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Hardware-software complex for monitoring and research of the artificial and nature ionosphere disturbance

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Abstract

The possibilities of global navigation systems GPS and GLONASS for monitoring of the Earth's ionosphere in real time are presented. The diagram of data measurement and interpretation, as well as the algorithm of parametric identification of inverse radio sounding of the ionosphere used in a 'hardware-software complex' are demonstrated. It is shown that continuous observations of navigating satellite systems Glonass and GPS allow receiving values in time variations, both in maximum height of an ionosphere and high-altitude structure of electronic concentration of an ionosphere simultaneously on several azimuthal directions in real time. It is important for detecting the perturbations caused by seismic effects. An overall review of the complex and the results of its work are reviewed.

Key Words: Earthquake; Ionosphere; Precursor; Monitoring; Navigation Systems

1. Introduction

Studying the state of the ionosphere is important for understanding the physics of the processes occurring in it, and for solving a variety of radio physical problems associated with the propagation of radio waves through it. Analysis of these processes requires continuous observations of the ionosphere on a large enough territory. Such observations can be conducted using the data of the satellite navigation systems which allow monitoring of the ionosphere in real time. It is especially important at detecting the ionospheric precursors of the earthquakes as the process of the earthquake preparation takes, as a rule, a significant period of time and consequently requires carrying out long observations above the possible earthquake focus.

Difficulties in the identification of the ionospheric perturbations caused by seismic effects on the background of existential variability of the ionosphere, especially during electromagnetic perturbances, are main object of criticism in the use of the ionosphere as a foreshock detector. Variations of the electronic density of the ionosphere interpreted as ionospheric precursors of strong earthquakes have the same order of size and sometimes even a smaller one on amplitude than the variations connected with the ionosphere fluctuations. However, intensive studies during the last several years have shown that the seismic phenomena are unique among other reasons of the variability of the ionosphere.

The applicability of these systems for solving the tasks of remote sensing is due not only to their high performance, but also to the fact, that radio signals accumulate all the information about the environment during the propagation in time and space. The presence of such information in the characteristics of the signal gives opportunities for eventual restoration of radio physical parameters of the propagation medium.

It is necessary to stress, that the account of all parameters of an ionospheric precursor allows marking it out against the background of the ionospheric variations caused by other effects. This favourably distinguishes it from the plasma and electromagnetic variations of a different kind suggested as precursors, because they can be observed under the impact of other factors, too. The obtained results state, that ionospheric foreshocks are real existing phenomena [Oraevsky et al., 1994; Oraevsky et al., 1995, Ruzhin and Depueva 1996;Liu et al., 2000; Bondur and Smirnov, 2005; Bondur and Smirnov 2006; Devi et al., 2010] and the developed techniques of their detection offer an opportunity to use them in the warning systems and the short-term forecast of catastrophic earthquakes.

Destruction processes in the environment are known to appear at the preparatory stage of earthquake in the vicinity of its seismic focus. They are accompanied by the apparition of new commonly linked mechanisms of electromagnetic and mechanical fields' generation in the destruction zones. These factors cause perturbations in conductivity, porosity, chemical state of the environment surrounding a seismic center. Such perturbations in the stability of the underlying crust 5-6 days prior to the onset of an event with magnitude more than 5 , will affect the behavior of the ionospheric layer F2. Its direct influence should manifest in the behavior of critical frequency of layer F2 (foF2) , in the range of frequencies from 5 MHz up to 15 MHz .

Today, a 'hardware and software complex ' of passive sounding in the space environment based on the use of signals from navigation satellite systems , has been created. In such a complex, the continuous monitoring technology has been used. It is designed for the reconstruction of the spatiotemporal structure of the ionosphere and solving operational control tasks and full height distribution of the electron concentration of the ionosphere by radio translucence method on the track “satellite - the Earth” using radio navigation satellite system GPS/GLONASS in real time [Smirnov, 2007].

2. Hardware-software complex

The ionosphere monitoring is currently implemented usually with the help of ground stations of vertical sounding of the ionosphere. Modern Vertical Sounding stations of the Ionosphere (VSSI) are sufficiently sophisticated radio systems and allow determining the altitude profile of the ionosphere electron concentration with high accuracy. However VSSI have several drawbacks: significant mass-dimensional characteristics (due to the presence in the composition VSSI of bulky antenna feeder and masts), high energy consumption (due to the necessity of zenith radiation probing signals of sufficient capacity) and the relatively high cost (including the high cost of operating expenses). In addition, most applications do not require monitoring of all characteristics of the ionosphere; they are limited to the determination and control of the main ionosphere parameters: the critical frequency and the height of the ionosphere layer F2, as well as total electron content (TEC) of the ionosphere.

A promising approach to ionosphere monitoring consists in the definition of the electron density profile in the altitude range of 100-1000 km, the parameters of the ionosphere layer F2 and TEC after processing of the received radio signals of global navigation satellite systems GLONASS and GPS. This approach is implemented in the proposed small-sized products HSC-MI (hardware-software complex of monitoring ionosphere) and it provides certain real-time distribution of the electron density at altitudes 100-1000 km along the trajectory of subionospheric points, the parameters of the ionosphere layer F2 and TEC in the passive (without emitting radio signals) mode in different azimuthal directions [Smirnov and Tynyankin, 2011].

The structure of this product is shown in Figure 1; its functionalities are presented in earlier reports [Smirnov and Smirnova, 2010; Smirnov and Tynyankin, 2011]. It contains of two parts: an antenna unit and an analog-to-digital module complex consisting of analog and digital parts of signals receiver. The output of the antenna unit is connected to the input module by a coaxial cable. The length of the antenna cable does not exceed 50 m. The receiver is connected to the computer by means of a combined USB/

COM cable. Provided the electricity is available, this complex can be located anywhere.

The main element of the hardware and software complex is a software module, based on the radio translucence method of the Earth's ionosphere on the track "ground station- navigation satellite". Its practical realization is based on the use of the measurements of the radio signals parameters from one receiver observations, an effective area of which covers more than 1000 km in radius [Smirnov, 2007; Andrianov and Smirnov, 1993].

Figure 1. Hardware-software complex of monitoring ionosphere: 1 - navigation receiver, 2 –antenna, 3 - computer, 4 - power adapter, 5 - antenna cable, 6 - interface cable.

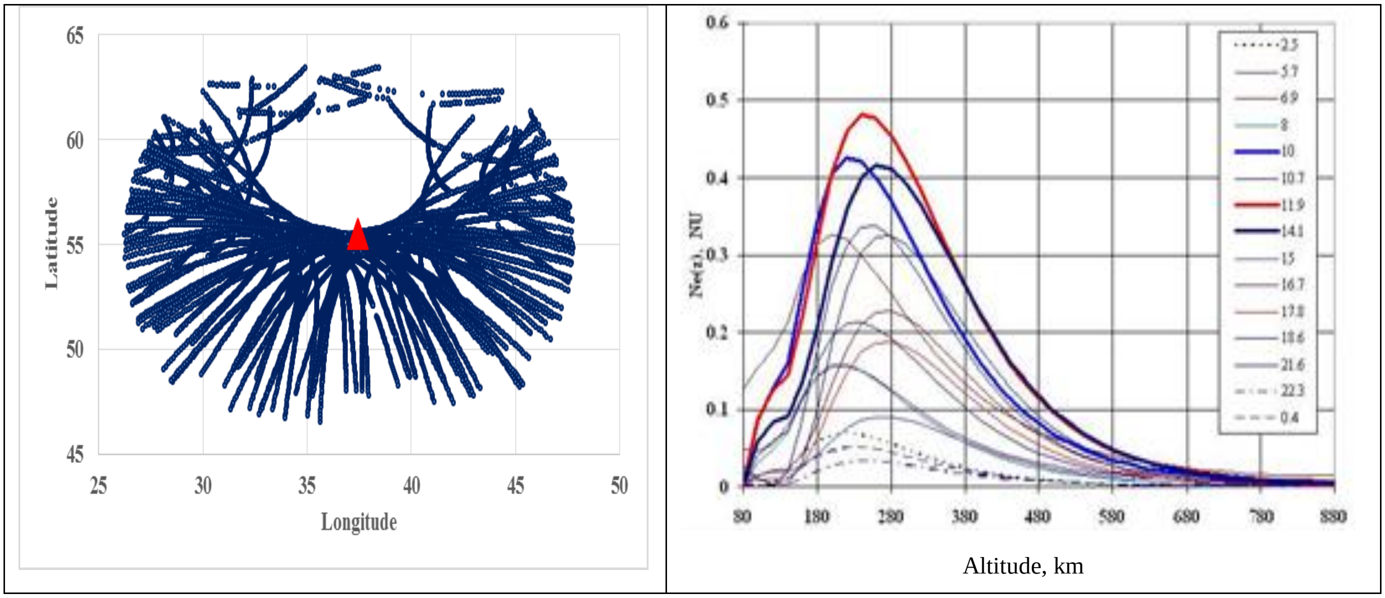
Obtained in the assumption of local spherically stratified medium , the integral equation relates the difference in pseudorange $\Delta R(f_1, f_2) = R_I(f_1) - R_I(f_2) + \delta,$ measured by radio translucence method, with altitude distribution function of electron concentration *N(z)* as follows [Smirnov, 2001]:

$$\int_{z_1}^{z_2} N(z) \frac{(a+z)dz}{[(a+z)^2 - a^2 \sin^2 \vartheta]^{1/2}} = 2{,}475 \cdot 10^{-8} \frac{f_1^2}{k} \left[\Delta R(f_{1,} f_2) - \delta\right],$$

where z_1 and z_2 - the estimated lower and upper bounds of the ionosphere, respectively, ϑ - the zenith angle of observation with satellite measurement point, z- the current height of the Earth's surface, f_1 - the signal frequency in Hz.

Expression on the left is the total electron density of the ionosphere along the propagation path of the navigation signal. Thus the difference of the pseudoranges measured at two frequencies is effectively equivalent to the total electron concentration of the ionosphere. In addition, the equation of radio translucence is an integral equation of the 1st kind of Fredholm type. Its solution for the unknown function *N(z)* is reduced to solving ill-posed problems [Andrianov and Smirnov, 1993; Smirnov, 2001; Tikhonov et.al ., 1987].

By determining the electron density of the ionosphere over a specific territory it is possible to detect the presence of potential specific features in its distribution. During the day, with one receiver we can get more than 100 trajectories of subionospheric points, each of them contains an average of about 20,000 measurements at 1 s steps. This allows us to get more than 20,000 vertical profiles of electron concentration, examples of which are shown in Figure 2.



a) b)

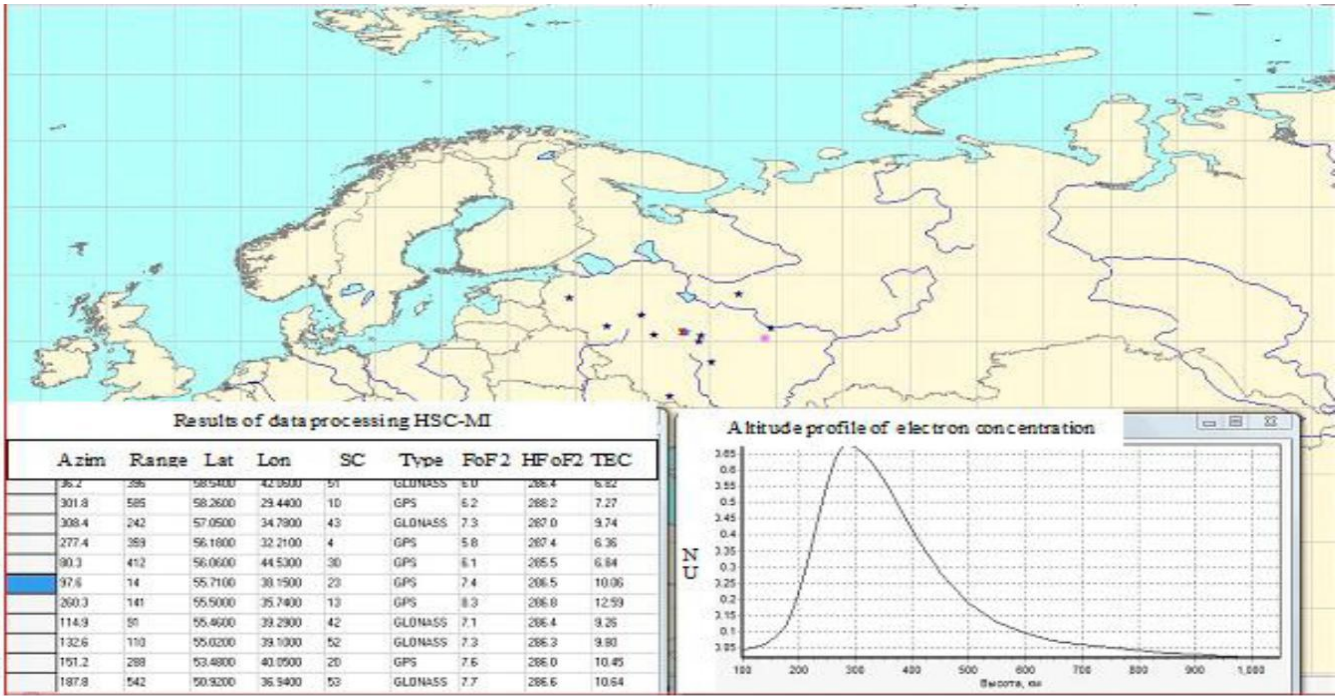
Figure 2. Trajectory of subionospheric points a) and electron density profiles b) obtained during the day from observations from one receiver at evaluation angle 15^o.

The application of global navigating satellite systems together with the methods for ill-posed problems allow for conducting long and regular measurements. It enables studying space-temporary mechanisms occurring in the Earth ionosphere. It also enables us to determine the ionospheric effects of the earthquakes based on the analysis of an electron density of F2 layer. The existing complex allows us for carrying out observations of the state of the ionosphere in real time and, hence, helps to determine ionospheric effects of the earthquakes.

3. Results of testing complex

Currently, the hardware-software complex of monitoring ionosphere is under test. The complex is located in Troitsk, on the territory of the Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences in the immediate vicinity of the vertical sounding ionosonde DPS-4.

HSC-MI has a high degree of automation and provides a 24h continuous operation mode with thematic and service information archiving. An example of thematic mapping and service information on the screen HSC-MI is shown in Figure 3. Presented in Figure 3 the characters displayed as asterisks show the coordinates of sub-ionospheric points for which ionosphere parameters have been obtained at a specific time. To compare we used the results obtained according to the navigation satellites coordinates of sub-ionospheric points which were closest to the location of the ionosonde DPS- 4. The results of the ionosonde and those obtained from hardware-software complex are shown in Figure 4 and Figure 5 as examples.



Results of data processing HSC-MI

Azim	Range	Lat	Lon	SC	Type	FoF2	HFoF2	TEC
36.2	396	58.5400	42.0600	51	GLONASS	6.0	286.4	6.82
301.8	585	58.2600	29.4400	10	GPS	6.2	288.2	7.27
308.4	242	57.0500	34.7800	43	GLONASS	7.3	287.0	9.74
277.4	359	56.1800	32.2100	4	GPS	5.8	287.4	6.36
80.3	412	56.0600	44.5300	30	GPS	6.1	285.5	6.84
97.6	14	55.7100	38.1500	23	GPS	7.4	286.5	10.06
260.3	141	55.5000	35.7400	13	GPS	8.3	286.8	12.59
114.9	51	55.4600	39.2900	42	GLONASS	7.1	286.4	9.26
132.6	110	55.0200	39.1000	52	GLONASS	7.3	286.3	9.80
151.2	288	53.4800	40.0500	20	GPS	7.6	286.0	10.45
187.8	542	50.9200	36.9400	53	GLONASS	7.7	286.6	10.64

Figure 3. Display of the HSC-MI product.

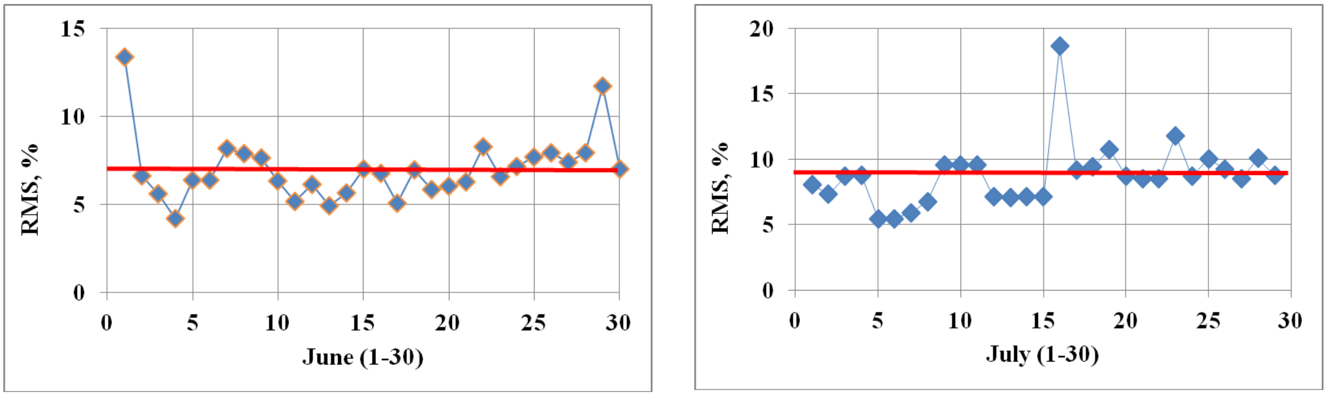


Figure 4. The error in determining the critical frequency of the ionosphere layer F2 (diamond mark identifies a day, the horizontal (red) line - the average daily standard deviation for the month).

For the month of June, the average daily value of RMS was 7% , 6.65%, during day and 6.71% at night ; for the month of July these values are - 8.77%, 7.34% and 9.5%, respectively. Night data considers the results obtained one hour after sunset and an hour before sunrise. Daily data were obtained at the time of sunrise and sunset. HSC-MI was previously tested in sessions of short wave radio links [Smirnov and et al, 2008].

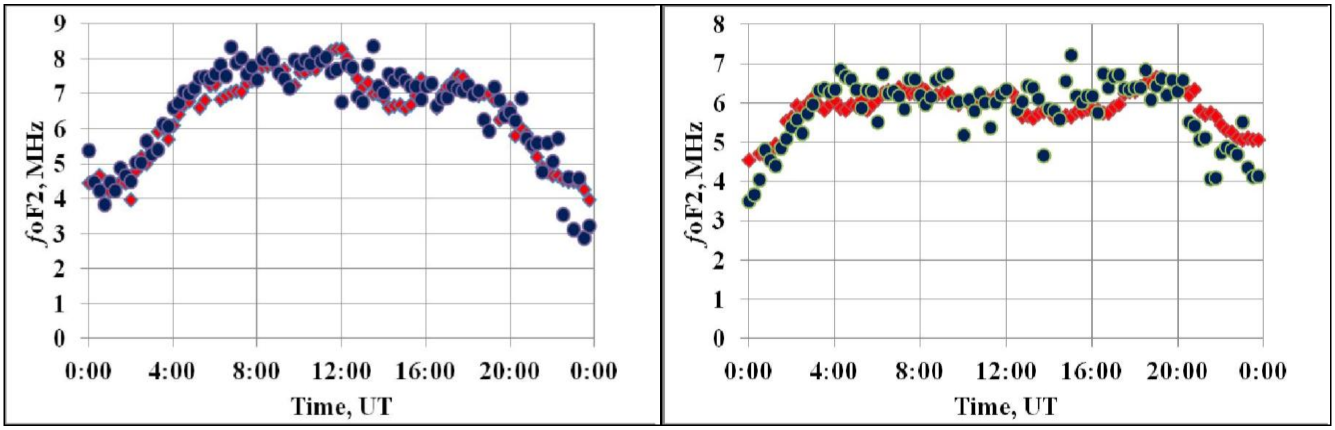


Figure 5. The values of the critical frequency of the ionosphere layer F2 for June 2 and July 2 (diamond - ionosonde data, circle - HSC-MI data).

4. Variations of the ionosphere electron density during seismic events

The analysis of potential software opportunities for using GPS-monitoring for possible seismic foreshocks detection is considered on the example of Hector Mine earthquake on October, 16, 1999 in California. The choice of this event has been determined by the fact that during this powerful enough earthquake (magnitude M=7.1) geomagnetic environment was moderately disturbed. The chosen earthquake occurred on the territory characterized by increased seismicity. High seismicity of the territory brings additional difficulties in the interpretation of ionospheric perturbations. Therefore to divide the ionospheric effects caused by the influence of heliophysical factors from seismic, receivers located both close to and remote from the epicenter of the seismic event were used for ionosphere monitoring.

The analysis of variations of the electronic concentration distribution received with the use of a radio translucence method was conducted during a long enough period of time (from October, 11 till October, 17, 1999). Subionospheric point tracks relative to the location of the earthquake epicenter and the navigating receivers used for monitoring are shown on figure 6.

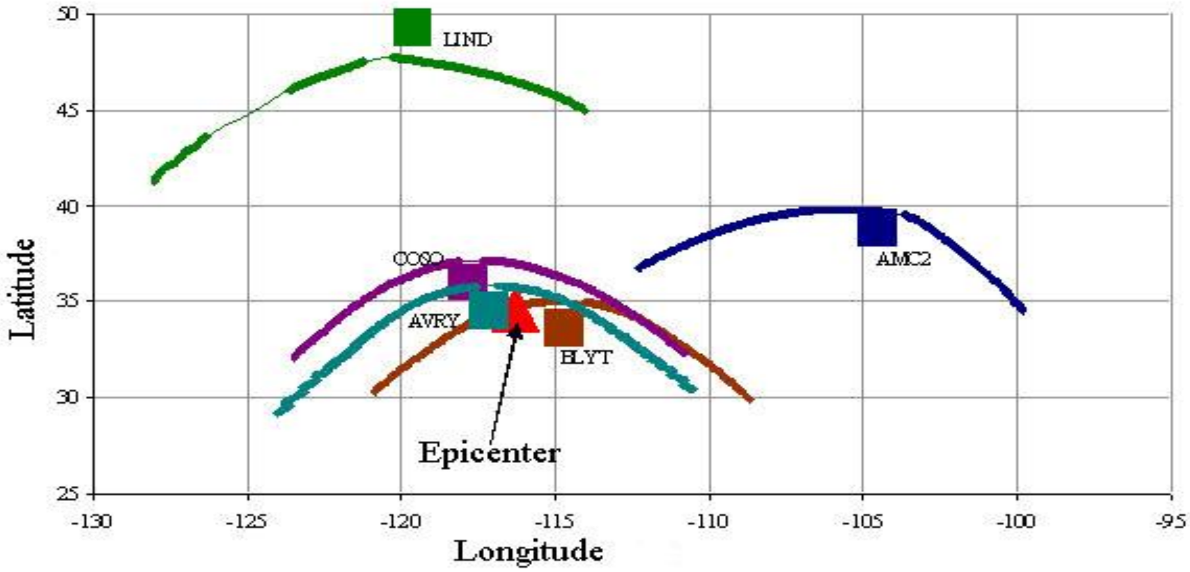


Figure 6. Trajectories of subionospheric points.

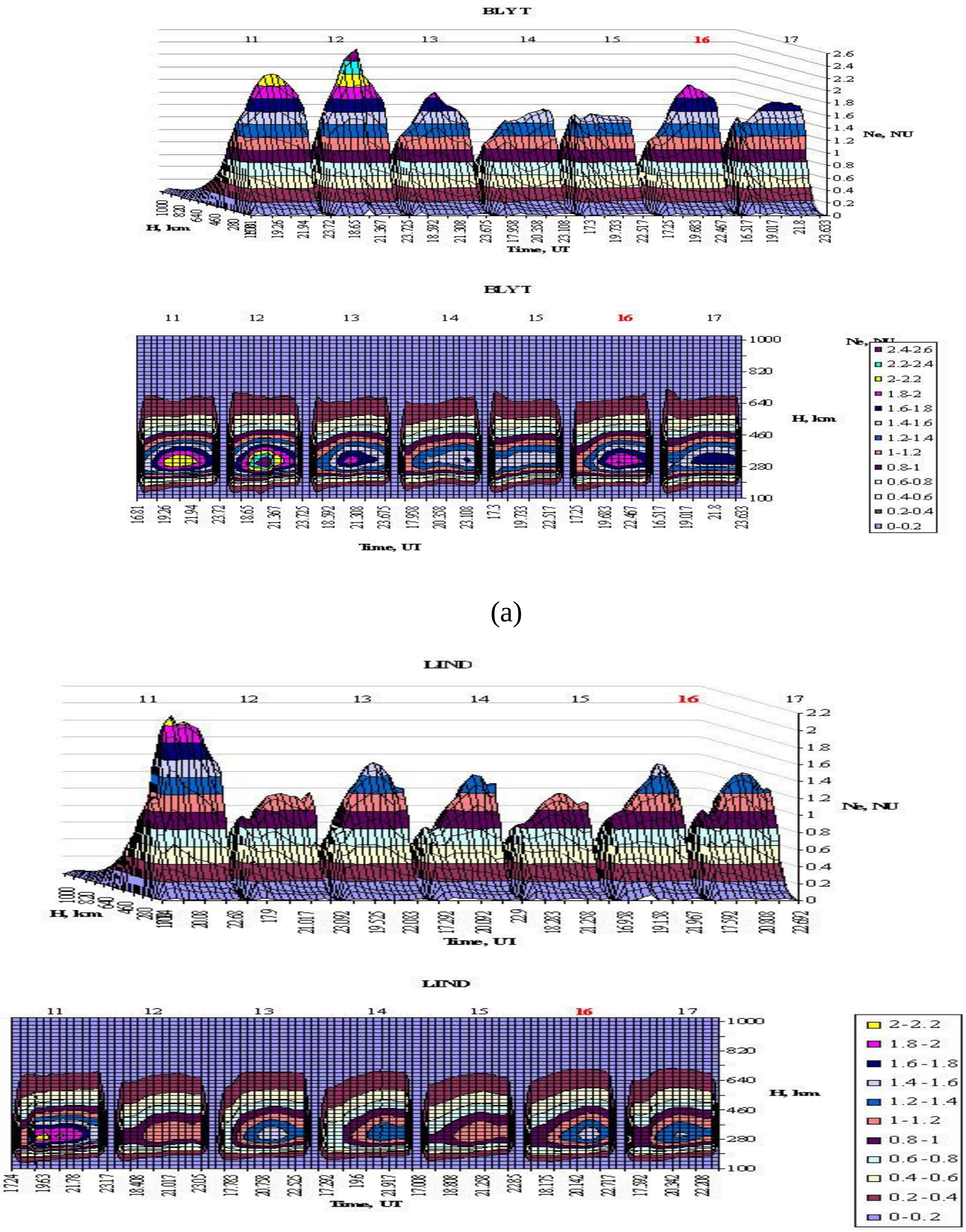
High-altitude structures of the electron density distribution, received from October, 11 till October, 17, 1999 by radio translucence method, are presented on figure 7. Here are shown the profiles received with the help of receivers, located both close to and remote from the epicenter of seismic event. The analysis of electron density distribution shows an increase in electronic concentration 3-5 days and its significant reduction 1-3 days prior to the earthquake. Such changes in the electronic concentration were observed for all stations located close to the event's epicenter. Furthermore, there observed not only reduction of electronic concentration, but also "disturbance" of its space-temporary course of the last few days. It is well visible on 2D-representations of the electronic concentration distribution.

A different picture was observed at the remote stations LIND and AMC2. They did not register any expressed increase in electronic concentration 4-5 days and its sharp reduction 1-3 days prior to the seismic event. It is necessary to notice, that for the station LIND located on the longitude close to the earthquake, but remote on latitude, no expressed modification of the space-temporary course is observed. Some profile modification, less expressed in comparison with the stations COSO, AVRY and BLYT, was observed for the station AMC2 located on the latitude close to the earthquake epicenter.

A different character of space-temporary course of electron density in the given region cannot be explained by the influence of the geomagnetic perturbations observed during this period. The analysis of heliogeophysical conditions during October, 11-17 has shown that the presence of perturbations in geomagnetic conditions at this time could not result in such significant changes in the electron concentration distribution of the ionosphere in the given region.

Data on Dst and Kp geomagnetic indexes for the period October, 11-17, 1999, available on the website of World Data Center, indicate that this interval can be considered as a period of moderate geomagnetic activity. The index Kp value changed in the range 2-4, and on October, 15, 1999 reached 5. The index Dst varied in the range 20-60 nT with the maximum deviation up to 70 nT one day prior to the earthquake (Figure 8).

The analysis of geomagnetic variations allows drawing a conclusion, that changes in space-temporary distribution of the electronic concentration, observed at the stations COSO, AVRY and BLYT, could have been results of the seismic effects.



(a)

(b)

Figure 7. High-altitude structures of electronic concentration (3D-representation) and their bi-dimensional display (2D-representation) close to (a) and far from the epicenter (b).

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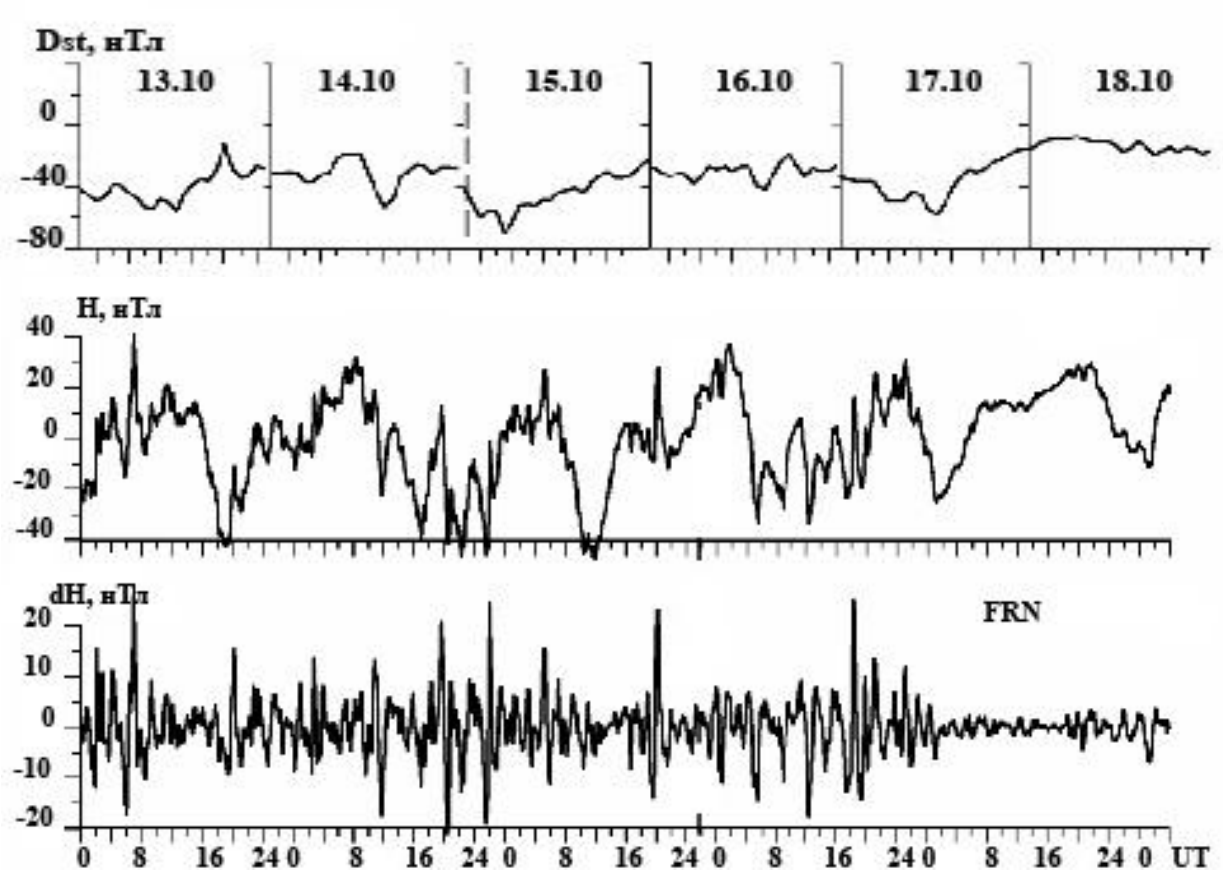

Figure 8. Variations of Dst geomagnetic index, magnetic field H and its temporary changes for October, 13-18, 1999 according to the stations FRN

5. Conclusion

The developed technology of the high-altitude electronic concentration profile determination allows for accurate diagnosing of the ionosphere state and the development of ionospheric perturbations above a vast territory. This technology does not depend on the conditions of observations. The simultaneity of observations on a large territory allows for figuring out the features of the ionosphere under the influence of different factors.

The application of radio translucence method, based on the results of data processing from navigating satellite systems, enables carrying out long monitoring of the ionosphere state in seismic period. The results of such data processing have shown, that the change of the ionosphere state in dangerous seismic areas can be observed by means of navigating satellite systems. Unlike ionospheric stations of vertical sounding the offered approach allows for localizing of possible areas of earthquake and determining the occurrence time of this phenomenon.

Equipment of the ground vertical ionosonde hardware and software complex based on the use of dual-frequency navigation receivers and specialized mathematical apparatus for solving inverse tasks of radio sounding of the Earth ionosphere allows to monitor the state of the ionosphere over an area about 3 million km^2. Such a construction point in the future may serve as a cell of the system of global and continuous monitoring of the Earth's plasma sheath. At appropriate calibration on vertical sounding ionosonde data the complex can provide the formation of data array containing the coordinates of the point for a maximum layer F2, the value of the critical frequency layer and its height depending on the observation time for the entire line of sight of the ground station at distances up to 1000 km.

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