# DETERMINATION OF THE TEC PARAMETER BASED ON GPS RECEIVED SIGNALS

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Abstract: **The scope of this paper is to provide a method to determine the variation of the TEC of the Ionosphere by means of GPS received signals. The solution makes use of dual carrier phase and pseudo-range measurements from a terrestrial receiver, stored in specific RINEX files. The implemented algorithm processes the data and provides the variation of TEC and TEC gradient. For a considered period of time, the TEC variation indicates the behavior of the Ionosphere allowing a better modeling of the radio channel.**

***Keywords:*** *TEC parameter, Ionosphere, channel modeling, GPS signals, MATLAB implementation.*

## I. INTRODUCTION

The Total Electron Content (TEC) of the ionosphere is of great importance in radio communications as it influences the radio wave propagation. Its accurate estimation may be used to correct the errors introduced by the ionosphere and to model a radio channel that allows transmissions in good conditions. The propagation of the radio waves through the ionosphere is affected by its proprieties, producing reflections and refractions due to the variability of ionization and electron content of the layer. As described in [1], the scintillation is a rapid fluctuation of a radio-frequency signal in phase or amplitude generated as the signal passes through the ionosphere. This phenomenon occurs when a signal in form of a plane wave passes a region of irregularities in the content of the electrons (electron density). These irregularities produce a small-scale fluctuation of the refractive index and induce the apparition of the scattering effect on the plane wave that produces phase variations. As the signal continues its way through environments of different densities, phase and amplitude scintillation appears due to the interference with multiple scattered signals [1].

The scope of this paper is to presents a solution to determine the TEC parameter using GPS signals. The algorithms used in this paper are able to extract the vertical TEC (VTEC) based on carrier phase measurements of L1 and L2 signals, and pseudo-range measurements. The measurements used in this study are taken from a GPS receiver, in Receiver Independent Exchange (RINEX) file format. The TEC variation is plotted on graphs that allow to determine and predict how the ionosphere varies during a day. The obtained results present the main periods of the day when the variations occur, and indicate that near equatorial regions the TEC has great values and high variations.

This paper proposes an easy approach to determine the TEC parameter using mathematical computations over a GPS signal, extracted from a fixed terrestrial receiver, in order to plot the variation of the TEC and TEC Gradient parameter that can be further used to obtain more sophisticated description of the behavior of the ionosphere.

The results could be implemented in GPS receivers, augmentation systems or radio transmitters that based on proper algorithms could improve the precision of the GPS system and set the parameters of radio transmissions.

The remainder of the paper is organized as follows. Section II describes the TEC parameter and the impact of Sun ionization, cosmic rays and another atmospheric phenomenon over the ionospheric TEC. Moreover, it presents the RINEX file format used to extract the content of TEC parameter. Section III presents the two basic parameters that are used to determine the value of the TEC parameter (the carrier phase and the pseudo-range measurements that are acquired form a GPS receiver station) and includes some mathematical models used to compute the variation of the TEC parameter. Section IV describes the VTEC implementation algorithm using MATLAB. VTEC experimental results are presented in Section V. Finally, Section VI concludes the paper.

## II. TEC PARAMETER DESCRIPTION

TEC is an important descriptive quantity of the ionosphere. It is defined as the total number of electrons present along a path between two points and is significant in determining the group delay of a radio wave through a medium.

$$1016\ electrons/m^2 = 1\ TEC\ unit\ (TECU) \quad (1)$$

Ionospheric TEC is characterized by observing carrier phase delays of received signals transmitted from satellites located above the ionosphere. It is strongly affected by solar activity. Ionosphere is the part of the atmosphere of the Earth where the density of free electrons is high enough to have an appreciable influence on the propagation of the radio waves. The ionization degree depends primarily on the Sun activity, as indicated by the ionospheric structures and the peak densities in the ionosphere that vary a lot in time.

Variations of the sunspot cycle, weather seasons as well

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as diurnal and nocturnal variations affect the behavior of the ionosphere. Moreover, the influence of the solar related ionospheric disturbances may be experienced differently in various geographic locations. Inside the ionosphere the ionization is produced by solar X-ray and ultraviolet radiation and by corpuscular radiation from the Sun. The most intense ionization of the ionosphere is produced in the sunlit atmosphere and the lowest ionization appears in the shadowed side. Apart from the Sun, there are other contributors to the ionization of the ionosphere as the cosmic rays and other atmospheric disturbances.

The impact of such a phenomenon is that it affects radio signals up to a few GHz, mainly affecting the satellite based communications and navigation systems (such as GPS-based systems). The scintillation of the amplitude affects the signal-to-noise ratio (SNR) of a signal in a GPS receiver, as well as the noise levels in code and phase measurements. Because the signal power on the GPS L2 frequency is approximately 6 dB lower than that of L1 signal, and because the non-optimal or codeless civil receivers need L2 signals for processing, it results in even lower SNR values, meaning higher disturbances of the measurements [9].

### 2.1 RINEX FORMAT AND TEC DETERMINATION

The RINEX format is a standard format that allows managing of the results from a receiver and after that post-processing it using a multitude of applications. The TEC parameter is determined using a RINEX observation file [7] and a dual frequency GPS receiver by measuring the difference of the ionospheric delay between L1 and L2 GPS frequencies (f1 = 1575.42 MHz and f2 = 1227.60 MHz). The TEC parameter can be determined using equation (2):

$$TEC = \left(\frac{1}{40.3} * \frac{f1^2 * f2^2}{f1^2 - f2^2}\right)(P2 - P1) \qquad (2)$$

P1 and P2 are the pseudo-range measured in L1 and L2. The method of using differential carrier phase measurements gives a more precise evaluation of the TEC parameter, but the number of phase cycles is not known. Therefore, the absolute value of TEC cannot be determined unless pseudo-range is used. In this context, the pseudo-range gives the absolute value for TEC and the pseudo-range measurements increase the precision of measurements.

### 2.2 CARRIER PHASE AND PSEUDO-RANGE MEASUREMENTS

There are two types of observables used to calculate TEC: (a) the pseudo-range (the P(Y)code) measurement and (b) the phase of the carriers of the GPS signal [4]. Firstly it is needed to compute the pseudo-range difference from the two types of observables. The easiest way is to obtain the pseudo-range difference from the code measurements by taking the difference between the measured pseudo-ranges.

To obtain the pseudo-range difference using the carrier phase measurements it is needed to perform a multiplication between the two measured carriers and their corresponding wavelength. However it is important to take care of integer ambiguity. It is easy to measure the phase of a carrier wave accurately but is impossible to make the difference between different carrier cycles since the signals transmitted by the GPS are pure sinusoidal waves (ignoring PRN codes) [8]. The equations (3) and (4) describe the pseudo-range measurements with the offset:

$$P_{L1} = lambda_{L1} * \varphi_{L1} + lambda_{L1} * N_{L1} \qquad (3)$$
$$P_{L2} = lambda_{L2} * \varphi_{L2} + lambda_{L2} * N_{L2} \qquad (4)$$

where $lambda_{L1}$ and $lambda_{L2}$ are the space wavelength of L1 and L2 signals and $\varphi_{L1}$ and $\varphi_{L2}$ are the number of cycles on the path between the satellite and the receiver; $N$ is the integer ambiguity.

Variations of the sunspot cycle, weather seasons and diurnal and nocturnal variations affects the behavior of the ionosphere. Also the geographical location (polar zones, aurora zones, mid-latitudes, equatorial regions) produces solar - related ionospheric disturbances. The difference between the two pseudo-ranges is given by equation (5):

$$\Delta P = P_{L1} - P_{L2} \qquad (5)$$
$$\Delta P = lambda_{L1} * \varphi_{L1} - lambda_{L2} * \varphi_{L2} + offset$$

The resulted pseudo-range will contain an unknown offset value. This value affects the measurements regarding the offset values, due to the integer ambiguities of the phase measurements. This problem can be solved using code based pseudo-range measurements and cycle-slip algorithms.

## III. SLANT FACTOR AND IONOSPHERIC PUNCTURE POINT

The ionosphere Puncture Point (IPP) is the parameter that defines the place where the GPS signal travels the maximum electron density layer of the ionosphere. In order to avoid the effect of the increased path due to obliqueness the measured TEC parameter needs to be multiplied by a slant factor which is function of the elevation angle of the satellite. The slant factor is computed using equation (6):

$$Slant\ factor = \sqrt{1 - \left(\frac{R_e \cos\emptyset}{R_e + h_{ion}}\right)^2} \qquad (6)$$

where $R_\theta$ is the radius of the Earth, $\Phi$ is the satellite elevation angle, and $h_{ion}$ is the IPP altitude.

The coordinates are loaded from a location file created by the GPS receiver. A reading error may appear due to the fact that the sampled period of the position coordinates and the observation data used for measurements can differ, as the interval for gathering the data is of 15s to 30s.

Even if the assumption that the ionosphere thickness is constant is not realistic since the physical characteristics of the ionosphere vary slowly in time, it is sufficient for taking into consideration the variation of TEC parameter in time.

The slant TEC (STEC) represents a measure of TEC of the ionosphere along a straight path from the satellite to the receiver. By performing and correlating the pseudo-range and carrier phase measurements, the receiver (known as codeless receiver because it does not need knowledge of the C/A or P pseudo-random noise codes) computes the delay of the P code and the carrier phase difference. Therefore, from the pseudo-range and differentiating the carrier phase measurements one can compute the value of the STEC [5].

As depicted in Figure 1, the TEC parameter value is determined according to (7):

$$TEC = STEC \cos z_{ip} \qquad (7)$$

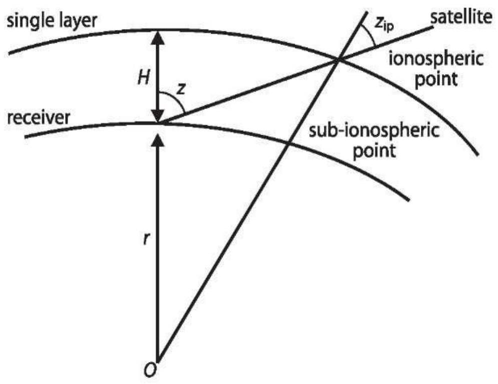


*Figure 1. Ionospheric single layer model*

The limitation of using STEC is the dependency of the ray path geometry through the ionosphere [6]. In order to determine a more precise value, we need to compute the equivalent VTEC value which is independent of the elevation of the ray path. The TEC calculations are usually taken from different GPS satellites that are located at different elevations. This is because the GPS signals have to cross different portion of the ionosphere. To obtain a TEC value from paths with different elevation angles, the STEC must be transformed into a VTEC values.

## IV. VTEC ALGORITHM IMPLEMENTATION

The first implemented function used for TEC determination is *rinex_param* function. It implements the algorithm used to extract the information from the RINEX file and the IGS file that contains the measurements of the position of the satellite at a specific time.

The RINEX file format is a standard one, but there may appear some changes from one receiver to another, in the way that optional fields may appear or not, or there may appear changes in the position of some elements in ASCII format. The elevation and the azimuth calculations necessary to compute the value of the VTEC parameter are performed by *elevat_azimuth* function. This function has as input a matrix that contains the position of the satellite in (Earth Centered Earth Fixed) ECEF coordinates, the identification number of the satellite and the time in GPS format. Moreover, in order to determine the elevation and azimuth of a satellite you need the coordinates of a reference position, the terrestrial receiver where the measurements are performed. Therefore, the algorithm firstly checks if the number of the satellites from which measurements are performed is different from zero, and if it is then the calculations are performed. Next the algorithm computes the unit vector that holds the distance from the observation station to the satellite position by creating a vector that will contain the difference of the coordinates in ECEF coordinates, followed by the normalization of the vector.

The conversion of ECEF coordinates to WGS-84 format is computed by *coord_conv* function. The WGS-84 standard format is used in the computation in order to increase the accuracy and requires the values of the major and minor semi-axes of the Earth ellipsoid. This values are constants and are defined in the algorithm as *A_maj = 6378137.00000* and *B_min = 6356752.31425*. The longitude is calculated by performing *arctangent* of the *y* over *x* position, the result being in radians as it is expressed in equation (8):

$$long = atan2(ECEFy, ECEFx) \tag{8}$$

For the calculation of the latitude we use the two axis variables and a variable that defines the value of the square of the Earth's orbital eccentricity computed by equation (9):

$$square = \frac{(A^2 - B^2)}{A^2} \tag{9}$$

where *A* and *B* are the major and minor Earth's semi-axes.

This variable is used to compute the latitude as:

$$lat_0 = (\tan^{-1} \frac{ECEFz}{\sqrt{ECEFx^2} + \sqrt{ECEFy^2}} \; / \; (1 - \frac{A^2 - B^2}{A^2}) \tag{10}$$

Next, the variable is used to compute the approximate radius of curvature as:

$$N_0 = \frac{a^2}{\sqrt{a^2 cos^2 \varphi_0 + b^2 sin^2 \varphi}} \tag{11}$$

where

$$\varphi_0 = \arctan\left(\frac{Z}{p(1-e^2)}\right) \tag{12}$$

and *e* being the square of the Earth's orbital eccentricity.

The algorithm then determines the height based on previous calculations as:

$$h = \frac{p}{\cos \varphi} - N_0 \tag{13}$$

and the new latitude using element by element squaring:

$$\varphi = \arctan\left(\frac{Z}{p(1-e^2)\frac{N_0}{N_0+h}}\right) \tag{14}$$

As the values determined so far are expressed in radians, they need to be converted in order to accommodate the WGS-84 standard format. A dedicated function was used to perform this conversion. The next step in the algorithm is to compute the rotation of the unit vectors of latitude and longitude to Vertical East North (VEN) coordinates from ECEF. The azimuth data interpolation is performed by a function that is able to make the interpolation between the measurements of the position of the satellite sampled at 15min, and to convert them into 30s intervals. This interpolation is needed to make all the system work at 30s intervals of time.

## V. VTEC EXPERIMENTAL RESULTS

The VTEC computation considers the L1, L2, P1, P2 measurements extracted from the RINEX file and includes the *numsat* variable (the number of the satellite that one could plot), the satellite position in ECEF coordinates, and the ECEF coordinates of the observation station.

On the first day of observations, the position of the satellites seen by the receiver, according to one extracted from the observation file is presented in Figure 2.

It is shown that after the conversion of the coordinates from ECEF to WGS-84 the line of sight above the receiver is always covered by the presence of the satellites, meaning that the measurements are performed continuously, and there are no moments when there is a lack of satellites to provide measurements.

The simulation results are performed on the receiver station located on US VIRGIN ISLANDS using a GPS receiver that can be identified in the IGS station list by the acronym CRO1. The observation data files are available online at [10].

Figure 3 presents the results of the variations of the VTEC calculation on the first day of observation. The results show that several big ionospheric scintillations occur, being characterized by rapid changes in the VTEC level, or fluctuations of TEC gradient. The gradient of TEC varies greatly when these fluctuations appear suggesting that the density of the electrons varies a lot.

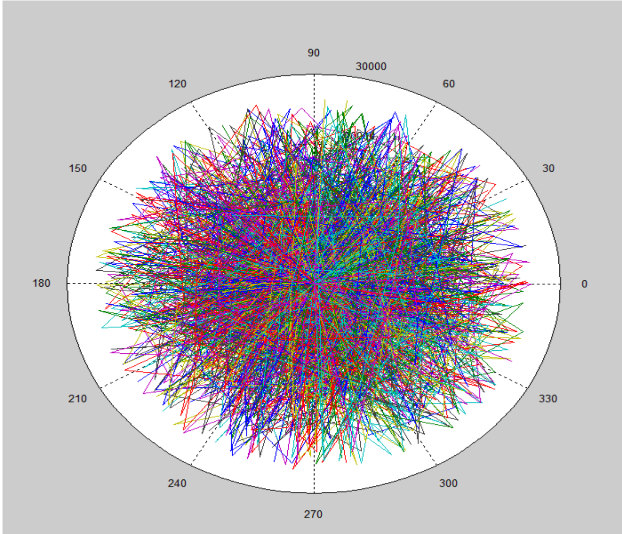


*Figure 2. Positions of the satellites located above the GPS receiver on the first day of observation*

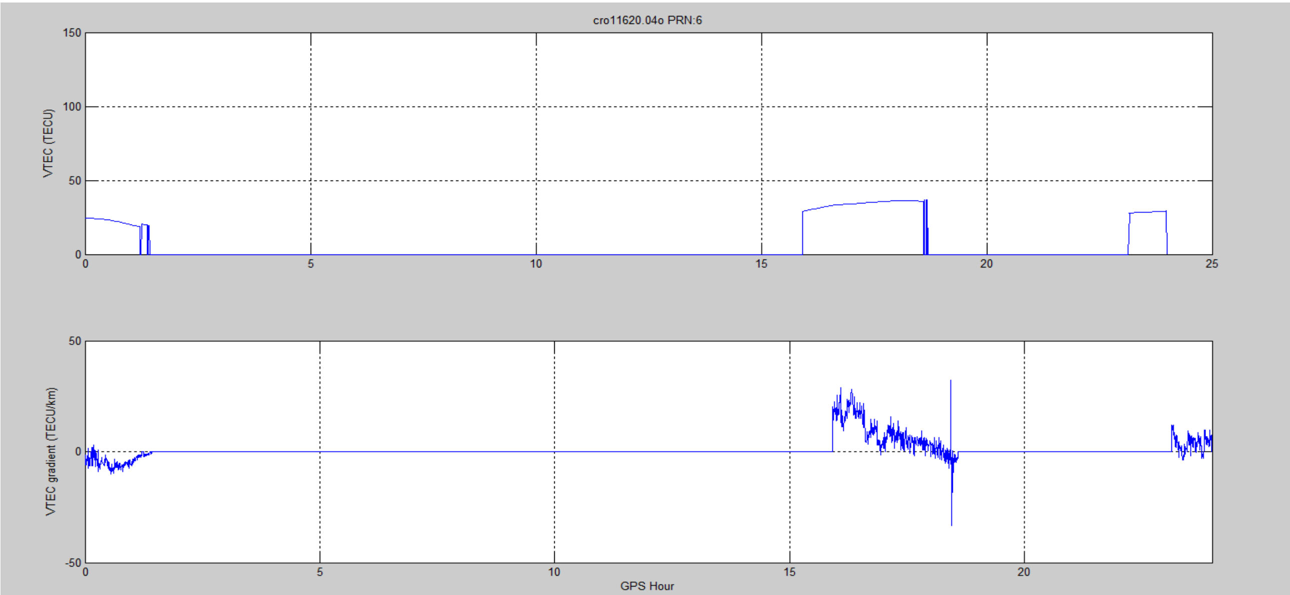


*Figure 3. Results of the first day of observation*

Figure 4 shows that when the first variations occur, the signal is degraded, as demonstrated by the dropping of the VTEC values to zero, occurring around 00:30 in UTC time. Thus, the measurements quality may decrease in the way that it is unclear if the loss of the signal was caused by the ionospheric irregularities or by multipath effects.

The remaining peaks which are unaffected by the loss of the signal indicate that the value of the VTEC decreases. This may be explained by the fact that the first observation satellites always come into view at low elevation angles. As the elevation angle increases, the path length through the ionosphere decreases. The next measurements present an increase in the VTEC value as the ionosphere scintillation variation occurs.

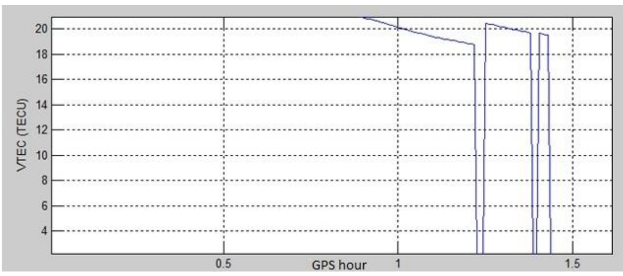


*Figure 4. Results of the first VTEC variation*

Figure 5 shows that a big variation in the ionosphere scintillation occurs between 15 and 19 in GPS time. A significant increase of the TEC, possibly due to the passing of the Sun above the receiver at sunset, is followed by a rapid variation due to signal loss and errors in the measurement, diminishing the quality of the measurements.

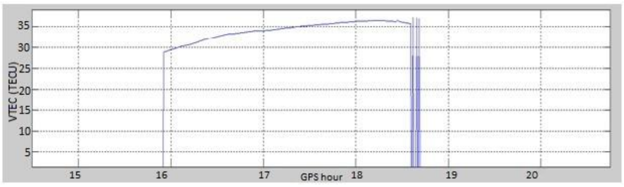


*Figure 5. Results of the second VTEC variation*

After the loss of the tracking signal, the VTEC has a slightly lower value caused by the imperfections of the cycle slip algorithm, generated by the fact that the offset value of the carrier pseudo-range was calculated from the median value of the code-based pseudo-range.

Next, Figure 6 presents the VTEC variation close to the middle of the night, without signal loss, meaning that the ionosphere variations is not that high.

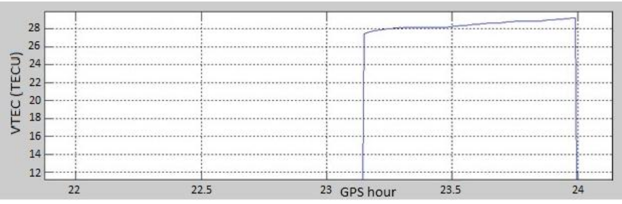


*Figure 6. Results of the last VTEC variation*

Another error that may be noticed is that under normal conditions the ionospheric scintillation and the space weather effect are affected by some biases that can result from characterizing the TEC parameter with the GPS data.

This aspect is presented in Figure 7. According to [2], the biases can range from 1 to 5 TECU.

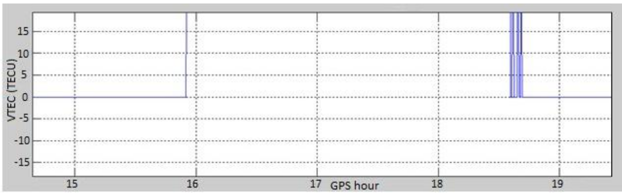


*Figure 7. Lack of code biases*

For the plot in Figure 7 the normal condition of TEC is 0. One of the explanations could be that the algorithm does not take into account the fact that plasma induces a group delay and an advance of the phase [2] causing a divergence of ionospheric contributions to pseudo-ranges and carrier phases that affects the measurements at the receiver.

More elaborate GPS receivers have an internal algorithm that produces an accurate estimation of the TEC using divergence free algorithms [2].

The variation of the TEC gradient parameter is important to determine the spatial variations of the VTEC.

This kind of variations could affect the performance of the differential GPS systems, in terms that the accuracy of the navigation data for a mobile user depends on the correlation of the environment around the reference station and the user equipment.

As presented in Figure 8, the second variation of the TEC which has an increased value introduces some important variations of the gradient, leading to big delays between the user and the reference station.

The precise positioning using differential GPS system could be highly affected at the times when these variations occur.

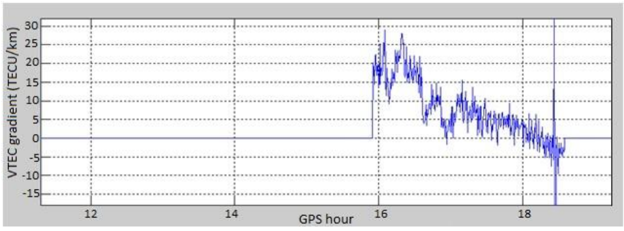


*Figure 8. VTEC gradient variation corresponding to the biggest variation of the VTEC*

As presented in Figure 9, the gradient of the TEC parameter varies mainly during the dawn (the period that marks the beginning of the twilight before sunrise) and dusk (darkest stage of twilight in the evening), these being the main sources of the ionization.

Another cause could be the presence of the Appleton – Hartree anomalies in regions near the geomagnetic equator that induces large variations in the electron density.

These variations as the literature presents them [3] may reach 50 TECU in the equatorial vicinity, or even more. These large variations may also indicate the presence of a geomagnetic storm.

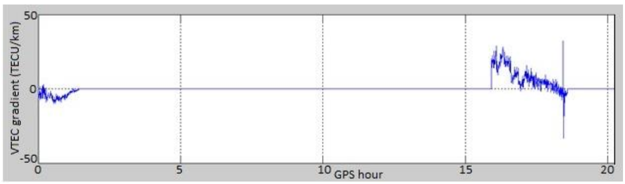


*Figure 9. Large variations of the VTEC gradient during ionosphere variations*

For the second day of observations, represented in Figure 10, one can observe the fact that the variations of the TEC parameter are not as high as in the previous day.

This results in a different variation of the VTEC gradient with the TEC parameter having values around 30-40 TECU. Moreover, it can be observed that the variations of the VTEC occur almost at the same time and have almost the same variation in amplitude.

## VI. CONCLUSIONS

The TEC parameter determines the link quality for GPS communications and other types of radio communications. Therefore, TEC measurements are used to correct the errors introduced by the ionospheric layers and to model the ionospheric radio channel.

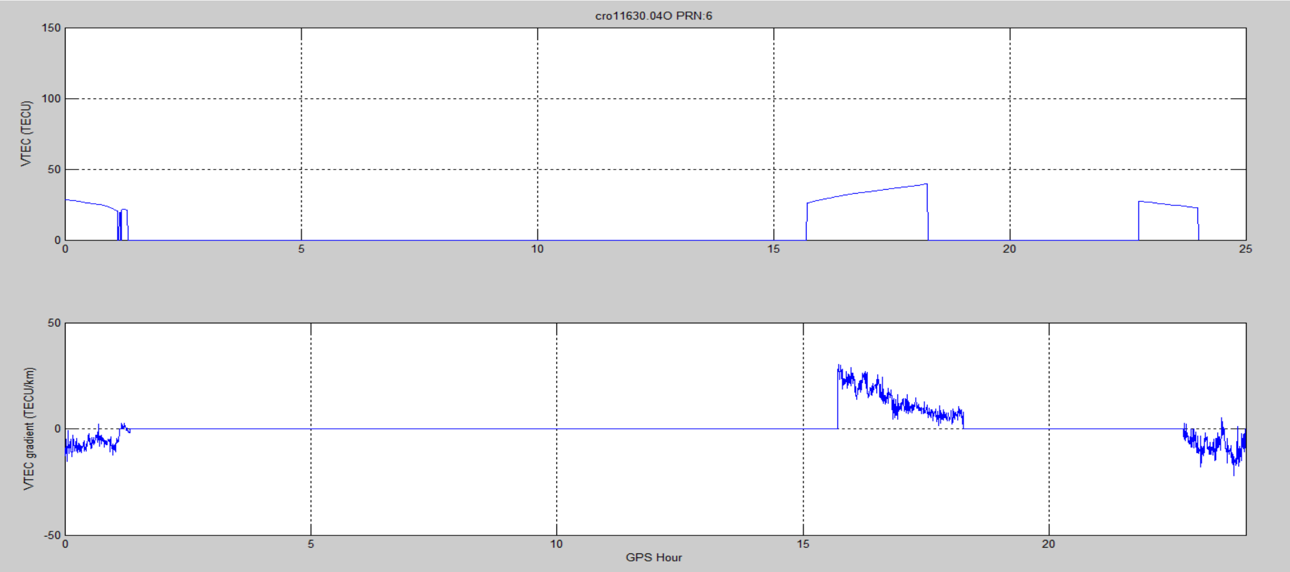


*Figure 10. The results from the second day of observation*

The scope of this paper is to provide a method to determine the variation of the TEC by means of GPS signals. The algorithm implemented in this paper is able to extract VTEC from observation data files, based on measurements performed by a GPS receiver, and plot many samples of the ionospheric scintillation.

These measurements were processed by an algorithm that contains several functions able to plot the variation of the VTEC parameter and VTEC gradient. It was observed that in the hot season the ionosphere presents a strong variation of VTEC in several parts of the day. The strong variations of the VTEC gradient suggest that on high solar activities and especially during summer the ionosphere is very unstable.

The variation of the VTEC gradients reveals that for an augmentation differential system the mobile user must be in a close range within the reference station in order to get a GPS ranging error of less than a few meters. Also this variation shows that other types of radio transmissions are affected by the ionospheric scintillation. Therefore, to model a channel based on TEC, and to achieve an appropriate prediction, the pattern must be implemented considering a close distance towards the receiver.

Future work regards the implementation of a more precise algorithm that considers other parameters that could affect the measurements, and to use filters to smoothen the measurements to obtain more precise results. Also, another aspect would be the comparison of the results obtained using a dedicated measurement system with the results of the proposed solution. Moreover, there is a possibility to extend the process of ionosphere predictions over larger areas, by using measurements from more receivers, to create a TEC Map based on the performed observations.

## ACKNOWELEDGEMENT

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