Monitoring of Ionosphere Variations During the Preparation and Realization of Earthquakes Using Satellite Navigation System Data

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Abstract - This paper discusses a method of radio-translucence allowing the reconstruction of altitude profiles of ionosphere electron content distribution using data from two-frequency signals of satellite navigation systems. Despite the difficulty of detecting ionosphere variations caused by seismic effects in the period preceding an earthquake, the use of the GPS and GLONASS satellite navigation systems seems to be the best way to realize global monitoring of the ionosphere over seismic hazard areas.

Results from implementation of the radio-translucence method are presented for earthquakes that have occurred in two regions of different seismicity. Variations in ionosphere electron content, registered using GPS satellite observations, were analyzed for the preparation and realization periods of earthquakes occurred in the Kaliningrad region on September 21, 2004 (seismically calm area) and in Turkey on August 17, 1999 (seismically active area). Standard RINEX files based on observations carried out at various ground stations were used to build altitude profiles of the ionosphere. It was shown that time-space ionosphere anomalies above epicenter areas of future earthquakes can be used as precursors of significant seismic events.

Keywords: earthquake, ionosphere, radio-translucence method, GPS, monitoring.

1. INTRODUCTION

The detection from satellites of various seismic effects has stimulated the use of space technology in solving the problems of earthquake forecasting (Calais, 1995; Liperovsky, 1992; Savin, Bondur, 2000). 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 (Andrianov, Smirnov, 1993; Savin, Bondur, 2000; Bondur, Smirnov, 2005a, b).

Recent studies have shown that satellite navigation systems can be successfully used for continuous global monitoring of the Earth's ionosphere (Bondur, Smirnov, 2005a,b). 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 analysis of critical frequencies for the F2 layer presented in (Liperovsky, 1992; Gokhberg et al, 1983; Calais, 1995) allows us to state that a general increase in electron content for an extensive area of this layer is observed 2-3 days before the shock. On the day preceding an earthquake a local minimum of electron content is situated above the epicenter area.

However, no generally accepted technique for the monitoring of such ionosphere effects caused by forthcoming earthquakes based on GPS satellite data was known until recently.

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 Kaliningrad area (low seismicity zone, 2004) and in Turkey (seismically active zone, 1999) are also presented.

2. METHOD OF RADIO-TRANSLUCENCE OF THE IONOSPHERE

The radio-translucence method is based on the transformation of normalized phase difference for radio waves. Mathematically, it corresponds to the transformation of integral equations of first kind (Andrianov, Smirnov, 1993; Bondur, Smirnov, 2005a).

Implementation of this method involves measurement of radio signal parameters along the path "satellite – ground receiver" carried out at one station (Bondur, Smirnov, 2005a). When the measurements are performed within the angle range ΔE , the minimum size of which is determined by the inverse problem solution algorithm, the parameter ΔS_I may be considered as a horizontal magnitude of averaging within the ionosphere in reconstructing the altitude profile of electron content. This profile abuts to the midpoint of the projection of the arc ΔS_I onto the earth's surface. For angles E_o of 10^o - 90^o the projection of intersection of the line "satellite – receiver" may be located at the distance L up to 1,100 km from the station. Evaluation of zones of observations for the interval of observations T = 600/30 sec is given in Table 1.

Table 1. Evaluation of Zones of Navigation Satellite Observations

Parameter	Geometrical scales of radio-translucence of the ionosphere				
E_0, degrees	10	30	50	70	90
ΔE, degrees	5.8/0.29	6.3/0.31	6.8/0.34	7.1/0.35	7.2/0.36
ΔS_I, km	282/16.8	96/5.4	53/2.9	40/2.1	38/1.9
L, km	1096	467	237	104	0

Integral equations of first kind appropriate to such a technique of measurement of ionosphere parameters, have no analytical solution and require methods of inversion in the class of so-called ill-posed problems to be developed (Bondur, Smirnov, 2005a). Such methods are well advanced thanks to the efforts of the mathematical school of A.N.Tikhonov (Tikhonov, Arsenin, 1986). They are essentially based upon digital algorithms for the inversion of radio signals' measurements and can be realized by means of modern computers.

The ill-posed nature of the problem of reconstructing electron content distribution using the results of radio-translucence does not allow us to obtain an exact solution for the main integral equation that would be stable under small variations in input data. In this case it is necessary to look for some approximate solution, choosing an acceptable solution from all the possible ones. Mathematical difficulties encountered when trying to apply this approach quite often force us to abandon the idea of obtaining a general solution to the problem of determining environmental parameter distribution. Most frequently, the problem is to be reduced to some elementary cases, for which acceptable results could be obtained.

The equation of radio-translucence built with the assumption of local spherically stratified medium links the measured difference of pseudo ranges and the function of altitude distribution of electron content $N(z)$ (Andrianov, Smirnov, 1993; Bondur, Smirnov, 2005a):

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

where z_1 and z_2 are the assumed lower and upper boundary of the ionosphere,

$\vartheta = 90 - E$ is the zenith angle of the satellite observed from the ground station,

a is the radius of the Earth,

z is the current altitude from the Earth's surface,

δ is the error in radio measurements,

$f_{1,2}$ are GPS frequencies, $k = (f_1/f_2)^2$.

In operator notation the equation (1) can be represented as:

$$A\varphi = U_\delta, \tag{2}$$

where A is the integral operator,

$\varphi \equiv N(z)$, U_δ are the data from measurements.

The left part of (1) represents total electron content of ionosphere (TEC) along the path of radio signal propagation:

$$TEC = \int_L N(l)dl = = 2{,}475\cdot 10^{-8}\frac{f_1^2}{k}\left[\Delta R(f_1, f_2) - \delta\right] \tag{3}$$

The search for a possible solution to equation (1) is more expediently carried out using the method of conjugate gradients (Tikhonov, Arsenin, 1986). It is a mathematically strict method for the solution of inverse problems, with imposed restrictions enabling us to obtain admissible solutions on convex sets.

When the finite-dimensional approximation is applied, the functional

$$\Phi(\varphi) = \left\|A\varphi - U_\delta\right\|^2 . \tag{4}$$

converts into the quadratic function $\phi(z)$ which can be represented by the following generalized expression:

$$\varphi(z) = (z, Qz) + (b, z) + c, \tag{5}$$

where Q, b, c are the coefficients of quadratic polynomial.

When using the difference approximation, the problem of minimization is reduced to the minimizing series, the elements φ_i of which should minimize quadratic function $\varphi(z)$ and should comply with the restrictions imposed by a priori information. The procedure of minimization consists of following operations. The elements φ_i of the minimizing sequence are determined using the following rule: each successive element φ_{i+1} is calculated from the previous one φ_i as follows:

$$\varphi_{i+1} = \varphi_i - \beta_i p_i, \tag{6}$$

where $p_i = -grad\varphi\big|_{Z=Z_i} + \dfrac{\left\|grad\varphi(z_i)\right\|^2}{\left\|grad\varphi(z_{i-1})\right\|^2} p_{i-1}$ is the gradient of the function,

$p_0 = -grad\varphi(z_0)$, $\beta_i = \dfrac{1}{2}\dfrac{(grad\varphi(z_i), p_i)}{(Qp_i, p_i)}$ is the gradient step,

$\varphi(z_0)$ is the initial approximation.

Results from computer-aided simulation show that the root mean square error of approximation for the ionosphere electron content altitude distribution function does not exceed $\delta_N = 0{,}02NU \quad \left(1NU = 10^6 el/cm^{-3}\right)$. The discrepancy between the modeled values and values reconstructed using inverse problem solution, is evaluated by $\delta N = N_{\mathrm{e\,max\,mod}} - N_{\mathrm{e\,max\,rec}} = 0{,}014NU$ (Smirnov, 2001).

Let's consider the application of the above described method to the analysis of the situation that took place within the periods of earthquakes occurring in the Kaliningrad region (low seismicity zone, September 21, 2004) and in Turkey (seismically active zone) on August 17, 1999).

3. SEISMO-IONOSPHERIC VARIATION 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. The last significant earthquake registered there was in 1977.

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.

Trajectories of sub-ionospheric points for some GPS satellites observed simultaneously from the stations RIGA, BOGI and MDVJ during the period preceding the quakes and during the shocks are shown in Fig. 1.

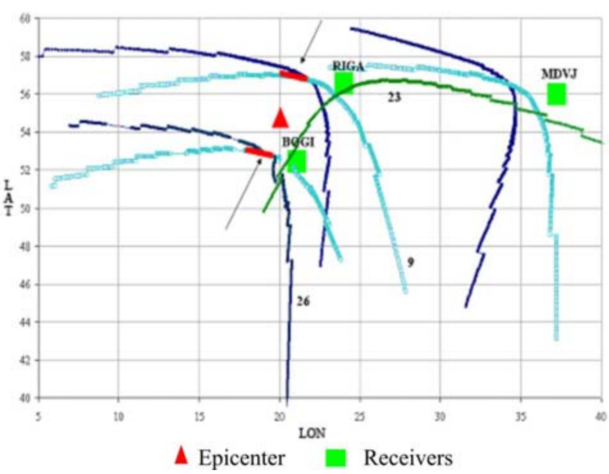

Figure 1. Trajectories of sub-ionospheric points in relation to the epicenter and receivers (Kaliningrad, September 21, 2004)

For the monitoring of ionosphere conditions there were mainly chosen satellites observed in the period the most close to the seismic shocks. One of those satellites (#23) was available in the early morning, 4 - 7 hours before the earthquakes happened. The shortest distance between the sub-ionospheric point and earthquake epicenter was about 180 km for the satellite #23, 290 km for the satellite #26 and 230 km for the satellite #9.

For determining background ionosphere conditions there was used data collected during six full days (September 16 - 21, 2004) at the station MDVJ (Bondur, Smirnov, 2005a) were used. Fig. 2 presents altitude profiles of electron content distribution obtained by observations of the satellite # 26 from the ground station RIGA.

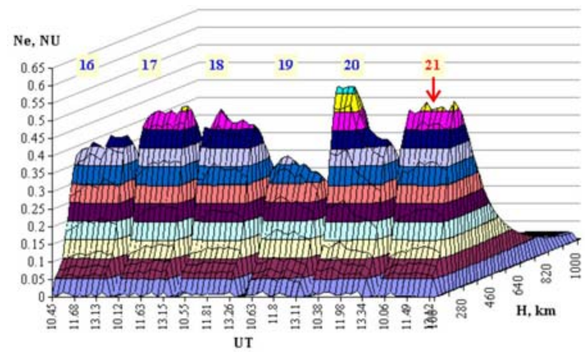

Figure 2. Profiles of electron content (September 16-21, 2004; RIGA station; satellite #26)

As the analysis of this Figure shows, on September 19, 2004 (two days before the earthquake) the maximum value of electron content in F2 stratum of ionosphere has considerably decreased in comparison with that registered on September 18, 2004. Electron content was constantly growing in the period of September 16 - 18. Such ionosphere state is typical for the preparative phase of an earthquake. Moreover, the changes in maximum values of electron content obtained with using satellite #29 observations (trajectory of its sub-ionospheric point is close that of the satellite #26) has a wave-like character with a period of about one hour. The graph of the electron content maximum Ne_{max} built based on the observation of satellite #9 has a saddle-like shape. The Minimum value of Ne_{max} was observed in the area of ionosphere closest to the epicenter during the time interval of 12:50 -13:30 UT. The character of variation in the altitude distribution of electron content determined using the receiver BOGI is similar to that described above.

The area of local minimum is indicated by arrows in Fig. 1. Apparently, this area was extended in northeastern direction, as it was registered simultaneously from stations RIGA and BOGI. Profiles of electron content built using data collected by the GPS receiver at the MDVJ station, situated more than 1000 km away, have no perceptible variation (Bondur, Smirnov, 2005a). It allows us to draw a conclusion that the variations in the ionosphere detected by GPS receivers at RIGA and BOGI stations are stipulated by the effects bound up with the earthquake.

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. Fig. 3 presents the trajectories of sub-ionospheric points for the satellites observed at the time of the Izmit earthquake. The Epicenter of this earthquake had the following coordinates: 40.70°N and 29.99°E. The Satellite observation center was in Ankara (39.89°N, 32.76°E) situated at the distance of about 400 km from the epicenter.

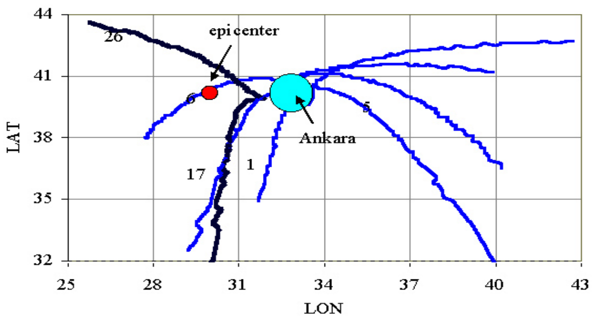

Figure 3. Trajectories of sub-ionospheric points in relation to the epicenter and receivers (Turkey, Izmit, 17.08.1999)

Trajectories of sub-ionospheric points for satellites #26 and #6 were passing almost directly above the earthquake epicenter. Satellite #6 was observed from 0^h until 5^h UT during this seismic event, while data from the satellite #26 was collected in the day time: 18 - 22 UT.

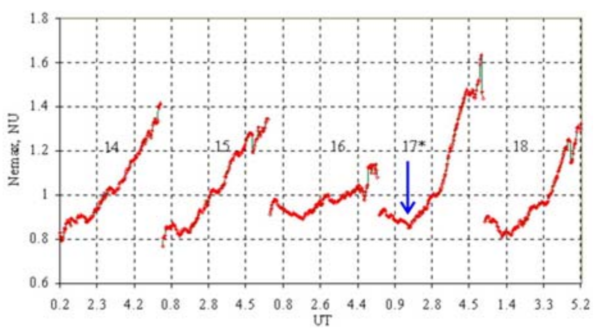

Figure 4. Variation of electron content maximum in the ionosphere (station Ankara; August 14-18, 1999; satellite #6)

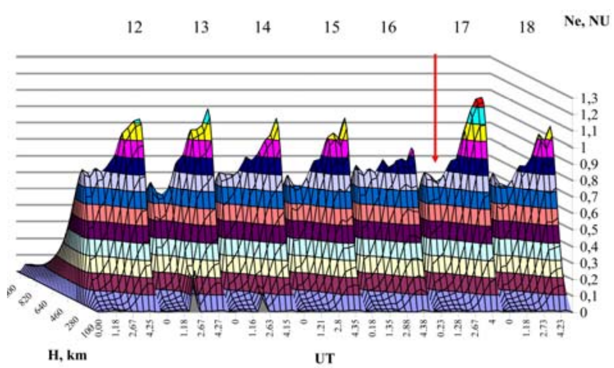

Figure 5. Altitude profiles of electron content in the ionosphere (Izmit, Turkey, August 12-18, 1999)

Observations of 4 satellites enabled us to detect a sharp change in the behavior of the electron content maximum in the ionosphere on August 16, 1999 (one day before the earthquake). The results of determining the electron content maximum in the ionosphere based on satellite #6 data are shown in Fig. 4.

The minimum value of Ne_{max} registered on August 16, 1999, was detected at the point closest to the earthquake epicenter. The profiles of electron content obtained in the period of August 12 – 18, 1999 are displayed in Fig. 5 clearly show the significant modification of their shape one day before the earthquake.

4. CONCLUSION

The method of radio-translucence 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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