Ionospheric Disturbances during of the Thsunamigenic Earthquake on Navigation System Data

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Abstract: The generation of tsunamis is one of the most dangerous consequences of underwater seismic events. These events may be caused by strong underwater earthquakes. The strength of tsunami waves correlates with the earthquake magnitude. This circumstance may be used as an early warning system for dangerous tsunamis. A tsunami is not only manifestation of the Ocean's reaction to underwater earthquakes. The seismic events are accompanied by disturbances of the electron density of the Earth's ionosphere. The detection of these ionospheric irregularities can serve as one precursor of the earthquake appearance. The monitoring of ionospheric state in F2 layer may be based on using global navigation systems. GPS receivers located along sea coast allow to control the Earth's ionosphere in F2 layer at the distance up to 1500 km from the station. Early it has been shown that satellite navigation system can be successfully used for continuous global monitoring of the Earth's ionosphere. Particularities in the orbital configuration of these systems allow to observe the ionosphere in the same time in the certain region. Ionospheric precursors of an earthquake can be visualized 1-3 days before the seismic events. In this paper results from implementation of the radio-translucence method are presented for strong underwater earthquake. This seismic event took place on December 26, 2004 near Sumatra. The magnitude of this earthquake is M=9. The earthquake caused a catastrophic tsunami. The strength of tsunami waves registered at sea cost correlates not only with the magnitude of underwater earthquake. It depends on epicenter depth, geographical position of the proximate dry land sites and other factors.
Keywords: earthquake, ionosphere, radio-translucence method, GPS, monitoring, tsunami.

1. Introduction

The detection from satellites of various seismic effects has stimulated the use of space technology in solving the problems of earthquake forecasting [1-2]. 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 [2-4].

Recent studies have shown that satellite navigation systems can be successfully used for continuous global monitoring of the Earth's ionosphere. 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 [1, 5] 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. Based on the example of underwater earthquakes shown hereunder, the possibility of detecting anomalies originating in the Earth's plasma envelope before and during seismic events is demonstrated.

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 the catastrophic underwater tsunamigenic earthquake that occurred in the Indian Ocean on December 26, 2004 (M=9) are presented.

2. Radio-translucence method of the Earth 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 [3-4].

Implementation of this method involves measurement of radio signal parameters along the path "satellite – ground receiver" carried out at one station. 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 elevation 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. Radiotranslucence method geometry is presented on Fig.1. Evaluation of zones of observations for the interval of observations T = 600/30 second is given in Table 1.

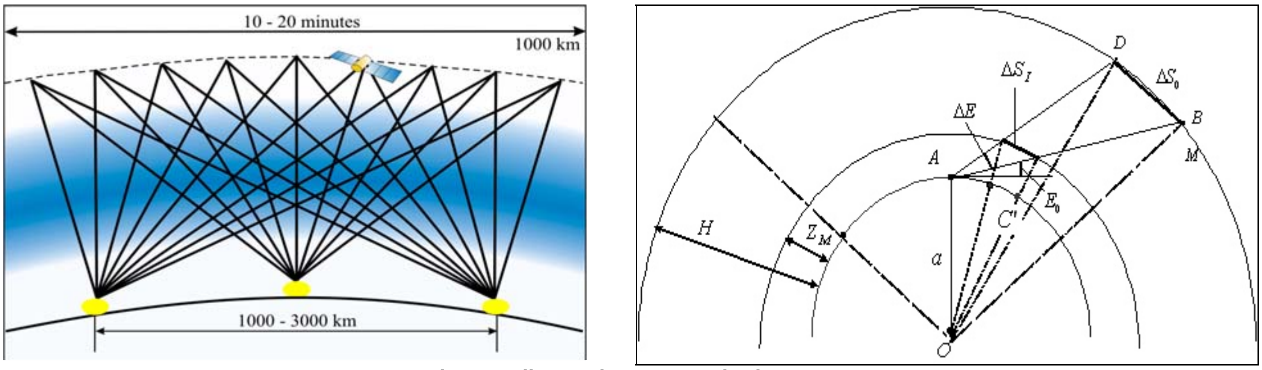


Fig.1. Radiotranslucence method geometry

Table 1. Evaluation of Zones of Navigation Satellite Observations

Parameter	Geometrical scales of radio-translucence of the ionosphere, ΔT=600/30 s				
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. Such methods are well advanced thanks to the efforts of the mathematical school of A.N.Tikhonov [6]. 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 process of determining electron density profiles from total electron content (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.

$$STEC(\vartheta) = \int_{P(s)} N(s)ds = \int_{P(\vartheta,z)} K(\vartheta,z)N(z)dz \qquad (1)$$

where $STEC(\vartheta)$ is the slant TEC along a ray path $P(\vartheta,z)$ and $K(\vartheta,z)$ is the Hilbert-Schmidt kernel of the integral equation.

The kernel $K(\vartheta,z)$ 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. 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 $N(z)$ [7-8]:

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

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, $k = \left(f_1 / f_2\right)^2$.

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

$$A\varphi = U_\delta , \quad (2)$$

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 along the path of radio signal propagation:

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

The search for a possible solution to equation (1) is more expediently carried out using the method of conjugate gradients [6]. 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

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

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

$$\varphi(z) = (z, Qz) + (b, z) + c , \quad (5)$$

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:

$$\varphi_{i+1} = \varphi_i - \beta_i p_i , \quad (6)$$

where $p_i = -grad\varphi\big|_{Z=Z_i} + \frac{\left\|grad\varphi(z_i)\right\|^2}{\left\|grad\varphi(z_{i-1})\right\|^2} p_{i-1}$ is the gradient of the function, $p_0 = -grad\varphi(z_0)$,

$\beta_i = \frac{1}{2}\frac{\left(grad\varphi(z_i), p_i\right)}{\left(Qp_i, p_i\right)}$ is the gradient step, $\varphi(z_0)$ is the initial approximation.

The better the initial approximation, the faster the convergence. The IRI model [9] proved to be a useful initial approximation in the conjugate gradients method.

Results from computer simulation show that the root mean square error of approximation for the ionosphere electron content altitude distribution function does not exceed $\delta_N = 0{,}02NU$ $\left(1NU = 10^6 el/cm^{-3}\right)$. The discrepancy between the modeled values and values reconstructed using inverse problem solution, is evaluated by $\delta N = N_{\mathrm{e\,max\,mod}} - N_{\mathrm{e\,max\,rec}} = 0{,}014NU$ [7].

3. Monitoring geometry of seismic region

The monitoring of ionospheric conditions during the period of the extremely strong underwater tsunamigenic earthquake that happened in the Indian Ocean (M=9) was carried out from December 19 to December 26, 2004. The GPS-NAVSTAR navigation system was used for the monitoring. Analysis of ionosphere parameter variation was carried out using the radio-translucence method. Ground stations of the international geophysical network (IGS) were used as observation centers. The nearest station (NTUS) was situated about 1,000 km from the earthquake epicenter. Locations of GPS receivers and the trajectories of sub-ionospheric points based on GPS observations carried out during the preparation and realization phases of this tsunamigenic earthquake are shown in Fig. 1.

The radio-translucence method enables to organize the monitoring of an area of the ionosphere situated at a distance of up to 1,500 km from the station [4]. The trajectory of GPS satellite #7 was closest to the earthquake epicenter (about 180 km). The data collected using this satellite over the epicentral area of the underwater earthquake enabled to detect an abnormal change in electron content for the F2 ionospheric layer.

GPS receivers installed at the stations HYDE and BAN2 were used for determination of background ionospheric condition, and for inspection of on-board equipment operation on satellite involved.

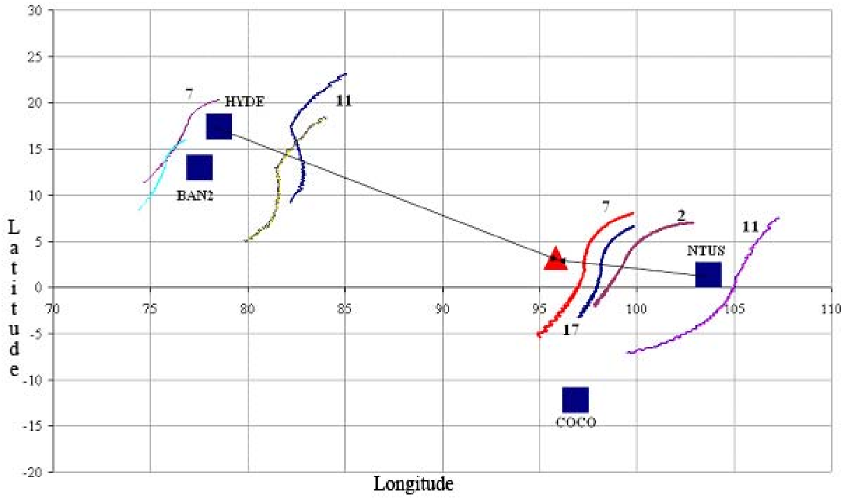


Fig. 2. Location of GPS receivers and trajectories of sub-ionospheric points in relation to the earthquake epicenter

4. Monitoring results and their analysis

Results of data processing obtained by radio-translucence of the ionosphere (satellite #7) during the period of December 19 - 26, 2004 (4:00 - 7:30 UT) are displayed in Fig. 2. Processing results show that some days during the period of 5:30-6:30 UT a noticeable decrease in electron content for the F2 layer took place above the area limited by the coordinates 2.01^{o}-5.33^{o}N and 97.3^{o}-97.4^{o}E, (see Fig. 2). As can be seen, this area is close to the earthquake epicenter (3.259^{o}N, 95.824^{o}E). As we can see in Fig. 2, the decrease of the electron content maximum Ne_{max} in the ionospheric layer F2 started on December 21, 2004 (5 days before the earthquake) and restarted on December 25, 2004 (one day prior to earthquake). No significant change in electron content evaluated on the basis of data collected from ground stations HYDE and BAN2, situated at greater distances, was detected. It seems that Ne_{max} decrease was caused by the processes related with the growing seismic activity, since the data collected from other satellites observed during the same period in other areas have not revealed any unique features in the variation of electron content in this ionospheric layer. Moreover, the decrease in Ne_{max} was registered in the daytime (local time) when the electron content maximum in the F2 layer over this region was usually observed. It's possible that such a change in the state of the ionosphere may be typical of tsunamigenic earthquakes.

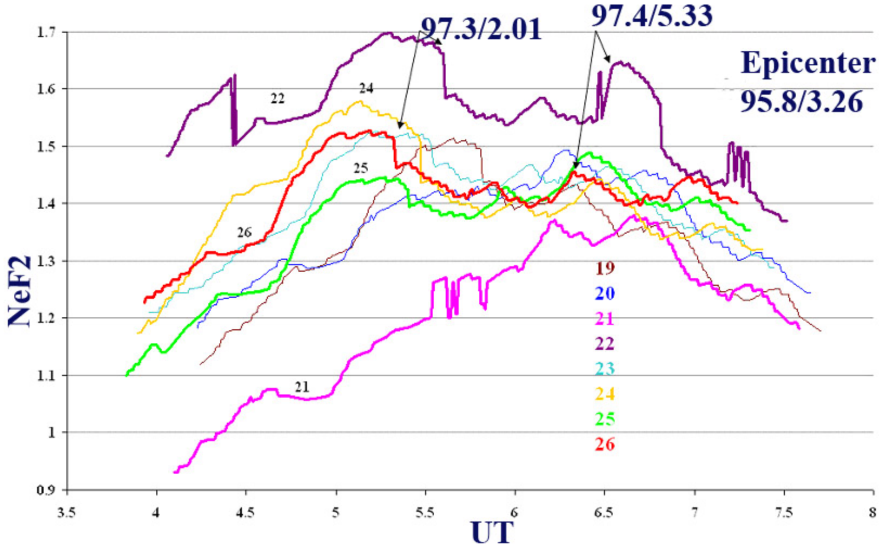


Fig. 3. Changes in maximum values of electron content in the F2 ionospheric stratum derived from the satellite #7 observations (December 19 - 26, 2004; NTUS).

Results from monitoring the ionosphere altitude distribution of electron content obtained using the radio-translucence method are shown in Figures 3 and 4. A sharp (almost 2x) decrease in electron content Ne_{max} was detected on December 25, 2004 (one day before the earthquake) using observations of satellite #11 carried out from ground station HYDE situated quite far from the earthquake epicenter (see Fig. 3). The minimum values of electron content were also detected five days before the earthquake based on data for satellite #7 observations (see Fig. 2). Then, during the three days that followed we registered a growth in electron content maximum (see Fig. 3). In data obtained for this satellite from other (more remote) points, no anomaly in the distribution of electron content was detected during these days.

A local decrease in the maximum value of ionosphere electron content was also detected on December 24, 2004 using data from satellite #7 (Fig. 4a). The process of change in electron content distribution in the plasma envelope is well seen in Fig. 4b. This process began on December 23-24, 2004. A rather low value of electron content registered on December 21, 2004 is, apparently, caused by changes in general geophysical situation, since the similar type of variation of altitude distribution Ne was observed for all available satellites irrespectively of azimuth, nor area of observation.

According to data obtained by the specialists of the US National Earthquake Information Center (NEIC) and the US-based Harvard Center (HARVARD), the movements in the earthquake epicenter were caused by compressive strains of almost the same magnitude and oriented in South-West direction, as well as by tension stresses oriented in North-East direction [10]. This data was obtained through calculation based on the centroid moment tensor method. Fig. 5 presents a map of the area, the rectangle being used to outline the fault site. The epicenter of the earthquake is marked by an asterisk. The map was downloaded from the site of USGS [10].

It should be noted that the decrease in electron content detected before the earthquake was observed over specific local area. Its minimum value was registered at about 5^h UT at a point with coordinates 17.51°N and 82.37°E. The orientation of this area has practically corresponded to the direction of tension stresses, i.e. North-East. The local and short-term character of this phenomenon is confirmed by the fact that the decrease of Ne_{max} was not detected in the data collected from ground station BAN2. The trajectory of sub-ionospheric points for this station passed through the same area at about 1.5 hours before the moment of appearance of this ionospheric effect. It could be concluded that the seismic effect on the ionosphere was in this case of short-term (less than 2 hours) character, and that the area of this effect was mainly oriented to the North-East which corresponds to the direction of tension stresses.

The data collected by the US Geologic Service allows us to draw a conclusion that the direction of tension stresses almost coincides with the direction «epicenter – ground station HYDE». This could explain the sharp decrease in electron content detected on December 25, 2004 by our team using satellite #11 data registered from ground station HYDE (see Fig. 3). The size of the fault area did not exceed 200 km in width and 500 km in length. The earthquake epicenter was located in the lower right corner of the fault area. That enables to assume that the orientation of the fault can be determined based on shift of ionospheric disturbances. Moreover, the size of the area of the dip in electron content in the latitudinal direction corresponds quite well to the size of the fault area in this direction (2°-6°N).

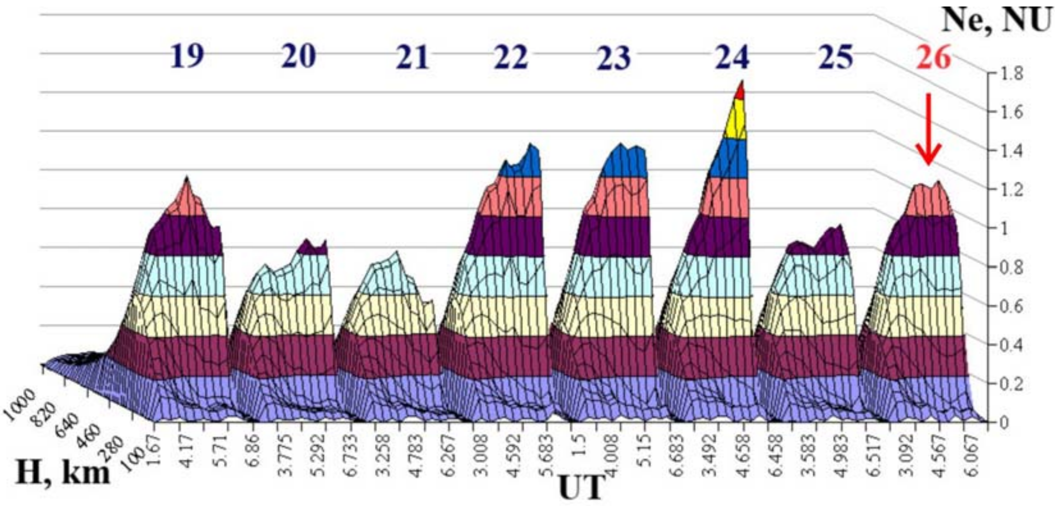
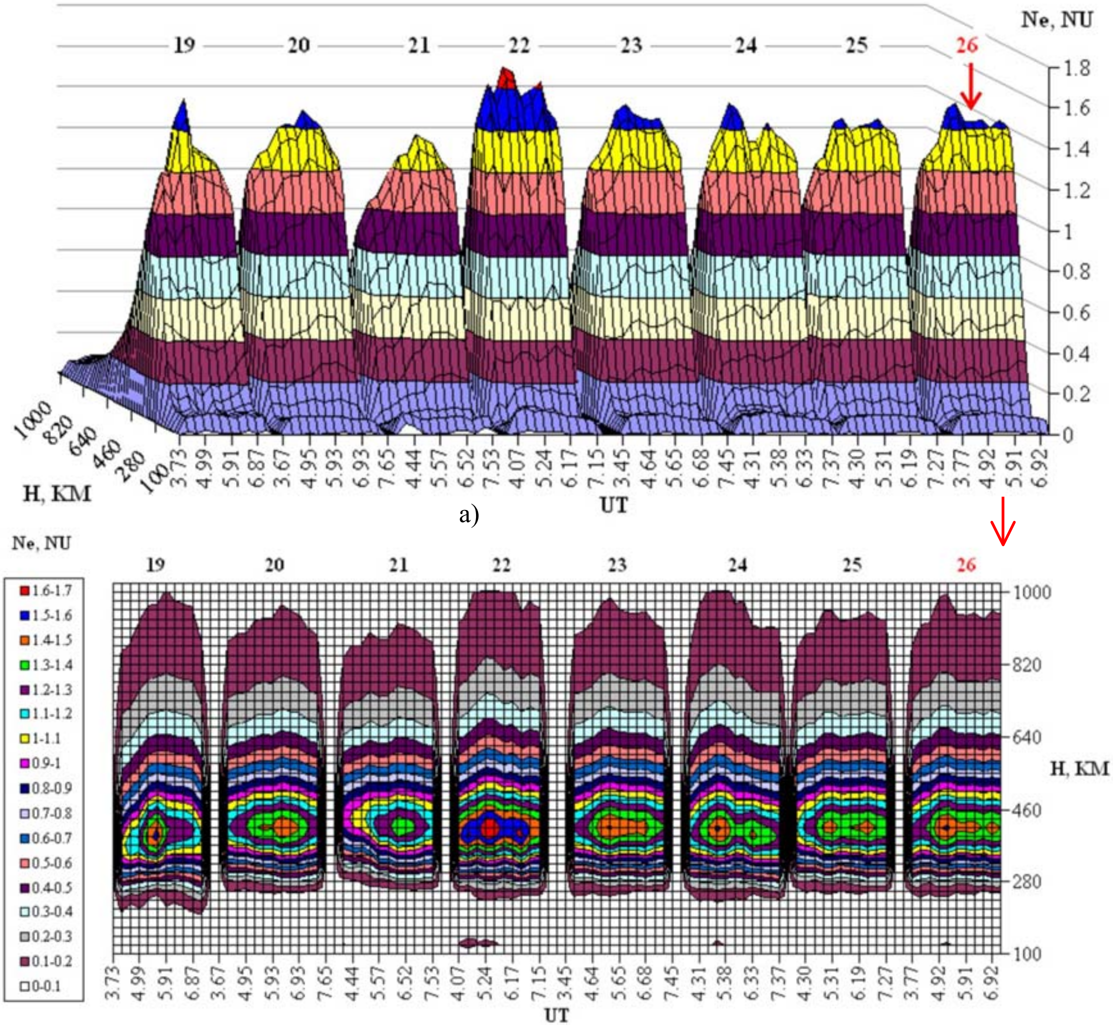


Fig. 4. Altitude distribution of electron content in the ionosphere (satellite #11, HYDE, December 19 - 26, 2004)



b)

Fig.5. Altitude distribution of electron content in the ionosphere (a) and its plan view (b) (satellite #7, ground station NTUS, December 19 - 26, 2004)

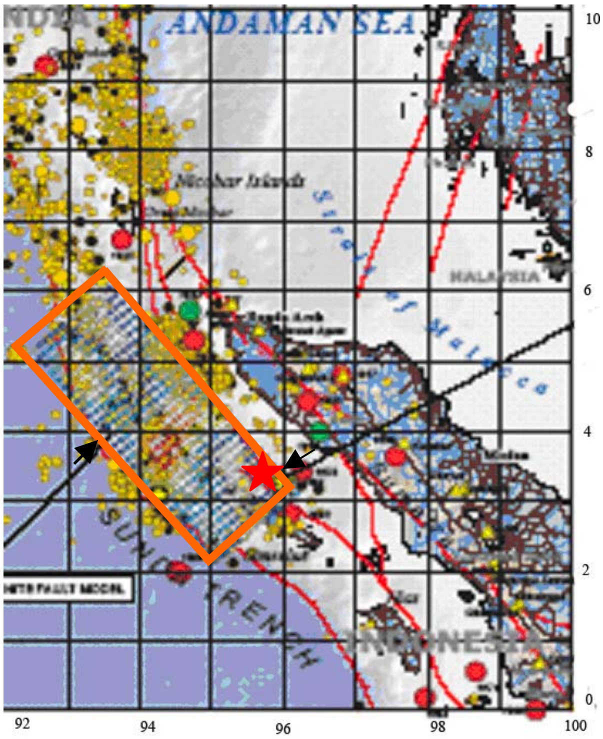


Fig. 6. Map of underwater earthquake region near Sumatra (USGS, 2004)

5. Conclusions

There were detected ionospheric precursors of the catastrophic (M=9) underwater tsunamigenic earthquake which can be used for monitoring of seismically endangered and tsunami hazardous regions of the ocean.

It was established that the area of electron content decrease is observed several days before an earthquake. Such long-term variations in electron content were not yet detected before for ground earthquakes. It may be a characteristic only of tsunamigenic earthquakes. The propagation direction and magnitude of ionospheric disturbances allows us to evaluate the orientation and size of the fault area.

These hypotheses need to be confirmed by further research.

Acknowledgement

The research has been conducted under the support of the Russian Foundation for Basic Research (RFBR grant № 04-05-64207) and the program of Russian Academy of Sciences «Plasma processes in the solar system».

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