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RUSSIAN STATE HYDROMETEOROLOGICAL UNIVERSITY

(RSHU)

Admitted to defense
The head of department
A.D. Kuznecov PhD,
Associate professor

Experimental physics of
atmosphere department

BACHELOR GRADUATION WORK

Global Navigation Satellite Systems Monitoring of Ionosphere

Done by E. V. Kuzminykh,
group MA-453
Supervisor V. V. Chukin PhD,
Associate professor

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CONTENT

Abbreviations

EUV	-	extreme ultra violet
CTIM	-	Coupled Thermosphere-Ionosphere Model
CTIP	-	Coupled Thermosphere-Ionosphere-Plasmasphere Model
COSPAR	-	Committee on Space Research
GNSS	-	Global Navigation Satellite Systems
GPS	-	Global Positioning System
HF	-	high frequency
IR	-	infrared
IRI	-	International Reference Model
JPL	-	Jet Propulsion Laboratory
MEO	-	Medium Earth Orbiting
NCAR	-	National Center for Atmospheric Research
NOAA	-	National Oceanic and Atmospheric Administration
SUPIM	-	Sheffield University Plasmasphere Ionosphere Model
TEC	-	Total Electron Content
UHF	-	ultra high frequency
URSI	-	International Union of Radio Science
VHF	-	very high frequency

Introduction

The ionosphere is that part of the upper atmosphere, where variation of free-electron and ion concentration influence the propagation of electromagnetic waves. Passing through ionosphere phase velocity of radio wave changes and a delay occurs. This delay is a reason for mistake in determination of user position (navigation) and problems with communication. The delay is proportional to the so-called Total Electron Content along the ray path.

The main goal of this work was to compare different methods of TEC calculation with data received making use of GNSS. To achieve this goal the following objectives were defined. First, to process real experiment data from Digisonde DPS-4, located in Tomsk. Then to realize numerical modeling of TEC on the basis of IRI model and in the end to make qualitative and quantitative analyses of mentioned above methods with GNSS data from JPL (Jet Propulsion Laboratory, California, USA).

In first chapter we are speaking about how ionosphere appears: processes of ionization and recombination. Also division into layers is explained. The second part of this chapter is devoted to different ionospheric models. In the next chapter ionosphere is represented as a dispersive medium, so the radio wave propagation specific features are discussed. The third chapter is dealing with different methods for ionosphere measurements, such as ionosphere sounding and passive measurements, among which there is GNSS. So, the fourth chapter is telling about ionosphere and GNSS interactions. Results of numerical and real experiments for total electron content distribution are represented in the last chapter.

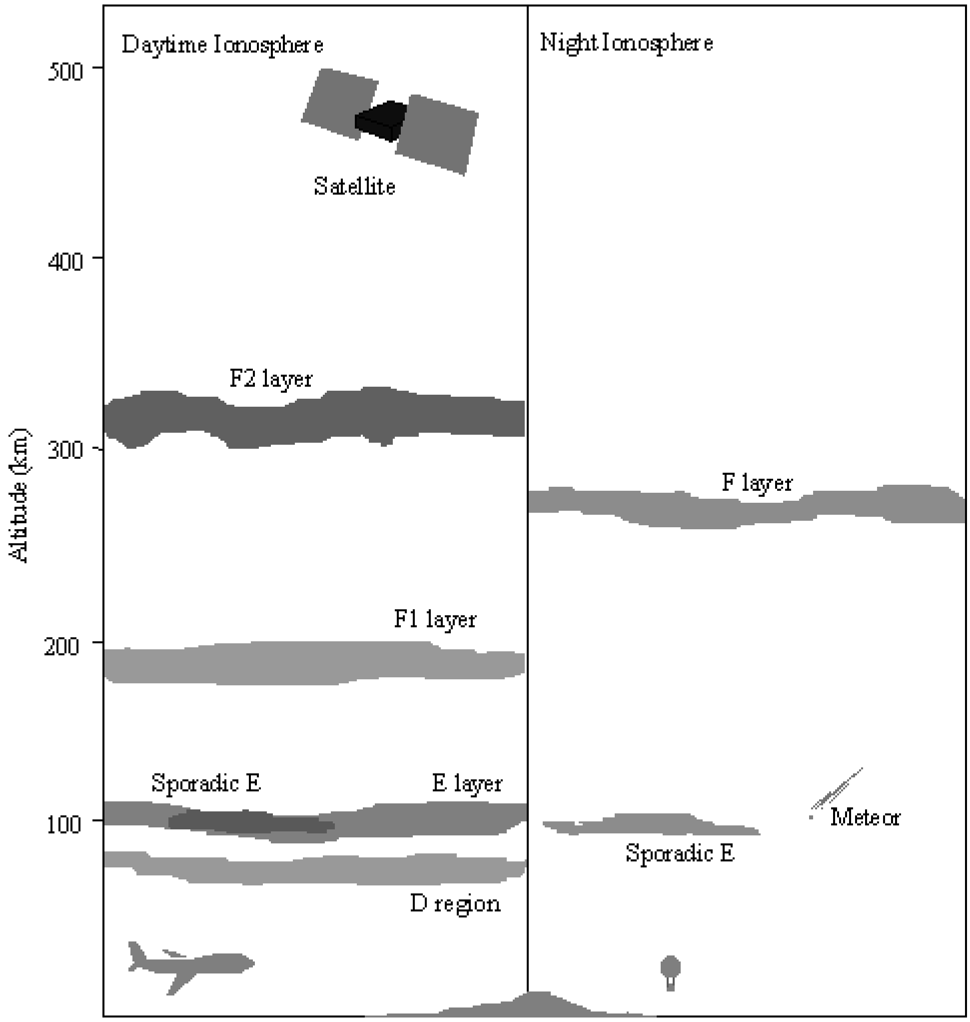
1 Ionosphere

1.1 Physics of formation, structure and composition

Hypothesis about existence in the upper atmosphere some kind of conductive layer was first suggested by English scientist Stuart(1878). In the beginning of 20 century American and English scientists Kennedy and Heaviside independently of one another confirmed it, while illustrating radio wave propagation for long distances. However, experimentally this fact was first proved only in 1925 by English rehearses Appleton, Barnet and Breit. Since then systematic measurements of this layer, which is now known as ionosphere are conducted.

What is ionosphere? Ionosphere is an ionized part of upper atmosphere. It extends from 60 km to about 10000 km. By the top of ionosphere scientists sometimes meant an external part of Earth, but there is no real boundary. Ionosphere is a certain discharged and weak ionized formation of plasma which is situated in the Earth's magnetic field and due to its high electro conductivity appeared to have specific properties. By using them we can suggest radio wave and other perturbations propagation in different layers of ionosphere.

According to global observations data it was made a conclusion about variations of electron and ions concentration. There are some layers, where concentration is maximum. These layers don't have any certain boundaries and their position and intensity changes regularly during a day, season and 11-year sun cycle. Upper layer F conform to main maximum of ionization. At night time it can reaches height of 300-400 km, while during the day(especially in summer) divides into two: F1 and F2 with heights of maximum at 160-200 km and 220-320 correspondingly. There is another layer E at 90-150 km. Layer lower 90 km is known as layer B. (Picture 1.1)



Picture 1.1- Ionospheric layers

Development of satellite technology allows to measure ionic composition and main physic characteristics (temperature, electron and ion concentration) on heights, analyze sources of ionization. Main properties of ionosphere layers you can see in table 1.1. Such cleavage of ionosphere can be explained by sharp change of formation conditions in height.

Formation of ionosphere

Observed variations of electron and ion concentration in ionosphere is a result of balance between the speed of their formation and speed of distraction due to recombination. Ionization sources and processes of recombination in different layers are different.

Table 1.1 - Main properties of ionosphere layers

Layer of ionosphere	Average height of maximum, km	Temperature, K	Electronic concentration n_e, sm^{-3}			Effective coefficient of recombination a, sm^3*sec^{-1}
			Day		Night	
			Sun activity			
			max	min		
D	70	220	100	200	10	10^{-6}
E	110	270	$3*10^5$	$1,5*10^5$	3000	10^{-7}
F1	180	800-1500	$5*10^5$	$3*10^5$	-	$3*10^{-8}$
F2(winter)	220-280	1000-2000	$25*10^5$	$6*10^5$	~ 10^5	$2*10^{-10}$
F2(summer)	250-230	1000-2000	$8*10^5$	$2*10^5$	$3*10^5$	10^{-10}

Let's first speak about ionization. Main source of ionization is short wave radiation. However, there are also such important parts as corpuscular streams, galactic and sun space rays. Each type influences only in some layers of height.

For example, sun short wave radiation forms most part of ions at height of 120-200 km, while long wave radiation causes ionization in layer E (95-115 km). In the upper part of layer D (85-100 km) main source of ionization are X-rays. Speaking about lower part (<60-70 km during day time and <80-90 km at night) we should mention so called galactic space rays. Near 80 km height essential part of ionization is invested by corpuscular streams.

There are some specific ionization conditions. Few hours later after solar flakes Solar space rays appear in the Earth's atmosphere, causing raised ionization at height of 50-100 km especially in Polar Regions. In particular time periods proton and electron fluxes effect not only process of ionization. They create noticeable glow known as aurora at height of 100-120 km, but also can act lower in region D. During magnetic storms these fluxes are increasing with expanding of coverage to lower latitudes.

Process reverse to ionization is called neutralization or recombination. Effective coefficient of recombination shows how fast ions disappear in ionosphere. These values for different layers can be found in table 1, mentioned above.

Ionization, recombination and ion-molecular reactions correspond to three stages of ions life: formation, destruction and transformation. We have already mentioned that in different parts of ionosphere processes occur different which leads to distinction of ion composition. During day time at height of 85-200 km was found a dominance of positive molecular ions NO^+ and ${O_2}^+$, above 200 km in layer F – atomic ions 0^+, above 600-1000 km – protons H^+. In lower part of layer D (<70-80 km) there is an active formation of complex ion-hydrates type $(H_20)_nH^+$ and negative ions, most stable are NO_2^- and NO_3^-. We can find negative ions only in layer D.

Description of ionospheric layers

In layer D degree of ionization is lowest. High molecular concentrations and consequently high frequency of collision with electrons leads to strongest absorption of radio waves. So radio communication can sometimes shutdown. Most properties of layer D are caused by presence of negative ions. By the way it is the main reason for difference between layer D and others. Negative ions is a result of triple collisions between electrons and neutral molecules O_2. A lot of such collision happen lower 70-80 km, so there are much more negative ions here than electrons. Effective coefficient of recombination in layer D is rather high because the process of combined neutralization with positive ions (that's how negative ions can disappear) is quite fast.

Scientists used to think that layer D disappears at night. It can be explained by the fact that while night changes day, electron concentration decreases and so decreases radio wave absorption. During solar flares intensity of X-ray radiation expands. The same happens with ionization of layer D. In its turn rises the absorption. Such sudden perturbation of ionosphere is called Dellinger effect. Usually it takes not more than one hour and a half, but can be longer(couple of days) at high latitudes caused by solar cosmic rays.

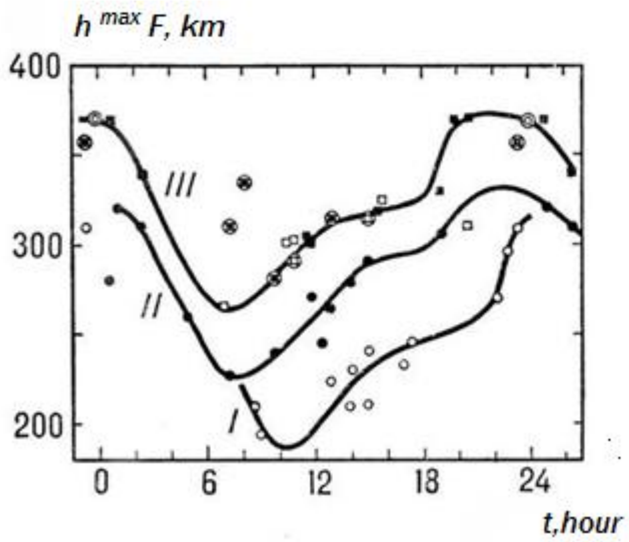
The most regular variations are observed in layers E and F1(100-200 km). First of all the main part of solar radiation is absorbed in these layers. Photochemical theory which consider “simple fiber of ionization” theory explains all regular changes of n_e and ion content during day time depending on different solar activity. As there is no source of ionization at night at heights of 125-160 km value of n_e decreases. However at 100-120 km it remains high. Opinions about nature of night ionization in layer D are different.

At heights of regions D and E it is always found a short-period extraordinary tight layer of high ionization. They are also known as sporadic layers Es (picture 1). These layers contain ions of metals Mg^+, Fe^+, Ca^+. Process of formation can be explained by so called “theory of wind share” due to which in conditions of magnetic field gas flow shift ions to the layer where wind speed is zero and Es is formed. Thanks to Es existence long distance propagation of TV radiobroadcast is possible.

At 170 - 180 km higher during day time and 215-230 km higher in the morning, afternoon and night concentration of O^+ grows by 50 %. Condition of formation up and down these layers are completely different. Layer F1 is observed regularly on ionograms only when solar elevation is high primary at summer time and with low solar activity. If it is winter and sunspot activity is high no F1 layer is formed. Still it can be found below maximum of ionization while higher good conditions for F2 are created.

Behavior of layer F or maximum of ionization is rather difficult. Average concentration is determined by Solar activity, but changes dramatically from day to day. In diurnal variation it is sometimes shifted from noon and strongly depends on latitude, season and even longitude. Increasing of n_e also can be found in winter versus summer. In equatorial part there is one maximum before noon but two of them afternoon and during night hours, which are situated at geomagnetic latitudes ±15. Sunrise stimulates both maximums to separate, moving to higher latitudes and disappear in order to show up on equator. Moreover at high latitudes parallel to zone of auroras some tight layers of low ionization was found. It shows that besides solar radiation variations of n_e in layer F are also determined by geophysics factors.

Height of main maximum in mid-latitudes is represented in figure 2. Its change is rather complicated during 24 hours, decreasing in the morning and becoming maximum near midnight. In winter (curve I) it is lower than in summer (curve II), and at high Solar activity (curve III) is higher versus low(curve I and II).



Picture 1.2 - Height of main maximum of ionosphere (northern latitudes of northern hemisphere)

Theory which considers effect of ambipolar diffusion connects such F height variations with changes of ionization intensity and atmospheric temperature. Existence of this layer at night is explained by inflow of ions from above protonosphere, where they accumulate during day time. According to different mechanisms layer is higher at night comparing day.

Specific features of upper atmosphere (situated above F layer) changes mostly follow the diurnal variation of n_e in F maximum. It shows us their strong interrelation.

Above F layer concentration of ions decreases with height by barometric formula, while part of light electrons increases. That's why in layer F during day time upper 1000 km O^+ ions prevail over H^+ ions. As temperature decrease at night so the height falls approximately to 600 km. In the same layers but at higher latitudes an increase of ions was found that is connected with temperature increasing.

Existence of turbulence inhomogeneity of electron concentration can be explained by movement of electro jet current. Reason for their origin is fluctuation of ionizing radiation and continuous meteor invasion in atmosphere, which in its turn influence on radio wave propagation.

1.2 Ionospheric models

There are a lot of different ionospheric models. Which one you are going to use depends on your purposes. According to "Guide to Reference and Standard Ionosphere Models", established by "American National Standards Institute" we can name 10 global ionospheric models: USU Time-Dependent Model of the Global Ionosphere; NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model; Coupled Thermosphere-Ionosphere Model (CTIM); Coupled Thermosphere-Ionosphere-Plasmasphere Model (CTIP); Global Theoretical Ionospheric Model (GTIM); Parameterized Ionospheric Model (PIM); International Reference Ionosphere (IRI); Empirical Model of the Ionosphere; The Sheffield University Plasmashphere-Ionsophere Model (SUPIM); The Field Line Interhemispheric Plasma Model. Let's focus on some of them in more details.

1.2.1 Standard ionospheric model

This model is known as standard ionospheric model of ionosphere concentrations and temperatures (IRI). It is developing by a joint Working Group of Committee on Space Research (COSPAR) and International Union of Radio Science (URSI).

IRI is based on time series of ionospheric measurements so the model is empiric. In the lower part (<150 km) geodetic system of coordinates is used and in upper part – geomagnetic one. It can be explained by strong correlation between ions and neutral gases (high frequency of collision) in the low ionosphere and increase of magnetic force lines impact on processes in ionosphere with height. Modified dip latitude as the most convenient one was selected for geomagnetic coordinate.

Different parameters can be used while describing diurnal variations to height. For example, for E-layer, where ionization is the highest, impact of solar radiation can be best defined by inclination. For F-layer and higher local or universal time will be a such parameter, because of redistribution of plasma along magnetic force lines due to transfer processes. At high latitudes dependence on time plays more important role owing to rotation of magnetic poles.

It is known that a strong relation between sun and ionosphere exists. From ionospheric data we can even get 11-years solar cycles [1]. This should be mentioned while modeling with some indexes of solar activity. Unfortunately everything is not so good, as it seems to. Using ground measurements it is impossible to get index, which will allow to control variability in the range of ultraviolet radiation, that’s why we have indexes only for separate relatively short periods of time, when we have satellite data. Hence, number of sun spots(R) and F10.7 index (a measure of the noise level generated by the sun at a wavelength of 10.7 cm at the earth's orbit) are used. The latter is usually applied to layers lower maximum F, which as we know are determined by direct solar radiation, while first one is better for upper layers, where dynamic processes compete with solar radiation. What about IRI model a 12-month moving average R, calculated in observatory of Zurich is used. Alternatively we can name global ionospheric index IG12 [2], based on measurements of maximum F layer electron density with 13 ionosondes.

1.2.2 Klobuchar model

GPS «Eight-coefficient» TEC Model also known as Klobuchar model was developed in the late 70-s for correction of ionospheric delay in a single-frequency GPS receivers. Due to severe limitations on length of navigation message, all data about current state of ionosphere must be translated only by 8 coefficients.

Klobuchar model defines electron concentration as a function of latitude, longitude, time of day, season and solar radiation flux on 10.7 cm wavelength. Algorithm is a diurnal variations approximation of total ionospheric delay on 1.6 GHz proportional to total electron content, so cosines with period and amplitude, depending on latitude is used. In night time delay is considered to be constant. Hence, there are 4 parts: 1) night constant part, 2) amplitude, 3) phase and 4) period of cosines.

Analyzing behavior it was made a conclusion that first and third parts to a high accuracy are constant. Second and fourth are function of geomagnetic latitude and can be defined by polynominals in 3 degree.

Klobuchar model is applied for one-frequency GPS receivers. As in most cases GPS satellites are observed at an angle to the horizon, there is no way model can be used for total electron content (TEC) over location of receiver. It is necessary to choose a point where line satellite-receiver crosses average height of ionosphere. In Klobuchar model such height is 350 km.

Another not less important factor is an inclination in the form of coefficient, which should be multiplied by value received from model. Besides, TEC is best described as a function of geomagnetic coordinates, so it should be recounted. All these factors lead to use of some simplifications:

1) reductive formula for calculation the angle between direction from Earth center to receiver and direction to satellite is used,

2) for determining under ionosphere point, curvature of the earth is ignored,

3) to recount coordinates the Earth magnetic field is considered as a dipole with center point in the center of Earth,

4) local time is derived by latitude and universal time,

5) for coefficient of inclination approximation is used.

However, in spite of such simplicity model gives very fair results with mean-square error equals 50 % [3].

In order to replace Klobuchar model a CPI-TEC Model was developed. It uses significant calculating power of modern mobile devices. The main difference is that besides data of solar activity there are also of equatorial vertical drift and thermosphere winds [4]. In practice model is used for correction in one-frequency GPS receivers and also for researches connected with TEC variations.

1.2.3 Other models

Utah State University Time-Dependent Ionospheric Model

Model deals with 3 main (NO^+, $O_2{}^+$ and O^+) and 3 small (N_2^+,N_2 ,He^+) ions. It considers 3 types of ionization: solar radiation in EUV part of spectrum, auroral eruptions and resonant scattered solar emission. Model also takes into account influence of plasma diffusion along power lines and, calculating the speed of recombination, includes ion content changes in chemical reactions and temperature dependence on speed of these reactions. Hence, present model numerically solves continuity and motion equations for ions and also heat balance equation for ions and electrons in layer F. Together these parameters describe charged components behavior of ionospheric plasma. What about other parameters, none of them are calculated in the model, but are entered from outside. For neutral atmosphere MSIS model is used, auroral eruptions are distributed by statically averaged auroral ellipse, spectral density is defined by only by F10.7 coefficient.

This leads to smoothed input and does not allow to reconstruct all specifics of atmosphere dynamics.

Standard Plasmasphere-Ionosphere Model

It is a project of International Organization for Standardization, which purposes are development of electron content model, ionosphere temperatures and frequency of collisions in ionosphere and plasmasphere (interval of heights is from 65 – 20000 km). In whole it is an IRI model till 1000 km and Russian model SMI higher 1000 km.

The National Center for Atmospheric Research Thermosphere-Ionosphere-Electrodynamics General Circulation Model

It is a general circulation model of thermosphere-ionosphere with a glance of electrodynamics. It is developing by National Center for Atmospheric Research. Model is a numerical one in the range of heights from 95-500 km. It is not based on empiric data and all needed parameters are calculated over solution of hydro thermodynamic equations together with chemical and electrodynamics blocks. This model allows to get not only global distribution of neutral atmosphere (wind speed and direction, pressure) and ionosphere (electron density, ion and electron temperature, concentration of main ions) parameters, but also global distribution of electric fields, currents and perturbation of magnetic field at the ground level [5],[6]. What is more important model is not for real time use, but scientific researches.

Coupled Thermosphere-Ionosphere Model (CTIM)

CTIM is a conjectured thermosphere-ionosphere model and is developing for 30 years by different groups, including those in University College London, Sheffield University and Space Environment Center (NOAA, Boulder Colorado). Along with model of ionosphere convection (100-10000 km) a system of equations for neutral atmosphere (80-500 km) is solved. This model is also used only for investigations.

The coupled thermosphere-ionosphere-plasmasphere model (CTIP)

CTIP is a modified version of CTIM. Main difference is that in CTIM for different latitudes and plasmasphere empirical models are used while in CTIP there is a fully concerted one.

The Sheffield University Plasmashphere-Ionsophere Model (SUPIM)

It is a numerical model of ion and electron distribution in mid and low latitudes. Model is based on idea that plasma movement along magnetic force lines occurs due to ambipolar diffusion, while in perpendicular direction this happens because of electromagnetic drift. SUPIM is used for theoretical researches and climatological calculations.

2. Influence of ionosphere on radio wave propagation

Environment plays a significant role in radio wave propagation. As earth’s surface and atmosphere can be such a surrounding, so can the outer space. Particular qualities are defined by value and distribution of electric parameters in time and over distance. Among parameters we can define relative electric ε and magnetic μ permittivity and also electrical conductivity γ. However, usually only one parameter is used, that is refractory index, which depends on interaction between vectors of magnetic and electric fields of radio wave with surrounding.

To describe trajectory of wave propagation in ionosphere we can use a radial interpretation. Hence, the equation of wave trajectory looks like:

$$n * r * cos\theta = n_0 * \alpha * cos\theta_0, \qquad (2.1)$$

where

n, n_0 - refractory indexes in concerned point of ionosphere and near the ground respectively,

θ, θ_0 - gliding angle of ray relatively to ionosphere layer and earth surface;

α - earth radius,

r - the distance to observation point.

It is natural that some deformations happen to wave getting in ionosphere, exactly bulge of trajectory is orientated clear of earth surface. More wave penetrate in ionosphere , less is gliding angle until at some height equals zero. So, equation 2.1 takes the form of:

$$n * r = n_0 * \ \alpha * cos\theta_0 \ . \qquad (2.2)$$

Equation 2.2 is known as condition of full internal reflection (turn) of angle.

As the coefficient of refraction depends on frequency of wave , so this frequency on some height after turn of the angle can be defined by formula:

$$f = \frac{\sqrt{80.8N_e}}{\sin\theta_0} = f_0 * sec\varphi_0, \qquad (2.3)$$

where

N_e - electrons concentration in the point of turn,

f_0 - own frequency of ionosphere,

φ_0 - the angle of incidence to ionosphere.

Equation 2.3 is referred to secant law: ray frequency$f$, falling to ionosphere at an angle φ_0 , reflects on height z the same way as ray frequency f_0 oriented to ionosphere vertically.

Frequency when incident ray reflects from ionosphere (index of refraction equals 1) is called critical frequency. On practice, when $f < f_{cr}$ total reflection is observed and when $f > f_{cr}$ - transmission.

First of all critical frequency is defined by electron concentration, that's why it is necessary to speak about own critical frequencies for D,E,F1,F2 layers. Obviously that maximum value will be in maximum layer F2.

According to 2.3 f_{max} will be in $sec\varphi_0$ more than f_{cr} and will be approximately equal to 4, 1[7]. Experiments show that frequency of rays falling to ionosphere can't be more than 30-40 MHz, so we can made a conclusion that rays with wavelength more than 8-10 meters (short, medium and long) are reflected from ionosphere.

We also should mention another effect when $f > f_0$ which is appearance of limiting incidence angle φ_{cr}. In this case trajectory appears to be higher. Ray, being reflected can go through ionosphere, if angle of incidence value is less than critical. Vice verse reflection will occur with less electron concentration and on lower height.

It is considered that rays being multiply reflected from ground surface and ionosphere expand over bow of big circle, moreover trajectory assumed to be symmetric. To know propagation distance along earth surface there are some specifics:

1) every radio wave frequency f has its own incident angle φ_{dz}, when propagation distance along ground surface will be minimal. Such distance is known as dead zone, within which receiving of radiation is impossible;

2) in order to increase propagation distance operation frequency should be increased on condition that incident angle and critical frequency are specified values. It can be explained by expansion of penetration in ionosphere, height and curvature radius of reflection;

3) when $\varphi_0 > \varphi_{dz}$ increase of trajectory steepness leads to decrease of distance;

4) when $\varphi_0 < \varphi_{dz}$ more steepness trajectories will refer to higher distances;

5) two rays with different incident angles can cover the same defined distance along surface: flat ray with small curvature radius and sharp one with high value of curvature radius, which is also known as Pedersen ray;

6) to determine the maximal distance for one step, tangent rays to the ground surface are used, which reflect in the layer with maximum electron concentration. For F2 layer this distance equals 3000 – 4000 km and for E layer – 2000 km.

Besides mentioned above simple trajectories there are also more complicated. The main difference is that rays can reflect alternatively from different ionospheric layers. We should pay attention on the fact that with intermediate refraction from earth surface energy loss falls since the way of ray in layer D diminishes.

Engineering analysis usually use only simple trajectories as there is not enough data along the whole route for complicated one.

In the presence of the Earth magnetic field ionosphere becomes anisotropic, so the refraction and absorption coefficients depend on wave propagation toward magnetic field lines and changes with different polarization. Hence, wave trajectory gets some specific features.

There is one effect known as birefringence effect. The decomposition of a ray of light into two rays (the ordinary ray and the extraordinary ray) happens when passing through certain layer of ionosphere with refraction index equals 0[.1]. It is easily explained by fact that refraction index can assume two values. Critical frequency of extraordinary wave is more than of ordinary one. Their difference can be calculated by formula:

$$f_{cr.exo} = f_{cr.o} + 0{,}7MHz. \tag{2.4}$$

Here,

$f_{cr.exo}$ - critical frequency of extraordinary wave ,

$f_{cr.o}$ - critical frequency of ordinary wave.

Refracting from various heights, rays return to different points on earth surface with time lag. In the context of radio physics it can be a reason for appearance of two magneto split impulses when pulsing and interference fading, when several rays come to one point.

As there is a geomagnetic field there is a change in wave polarization. It depends on direction of wave propagation toward magnetic field lines, electron density and frequency. Polarization can be presented by figure, which describes the end of electric vector over a period of high-frequency oscillation. Analyzing the polarization in ionosphere following conclusions were made:

1) ordinary and extraordinary wave are polarized elliptically with opposite direction of electric vector rotation, major axis incline apart wave propagation and are orthogonal to each other;

2) in case when propagation is transverse, ordinary wave has linear polarization along the magnetic force lines direction, extraordinary wave in fronts surface is polarized linear, but is perpendicular to force lines while in propagation surface polarization is elliptical;

It is known that retracing to receiver point after leaving ionosphere wave gets the polarization at the exit which is not the same to entrance. Such effect is named by Faraday and is typical for ultra-short waves.

In passing through ionosphere energy loss takes place, which leads to decrease in electric-field intensity in receiving point. All influence consists in heat loss.

Intensity of wave can be determined by the following law:

$$E = E_0 * e^{-\Gamma_i}, \tag{2.5}$$

where

E_0 - field intensity at entrance to ionosphere,

$\Gamma_u = \int_s a_a(s)ds$ - integral coefficient of absorption on the way of wave propagation.

Absorption coefficient a_a depends on ray transmits with reflection or without. For reflecting layer it is counted by formula:

$$a_a = \frac{v}{2c}\frac{1}{n_u}(1 - n_u^2)\ . \tag{2.6}$$

For unreflecting:

$$a_a = \frac{v}{2c}(1 - n_u^2). \tag{2.7}$$

Here,

v - electron velocity,

c - speed of light,

n_u - refraction index.

When calculating the integral coefficient, it is defined as sum of private absorption coefficients in layers ray passed.

It necessary not to forget about path length, because it changes distance wave propagates in absorbed environment. For unreflecting surroundings it can be approximately defined by formula:

$$S = h * sec\varphi_0, \tag{2.8}$$

where

h - thickness of ionospheric layer,

φ_0 - angle of incidence of the wave passing through the layer .

3 Methods to measure ionosphere

Nowadays exist a lot of methods to study the Earth's atmosphere-ionosphere environment. First of all these are radars and radio methods. Then go such techniques as rockets and satellites. We will consider all of them.

3.1 Ionosphere Sounding

Ionospheric sounding can be easily performed by using transmitter and receiver. But how does it work? Whence radio signal travels overall to receiver from transmitter is gathered by radio wave as it passes through layers with different electron density. As we know ionosphere is not uniform in vertical distribution, moreover in horizontal one (horizontal gradients can be caused by passing of dawn and dusk terminator each day).

To determine the electron density profile of the ionosphere either scatter radar techniques or ionosonde sounding can be used.

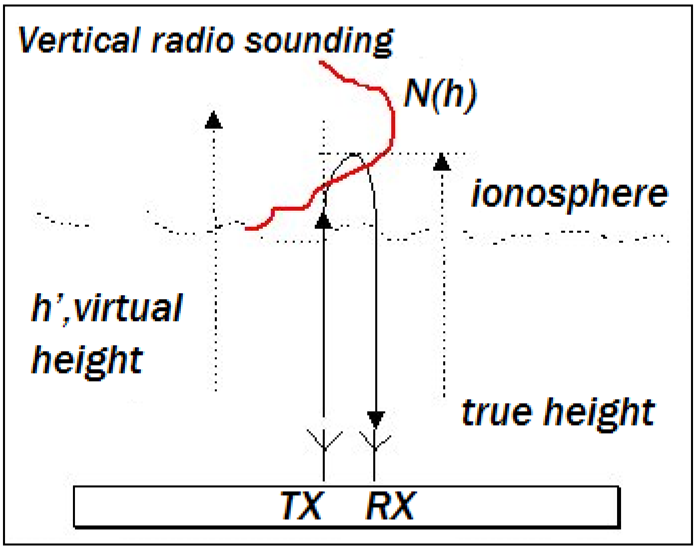
The ionosphere intrusion on communications systems is not just limited to propagation effects. Many satellites are actually flying within the ionosphere and the presence of the ionization fluctuating levels with electric and magnetic fields often moves satellites out of position, causes electronic failures and even breaking down the satellites.

3.1.1 Ionosondes

The technique using a radio transceiver that can transmit and receive vertically incident radio waves was first used by G. Breit and M.A.Tuve [8]. The device used to probe the ionosphere is known as an ionosonde. It consists of a combined radio transmitter and receiver capable to transmit pulses toward the above ionosphere and receiving the same signal pulse as it returns back. The time delay at different frequencies can be recorded when varying the carrier frequency of pulses (typically from 1 to 20 MHz).

Vertical Sounding

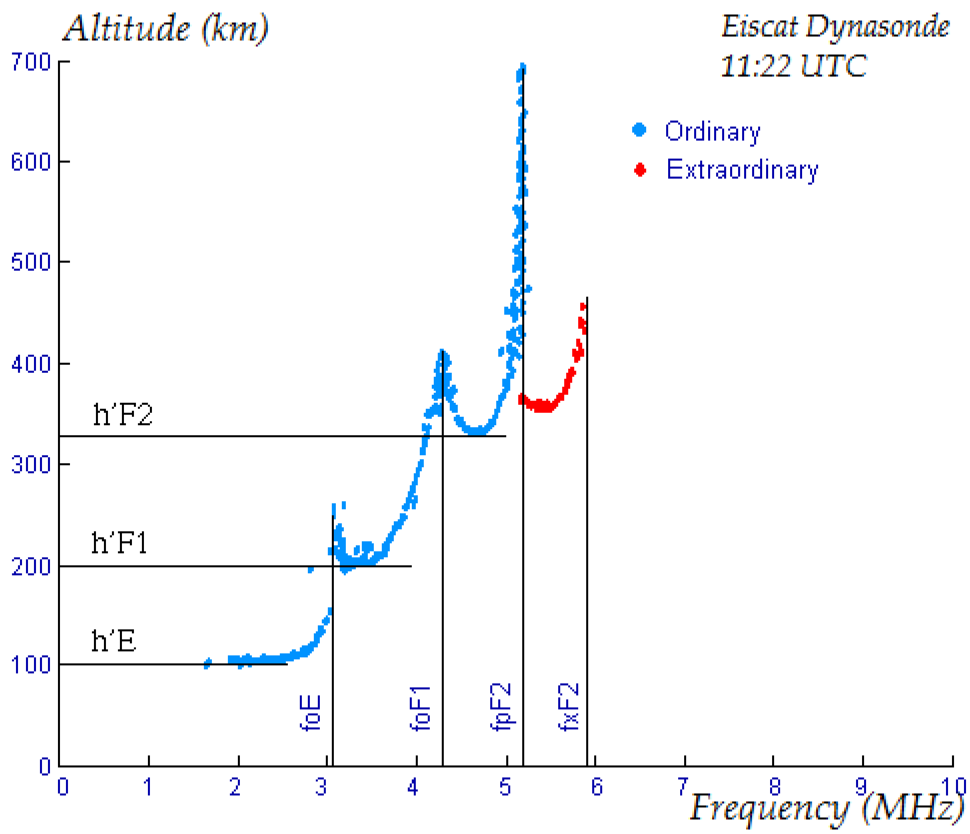
To carry out a vertical sounding, transmitter (TX) and receiver (RX) are located in the same place. High-frequency (1- 30MHz) radio waves are passed vertical up to the ionosphere. Receive antennas detect the return echoes from the ionosphere (picture 3.1).



Picture 3.1 Ionospheric vertical sounding

In order to know height of the reflecting layer (typically between 70 - 400 km), the time-of-flight of the radio signals at a particular frequency is required.

So, vertical ionogram appears (picture 3.2). Here the virtual range or altitude in km to the reflecting layer in the ionosphere is plotted against the receiver frequency.



Picture 3.2 - A typical vertical ionogram

The asymptotes in the plot correspond to the critical frequencies of the ionospheric layers. The virtual heights of the ionospheric layers are scaled at the lowest points on each curve between the critical frequencies, where the incident radio wave from the ionosonde has reached maximum resonant frequency of the layer and the radio wave does not propagate. Radio wave stop reflecting by the layer as soon as frequency transcends critical value. It is transmitted to higher layers and then continues into space when eventually the transmitter frequency exceeds the maximum ionospheric critical frequency.

The green trace is an ordinary ray, that is returned echoes from the component of signal which is parallel with magnetic field direction. The red trace is the extraordinary ray, here the transmitted radio signal has been split into two polarizations by the interaction with the Earth's magnetic field.

To calculate the features of a received radio signal through the ionosphere (amplitude, polarisation, relative phase, time of flight, dispersive spread), what we need is the path the radio rays took from transmitter to receiver. So, delails of the electron density profile are to be extracted from the ionograms.

What ionosonde actually measures is the time of flight from receiver to transmitter that can be converted to a 'virtual' height in kilometres, using the following expression:

$$h' = \frac{(c*\Delta t)}{2}, \tag{3.1}$$

where

Δt - the time delay,

h′ - the virtual height,

c - the speed of light in vacuum.

What we are interested in is the true altitude of the reflecting layer and equation 3.2 shows that real height has to allow for the true speed at which the radio wave has travelled.

$$h_v = c \int_0^{h_r} \frac{dh}{v_g}, \tag{3.2}$$

where h_v - the real height of the reflection,

v_g - the group velocity of the radio signal.

The real height in the ionosphere is always less than virtual one. That's because the group velocity is less than speed light. The discrepancy depends on the quantity of ionisation below the reflecting layer.

Group refractive index μ_g can be expressed by speed of the light divided by group velocity. The relationship between the group refractive index and the phase refractive index μ_p, for a non-isotropic medium, is given by Equation 3.3.

$$\mu_g = \mu_p + w\frac{d\mu_p}{dw}, \quad (3.3)$$

where

w – angular frequency of transmitted radio wave.

Hence, in terms of the phase refractive index using equation 3.3 the virtual height measured by an ionosonde becomes:

$$h_v = \int_0^{h_r} (\mu_p + w\frac{d\mu_p}{dw})\, dh \quad (3.4)$$

To get a connection between the measured virtual height at a particular frequency as observed by an ionosonde and the electron density profile two expressions are to be susbstituded in equation 3.4. One for the phase refractive index (Equation 3.5) and the relationship between the plasma frequency and the electron density (Equation 3.6).

$$\mu_p = \frac{c}{v_p} = \sqrt{1 - \frac{w_p^2}{w^2}}, \quad (3.5)$$

$$w_p = 2\pi f_p = \sqrt{\frac{N * e}{\varepsilon_0 * m_e}}, \quad (3.6)$$

where μ_p - angular plasma frequency,

f_p - plasma frequency,

N - density of electrons,

e - the charge on the electron,

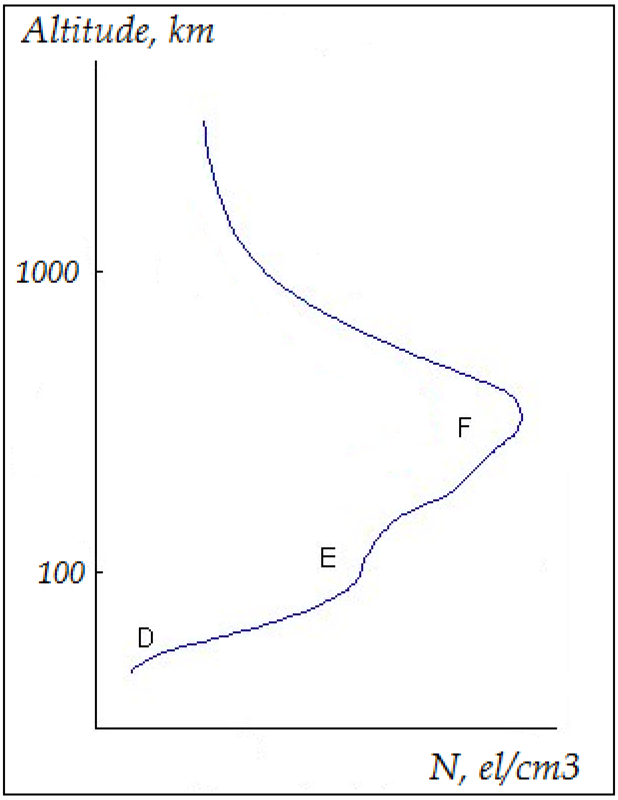
m_e - electron mass,

ε_0 - permittivity of free space.

Hence,

$$h_v = \int_0^{h_r} \frac{1}{\sqrt{(1 - \frac{N(h) * e^2}{\varepsilon_0 * m_e * w^2}}} dh \quad (3.7)$$

The virtual height is measured. N(h) is what is required, if analysing a radio signal propagation through an ionosphere. Picture 3.3 shows the sketch of a 'typical' ionospheric electron density profile which would be constantly varying in reality.



Picture 3.3 - A typical day time ionospheric electron density profile.

The Pulsed Ionosonde

The pulsed ionosonde is the basis for most modern ionosondes. It works by transmitting a series of pulses vertically upwards into the ionosphere. To form view screen there is an oscilloscope. As timing device to measure the delay time the time-base of a cathode ray tube is used. When the echo or reflected radio pulse signal is received by ionosonde, it is fed to the Y-plates of the tube in such a way that the electron beam deviates in direction (Figure 3.4 (the A scan method)).

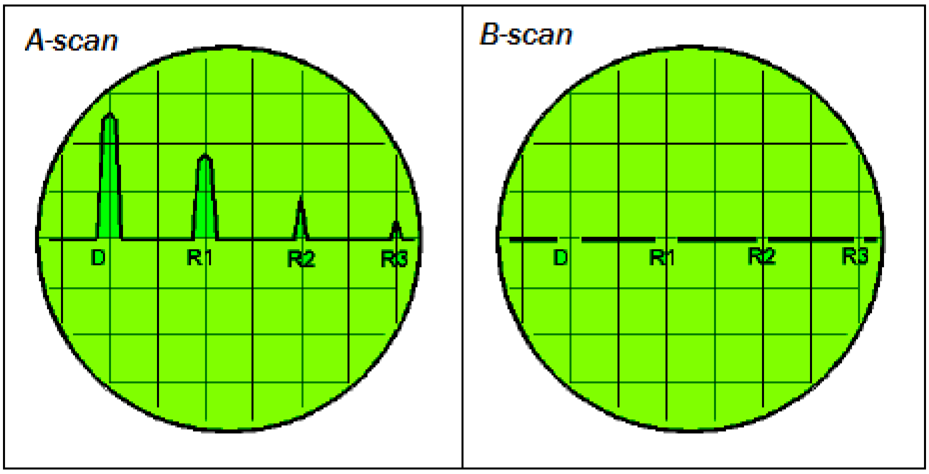


Figure 3.4 - The D pulse is the direct transmitted pulse and R1, R2 and R3 are the received reflected echo pulses.

The position of the pulse on the time base is defined by the traveling time of the pulse and hence of the virtual height of reflection. The Y-deflection is related to the echo amplitude. Another way to apply the echo pulse to the grid of the oscilloscope is to blank out the time base (Figure 3.4 (the B scan method)).

To measure the virtual height of the ionized layers and respectively their critical frequencies is a sweep frequency pulsed radar device with frequency range from about 0.1 MHz to 30 MHz. A sweep duration varies from a few seconds to a few minutes. There is a strong correlation between frequency of the transmitted pulses and the path of each pulse through the ionosphere. The time taken for the pulse to reach the ionosonde can be changed. Higher frequencies penetrate deeper into the ionosphere.

Slower ramp-up times can increase the resolution of the probed ionosphere which results in better signal to noise ratios, and prevent the ionosonde from rapid changes that might occur in the ionosphere. Rapid ramps in frequency provide a better instantaneous snapshot of the ionospheric layers and state, but suffer from lower signal to noise ratios. Hence, a compromise has to be taken between better resolution and instant picture.

The Digisonde

Digisonde is a highly sophisticated pulse amplitude sounder. Special about digisonde is the capability to measure a host of additional parameters such as the amplitude of returned echoes, the travel time of the reflected echoes, the precise Doppler frequency, the angle of arrival and the separation of the ordinary and extraordinary waves, the wave polarization and the curvation of the wave front of the returned pulses.

The obtained parameter values are digitally preprocessed and displayed on a computer monitor or can be printed. The leader in digisondes development is The Center for Atmospheric Research at the University of Massachusetts Lowell. The Lowell Digisondes are the most usable worldwide.

The receiver uses an array of crossed loop antennas to facilitate the measurements of the angle of arrival of the ordinary and extraordinary components of the received pulses. An array of four (DSP-1) or seven (DGS-256) of these antennas is used and by switching in the appropriated delay filters, the receiver beam is pointed vertically and in 14 directions arranged in two circles at two angles that are off from the vertical direction [8].

For each receiving antenna there is a preamplifier (1-30 MHz) and it is connected with switching and receiver antenna system by low lass coax cable. Then the direction and magnitude of the maximum signal can be measured, the Doppler shift is recorded as either positive or negative from normal. The digisondes include stages of band pass filters capable of filtering out spurious transmissions and interference that could destroy the results.

Even digisondes are very complex devices they are successfully used to uncover many features of the ionosphere. All calculated parameters are plotted as an ionogram although the automatic interpreting of the data to compute those parameters is not always correct.

Global digisonde network can be found in [9]. We will just mention that in Russia digisondes DPS-4 are placed in Irkutsk (from 2002), Norilsk, Yakutsk, Zhigansk and Tomsk.

The Chirp Sounder

Chirp sounders broadcast continuous modulated and linearly ramped signals into the ionosphere. The signal being reflected returns back to the receiver. Meanwhile, the transmitter frequency will have increased by an amount proportional to the time that has elapsed for the returning signal. When the transmitted frequency is subtracted from the echoed signal then an audio frequency is the result (chirp sound) [8].

The chirp tone frequency is proportional to the time delays of the signal. To determine time delays and reflection height Fat Fourier Transformations are to be applied.

Chirp sounders are preferred to other types of sounders because they require very low transmitter power to function (10 to 100 watt) and the Doppler and phase components are easily determined by use of the Fourier transformations.

However, there is a disadvantage connected with chirp sounders. They take longer time to complete a frequency sweep. If the resolution is 3 kilometers in height with frequency range from 1 to 30 MHz, it may require as much as 10 minutes completing a sounding. Meanwhile substantial ionospheric characteristics changes may occur. So the chirp sounding is only practical when the state of the ionosphere is fairly constant over time periods from 5 to 10 minutes [8].

Oblique Sounding

Although vertical ionosonde stations are located worldwide, there are locations like oceans, deserts and other remote places, where it is not easy to operate them. The method to reach those locations is known as the oblique sounding technique.

With oblique sounding the transmitter and the receiver are far apart from each other. Usually this distance is around 3 000 km but may be more or less depending on what area is investigating. The geometry of oblique sounding is illustrated in Figure 3.5 along with two alternative routes for the radio signals.

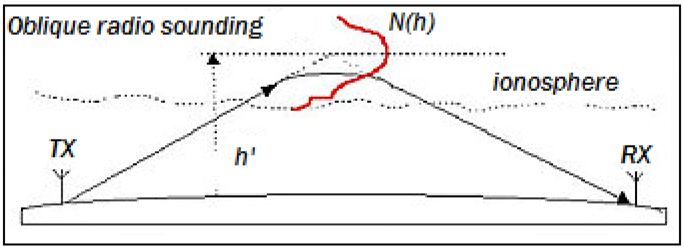


Figure 3.5 – Oblique radio sounding

An obliquely transmitted wave reaches the Earth's surface after reflection in the ionosphere. Besides a small amount of the radar wave energy is scattered because of targets on the ground or in the air. The back-scattered wave, which had propagated back to the transmitter, is received at that location and yields information about the scattering properties of the remote target as well as on the passed ionosphere.

Despite the additional complications in understanding oblique propagation and not so many ionospheric parameters being collected, the oblique ionospheric sounder offers several important advantages. We already mentioned first one. Such sounding enables the ionosphere to be monitored across large otherwise inaccessible distances such as across oceans. Secondly one receiver can detect a network of remote transmitters. And the last one perhaps the most important is the opportunity to investigate how radio signals in communications systems actually travel by re-creating real life propagation scenarios.

Oblique ionograms provide high-resolution images that permit quickly to identify frequencies that are propagating between a selected transmitter and receiver.

The effect of propagation paths that involved multiple reflections from the ionosphere is apparent by the separate curves. By looking at the frequency axis and noting where there is a receive echo the available combinations bands and the likelihood of experiencing interference can be determined. However because of the multiple routes available the signals would suffer distortion from multipath interference and fading. This could contaminate the reception of signals due to existence of more than one route within the single hop, a high altitude propagation path (high-ray) and low altitude route (low ray) [10].

An oblique ionogram usually clearly shows the available communications bands and the gaps where no link is. Since the ionosphere changes on time scales can be less than a minute, the information on the available frequencies needs to be constantly updated. It can be concluded that main purpose of the oblique sounding is to understand the factors effecting the propagation, so reduce one day the link unreliability produced by natural ionospheric variability.

3.1.2 Radars

When the wave frequency is much larger than the plasma frequency, incoherent scatter from thermal motions of free electrons in the ionosphere takes place. This is called incoherent or Thomson scatters. Instabilities in the ionosphere generate plasma turbulence, i.e. a direct perturbation of the ionization structure, which cause coherent scatter on HF, VHF and UHF and is used to study the E- and F-region irregularities. At mesospheric altitudes neutral air turbulence causes an indirect perturbation of the ionization (mesosphere and D-region irregularities), which in turn results in coherent scatter. This is used with the mesosphere-stratosphere-troposphere radars, operating in the VHF and HF [11].

Coherent scatter radars, ambiguously also called coherent radars, is used for radars observing backscatter from ionospheric irregularities, which are aligned with Earth's magnetic field and for studies of the corresponding plasma instabilities.

Incoherent scatter radars, detecting backscatter from in the ionospheric plasma, are the most powerful tools for studying the full profile of many ionospheric parameters, such as electron density, electron temperature, ion temperature and plasma velocity. Also incoherent scatter is basically coherent, since it results from the radar wave number component of the spatial spectrum of ion-acoustic waves existent in the ionospheric plasma.

Observation principles

There are three basic methods used by coherent scatter radars to observe the ionosphere: Doppler beam swinging, spaced antenna drift and interferometer technique.

The spaced antenna method, where the changing diffraction pattern on the ground caused by backscattering from aloft is measured, is applied to deduce the horizontal velocity, shape and coherence of the scattering layers by analyzing the cross correlation or cross spectra analysis of signals received at spaced antennas.

The interferometer method is a natural extension of the spaced antenna method. It utilizes the fact that the modern radar systems are phase-coherent and the amplitude and phase are measured. Phase information at separated antennas allows the determination of the angle of arrival. It yields, with better accuracy, similar parameters as the diffraction pattern method and the Doppler beam swinging method. Interferometry in the frequency domain is often used to overcome limitations in using very short pulses to detect thin layering. The exceptions are the incoherent scatter radars where the scattering process itself prevents the required coherency of the diffraction pattern at the receiving site. Here the Doppler method with different antenna beam pointing angles is used.

3.1.3 Sounding Rockets

Sounding rockets are used to carry scientific payloads, mostly for measuring the Earth's atmosphere, ionosphere and aurora, to sub-orbital altitudes. The history of sounding rockets development can be found in [12]. Here we are going to deal with some main features.

While balloons cannot float above approximately 50 km, many satellites can fly over 250 km in altitude. Thus, only sounding rockets are capable of directly observing space between these two altitudes. They have been best-suited for in-situ studies at altitudes between 40 and 200 km of such ionosphere features as electric currents, electron and ion densities, propagation of radio waves, magnetic-field disturbances [12]

Sounding rockets are an excellent means of taking measurements at very short notice of transient phenomena such as aurora, radiation and magnetic field properties in low Earth orbit shortly after solar eruptions.

Rockets perform an observation mission during their flight in space before impact. When the experiment is over, the rocket dives into the sea along with its observation instruments, which are usually fixed to the rocket's nose fairing and covered by a nosecone like a pointed hat for protection from aerodynamic heating. When reaches a given altitude, timer-fixed functions start to open the nosecone, extend antennas, sometimes release test samples for observation. The observation continues till the rocket reaches its maximum altitude and ends before it splashes down in the sea.

A sounding rocket comprises two main sections: solid-fueled rocket motor(s) and payload. The specific make-up of a sounding rocket payload will depend on the mission.

3.2 Passive Ionospheric Measurements

Ionospheric measurements are also performed recording the rapid fluctuating characteristic of a radio signal passing through ionosphere. Such techniques can be described like passive.

Riometric measurements

The riometer receive radio energy from several natural astronomical sources (the Sun, Jupiter, the center of the Milky Way, and other lesser sources). It is able to receive energy from much of the sky , as typically antenna of riometer has rather broad coverage. In response to the received radio energy a voltage is produced. Then, using a calibration curve it is related to the noise power, expressed in degrees Kelvin or watts per hertz.

Variations in output can be caused by:

1) variations in radio emission by the sources;
2) absorption of the radio wave energy by the ionosphere;
3) movement of artificial radio sources across the sky (airplanes, satellites);
4) variable energy from man-made radio sources on earth.

What we are interested in, of course is the second one: absorption of the radio wave energy by the ionosphere. All other causes of output are just complications we must deal with [13].

GPS ionospheric measurements

Global Positioning System is a location system based on a constellation of about 24 satellites orbiting the earth. It was first developed as application for military locating purposes. Meanwhile now GPS is being used not only for non-military mapping but scientific investigations as well.

GPS receivers, used for navigation are mostly single-frequency. A position fix obtained by use of such receivers contains some errors due to several sources (Table

3.1).

Table 3.1 Positioning error contributions

Effect	Error
Ionospheric effects	± 5 meter
Shifts in the satellite orbits	± 2.5 meter
Clock errors of the satellites' clocks	± 2 meter
Multipath effect	± 1 meter
Tropospheric effects	± 0.5 meter
Calculation and rounding errors	± 1 meter

Over the last several years GPS observations are used to derive information about ionosphere variations according to its effect. The data we get varies from the difference between the two-frequency measurements to the Total Electron Content (TEC) along the signal path between the GPS satellite and the ground-based GPS receiver.

The dual frequency GPS receivers can be also used to monitor ionospheric scintillations, which are the rapid fluctuations of the phase and intensity of a radio signal that has passed through the Earth's ionosphere [13].

More detail about Global Navigation System and different TEC measurements in the chapter 4.

4 Total Electron Content calculations with use of Global Navigation Satellite System

4.1 Global Navigation Satellite System

Global Navigation Satellite System (GNSS) are satellite navigation systems providing geo-spatial analysis: determination of location parameters, which include geographical coordinates and altitude, and trajectory parameters such as speed and direction.

The GNSS consist of three main satellite technologies: GPS, Glonass and Galileo. Each of them consists mainly of three segments: space segment, control segment and user segment. These segments are almost similar in the three satellite technologies.

Global Positioning System

The United States Department of Defense has developed the GPS, which is an all-weather, space based navigation system to meet the needs of the USA military forces and accurately determine their position, velocity, and time in a common reference system, anywhere on or near the Earth on a continuous basis [14].

GPS provides particularly coded satellite signals that can be processed in a GPS receiver, allowing the receiver to estimate position, velocity and time[15].

There are four GPS satellite signals that are used to compute positions in three dimensions and the time offset in the receiver clock. GPS comprises three main components (Figure 4.1):

1) Space segment: The Space Segment of the system consists of the GPS satellites, space vehicles send radio signals from space;

2) Control segment: The Control Segment consists of a system of tracking

stations located around the world. The Master Control facility is located at Schreiber Air Force Base in the State of Colorado, USA;

3) User segment: The GPS User Segment consists of the GPS receivers and the user community. GPS receivers convert space vehicle signals into position and velocity.

The satellites are dispersed in six orbital planes on almost circular orbits with an altitude of about 20,200 km above the surface of the Earth, inclined by 55 degree with respect to the equator and with orbital periods of approximately 11 hours 58 minutes (half a sidereal day).

The generated signals on board the satellites are based from generation of a fundamental frequency equals 10.23 [15]. The signal is controlled by atomic clock and has stability in the range of 10^{-13} over one day. Two carrier signals in the L-band, denoted L1 and L2, are generated by integer multiplications of fundamental

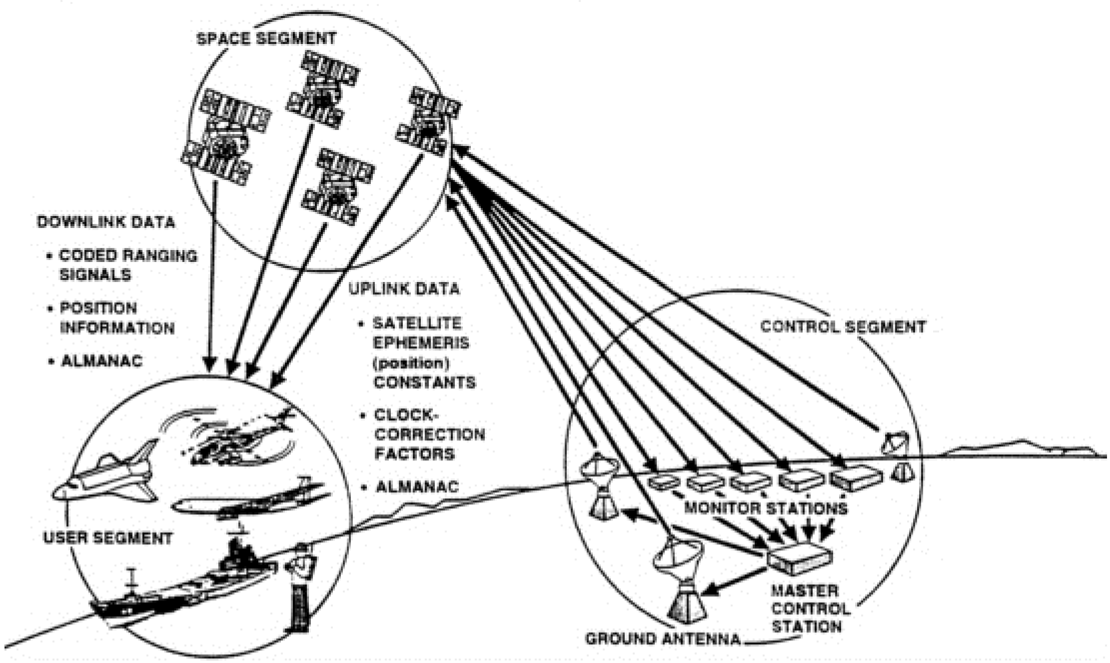


Figure 4.1 - GPS segments

frequency. The carriers L1 and L2 are biphasic modulated by codes to provide satellite clock readings to the receiver and transmit information such as the orbital parameters. The codes consist of a sequence with the states plus or minus one, corresponding to the binary values 0 or 1. The biphasic modulation is performed by a 180° shift in the carrier phase whenever a change in the code state occurs. The navigation message is modulated using the two carriers (L1 and L2) at a chipping rate of 50 bps. It contains information on the satellite orbits, orbit perturbations, GPS time, satellite clock, ionospheric parameters and system status messages [16].

Glonass system

The GLONASS (GLObal NAvigation Satellite System) is nearly identical to GPS. Glonass satellite-based radio-navigation system provides the positioning and timing information to users. It is operated by the Ministry of Defense of the Russian Federation.

Glonass space segment consists of 24 satellites, equally distributed in 3 orbit separated by 120 ° in the equatorial plane. Satellite orbital altitude is about 19,130 km above the ground surface. This results in an orbital period of 11:15:44 corresponding to 8/17 of a sidereal day [17].

As of May 27 2010, a total of 21 GLONASS satellites are operational, with 2 spares [18].

Glonass observables (code and phase) are similar to GPS. The main difference between GPS and GLONASS is that GLONASS uses Frequency Division Multiple Access (FDMA) technology to discriminate the signals of different satellites, but GPS and Galileo use Code Division Multiple Access (CDMA) to distinguish between the satellites. Each satellite has slightly different carrier frequencies.

The nominal carrier frequencies for the L1and L2 signals may be written as shown below [16]:

$$f_1^n = 1602 + 0.625n\ MHz, \tag{4.1}$$

$$f_2^n = 1246 + 0.4375n \ MHz, \quad (4.2)$$

$$\frac{f_1^n}{f_2^n} = \frac{9}{7} \ , \quad (4.3)$$

where f_1^n - nominal carrier frequency for L1signal,

f_2^n - nominal carrier frequency for L2 signal,

n - the frequency channel number $24 \leq n \leq 1$.

The navigation message is contained in so-called sub frames, which have duration of 2.5 minutes. Each sub frame consists of five frames with a duration of 30 seconds. The navigation message contains information, similar to GPS navigation message, about the satellite orbits, their clocks, among others. On the contrary to GPS, where the broadcast ephemerides are defined by modified Keplerian elements, the broadcast ephemerides of GLONASS satellites are defined by positions and velocities referred to an Earth-centered and Earth-fixed systems. The broadcast ephemerides of the Glonass satellites are updated every 30 minutes. [17]

GALILEO

The Galileo system, sponsored by the European Union and managed by the European Space Agency (ESA), launched the GIOVE-A test satellite on December 28, 2005. Full operational deployment of the constellation is expected by 2012. 30 satellites will be organized into three orbital planes consisting of 9 satellites and one spare with an inclination of 56 degrees, making a complete orbit in approximately 14 hours, 21 minutes [19].

Galileo segments are almost similar to GPS, but with some modification. The main extension of Galileo compared to GPS is the implementation of a global/ regional segment for integrity monitoring. The objective is to assist the safety critical aircraft navigation and locate and guide railway trains.

The space segment or the constellation features consists of 30 Medium Earth Orbiting (MEO) satellites (27 and 3 active spare satellite), distributed evenly and regularly over three orbit planes. The projected altitude is slightly larger than for GPS 23,616 km and the inclination is 56°.

The Galileo ground segment is responsible for managing the constellation of navigation satellites, controlling core functions of the navigation mission such as orbit determination of satellites, and clock synchronization, and determining and disseminating (via the MEO satellites) the integrity information, such as the warning alerts within time-to-alarm requirements, at global level. The Global ground segment will also provide interfaces with service centers. The Ground Control Segment will consist of about 12-15 reference stations, 5 up-link stations and two control centers. The ground segment also will include 16-20 monitor stations, three up-link stations for integrity data and two central stations for integrity computations.

The user segment consists of different types of user receivers, with different capabilities related to the different GALILEO signals in order to fulfill the various GALILEO.

Galileo will provide several navigation signals in right-hand circular polarization (RHCP) in the frequency ranges of 1164–1215 MHz (E5a and E5b), 1260–1300 MHz (E6) and 1559–1592 MHz (E2-L1-E1) that are part of the Radio Navigation Satellite Service (RNSS) allocation.

4.2 Ionospheric delay

Free electrons are the reason ionosphere impacts the radio wave propagation, primarily affecting the measured range.

The refractive index of microwaves is a function of frequency and the density of free electrons, and may be expressed by [15]:

$$n = 1 \pm \frac{A * N_e}{f^2}, \tag{4.4}$$

where A - a constant,

N_e - the total electron density (el/m^3),

f - the frequency.

The sign will depend on whether the range (+) or the phase (–) refractive index is required. The propagation speed is related to the refractive index according to Equation 4.5.

$$v = \frac{c}{n}, \qquad (4.5)$$

where v - the propagation speed,

c - the speed of electromagnetic radiation in a vacuum,

n - the refractive index.

Equations 4.4 and 4.5 shows that the speed of the carrier wave (the "phase velocity") is actually increased; hence the phase refractive index is less than unity. However, the speed of the ranging codes is decreased (the "group velocity") and therefore the pseudo-range is considered "delayed", and hence the range (or group) refractive index is greater than unity.

It can be concluded that the distance as implied by the integrated carrier phase is too short, but the pseudo-range is too long. The correction terms are, of course, quantities with a reversed sign, that is, the carrier phase correction is positive, while the pseudo-range correction is negative [20].

An expression for the ionospheric group delay and the ionospheric phase delay for a microwave propagating from a satellite to the ground is [20]:

$$d_{ion} = -\phi_{ion} * \frac{c}{f} \approx 40.28 * \frac{STEC}{f^2} \approx \frac{40.28}{cosec\xi} * \frac{VTEC}{f^2}, \qquad (4.6)$$

where d_{ion} - the ionospheric group delay in units,

ϕ_{ion} - the ionospheric phase delay,

f - is the signal frequency,

STEC - the Slant Total Electron Content,

$cosec\xi$ - the cosecant of the zenith angle of the line-of-sight to the satellite,

VTEC - the Vertical Total Electron Content.

The higher the frequency, the smaller is the ionospheric delay effect.

4.3 Total Electron Content

The ionosphere causes GNSS signal delays due to the TEC along the path from the satellite to receiver. Under normal solar activity conditions, the influence on signal by TEC are usually in the range from a few to tens meters.

The Total Electron Content is the amount of free electrons along the path of the electromagnetic wave between each satellite and the receiver, given by [21].

$$TEC = \int_S^R N * dl, \tag{4.7}$$

where R - receiver,

S - satellite,

N - local electron density.

Integration is along the signal path from the satellite to receiver.

There are a number of factors which influence the magnitude of the TEC which include: the latitude of the receiver, the season, the time of day the signal observation is being made and the level of solar activity at the time of observation.

TEC is a maximum at low latitudes (the tropical zone) and at the poles (the auroral zone), and is a minimum at mid-latitudes. At night the ionospheric delay is approximately five to ten times less than for day time observations. The diurnal cycle for TEC is such that the maximum occurs two hours after solar noon, and is a minimum before dawn.

5 Results and analysis of numerical and real experiments for total electron content distribution

According to our goal, we use GNSS data received from JPL. In the network of 2009, according to different solar activity we took 3 months with the most significant values. That is May for middle activity, August for low and December for high activity (sunspot activity for 2009 is represented on figure 5.1) and plot spatial distribution of Total Electron Content. Results are represented on Figurers 5.2 – 5.4.

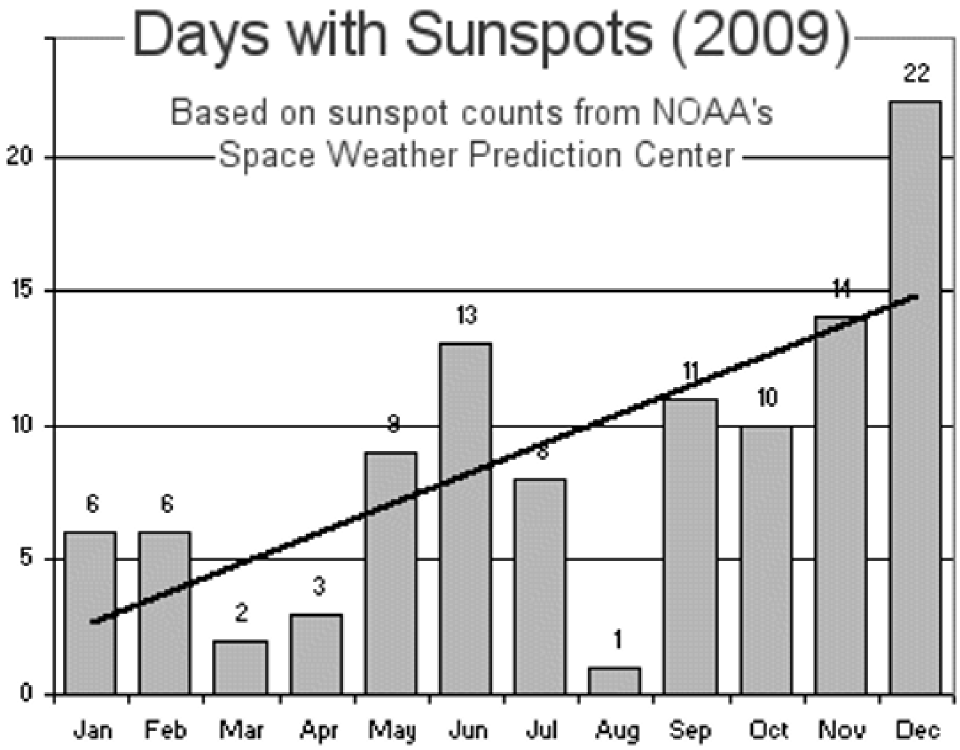


Figure 5.1 – Sunspot activity

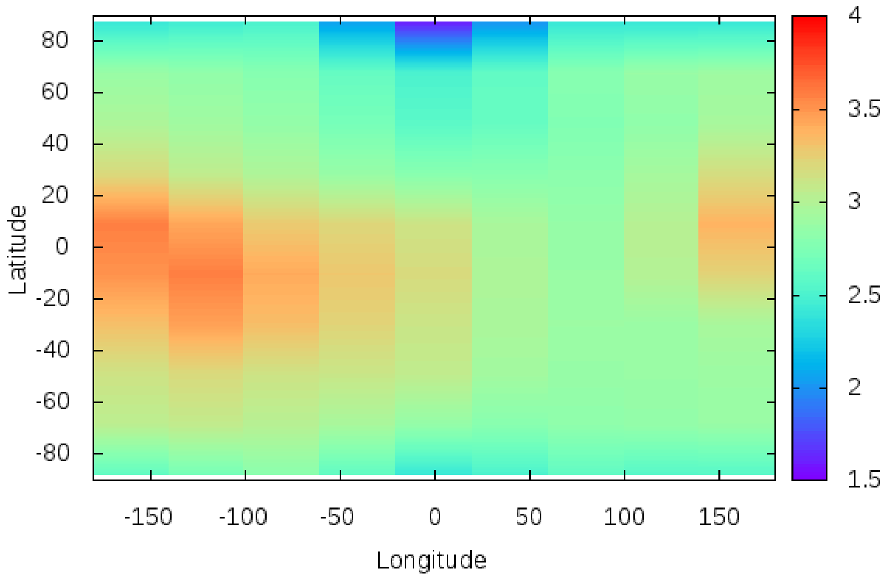


Figure 5.2 - 15.05.2009 00:00:00

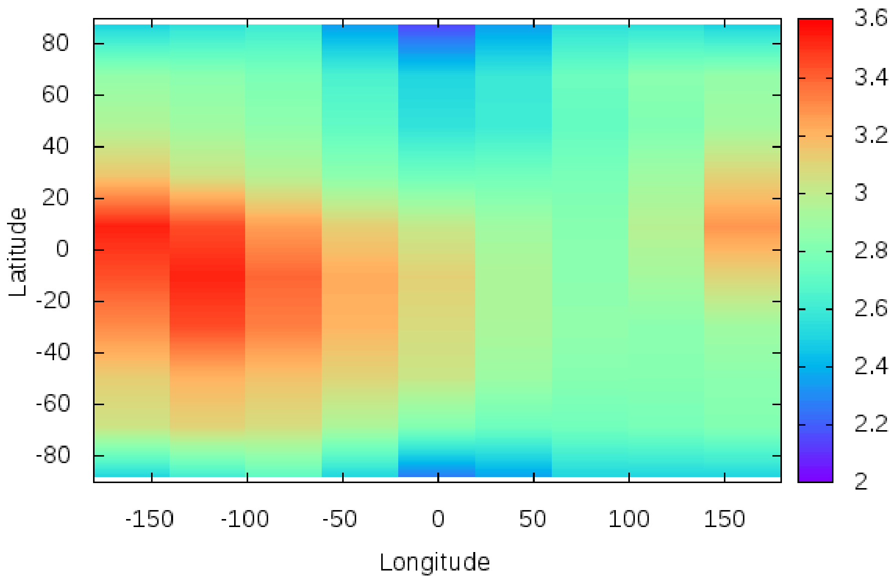


Figure 5.3 - 15.08.2009 00:00:00

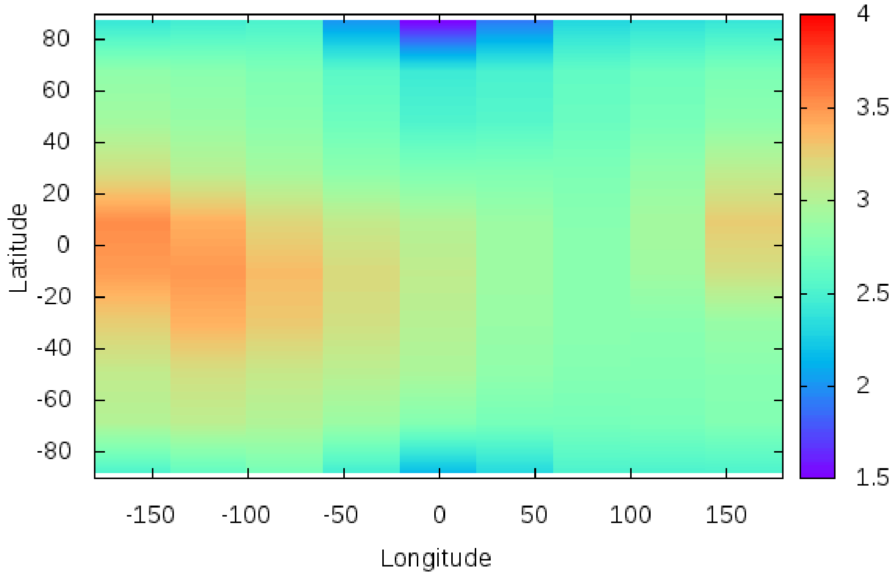


Figure 5.4 - 15.12.2009 00:00:00

In order to compare received values we realize modeling on the basis of IRI model for the same dates and moments of time (Figure 5.5 – 5.7)

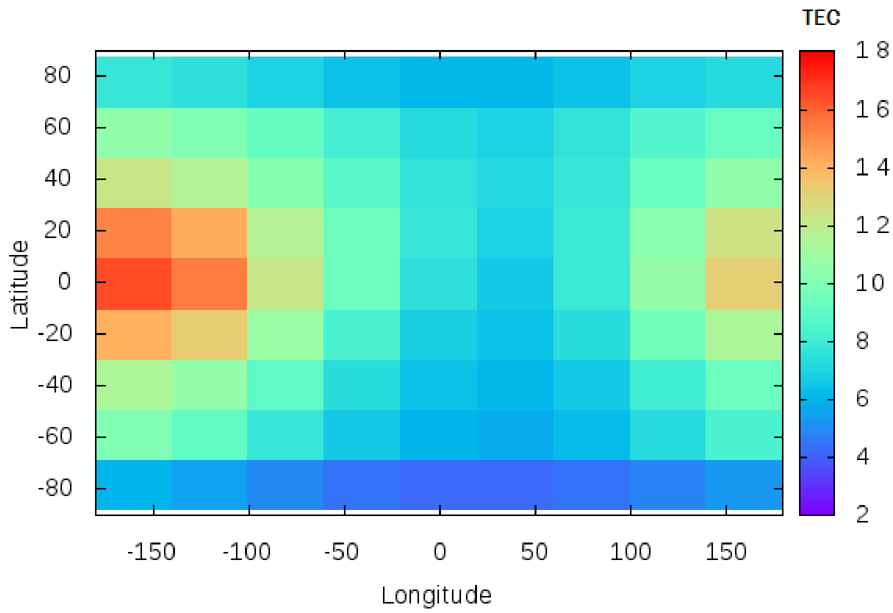


Figure 5.5-15.05.2009 00:00:00

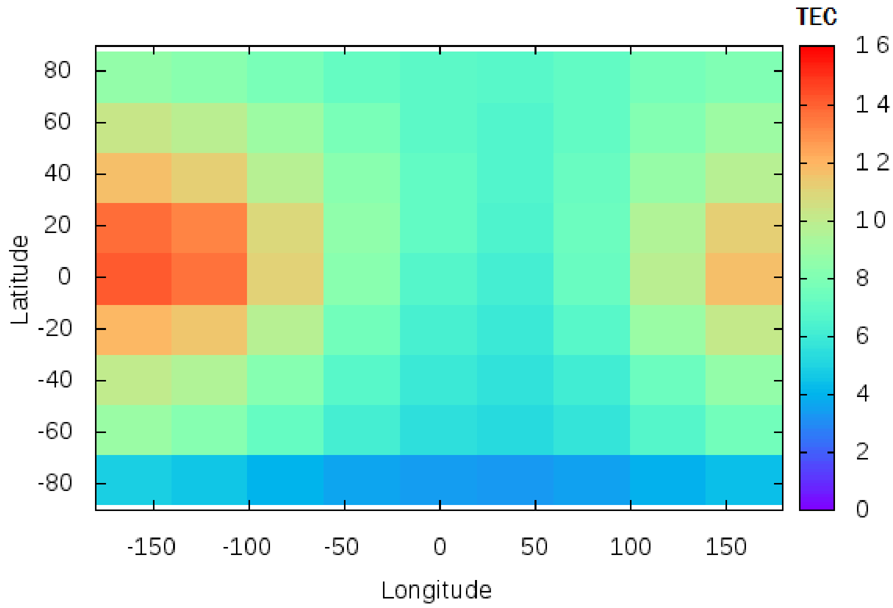


Figure 5.6 – 15.08.2009 00:00:00

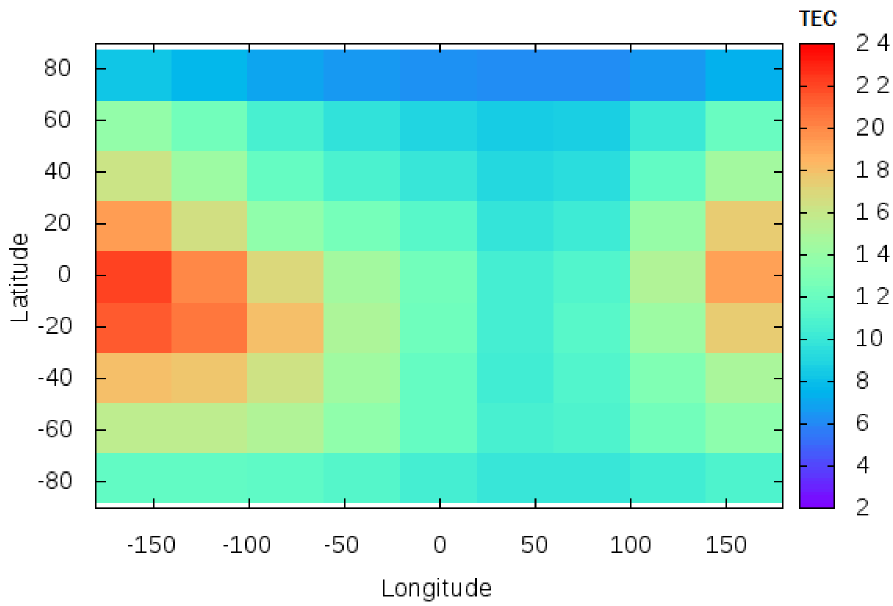


Figure 5.7 – 15.12.2009 00:00:00

As we can see results are quite similar to each other, while IRI model shows higher values of TEC. Analyses of global distribution shows the same maximums and minimums. However, it is not as it should be. For IRI model it can be easily explained by the fact that this model was developed for mid latitudes and do not have enough data for Polar Regions. Absence of receivers in this region is the answer the GNSS data.

To compare GNSS values with real date we used one received from ionosonde DPS-4, located in Tomsk and plot graphs for the same months, but for more dates. Our choice is again explained by solar activity. Results of comparison between real, numerical and GNSS data are represented on Figures 5.8 – 5.18. On the graphs below we can see that GNSS data shows much better quantitative results in comparison to IRI model. However the last one is better to diurnal variation. Red line always show clear maximum in day time and minimum in the night. As in the case of global distribution values are higher. Blue line seems to be average within green real data with one minimum afternoon.

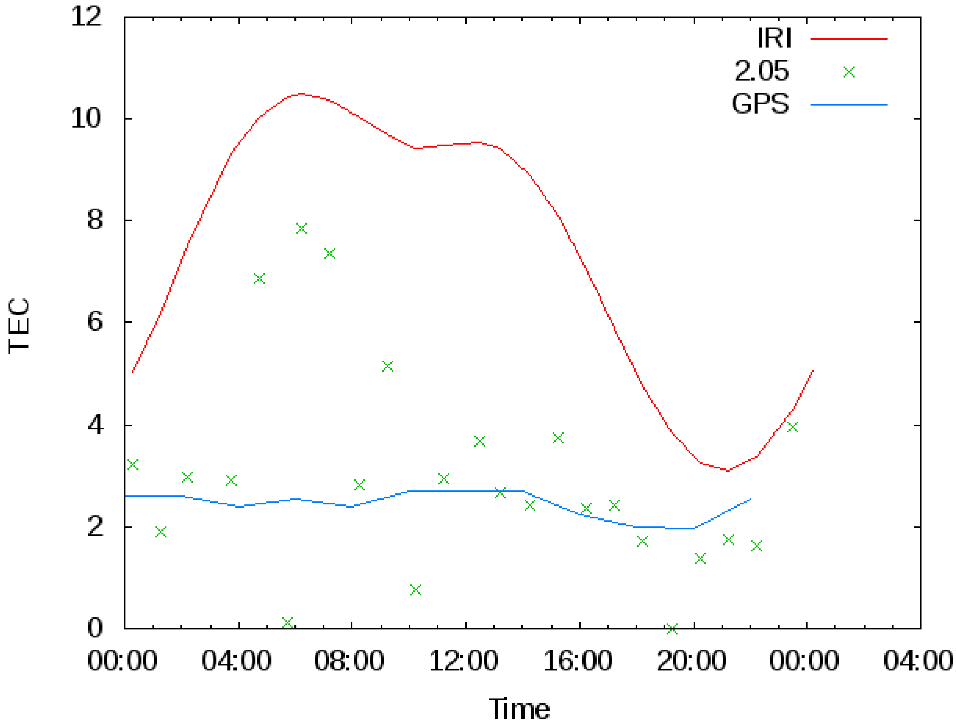


Figure 5.8 – 2.05.2009

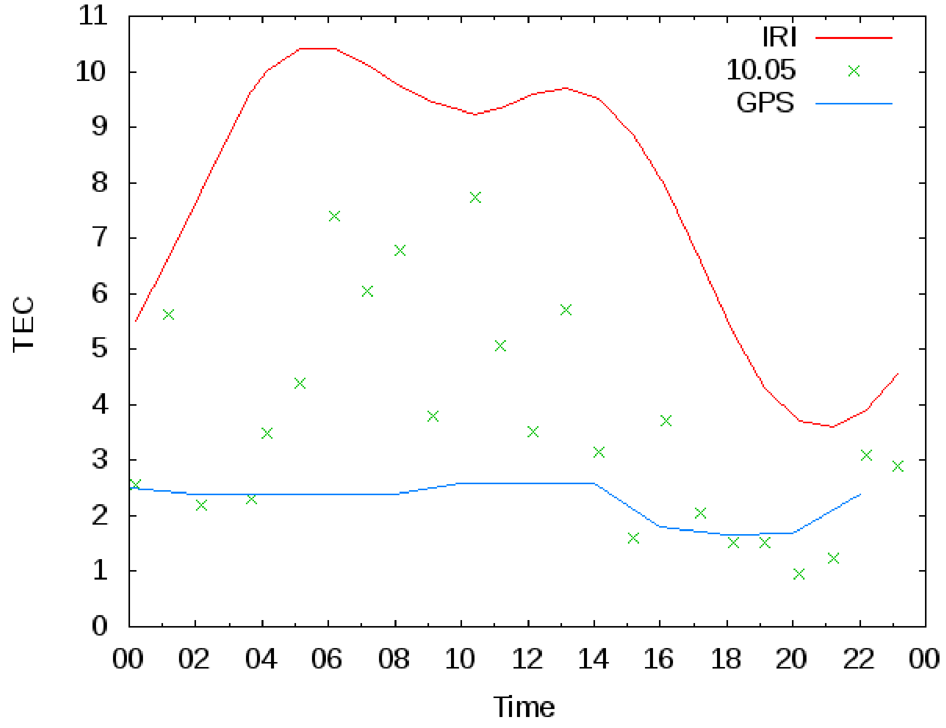


Figure 5.9 – 10.05.2009

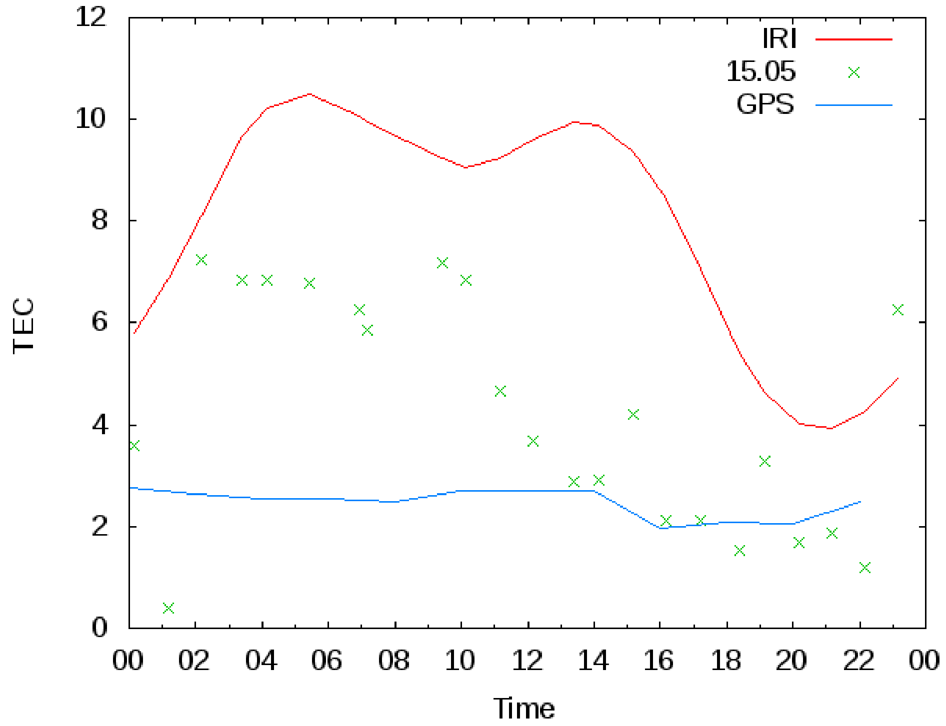


Figure 5.10 – 15.05.2009

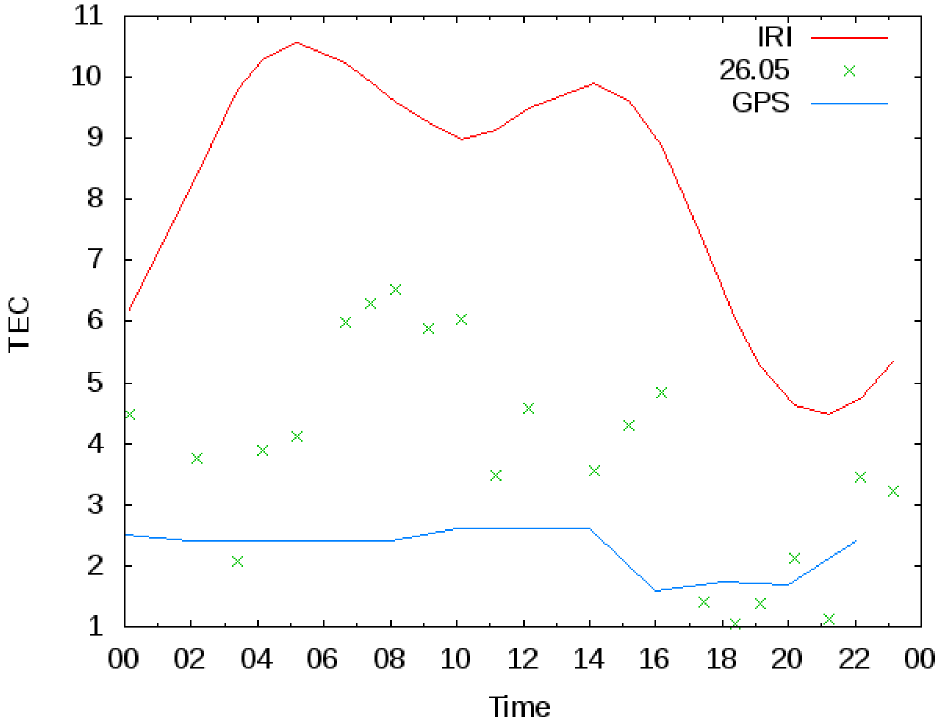


Figure 5.11 – 26.05.2009

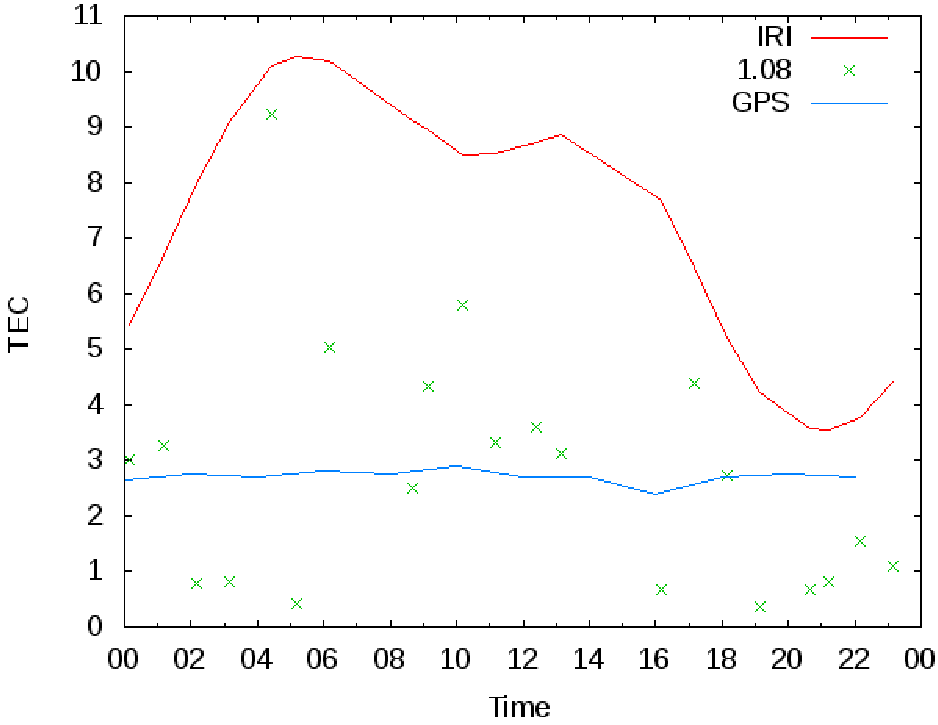


Figure 5.12 – 1.08.2009

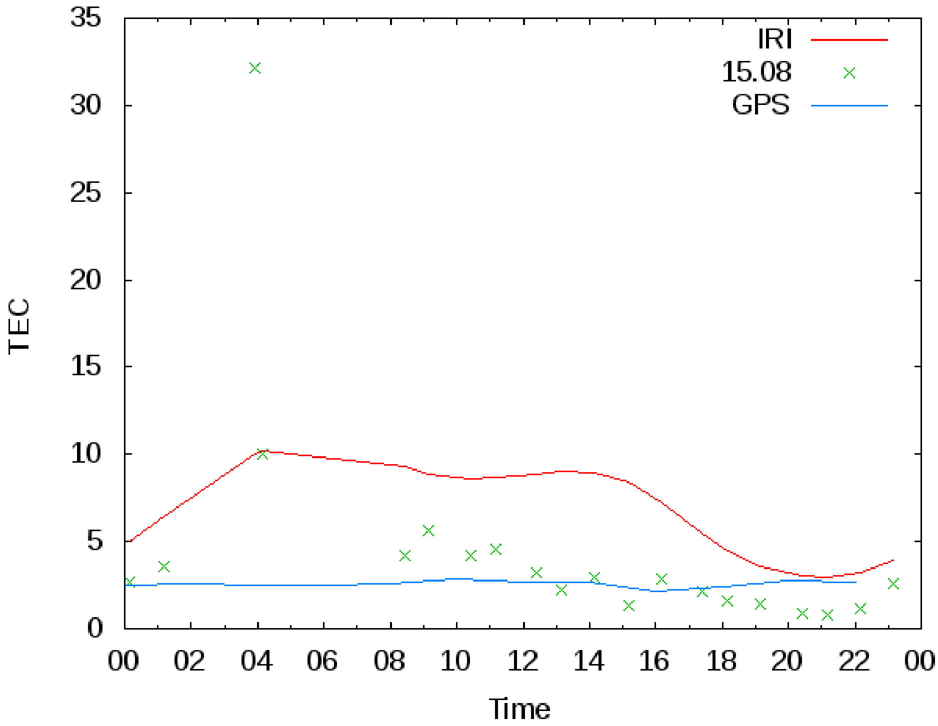


Figure 5.13 – 15.08.2009

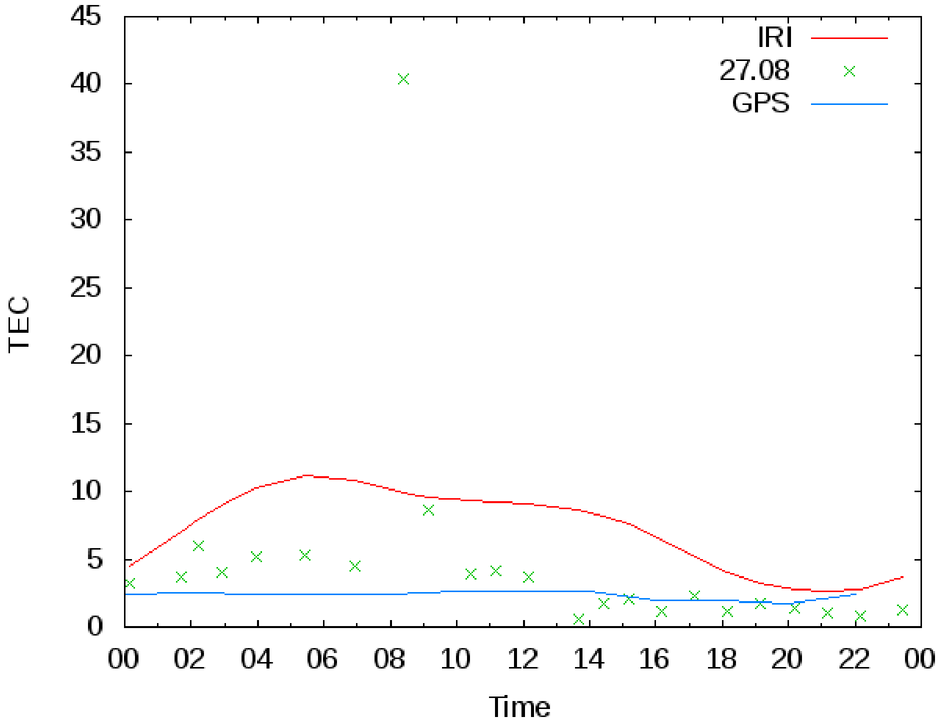


Figure 5.14 – 27.08.2009

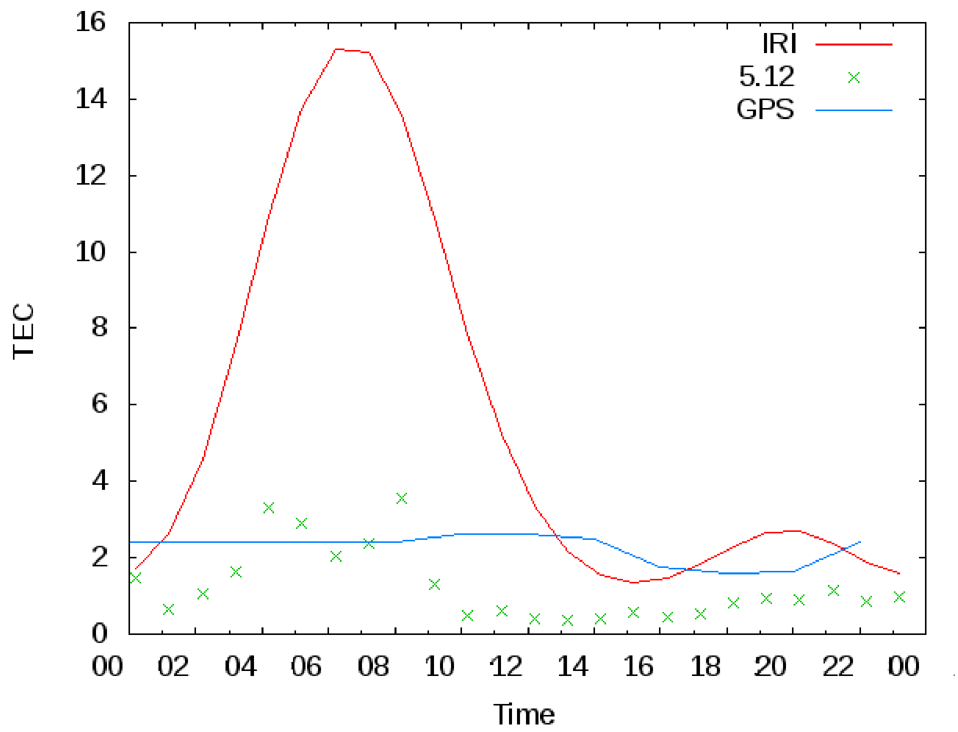


Figure 5.15 – 5.12.2009

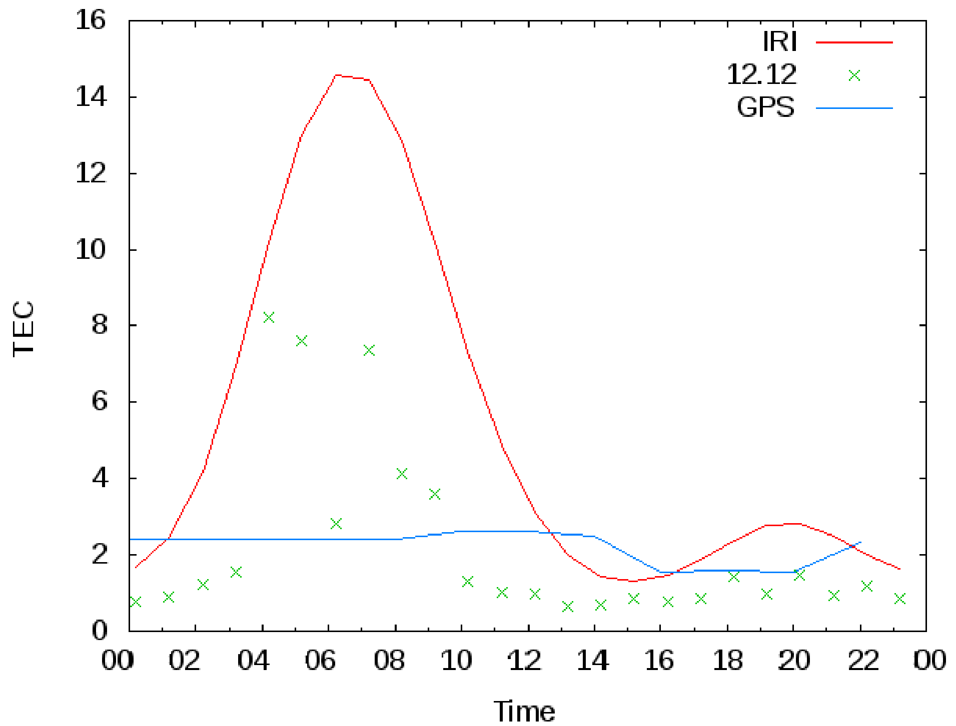


Figure 5.16 – 12.12.2009

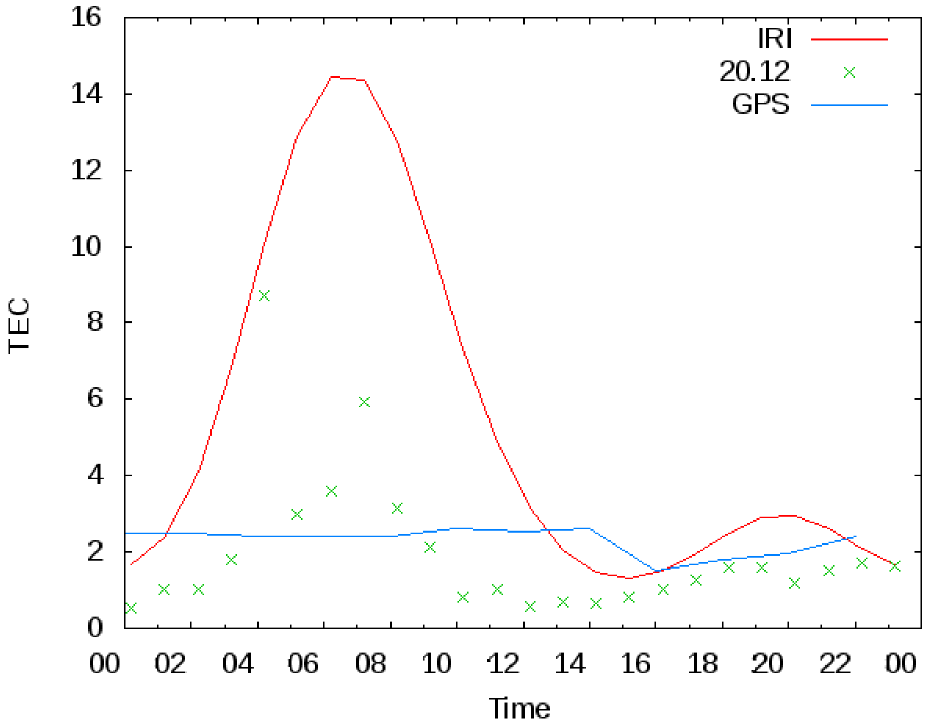


Figure 5.17 - 20.12.2009

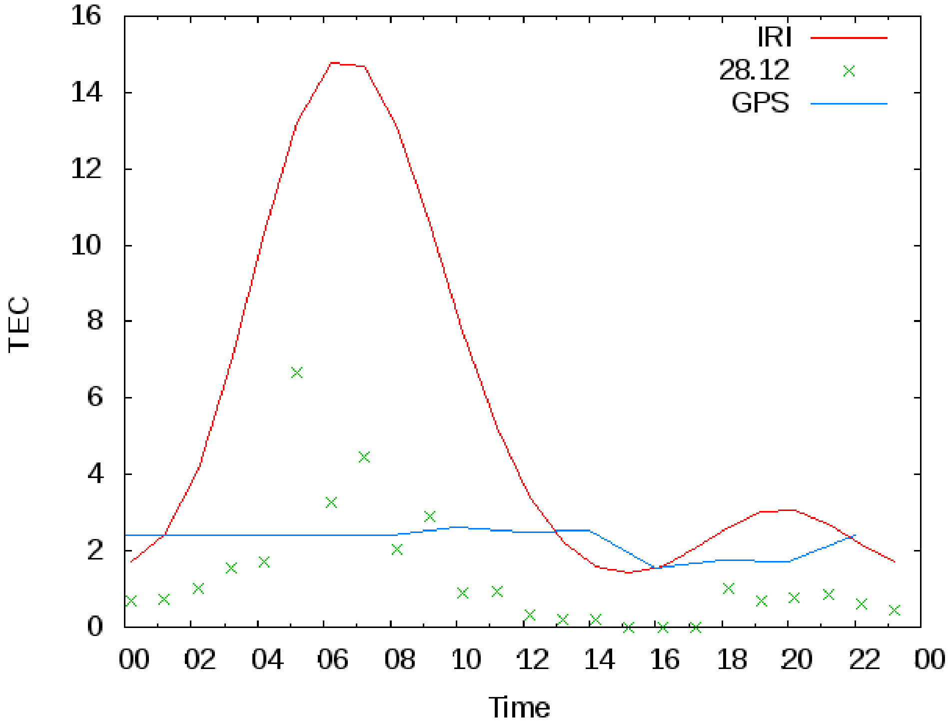


Figure 5.18 – 28.12.2009

Conclusion

Based on the obtained results following conclusions can be drawn:

1) Global Navigation Satellite System plays an important role in monitoring of ionosphere;

2) Use of GNSS network allows to calculate global TEC distribution with high accuracy and operability;

3) Received information about TEC can be widely used for navigation, radio communication and geophysics. Concerning the last one it is known that some of ionospheric disturbances can be caused not only by solar activity, but the seismic one. So, being up to this information prediction of earthquakes is possible.

Methods for TEC calculation are developing as far. There are different techniques with the use of dual frequency receivers. Some of them are used for local purposes, another work with global distribution.

But as we understand importance of ionospheric investigation, new goals and objectives can be obtained. Speaking about this work estimation of methods for GNSS errors correction is required; thereupon a larger data set must be used.

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