Radiophysical Investigations and Modeling of Ionospheric Processes Generated by Sources of Various Nature. 1.Processes in a Naturally Disturbed Ionosphere. Technical Facilities*

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Introduction

At present, the central problems in the physics of the near-Earth space are those of interaction between different regions of the geospace and the "space weather". The first of these concerns processes both in naturally and an artificially disturbed ionosphere. The artificial sources of disturbances are very convenient, since they allow controlling the amounts of energy released, as well as the time and place of the event. When studying the "space weather", it is no longer sufficient to know the mean magnitudes of its parameters. A need has arisen of introducing into the general scheme such events as solar flares, magnetic storms, the traveling solar terminator, lightning discharges, earthquakes, etc. As has become known over the recent decades, the near-Earth space can also be influenced by artificial sources characterized by significant levels of power release, such as powerful explosions, launches and flights of spacecraft, powerful radio emissions, etc (see, e.g. [1-5]).The problems mentioned relate to fundamental science. Among the applied aspects note the selection of disturbances of a specified type as against the background of other processes and the employment of those disturbances for the control of signal propagation conditions for various radio systems. Equally important are the medico-biological aspects of such investigations. In particular, of topical importance is the problem of detecting the response of geospace to the action of powerful earthquake precursors or forerunners (the relevant Ukrainian research project of priority is known as Project Warning).

The present paper is aimed at presenting, comparing and generalizing the results of experimental investigations of ionospheric perturbation processes due to various natural sources, and describing the technical facilities for their observation.

The radiophysical observatory: technical facilities

In 1970's through 1990's scientists and technical staff of the University of Kharkov performed a series of radiophysical investigations of global, large-scale and localized ionospheric disturbances generated by energy releasing sources of electromagnetic, acoustic, seismic, chemical and other nature (see, e.g. [1, 2, 6-16)]). The experiments were characterized by a certain degree of diversification (several independent methods were used for diagnosing the propagation medium), global nature of the processes under investigation (the sources of disturbances were at distances R between 50 and 10,000 km from the observation site, and the radio propagation paths $D \sim 100$ to 1000 km), a considerable interval of altitudes covered ($z \sim 50$ to 1000 km) and a broad range of sounding frequencies ($f \sim 1$ kHz to 1 GHz). The main purpose of the study was to establish both general and specific features in the generation of primary perturbations as a result of localized power releases; their propagation on the global scale and appearance of secondary perturbations near the observation sites.

The ionospheric disturbances are investigated at the University of Kharkov with a set of technical facilities characterized by a high level of automatization and computerization [3, 7, 15, 17-19]. Normally, the observations are conducted at the Radiophysical Observatory of the University of Kharkov (near the villages of Gaydary and Grakovo in the Kharkov Region), and at other observation sites (see Fig. 1). To that end, fixed and mobile radio facilities have been developed, covering a variety of frequency bands (see Table 1).

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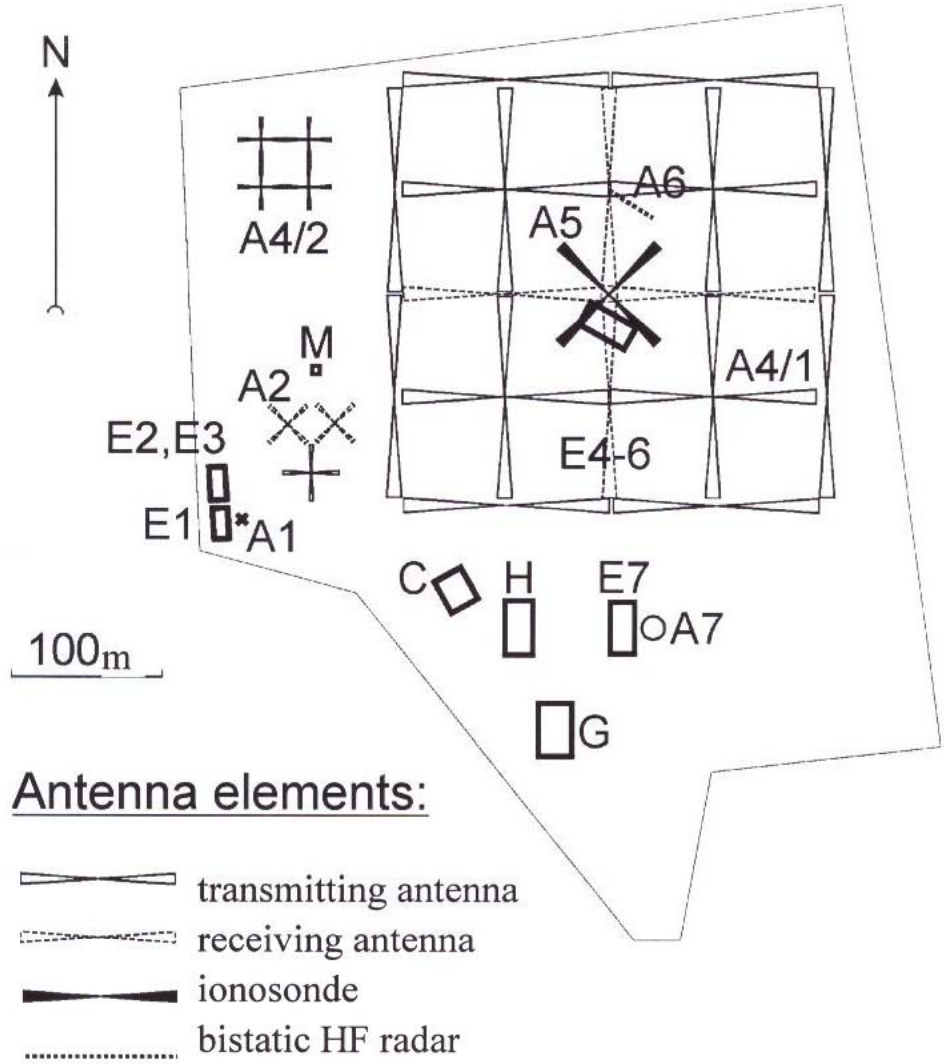

Fig. 1. Layout of the facilities and antenna fields at the Radiophysical Observatory: E1 and A1 are the receivers and antennas, respectively for signals from the "Цикада-М" series satellites; E2 and A2 the Doppler sounding facility and antennas; E3 and M the equipment and sensors, respectively, of a three-component magnetometer; E4 and A4 the facilities and antennas for investigations of the lower ionosphere (A4/1 and A4/2 are the antennas for the frequency ranges $f = 1.5 \div 4.5$ MHz and $f = 4.5 \div 15$ MHz, respectively, including spaced reception of the partially reflected signals); E5 and A5 are the same for the ionosonde; E6 and A6 are the transmitter and 15×30 m^2 antenna array of a bistatic HF radar for sounding the artificial ionospheric turbulence stimulated by the HF heater "SURA" (Nizhny Novgorod, Russia); E7 and A7 the same for the incoherent scatter radar; H is living quarters; C the dining room; and G the garage.

Partial reflections complex. The transmit antenna system consists of two spaced arrays, one operating at $f = 1.5$ to 6 MHz and the other covering the 6 to 15 MHz band. The elementary radiating component of the arrays is a double-rhombic vertical antenna. These are placed at 20 m above the average terrain. The array dimensions are $300\times300\text{m}^2$ and $60\times60\,\text{m}^2$. The calculated antenna gains are $G \approx 40 \div 150$ and $G \approx 40 \div 20$, respectively (the decrease in the magnitude of G at higher frequencies is due to the rapid growth of the power radiated through side-lobes).

The partially reflected signals are received with two orthogonal antennas, each representing two rhombs located side-by-side along the same line. The design allows considerable flexibility in reconnecting the antenna elements.

The transmitter represents a two-channel power amplifier employing one and the same modulator for both channels. The modulator provides radio pulse shaping out of a continuous signal arriving from the master oscillator output. The frequency synthesizer Ч6-31 is used in the capacity of the master oscillator in the fixed complex. The pulsed power of the transmitter is 150 kW, with the pulse length 25 to 100 μs and the repetition frequency 1 to 100 Hz.

The receiver of the fixed complex is built around a modified commercial receiver and includes a wideband (1 to 10 MHz) circular polarizationmeter and an antenna switch.

The output signal of the receiver is fed into the data processing/data storage system where it is digitized and recorded on a magnetic carrier.

When sounding the ionosphere under real conditions, either an additive mixture of the useful signal and noise is recorded or noise alone, which is necessary for estimating their statistics.

A mobile complex of the method was also used for the measurements.

Table 1. Ionospheric programs of the University of Kharkov: Specifications of radio facilities

Facility parameters	Operating frequency range, MHz	Pulsed power transmitted, kW	Pulse length, μs	Pulse repetition frequency, Hz	Antenna gain
Partial reflection complex:					
fixed	1.5 - 6 *	up to 150	25 - 300 **	up to 100	40 - 150, f=1.5- 6 MHz 40 - 20, f= 6 -15 MHz
mobile	1.5 - 6	up to 150	25 - 300 **	up to 100	up to 50
Doppler sounder					
fixed	1 -24	1	500	100 - 200	~ 1 - 10
mobile	3 - 24	1	500	100 - 200	~ 1 - 10
Ionosonde	1 - 20	20	50; 100	50	~ 10
VHF sounder	150 - 160	---	---	---	800
UHF sounder	1800 - 2000	$3 \cdot 10^3$	2 - 2500	100	$5 \cdot 10^4$
Satellite sounding complex	150; 400	---	---	---	1 - 10

* The highest operating frequencies of the fixed and mobile partial reflections complexes are 30 and 10 MHz, respectively

** The pulse lengths of 100 to 300 μs are expected to be used in the pulsed cross-modulation mode.

Vertical Doppler sounding facility. The sounding signals at two coherent frequencies are radiated, received and processed simultaneously in the stationary complex.

The complex includes a two-channel transmitting system (consisting of transmitters, master oscillators and two transmitting antennas); a double-channel receiving system (receivers with high stability oscillators); a system to control and switch the transmit and receive channels; a data processing and recording system; a standard reference oscillator of high stability and an auxiliary system to calibrate the reference oscillator. The use of a single reference oscillator being common all the oscillators in the receive and transmit channels ensures coherency of the radio signals emitted. A stable rubidium-based reference standard is involved in the system for control of the relative instability and accuracy of setting the nominal operating frequency. The measured data are tape-recorded in a digital format.

A mobile complex similar to the fixed one has also been created.

Multi-frequency sounder. This computer controlled, programmable complex has been constructed as based on P-399A, P-391B2, and P-260 receivers; the "Бриг-2" transmitter and a PC. The complex also includes an interface and synchronization unit. The signals for oblique Doppler sounding are provided by broadcasting stations and transmitters of the navigation or Time Keeping Services. The existing set of such stations permits measurements with various orientations of propagation paths with respect to the sources of disturbance.

Ionosonde. Until recently, the general state of the ionosphere was controlled with an automatic analog ionospheric sounder operating at frequencies between 1 and 20 MHz. The ionograms were photographed once for every 15 minutes. The ionosonde frequency and, accordingly, the CRT time-base were changed through mechanical rotation of a precision resistor and capacitor driven by an electric motor. The receive section of the ionosonde has been modified through replacing the mechanical frequency tuning system by an electronic unit and connecting an ADC to the receiver output to provide ionograms in an electronic format. An IBM AT-compatible computer is used to control the ionosonde and store the digital ionograms.

Panoramic meter of ionospheric radio noise. Analysis in a given range of the electromagnetic field which is a superposition of signals from various transmitters and of noise generated by natural sources, can be regarded as a diagnostic method for disturbances in the near-Earth plasma. The above described programmable measuring complex can be suitably used for the purpose. To run the complex in this mode, a special control program has been developed that implements an operation algorithm as follows [7, 19]. It is assumed that the band selected accommodates powerful narrow-band signals, as compared to the analysis band (like broadcasting or communication stations, etc.) and a wide-band noise background (remote sources of artificial or natural radio emission). The total band of analysis is divided into several subbands of shorter width to estimate the power level of electromagnetic field within each of them. The data file obtained is used to plot a histogram of the EM field power distribution. By processing the data it proves possible to separate the wide-band noise from the narrow-band powerful signals throughout the range of analysis.

Powerful radiation complex. The complex has been constructed around the "Бриг-2" transmitter with a specially designed powerful double-channel output stage. The transmitter is used as a driver for the end stage incorporating the ГУ-35Б generator tetrodes characterized by a high linearity of their transfer function and a considerable power gain factor. The output is connected to an assembly of powerful high-frequency ferrite-ring transformers used to match the transmitter output to the transmission line and antenna (the CW radiated power is $P \approx 50$ kW). Being loaded with orthogonal linear antennas, the two channels radiate circularly polarized waves. An advantage of this design of the power-amplifying stage is the broad band of operating frequencies. Characteristic features of the "Бриг-2" transmitter are its relative insensitivity to characteristics of the load and the possibility of remotely controlling its basic parameters. This has permitted an automatic control of the radiation regime of the complex.

The basic parameters of the heating bench are $P \approx 70$ kW and $G \approx 10 \div 100$ at $f \approx 1.5 \div 6$ MHz, respectively.

The VHF sounding complex. This computer controlled programmable complex serves to receive sporadic radio emissions within the frequency band $f \approx 150 \div 160$ MHz (passive mode) and to investigate the ionosphere and atmosphere by the methods of incoherent and coherent scattering (active mode). When in active mode, the complex receives the signals from the Incoherent Scatter Radar of the Kharkov Polytechnic University ($P \approx 2$ MW, $f \approx 150 \div 160$ MHz, $\tau = 100 \div 200$ μs, $F = 100$ Hz and $G \approx 10^4$). The receiving and transmitting sites are separated by 20 km. The antenna system represents a phased array of basic elements of the "vertical rhomb" type with $G \approx 800$. A highly sensitive receiver with $P_{\min} = 4 \times 10^{-16}$ W is incorporated in the complex. The data processing/data storing system incorporates a computer, permitting statistical analysis of the data and their storage and output onto the external devices both in the analog and digital form. The complex is run mainly in the passive mode, receiving and processing the ionospheric radio noise.

UHF sounding facility. The multipurpose computer controlled, programmable UHF complex ($f \approx 1800 \div 2000$ MHz) is intended for investigating the ionosphere in the incoherent or coherent scattering techniques and also, in the passive mode, for reception and analysis of sporadic radio emission from the ionosphere.

The transmit system of the complex involves two transmitters with a common master oscillator (it is possible to run each of the transmitters separately). The system allows generating pulses of average power $P \approx 60$ kW and $\tau \approx 2 \div 2500$ μs. The receiver sensitivity is $P_{\min} \approx 10^{-14}$ W, the gain of the radio frequency amplifier is about 60 dB and the bandwidths of the radio frequency and intermediate frequency amplifiers are $\Delta f \approx 10$ MHz. The antenna system of the complex represents a fully steerable parabolic antenna 15 m in diameter. The antenna pattern width is 36×40 angular minutes, and $G \approx 5 \cdot 10^4$. The computer is a "ДВК-3" PC with the software including control and self-test programs of the complex, a package for data pre-processing and storage, statistical data processing and tests. For lack of financing, operation of the complex has been suspended.

Beacon-satellite receiving complex. High frequency radio signals from navigation satellites of the "Цикада" (Russia) and "Transit" (USA) series are used for trans-ionospheric sounding at the frequencies $f_1 \approx 150$ MHz and $f_2 \approx 400$ MHz. The "Цикада" mission involves satellites of the "Cosmos" series with circular orbits (altitude $z \approx 1000$ km) inclined at an angle $i \approx 83^{\circ}$ with respect to the equator, with the revolution period about 105 minutes. The "Transit" satellites have near-polar, almost circular orbits ($z \approx 1000$ km). The time of radio visibility of these satellites from the ground-based site is about 18 min. The great number of low-orbit satellites in the "Цикада" and "Transit" missions (totally more than 15) provides for such a duration of signal records (above 50 transits at mid-latitudes and even more in polar regions) that is sufficient for organizing remote ionospheric monitoring over a region of radius $R \approx 1000$ km around the observation site.

The equipment involves an antenna with transmission lines, a master oscillator, a receiver, a computer, an input-output device, a data processing and representation unit and a power supply unit.

To detect ionospheric disturbances, we use an upgraded "Шхуна" receiver initially intended for determining object coordinates through measurements of signals from low-orbit satellites of the navigation system "Цикада". A combined use of radio signals from satellites of the "Цикада" and "Transit" missions permits a great increase of the amount of information obtained. To that end, a receiver has been developed (at the functional diagram level) based on the regular device "СЧ-1". The standard operation mode involves independent measurements of the total Doppler frequency shifts at 150 MHz and 400 MHz. Accordingly, the ionospheric component, f_{di}, can be measured to an accuracy of 0.2 Hz which is evidently insufficient for ionospheric investigations. For this reason, separation of the f_{di} component by built-in means is suggested through an appropriate signal transformation. When processing the signals from the "Transit" satellites, an additional transformation is performed in the receive channels. Afterward, the signals are fed to the mixer where all the components of the total Doppler frequency shift, except the one proportional to $1/f$, are nullified. The mixer output containing information on the reduced Doppler frequency f_{di}, is fed to the computer to be processed. The measurement error of the informative parameter is $f_{di} \approx 5 \cdot 10^{-3}$ Hz with data digitization about 2 s.

Magnetometers. An automatic complex, based on the ИМ-II magnetometer (Institute of Physics of the Earth, Russian Academy of Sciences), has been put into operation at the Radio/Physics Observatory (near village of Grakovo) to measure geomagnetic field pulsations. The measurement resolution is between 1 and 60 nT within the frequency range 1 to 0.001 Hz. Automatic measurements are possible, owing to the specialized controller that was designed and implemented as based on a mono-crystal microcomputer КР1816ВЕ35 with the RAM extended to 1 MB. The power supply unit can provide both for the regular or emergency operation (up to 3 hours per day in the case of power interruption). The complex allows unattended measurements for up to 3 days with the mean data flow of 32 baud. After this term it is necessary to forward the information recorded to an external computer for storage on a magnetic carrier. Further processing of the data consists either of bandpass digital filtering or digital spectral processing with the use of either classical or autoregressive algorithms, as well as correction of the geomagnetic pulsation amplitudes with account of dynamic characteristic and amplitude response of the magnetometer.

In addition, the Radiophysical Observatory in Grakovo employs a three-component magnetometer whose sensitivity is lower approximately by an order of magnitude.

Sources of disturbances in the near-Earth environment

The geospace is an open physical structure receiving energy from the Sun and the deep space from above and from the lithosphere from below. Depending on its carrier, the energy is effectively dissipated in either the atmosphere, the ionosphere or the magnetosphere.

According to their origin, the sources can be divided into natural and artificial (anthropogenic). Some of them are listed in Tables 2 and 3. The important point here is point that the power levels of anthropogenic and natural sources are comparable, This means, in particular, that space weather conditions are becoming dependent on power releases of anthropogenic origin. However, the role of these agents still remains poorly studied.

Processes in a naturally disturbed ionosphere

Solar flares [9, 11, 20, 21]. The influence of solar flares upon the ionospheric D-region and characteristics of partially reflected signals was studied through sudden ionospheric disturbances (SID), as an example. We have analyzed variations of $A_{mO,X}(z,t)$ and $A_{(c+m)O,X}(z,t)$ (as well as their statistics) and parameters of the D-layer for 8 SID-events (four SIDs of duration $\tau < 30$ min, and four with $\tau > 30$ min, were investigated separately). Analysis of $A_{mO,X}(z,t)$ and $A_{(c+m)O,X}(z,t)$ has shown damping quasiperiodic oscillations to be observed in $A_{mO,X}(z,t)$ and $A_{(c+m)O,X}(z,t)$ during short-term SID events and 10 to 20 minutes after. It has been found that SID events can trigger generation or amplification of wavelike disturbances in the D-region with periods $T < 5$ min, which die down within 20 to 25 min. In the case of SID events with $\tau < 30$ min the wave-like processes are less pronounced or unobservable at all. A possible reason for this behavior of the partially reflected signals might be the generation or amplification of atmospheric gravity waves (AGW) resulting from a sharply strengthened X-ray radiation from the Sun during SID events.

An appreciable increase (by a factor of 1.5 to 4) in N at $z = 70$ – 85 km was observed in our measurements when SIDs occurred. The $N(z)$-profiles calculated for every successive 3 - 4 min periods during SID events differed both in shape and N-magnitudes at fixed heights. In most cases, the electron density in the D-region recovered to roughly the initial values within a few minutes after the SID.

Magnetic storms [9, 20, 22, 23]. Eight magnetic storms have been investigated by the partial reflection technique. Characteristic of all those measurements was the appearance of strong reflections from the altitudes $z = 45$ – 70 km, whose level exceeded noise by a factor of 5 to 15. The electron density at these heights rose to (2 - 8)$\times 10^8$ m^{-3}. Fig. 2 shows an example of electron density variations in the ionospheric D-region for two magnetic storms (the measurements were conducted for zenith angles of the Sun $\chi = 77^\circ$ (curve 1) and $\chi = 50^\circ$ (curve 2)). Apparently, the extra ionization at $z < 65$ km during the magnetic storms was due to the charged particles precipitation, while the changes in $N(z)$ owed to variations in the intensity and spectrum of the particle flow. Comparison of the measured $N(z)$-profiles with undisturbed profiles characteristic of the given year season allows estimating the rate of the additional ionization $q_i \approx$ (1 - 4) $\times 10^6$ m^{-3} s^{-1} for $z = 50$ – 65 km. Assuming the major contribution in $N(z)$ at these heights to be due to ionization by precipitating protons with energies of $E \approx 15$ – 50 MeV, the particle flux density during magnetic storms can be estimated as (5 - 12) $\times 10^2$ m^{-2} s^{-1}steradian.

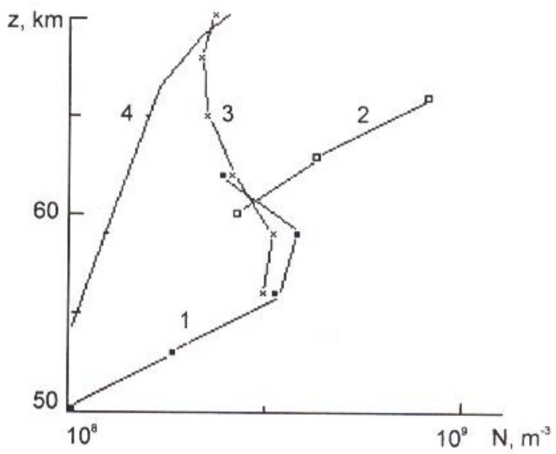

Fig. 2. Height profiles of electron density, $N(z)$, in the ionospheric D-region measured for the magnetic storms of 13.12.1985 (curve 1) and 18.12.1985 (curve 2). Curve 3 corresponds to the proton precipitation event of 15.05.1983 that occurred after a magnetic storm, and curve 4 shows a model (undisturbed) profile

Table 2. Parameters of natural processes

Sources of disturbance	Energy, J	Power, W	Duration, s	Comments
Optical radiation from the Sun	10^{22}	10^{17}	10^{5}	Round-the-clock, near the Earth's orbit
Regular Solar wind	10^{17}	10^{12}	10^{5}	the same
Solar flares	10^{16}	10^{13} - 10^{14}	10^{2} - 10^{3}	near the Earth's orbit
Magnetospheric substorms	10^{15}	10^{11}	10^{4}	
Global winds				Round-the-clock
D-region	10^{17} - 10^{18}	10^{12} - 10^{13}	10^{5}	
E-region	10^{15} - 10^{16}	10^{10} - 10^{11}	10^{5}	
F-region	10^{16} - 10^{15}	10^{9} - 10^{10}	10^{5}	
Solar terminator				
D-region	10^{15} - 10^{16}	10^{13} - 10^{14}	10^{2}	
E-region	10^{13} - 10^{14}	10^{11} - 10^{12}	10^{2}	
F-region	10^{13} - 10^{14}	10^{10} - 10^{11}	10^{3}	
Particle precipitation				Middle (high) latitudes
D-region	10^{10} (10^{13})	10^{7} (10^{10})	10^{3}	
E-region	10^{8} (10^{11})	10^{5} (10^{8})	10^{3}	
F-region	10^{7} (10^{10})	10^{4} (10^{7})	10^{3}	
Tungus-like accident	10^{16}	10^{15} - 10^{16}	1 - 10	
Lightning	10^{10} - 10^{12}	10^{10} - 10^{12}	1	
Cyclone	10^{19} - 10^{21}	$2 \cdot 10^{13}$ - $2 \cdot 10^{15}$	$5 \cdot 10^{5}$	During 5 days
Hurricane	10^{18} - 10^{20}	10^{13} - 10^{15}	10^{5}	Round-the-clock
Tornado	10^{11} - 10^{13}	10^{8} - 10^{10}	10^{3}	
Volcanic eruption	10^{20} - 10^{21}	10^{15} - 10^{19}	10^{2} - 10^{5}	
Earthquake	10^{19} - 10^{21}	10^{17} - 10^{18}	10^{2} - 10^{3}	
Tsunami	10^{18} - 10^{20}	10^{16} - 10^{19}	10 - 10^{2}	

Table 3. Parameters of anthropogenic sources

Sources of disturbance	Energy, J	Power, W	Duration, s	Comments
Nuclear explosion	$4 \cdot 10^{15}$	$4 \cdot 10^{22}$	10^{-7}	1 Equivalent of Mtonne TNT
Industrial explosion	10^{11} - 10^{12}	10^{14} - 10^{15}	10^{-3}	Charge mass between 25 and 250 tons of TNT
Nuclear power station accident	10^{18}	10^{13} - 10^{14}	10^{4} - 10^{5}	100 tons of the nuclear fuel mass
Explosion of a large rocket	10^{11} - 10^{15}	10^{12} - 10^{14}	0.1 - 10	1000 tons of the fuel mass
Powerful rocket launch	10^{12} - 10^{14}	10^{10} - 10^{11}	10^{2} - 10^{3}	Same
Ignition of a control rocket engine	10^{7} - 10^{9}	10^{7} - 10^{8}	1 - 10	
Fall-down of a large spacecraft	10^{12} - 10^{13}	10^{9} - 10^{11}	10^{2} - 10^{3}	100 tonne mass
Electric power transmission line	10^{14} - 10^{15}	10^{9} - 10^{10}	10^{5}	Round-the-clock
Emissions from radio facilities	10^{12} - 10^{13}	10^{7} - 10^{8}		Same
Meteotron	10^{11} - 10^{15}	10^{8} - 10^{10}	10^{3} - 10^{5}	Serves for weather monitoring
Electric power station	10^{14} - 10^{15}	10^{9} - 10^{10}	10^{5}	Round-the-clock
Plasma injectors:	10^{7} - 10^{8}	10^{10} - 10^{11}	10^{-3}	100 kg mass
electrons	10^{5}	10^{11}	10^{-6}	10^{4} A current, 10^{2} keV particle energy
protons	10^{7}	10^{13}	10^{-6}	10^{4} A current, 10 MeV particle energy

After magnetic storms, partially reflected signals, also several times exceeding the radio noise level, were observed for 5 to 10 days at the heights $z = 55 - 65$ km. As was found, such events correlated with charged particle precipitations from the magnetosphere. Fig. 2 shows a $N(z)$-profile (curve 3) measured on 15 June, 1983 by the partial reflection technique near Kharkov, Ukraine (f =2.6 MHz and $\chi = 48^o$). According to the data of the "Метеор" satellite at that period, a proton flux of density $7.7 \cdot 10^5$ m^{-2} s^{-1} with energy $E \approx 15$ MeV was registered.

Day-time variations in the electron density of the ionospheric D-layer were also investigated at $z > 75$ km during magnetic storms. As was found, the values of N during magnetic storms were 1.5 to 6 times higher than before the storms.

Solar terminator. In papers [9, 24 ,25] we analyzed the changes in characteristics of partially reflected signals and noise at the frequencies $f = 2 - 4$ MHz, as well as variations of the D-layer parameters during near sunrise and sunset, using the data obtained by the partial reflection technique between 1983 and 1992. The measurement time lengths for the sunrise and sunset periods were between 2 and 8 hours. Additionally, several round-the-clock observations were performed for different seasons. The total number of records, roughly uniformly distributed over the seasons, was ~ 100.

The partially reflected signals were observed in about 40 - 50% of the cases for the morning passages of the solar terminator. As a rule, they were observed for 10 to 30 minutes, and then vanished to reappear from the same heights 1.5 to 2.5 hours later (normally, one hour earlier in summer than in winter). In 70 - 75% of cases, the $A_{mO,X}(z,t)$ and $A_{(c+m)O,X}(z,t)$ measured at fixed altitudes show a quasiperiodic behavior. The lower observation edge for the partially reflected signals went down by 5 to 7 km and the interval of heights over which the signal reflections appeared was normally between 10 and 15 km (seldom greater than 15 km). Partially reflected signals from fixed heights appeared with time-delays of several units to tens of minutes after passage of the morning terminator. The signals showed no essential difference in the behavior over the seasons.

In the evening, the reconstruction of the D-layer used to start 1 to 1.5 hours before passage of the solar terminator. The signals intensities decreased and the lower edge of the partially reflected signal existence went up some ~ 10 to 15 km over 30 to 60 minutes after the sunset, which effect was accompanied by a gradual narrowing of the scattering region to 10 or 15 km (the higher boundary elevated by 8 to 12 km). The $A_{mO,X}(z,t)$ and $A_{(c+m)O,X}(z,t)$ dependences at fixed heights showed a quasiperiodic character, like in the morning. As it occurred, the solar terminator could either generate (amplify) or suppress quasiperiodic disturbances of the D-region. A spectral/time domain analysis has allowed to estimate the periods, T, and life-times, ΔT, of such disturbances (see Table 4). As can be seen, the disturbances in the D-region are characterized by $T \approx 2 - 40$ min, with the most probable value $T \approx 4 - 15$ min.

Table 4. Parameters of the quasiperiodic disturbances generated by the solar terminator in the ionospheric D-region

Season	Dawn		Dusk	
	T, min	ΔT, min	T, min	ΔT, min
Winter	3 - 5	20 - 25	7 - 15	35 - 50
Spring	4 - 6	25	2 - 3	15
Summer	2 - 3	10 - 15	15 - 20	80 - 120
	6 - 10	60		
Autumn	3 - 5	20 - 25	4 - 7	40

The solar terminator effects in the E- and F-layers were studied with the use of a Doppler sounder (the vertical sounding proved to be of poor sensitivity). The measurements have shown that the solar terminator can generate (amplify) or, on the contrary, suppress quasiperiodic disturbances at the heights between 100 and 300 km as well. The periods observed were ~ 5 to 15 min and 10 to 30 min (or longer) for the E- and F-regions, respectively, with $\Delta T \sim 1$ or 2 hours and $\Delta N / N_0 \sim 1 - 5\%$. Such quasiperiodic disturbances are attributed in all the ionospheric regions to the generation of AGWs.

Earthquakes [4, 7, 26 - 29, 55]. Consider the observational results obtained for earthquakes of energies $E \approx 10^{12}$ - 10^{16} J. Fig. 3 shows time-dependences of radio noise intensity, normalized to its mean value over a 20 min averaging period (zero-time corresponds to the quake moment). The dependences were obtained in the method of epoch superposition; the total number of recorded samples was 115 (82 were on-land earthquakes, with the rest being underwater events). As can be seen, during an earthquake (about 1 min before and 2 to 4 min after the shock) $< a_{mO,X}(t) >$ increases with a characteristic time of signal growth about 10 to 30 s.

Table 5 presents data on variations of the radio noise intensity at the frequencies 2 to 4 MHz during powerful distant earthquakes. The presence of a "burst" (increased) of $< a_{O,X}(t) >$ at the moment of the quake occurrence is is marked by the "+" sign, while its absence by the sign "-". It is seen that in the general case (when all the earthquakes on land and sea were taken into account) the effect was observed in just slightly more than 50% of cases. The appearance frequency of "bursts" of $A_{(c+m)O,X}(z,t)$ was ~ 60% and 27% for the land and sea earthquakes, respectively.

Analysis of the data bank on the $A_{mO,X}(z,t)$ and $A_{(c+m)O,X}(z,t)$ measured during earthquakes and on reference days (in the absence of powerful earthquakes) has shown that the effect is not detected with earthquakes of energies lower than $E \approx 10^{11}$ J. In the case of stronger earthquakes, $E > 10^{12}$ J, quasiperiodic variations in $A_{mO,X}(z,t)$ and $A_{(c+m)O,X}(z,t)$ were observed with frequencies of $\varpi \approx 65$ - 70% for land quakes and $\varpi \approx 40\%$ for underwater events.

Table 5. The response of radio noise in the range 2 to 4 MHz to distant strong earthquakes of various center depths, *h*, and distances, *R*, from the observer

Event		Total number	On land	On sea
"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
$R < 1000$ - 3000 km				
$h > 50$ km	+	1	---	1
	–	1	1	---
$h < 50$ km	+	10	10	---
	–	3	3	---
$R > 3000$ km				
$h > 50$ km	+	7	4	3
	–	14	7	7
$h < 50$ km	+	39	36	3
	–	40	21	19

Fig. 4 shows distributions of the apparent disturbance propagation velocity, v, calculated for the land (curve 1) and underwater (curve 2) earthquakes. The total number of the disturbances was 168. Analysis of the dependences shows the most probable disturbance velocities to be $v \sim 0.3$ and 3 km/s, which values correspond to the AGW and seismic waves, respectively.

Listed in Table 6, are basic parameters of the disturbances (apparent propagation velocities, durations and periods) derived from the data on $A_{mO,X}(z,t)$ and $A_{(c+m)O,X}(z,t)$ as well as from their spectral analysis.

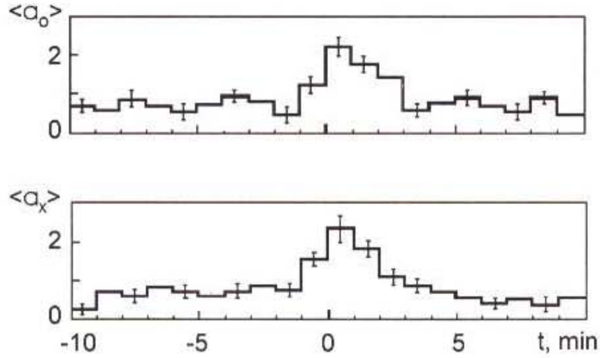

Fig. 3. Time-dependences of radio noise intensity normalized to their mean value as obtained by a 20 min averaging during the earthquake (the zero on the time axis corresponds to the shock). The dependences have been obtained by the epoch superposition method

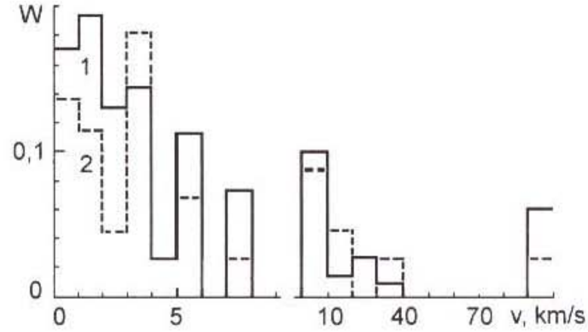

Fig. 4. Histograms of disturbance velocities obtained by the partial reflection method for earthquakes of magnitudes $M > 5$.

Table 6. Basic parameters of earthquake-generated disturbances in the lower ionosphere

Process duration, min	Quasiperiod, min	Apparent velocity, km/s	Probable wave mode
~ 1	---	100	MHD
~ 1	---	10 - 50	gyrotropic, ion-acoustic
~ 10	2 - 3	6 - 8	seismic
~ 10	~ 3	5 - 6	seismic volumetric
10 - 15	~ 3	3 - 4	seismic surface (Rayleigh)
10 - 20	3 - 8	1.2 - 3	acoustic, slow MHD wave
15 - 35	3 - 10	0.4 - 1	acoustic-gravitational

Evidence for strong effect of earthquakes upon the ionospheric D-region is presented, also, for example by the observations of 06.03.1986 [4].

After an earthquake of magnitude 7 in the Caspian Sea, the VLF radio signal at 16 kHz propagating along the Great Britain - Kharkov path showed a 0.6 radian increase in its phase variations; the signal amplitude increased nearly by a factor of two and $v \approx 0.3 - 0.4$ km/s. During the same earthquake, the signal phase at $f = 60$ kHz (Great Britain-Kharkov propagation path) first decreased by 0.3 rad (time lag $\Delta t \approx 1 - 1.5$ h, $v \approx 0.4 - 0.3$ km/s and $\Delta T \approx 1.5$ h), and then increased by 0.5 –0.6 rad ($\Delta t \approx 2$ h, $v \approx 0.2$ km/s and $\Delta T \approx 2.5$ h). Most probably, these changes can be attributed to a wave process with $v \approx 0.3 - 0.4$ km/s.

The impact of earthquakes upon the E- and F-ionospheric regions will be analyzed for the Spitack, Armenia earthquake of 7 Dec. 1988. The magnitude was 6.8 [18]. The ionospheric response was observed with an ionosonde located at 1700 km to the North of the epicenter. Time resolution for data taking was 15 min. Let us compare the time dependences of f_0F2 and $f_{\min}$ for the period between 6 Dec. 1988 and 9 Dec. 1988. The geophysical conditions were about the same on all the observation days, in particular, the A_p index varied between 4 and 6. The day0time value of $f_{\min}$, on 8 and 9 Dec. 1988 (quiet days) varied between 1.5 and 2 MHz. One day before the earthquake (within the same period) $f_{\min}$ was 4 MHz during 6 hours. On the very day of the earthquake, $f_{\min}$ was equal to 3 MHz during two hours only (one hour before the event and during one hour after). Outside that interval, $f_{\min}$ varied between 1.5 and 2 MHz.

The day-time value of f_0F2 on 6 Dec. And 7 Dec., 1988 was as high as 12 MHz, while on 8 Dec. 1988 and 9 Dec. 1988 it dropped down to 10 or 11 MHz. On 7 Dec., 1988 1.5 h after the quake f_0F2 grew 1 MHz higher (as compared with the same period of 6 Dec. 1988). The increased value of f_0F2 lasted for $\Delta T \approx 1$ h. As follows from the calculated electron density profiles, constant-density levels varied in the day-time of 7 Dec. 1988 as much as 100 km in height, over a characteristic time scale of 1 to 2 hours, while the total electron content varied as much as by a factor of 3.

The global response of the E- and F-regions of the ionosphere can be considered as exemplified by the Los Angeles earthquake (magnitude 6.1) that occurred at 15:42 UT on 1 Oct., 1987 [18]. The measurements were performed at hectometer and decameter wavelengths. The longer wavelengths paths were of nearly latitudinal orientation extending along the Earth's surface to $D \sim 50$ ÷ 150 km. This geometry allowed neglecting the effect of the solar terminator that passed through the ionosphere at a height $z \approx 100$ km about 18:00 UT. On the contrary, the radio path for $f = 4.94$ kHz was from West to East. The sunset at the reflection height (~ 200 km) occurred about 18:00 UT. Still another radio path at the operating frequency $f = 6.015$ kHz was used as a reference. Appreciable and almost sinchronous variations of the signal in the sonograms of paper [18] appeared with time lags $\Delta t \approx 30$, 48 and 70 min. Taking into account the propagation time of the acoustic pulse from the earthquake to the ionosphere (5 and 10 min for the lower and middle ionosphere, respectively), the corrected values of the time lags are $\Delta t' \approx 20$ - 25; 38 - 43 and 60 - 65 min, which correspond to $v = 7$ - 8; 3.9 - 4.4 and 2.6 - 2.7 km/s, respectively. As can be seen from the sonograms of paper [18], the ionospheric response to the earthquake is supposedly associated with broadening of the signal spectra, appearance of additional modes with Doppler frequency shifts $f_D \approx 0.3$ ÷ 0.6 Hz and also, with variations in f_D up to 0.5 Hz at $f \approx 5$ - 6 MHz.

Thunderstorms [30, 33]. Of special interest, is the possible occuranceof thunderstorm activity in the ionospheric D-region, the latter being closest to the source and the least studied. In what follows, we will briefly review the experimental results obtained in the partial reflection technique near Kharkov, Ukraine.

As has been found, thunderstorms are occasionally accompanied by intense partial reflection signals (signal-to-noise ratio between 3 and 10) from $z < 75$ km. Such effect occurred in about 40% of the observation cases and lasted normally for tens of minutes (up to 90 min).

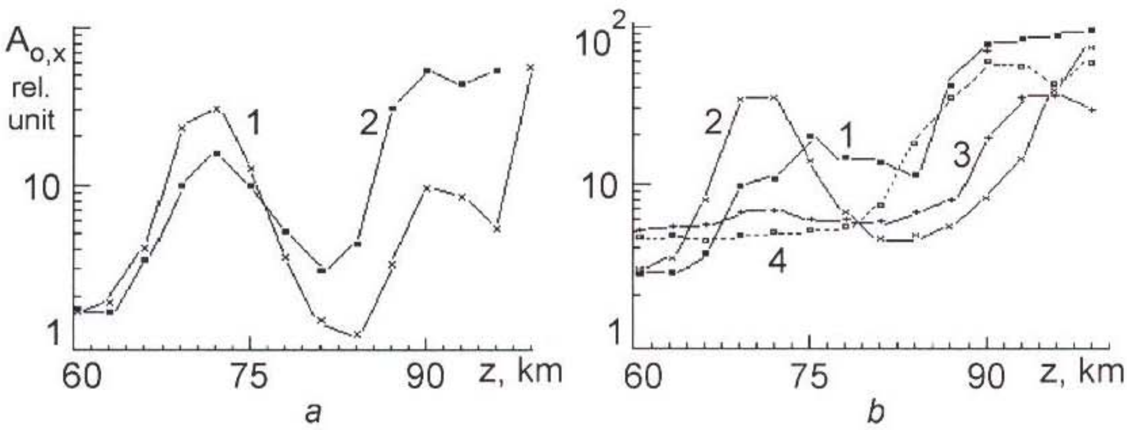

Fig. 5. Examples of A_X (curve 1) and A_O (curve 2) dependences measured during thunderstorms: a) 3 June, 1987 and b) 27 March, 1987 (curves 3 and 4 were obtained before the thunderstorm)

Fig. 5 presents examples of $A_{O,X}(z)$ functions measured during thunderstorms (curves 1 and 2). $N(z)$ profiles have been calculated for such events.

The principal effect of strong thunderstorms on the ionospheric D-region consists in that the electron density N at heights between 55 and 68 km can increase by several times over 1 to 10 min (up to $8 \cdot 10^8$ m^{-3}, while, normally, the value is $N \leq 10^8$ m^{-3}). The reason might be energetic particle precipitation from the magnetosphere. Besides, weak AGWs with $T \approx 4$ - 5 min are sometimes observed.

One cannot exclude [33, 35] the possible increase in the electron-neutral collision frequency in the lower part of the D-layer (a factor of 1.7 to 1.8). The effect can be caused by an increased strength of the quasi-continuous component of the geoelectric field before and after the thunderstorm [34 - 36]. Such processes last for $\Delta T \leq 10$ min.

Conclusions

1. The highly automated computer controlled radiophysical observatory of the University of Kharkov permits diversified rediophysical investigations of the near-Earth space throughout the height interval ~ 50 to 1000 km and at the frequencies between 1 kHz and 1 GHz.
2. The geospace is greatly affected by a variety of disturbing sources, both of natural and artificial origin. The power specifications of the two categories are comparable.
3. The measurements performed between 1970s and 1990s have allowed to reveal major nonstationary ionospheric processes forming the space weather. They are stimulated by solar flares, magnetic storms, the solar terminator, earthquakes and powerful thunderstorms. The basic spatial and temporal parameters of such processes have been determined, which serve as the foundation of empirical models for the geospace disturbances.

The results of investigations in an artificially disturbed ionosphere, concerning the processes that affect parameters of radio signals and noise will be discussed in further parts of the paper.

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