The ability of the navigation systems for detecting seismoionospheric variations in F2-layer of the ionosphere

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Abstract

The ionosphere is the good indicator of the processes occurring on the Earth. It has been proved that the ionosphere above an epicenter undergoes various specific disturbances during the stages of the preparation of an earthquake. The results received earlier on monitoring an ionosphere above seismo-dangerous regions have shown that for the analyses of the ionosphere state it is enough to use the observation data for five full days. Such period allows reveal dynamics of change of a background state of the ionosphere in the given region caused by the seismic processes.

1. Introduction

The detection from satellites of various seismic effects has stimulated the use of space technology in solving the problems of earthquake forecasting. The process of earthquake preparation takes, as a rule, a considerable period of time and thus requires long-term observations to be carried out above their probable centers. Such data could be obtained only using spacecraft and, in particular, satellite navigation systems [1].

Recent studies have shown that satellite navigation systems can be successfully used for continuous global monitoring of the Earth's ionosphere [2]. Particularities in the orbital configuration of these systems and the great number of ground receivers that can be installed at practically any site allow simultaneous examination of ionosphere conditions over seismically hazardous areas situated at distances ~1500 km from ground stations.

The difficulties in identification of the ionosphere perturbations caused by seismic effects on a background of existential variability of an ionosphere, especially during electromagnetic indignation, are the basic object of criticism at use of an ionosphere, as detector of the earthquake precursors. The researches within last several years show, that the seismoionospheric phenomena are unique among a set of other reasons of variability of an ionosphere. Difference of physical mechanisms of seismoionospheric relations from mechanisms ionospheric storms and other sources of the ionosphere variability conduct to their various display in ionospheric variations.. The ionospheric perturbations connected with lithosphere processes, are much more accessible to detection and registration by space radiophysical methods. Until recently there were no standard techniques of allocation in an ionosphere of the effects caused by seismic processes, according to satellite navigating systems.

It is necessary to note especially, that the account of all parameters of the ionospheric precursor allows allocate it on a background of variations of the ionosphere caused by other influences. It profitably distinguishes it from the plasma and electromagnetic variations of other type offered as precursors as they can be observed and as a result influences of other factors. The received results allow to assert, that the ionospheric earthquake precursors - really existing phenomena [3-6], and the developed techniques of their detection give an opportunity of their practical use in systems of the prevention and the short-term forecast of catastrophic earthquakes.

Process of preparation of earthquakes occupies, as a rule, the significant period of time and consequently demands carrying out of long observation above the possible seismic focus. The existing network of ground navigating stations of tracking allows carry out such observation over a condition of an ionosphere and, hence, enables to determine the ionospheric effects of earthquakes. The radio-translucence method examined in this paper allows the creation of altitude profiles of ionosphere electron content distribution with discretization of GPS signal registration. Some results of its practical implementation within the periods of earthquakes in different regions are presented.

2. Radio translucence of the Earth ionosphere

As a matter of fact radio translucence method is similar to tomography. The difference is in the scheme of realization. In a radio translucence method only one receiver is used in contrast to tomography.

Therefore the problem of interpretation of experimental data - problem of the solution of incorrect inverse tasks of ionosphere sounding acts as on the foreground. The ill-posed tasks are characterized, as it is known, by strong dependence of the received solution on an error of the initial data. It results in a practical non-singularity of the solution within the framework of the given accuracy [7].

It is known that at measurement execution on two frequencies f_1 and f_2 it is possible to generate a difference of pseudoranges $R(f_1)$ and $R(f_2)$:

$$\Delta R(f_1, f_2) = R_I(f_1) - R_I(f_2) + \delta, \tag{1}$$

where δ - ineradicable error of measurements caused by dependence on frequency, the influence of the ionosphere $R_I(f)$ can be determined by the formula [8]:

$$R_I(f) = \frac{40{,}4 \cdot 10^6}{f^2} \int_L N(l) dl \cdot \tag{2}$$

Here f - frequency of a signal in Hz, dl - propagation path element, $N(l)$ - distribution of electron concentration of the Earth ionosphere along the propagation trajectory, el / cm^{-3}.

Taking it in to consideration, it is possible to write down, that

$$\Delta R(f_1, f_2) = 40{,}4 \cdot 10^6 \frac{k}{f_1^2} \int_L N(l) dl + \delta, \quad k = 1 - \frac{f_1^2}{f_2^2} \cdot \tag{3}$$

Received in the assumption of spherically layered medium the integral equation (3) connects the difference of pseudoranges, measured by a radio engineering method, with function of altitude distribution of electronic concentration $N(z)$ as follows [9]:

$$\int_{z_1}^{z_2} N(z) \frac{(a+z)dz}{[(a+z)^2 - a^2 \sin^2 \theta]^{1/2}} = 2{,}475 \cdot 10^{-8} \frac{f_1^2}{k} \left[\Delta R(f_{1,} f_2) - \delta \right], \tag{4}$$

where z_1=80 km and z_2=1000 km (typically) - assumed the bottom and top border of the ionosphere accordingly, θ - zenith angle of observation of the satellite from station, a - radius of the Earth, z - current height from the Earth surface.

The expression at the left represents complete integrated concentration of the ionosphere along the path of propagation of a navigation signal:

$$STEC = 2{,}475 \cdot 10^{-8} \frac{f_1^2}{k} \left[\Delta R(f_{1,} f_2) - \delta \right], \tag{5}$$

where *STEC(θ)* is the slant TEC along a ray path *P(θ,z).*

Thus, the formation of a pseudoranges difference of measured on dual frequencies, is actually equivalent to determination of complete integrated concentration of the ionosphere.

The process of determining electron density profiles from TEC data requires the solution of an ill-posed inverse problem in the form of a Fredholm integral equation of the first kind i.e.

$$STEC(\theta) = \int_{P(s)} N_e(s) ds = \int_{P(\theta,z)} K(\theta,z) N_e(z) dz \tag{6}$$

K(θ,z) is the Hilbert-Schmidt kernel of the integral equation given by

$$K(\theta, z) = \frac{ds(\theta)}{dz} = \left[1 - \left(\frac{a}{a+z} \sin(\theta) \right)^2 \right]^{-\frac{1}{2}}. \tag{7}$$

The kernel *K(θ,z)* is the ratio between the slant path increment *ds* and the corresponding vertical increment *dz* for a ray path with zenith angle *θ* at altitude *z*. Using these simplifications in the integral equation results in the discretized version of this integral equation becoming

$$b_i(\theta) = \int_{P_i(s)} N_e(s) ds = \int_{P_i(\theta,z)} K(\theta,z) N_e(z) dz = \sum_{j=1}^{n} x_j a_{ij} \ , \tag{8}$$

which can be expressed as a matrix equation ***Ax=b***, where ***A*** is the *m*x*n* operator matrix .

In the matrix equation ***Ax=b**, **x*** is the *n* x *1* vector of unknown layer densities, and ***b*** is the *m* x *1* set of measured slant TEC values.

A uniform approximation to the exact solution can in principle be constructed, if the exact solution is a continuous function of the limited variation in the measured data. The structure of the distribution of electron density satisfies this restriction. Hence it is possible to construct an effective numerical algorithm for the electron density from measured TEC data. The use of a priori information allows one to search for the required solution by constraining acceptable solutions to the set of special structures with the properties of being monotonic, convex and positive definite. In this case there is no necessity to use a regularization parameter. The task is reduced to minimization of the functional $\mathbf{\Phi(x,b)=||Ax-b||^2}$.

In the use of the iterative conjugate gradient projection method, minimization of the functional amounts to minimizing the discrepancy functional i.e. choosing the minimizing sequence for square-law function. The iterative conjugate gradient projection method has some inherent regularization effect where the number of iterations plays the role of the regularization parameter. The CGP method may be more suitable to implement in hardware since it is possible to solve for x without actually forming A^TA and thus requiring less memory and fewer computations than the direct method. The iteration is terminated when the discrepancy between the measured STEC and the STEC derived from the particular step in the solution reaches as preset minimum [9].

It proved to be possible to determine simultaneously the vertical electron density profiles from most visible satellites with monotonically increasing or decreasing elevations during the period of observation. The vertical electron density profile is reasonably well approximated by the CGP method with the use of 40 slant TEC measurements over a period of a few minutes. The vertical electron density profiles can be determined along the whole trajectory of the ionospheric pierce points of the satellite to receiver ray paths.

3. Seismo-ionospheric variations during earthquake preparation and realization

Two earthquakes of magnitudes M=4.8 and M=5 occurred in the Kaliningrad region (Russia) on September 21, 2004. The unique feature of these earthquakes is that they took place in a zone with low seismicity. Both earthquakes happened almost at the same place with an interval of 2.5 hours (11:05:04 UTC and 13:32:31 UTC) between the shocks. Their epicenters had the following coordinates: 54.914°N, 20.172°E and 54.789°N, 20.055°E.

For the monitoring of ionosphere conditions there were mainly chosen satellites observed in the period the most close to the seismic shocks. For determining background ionosphere conditions there was used data collected during six full days (September 16 - 21) at the station MDVJ. Fig. 1 presents altitude profiles of electron content distribution obtained by observations of the GPS satellite from the ground station RIGA.

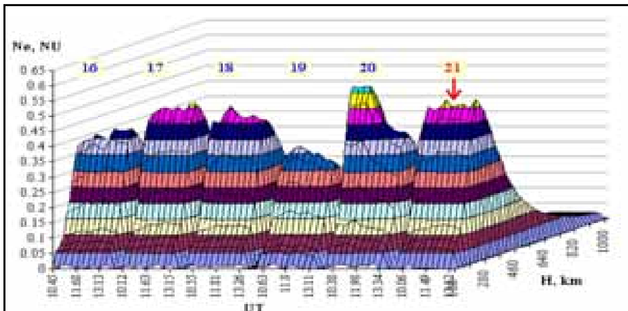

Figure 1. Profiles of electron content (September 16-21, 2004; RIGA station).

The method of radio-translucence has allowed us to monitor the behavior of the electron content maximum along the trajectory of the sub-ionospheric point for several GPS satellites during the period preceding the Turkey earthquake and at the moment of the shock on August 17, 1999. The magnitude at the epicenter was 7.7. The satellite observation center was in Ankara situated at the distance of about 400 km from the epicenter. The profiles of electron content obtained in the period of August 12 – 18, 1999 are displayed in Fig. 2 clearly show the significant modification of their shape one day before the earthquake. The minimum value of Ne_{max} registered on August 16, 1999, was detected at the point closest to the earthquake epicenter.

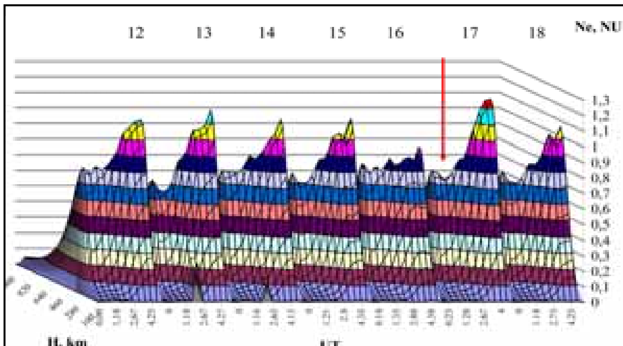

Figure 2. Altitude profiles of electron content in the ionosphere (Izmit, Turkey, August 12-18, 1999)

On the basis of the navigation measurements data obtained from 30th September till 10th October 2005 the monitoring of the state of the ionosphere was conducted in the area of a strong earthquake in Pakistan which occurred on 8th October at 3:50:35.9 UTC with the magnitude of 7,6. The monitoring was conducted from several stations equipped with dual-frequency GPS receivers.

The results of the monitoring performed 24 h prior to the coming earthquake revealed a significant decrease in electronic concentration in the maximum of F2 layer of the ionosphere. The analysis of the heliogeophysical situation showed that the observed changes in electronic concentration can be provoked by the impact of seismic activities in this region. The earthquake with the magnitude M=7.6 occurred on 8th October 2005 at 3:50:35.9 UTC. Position data of its epicenter are: latitude 34.47 N, longitude 73.63 W. The analysis of the distribution of the electronic concentration of the ionosphere during the time concerned has revealed that according to the observation results obtained from URUM, KIT3, SELE, POL2 receivers, the nature of the longitudinal distributions of the electronic concentration is identical. Graphs of the space-time distributions of the electronic concentration where is explicitly visible the structure of the longitudinal distribution and its typical changes are shown on figure 3. For these stations, located relatively close to the epicenter zone of the earthquake, on 6th and 7th October a significant decrease of the electronic concentration in the maximum of F2 layer was detected. Most explicitly it was observed at URUM station which may signify that the area of ionosphere disturbance was stretched to the north-east from the epicenter.

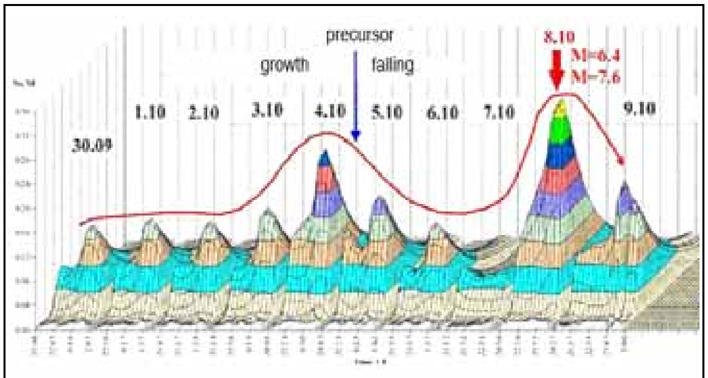

Figure 3. Vertical structures of electronic concentration, received according to GPS -measurements from URUM station

4. Conclusions

The radio-translucence method of the ionosphere enables us to carry out long-term monitoring of the ionosphere above seismically hazardous regions of our planet. The results discussed above show that changes in the state of the ionosphere during periods preceding the earthquakes can be detected using GPS observations. In contrast to ionosphere stations of vertical sensing, the approach proposed enables us to locate the regions of probable earthquakes and to forecast the time of these natural disasters. Results from monitoring of ionosphere state using two-frequency radio signals of GPS satellites during the preparation periods of earthquakes and during these seismic events clearly show the trend of electron content growing 3-5 days before the forthcoming earthquake and decreasing 1-3 days before it happens.

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