ionosphere over the Brazilian stations studied during the month of March, 2015. Changes were observed in the ionospheric parameters (TEC, $foF2$ and SF), so that there are similarities between Boa Vista and Campo Grande, and also between São Luís and Fortaleza. But what stands out the most, when comparing the day of the storm with the monthly average of March 2015, is the increase observed in SF during the main phase of the storm. In general, SF is improved during the main phase, presenting an oscillating behavior pattern throughout the period, characterized by the maxima observed in each season. The increase in SF values can be mainly due to the plasma flow aligned to the field of the protonosphere towards the ionosphere where large downward flows of H^+ can decrease O^+ for H^+ transition levels, thus increasing the electron content and therefore the ionosphere thickness [16].

As shown in Figure 3, the variation in the electric field is due to the variation of protons penetration in the ionosphere, with this increasing the number of particles in the ionosphere, there is a significant increase in the electron density, with this increase in the thickness of the ionosphere.

The neutron winding effect may also play a role in ionospheric storms and may increase foF2 and consequently the Ionosphere thickness. [11] studied the storm from March 6-8, 2012 found the negative variation of the TEC during the main phase and the improvement in the TEC during the recovery phase that may be due to local weather oscillation of the neutral winds. [9] found that the winds push the plasma from layer F2 upward and lead to a peak density of the reduced F2 layer, analyzing effect caused by strong meridian winds during January 10, 1997, At the same time, there is increase of TEC, which is reverse for the decrease of the peak density of the F2 layer.

The increase in SF during the geomagnetic storm does not occur simply by increasing the quotient value between the TEC and the term $(1.24\,10^{10}\ (foF2)^2)$, but rather the variation of the electron density in the Ionosphere during the storm. Thus SF is greatly influenced by the electron density profile shape of the ionosphere, which makes it a convenient parameter that represents the electron density profile and is related to the different physical processes in the ionosphere. In sum, the thickness variation in the ionosphere is an indication to predict and characterize the electron density distribution since this parameter has information about the TEC and foF2.

The SF parameter (associated with the layer thickness) is a good proxy for estimating the occurrence of the F3 layer. The occurrence of F3 layers at conjugated sites in Brazil seems to be well in agreement with the physical mechanism proposed by [19] for their formation. During disturbed conditions, the layer F3 strata, the occurrence of the F3 layer in the conjugated sites occurs only in favorable wind conditions, where this disturbed wind plays an essential role in the development of these ionospheric stratifications. Therefore, the effects on the ionospheric parameters due to the geomagnetic storm of March 17, 2015 and, in particular, the considerable positive variations in the thickness of the ionosphere were identified in the present study, through the stations of Boa Vista, Campo Grande, Fortaleza and São Luís . Many effects may have been produced in the terrestrial ionsphere by winding the CME on March 17, 2015, but this work contributed little, only studying with greater emphasis the variation of SF and showing evidence of formation of the F3 ionospheric layer. However, other physical phenomena produced by the geomagnetic storm can be studied in the Brazilian region, the formation of ionic ducts during the storm period, the formation of plasma bubbles.

ACKNOWLEDGMENT

National Institute of Space Research, Federal University of Roraima, CAPES and Dra. Natalia Papitashvili (Space Physics Data Facility-SPDF) thank you for the data.

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