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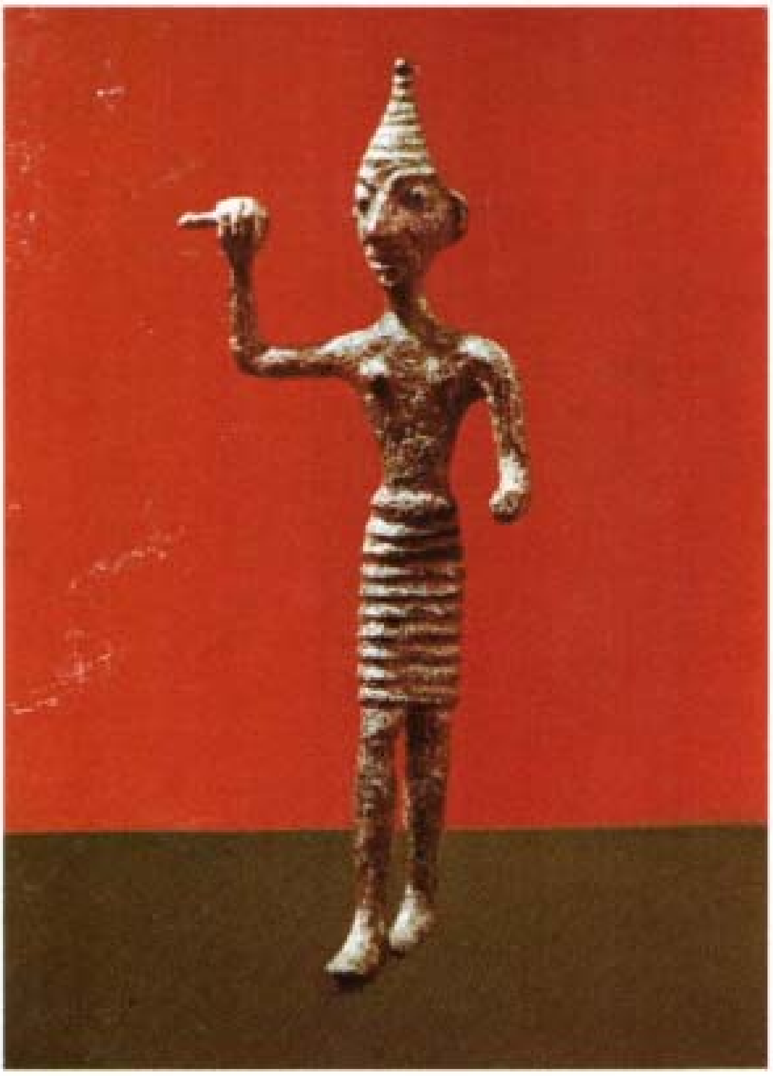

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PARTIAL REFLECTION TECHNIQUE INVESTIGATION OF THE LOWER IONOSPHERE RESPONSE TO STRONG REMOTE EARTHQUAKES

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Abstract. Using the technique of partial reflections there were experimentally studied and determined characteristics of wave disturbances (their type, period, duration and propagation velocity) generated and enhanced in the midlatitudinal lower ionosphere after strong earthquakes. There were investigated influences of the earthquakes on temporal characteristics of radio noise at f=2-4 MHz depending on power, distance to an observation site, kind of place (over land, under water) and depth of an earthquake.
Key words: earthquake, partial reflections, wave disturbances, ionosphere.

1. Introduction

Earthquakes of sufficient intensity may be a source, fixed in space and time, of wave disturbances in the ionosphere and of geomagnetic-field variations connected with them. This is valid for both an earthquake preparation-stage and a seismic shock moment as a seismic centre is a source of not only intensive large-scale electric fields and radio-frequency radiation (earthquake preparation) but of a powerful acoustic pulse as well. There are two kinds of investigations of the ionosphere's response to earthquakes: 1) the investigation of short period (from tens of seconds to tens of minutes) and long-period (from hours to days) precursors of the earthquakes and 2) the investigation of effects of the earthquake itself on ionospheric parameters, which is important for aims of radio communication, radio navigation, etc. During the last two decades there are conducted intensive investigations in both the directions. There is a great amount of literature on electromagnetic precursors of earthquakes at ionospheric heights. Many papers are devoted to earthquakes having effects on characteristics of LF- and VLF-radiowaves. Reactions of the E- and F- regions of the ionosphere to seismic events have been studied in rather good way. A wide amount of literature on these problems is given, for instance, in the monographs by Hayakawa and Fujinawa (1994), and Hayakawa (1999). A question as to the ionospheric D-region reaction to such events both near the earthquake epicentre and at considerable distances from it remains studied insufficiently till present. In Garmash et al. (1990), Gokov et al. (1993), Gokov and Gritchin (1996) and Gokov and Tyrnov (1997) using the measurements obtained by the partial reflection technique, there was found an increase of several times in the radio noise signal intensity at f = 2-4 MHz during (over about 3-5 min) some strong distant earthquakes, the ionospheric D-region response to such events being also considered.

In this paper using the data obtained at Kharkiv National University by means of the partial reflection technique during more than 180 earthquakes of different intensities, we have studied radio noise variations at f = 2-4 MHz and characteristics of the disturbances in the D-region of the ionosphere, generated or enhanced over these periods.

2. Experimental Equipment and Investigation Methods

Our investigations were carried out on the basis of a retrospective analysis of the data obtained by the partial reflection technique over 1983 to 1998. The measurements of partially-reflected signals and radio noise were conducted using the equipment from Tyrnov et al. (1994) in the middle latitudes in the vicinity of Kharkiv. The main parameters of the facility are as follows: the operating frequencies being f = 2-4 MHz, the duration of sounding pulses being 25 ms with the repetition frequency F = 1-5 Hz. The amplitudes, $A_{no,x}$, of radio noise and those of mixture of radio noise and partially-reflected signals, $A_{o,x}$, of the ordinary (o) and extraordinary (x) magnetic-ionic components were recorded at 15 height levels (beginning from 45 or 60 km) in a 3-km step. Durations of the $A_{no,x}(t)$ and $A_{o,x}(z,t)$ records (here t is the time, z is the height above the Earth) obtained during different seasons and days were 20 min to 24 hours and more (the continuous measurements). For a further analysis there was carried out statistical processing of the height-time data of $A_{no,x}(t)$ and $A_{o,x}(z,t)$: by means of averaging $A_{no,x}$ and $A_{o,x}$ over 60 s, there were obtained data of $\langle A_{no,x}(t)\rangle$ and $\langle A_{o,x}(z,t)\rangle$; the amplitudes of the partially-reflected signals were determined by subtracting as follows: $\langle A_{so,x}\rangle = \langle A_{o,x}\rangle - \langle A_{no,x}\rangle$. For each record there were calculated temporal dependences of $a_{o,x}(t) = \langle A^2_{no,x}\rangle / \overline{\langle A^2_{no,x}\rangle}$ over a 20-minute interval (±10 min with respect to an earthquake moment; here the line above being an average sign and $\overline{\langle A^2_{no,x}\rangle}$ is the average value of $\langle A^2_{nn,x}\rangle(t)$ over this time interval), which were used when analysing the data by the epoch superposition technique. The total number of the earthquakes with energy $E > 10^{11}$J occurred over land and under water (oceans, seas) at the range of $R \geq (1\text{-}15)\ 10^3$ km and the depth of h = 1-100 km was more than 180. 115 events were recorded with $E > 10^{12}$J (the Richter scale magnitude being $M > 5$). The information on the earthquakes were taken from Catalogues of strong earthquakes: Moscow, WDC-B. Effects of other natural and artificial sources of disturbances were excluded by selecting experimental records of $A_{no,x}(t)$ and $A_{o,x}(z,t)$.

3. Radio Noise Variations over 2-4 MHz.

There were analysed $A_{no,x}(t)$-variations for 65 earthquakes with $E < 10^{11}$ J and h ~ 1-100 km, occurred over land and under water at different R-distances from the observation site. Radio noise reactions ($A_{no,x}(t)$ being increased several times over 1-5 min) at earthquake moments were recorded in 6 cases (R_1 < 1000 km, h < 40 km, the magnitude M ~ 4.5).

Let us consider our experimental results obtained for the earthquakes with $E > 10^{12}$J ($\sim 10^{12}$ - 10^{16}J). Fig.1 shows time dependences of the radio noise intensity, $<a_{o,x}(t)>$, normalized to the average value during a 20-minute observation over the earthquake periods. The earthquake moments are marked with arrow. When plotting the $<a_{o,x}(t)>$ - dependences, there was used the epoch superposition technique, the number of the $a_{o,x}(t)$- realizations being 115 and 82 out of them were obtained for the earthquakes over land, the rest occurred under water. It is seen that at the moment of the earthquake (about 1 minute before and 2 -4 minutes after), there occurs an increase in $<a_{o,x}(t)>$ ($A_{no,x}$ (t)). Note that the duration of the fronts in bursts (increasing) of $A_{no,x}$ (t) is t_1 ~ 10-30 s.

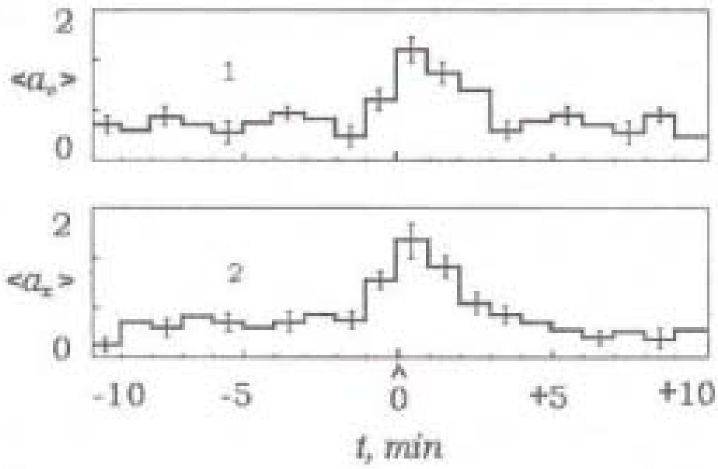

Fig. 1. Temporal dependences of radio noise intensity, normalized to the average value in an earthquake period.

Table 1. Quantitative characteristics of radio noise reactions over 2-4 MHz to remote powerful earthquakes

Events		Total number	Over Land	Under Water
"yes":	+	58	49	9
"no":	-	57	33	24
h >50 km	+	8	4	4
	-	16	9	7
h <50 km	+	50	45	5
	-	41	24	17
h <10 km	+	18	17	1
	-	15	7	8
R_l < 1000 - 3000 km				
h >50 km	+	1	-	1
	-	1	1	-
h <50 km	+	10	10	-
	-	3	3	-
R_l > 3000 km				
h >50 km	+	7	4	3
	-	14	7	7
h <50 km	+	39	36	3
	-	40	21	19

In Table 1 there are presented quantitative data on radio noise reactions to remote powerful earthquakes. The presence of a burst (an increase) of $A_{no,x}(t)$ at an earthquake moment is marked with "+", the absence of it being marked with "-". It is seen that in the general case when the $A_{no,x}$ (t) -records were obtained during the earthquakes over land and under water, reactions in $A_{no,x}$ (t) were observed in ~50% of the events. For the earthquakes over land, bursts in $A_{no,x}$ (t) were observed rather frequently: in about 60 % of the events; as to those under water, they occurred in 27 % of the events. A similar classification of the data was made for the shallow (h < 50 km) and deep-focal (h > 50 km) earthquakes, the surface ones (h < 10 km) being included as well. These results are given in Table 1. For the shallow-focal and surface earthquakes over land, the probability, W, of arising disturbances in $A_{no,x}(t)$ is considerably higher than that for the deep-focal ones. And vice versa, for the earthquakes under water, disturbances in $A_{no,x}$ (burst-increasing) were observed to be for h> 50 km 1.5-3 times more frequently than those for h < 50 km. Moreover, practically the same probability of disturbances in $A_{no,x}(t)$ during the earthquakes over land and under water is characteristic of the deep-focal earthquakes.

We considered the earthquakes with R_l < 1000 - 3000 km and those with R_l > 3000 km separately (see Table 1). In the first case the probability, W, of disturbances in $A_{no,x}(t)$ is rather high, being about 77 %. In the second (R_l > 3000 km, h <50 km), the W-value is slightly lower for the land events, being low ($W \approx 13.6$ %) for the earthquakes under water. For those with h > 50 km, we have in this case $W \approx 35$ % over land and under water. On the whole, the probability of arising disturbances in $A_{no,x}(t)$ is W < 50 % for R_l > 3000 km.

4. Disturbances in the Lower Ionosphere

Earlier it has been found in Garmash et al. (1990) and Gokov and Gritchin (1996) that it is possible to record quasi-periodical disturbances in ionospheric plasma after earthquakes using the partial reflection technique: height - time dependences of $A_{o,x}(z,t)$ and $A_{no,x}(t)$ display quasiharmonical variations with different time delays. When there are no other sources of disturbances, such variations of $A_{o,x}(z,t)$ and $A_{no,x}(t)$ seem to be caused by earthquakes. On the basis of analysing the bank of the data on $A_{o,x}(z,t)$ and $A_{no,x}(t)$, obtained during the earthquakes and control days (when there were no strong earthquakes), it has been found that for the earthquakes with E < 10^{11}J there are no above-mentioned effects under any R_l- or h- values. With

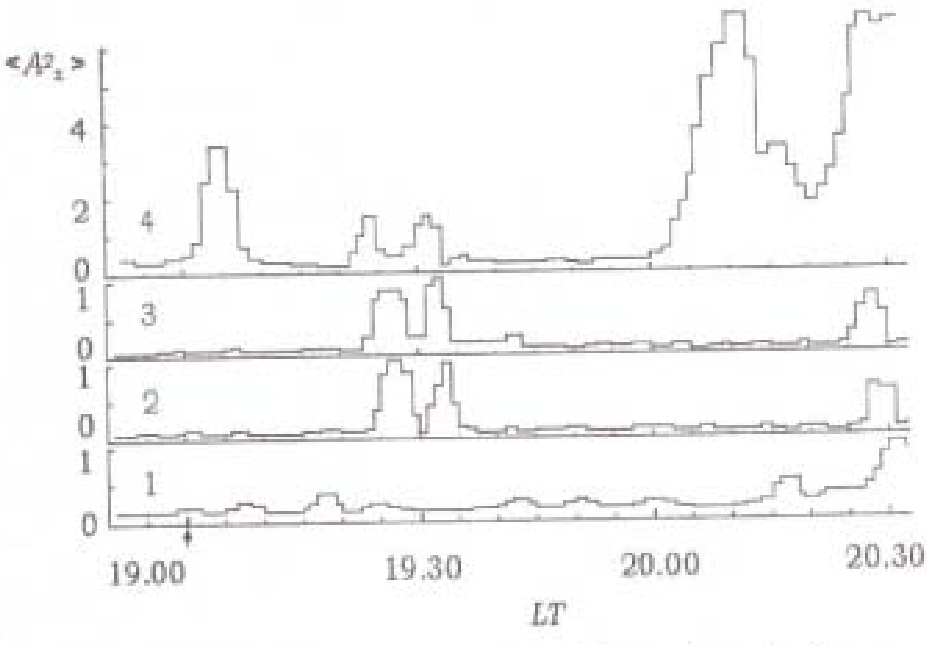

Fig. 2. Dependences of intensities of partially reflected signals from 105, 81 and 57 km (curves 2-4) and those of radio noise (curve 1) which were obtained during the earthquake on August 13, 1987

the probability $W \approx$ 65-70% quasi-harmonical variations of $A_{o,x}(z,t)$ and $A_{no,x}(t)$ were observed for the earthquakes with $E > 10^{12}$J over land; as to those under water, $W \approx$ 40%. Fig.2 shows an example of disturbances during the earthquake with $E > 10^{14}$J and $R_1 \approx 10^3$ km (curve 1 is $<A^2_{nx}>(t)$, curves 2-4 are $<A^2_x>(t)$ for z = 57, 81 and 105 km, respectively). The experiment was carried out in the afternoon, about 3 hours before sunset. Using time delay of the moment of a burst-increase in $A_{o,x}(z,t)$ with respect to an earthquake, the calculated apparent velocities of propagating disturbances were as follows: $V\sim$ 50; 7-8 and 2 km/s. On the basis of analysing the data bank of the height-time dependences of $A_{o,x}(z,t)$ and $A_{no,x}(t)$, a number of disturbances in the lower ionosphere were found to have $V\sim$ 0.5-100 km/s. Fig. 3a shows a histogram for distribution of apparent velocities of propagating disturbances, $W(V)$. The total number of the disturbances was 168. Fig. 3b shows $W(V)$ histograms for the earthquakes over land (curve 1) and under water (curve 2).

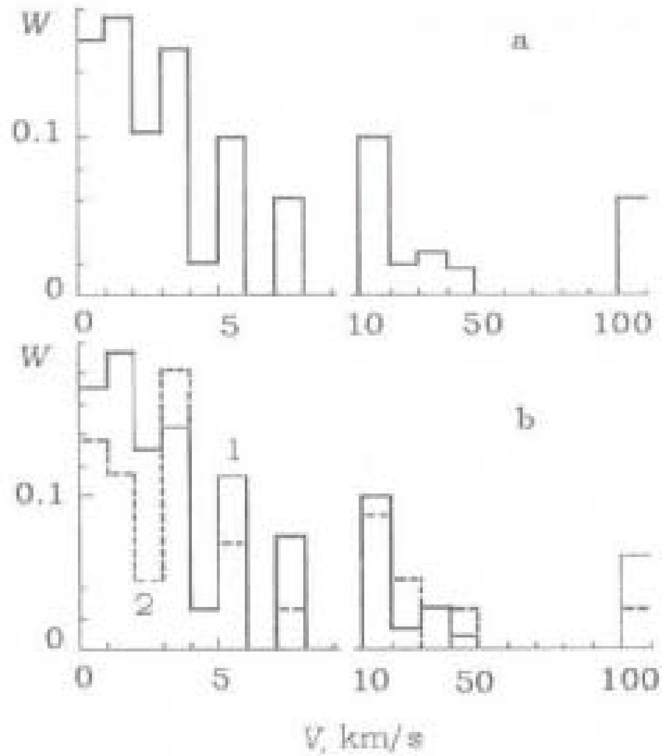

Fig.3. Distribution histograms of disturbance velocities recorded by the partial reflection technique after the earthquakes having $M > 5$.

Our analysis of the given dependences indicates that disturbances having $V \sim$ 0.5- 4, 10-20 and 100 km/s were recorded most frequently during both the earthquakes over land and those under water. There are, however, some differences between the $W(V)$ distributions; thus, for instance, during the earthquakes under water there were most frequently recorded disturbances having V = 3-4 km/s; those having $V >$ 100 km/s were recorded much more rarely. As to the earthquakes over land, disturbances with $V \sim$ 1-4 km/s are recorded more frequently. A classification of possible types of the disturbances having such velocities and giving some information on earthquakes is considered in the next section.

In Table 2 there are presented main parameters of the disturbances (apparent velocities of propagation, durations and periods of disturbances) obtained from the data for $A_{o,x}(z,t)$ and $A_{no,x}(t)$ and from their spectrum analysis. Note that sometimes in addition to the horizontal velocities, V, of the disturbances in the lower ionosphere, one can succeed in determining

Table 2. Main parameters of disturbances in the lower ionosphere, caused by earthquakes

Process duration, min	Quasi-period value, min	Apparent velocity, km/s	Possible wave type
~ 1	-	100	MHD
~ 1	-	10-50	gyrotropic, ion-acoustic
~ 10	2-3	6-8	electromagnetic
~ 10	~ 3	5-6	volume
10-15	~ 3	3-4	surface Rayleigh
10-20	3-8	1.2-3	plasma-acoustic (magnetic-sound, slow MHD-waves)
15-35	3-10	0.4-1	acoustic-gravitational

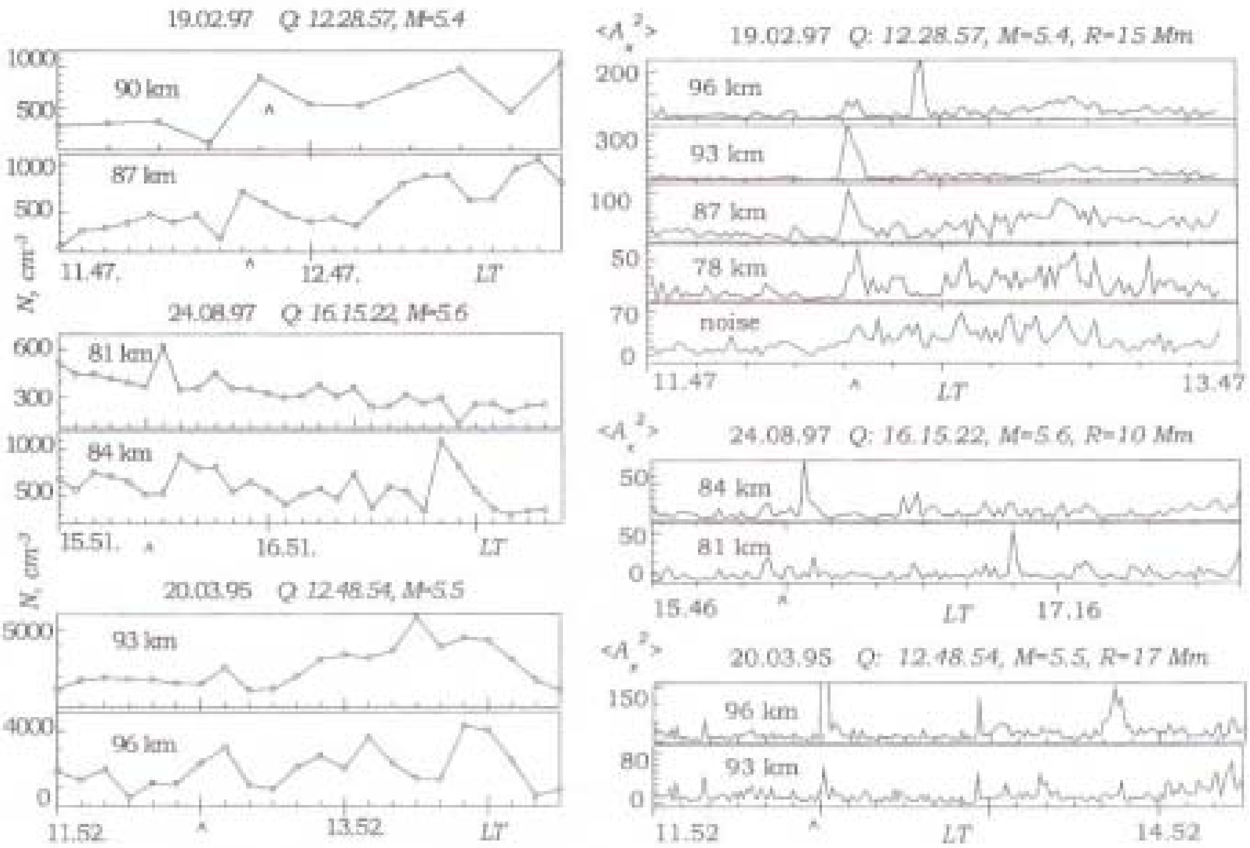

Fig. 4. Examples of $N(z,t)$- and $<A_x^2>(z,t)$ -dependences obtained over a period of strong earthquakes (the earthquake time being marked by an arrow).

apparent velocities, V, of the disturbances propagating in vertical directions. For instance, in the above-mentioned experiment for z = 105-57 km, the delay difference between the disturbances of $<A^2_x>$ is about 3 min, which corresponds to V ~ 300 m/s. In order to find out behaviour of the electron

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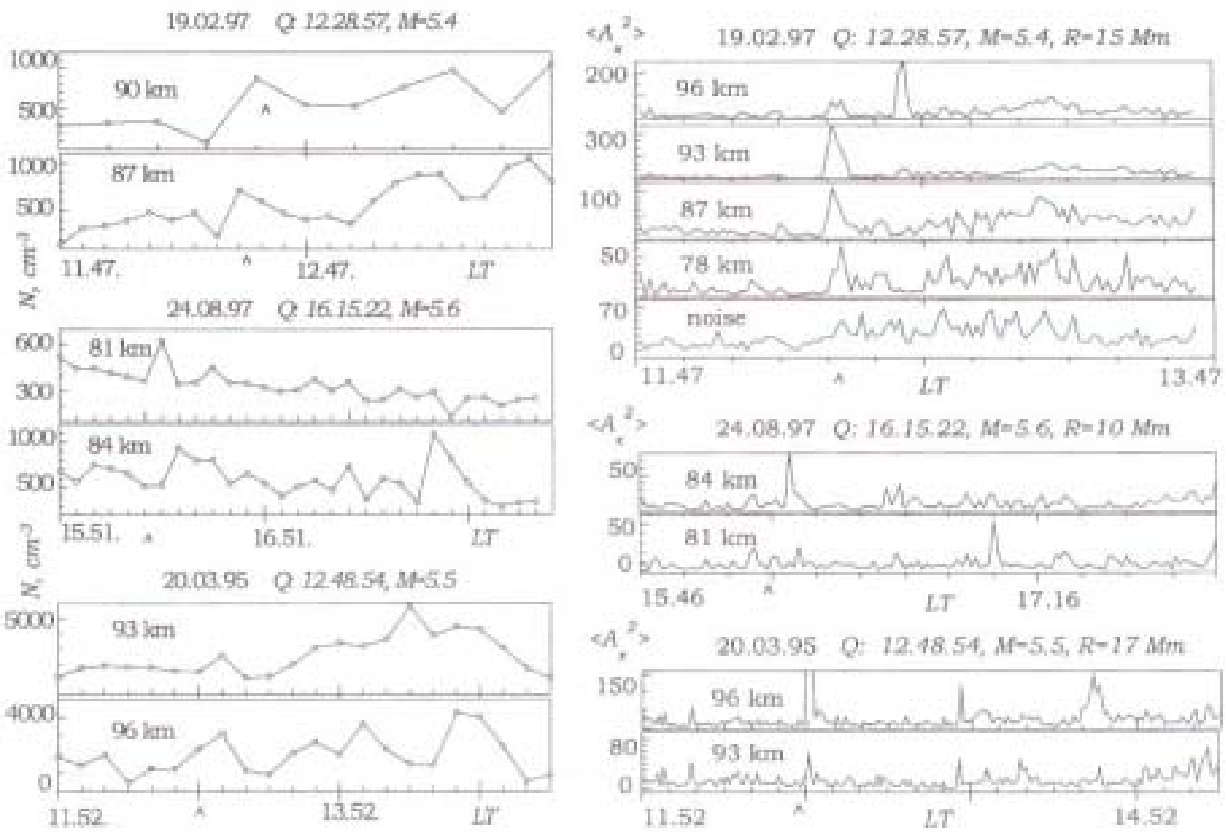

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apparent velocities, V, of the disturbances propagating in vertical directions. For instance, in the above-mentioned experiment for z = 105-57 km, the delay difference between the disturbances of $\langle A^2_x\rangle$ is about 3 min, which corresponds to V ~ 300 m/s. In order to find out behaviour of the electron where $\bar{\alpha}$ -parameter of regularization, Ω - stabilizer. In this piece of research, the stabilizer is chosen to have the form:

$\tilde{\Omega}[N] = \|(N/\bar{N} - 1)(q_{max}/q)^{1/4}\|^2,\ q^{-1} = q_o^{-1} + q_x^{-1}, q_{max} = \max\{q(z)\}$.

Here, $q_{o,x} < A^2_{so,sx} > / < A^2_{no,nx} >$ - signal-to-noise ratio of «o» and «x» waves, respectively, $\bar{N}(z)$ - initial approximation to *N(z)*.

Dependence of the stabilizer $\tilde{\Omega}$ on *N(z)* is not very strong and weakens the effects of data obtained from the altitudes where $q_{o,x}$ are small. The applying of this regularization algorithm allows us to reduce (3 to 5 times) the effects of measurement errors on the restoration of *N(z)* from *R(z)* and extend the altitude range by approximately 10 km. It should be added that the optimization of estimating $< A^2_{m,sx} >$ is achieved at the values of time smoothing intervals ΔT of the order of 5 to 10 min. With decreasing ΔT, errors in the estimates of $< A^2_{m,sx} >$ rise significantly, and with increasing ΔT, variations in *N* are difficult to follow because of smoothing.

The error of the *N(z,t)* calculations was ~ 30%. Fig. 4 shows examples of the height-time variations of *N(z,t)* (the *N(z,t)* dependences were obtained over time intervals of 5 and 10 min) and $<A_x^2>(z,t)$ values corresponding to them (averaging over 1 min). Note main peculiarities in *N(z,t)* behaviour in the vicinity of a moment of the earthquake at z = 81-96 km: sometimes before an earthquake, the *N* value decreases by more than 50% over 5-10 min; at a moment of the earthquake or some minutes after it, we have observed a sharp increase in *N(z,t)* by ~50-200% over 5-10 min, then over 10-15 min *N* relaxing up to undisturbed values taken place. Here we do not consider following *N(z,t)* variation caused by earthquake effects discussed above as they require additional investigations.

5. Discussion

Interaction processes between the lithosphere and the ionosphere have not yet been studied to such an extent which would allow to construct an adequate model of transferring disturbances caused by earthquakes to the ionospheric plasma. Experimental investigation of ionospheric responses to remote earthquakes allows us, in particular, to determine more precisely possible mechanisms and types of the waves transporting disturbances from the earthquakes. Consider some of them.

An earthquake generates a powerful sound pulse propagating up to z ~ 10 km in the form of a knock wave which then transforms into an acoustic and an infrared wave. Some energy of the latter is transferred upwards (up to z ~ 90 km the propagation time being ~ 5 min), captured by the waveguide formed by the regular height anisotropy of the ionosphere conduction at z = 80-120 km (Sorokin and Fedorovitch(1982)). In this waveguide waves propagate with small absorptions over distances up to R_I ~ 10000 km. Propagation velocities of such infrasonic (acoustic-gravitational) waves are within $V \sim 0.4$ -1 km/s, periods being $T \sim$ 3-6 min; according to our experimental data, the process duration corresponds to several periods. Moreover, under an earthquake there occur seismic waves (Yuen et al. (1969)) with propagation velocities of $V \sim$ 3-8 km/s. Surface Rayleigh waves correspond to $V \sim$ 3-4 km/s, volume and electromagnetic waves corresponding to $V \sim$ 5-6 km/s and $V \sim$ 6-8 km/s, respectively.

Seismic waves can propagate globally due to their weak fading. As they propagate along the Earth's surface, there occurs a transformation of these waves into long-periodical acoustic ones; their refraction into the ionosphere taking place as well (Egorov. et al. (1990), Yuen et al. (1969)).

Sound waves in the ionosphere may be transformed into plasma-acoustic waves with the horizontal propagation velocity $V \sim$ 1.3 - 2.2 km/s (Wickersham (1966)). An example of the plasma-acoustic waves may be magnetic-sound waves (Pavlov (1987)), and slow hydromagnetic (HM) waves (Pavlov (1987), Sorokin and Fedorovitch (1982)). Velocities of ion-acoustic wave propagating along the Earth surface are $V \sim$ 20-40 km/s; these waves may also be initiated in the ionospheric plasma by acoustic waves (Ponomarev and Erushenkov (1977)).

In order to explain experimental results, one may also apply a hypothesis of "part-taking" of gyrotropic waves (Sorokin and Fedorovitch (1982)) as a kind of slow HM- waves; their propagation velocities being $V \sim$10-50 km/s.

Moreover, it is known that under certain conditions in plasma, MHD-waves are excited, and their velocity equals to the Alfven one ($V \sim$100 km/s) (Sorokin and Fedorovitch (1982), Rudenko (1985)). Such waves may transfer "information" on disturbances, having minimum time delays ($t \sim$ 10-100 s); we recorded this feature in the $A_{no,x}$ (t) - changes. Assuming this transfer mechanism of disturbances, the $\langle a_{o,x}(t) \rangle$ increase over 2-4 minutes after an earthquake may be explained by different delays (under the same V - values) for different R_l-ranges from an earthquake location. Note that the HM-wave in this case is a trigger factor affecting a magnetic field in the magnetosphere and causing precipitating of the charged particles from the radiation belt into the Earth's atmosphere. These particles cause an ionization increase in the lower ionosphere over the time intervals of $t \sim$1-10 min, resulting in the observed changes in the intensities of radio noise and partially-reflected signals and height-time variations of electron density.

6. Conclusion

The given analysis of the experimental data obtained by the partial reflection technique indicates that earthquakes having a magnitude of $M > 5$ cause in the lower ionosphere several types of the disturbances which appear over distances up to ~ 10 Mm from the epicentre. It is shown that horizontal transfer velocities of these disturbances change within wide ranges, $V \sim$ 0.5-100 km/s. There is given a possible classification of the disturbances, corresponding to the up-to-date ideas about the lithosphere-ionosphere interaction.

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