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Low-latitude ionospheric disturbances associated with earthquakes

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Abstract
Topside electron density measured on satellite board was analyzed. It was shown that before the two considered earthquakes with their epicenters located at low and equatorial latitudes the stable modification of the ionosphere both at and above the height of the *F*-layer peak was observed. Electron density gradually decreased and its spatial distribution looked like a funnel located either immediately over the epicenter or from its one side. Electron density irregularities of 300-500 km size in a meridional direction also occurred side by side with the aforesaid background large-scale depletions. For detection of local structures of more than 1000 km extent, the method of natural orthogonal component expansion was applied; spectra of smaller scale inhomogeneities were investigated by means of the Blackman-Tukey method. A proposal is made for observed experimental data interpretation.

Key words *ionosphere – equatorial anomaly – low latitudes – earthquakes*

1. Introduction

There is a fairly large body of literature now to show that earthquake-correlated events do exist. Most attention has been focused on those that occur prior to an earthquake because it is hoped that they can be used to predict earthquakes. Of special interest are ionospheric perturbations at the stage of preparation of an earthquake in a seismoactive area (Liperovsky, 1992; Hayakawa and Fujinawa, 1994; Hayakawa, 1999). The main task in this connection is to distinguish ionospheric disturbances of internal origin (caused by a tectonic activity) and external ones (caused by the rest of reasons, including solar and geomagnetic activity, neutral atmosphere dynamics, etc.). The solution turned out to be not so simple. Despite the many reports of ionospheric parameters variations observed prior to earthquakes, however, no clear cause-and-effect relationship has been identified so far.

Another way seems to be more realistic. It is necessary to make a ionosphere modification empirical model on the eve of the forthcoming earthquake based on all available retrospective data and a uniform approach. Common specific features of the ionosphere behavior before earthquakes would be included in such a model; therefore a valuable conclusion of the seismo-ionospheric effect existense or absence would be possible on its base. It has to be done with due care with regard to the epicenter position, because physical processes in the ionosphere of high, moderate and low latitudes differ from each other. Unfortunately, publications in this area imply observations made only at moderate and high latitudes. Equatorial events have not been mentioned at all.

The aim of the present work is to study the modification of the equatorial and low-latitude ionosphere before two strong earthquakes.

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2. The experimental data description

Data of electron density onboard measurements of ALOUETTE-1 (Alouette-1, April, August, 1963) satellite were used. Two earthquakes were considered with their epicenters placed in equatorial and low latitudes in American longitudinal sector. The former of magnitude $M = 7.75$ occurred on August 15, 1963 at 17 h 25 min UT, the epicenter being placed at a point with coordinates $\varphi = -13.8^\circ$, $\lambda = -69.3^\circ$, $(I \approx 0^\circ)$ in the immediate proximity from the magnetic equator. The latter earthquake $(M = 6.88)$ occurred on April 13, 1963 at 2 h 21 min UT, the epicenter being located at a point with coordinates: $\varphi = -6.3^\circ$, $\lambda = -76.7^\circ$, $(I \approx +11^\circ)$. Hereinafter it will be named low-latitude earthquake contrary to the above-mentioned equatorial one. In fig. 1 the epicenter locations of both are pointed by asterisks, the fault position is marked by triangles; the equatorial latitudinal belt is shaded.

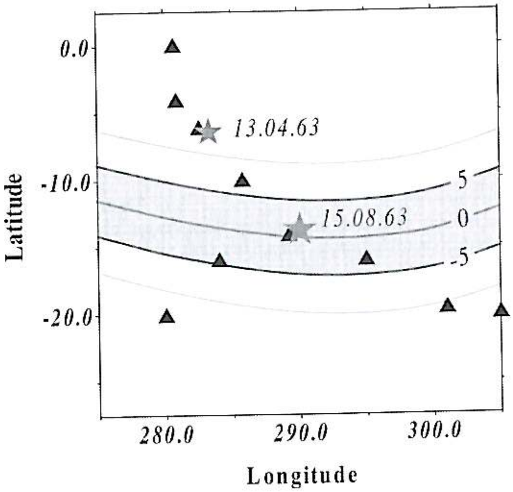

Fig. 1. Locations of considered earthquakes epicenters.

Figure 2a presents the F-layer critical frequencies (f_0F_2) spatial distribution for the former event based on the data collected during 20 satellite passes from July 31 till August 14. Local time of measurements was from 16 h 27 min up to 18 h 27 min. Over the earthquake epicenter and within $\approx 10^\circ$ (1000 km) from it a sufficiently deep (in average to ≈ 5.5 MHz, but for separate satellite passes down to 4.5 MHz) f_0F_2 fall in comparison with the ambient background level of $8 \div 10$ MHz is observed.

For the latter event, f_0F_2 distribution represents a fall as well but the lowest values of frequencies are recorded not exactly over the epicenter, as it is in fig. 2a, but are biased a little to the southwest closer to the magnetic equator. For a map construction (fig. 3a) data of 13 satellite passes, from April 2 till April 13, local time from 21 h 01 min up to 22 h 26 min were used.

The aforesaid observations were made during quiet geophysical conditions.

It is also necessary to note that direct comparison of f_0F_2 dependencies on I $(f_0F_2(I))$ for separate passes shows that the closer the measurement date to an earthquake commencement, the more visible the fall in f_0F_2.

In fig. 4a,b two sets of f_0F_2 (I) curves are presented, namely: for the database covered observations made from the 1st to 9th August (fig. 4a), and those made from 10th to 14th August (fig. 4b) 1963. Contrary to what is normally expected more than 6 days before the event, f_0F_2 values corresponding to equatorial anomaly trough are $7 \div 10$ MHz, and less than 5 days before – they are $5 \div 7$ MHz. Such an effect cannot be due to diurnal f_0F_2 behavior. The satellite working conditions, meant that data used for fig. 4a construction were collected during 16 h 30 min – 17 h LT, *i.e.* somewhat earlier, than data used for fig. 4b construction – 17-18 h LT. In usual conditions, the former curves set have to be placed below the latter and not *vice versa* as seen in fig. 4a,b.

3. Application of the natural orthogonal components expansion method

We applied the Natural Orthogonal Components (NOC) expansion procedure which may be a useful tool for spatial-temporal structure studies (Pushkov, 1976) to a particular case of aforesaid onboard measurements of electron concentration before the earthquake that occurred on April 13, 1963 in order to examine results presented in fig. 3a.

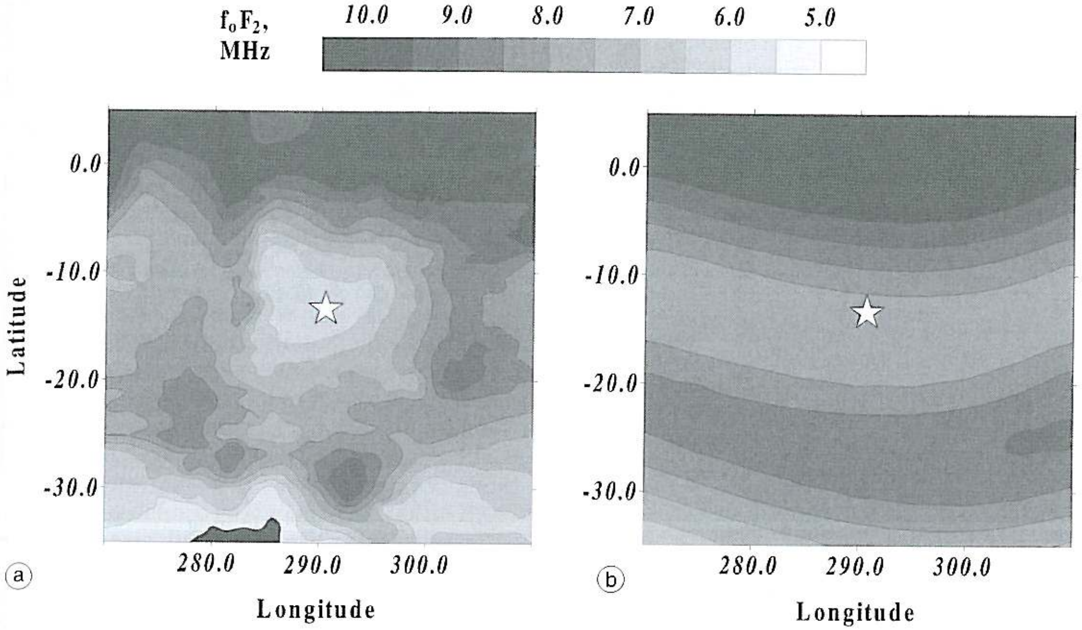

Fig. 2a,b. Spatial distribution of critical frequencies of *F*-layer before the equatorial earthquake occurred on August 15, 1963: a) measured distribution; b) calculated by CCIR model.

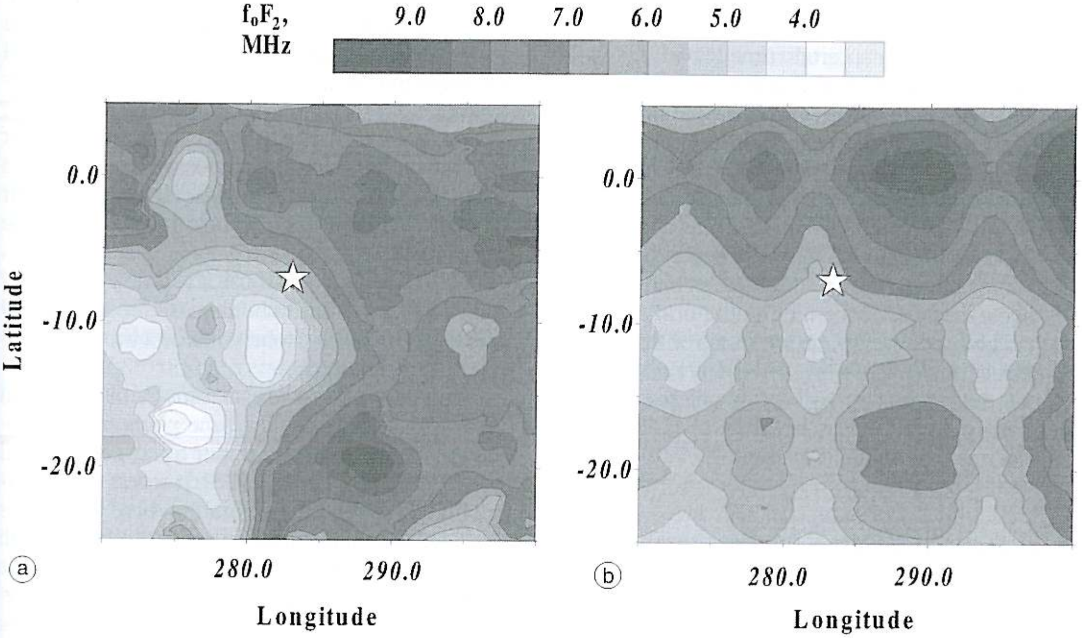

Fig. 3a,b. Spatial distribution of critical frequencies of the *F*-layer before the low-latitude earthquake occurred on April 13, 1963: a) measured distribution; b) calculated by NOC method.

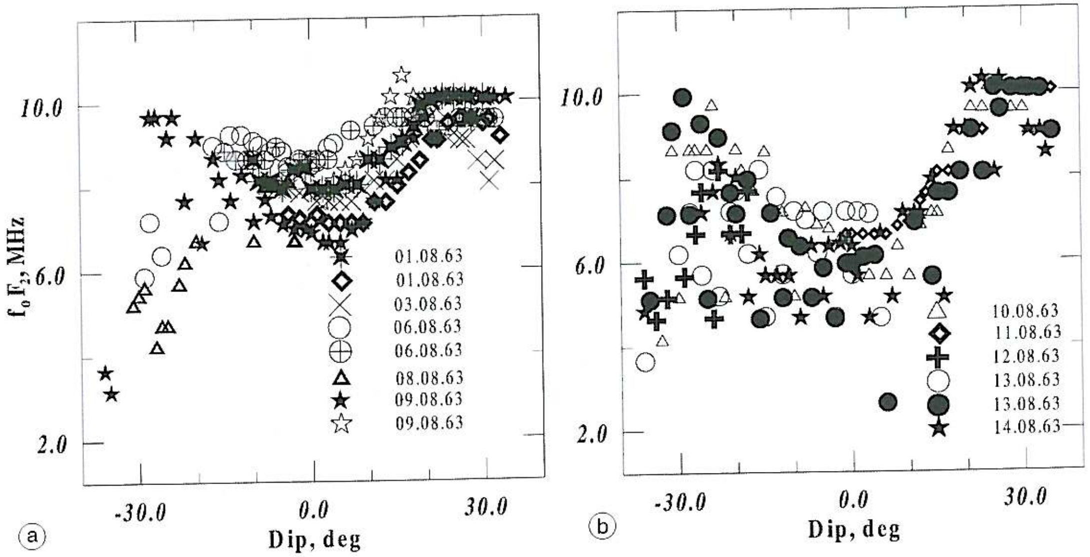

Fig. 4a,b. Ionospheric *F*-region critical frequencies latitudinal dependence: a) more than 6 days; b) less than 5 days before the equatorial earthquake.

The database used consists of a two-dimensional grid of $(f_0F_2)_{i,j}$ numerical values obtained by measurements at a certain time $t_i (i = 1, 2, ..., m)$ and in a certain number of points x_j ($j = 1, 2, ..., n$). In our case m, the number of analyzable orbits in a database ($m = 11$), n, the number of points along each orbit ($n = 49$). Unfortunately, a more representative database for this satellite is not available.

The few first NOC items contain the main properties of the examined field. Especially large changes were found for the first natural component. The spatial temporal structure of this component is presented in fig. 3b and is rather similar to that shown in fig. 3a. A steep fall in a comparison with the ambient level is also observed over the magnetic equator.

4. Experimental data analysis

In preceding sections it was shown that in the two cases considered approximately 10-15 days before earthquakes over the area of their preparation specific modification of the f_0F_2 spatial distribution was observed. It allows us to make the supposition that we really observe the response of the ionosphere at *F*-layer peak level on lithospheric processes on the eve of earthquakes as a sharp reduction of electron density. Whether this fact is really a consequence of earthquake preparation processes in the Earth's lithosphere is not obvious, nevertheless in our opinion there are some arguments in favor of the affirmative.

The assumed seismo-ionospheric effect is exhibited as a strengthening of the equatorial anomaly of the ionosphere inside a limited space over the epicenter.

Generally, equatorial anomaly, or Appleton anomaly, is a regular daytime phenomenon observed at low latitudes under quiet geophysical conditions (Anderson, 1973). It refers to the latitudinal f_0F_2 variations, which involve two crests on either side of the magnetic equator and a trough exactly at the magnetic equator. As a rule, the more clearly the anomaly is expressed, the better-emphasized the displacement between the crests.

Our problem is to show the difference, if any, between regular background spatial distribution of critical frequencies and those observed before earthquakes. For this aim we shall take advantage of the usual methods of seismo-ionospheric disturbances identification (Liperovsky *et al.*, 1992): at first, we compare experimental data recorded close to the epicenter with similar data sufficiently far from it, and, secondly, we compare experimental data with simulated ones (not only over the epicenter position, but also in the whole region between Appleton anomaly crests).

1) Above we have already noted that the size of perturbed areas does not exceed 20°, the ionosphere being quiet outside (see figs. 2a and 3a). This size at least in a zonal direction most likely is determined by the earthquake magnitude. It corresponds to earthquake preparation zone radius defined as $R = \exp M \approx 1000 \div 2000$ km. Moreover, the degree of Appleton anomaly development (the ratio of f_0F_2 values at crests and trough) gradually decreases and the distance between crests becomes less, moving off the epicenter in an east or west direction.

2) According to the CCIR model (CCIR, 1967) for really observed gelio-geophysical conditions before the equatorial earthquake, f_0F_2 values in a trough of the equatorial anomaly should be equal to $6.9 \div 8.0$ MHz; in the northern crest – $8.8 \div 10.3$ MHz, and in the southern crest – $8.0 \div 9.4$ MHz. (Dispersion is caused by the fact that both longitudinal and temporal variations were taken into account). The simulation results testify that the equatorial anomaly in electron density during the considered local time interval should still exist but the degree of its development observed during the experiment (≈ 1.8) exceeds the evaluated one (1.5) even for the most unfavorable version. According to the CCIR model the northern crest of the anomaly should be located at $\approx -5°$, the southern crest – at $\approx -20°$ irrespectively of longitude. In practice, they are separated much further, up to $\approx +5°$ and $\approx -0°$, correspondingly, for longitudes located close to epicenter ($\approx 10°$ to east and west from the latter). Outside the f_0F_2 distribution is similar to simulated one. The simulated f_0F_2 map is shown in fig. 2b.

For low-latitude earthquake CCIR model gives f_0F_2 values in a trough of $7.3 \div 8.3$ MHz and in crests $8.2 \div 8.8$ MHz, the northern crest should be placed at $\approx -5°$ and the southern one at $\approx -25°$. The degree of the anomaly should be small, not more than 1.2, but the really observed value was approximately of 2. In this case, deviation of experimental data from the model is even more obvious than in the previous case. Probably, it is caused by the fact that here we are talking about late evening hours when the natural Appleton anomaly is not already actually observable.

Similar simulation results were obtained with calculations made by the URSI model as well.

Thus, both tests confirm the anomalous behavior of the ionosphere over the restricted zone of equatorial and low-latitude earthquake preparation. For the latter, the existence of an anomalous f_0F_2 structure was supported not only by direct submission of experimental data but also by means of NOC formalized processing.

Above we have considered the f_0F_2 parameter describing electron concentration at F_2 peak height level only. From the analysis of $N(h)$-profiles calculated on the basis of topside ionograms, we detected that the disturbance looking like electron density depletion envelopes even to upper heights. In fig. 5a,b equal electron density variations against geographic latitude are presented beginning from the main peak up to 600 km. Solid triangles designate the latitude of the earthquake on August 15, 1963. Figure 5a is constructed according to data obtained on August 8, the satellite being moved along the orbit displaced relatively to the epicenter by 10° to the west and 5 days before the earthquake commencement. Figure 5b reflects the situation of August 14, on the eve of the event, the orbit being placed immediately over the epicenter. In the figure an increase in equatorial anomaly development degree is clearly seen at all altitudes, beginning from the F-layer maximum up to 500 km. Exactly over the epicenter such an effect is emphasized much better. Taking into account this fact, the ionosphere modification before the two earthquakes considered (at least, topside ionosphere) can be imagined as the funnel located either just over the epicenter or some distance apart.

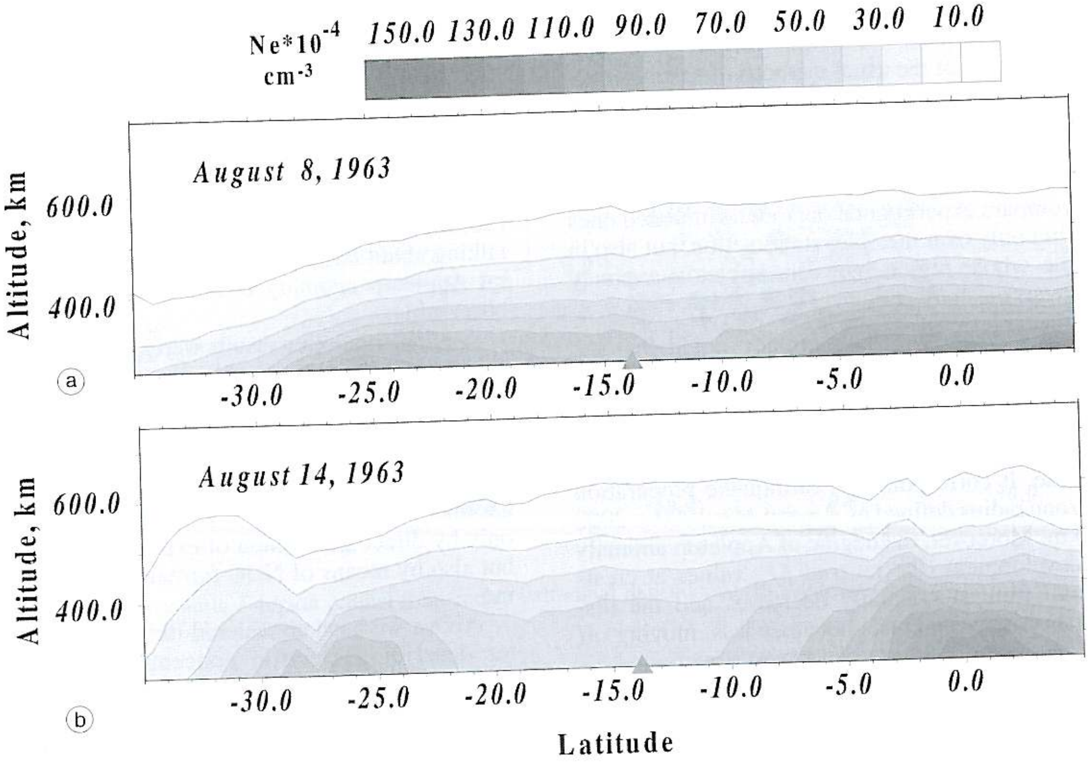

Fig. 5a,b. Equal electron density latitudinal profiles: a) for satellite pass displaced by 10° to the west from the epicenter; b) for the pass exactly over the epicenter.

5. Inhomogeneous structure before the earthquake

Let us turn again to fig. 4a,b. The curves represented in fig. 4a are «smoother» than those represented in fig. 4b. It allows us to assume that 5-6 days prior to earthquakes alongside the more precisely expressed equatorial anomaly in f_0F_2, it is possible to observe large-scale electron density irregularities of several hundred kilometers in size. Spectral analysis of f_0F_2 variations for each satellite orbit was made. The observational database was exposed to the following procedures: at first, the data rows were centered; secondly, in order to remove a low-frequency trend caused by large-scale spatial changes in the ionosphere (in particular, equatorial anomaly, etc.) polynomial approximation of an initial row was applied, the coefficients being determined by the least squares fits method; thirdly, HF-noise of frequencies close to Nyquist frequency was excluded by sliding averaging.

For filtered rows the criteria of least squares estimate constancy in time is fulfilled. It allows us to consider them stationary ones and to apply the standard procedures of spectral analysis. In our case, selective evaluations of normalized spectral density were calculated by the Blackman-Tukey method (Jenkins and Watts, 1969) by means of weighing the autocorrelation function. We used a cosine Tukey window (side band level was of 32 dB, maximum losses o transformation were of 3,18 dB). The window width was selected sufficiently short (~ 10-15% of the row length) in order to provide the spectral estimates stability, the frequency permission being slightly worse.

Figure 6 presents f_0F_2 spectra obtained as a result of calculation for particular satellite passes. It is obvious that spectra for orbits located far from the epicenter (08.08 and 09.08, dashed line) essentially differ from those for orbits located immediately over the epicenter (14.08) and in limits of > 10° to the east and west of it (9.08, solid triangles and 10.08). Besides, for orbits located exactly over the epicenter the spectra also differ from each other: the curve 14.08 was obtained one day before the earthquake, curves 31.07 and 07.08 – 14 and 7 days before, respectively.

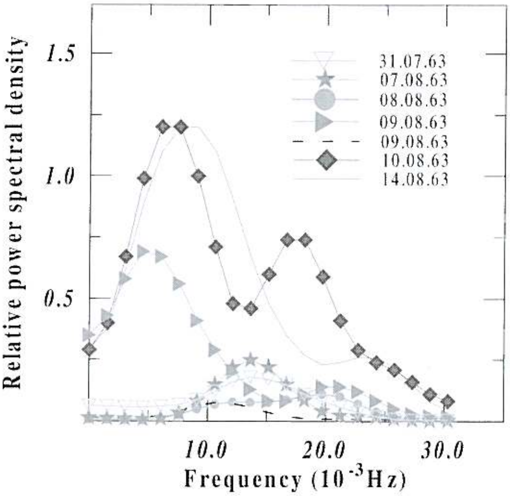

Fig. 6. *F*-layer critical frequencies relative power spectra for the earthquake which occurred on August 15, 1963.

Thus, electron density inhomogeneities at 300-500 km along a meridian is a characteristic feature of the ionosphere before an equatorial earthquake. They became more evident closer both in time to an earthquake or in distance to the epicenter location. The same also applies to low-latitude earthquakes.

It is known that such kind of ionospheric irregularities have to lead to oblique traces and some other peculiarities on vertical sounding ionograms. They really were observed experimentally. As a rule, they trigger the «hierarchy» of smaller scale inhomogeneities.

There are several generation mechanisms proposed to explain the variety of inhomogeneities in low-latitude ionosphere during quiet conditions (Gershman, 1974). They deal as a rule with background plasma variations due to electric fields, neutral winds, etc. Our case is not exclusion: it seems that the observed phenomena could also be caused by the aforesaid background plasma perturbation before the two considered earthquakes.

6. Discussion

Thus, one-two weeks prior to the considered equatorial or low-latitude earthquakes at a level of the main ionosphere maximum and somewhat higher the funnel-shaped reduction of electron density was observed inside the restricted area. In *both* cases minima were recorded close to the earthquake epicenter longitude over the magnetic equator. In another words, an increase of the f_0F_2 equatorial anomaly degree and crests displacement further from each other were the main peculiarities for seismically disturbed areas. This effect becomes more noticeable approaching the earthquake commencement time and its epicenter position. The above information does not claim sufficient completeness, but only indicates the existence of a number of specific features of the equatorial and low-latitude ionosphere during the earthquake preparation process. Whether they are essential regional properties caused by forthcoming earthquakes can only be confirmed by further studies.

Nevertheless, already at the given stage it is possible to offer a version of their interpretation based on the supposition of electromagnetic connection in the «lithosphere-ionosphere» system taking into account a conventional model of Appleton equatorial anomaly formation. Let us suppose that the electric field generated due to lithospheric processes penetrates up to *E*-layer height and its horizontal component sufficiently increases the field of equatorial electrojet. The upward E×B-drift will therefore be amplified. Consequently, it would lead to the same phenomena as were observed experimentally. The problem of lithospheric disturbance transport up to the ionospheric dynamo-region altitude remains unsolved. A similar approach will also be valid for the low-latitude earthquake if we assume that the electric field of lithospheric origin is generated not only over the epicenter, but also in the whole area of earthquake preparation. If this is so, electron density depletion will already be observed close to zero inclination and the dimension of the seismoionospheric disturbance will depend on the earthquake magnitude.

7. Conclusions

1) The topside ionosphere vertical sounding data before the two strong earthquakes with their epicenters placed near the magnetic equator were analysed. It was shown that 10-15 days prior to the event at the main peak height and somewhat higher the funnel-shaped reduction of the electron density in comparison with an ambient background level and simulated values was observed in a restricted area over the earthquake preparation zone. There are some reasons to suppose that the observable effect is connected to seismic events. The considered examples show that the low-latitude and equatorial ionosphere behavior during earthquakes preparation have specific features in comparison with mid-latitude ones.

2) The possible approach to the interpretation of the observed phenomenon is offered within the framework of the supposition of the availability of electromagnetic interaction between lithosphere and ionosphere.

Acknowledgements

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