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STUDY OF THE TOTAL ELECTRON CONTENT, GRADIENT CHARACTERISTICS OF THE IONOSPHERE AND THEIR INFLUENCES ON THE GPS SIGNAL PROPAGATION OVER VIETNAM REGION

Specialty: Geophysics

Code: 62 44 01 11

ABSTRACT

Ph.D THESIS IN PHYSICS

Hanoi - 2015

INTRODUCTION

ORIGIN OF THE THESIS

Vietnam's territory located in low latitude region in the Southeast Asia, encompasses the geographical latitude from 8º37'30 "N (Ca Mau cape) to geographical latitude 23º21'30" N (Lung Cu peak), corresponding to the magnetic latitudes from 0.84ºN to 16.89ºN (epoch 2010.0). Thus the magnetic equator is far from the Ca Mau cape less than 100 km in southward, so the variation of ionosphere in Vietnam region are more complex than other latitudes, related to the equatorial fountain effect, ionospheric scintillation…Before 2005 continuous GPS stations network in Vietnam has still not been installed and the ionospheric scintillation has not been studied yet. Since April 2005, in the framework of the scientific co-operation between the Institute of Geophysics (Vietnam Academy of Science and Technology) and University of Rennes 1 and National School of Telecommunication of Brest (France), three dual frequency GPS receivers have been installed in Vietnam for monitoring the total electron content (TEC) and ionospheric scintillation in the region. The installation of three dual frequency GPS receivers at Hanoi, at Hue, and at Ho Chi Minh city (Hocmon station) has opened a new ionospheric research branch in Vietnam using GPS data beside of the traditional study using the ionosonde data. In this context, the thesis with the title "***Study of the total electron content, gradient characteristics of the ionosphere and their influences on the propagation of the GPS signal in Vietnam region***" is proposed under the direction of Dr. Le Huy Minh (Vietnam) and Dr. Patrick Lassudrie-Duchesne (France).

OBJECTIVES AND TASKS OF THE THESIS

The thesis focused to research the characteristics of TEC variation, ionospheric scintillation over Vietnam region using continous GPS data from 2006. For this purpose, the thesis will solve the problems such as:

1. Learning the methods and the algorithms to extract ionosphere information from GPS satellites data.
2. Studying the time variation characteristics of TEC over Vietnam region such as: diurnal variation, seasonal variation and dependence on solar activity during the study period.
3. Statistics of the occurence of ionospheric scintillation (gradient TEC), searching the time appearance rules, distribution in space, its relationship with the solar activity and its influence on the GPS signal propagation.

SCIENTIFIC RESULTS AND SIGNIFICATION

1. This is the first study in Vietnam for TEC variation and ionospheric scintillation using GPS data.
2. It contributed to affirm the characteristics of TEC variation and the occurence of ionospheric scintillation in Vietnam region.
3. It created a initial database for the ionospheric forecasting research, ionospheric scintillation for Vietnam region in the future.

NEW CONTRIBUTION OF THE THESIS:

1. Applied the new method to determine the differential code bias (satellite and receiver) in absolute TEC determination from dual frequency GPS data and completed the program to calculate TEC using pseudo-range measurements.
2. Indicated the variation of TEC with time, season and solar activity. Constructed the time and latitudinal TEC maps for Vietnam region during 2006-2010.
3. For the first time, presented the statistical results and indicated the occurence characteristics of ionospheric scintillation over Vietnam region.

DEFENSIVE THEORETICAL POITS

Theoretical poit 1: Applied the new method to determine the differential code bias (satellite and receiver) in absolute TEC determination from dual frequency GPS data. Using this method to calculate TEC for the continuous GPS data in Vietnam, indicated the characteristics of TEC variation with time, season and solar activity during the considered period.

Theoretical poit 2: Indicated the occurence characteristics of ionospheric scintillation over Vietnam region: the time occurrence rules, such as diurnal, seasonal and dependent on solar activity.

STRUCTURE OF THE THESIS

The thesis includes 151 typed pages, 8 tables, 77 figures and 102 references with the following arrangement:

- Introduction
- Chapter 1. Overview of the situation of research in the world and in Vietnam
- Chapter 2. Overview of the ionosphere and global positioning system
- Chapter 3. The total electron content and the rules of time variation of TEC in the Vietnam region
- Chapter 4. The occurence characteristics of ionospheric scintillation

over Vietnam region and its influence on the GPS signal propagation.

- Conclusions and petitions

RESULTS OF THE THESIS WERE PUBLISHED IN

1, The International Scientific Conference SEALION, Bangkok-Thailand, 2011.
2, The International Scientific Conference " Geophysics - Cooperation and Sustainable Development", 14-17 / 11/2012, Hanoi.
3, The International Scientific Conference Ginestra on the exploration and study the ionospheric in Asia – Pacific regions, 24.01.2013, Hanoi.
4, The Annual Scientific Conference of the Institute of Geophysics and published 05 papers in the Journal of Sciences of the Earth and International.

CONTENTS OF THE THESIS

CHAPTER 1. OVERVIEW OF THE SITUATION OF RESEARCH

From the late 70's when the first beams of GPS satellites was launched into the orbit, the researches using the informations from this navigation system with many different purposes began to develop. After 1994 when the GPS system was launched completely, the study about the effects of the ionosphere on the GPS signal propagation to receivers on the Earth's surface begin developing and then the scientific application of GPS technology is growing strongly.

The international scientific community has make an effort to promote international standards for GPS data acquisition and analysis, and in January 1994, the International GPS Service (IGS) has been established and officially operated. A group inludes 5 ionospheric analysis centers of IGS (CODE, ESA, JPL, EMR and UPC) was established and started to operate from May 1998, providing the global ionospheric maps every 2 hours (Global ionospheric Mapping - GIM) and information about daily sets of differential code biases for satellites and receivers (Differential Code Biases - DCBs) based on data from global IGS stations (Schaer, 1999). From these results, there were a series of studies in TEC using global GPS receivers or regional ones published (Schaer et al., 1999; Mannucci et al., 1998; Otsuka et al., 2002; Ma et al., 2003).

As you known, network of GPS stations is scattered in the word, but mainly concentrated in the high latitudes and mid-latitudes region. Now, there are many research results for two latitudes region be published, so the information about the ionosphere in high latitudes and mid-latitudes region is very detailed (Hernandez et al., 1997; Schaer et al., 1999; Mannucci et al., 1998; Breed et al., 1998; Tsai et al., 2001 ...). Whereas, the distribution GPS stations in the equatorial region is very sparse, in addition to the complex characteristics of the equatorial ionosphere caused by the fountain effect, formation of plasma bubble, the concentration of ionospheric scintillation activity... then the study of the equatorial ionosphere and its influence on the propagation of satellite signals is a interesting subject. The study focused for each meridian regions, as for the American (Basu et al., 1996; Aarons et al., 1997; Beach et al., 1999; Valladares et al., 2004; Zhao et al., 2005; Zhou et al., 2007 ...); for the Asian (Breed et al., 1998; Liu et al., 1999; 2010; Tsai et al., 2001; Thomas et al., 2001; Cervera et al., 2006 ...); and for Indian (Chandra et al., 1979; Banola et al., 2005; Rama Rao, et al., 2006; Bhuyan et al., 2006 ...)

The application of GPS technology to study the ionosphere was be carried out many years ago by the scientists community, and had a large number of studies published to indicate the ionosphere characteristics for each study area. However, the ionosphere has the local specific characteristics remarkably, especially in the equatorial ionosphere, while the ionosphere in Vietnam region is still the lack of information on the world map today. In Vietnam, The last ionospheric studies was mainly based on ionospheric sounding data, collected from the ionosonde in Hanoi, Nha Trang, Bac Lieu and Hoc Mon - Ho Chi Minh city to investigate the variation of ionospheric parameters (Pham Van Tri et al (1997); Le Huy Minh et al. (2001); Hoang Thai Lan et al (2003, 2009, 2013), Tran Thi Lan (2004); Nguyen Thanh Dung (2009); Pham Thi Thu Hong et al., (2011)).
Using GPS technology to study the ionosphere in Vietnam has begined in recent years and quite new (Le Huy Minh et al (2006, 2007); Nguyen Chien Thang (2007)). The installation of three GPS stations in the Northern, Central and Southern parties scince April 2005 is an advantage in studying the ionosphere for all Vietnam region. To develop this research, the thesis was built with the intention to use the data from three GPS receivers to study the variation of TEC and ionospheric scintillation for Vietnam region during from 2006 to 2011. The results of the thesis will be an important database for the ionospheric forecasting research, ionospheric scintillation for Vietnam region in the future.

CHAPTER 2. OVERVIEW OF THE IONOSPHERE AND THE GLOBAL POSITIONING SYSTEM

2.1 The Earth's Ionosphere

2.1.1 The ionosphere and ionospheric layers

The ionosphere is a region of the upper atmosphere from about 150 km to 1,000 kilometers or more above the Earth's surface, is formed and exists under the effect of solar radiation and other physical processes. The process of ionization in the ionosphere makes ionospheric electron and ion concentration strong enough to affect the propagation of radio waves. The degree of ionization in the ionosphere depends on three basic factors:

- Ionizing solar radiation energy.
- The energy absorption coefficient of the gas components in the ionosphere.
- The density of neutral atmospheric molecules.

To a certain height that the ionization has a combination by 3 elements mentioned above, then it reachs a maximum ionization, this process leads to the maximum value of the electron density with altitude. Because in the ionosphere have many different kinds of molecules so it will have some maximum levels of the electron, from what we can divide the ionosphere into four layers: D layer, E layer, F1 and F2 layers. Characteristic parameters in each layer are:

+ The height of layer: h
+ The thick of layer: y
+ The maximum value of the electron density: N_e

These parameters are strongly dependent on the factors such as time in a day, season of the year, level of solar activity and geographical location of the observatory.

2.1.2 Theory of formation of the ionospheric layers and vertical profile

2.1.2.1 The formation of the ionospheric layers

The formation of the Earth's ionosphere, primarily due to ionizing atmospheric molecules by solar radiations. Photochemical processes can be divide as follows: Solar photoionization, corpuscular ionization, loss reactions and ion transport process. Thus in the ionosphere always exist a dynamic equilibrium state in which the free electrons content depends on the speed of the production process and loss of electrons.

2.1.2.2 Ion composition in the ionosphere

Main neutral gas in the thermosphere is O, N2 and O2, so the ions generated by the ionization and optical interactions in the thermosphere are O^+, NO^+, O_2^+.

2.1.2.3 The ion production function of Chapman

Chapman's theory represented the rate of production of ion pairs in the ionosphere as follows:

$$q(h,\chi) = q_0 e^{(1-z-\sec\chi \exp(-z))} \text{ với } z=(h-h_0)/\Delta h \qquad (2.2)$$

where $q\ (h, \chi)$ is the ion production rate; h is the height; χ is the zenith angle with respect to the Sun; q_0 is the ion production rate at $z = 0$; z is the scaled altitude; h_0 is the reference height of maximum ion production, and Δh is the scale height.

2.1.3 The propagation of radio wave in the ionosphere

For radio waves with frequencies less than 100 MHz, the ionosphere is considered to be an environment of wave absorbtion and reflection. For the microwave, with frequency greater than 100 MHz, the ionosphere is an interference source. The process of radio propagation through the ionosphere is determined by the refractive index of the medium. Refractive index of an ionized medium received from Appleton-Hartree equation (Hargreaves, 1992).

2.1.4 Solar activity

The process of ionization in the ionosphere is controlled by solar radiation, so it is a function of solar activity. The level of solar activity is represented by the sunspots number observed on the surface. Sunspot number is determined by the formula of R. Wolf (W), or the number of Rz observed at the Zurich observatory:

$$R_z = k\ (10g + s) \qquad (2.10)$$

where: g - the number of sunspot groups; s – the number of individual spots; k – the adjustment coefficient (Wolf coefficient $k = 1$).

2.1.5 The ionosphere at low latitudes and ionospheric disturbances

2.1.5.1 The ionosphere at low latitudes

The ionosphere at low latitudes is identified in the range of $\pm 20^0$ in both side of the magnetic equator. The state of the ionosphere at low latitudes is completely different with respect to in the high latitude and mid-latitude regions due to the exist of the equatorial anomaly with the decrease of the electron density in the magnetic equator and the increase of the electron density at two anomalous peaks around ± 15° latitudes from north and south of the magnetic equator.

2.1.5.2 Sporadic-E

Sporadic-E, also known as Es layer in the E region of the ionosphere, appears in the altitude about from 100 to 130 km. Es is characteristic for the presence of disturbance in the E region, with the dimensions about few hundred meters in thickness.

2.1.5.3 Spread-F

Equatorial Spread F (ESF), the phenomenon of instability in ionospheric plasma, usually occurs in the equatorial F region after sunset. The formation mechanism of ESF mainly caused by the Rayleigh-Taylor instability (Gravitational Rayleigh-Taylor, GRT) in relation with the different physical processes in the equatorial ionosphere.

2.1.5.4 The ionospheric disturbances

Ionospheric disturbance is a global phenomenon. Currently we have not much understanding about the climatology of ionospheric disturbance. By various techniques they observed that the ionospheric disturbance has scale from tens of centimeters to hundreds of kilometers. Traveling ionospheric disturbances (TID) may cause variation in the integrated electron density of several percents.

2.2 Global positioning system and basics of the GPS data analysis

2.2.1 Introduction to global positioning system

The Global Positioning System GPS is a navigation system by radio waves in the space, it has been developed by the United State government for civilian and military purposes in determining the precise position, velocity and time everywhere above and near to the ground. The GPS is a one-way ranging systems, divided into 3 segment: the space segment, controls segment, and users segment including multiple receiver types.

2.2.2 GPS signal

Each GPS satellite is a high-quality oscillator, it is a ensemble of rubidium and cesium atomic clocks, which is sequentially used to generate two coherent carrier L_1 and L_2 in the L-band, corresponding to two GPS frequencys is $f_1 = 1575.42\ MHz$ and $f_2 = 1227.60\ MHz$.

There are two codes are modulated on two carriers:

+ The first code is the C/A-code (Coarse/Acquisition) can be used for civilian purposes, is modulated only on the carrier L_1.

+ The second code is the P code (Precision) used for military purposes and other authorized users. P Code (P_1 and P_2) is modulated on both the carrier L_1 and L_2. P_1 code is rewritten code encrypted verson and converted into Y code and can only be used when users have the open cryptographic keys, so only the C/A-code and P_2 codes are used widely.

2.2.3 The GPS observables

2.2.3.1 Pseudo-range (code observation)

The C/A-code, P- code or Y-code emitted by the satellite k at time t^k and registered by receiver i at time t_i is defined as

$$P_i^k = \rho_i^k + c(\Delta t_i - \Delta t^k) + \Delta\rho_{i,trop}^k + \Delta\rho_{i,ion}^k + c(b^k + b_i) + \varepsilon \qquad (2.12)$$

where: P_i^k is the pseudo-range, expressed in units of length; ρ_i^k is the geometric distance between the satellite k and the receiver i; Δt_i, Δt_k are the offsets of the receiver and satellite clocks with respect to the GPS system time; $\Delta\rho^k_{i,\ trop}$ is the delay of the signal due to the troposphere; $\Delta\rho^k_{i,ion}$ is the delay of the signal due to the ionosphere; b_i, b^k are the receiver and the satellite hardware delays; c is the speed of light in vacuum; ε is a random error, which includes errors due to multipath effects.

2.2.3.2 Carrier phase observation

Carrier phase observation is the phase measurements of signals from the satellite to the receiver, the observation equation can be written as:

$$L_i^k = \rho_i^k + c(\Delta t_i - \Delta t^k) + \Delta\rho^k_{i,trop} - \Delta\rho^k_{i,ion} + \lambda B_i^k + \varepsilon \qquad (2.13)$$

where L_i^k is the carrier phase observation, expressed in units of length; B_i^k is a constant bias, expressed in cycles, principally containing the initial carrier phase ambiguity N_i^k.

2.2.3.3 Doppler observation

Doppler frequency is the variable coefficient when one observes carrier phase, it reflects the relationship between velocity of receivers and GPS satellite:

$$\varphi^k_i = \rho^k_i + c(\Delta t_i - \Delta t^k) + \Delta\rho^k_{i,trop} - \Delta\rho^k_{i,ion} + \varepsilon \qquad (2.14)$$

where, φ^k_i is the phase coefficient of carrier phase, expressed in units of length.

2.2.4 Sources of GPS errors

The main GPS error sources can be devided into 3 groups: Group 1: errors related to satellite including errors due to satellite clock and errors due to satellite orbit. Group 2: errors related to receiver including errors due to the eccentricity phase antenna, receiver clock bias, noise. Group 3: errors related to the propagation medium including troposphere delay and ionospheric delay, multipath effects.

2.2.5 Effect of ionosphere on GPS signals

Ionosphere can be considered as the most significant error on the precision in positioning satellite navigation. Parameters of the ionosphere caused the most impact on GPS signals is the total number of electrons in the ionosphere, usually called total electron content (TEC).

2.2.5.1 Ionospheric group delay - Absolute range error

The group delay of the ionosphere produces range error, is calculated by the formula:

$$\Delta t = \frac{1}{c}\int(1-n)dl \quad \text{hay} \quad \Delta r = \int(1-n)dl \qquad (2.16)$$

where Δt, Δr is the group delay expressed in units of time and in units of distance, c is the speed of light in vacuum, n is the refractive index in the ionosphere

2.2.5.2 Ionospheric carrier phase advance - Relative range error

The carrier phase advance related to the refractive index in the ionized medium with the presence of free electrons, is calculated by the formula:

$$\Delta\phi = \frac{1}{\lambda}\int(1-n)dl \text{ , cycles, or wavelengths} \qquad (2.22)$$

2.2.5.3 Ionospheric Doppler shift – Range rate errors

The Doppler shift results due to the ionosphere because of changing TEC, can be calculated according to the formula:

$$\Delta f = \frac{dn}{dt} = \frac{1{,}34*10^{-7}}{f}\frac{dTEC}{dt} \quad , \quad Hz \qquad (2.25\ )$$

2.2.5.4 Ionospheric scintillation

When the GPS signals transmitted in a small-scale irrigularities in the ionosphere, it can produce the rapid fluctuation of radio waves in the amplitude and the phase, this phenomenon is called ionospheric scintillation. Ionospheric scintillation causes a reduction in the accuracy of GPS positioning, when the scintillation on a transmission line is strong enough then the transmission line become discontinuous, that causes the loss of lock or valueless for the use of the positioning.

CHAPTER 3. THE TOTAL ELECTRON CONTENT AND THE RULES OF TEC VARIATION WITH TIME IN VIETNAM REGION

3.1 Data and methods

3.1.1 Data

Three GPS receivers have been instaled in Vietnam scince April 2005 in frame of the Vietnam-France cooperation in the locations with the geographical coordinates shown in *Table 3.1*.

Table 3.1, Location of GPS stations in Vietnam

Station	Geographical Coordinates		Magnetic Latitude (N) (epoch 2010)
	Latitude (N)	Longitude (E)	
Hanoi	21^{o}02’50’’	105^{o}54’59’’	14,37^o
Hue	16^{o}27’33’’	107^{o}35’33’’	9,45^o
Ho Chi Minh City	10^{o}50’54’’	106^{o}33’35’’	3,34^o

This is the dual frequency GPS receiver GSV4004 manufactured for monitoring TEC and ionospheric scintillation for all visible GPS satellites.

3.1.2 Research method

3.1.2.1 Extracting ionospheric information from the dual frequency GPS receiver

Using the difference pseudo-range measurements to calculate the absolute TEC:

$$STEC = \frac{1}{40,3}\left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)\left(P_{2i}^k - P_{1i}^k + c(\Delta b^k + \Delta b_i)\right) \qquad (3.8a)$$

where *STEC* is the total electron content in the ionosphere along a satellite-receiver path (slan TEC); *i, j* index are the pair of receiver *i* and satellite *k*; P_1, P_2 is pseudo range measurements on frequency f_1 and f_2, $\Delta b^k = b_1^k - b_2^k$, $\Delta b_i = b_{1i} - b_{2i}$ is the differential code bias of satellite *k* and receiver *i* .

To obtain absolute STEC, we must determine the differential code bias of receiver and satellite (Δb_i and Δb^k). Slan TEC are converted to the vertical TEC (TECV) or for briefly we often called the TEC at the ionospheric pierce point by the formula:

$$TEC = STEC.\cos z', \quad z' = \arcsin\left(\frac{R}{R+H}\sin z\right) = \arcsin\left(\frac{R}{R+H}\cos\alpha\right)$$

where *z, z'* are the zenith distance of the satellite and the receiver at the ionospheric pierce point, R=6371km is the earth radius, and H is the height of the single layer, α is the elevation angle.

3.1.2.3 Global TEC model GIMs

The ionospheric study produces from the GPS receiver system is Global Ionospheric Model GIMs. The distribution maps of TEC, the differential code bias of satellites and receivers (DCBs) are notified daily in global TEC model and can be downloaded from the website: http://www.aiub.unibe.ch/download/code/.

3.1.2.4 Defining hardware bias of satellite and receiver

For the receivers in Vietnam, Le Huy Minh et. al., (2006) have developed a method to calculate the differential code bias by calculating the mean square deviation between the observed TEC in case unadjusted differential code bias of receivers and TEC derived from global models in period from 01LT to 05LT at night for the same position. The limit of this method is that the daily local ionosphere will impact directly on the receiver bias values. On the other hand, on the day there are no data in these periods, so we can not calculate the receiver bias values for this day. To overcome these limitations, we build a program to calculate the differential code bias of satellite and receiver based on the idea of Komjathy et al. (2005), the TEC values is calculated in cases unadjusted the bias of satellite and receiver $(\Delta b^k + \Delta b_i = \Delta b_i^k = 0)$ for all visible satellites with elevation angles greater than or equal to 20^0, then compared with the TEC values from the model at the same location for each observation. The corresponding deviation value will be assigned to the bias of satellite and receiver for this observation ($\Delta b_i^k(t)$). The deviation values were calculated for each pair of receiver-satellite (each station will have 32 pairs of values corresponding to 32 satellites) and for every time t in a day. The deviation value pairs for the day will be the median of deviations for every time in a day. To limit the local effect of the ionosphere on the calculated results, the bias values are calculated for several days, in here we choose the time period is one month. Results showed that, at each station the bias values vary depending on the satellite, the range of bias values at Hanoi station varies from -70 TECu to -20 TECu, at Hue station it varies from 5 TECu to 60 TECu and from 5 TECu to 50 TECu at Ho Chi Minh stations depending on each satellites. All the pair of receiver - satellite bias were calculated for each data month and will be used to get the absolute TEC for each pair of satellite - receiver respectively at all observation times in the month. To verify the method, we compared the calculated TEC values with TEC from GIM models in the same location. The obtained results showed the diural variations of the calculated TEC suit to the ones of TEC from GIM models, but in the time scale of decade minutes or so especially in the day time, there are the significant differences between calculated and GIM TEC values, because the global model can not reflect the local characteristics of the equatorial ionosphere.

This method was introduced and applied to research for Southeast Asian equatorial ionization anomaly, the results are published in the Journal of Advances in Space Research and received more attention of scientists in the world.

3.1.2.5 The program for calculating total electron content from GPS data

From the method mentioned above, a program was built to calculate TEC. The program is written in Matlab, with about 1000 lines and divided into two steps corresponding to two main programs. Input data files of the program are the RINEX file, YUMA file, CODG; Output data file are the coordinates of ionospheric pierce point, time, slan TEC, vertical TEC and elevation angle.

In order to limit the affect of scattering, multipath, noise... the observables with the elevation angle greater than 20^0 will be used to calculate TEC. The set of such calculated TEC values is the data base for studying the time variation of TEC.

3.2 The diurnal variation of TEC in Vietnam

To see the diurnal variation of TEC, TEC values at each time will be averaged for all visible satellites. The monthly mean diurnal variation of TEC in every year from 2006 to 2010 are plotted for three stations in Hanoi, Hue and Ho Chi Minh City. Figure 3.9 presents the diurnal variation of monthly mean TEC in 2006. We can see that diurnal variation of TEC reached a maximum in daytime (06-09UT, i.e 13-16LT) and a minimum at night (about 21-22UT, i.e 04-05LT). Diurnal amplitude of monthly mean TEC changes from the minimum value at night of about 5 TECu to the maximum value of about 50 TECu in daytime depending on the month of the year and on the solar activity.

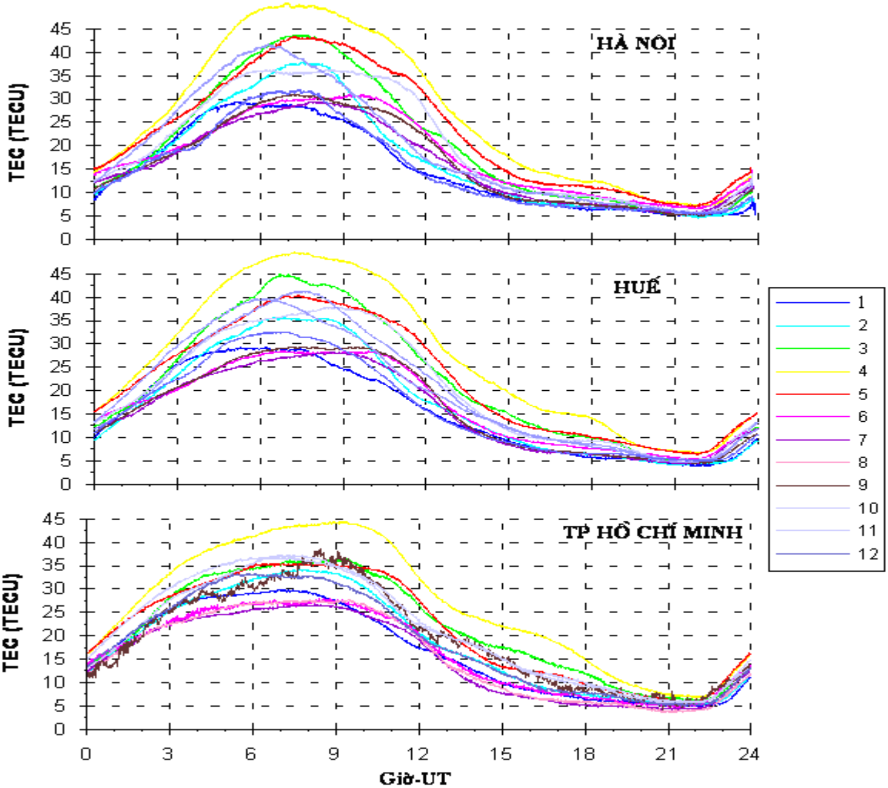

Figure 3.9 The diurnal variation of monthly mean TEC in 2006 at Hanoi, Hue and Ho Chi Minh city

In comparaison with the diurnal variation of the critical frequencies from the ionospheric sounding data published by the previous authors (Le Huy Minh et al, 2001; Hoang Thai Lan et. al., 2013), we found that the diurnal variation of TEC is similar to the one of critical frequency of F_2 layer, f_0F_2, in the same station.

3.3 The seasonal variation and the dependence on solar activity

To study the seasonal variation of TEC, we ploted the monthly mean TEC values in contour for each station in Hanoi, Hue and Ho Chi Minh City during 2009 and 2010. Figure 3.15 presents the seasonal variability of TEC in 2009 and 2010 in Hanoi.

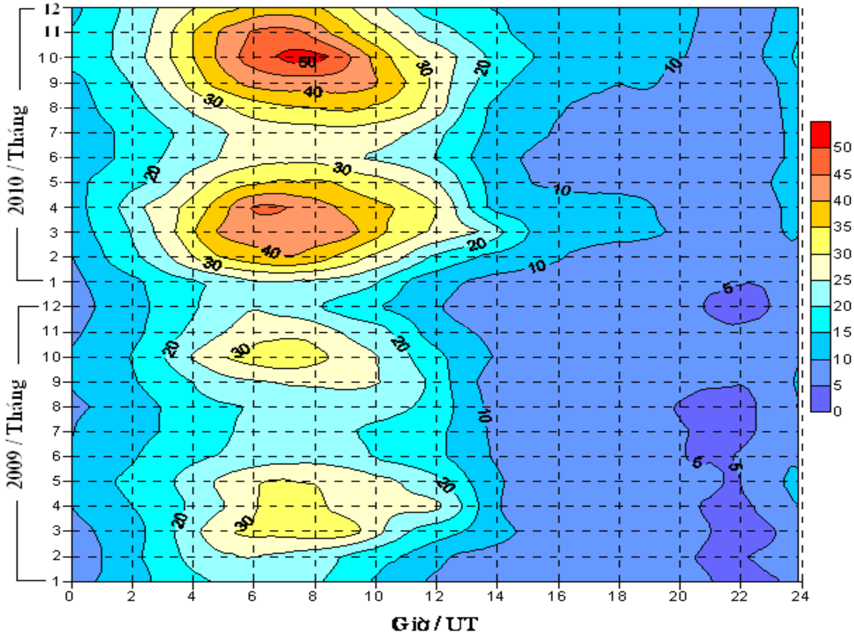

Figure 3.15, The seasonal variation of TEC in 2009 and 2010 in Hanoi, the distance between the contour line is 5 TECu.

The TEC manifests a seasonal variability very clear at all three stations, reaching its maximum in the equinoctial months: the vernal equinox (March-April) and the autumnal equinox (September-Octorber) and minimum in the winter and summer months. The seasonal variation of TEC could be explained by the composition of ions and the balance between the production processes and loss processes of ions in the ionosphere.

The TEC depends not only on the season, but also on the solar activity. In order to examine this relationship, diurnal amplitude of monthly mean TEC is calculated for all data from 2006 to 2010, the result is shown in *Figure 3.19.*

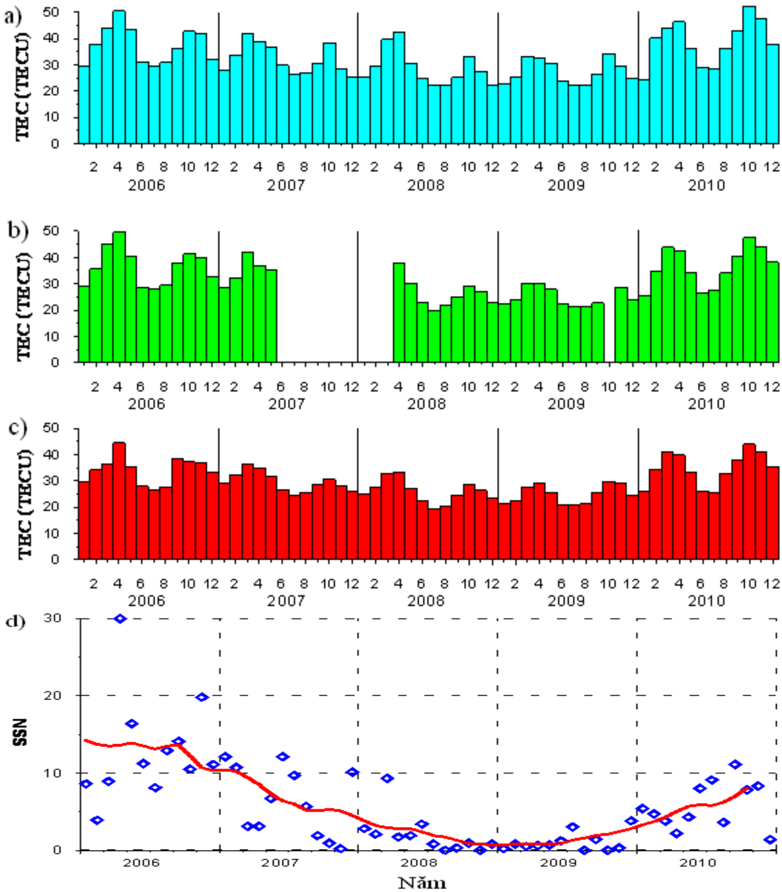

Figure 3.19, The maximum amplitude variation of TEC in a) Hanoi, b) Hue, c) Ho Chi Minh City and d) The sunspot number from 2006 to 2010.

The diurnal amplitude of monthly mean TEC also shows seasonal variation and depends on solar activity levels. From Figure 3.19 we found that the amplitude of TEC decreases during the descending phase of solar activity from 2006 to 2009 and then increases during increasing phase from 2009 to 2011. Equinotial maximum values of TEC vary with the level of solar activity: during decreasing phase the vernal maximum is higher than the autumnal one, during increasing phase in contrast, the autumnal maximum is higher than the vernal one. The seasonal variation and the relationship to the solar activity is also found in the frequency variation f_0F_2 at Phu Thuy (Le Huy Minh et al, 2001; Pham Thi Thu Hong et al, 2011).

3.4 Characteristics of time and latitudinal distribution of TEC

To have a comprehensive view of the TEC distribution over Vietnam region, we construct the time and latitudinal maps of TEC for this area. From the continuous GPS data of 3 stations in Hanoi, Hue and Ho Chi Minh City, the this map were built for each day during the concerned period. *Figure 3.25* present the time and latitudinal map of monthly mean TEC in 2010.

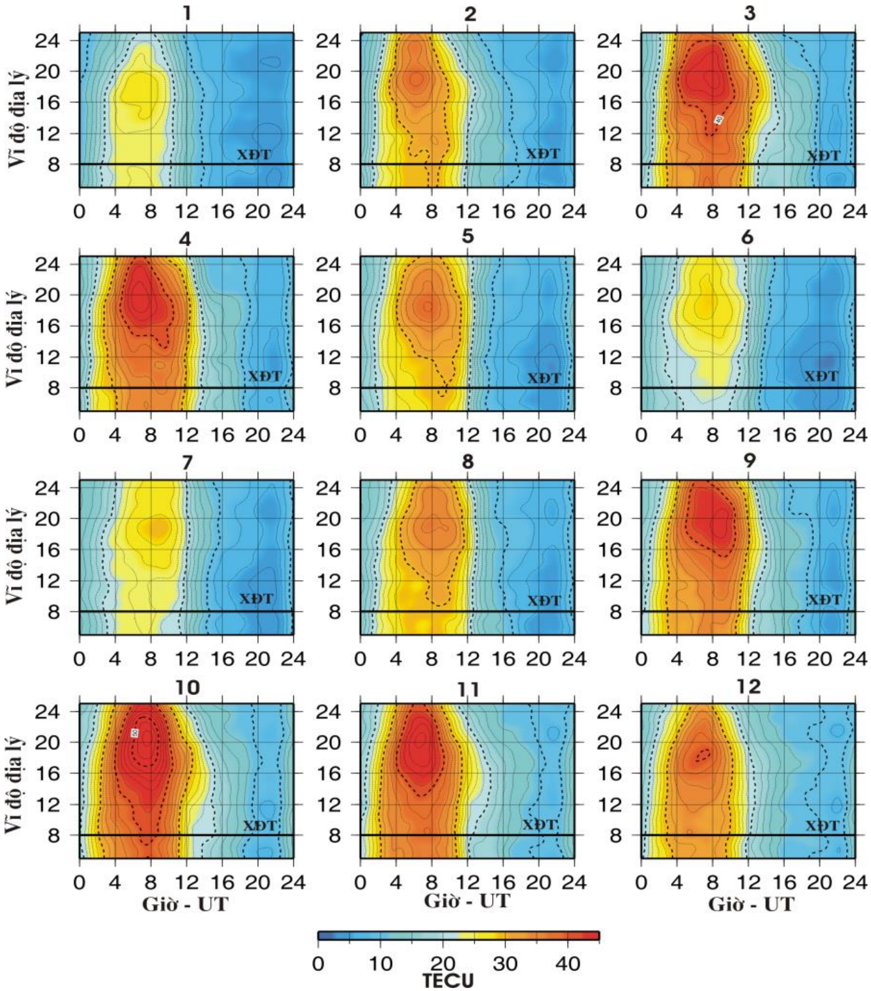

Figure 3.25, The time and latitudinal maps of monthly mean TEC in 2010. The distance between the contour lines is 2 TECu.

We can see that the time and latitudinal maps of TEC has a maximum at about 18°- 20^0 latitude in the period from 5hUT to 9hUT (12-

16hLT), which is the northern crest of the equatorial ionization anomaly in the Southeast Asian region. So northern part of our country is in under this crest, and the southern region is in the trough of the anomaly. At night from 22hLT to about 6hLT of next day, the ionosphere is nearly identical with the mean TEC value smaller 10 TECu.

The time variation characteristics of TEC observed over Vietnam region, are according to the results obtained in other stations in equatorial region (Bhuyan et al., 2006; Breed et al., 1998; Chauhan et al., 2011; Rama Rao et al., 2006b).

CHAPTER 4. THE OCCURENCE CHARACTERISTICS OF IONOSPHERIC SCINTILATION OVER VIETNAM REGION AND ITS EFFECTS ON GPS SIGNAL PROPAGATION

4.1 Equipment and research method

4.1.1 Equipment

Three GPS receivers in Vietnam are the dual frequency GPS receiver GSV4004 manufactured according to standard principles to monitor TEC and ionospheric scintillation (GISTM - GPS ionospheric Scintillation Monitor & TEC) for all visible satellites, the information of ionospheric scintillation is provided from the output data of the software.

4.1.2 Research methodology

In our thesis, the amplitude scintillation parameter is selected for studying the occurence characteristics of ionospheric scintillation over Vietnam region.

The amplitude scintillation S_4 is derived from the signal intensity by the formula:

$$S_4 = \sqrt{\frac{<I^2> - <I>^2}{<I>^2} - \frac{100}{C/No}\left[1 - \frac{500}{19C/No}\right]} \quad (4.3)$$

The amplitude scintillation S_4 is a dimensionless number and commonly estimated over an interval of 60 seconds, I is the signal intensity of one satellite and $<I>$ is the mean intensity value, C / N_0 is the signal/noise ratio.

When researching ionospheric scintillation using GSV4004 receiver types, we must use a filter limit S_4 due to multipath effect defined as follows [97]:

$$\sigma_{min} = 0,652.\ S_4 - 0,125 \quad (4.4)$$

This filter limits are showed in Figure 4.1, the S_4 values lies below the limit line due to ionospheric scintillation, the S_4 value above this line due to multipath effect must be removed.

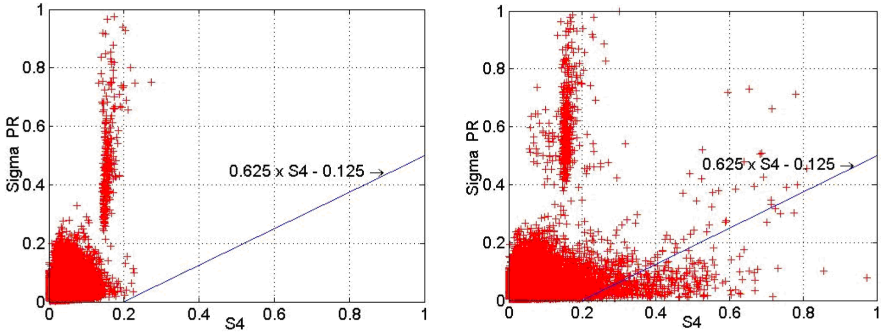

Figure 4.1, The filter limit for amplitude scintillation in two cases at Hue station: Non scintillation environment (left) and Scintillation environment (right)

4.2 The diurnal ionospheric scintillation occurrence

Figure 4.2 presents the statistical results of the ionospheric scintillation with diurnal time for all visible satellites with the elevation angle greater then 20^o in the period from 2006 to 2010 in three stations of Hanoi, Hue and Ho Chi Minh. We can see that ionospheric scintillation occurs primarily in the night time (from 20hLT to 2hLT of the next day), generally concentrates on before midnight and rarely occurs in day time.

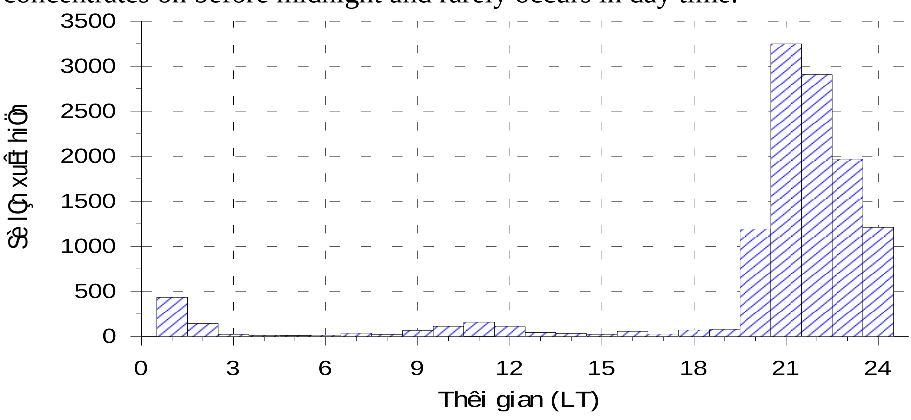

Figure 4.2, The occurrence characteristic of ionospheric scintillation with diurnal time in the period from 2006 to 2010 for all stations of Hanoi, Hue and Ho Chi Minh City

4.3 The occurrence characteristic of ionospheric scintillation with the season and with the solar activity

To study the seasonal characteristic of ionospheric scintillation occurence, we have done the statistics of the events of scintillation for the data series from 2006 to 2011. The results are expressed in histograms, by month of the year, magnitude of scintillation with the step 0.1 and number of events, as shown in Figure 4.3.

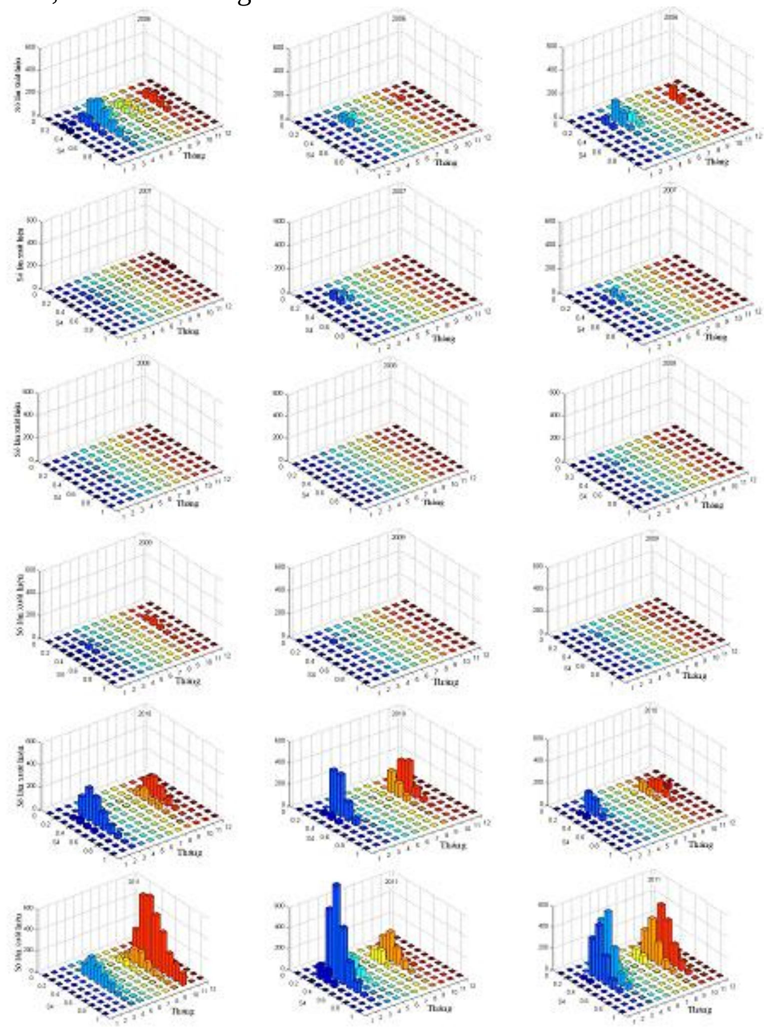

Figure 4.3, Statistical results of ionospheric scintillation occurence for each month in Hanoi (left), Hue (center) and Ho Chi Minh (right) stations, from top to bottom from 2006 to 2011, respectively.

The observed results shows that the occurence of ionospheric scintillation vary with seasons in each year: scintillation generally occurs on the equinox months (March-April and September-October) in every years and rarely occurs in the summer and the winter months.

The occurence of ionospheric scintillation vary from one year to another depending on the solar activity. During the minimum solar activity, 2008 and 2009, ionospheric scintillation occurs rarely, in 2010 and 2011 the Sun is more active, ionospheric scintillation occurs more frequently both in frequency and magnitude in the three stations in Vietnam.

To study the relationship between the occurrence of ionospheric scintillation and the geomagnetism activity, we consider two cases: the magnetic storm on 11/10/2010 and the magnetic storm on 24-25/10/2011. In each case, we used data of 5 days before and after the magnetic storm.

For the first case, the magnetic storm on 11/10/2010, is not the strong storms, the Dst index decreases and reach the minimum value about -80 nT. The statistical results of ionospheric scintillation occurence in these days as following: on the storm day (11/10) there is an increase of scintillation activity in the main phase of the storm, in the recovery phase (12/10) the scintillation activity decreases with respect to the previous day, an in other days before the 11 Octobre and after the 12 Octobre there is no scintillation activity.

For the second one, the magnetic storm happenned on 24-25/10/2011, It is a strong storm, the Dst index decreases to -140 nT. The sudden commencement occurs around 18hUT on 24/10 (01hLT morning of 25/10). The observations show that the ionospheric scintillation occurs for all days from the 23 Octobre to the 27 Octobre, except for one day, 25 Octobre during the recovery phase, scintillation activity is inhibited completely.

In the two cases mentioned here, it shows the effects of the magnetic storm on sintillation activity at Vietnam equatorial region. The magnetic storms increases scintillation activity (11/10/2010) or inhibits scintillation activity (25/10/2011); the scintillation activity depends on the penetration of the magnetospheric electric field (on the 11 Octobre 2010) and the impact of the disturbance dynamo (on the 25 Octobre 2011) which made an enhencement or inhibition of the eastward electric field in F-layer after the sunset.

4.4 Characteristic of spatial distribution

To study the spatial distribution of ionospheric scintillation, we calculated and ploted amplitude scintillation index S4 with the traces of satellite at the ionosphere over Vietnam region for each year using the single-layer model at altitude of 400 km. Figure 4.15 presents the spatial distribution of the scintillation occurrence over Vietnam region and adjacent in 2011.

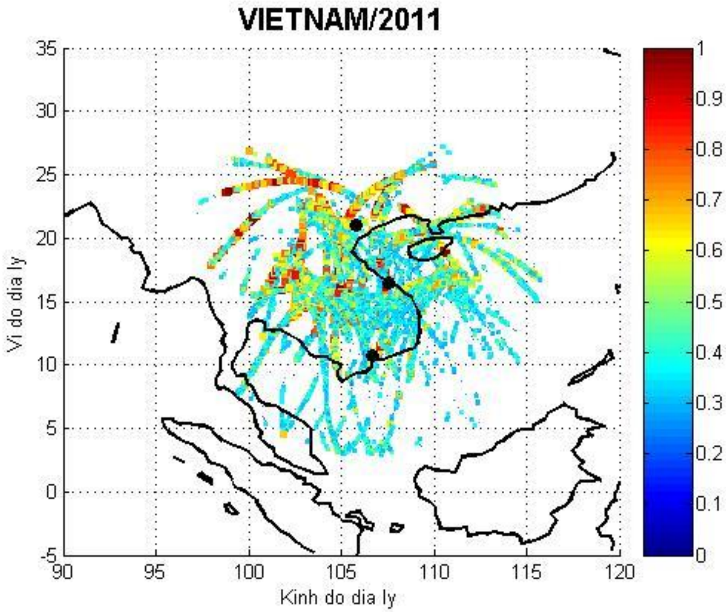

Figure 4.15, The statistical result of the scintillation occurrence over Vietnam region in 2011.

The trace of satellites is drawn at the ionospheric piece point and the amplitude scintillation index S4 is presented by the color scale. The black dots are the positions of stations. From this Figure we can observe the ionospheric scintillation acvitivity over the region from 3^0 to 27^0 geographic latitude and from 98^0 to 115^0 geographic longitude, so the ionospheric scintillaion occurs at all over the territory of Vietnam.

Figure 4.16 presents the statistical result of the scintillation occurrence in latitude for all data from 2006 to 2011, it shows that the occurrence of ionospheric scintillation varies clearly with latitude, at least in the magnetic equator (8^oN in latitude) and the most at about from 14^o to 21^oN in latitude. Strong amplitude scintillation ($S4 \geq 0.6$) lies from 14^0 to 25^0 in latitude, i.e. under the crest of the equatorial ionization anomaly and often observed from Hanoi and Hue stations. Our observation results are suit with the observations from other stations in the equatorial region such as: Valladares et al., (2004) for the South American meridian region; Rama Rao et al., (2006) for the Indian region.

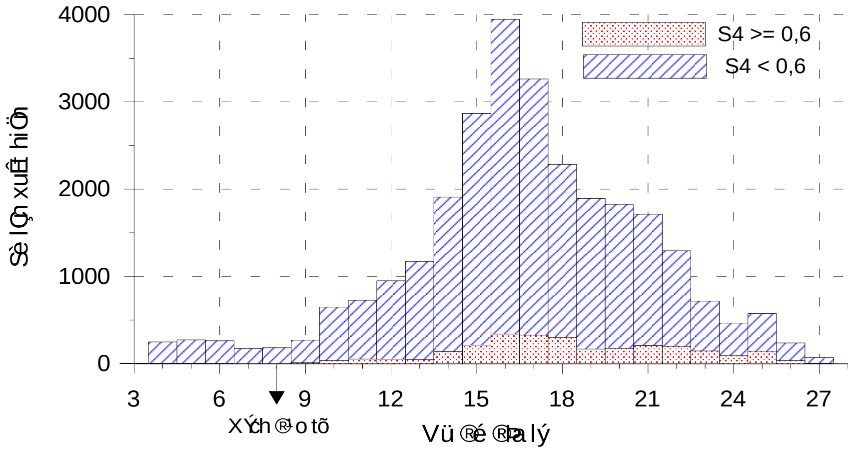

Figure 4.16, Statistics the scintillation occurrence in latitude from 2006 to 2011 for three stations.

4.5 Using the GPS carrier phase fluctuations to study ionospheric irregularities over Vietnam region

The GPS carrier phase fluctuations, the rate of TEC change, ROTI, initially are used to study the occurrence of equatorial ionospheric irregularrities in Vietnam region for two cases: the disturbed day 11/10/2010 and the disturbed day 24-25/10/2011. The observations show that ionospheric irregularities induce the GPS carrier phase fluctuations over Vietnam region generally after sunset (from 19hLT to 24hLT - before midnight) and concentrate in the equatorial ionization anomaly region. The magnetic storms made an enhencement of ionospheric irregularities (11/10/2010) or inhibits the ionospheric irregularities (25/10/2011) in comparaison with the days before and after the storms.

4.6 Effect of ionospheric scintillation on the GPS signal propagation over Vietnam region

Ionospheric scintillations reduce the accuracy of GPS positioning. Strong amplitude scintillation can cause a decrease of the signal power to below the threshold of receiver and then cause the loss of signal during the observation time. Any time, if there are less than 4 signal transmit lines of 4 satellites which are maintained then there would be a temporary loss the service for providing the positioning information (Andrzeij et al., 2004;

Beniguel et al., 2007; Cervera et al. , 2006; Dubey et al., 2006; Rama Rao et al., 2006).

To clarify the effect of ionospheric scintillation on the probability of loss of lock on frequency f_2, we have done the statistics of loss of lock on the frequency f_2 for two cases: we choose three disturbed days with the strongest scintillation activity and three quiet days without scintillation in each station in Octobre 2011, the results are shown in Table 4.1

Table 4.1, The probability of loss of lock on frequency f_2

Station	% loss of lock on frequency f_2 in three quiet days	% loss of lock on frequency f_2 in three disturbed days
Hanoi	7,6	14,6
Hue	3,6	12,1
Ho Chi Minh City	3,4	4,1

The statistical results showed that the probability of loss of lock is more intensity in the days with strong scintillation, the probability of loss of lock is up to 14.6% for Hanoi station, 12.1% for Hue station and 4.1% for Ho Chi Minh stations during the period from 19hLT to 24hLT for 3 disturbed days. Applying the model of Conker et. al, (2003), we calculated the range errors caused by ionospheric scintillation on 24/10/2011, the results are shown in *Figure 4.25*. The range error values are calculated for the minutely mean amplitude scintillation at every time t for each station.

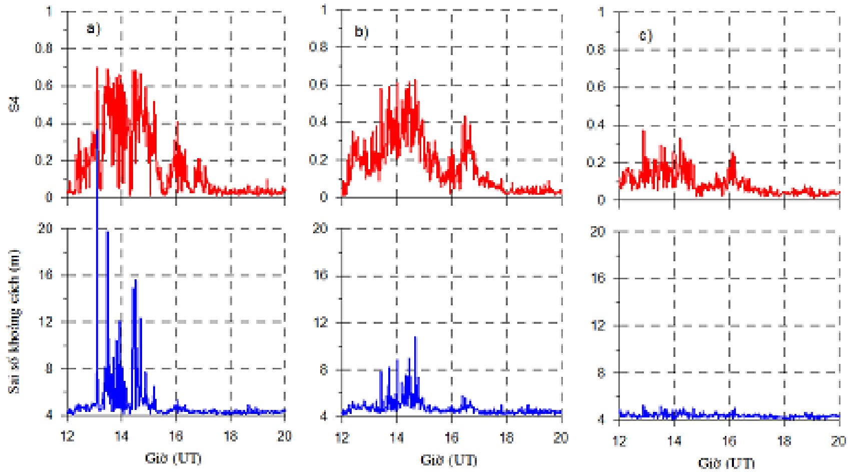

Figure 4.25, The mean amplitude scintillation and range error respectively (d = 0.1) at a) Hanoi, b) Hue and c) Ho Chi Minh City on 24/10/2011

Figure 4.25 shows that the range error on this day in all 3 stations reach about 4.5 meters in general and rise fast when the amplitude scintillation index is greatter then 0.4. At Ho Chi Minh City station, the ionospheric scintillaion on this day is weak (S4< 0.4) and has no significant influence on the range error. For Hue station, the strongest amplitude scintillaion is about 0.6 during from 13hUT to 15hUT, has caused the range error from about 8 to 11m. For Hanoi station, the ionospheric scintillaion is stronger than it in Hue station ($S_4 \geq 0{,}6$) in the period from 13h to 15hUT, causes the range error from 10 meters to more than 20 meters.

The statistical results of the scintillation occurrence over Vietnam region suit with the observed results for other stations in the equatorial region such as: Thomas et al., (2001) for South-East Asian meridian region; Valladares et al., (2004) for the South American meridian region; Rama Rao et al., (2006) for the Indian region.

CONCLUSION

Based on obtained results for the total electron content and the effects of the ionosphere on the GPS signal propagation over Vietnam region using the continuous GPS data at Hanoi station, Hue station and Ho Chi Minh station in this thesis, we can withdraw some conclusions as follows:

1. The method of determining the differential code bias of satellite and receivers presented in the thesis has overcome limitations in the previous calculation method, which decreases the calculation time and give the better results.

2. In Vietnam region, the total electron content varies continuosly in time, which reaches a maxima about 14-15hLT and minima about 5hLT. Diurnal variation of monthly mean TEC vary between 5 TECu at night-time to 50 TECu or so at day-time corresponding with the range delay on L_1 signal from 1m to 8m, depending on the month of the year and on the solar activity. The diurnal amplitude of TEC varies clearly with seasons, reaches maximum in the equinoctial months and minima in the winter and summer months. The daily maximum values of monthly mean TEC vary with solar activity, during the decreasing phase of solar activity the vernal equinox maximum is higher than the autumnal equinox one, during the increasing phase of solar activity, in contrast, the autumnal equinox maximum is higher than the vernal equinox one.

3. The time and latitudinal maps of TEC obtained from the GPS data from Hanoi, Hue and Ho Chi Minh stations, showed that Vietnam lies under the equatorial ionization anomaly in the Southeast Asia. The latitudinal position of the anomaly crest varies from 17^0 to 20^0 in geographic latitude and also depends on the season, moves the farthest from the equator in the equinox months and the nearest the equator in the winter.

4. Over Vietnam region, the ionospheric scintillation occurs quite often, almost at night time between 20-24 LT and rarely in day time. The ionospheric scintillation activity depends on solar activity; in the period of strong solar activity, the scintillation increase much more both in frequency and magnitude, than in the weak solar activity. The observed results shows that the occurence of ionospheric scintillation varies with seasons in each year, scintillation occurs frequently on the equinotial months. The ionospheric scintillation occurs concentrately in the crest region of the equatorial ionization anomaly from 14^0 to 25^0 in geographic latitude, with the maximum occurrence frequency at 16^o latitude.

5. The GPS carrier phase fluctuations, the rate of TEC change index ROTI, are used to study the activity of the equatorial ionospheric irregularrities over Vietnam region for two disturbed days on 11/10/2010 and on 24-25/10/2011. The ionospheric irregularrities occur frequently after the sunset (from 19hLT to 24hLT - before midnight) and concentrate in the crest region of the equatorial ionization anomaly. The obtained results showed that the magnetic storms could produce an enhencement of the ionospheric irregularities activity and cause the scintillation (11/10/2010) or inhibit the ionospheric irregularities activity, i.e. reduce the scintillation activity (25/10/2011) in comparaison with the days before and after magnetic storms depends on the time of occurrence of main phase and recovery phase of the storm.

6. Effect of the ionosphere on GPS signal propagation increases in the equinotial months and in the years of strong solar activity. In Vietnam the GPS signal propagation in the northern region will be affected more than in the southern region. Preliminary results estimated the effects of ionospheric scintillation on the GPS signal propagation over Vietnam region in several days of 10/2011 show that the ionospheric scintillation could produce an enhencement of the probability of loss of lock on frequency f_2 , causing the range error from 10 meters to more than 20 meters at Hanoi station, several meters at Hue station, while at Ho Chi Minh this error is almost negligible.

LIST OF PUBLICATION

1. **Tran Thi Lan, Le Huy Minh, P. Lassudrie Duchesne, R. Fleury, A. Bourdillon:** A primary study of the total electron content and ionospheric scintillation using the GPS continuous data in Vietnam, Journal of the Earth's Sciences (in Vietnamese), T.31(3), *212-223*, 9/2009.
2. **Tran Thi Lan, Le Huy Minh:** Temporal variations of the total electron content and ionospheric scintillation from the continuous GPS data in Vietnam, Journal of the Earth's Sciences (in Vietnamese), T. 33(4), *681-689*, 12/2011.
3. **Tran Thi Lan, Le Huy Minh, R. Fleury, P. Lassudrie Duchesne, A. Bourdillon:** Some variations of the total electron content and ionospheric scintillation in Vietnam from the continuous GPS data, Proceedings of the international scientific conference: Geophysics – Cooperation and sustainable development, *108-119*, 2012.
4. **Tran Thi Lan, Dao The Cuong:** Some characteristic of equatorial Spread F at Phuthuy over a solar cycle, Journal of the Earth's Sciences (in Vietnamese), T. 35(3) , *258-264*, 2013.
5. **M. Le Huy, C. Amory-Mazaudier, R. Fleury, A. Bourdillon, P. Lassudrie-Duchesne, L. Tran Thi, T. Nguyen Chien and T. Nguyen Ha, P. Vila :** Time variations of the total electron content in the Southeast Asian equatorial ionization anomaly for the period 2006-2011, Advances in Space Research, http://dx.doi.org/10.1016/j.asr.2013.08.03, **54**, 355-368, 2014.