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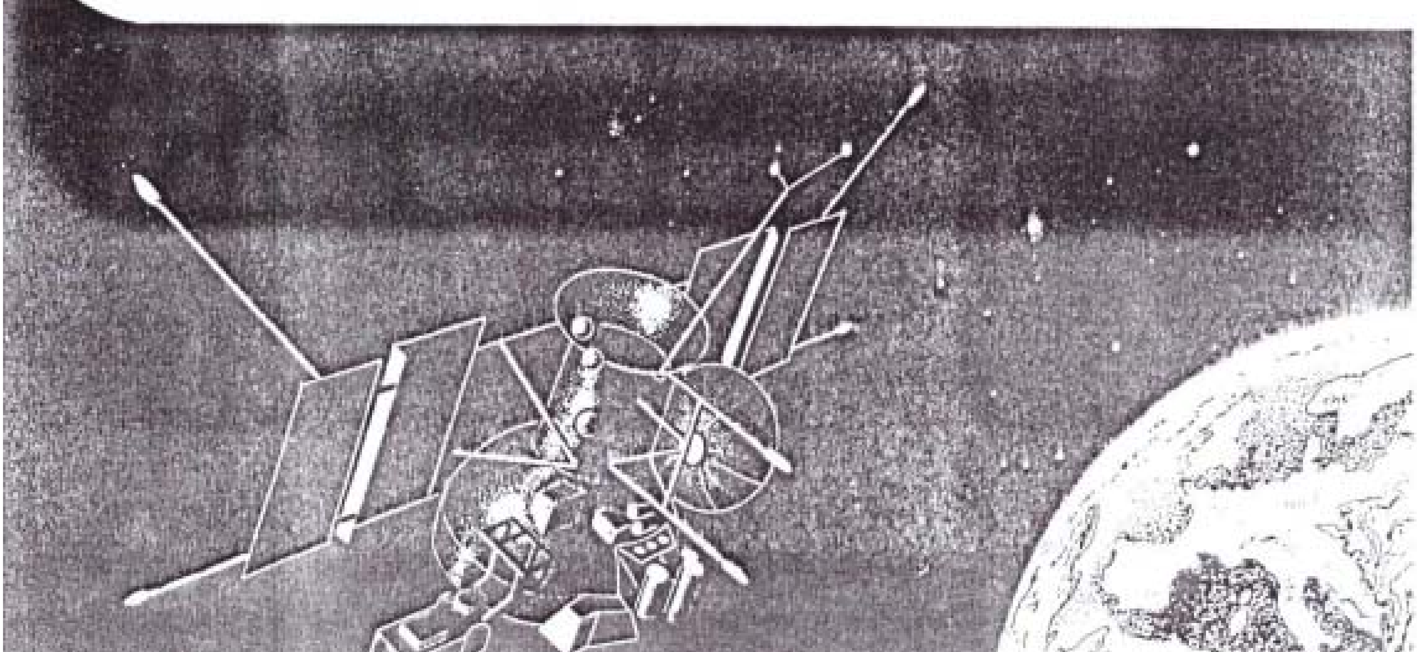

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Application of the Partial Reflections Technique to Studying the Response of the Lower Ionosphere to Strong Distant Earthquakes*

A.M.Gokov and O.F.Tyrnov

The partial reflections technique has been employed to study the generated or amplified in the mid latitude lower ionosphere after strong earthquakes. The effect of earthquakes on the characteristics of radio noise at frequencies f=2-4MHz has been studied in dependence of the power, distance, location (on the surface or under water) and depth of the earthquake.
Key words: earthquake, ionosphere, radio noise, partial reflections, wavelike disturbance.

1. Introduction. An earthquake of considerable intensity can serve as a source, localized in space and time, of wavelike disturbances in the ionosphere and their associated geomagnetic field variations. This relates both to the preparatory stage of the earthquake [1] and the shock moment [2], as the focus can emit intense electric fields of large spatial scale of variation and radio waves at the preparatory stage, and a powerful acoustic pulse during the chock proper. Accordingly, the investigations are performed along two major directions, namely the study of short- (tens of seconds to tens of minutes) and long-term (hours to days) earthquake precursors, and of the effects exerted by the earthquake itself on ionospheric parameters, which may prove important for radio communications, radio navigation, etc. The theoretical and experimental research of the last two decades has been concentrated in the both directions. Disturbances of the natural electromagnetic field about the Earth that occur during earthquakes have been observed and analyzed on many occasions. The effects included Optical emissions in the atmosphere [1]; quasistationary disturbances of the electric field potential [3]; increased intensity of the electromagnetic radiation up to a few thousand kilometers from the epicenter [4], and finally variations in the critical frequencies and height profiles of the electron density, N, in the ionospheric E- and F-regions [4 and 5]. Also known is the ionospheric reaction to the acousto-gravity waves generated during earthquakes [6] and [7]. A widely studied effect is the penetration of low- and very low frequency electromagnetic fields from seismic sources to the ionosphere and magnetosphere [8]. Papers [7] and [9] are dedicated to the partial reflections (PR) technique which has allowed detecting a considerable increase of the radio noise intensity at f=2 to 4 MHz during strong remote earthquakes (over 3 to 5 minutes), as well as the response of the ionospheric D-region.

The present paper is based on the partial reflections data obtained at the Kharkov State University during 180 earthquakes of different intensities. We analyze radio noise variations at f=2 to 4 MHz and parameters of the disturbances generated or amplified over such periods in the ionospheric D-region

2. Measuring equipment and investigation techniques. The research in the based on a retrospective analysis of the data bank obtained by the partial reflections method in 1983 through 1994. The reflected signals and radio noise were measured with the equipment described in paper [10], at mid latitudes near Kharkov, Ukraine. The basic parameters of the measuring complex were: operating frequencies f=2 to 4 MHz and sounding pulse lengths 25 to 100 μsec, with repetition frequencies F=1 to 5 Hz. The noise amplitudes $A_{n0,x}$ (2 to 6 samples picked in between the sounding pulses) and the noise-partial reflections mixture of the ordinary ("0", A_0) and extraordinary ("x", A_x) polarizations were registered from 15 height levels (in 3 km steps, starting from 45 or 60 km). The lengths of $A_{n0,x}(t)$ and $A_{0,x}(z, t)$ records (t is time and z is height above the Earth surface), taken for different seasons and times of the day, were between 20 minutes and 24 hours or longer (continuous observations). Here and below, $A_{n0,x}$ stands for A_{n0} or A_{nx}.

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Prior to computerized analysis the height-time dependent data arrays were subjected to statistical treatment, namely $A_{0,x}(z, t)$ and $A_{n0,x}(t)$ were averaged over 30 or 60 seconds to yield $\overline{(A_{no,x})}(t)$ and $\overline{(A_{o,x})}(z,t)$, respectively. The partial reflection amplitudes were estimated as $\overline{(A_{so,x})}=\overline{(A_{o,x})}-\overline{(A_{no,x})}$. More than 80% of the measured data, $A_{n0,x}(t)$ and $A_{0,x}(z, t)$, were also subjected to spectral analysis aimed at improving the estimates of disturbance parameters. For each of the records the time dependences of $a_{o,x}(t) = \overline{(A_{no,x}^2)}/\left\langle\overline{(A_{no,x}^2)}\right\rangle$ have been estimated over 20-minute intervals (specifically, ±10 minutes about the earthquake shock); $\left\langle\overline{(A_{no,x}^2)}\right\rangle$ is the mean value of $\overline{(A_{no,x}^2)}(t)$ over such an internal. The dependences found were employed for analyzing the data by the superposed epochs method.

The total number of underwater and underground earthquakes of energies $E>10^{11}$ J that occured at distances $R>(1$ to $15)\times10^3$ km from the observation point and at depths $h\sim1$ to 100 km exceeded 180. 115 of these were characterized by energies $E>10^{12}$ J ($M>5$ on the Richter scale). The data are quoted after paper [11].

Possible effects of other disturbing sources, either natural or anthropogenic, were excluded by proper selection of the $A_{n0,x}(t)$ and $A_{0,x}(z, t)$ records.

3. Radio noise variations at 2 to 4 MHz. We had analyzed the variations of $A_{n0,x}(t)$ and $A_{0,x}(z, t)$ measured during 65 earthquakes of energies $E>10^{11}$ that occured at depths $h\sim1$ to 100 km under the ground or under water at various distances from the observation point. Six cases were characterized by noticeable variations in the intensity of radio noise ($A_{n0,x}(t)$ increased by a factor of two or more over 1 to 5 minutes), with $R<1000$ km; $h<40$ km and $M=4.5$ to 4.8.

Consider the results obtained during strong earthquakes, $E>10^{12}$ J (10^{12} to 10^{15} J). Fig.1 shows time dependences, $\langle a_{0,x}(t)\rangle$, of the radio noise intensity normalized to their mean value oyer a 20-minute internal during the earthquake. (The shock moment is marked with an arrow). The $\langle a_{0,x}(t)\rangle$ dependences have been constructed by the superposed epochs method from $a_{0,x}(t)$ realizations (82 were underground earthquakes, the rest occured under water). An increase in $\langle a_{0,x}(t)\rangle$ (hence, $A_{n0,x}(t)$) can be seen at the shock moment (about one minute before and 2 to 4 minutes after). The front and trailing edges of the $A_{n0,x}(t)$ "surge" have characteristic widths of 10 to 30 s. Quantitative data on 2-4 MHz noise variations during strong remote earthquakes are listed in Table 1. $A_{n0,x}(t)$ enhancements at the shock moment are marked with a plus (+) sign, while absence of the "surge" is noted with a minus.

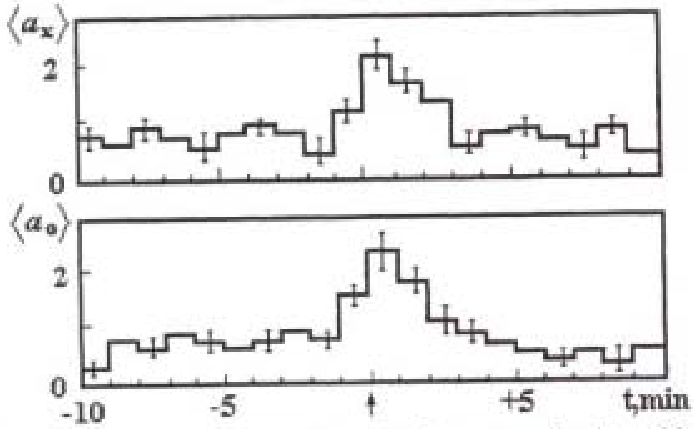

Fig. 1. Time records of radio noise intensity during earthquakes, normalized to a 20-minute mean value (the shock moment is marked with an arrow). The curves have been obtained by the epoch superposition method.

Table 1

Qualitative characteristics of 2-4 MHz noise reaction to strong remote earthquakes

Effect	Total	Under ground	Under water
"yes": +	58	49	9
"no": -	57	33	24
	$R<1000$ km		
h >50 km			
+	8	4	4
-	16	9	7
h < 50 km			
+	50	45	5
-	41	24	17
h < 10 km			
+	18	45	5
-	15	24	17
		$1000<R<3000$ km	
h < 50 km			
+	10	10	-
-	3	3	-
h > 50 km			
+	1	-	1
-	1	1	-
		$R>3000$ km	
h < 50 km			
+	39	36	3
-	40	21	19
h > 50 km			
+	7	4	3
-	14	7	7

In the general case of the underground and underwater earthquakes analyzed together, the positive reaction in $A_{a0,x}(t)$ is noted only slightly more often than for 50% of records. The figure becomes almost 60% for underground earthquakes and less than 27% for underwater events taken separately. A similar analysis has been done for shallow- (h<50 km) and deep-focus (h>50 km) earthquakes, as well as for surface (h<10 km) quakes. The probability W of "burst" appearance in the $A_{a0,x}(t)$ record proved to be much higher for shallow and surface than for deep-focused underground quakes. In contrast to this, the disturbances in $A_{a0,x}(t)$ records relating to underwater earthquakes were observed 1.5 to 3 times more often for h>50 km than for h<50 km or h<10 km. In the case of deep-focus quakes, the occurrence probability of disturbances in $A_{a0,x}(t)$ was nearly equal for underground and underwater earthquakes.

We have analyzed separately the records for "close-range" earthquakes, R<1000 to 3000 km (the data for h>50 km are extremely scarce) and distant events, R>3000 km (see Table 1).

In the first group, the probability W of disturbances in $A_{a0,x}(t)$ was relatively high for underground earthquakes (about 77%). In the second group (R>3000 km and h<50 km), W was slightly lower for underground quakes, W=63%, and low for underwater events (W=13.6%). Deep-focus events (h<50 km) showed roughly equal probabilities of disturbances, $W \approx 35\%$, under ground and under water. The overall probability of disturbances in $A_{u0,x}(t)$ estimated for all distant earthquakes ($R>3000$ km) was $W<50\%$.

4.Disturbances in the lower ionosphere. As was established earlier [7], the partial reflections method allows detecting the quasiperiodical disturbances in the ionosphere plasma occuring after earthquakes. The height-time records of $A_{u0,x}(t)$ and $A_{0,x}(z, t)$ contain quasiharmonical variations characterized by different delay times. In the absence of other perturbing agents, such disturbances in $A_{u0,x}(t)$ and $A_{0,x}(z, t)$ can be ascribed to earthquakes. By analyzing the data on $A_{u0,x}(t)$ and $A_{0,x}(z, t)$ recorded both during earthquakes and on reference days (when powerful quakes were absent) it has been established that the effect is absent during earthquakes of energies $E<10^{11}$ J, no matter what are the values of R and h. The quasiharmonical variations in $A_{u0,x}(t)$ and $A_{0,x}(z, t)$ were observed after earthquakes of energies $E>10^{12}$ J in 65 to 70% of underground events and in about 40% of underwater quakes.

An example of such disturbances is given in Fig.2 for an earthquake $E>10^{14}$ J and $R\sim10^{3}$ km (curve 1 corresponds to $A_{ux}(t)$, while curves 2 to 4 correspond to $A_x(z, t)$ for z=57 km; 81 km and 105 km, respectively). The records were taken in late afternoon, about 3 hours before sunset. The apparent velocities of disturbance transfer as calculated from time lags between the shock moment and the "bursts" (enhancements) of $A_{0,x}(z, t)$ were $V\sim50$ km/s; 7 to 8 km/s and 2 km/s. Analysis of the data bank on height-time dependences of $A_{u0,x}(t)$ and $A_{0,x}(z, t)$ has revealed disturbances in the lower ionosphere, characterized by transfer velocities $V\sim0.5$ to 100 km/s. A histogram of the apparent disturbance transfer velocities, $W(V)$, is given in Fig.3a. The total number of disturbances observed was 168. The $W(V)$ histograms for underground (curve 1) and underwater (curve 2) earthquakes are given in Fig.3b. Analysis of the measured dependences has shown higher occurrence probabilities to correspond to the apparent velocities $V\sim0.5$ to 4 km/s; 10 to 20 km/s and $\approx$100 km/s, both for underground and underwater earthquakes. However, the $W(V)$ distributions are different for the two categories, e.g. in the case of underwater quakes the probabilities are concentrated near $V\sim3$ to 4 km/s being markedly lower for $V>100$km/s. In the case of the underground earthquakes the disturbances with $V\sim1$ to 4 km/s were more frequent.

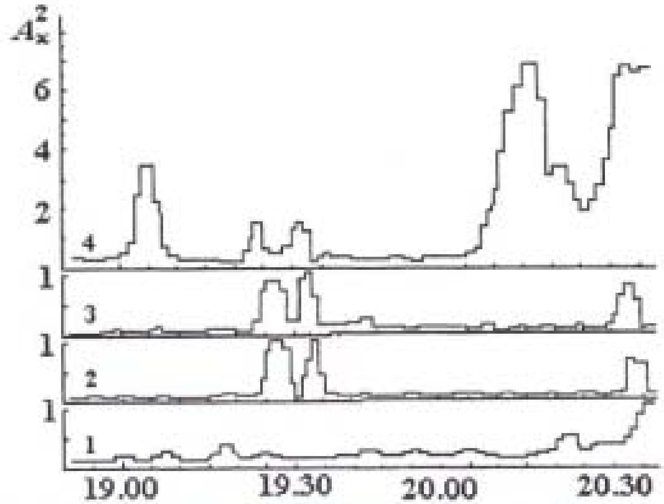

Fig. 2 Height-and-time dependences of the partially reflected signal intensities from 105 km, 81 km and 57 km (curves 2 to 4), and radio noise in the ionosohere (curve 1) recorded during the 13 Aug., 1987 earthquake.

The possible types of disturbances that might possess similar velocities and be capable of carrying information on the earthquake one considered in the next Section.

Listed in Table 2 are the basic parameters of the disturbances (apparent propagation velocities, durations and periods of disturbance) that have been derived from the $A_{u0,x}(t)$ and $A_{0,x}(z, t)$ records and spectra thereof.

The apparent vertical transfer velocities have been determined on occasion along with the horizontal velocities in the lower ionosphere. This is true in about 10% of cases. E.g., in one of the above considered cases the difference of delay times of $A_{0,x}(z, t)$ disturbances at z=105-57 km was close to 3 minutes, which value corresponded to a transfer velocity of V~300 m/s (from top to bottom).

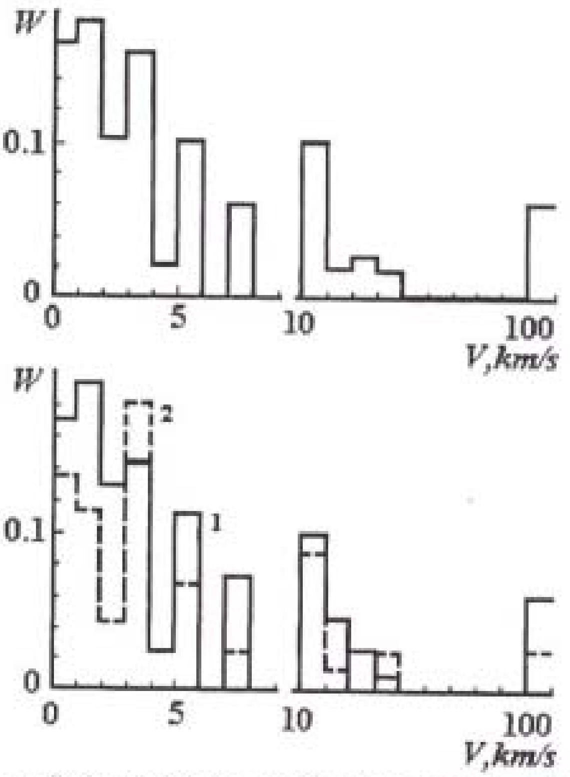

Fig.3. Histograms of perturbation velocities, obtained by a partial reflections method after earthquakes with magnitude M>5.

5. Discussion. The lithosphere-ionosphere interaction has not been studied sufficiently to allow suggesting an adequate model for the transfer of earthquake produced disturbances to the ionospheric plasma. By investigating the ionospheric response to distant earthquakes and wave modes that carry such disturbances from an earthquake. Consider some of the scenarios.

An earthquake generates a powerful acoustic pulse propagating to altitudes about z=10 km in the form of the shock wave, converted later into acoustic and infrasonic waves. The latter is partially transferred upwards (the propagation time to z~90 km is about 5 minutes) to be trapped in the duct owing to the regular anisotropic height profile of the ionospheric conductivity at z=80 to 120 km [12]. Then the wave can propagate to distances about R~10000 km, experiencing only low attenuation. The propagation velocity of similar infrasonic (gravito-acoustic) waves is V~0.4 to 1 km/s, with periods T~3 to 6 minutes. According to our measurements, the process duration can make a few periods. Other wave modes generated by the earthquake are the seismic waves [13], characterized by propagation velocities V~3 to 8 km/s. Specifically, the velocity of 3 to 4 km/s is characteristic of Rayleigh's surface waves; V~5 to 6 km/s belongs to bulk, and V~6 to 8 km/s to electromagnetic waves. Owing to their low attenuation, the seismic waves can travel to global distances. In the course of their propagation along the Earth surface, they are converted into long-period acoustic waves and refracted toward the ionosphere [6,13].

The acoustic waves may convert in the ionosphere into plasma-acoustic modes characterized by horisontal propagation velocities V~1.3 to 2.2 km/s [14], e.g. fast [15] and slow magneto-acoustic modes [12,15]. The sound waves may also give rise to ion-acoustic waves propagating along the Earth surface at V~20 to 40 km/s [16]. Some of the observational results can be interpreted within the hypothesis of gyrotropic waves [12] which are a veriety of slow hydromagnetic waves. Their characteristic velocities are V~10 to 50 km/s.

Under certain conditions, the ionospheric plasms can support the hydromagnetic waves propagating at the Alfven speed $V\sim10^2$ km/s [12,17]. The information on ionospheric disturbances that is carried by such waves is characterized by minimal delay times $t\sim10$ to 100 s. Such delays have indeed been noted in our measurements of $A_{a0,x}(t)$ and $A_{0,x}(z,\ t)$. Assuming this mechanism of disturbance transfer, it might be possible to explain the increase in $<a_{0,x}(t)>$ observed for 3 or 4 minutes past the shock moment by superposition of delayed responses at different observation ...It should be also noted that the hydromagnetic waves can serve as a triggering factor influencing on the magnetic field of the magnetosphere to start particle precipitation from the radiation belt to the atmosphere. The charged particles lead to in increased ionization in the lower ionosphere over time intervals of 1 to 10 minutes, which effect may result in an observable variation of the radio noise intensity and level of partially reflected signals.

6. Conclusions. The data obtained in the partial reflections technique are evidence for several types of disturbances produced in the lower ionosphere by earthquakes of energies $E>10^{12}$ J and observable at distances up to $R\sim10000$ km from the epicenter. The horisontal transfer velocities of such disturbances vary between 0.5 and 100 km/s. A tentative classification of the disturbances has been suggested that corresponds to the current level of understanding the litosphere-ionosphere interaction.

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