CHARACTERISTICS OF THE GPS SIGNAL SCINTILLATIONS DURING IONOSPHERIC IRREGULARITIES AND THEIR EFFECTS OVER THE GPS SYSTEM

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The ionospheric irregularities can give origin to amplitude and phase scintillations in the GPS signal and can affect telecommunication systems. In this work we present briefly the physical mechanisms that give origin to the ionospheric irregularities, and their dependence with season, local time, solar activity and magnetic activity. Following we will describe the potential effects of the scintillations on the GPS systems, like the loss of lock, increase of the dilution of precision (DOP), decrease on the available number of GPS satellites and effects on the WAAS (Wide Area Augmentation System) navigation and positioning system. This study was based on L1 (1.575 GHz) GPS signal amplitude scintillations measured by an array of 11 Scintillation Monitors located over the Brazilian territory. The GPS data were recorded at 50 samples/sec and the scintillation index S4 was used to quantify the scintillation intensity. Over the Brazilian territory the ionospheric irregularities incidence is normally from September to March, however they can be triggered at any month of the year during the incidence of a magnetic storm. The ionospheric irregularities incidence and intensity increase with the increase of the solar cycle. The irregularities are generated at equatorial region after sunset due to plasma instability processes and they occur in the pre-midnight time sector and after midnight during some magnetic storms. The ionospheric irregularity amplitudes are largely dependent of the ionospheric background ionization and over the Brazilian territory there are large ionization gradients from equator to low latitudes due to the Equatorial Anomaly. Due to this anomaly the Total Electron Content (TEC) presents 2 peaks at about 15^{o} S and 15 ^{o} N of magnetic latitude and a decrease at equatorial latitudes, and as a consequence the ionospheric irregularities give origin to larger amplitudes close to these crests. For instance stations like São José dos Campos and Cachoeira Paulista are under the Equatorial Anomaly peaks. The ionospheric irregularities can cause large fades on the GPS signal for stationary receivers that can cause losses of lock (tracking) that can persist for tens of seconds. As the ionospheric irregularity patterns (bubbles) drift in the east-west direction with about 150 m/s, for moving receivers like landing aircrafts, which have almost same velocity, the fades can be potentially much longer causing even longer tracking losses. In this work we show some statistics of loss of lock occurrence during ionospheric irregularities. One consequence of tracking loss is an increase in the dilution of precision due to the GPS satellite loosing, what increases the navigation errors. In severe conditions of irregularities incidence the number of tracked satellites may fall below 4 that is the minimum amount for calculating navigational solutions.

1- INTRODUCTION

In this work we present the interferences of the ionosphere, that is an atmospheric ionized layer extending from 60 to 1,000 km of altitude, in the electromagnetic signals that cross this medium. The signals from many telecommunication upward and downward links and the signal from the Global Positioning System (GPS) for navigation and positioning are affected by the ionosphere and plasmasphere Total Electron Content (TEC). The plasmasphere is another ionized layer located above the ionosphere, and depending of the local time and position in the Earth, it can contribute substantially to the TEC, however we will not discuss this contribution in this work. The ionosphere, being a refractive layer, affects these signals causing retard and refraction in the signal that crosses it.

Besides that, after the sunset and in the equatorial region, the ionospheric irregularities, that are regions of depleted plasma of scale sizes varying from centimeters to kilometers (Fejer, 1996, Kelley, 1985), are generated due to plasma instabilities. Phase and amplitude of a radio signal fluctuate when it passes through the ionospheric irregularities. The ionospheric irregularities can cause degradation in the GPS navigational accuracy and limitations in the GPS system tracking performance (Bandyopadhayay et al., 1997, Skone, et al., 2001).

Initially we present the effects of the TEC over the GPS signal. Following we present the physical mechanisms that give origin to the ionospheric irregularities and their characteristics, including their dependence with season, local time, solar activity and magnetic activity and their effects over TEC. Finally we discuss the potential effects of scintillations due to ionospheric irregularities on TEC, on the GPS performance like loss of lock, dilution of precision increase (degradation), on the SBAS (Space Based Augmentation System) to be implemented in Brazil, and on the differential GPS systems (DGPS) that use geostationary satellite to receive and to transmit to the users the ionospheric corrections.

2- Effects of the TEC over GPS signal

The Earth's ionosphere, that is a refractive medium, causes besides the refraction, a delay in the GPS signal which propagates with the group velocity (V_g) since this velocity is smaller than the light velocity and this delay is proportional to the Total Electron Content (TEC) along the GPS signal. Over the low magnetic latitudes, like over the Brazilian territory, the ionosphere presents the Equatorial Ionospheric Anomaly (EIA) that constitutes of higher electron density peaks at about 15^o magnetic north and south of the magnetic equator. In the magnetic equator the ionospheric plasma is uplifted by the **E** X **B** drift, where **E** is the electric field from the ionospheric E region (after sunset from the ionospheric F region) mapped to the F region and **B** is the magnetic induction, during the sunlight and post-sunset hours. Following this plasma diffuses along the magnetic field lines due to the gravity force and pressure gradient in the plasma, and the plasma cumulates at about 15 ^{o} north and south of the magnetic equator (see Figure 1). These electron density peaks are highly dependent on the season, solar cycle and local time and they give origin to large density gradients between the magnetic equator and low magnetic latitudes. Figure 2 presents the slant ionospheric delay over Brasília that is out of the EIA peak and at Rio de Janeiro, that is under the south EIA peak. It can be observed ionospheric delay differences of up to 20 m between these 2 stations, showing the substantial effect of the TEC over the GPS signal under the EIA region. Figure 3 also illustrates the effects of the TEC over the GPS signal over Brazil using one ionospheric model for high solar activity (F10.7 cm = 210) and for March, an equinoctial month. This figure shows differences of up to 30 m in the vertical ionospheric delay when comparing the equator region with low latitude regions (Klobuchar et al., 2002). Besides causing ionospheric delay the TEC affects substantially the GPS scintillations (de Paula et al., 2003), what will be discussed in details in the next topics.

3 – Ionospheric irregularities characteristics over Brazil

As described previously the ionospheric irregularities are electron density depleted regions of the ionospheric plasma along the magnetic field lines that are generated at the magnetic equator after sunset and during magnetically quiet time they drift from west to east with a velocity of about 150 m/s (de Paula et al., 2002). Figure 5 shows the signature of one plasma bubble detected by one all-sky photometer in the wavelength of 6,300 Å during March 18, 1999, at Cachoeira Paulista, that is in the center of the plot. As bubbles are electron density depleted regions there is consequently a drastic reduction in the aeroluminescence intensity over these regions. This plot, that represents one region of approximately 1,100 x 1,100 km^2, shows the width in the east-west and north-south directions of the structure (bubble signature at about 250 km of altitude) for that day (darker portion at the plot). The irregularities cover the tropical region all over the world, however with a larger incidence over Brazil due to the large magnetic declination over our country and they have a large spectrum of scale sizes varying since few cm to several kilometers, so they affect transmission frequencies since HF to several GHz. They present a large day-to-day variability and they have a large dependence with magnetic position (latitude and longitude), season, local time, solar activity and with the magnetic activity, as will be described in the sections 3.2 - 3.5.

3.1- Physical mechanisms that give origin to the ionospheric irregularities

Electron density irregularities, generically known as spread F, are generated at the magnetic equator during post sunset hour due to the Rayleigh-Taylor (RT) plasma instability. Many ionospheric ambient parameters like the electric field responsible for the vertical plasma drift at the equator, neutral wind and the plasma density gradient were included to the Rayleigh-Taylor instability and the generalized RT instability was proposed (Abdu, et al., 2001, Kelley, 1985, Sultan, 1966). The non-linear evolution of RT instability generates a large spectrum of irregularity scale sizes from few centimeters to several kilometers (Fejer, 1996), which can be monitored by different observational techniques that use different signal frequencies. The L1 GPS signal probes plasma irregularities with scale size of about 400 m. These ionospheric irregularities, if the ionospheric conditions are favorable, can grow along the magnetic field lines reaching continental dimensions and they are called ionospheric bubbles. Figure 4a shows one ionospheric electron density profile with a large gradient around 300 km, what is one condition for the irregularity to be generated. Figure 4b is an illustrative figure where one heavier plasma is resting over the neutral atmosphere in unstable equilibrium and Figure 4c shows another illustration of one grown bubble after its generation due to some seeding mechanism, probably due to gravity waves, that triggered the instability.

3.2- Dependence of the ionospheric irregularities with magnetic latitude and longitude

Figure 6 shows the GPS ionospheric scintillations over Brazil, for March 17, 2002. It can be observed that the intensity of the ionospheric scintillations, here represented by the scintillation index S4 (to be explained at the section 5), increases from the magnetic equator to the equatorial ionospheric anomaly peak showing the enhancement of the scintillations at regions with increased background ionization (TEC).

Abdu et al. (2000) showed that the scintillation occurrence at Tucumán, Argentina, although it is located at approximately the same magnetic latitude of Cachoeira Paulista, but located at a different longitude sector, presents a much smaller scintillation occurrence when comparing to the Brazilian longitudinal sector.

3.3- Dependence of the ionospheric irregularities with season

At the Brazilian sector the period of irregularity occurrence extends approximately from September to March during magnetically quiet days. The effect of the magnetic storms over the irregularities will be described at the Section 3.5. This seasonal effect of the scintillations over our territory was explained by Batista et al., 1986, and is basically due to the large westward magnetic declination (20^{o} W). Figure 7 shows the dependence of the scintillations with the seasons for 2 levels of scintillation intensity from 1997 to 2002, at São José dos Campos.

3.4- Dependence of the ionospheric irregularities with Local Time and Solar Activity

Figure 8 shows the influence of the local time and solar activity over the ionospheric irregularities for 3 solar flux levels and for São José dos Campos (23.21^{o} S, 45.86 ^{o} W, dip latitude 17.8 ^{o} S). At this figure we observe that over São José dos Campos the local time interval of irregularity, represented by the L-band scintillation occurrence, is from about 19:30 to 24:00 LT, however this time interval is shorter during solar minimum. This figure also shows that the percentage of occurrence of the irregularities increase with the increase of the solar flux. The irregularities occurrence for solar minimum (F10.7 = 96, 1997-1998) is confined to the summer solstice months, however this occurrence extends to September and April for high solar activity (F10.7 = 173, 1999-2000). The scintillation occurrence at São José dos Campos, is highly dependent of the Equatorial Ionospheric Anomaly peak position, which is dependent of the solar activity. During very high solar activity or during a strong magnetic storm this peak sometime moves south of this station, and the scintillation over this site is not as high as expected. Also the background ionization can present saturation when the solar activity is too high.

3.5- Dependence of the ionospheric irregularities with the magnetic activity

One magnetic storm can inhibit the irregularities during their period of occurrence or it can trigger irregularities at any month of the year, even during a period when irregularities are not expected (de Paula et al., 2004). This behavior during storm is very complex because it depends of the hour of the storm commencement, of the season, and if the storm occurred before the end of another storm. During a magnetic storm an electric field of magnetospheric origin can penetrate to equator reinforcing the normal E layer electric field (direct penetration) or can weaken it (disturbance dynamo). Figure 9 shows one example of storm triggered GPS scintillation during the April 10-12, 2001 storm (de Paula, et al, 2004). In the bottom panel we can observe that the storm that began on April 11 triggered strong ionospheric irregularities, represented by GPS scintillation, during the night 11/12 and that the scintillations in the previous night 10/11 and posterior night 12/13 were much weaker than the storm night. De Paula et al. (2004) showed that a very strong eastward electric field from magnetospheric origin penetrated directly to the equator in the post-sunset hours and intensified the vertical upward plasma drift, what is one of the most important condition for the irregularities to be generated and to grow (Fejer et al., 1999). Also at this Figure 9 we observe scintillations after the midnight sector, and this behavior normally occurs during magnetic storms (Fejer et al., 1999).

4- The effects of the ionospheric irregularities over TEC

Ionospheric scintillations (bubbles) can cause large depletions on the TEC and their signatures are clearly visible at TEC plots. These TEC depletions reflect on decreases on the ionospheric delays in the received GPS signal. Figure 10 is an example of slant delays decreases over 2 GPS receiver stations at Rio de Janeiro on January 2002. As these 2 stations are located in the magnetic east-west direction and as the bubbles move from west to east during quiet magnetic conditions, it can be observed at this figure that some structures appeared first at the west station and after a period of time in the east station. So using spaced GPS receivers it is possible to calculate the west-east movement of the bubbles.

5- Potential effects of the ionospheric scintillations on GPS system caused by ionospheric irregularities

To analyse the GPS scintillations over Brazil we used an array of 11 L1 band (1.575 GHz) GPS SCINTillation MONitors (SCINTMON) located at 8 sites. Figure 11 shows the SCINTMON receivers sites over the Brazilian territory. These receivers were settled up and are being operated in collaboration with Cornell University and they measure the GPS signal amplitude at a very high rate (50 samples/s). To quantify the amplitude scintillation, we use the S4 scintillation index that is the standard deviation of the signal intensity (I) relative to the average, calculated at each one minute and is given by:

$$(S4)^2 = (\langle I^2\rangle - \langle I\rangle^2) / \langle I\rangle^2$$

Figure 12 shows one example of GPS amplitude scintillations represented by the Wide Band Power versus Universal Time (top panel) during ionospheric scintillations represented by the S4 index (bottom panel), for São Luís, December 27, 2000, and for the satellite PRN 27. The scintillation begins exactly when the S4 index begin to increase and it is stronger for large S4 values, showing clearly the correlation between them. At São Luís LT=UT-3, so the scintillation occurrence local time interval for this day is from around 20 LT to 23 LT. Following we present the potential effects of the ionospheric scintillations on GPS systems, augmentation systems and differential GPS caused by ionospheric irregularities.

5.1- Loss of lock

During ionospheric irregularities the GPS signal amplitude or fading can be deep and long and they can potentially cause tracking loss and lengthen acquisition times and consequently can cause degradation of the accuracy (Kintner et al, 2001). Figure 13 shows an example of loss of lock with a time interval duration of 16 s that was preceded by another shorter duration one during November 16, 1998, at Cachoeira Paulista (22.57° S, 45.01° W, dip latitude 18.12° S) . Navigation and positioning information are affected during loss of lock. As the ionospheric irregularities move in the west-east magnetic direction Kintner et al. (2001) showed that if the GPS receiver is also moving in the same direction, like a landing aircraft, and its velocity matches the scintillation pattern, the probability of receiver loss of lock increases because the tracking loop cannot track through the long time-scales fades.

5.2- Degradation of the dilution of precision and decrease of available number of GPS satellites

The GPS receivers select the most favorable 4 available GPS satellites to solve the navigation solution and to have a precise timing at the receiver. The dilution of precision is a parameter that quantifies the best geometric GPS satellite distribution in the sky to minimize the positioning and timing errors. Of course one large number of available GPS satellites is a condition that contributes to a small (large dilution of precision implies in poor navigation solution) dilution of precision. However due to the ionospheric irregularities, when the GPS signal fading reaches less than 30 dB, there are losses of lock occurrences and the number of available GPS satellites decreases and the dilution of precision increases. If the number of available satellites is 4 or less than 4, what could happen during severe ionospheric irregularities, the GPS system performance is poor and in some extreme cases can be interrupted. Figure 14 presents an example of dilution of precision increase simultaneously with losses of lock and a decrease in the number of available GPS satellites during ionospheric irregularities occurrence represented by the S4 index, at São José dos Campos and for October, 1998. During such critical conditions the GPS positioning system presents larger errors than during periods when there are no ionospheric scintillations.

5.3- Effects on Space Based Augmentation System-SBAS

The Space Based Augmentation Systems (SBAS) consist of reference (and one master) GPS dual frequency receivers adequately distributed over the area of interest to infer the ionospheric delays. The Brazilian SBAS test bed is show at Figure 15. After getting such ionospheric corrections they are transmitted to one geostationary satellite (uplink) which transmits them back (downlink) to the potential users like aircrafts, boats, cars, personal handheld receivers and many others users, so they can have a higher accuracy at their one frequency GPS receivers (that are cheaper than dual ones). Many countries already have their own SBAS systems, like the United States where they implemented the WAAS (Wide Area Augmentation System). However at Brazil, and also along the tropical regions of the Earth, the large TEC gradients and mainly the presence of ionospheric scintillations can affect substantially the performance of the SBAS systems. During ionospheric irregularities the geo-messages that have to cross the ionosphere twice are drastically affected and in many cases they are lost. One test flight with a FAA (Federal Aviation Administration) aircraft, specially projected to test WAAS performance, over Rio de Janeiro on January 2002, found out that the WAAS system can fail during ionospheric irregularities. So over Brazil to implement the SBAS it will be necessary to develop one TEC model based on previous and actual measurements over our territory and to decide how to deal with the scintillations effects on the SBAS. Some limited solutions to improve SBAS performance over regions with incidence of ionospheric irregularities are proposed at the conclusions of this work.

5.4- Effects of the irregularities over DGPS system: a case study

The Brazilian Petroleum Company (Petrobrás) uses the DGPS as the secondary positioning system of their dynamically positioned vessels performing deepwater petroleum exploration at Campos Basin. In this system the ionospheric corrections provided by one station with precise position is transmitted to the geostationary satellite Inmarsat in the L band which transmits them back to the vessels, and similarly to the SBAS systems this signal crosses the ionosphere during the upward and downward links. If ionospheric scintillations are present during the transmission of the ionospheric corrections they can be affected or even lost. Figure 16 shows the occurrence of ionospheric scintillations at São José dos Campos (that was the closest to Campos basin GPS scintillation monitor) and the simultaneous failures in the Inmarsat service at the Campos basin for October, 1998 (de Paula et al., 1999). It can be observed a good correlation between the failures in the DGPS system and in the occurrence of ionospheric scintillations.

6- Conclusions and suggestions to improve the GPS performance during ionospheric irregularities

The Total Electron Content (TEC) causes a delay in the GPS signal and over Brazil the TEC is highly dependent of the Equatorial Ionospheric Anomaly (EIA). The EIA gives origin to large gradients from the magnetic equator to the low magnetic latitudes around 15^{o} S, where there is a TEC peak. There is a large variability of the EIA with local time, season, solar activity and magnetic activity. For the GPS positioning system, if more accuracy is needed, it is necessary to correct such ionospheric delay using a dual frequency GPS receiver or to use a single frequency GPS receiver that has the capability to receive the ionospheric corrections from one Spaced Based Augmentation System (SBAS). However at Brazil and tropical regions of the world, due to plasma instabilities, there is the occurrence of ionospheric irregularities that are electron density depleted regions with scales sizes varying since few cm to several kilometers. These irregularities cause strong scintillations in the amplitude and phase of the GPS signal with consequent decreasing of the GPS system performance. These ionospheric irregularities over Brazil occur after the sunset up to the local midnight time, and from September to March (April during high solar flux), are highly variable and are affected by the local time, season, background ionization and consequently by the EIA, solar activity and magnetic activity. During magnetic storms the ionospheric irregularities can be inhibited during a period when irregularities are expected or can be triggered at any month of the year even for periods when the occurrence of irregularities is not expected. During storm periods electric fields from magnetosphere can penetrate directly or indirectly to low latitudes modifying drastically the ionosphere electrodynamics. After midnight scintillations can be observed during the incidence of magnetic storms. The ionospheric irregularities move, during magnetically quiet periods, from west to east with a velocity of about 150 m/s and normally this velocity becomes westward during magnetic storms. The ionospheric irregularities can evolve to large structures named ionospheric bubbles, that reach continental dimensions and they can cause large depletion in the TEC. The ionospheric irregularities affect the GPS performance because they cause losses of lock of the GPS signal, decrease of the number of available GPS satellites, degradation of the signal dilution of precision, and loss of the geo-messages from Spaced Based Augmentation Systems and from some differential GPS systems that use geostationary satellites to receive and to transmit the ionospheric corrections in the L band.

Some suggestions to improve the GPS performance without the presence of ionospheric scintillations, if high accuracy is necessary, are to use dual frequency receivers what is an expensive solution for the user or to implement a Spaced Based Augmentation System (SBAS) that is also one very expensive system, however only efforts from the government could establish such system. To improve the GPS performance during ionospheric scintillations it is necessary to improve the number of available satellites, what will be a reality with the implementation of the European Galileo system and to build more robust GPS receivers with smaller bandwidth, however this procedure will cause a larger incidence of the losses of lock.

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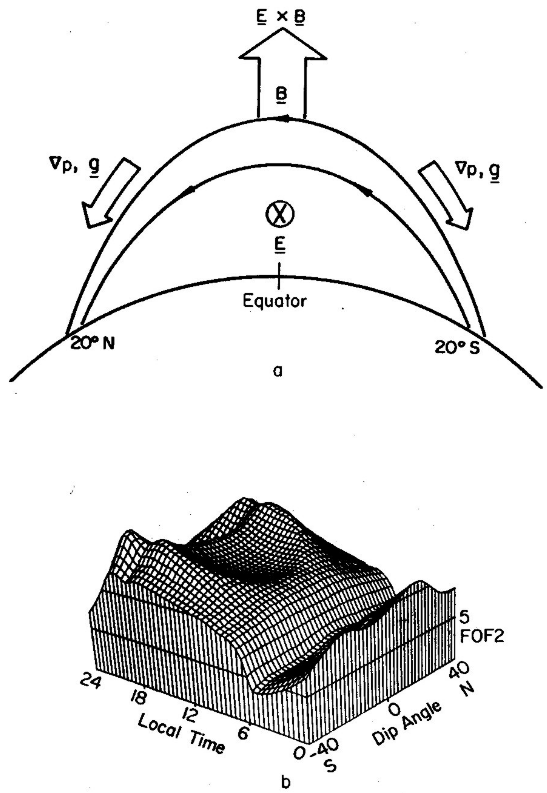


Figure 1- The mechanism responsible for the Equatorial Ionospheric Anomaly (EIA) formation (top) and its typical electron density peaks

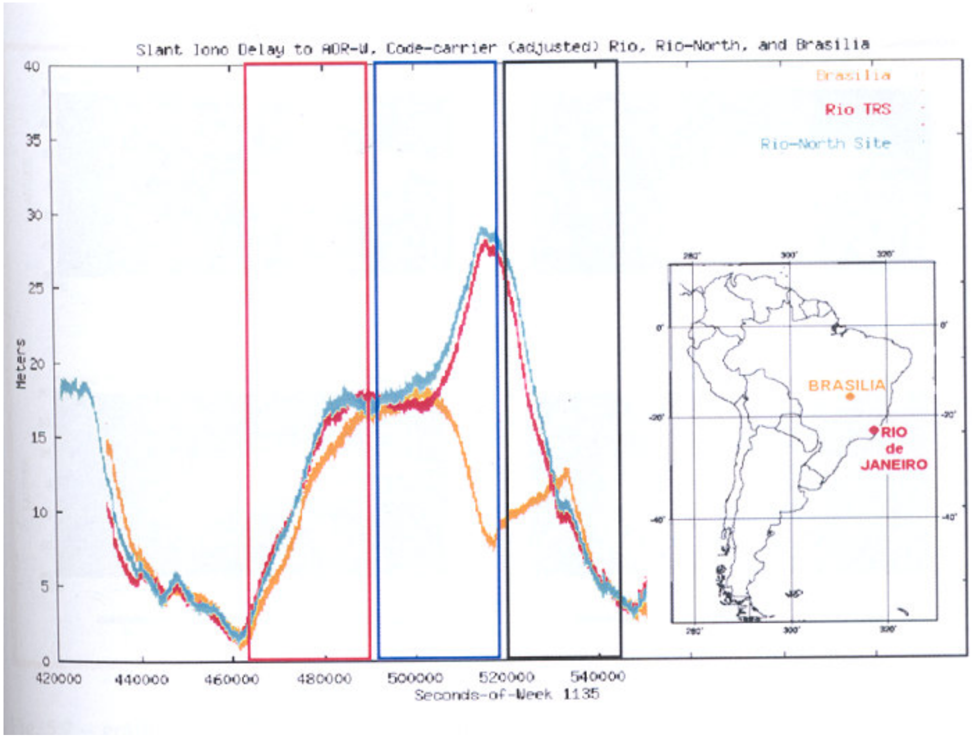


Figure 2- The effects of the Total Electron Content (TEC) over GPS signal under the Equatorial Ionospheric Anomaly region. Source: Tom Dehel (FAA – Federal Aviation Administration – USA), 2002

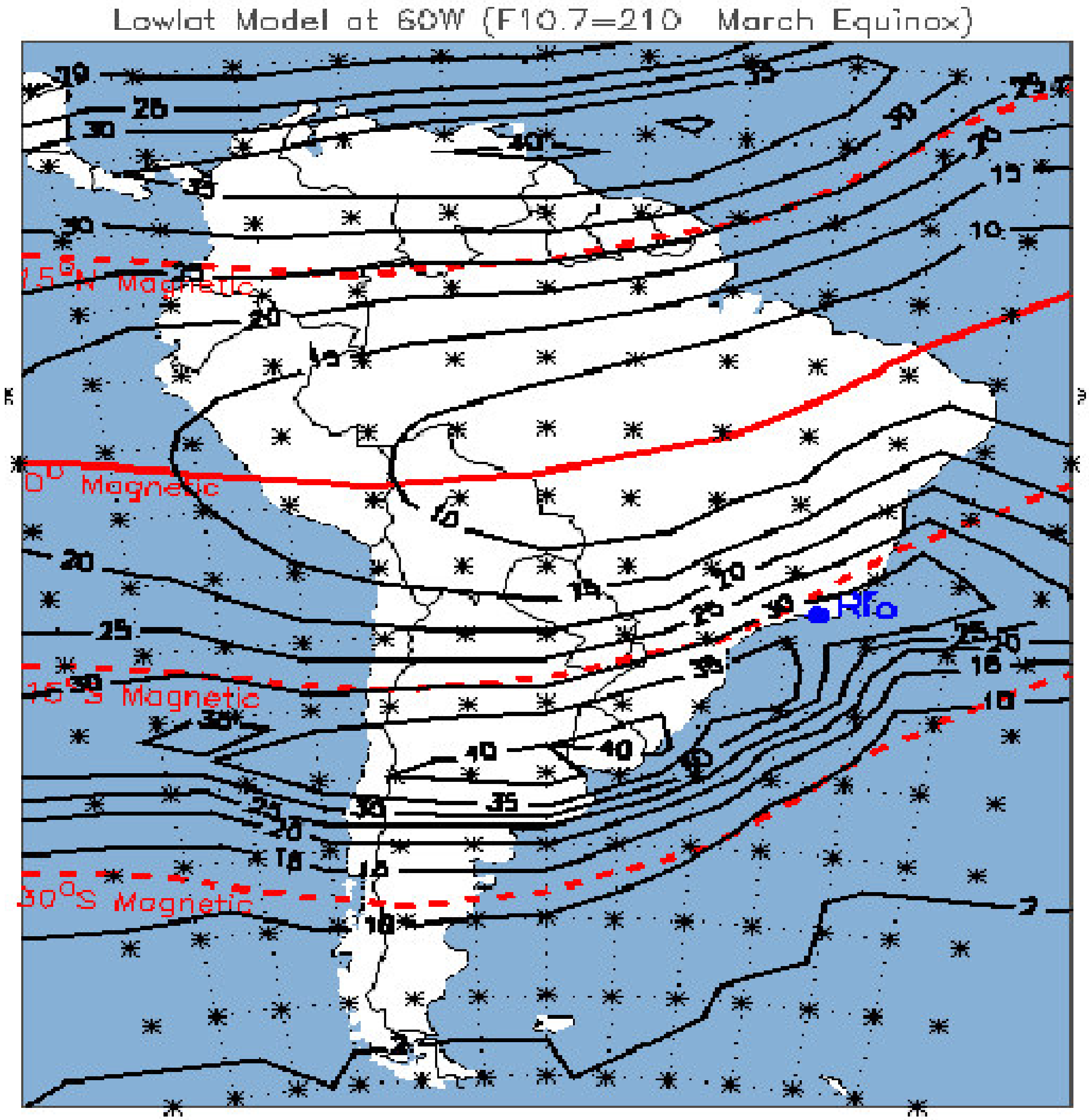
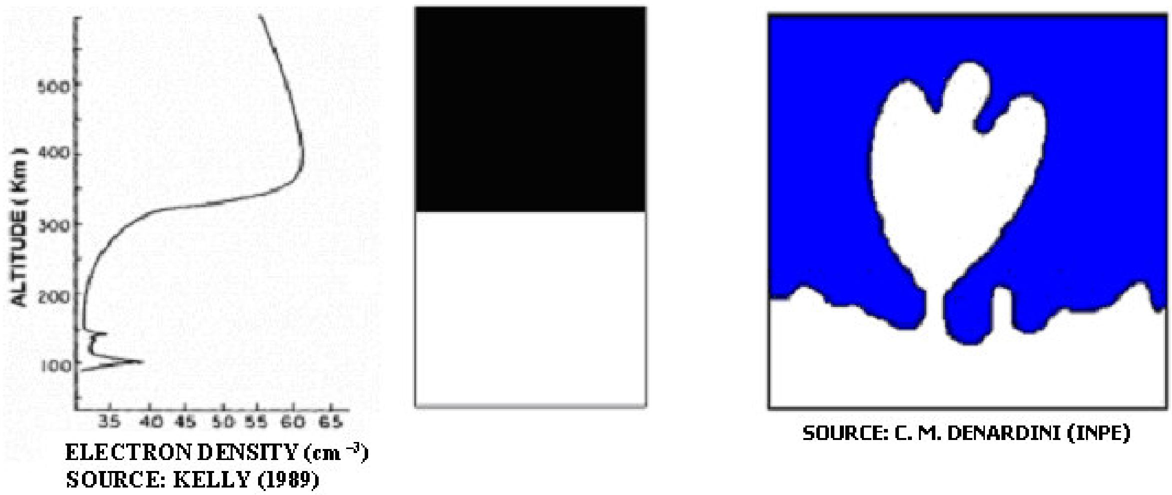


Figure 3- GPS vertical ionospheric delays due to TEC over South America calculated using a low latitude ionospheric model. Source: Klobuchar et al. (2002)



(a) (b) (c)

Figure 4- Ionospheric electron density profile with a large gradient around 360 Km (a); illustration of a heavier plasma resting over the neutral atmosphere (b); and the illustration of one bubble after its generation and evolution (c)

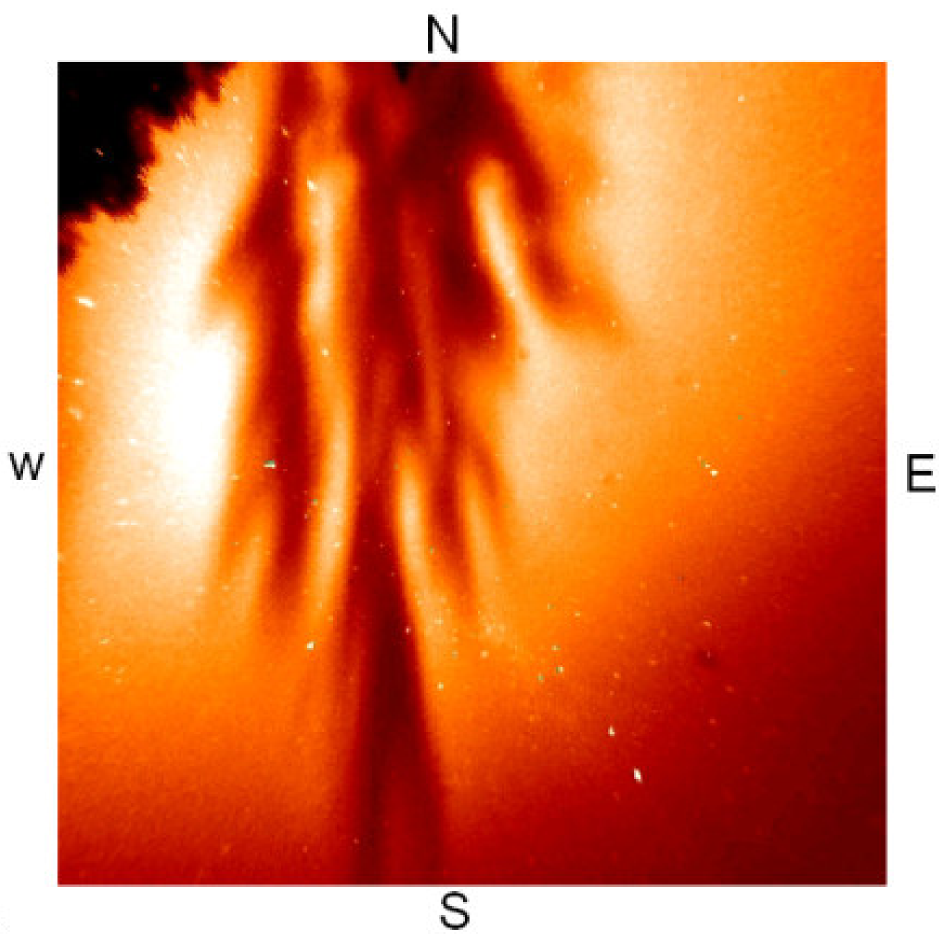


Figure 5- All-sky photometer bubble signature with wavelength of 6,300 **Å** , during March 18, 1999, at Cachoeira Paulista. Source: H. Takahashi (INPE)

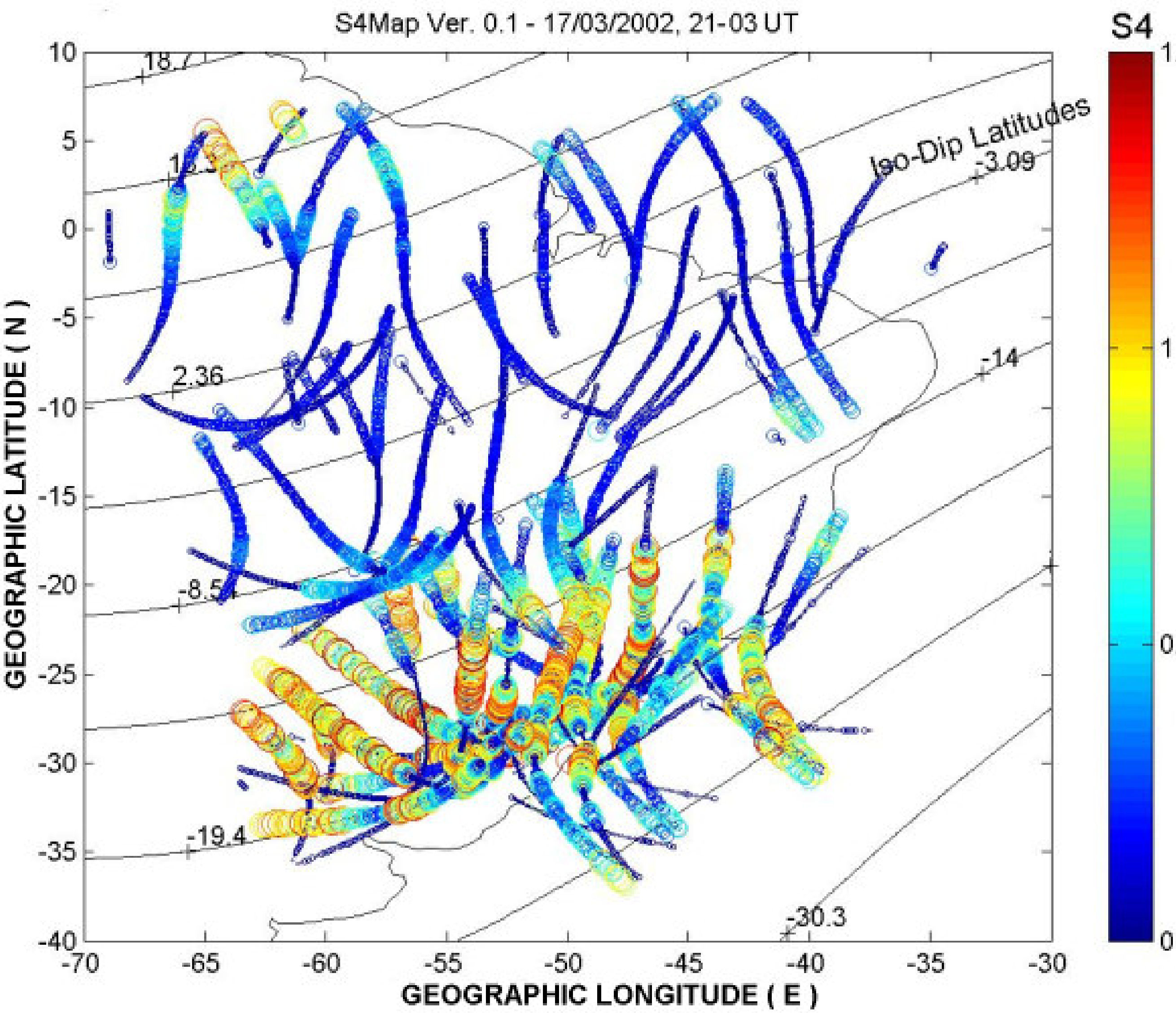


Figure 6- Ionospheric scintillations represented by the S4 scintillation index, during March 17, 2002, over Brazil. Source: Rodrigues (2003)

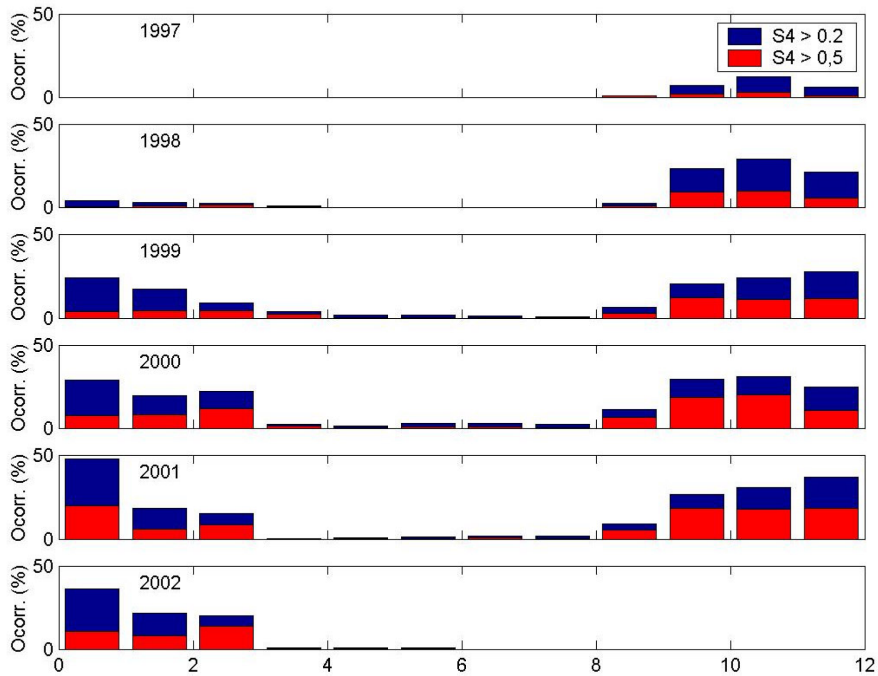


Figure 7- Dependence of ionospheric irregularities with season. Source: Rodrigues (2003)

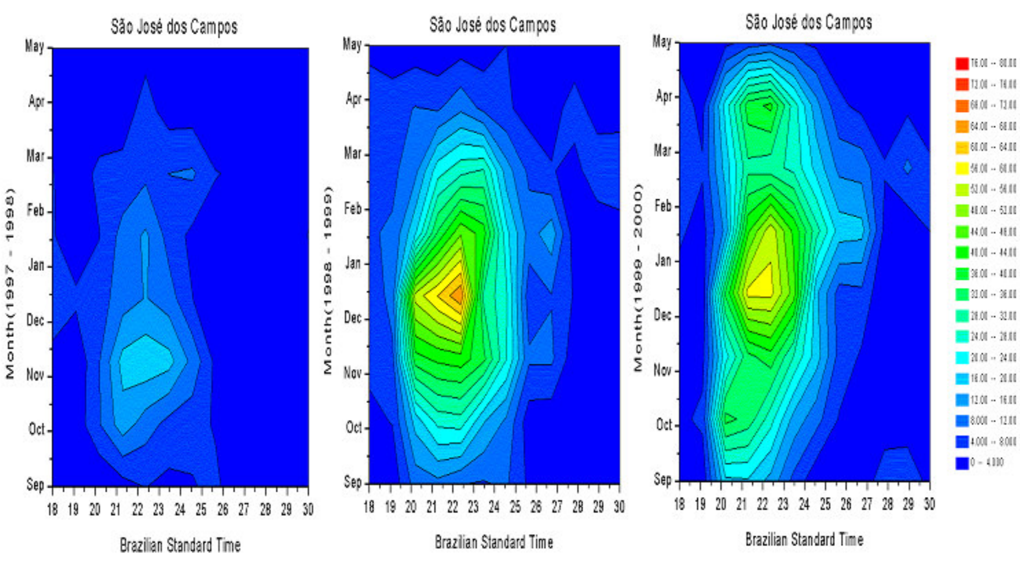


Figure 8- Dependence of ionospheric irregularities with local time and solar activity. Source: Klobuchar et al. (2002)

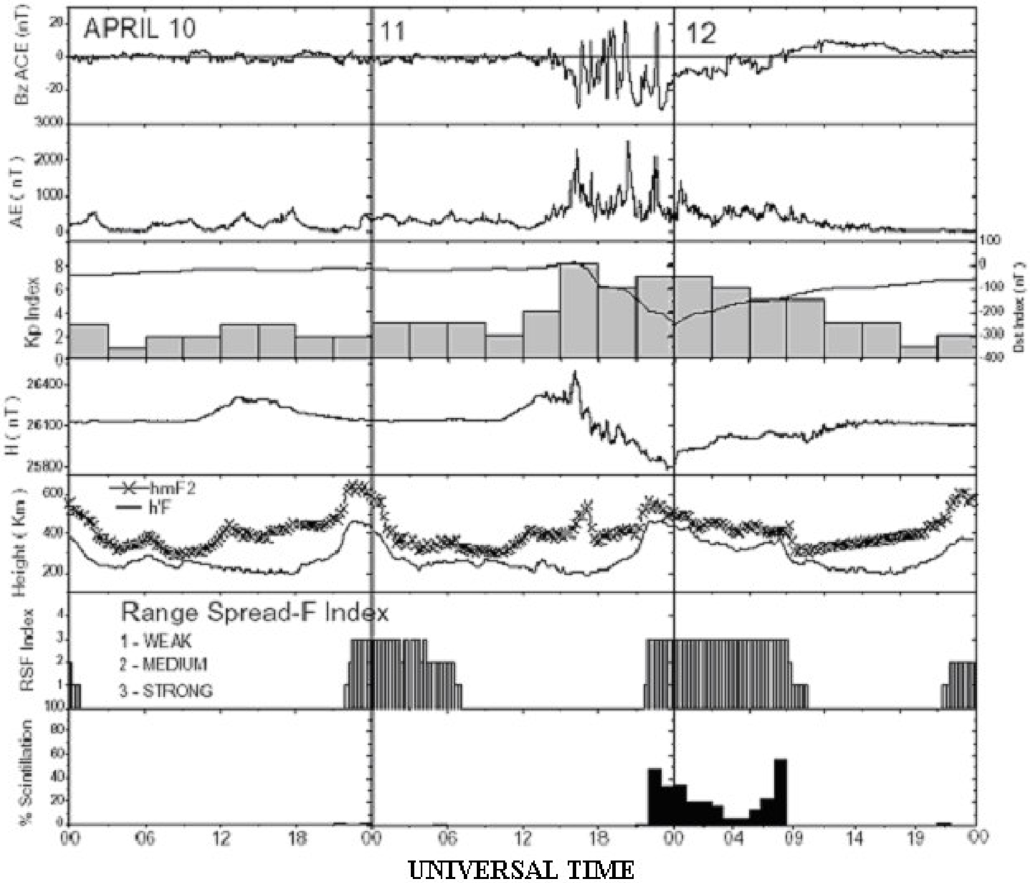


Figure 9- Example of ionospheric irregularities triggered by the April 10-12, 2001 magnetic storm. Source: de Paula et al. (2004)

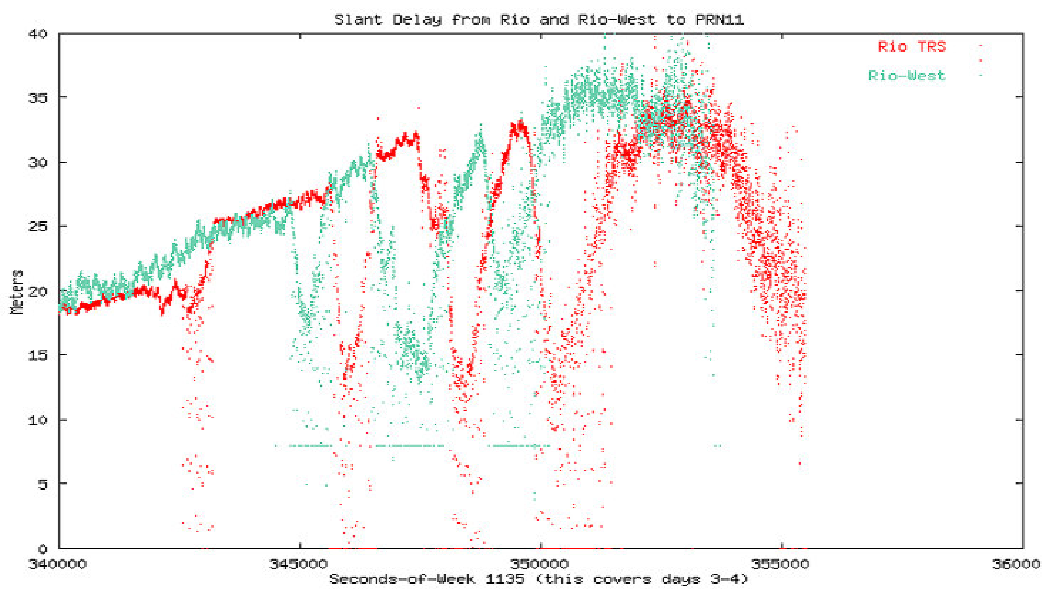


Figure 10- GPS slant delays at Rio de Janeiro associated with large TEC depletions due to the ionospheric irregularities. Source: Tom Dehel (2002)

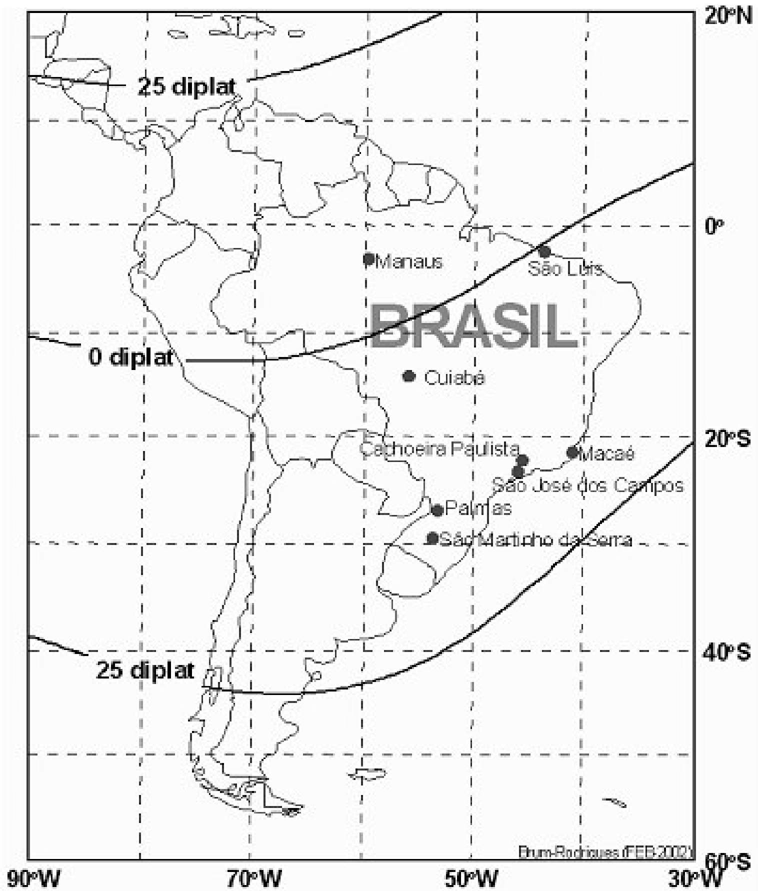


Figure 11- Scintillation monitors (SCINTMON) sites over Brazil

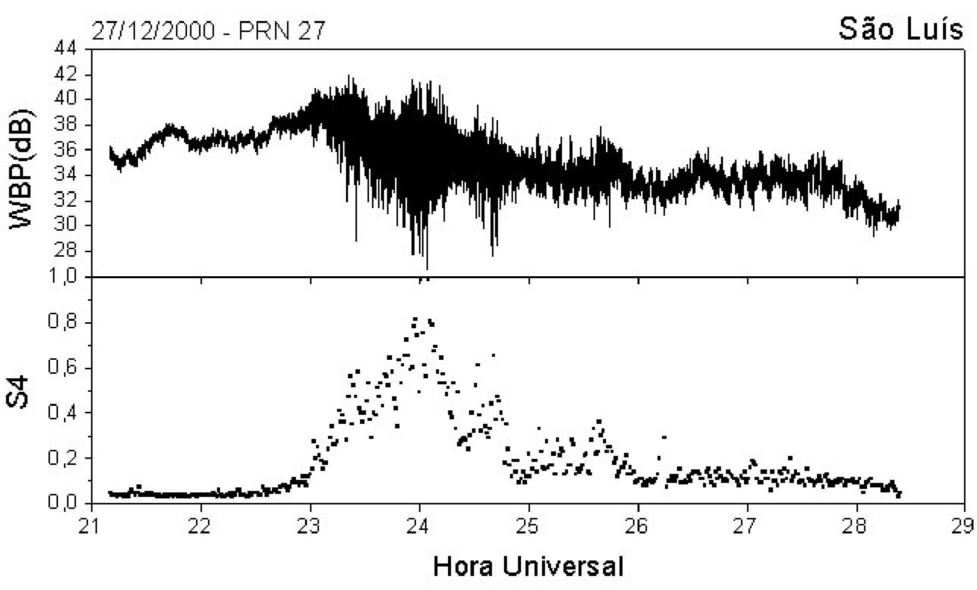


Figure 12- Example of GPS ionospheric scintillations during the occurrence of ionospheric scintillations represented by the S4 scintillation index. Source: Rodrigues (2003)

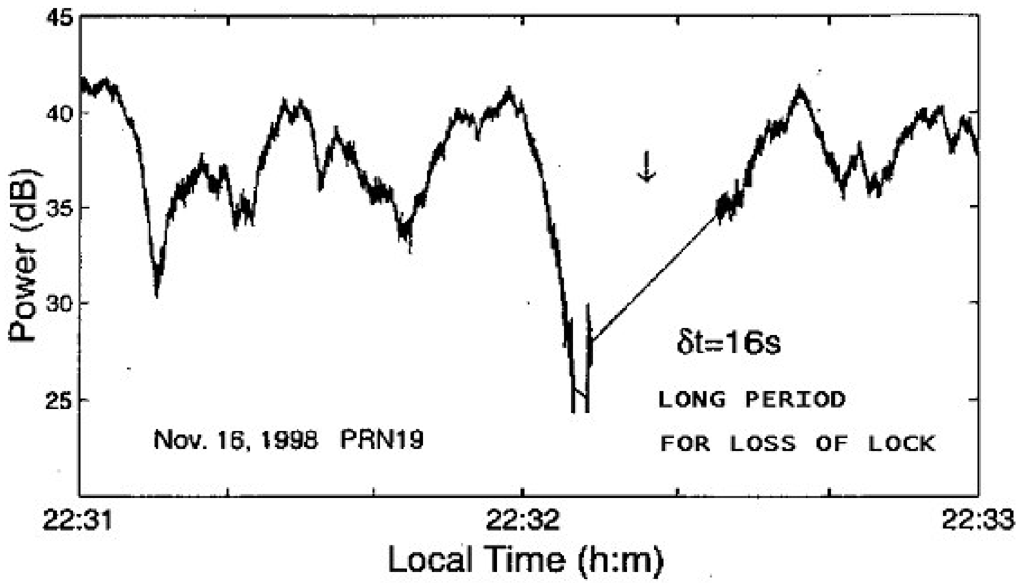


Figure 13- Example of losses of lock during ionospheric irregularities. Source: Kintner et al. (2001)

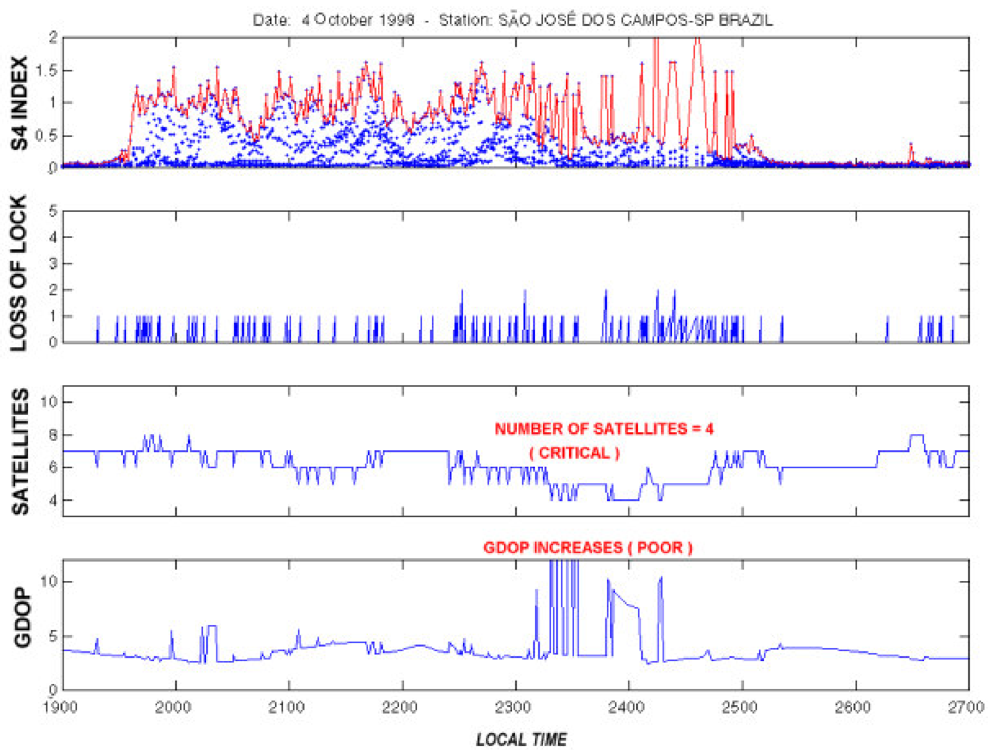


Figure 14- Example of losses of lock, increase in the dilution of precision and decrease in the number of available GPS satellites during ionospheric scintillations

Figure 15- Brazilian Space Based Augmentation System (SBAS) test bed

 **= IONOSPHERIC SCINTILLATION AT SJCAMPOS**

xxxxxx **= NO DGPS IN PETROBRÁS DYNAMIC POSITION VESSELS PERFORMING DEEPWATER PETROLEUM EXPLORATION AT CAMPOS BASIN (RJ) (INMARSAT L BAND SIGNAL PROBLEMS DUE TO IONOSPHERIC IRREGULARITIES)**

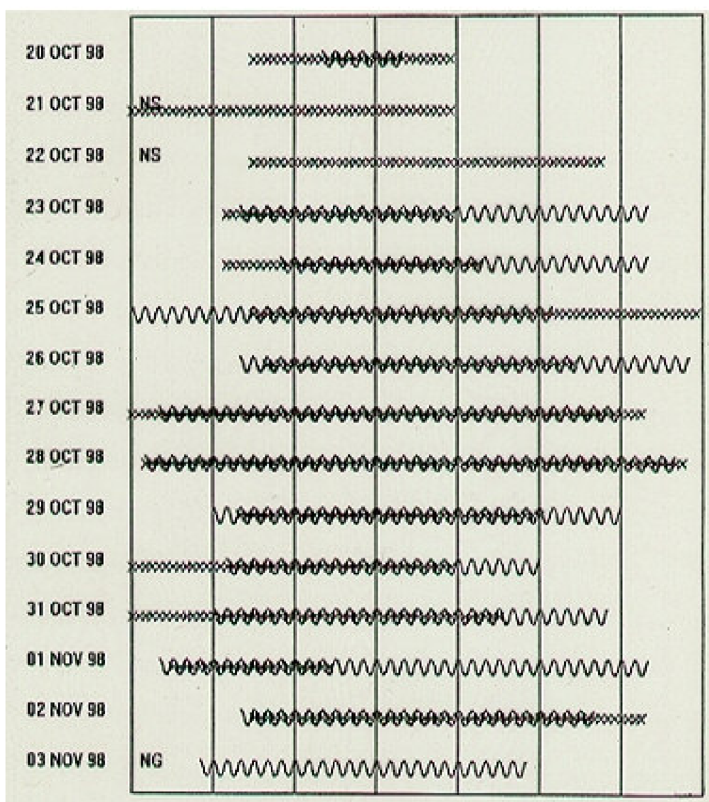


Figure 16- Effects of the ionospheric irregularities over DGPS (differential) system. Source: de Paula et al. (1999)