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WAVE PROPAGATION AND SIGNAL PROCESSING

Radiophysical Investigations and Modeling of Ionospheric Processes Generated by Sources of Various Nature*

2. Processes in a Modified Ionosphere. Signal Parameter Variations. Disturbance Simulation.

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The paper presents results of observations of the variety of processes triggered by rocket launches, flights and descents of space vehicles, chemical or nuclear explosions, impact of powerful radio waves of the decameter and hectometer wavebands, and injections of plasma extinguishing or plasma producing chemicals. The physical mechanisms responsible for transport of the plasma disturbances are discussed. Variations in the parameters of radio signals and noise at frequencies between 1 kHz and 4 GHz are investigated, and models of the disturbances described.

The technical facilities employed to investigate non-stationary processes in a naturally disturbed ionosphere and the results obtained were discussed in Part 1 of the present paper [1]. The aim of this communication is to present, analyze and summarize the experimental results and models relating to physical processes that can lead to variations of radio signal parameters in an ionosphere disturbed by anthropogenic energy releasing agents. Most of the measurements described were conducted at the Radio Physical Observatory (RPO) of the University of Kharkov.

Launches and flights of space vehicles

The processes in the terrestrial environment that are triggered by launches and flights of space vehicles have been studied at the University of Kharkov since middle 1970s. The phenomena involved proved to be complex and varied. At the active stage of its flight, a rocket exerts upon the medium hydrodynamic, thermal, electromagnetic and chemical actions, resulting in numerous geophysical, radio physical, optical and other effects.

Lower ionosphere (50 to 100 km). First, consider the effects in the ionospheric D-region observable in the partial radio reflections technique at various distances R from the launching site [2 - 7]. The distances typical of our measurements were ~100 km (measurements at the Kapustin Yar launching site); ~1500 km (cosmodrome Plessetsk – RPO); ~2500 km (cosmodrome Baykonur – RPO), and ~10000 km (Cape Canaveral – RPO). The observations were carried out for rockets of low, medium and high power ($P\sim 10^7-10^8$, 10^9-10^{10}, and $10^{10}-10^{11}$ W, respectively). Over 150 measuring sessions were performed, with about 100 for $R\approx 10000$ km. At R~100, 1500 and 2500 km the reflections from z~75 - 90 km were observed with time delays $\Delta t\approx 0.3$ -0.5; ~1 and ~3 min., respectively, with a 5 to 10-fold increase in $\overline{A_\pm^2}$, where $A_\pm$ are amplitudes of the partially reflected ordinary and extraordinary modes. The duration of such 'bursts' in $\overline{A_\pm^2}$ normally was ΔT~1-3 min. The intensity of radio noise in a 50 kHz band at $f\approx$ 2-3 MHz increased by a factor of 1.5 or 2, with Δt~1-10 min. and ΔT~1-2 min.

At R~10000 km, the partially reflected amplitudes changed only weakly, even with $P\sim 10^{11}$ W. The magnitude of variations in $\overline{A_\pm^2}$ never exceeded a few tens per cent, while Δt and ΔT were, respectively, 12 min. and 2 to 4 min. Meanwhile, the radio noise intensity increased by a factor of 7 or 10, with Δt~11 to 12 min. and ΔT~1 to 2 min. The process was for the most part quasiperiodic, with $T\approx 5$ min. and the number of quasiperiods

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equal to 4 or 5. The effects produced by rockets of lower power could not be observed with the same degree of reliability.

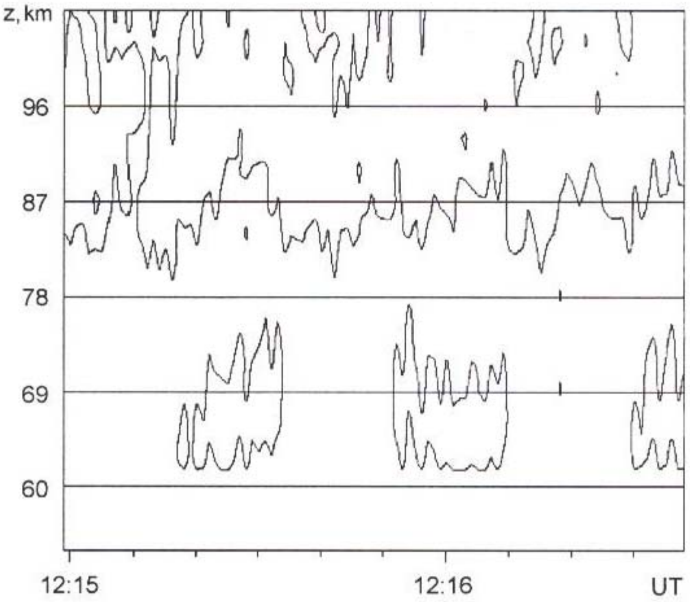

Fig.1. Height dependent temporal variations of the equal-amplitude levels for the partially reflected signal of extraordinary polarization mixed with noise, following the launch of the *Discovery* space shuttle from Cape Canaveral, 12:11 UT, 02 Nov.1992 ($f \approx 2.2$ MHz; $R \approx 10000$ km).

Fig.1 gives an example of height dependent variations with time of constant-amplitude levels for a mixture of noise with partially reflected signals observed after the launch of a space vehicle from Cape Canaveral. In this format, height-localized disturbances take the form of closed contours whose size changes but little with height, however expanding along the time axis from a few seconds to forty. In the extraordinary component such contours start to appear, throughout the interval of the disturbance existence, as of ~12:14 UT at altitudes of 63 to 69 km. The 'horizontal scale size' of the contours increases with time, reaching some 40 seconds by 12:30 UT at 60 to 66 km. The separation between individual contours along the time axis is roughly equal to their size. The 'vertical' size increases with time from 6 to 12 km over the interval 12:14 – 12:40 UT. It seems plausible that the observed character of the disturbances might be associated with the character of variations in the geomagnetic field. In particular, if the function representing geomagnetic pulsations is even with respect to the magnetic equator, then the disturbance happens to be localized in height. Otherwise the disturbance covers a broad range of altitudes.

As has been found, rockets of medium and high power are capable of producing short living disturbances in the lower ionosphere that are detectable over distances of thousands of kilometers. In our view, these effects result from stimulated precipitation of charged particles from the magnetosphere to the lower ionosphere, accompanied by an increase in the power of radio frequency noise emitted by the plasma in a wide frequency range. The increased radio noise has been observed on the global scale. The role of magnetic field disturbances requires further investigation.

The effects produced in the lower ionosphere by rocket launches have also been studied with the aid of signals from radio navigation systems (OMA, Czech Republic, f=50 kHz; MSF, UK, f=60 kHz, etc. [8-11]). The measurements were performed for $R \approx 2000$; 3000 and 10000 km. E.g., launching the *Proton* rocket on 31 March, 1987 ($P \approx 3 \cdot 10^{10}$ W) was accompanied by an increase in the signal phase, $\Delta\varphi$, as high as 2 radians ($\Delta t \leq 0.5$ hr and $\Delta T \approx 4$ hr). Launching the powerful *Energiya* carrier on 15 Nov. 1988 resulted in phase fluctuations $\Delta\varphi \leq 0.2$ rad. In the same experiment, the $\Delta\varphi$ at 50 kHz showed periodical variations with a 0.2 rad. amplitude

($\Delta t \leq$ 1.3 hr; $\Delta T \approx 1$ hr and $T \approx 0.3$ hr). The apparent velocities of the disturbances normally were $v \approx 0.3$ or 1 km/s.

Middle ionosphere (100 to 300 km). Various effects in the *E*-region and lower part of *F* were conveniently observable in the Doppler sounding technique applied to vertical and short-range (up to ~ 1000 km) oblique propagation paths, or in the traditional vertical sounding method [5,9,10,12,13]. In several cases the incoherent scatter method was used [14]. Below, a few examples of the observation results are given.

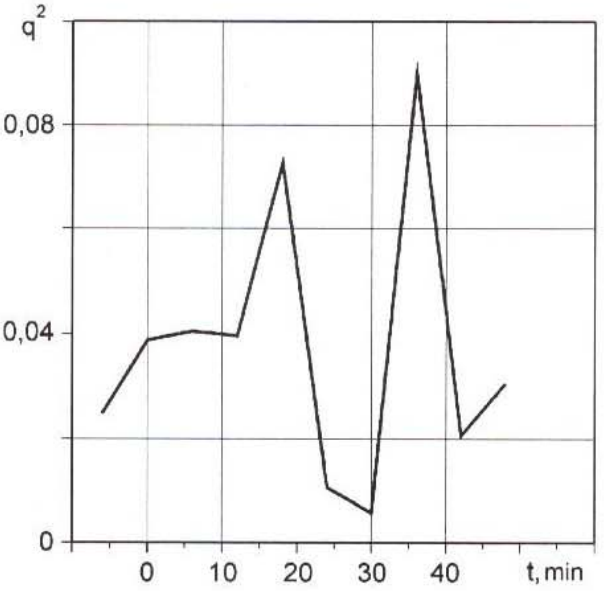

Fig.2. Time variation of the power ratio of an incoherently scattered signal to noise for the plasma line observed from 420 km after the launch of the *Soyuz-19* space vehicle from Baykonur ($R \approx 200$ km) on July 15, 1975. A quasiperiodic disturbance ($\Delta t \approx 15$ min; $\Delta T \approx 40$ min and $T \approx 20$ min) can be clearly seen. The zero point on the time axis corresponds to the moment of rocket start.

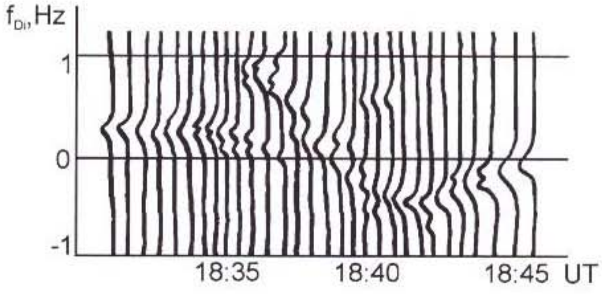

Fig.3. A dynamic spectrum of the signal recorded on a vertical propagation path ($f = 4.6$ MHz and $R \approx 2500$ km) after the launch of the *Energiya* rocket at 17:30 UT, 15 May 1987. The Doppler frequency variations appeared 66 minutes after the launch.

Fig.2 shows a time record of the signal-to-noise ratio for the incoherent scatter experiment performed 15 Aug.,1975 during the launch of the *Soyuz-19* spacecraft. The range R was about 200 km. As can be seen, the time delay is $\Delta t \approx 15$ min. The quasiperiodically varying processes that were observed resulted, most probably, from the impact of the acoustic shock wave whose propagation time from the launching site to the ionospheric *F*-region was close to 10 min. In that case, the corrected time delay can be estimated as $\Delta t' \approx 5$ min. and the corresponding apparent velocity $v' \approx 0.7$ km/s.

Fig.3 shows variations in the Doppler frequency shift, f_d, of the vertical sounding echo during the launch of the *Energiya* carrier at 17:30 UT on 15 May, 1987 (cosmodrome Baykonur, $R \approx 2500$ km; $f = 4.6$ MHz) [5]. The sharp increase in f_d up to 1 Hz, followed by quasiperiodic variations of the value with a 'period' $T \approx 10$ or 15 min., corresponds to the arrival of the acoustic wave whose apparent propagation velocity at ionospheric altitudes is $v' \approx 0.6$ - 0.8 km/s. The disturbed state of the *F*-region lasted for nearly 1 hr. A similar effect was observed in the Doppler shift recorded for the oblique Novossibirsk – Kharkov path after the launch of the *Magellanes* spacecraft from Plessetsk 16 Nov. 1992.

The statistics of global ionospheric disturbance observations in the Doppler sounding technique shows the response of the medium to rocket launches not to be equally distinct in all cases. E.g., the experiment of 13 March, 1989 at f = 3.7 MHz ($R \approx 10000$ km) was successful. The rocket started at 14:50 UT. Some 18 min. later quasiperiodic disturbances of amplitude $f_d \approx 0.7$ Hz could be detected in the ionosphere, with $T \approx 20$ min. and $\Delta T \approx 50$ min. Further on, the $f_d(t)$ dependence was complicated by the effects associated with the dusk terminator (the sunset moment at the Earth's surface was 16:00 UT). If the time necessary for an acoustic signal to reach the ionospheric F-region or the rochet flight time to ionospheric altitudes (about 8 min) were excluded, then $\Delta t' \approx 10$ min and the corresponding velocity v' would be $v' \approx 20$ km/s. This is the velocity of magnetosonic waves in the ionospheric E-region.

Other results concerning the disturbances in ionospheric E- and F-regions, obtained in the Doppler sounding technique at oblique radio propagation paths, can be found in our papers [5, 10 and 13]. The observations with multiple ionosondes are in a fain agreement with the above described results [12, 19, 20, 42]. In particular, the minimum frequency $f_{\min}$ observed on ionograms demonstrated a noticeable (0.3 ± 0.1 MHz) increase over $\Delta T \leq 15$ min, while the critical frequencies, $f_{o,x}F2$ showed quasiperiodic ($T \approx 15$ to 45 min) variations with amplitudes about 0.2 ± 0.1 MHz, lasting for $\Delta T \approx 1-2$ hr. The time delays corresponded to propagation velocities about $0.3-0.4$ km/s; $1-2$ km/s in the lower ionosphere and $0.5 \div 0.7$ km/s; $1-2$ km/s in the F-region. On rare occasions the velocities of $v \sim 10 \div 100$ km/s were observed. The ionosphere responded distinctly to launches of rather powerful rockets ($\sim 10^{11}$ W) that were performed within 3000 km. At $R \sim 10000$ km the effects were but extremely seldom observed [17].

Middle and upper ionosphere ($100-1000$ *km*). The F-region disturbances were investigated with the aid of coherent signal from low-orbit navigation satellites of the Cicada-M series [15, 16, 18]. The indicator of condition of the ionosphere sounded with these signals was the ionospheric component $f_{di}(t)$ of the Doppler frequency shift (t is the current registration time) selected at $f \approx 150$ MHz in the dispersion interferometry thechnique. The measurement error of $f_{di}(t)$ and the sampling rate were $\delta f = 0.005$ Hz and $1/(2s)$, respectively.

Shown in Fig.4 are a few $f_{di}(t)$ records taken before (curves 1, 2 and 3) and after (curves 4, 5 and 6) the launch of an Energiya rocket at 17:30 UT May 15, 1987. The radio sounding was performed over a region of scale size about 1000 km (Fig.5). Until the launching moment the ionosphere remained practically undisturbed, with the peak electron density N in the F-region $N_m \approx (4-4.5) \cdot 10^{11}$ m^{-3}. The beginning of curve 4 corresponds to minute 28 after the launch. The measurements were made some 2 to 2.5 hr after the sunset at $z = 300 \div 350$ km over the region mentioned. Accordingly, the disturbances observed cannot be ascribed to the dusk terminator. As can be seen from the Figure, the regular run of $f_{di}(t)$ was totally deteriorated. Between 17:58 and 18:00 UT the value demonstrated intense scintillations owing to small-scale (~15 to 30km) onhomogeneities of the electron density N. A reduced average concentration (about $3 \cdot 10^{11}$ m^{-3}) accompanied by small-scale inhomogeneities was observed at 18:01 to 18:03 UT. Quasiperiodic disturbances appeared at 18:06 to 18:08 and 19:00 to 19:05 UT. The apparent velocities of these inhomogeneities were ~0.8 to 0.9 km/s. Curve 6 illustrates the relaxation process where the disturbances remained observable between 19:42 and 19:45 UT but disappeared at 19:45 – 19:51 UT. Meanwhile, intense quasiperiodic disturbances were clearly seen oven the region only 50 minutes before. Assuming them to have appeared there at 17:58 UT (i.e. at the initial moment of the record of curve 4) we obtain a minimum estimate of the relaxation time, namely 107 min.

Fig.6 shows the $f_{di}(t)$ dependences recorded on 13 March, 1989 before (curve 1) and after (curves 2, 3 and 4) the launch at 14:57 UT a cargo space shuttle from Cape Canaveral. The brighter signatures of ionospheric disturbances produced by powerful rocket launches normally are intense scintillations and quasiperiodic variations of the radio signals (curves 2, 3 and 4). Meanwhile, the experiment under discussion also revealed a large-scale inhomogeneity extending along the latitude to 200 or 300 km. The ionization ratio in its central area exceeded the background level first by 40% (curve 2) and then by 10 to 15% (curves 3 and 4). The buckhound levels of N_m beyond the inhomogeneity area varied between $(0.4 \div 1.2) \cdot 10^{12}$ m^{-3}. The size and ground projection of the inhomogeneity were calculated, proceeding from the background concentrations and inhomogeneity localization at $z_i = 400$ km. The size estimated for the half-power disturbance level happened to be smaller by 30 to 50%. The ground projection of the disturbed region extended from the longitude of 35^{0}E to 45^0 at the latitude $\phi \approx 50^0 N$. The inhomogeneity seems to have lived for 2 hr.

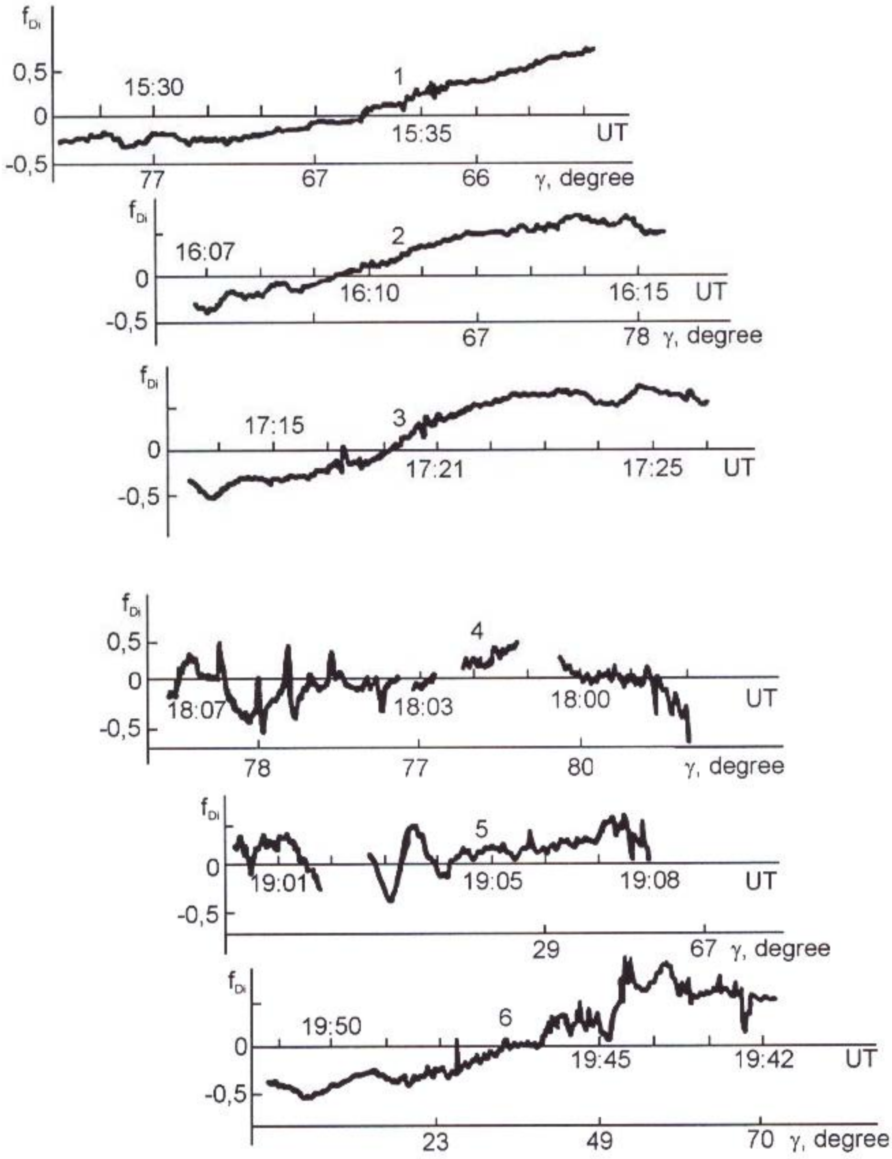

Fig.4. Time variations of the Doppler frequency shift, $f_{di}(t)$, in satellite signals: curves 1, 2 and 3 were taken before, while curves 4, 5 and 6 after the start of an *Energiya* rocket at 17:30 UT, 15 May, 1987. The values along the γ-axis are zenith angles of the satellite at the corresponding time moments. All the curves were taken with satellites flying from North to South.

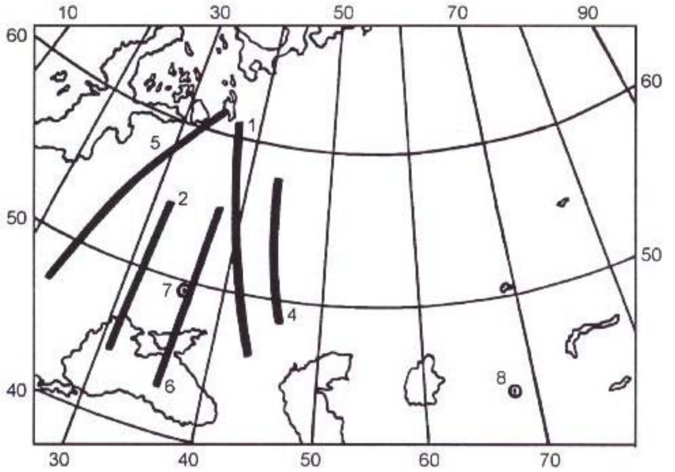

Fig.5. The solid lines represent loci of subionospheric points for the curves 1, 2, 4, 5 and 6 of Fig.4. Point 7 is the observation point and point 8 the launching site.

Curves 1-4 of Fig.7 characterize the region underlying the ionospheric areas that essentially influence formation of the $f_{di}(t)$ dependences of Fig.6. The dashed parts refer to the regions over which the ionosphere contains intense scull-scale irregularities.

Thus, by sounding the ionosphere with coherent radio signals from satellites it has been established that starts of powerful rockets can produce quasiperiodic disturbances of ionospheric parameters, of amplitude reaching 10% of the background value, latitudinal extent about 300 km and life times longer that 2 hr.

Space vehicle descents

The ionospheric processes accompanying shuttle returns or fall-downs of used craft are different from the effects at launches. A space vehicle entering the atmospheric layers of higher density ($z \leq 100$ km) generates a powerful shock wave, the gas in front of the vehicle gets heated to temperatures $T \sim 10^4$ K and ionized. Besides, atmospheric gravity waves (AGWs) with sizable variations of density are effectively generated. Hence, the atmosphere is subjected to a hydrodynamic, thermal, ionizing and chemical impacts giving size to geophysical, ratio, optical and other effects.

AGW generation. The US earth orbiter Skylab fell down at 16:45 UT 11 July, 1979 near Australia. The initial mass of the vehicle was ≈ 100 tons, accumulated energy $\sim 3 \cdot 10^{12}$ J and the deceleration power 10^{10} to 10^{11} W. The vertical sounders of the former USSR recorded fluctuations in $f_{\min}$ and $f_{o,x}F2$ reaching 0.2 to o.3 MHz. The corresponding velocities were $v \sim 0.6 - 1.1$ km/s, with $T \sim 30 - 60$ min and $\Delta T \approx 60 - 80$ min [5, 12, 18].

Ionization trail. The effects produced by the fall down of the Salute-7 orbiter at 03:47 UT 7 Feb., 1991 in South America were studied with a vertical Doppler sounder [5]. The measurements were done at the RPO some 50 minutes before the vehicle descent (Fig.8). The mass was about 40 t, and energy and deceleration power could be estimated as 10^{12} J and $10^9 \div 10^{10}$ W, respectively. As followed from the Doppler sounding, the vehicle was at its last orbital turn at the height ~100 km. The fall-down was accompanied by appearance of a highly ionized trail with $\Delta T \approx 200$ s. The Doppler shift f_d was $f_d \approx 0.1$ Hz (at the carrier frequency $f \approx 3.7$ MHz.

Explosions.

Chemical explosions in the atmosphere have a mostly gas-dynamic impact on the medium, generating a shock that gradually transforms into an acoustic disturbance. The energy released by the explosion is almost completely transferred to the shock wave. High altitude nuclear explosions are complex multicomponent agents exerting the ionizing, thermal, chemical, electromagnetic and other actions that produce optical, geo- and radio physical effects. The explosion-stimulated processes in the ionosphere depend upon distance from the explosion, height (depth) of its localization and amount of the energy released [2-4, 9, 11, 13, 20-22].

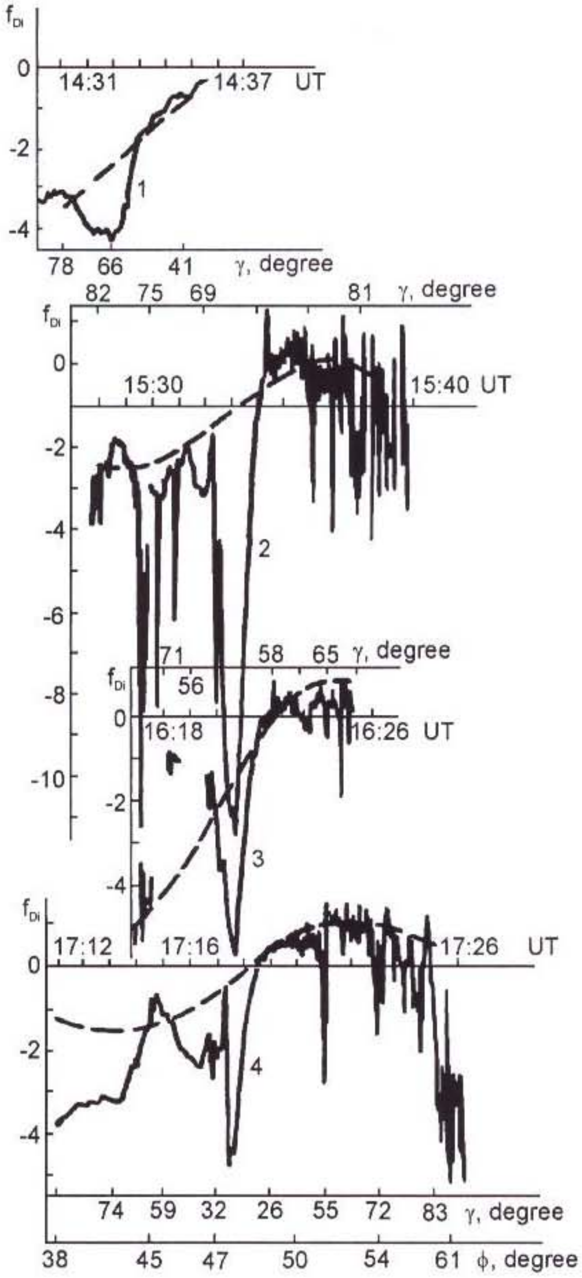

Fig.6. Time dependences $f_{di}(t)$ of the Doppler shift in satellite signals: curve 1 was recorded before arrival of the ionospheric disturbance, and curves 2, 3 and 4 after the launch of a space shuttle at 14:57 UT on 13 March, 1989. The dashed lines show model $f_{di}(t)$ dependences calculated for undisturbed conditions. All the curves correspond to satellite transits from South to North. The γ-axis is the same as in Fig.4. The values along the ϕ axis are latitudes of subionospheric projection points.

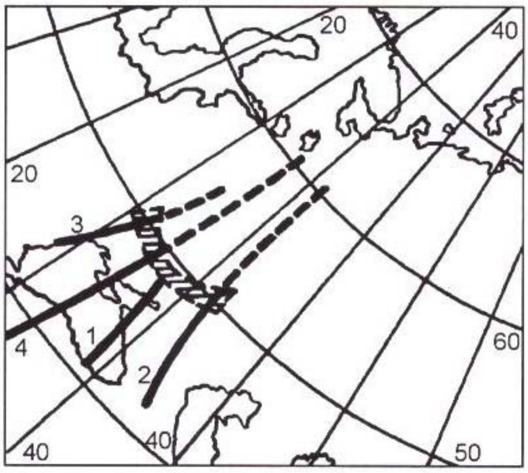

Fig.7. Loci of subionospheric points for curves 1-4 of Fig.6.

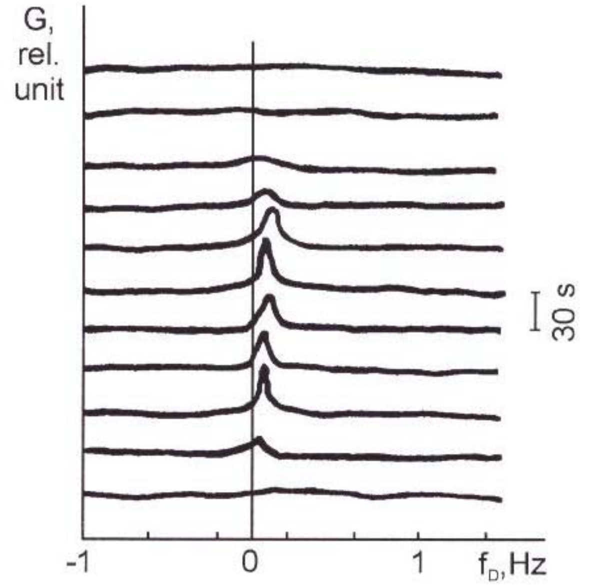

Fig.8. The dynamic spectrum of a vertical sounding signal ($f = 3.7$ MHz) 50 min prior to the fall-down of the *Salute-7* orbiter at 03:47 UT 7 February, 1991. The measurements were performed at the Radiophysical Observatory in Kharkov. The orbiter was at the altitude ≈ 110 km. The radar return was due to reflection from the ionized trail.

Ground based explosions. In the experiment of 12 October, 1987 (Kapustin Yar) Doppler sounding of the ionosphere was performed at $R \sim 30$ km off the ground explosion that was characterized by an energy release ~ 10^{11} to 10^{12} J. The propagation velocity of acoustic waves increased with altitude (at $z \geq 100$ km), bringing forth a height dependent "extension" of the acoustic pulse. An acoustic pulse passing through the ionospheric F-region produced alternating variations in the Doppler frequency shift of the sounding radio signal during $\Delta t \sim 60$ s (Fig.9).

In late 1980s a series of explosions with $E \sim 10^{11} \div 10^{12}$ J were performed at the Kapustin Yar test range to destroy mid-range missiles in accordance with the international agreement. The observation site was at 700 km. The response of the lower ionosphere was studied by the partial reflections method. About 20 events were analyzed and no definite response of the lower ionosphere was revealed. On some days certain effects were observed that admittedly could be related to the explosions. E.g., on 19 May, 1990 the intensity partial reflections from $z \approx 90 \div 100$ km dropped down after $\Delta t \approx 40$ min ($v' \approx 330$ m/s). The reaction took place after the first explosion only (they followed every 20 min from 09:00 to 10:20 UT). At z =90 and 93 km noticeable synchronous peaks of the reflected intensity appeared after two first explosions ($\Delta t \approx 12$ min, or $v' \approx 1.7$ km/s, and $\Delta T \approx 5$ to 10 min). The signal-to-noise ratio was 2 to 10. Finally, 40 min after two last explosions, these was a quasiperiodic disturbance at 96 and 99 km ($T \approx 5$ min; $\Delta T \approx 80$ min and ($v' \approx 330$ m/s).

Similar explosions of a different series were investigated in the multiple-frequency sounding technique. E.g., in the experiment of 17 Dec. 1989 five explosions were made at 20 min intervals between 06:30 and 07:50 UT. The sounding signal $f = 4940$ kHz showed a sizable broadening of its Doppler spectrum after each of the four first explosions (the distance R from the explosion to the middle of the propagation path was $R \approx 900$ km). The effect was observed after $\Delta t \approx 30$ to 35 min ($v' \approx 0.5$ to 0.6 km/s); occasionally new propagation modes appeared with $f_d \leq 1$ Hz and $\Delta T \approx 5$ to 10 min. At the same time wave processes of $T \approx 15$ min got increased, which effect persisted at least 1 hour after the last explosion. Similar effect were detected at $f = 6055$ kHz; however they were markedly less pronounced. At $f = 1503$ kHz ($R \approx 700$ km) the signal showed short-term ($\Delta T \approx 1$ to 5 min) enhancements of amplitude some 12 min past each of the four first explosions and 20 min after the fifth one. Besides, a weak signal from a simultaneous broadcast station was observed, shifted by $f_d \approx 0.2$ Hz. The Doppler spectrum of that lather changed its width by a factor of 1.5 to 2 with a period close to 10 min. The signal disappeared 12 min after the last explosion. The time delay $\Delta t \approx 12$ min corresponds to $v \sim 1$ km/s (or $v' \sim 1.7$ km/s). The effects at $f = 1593$ kHz were less pronounced.

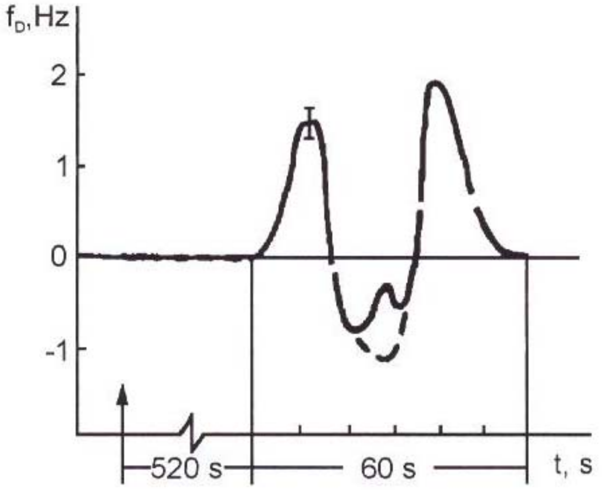

Fig.9. Time variations of the Doppler frequency shift for a vertical sounding signal ($f \approx 4.1$ MHz; $R \approx 30$ km) 520s after a surface chemical explosion (energy release ~10^{11} to 10^{12}J). The experiment was performed at the Kapustin Yar testing site 12 Oct., 1987.

Aerial explosions. The explosion at $z \approx 14$ km of the space shuttle Challenger at 08:39 UT Jan.28, 1986 (Cape Canaveral) first produced a 1.5 radian increase in the phase of a VLF ($f = 16$ kHz) signal on the path between the UK and the city of Kharkov ($\Delta t_1 < 0.5$ hr and $\Delta T_1 \approx 0.5$ hr), and then its decrease by a similar value ($\Delta t_2 \approx 1.5$ hr and $\Delta T_2 \approx 3.5$ hr). At the same time the signal amplitude dropped by a factor of 4 or 5 ($\Delta t_2 \approx 1.5$ hr and $\Delta T_2 \approx 3.5$ hr). The greater value of Δt corresponded to $v \approx 2$ km/s. Since amount of energy released and the source power were relatively low, the variations of the radio signals described cannot be unambiguously ascribed to the explosion in preference to some natural environmental processes. Reliable records of ionogram or magnetogram parameter variation after the explosion ($R \approx 10000$ km) are not known.

Underground nuclear explosions. Like their chemical analogs, the explosions of this variety exert a mostly gasdynamic (or, rather, acoustic) action on the atmosphere. We will consider by way of example, the partial reflections record of the global disturbances triggered by the Nevada explosion of 13 Aug., 1987 (($E \sim 10^{14}$ to 10^{15} J). The observations were carried out in the pre-dusk period (15:00 UT), some 3 hr before the local sunset at the Observatory. The first sizable (up to an order of magnitude) increase in the average intensity, $\overline{A_{\pm}^2}$, of the partially reflected signal was detected after $\Delta t \approx 3 \div 5$ min for $z \approx 105$ km. Twenty minutes after the explosion the disturbances of duration $\Delta T \approx 1 \div 3$ min could be observed throughout the D-region. Two or three disturbances of quasiperiod ≈ 6 min were also recorded. At lower altitudes Δt was greater. The apparent downward propagation velocity of the disturbances was close to 300 m/s. The disturbances vanished at minute 20 to 40, to reappear later. The next series of bursts in $\overline{A_{\pm}^2}$ was observed after the delay of $65 \div 85$ min (i.e. $v' \approx 3 \div 2$ km/s). These were accompanied by variations in the intensity of noise, $\overline{A_n^2}$, over the band $\Delta f = 50$ kHz at $f = 2.2$ MHz. Normally, bursts of $\overline{A_{\pm}^2}$ are associated with an increased intensity of electron density inhomogeneities, $\overline{\Delta N^2}$, and general increase of the average electron concentration, N, in the ionosphere.

The values $v' \approx 2 \div 3$ km/s and $v' \approx 6 \div 8$ km/s are close to the propagation velocities of seismic surface and volume waves, respectively. The magnitude of $v \approx 30 \div 50$ km/s suggests generation of a different wave mode (admittedly, either the gyrotropic or magnetoacoustic wave). The velocity $v \sim 1-2$ km/s is characteristic of the magnetohydrodynamic (MHD) slow mode.

In the same experiment, the E- and F-region disturbances were investigated in the multifrequency sounding technique. When sounded quasivertically at $f \approx 4$ MHz, the medium showed a response at minute 3 or 5. The response represented quasiperiodical variations of the Doppler frequency, f_d, with periods close to 15 and 30 min and duration $\Delta T \approx 80$min. The amplitude increased gradually from 0.1 to 0.2 Hz. Some 38 min later a second disturbance of duration about 20 min arrived, which overlapped with the first one. In all evidence, it was associated with the impact of an acoustic pulse, therefore we assumed $\Delta t' \approx 28$ min and $v' \approx 6$ km/s. The first disturbance was characterized by $v \approx 30 \div 50$ km/s. Upon arrival of both disturbances, the Doppler spectrum of the signal broadened and new modes appeared, $f_d \sim 0.1 - 0.2$ Hz.

Also significant was the underground nuclear explosion of 14 August, 1988 (04:00 UT, the Semipalatinsk test site in Kaxakhstan; $E \approx 6 \cdot 10^{14}$ J). Attempts of observing ionospheric disturbances were made at hectometer frequencies ($f = 1485$ kHz; the separation D between the transmitter and receiver was $D \approx 70$ km with the propagation path oriented from North to South, and $f = 1539$ kHz with $D \approx 50$ km and the South-North orientation), and decameter frequencies ($f = 4940$ kHz and $f = 6020$ kHz, with $D \approx 480$ km in the W-E direction, and $f = 9410$ kHz, with $D \approx 2500$ km, West to East). The experiment was performed at dawn, hence analysis may prove necessary of the role played by sunrise effects. Along the hecto- and decameter wave propagation paths, the moments of sunrise in the ionosphere were 1.5 to 2 hours before activation of the disturbance source. Since the transient effects associated with the solar terminator normally last about one hour, it can be stated that the terminator did not influence the effects of our interest. The brightest response to the explosion was observed at $f = 6020$ kHz as an increase in the signal level over $\Delta t \approx 6.5$ min ($R \approx 3200$ km). In the case of $f = 9410$ kHz, which signal was reflected from roughly the same height, Δt was $\Delta t \approx 8.5$min and $R \approx 3200$ km. The knowledge of Δt and R for two signals allowed estimating the development time Δt_0 of the process and propagation velocity v' of the disturbance. To within the temporal resolution (30 seconds), the values happened to be $\Delta t_0 \approx 0$ and $v' \approx 8.2$ km/s. The life time of the effect was 5 to 7 minutes. Later on, the signal $f = 6020$ kHz demonstrated broadening of its Doppler spectrum and appearance of new modes (after $\Delta t \approx 13$ min), with $\Delta T \approx 10$ min. With account of the acoustic delay time (about 6 min) we have $\Delta t' \approx 7$ min, and $v' \approx 8$ km/s. The delays characteristic of the next train of disturbances were $\Delta t \approx 25$ min and $\Delta t' \approx 19$ min (or $v' \approx 2.8$ km/s). Meanwhile, the signal $f = 4940$ kHz behaved in a different way because of its greater reflection height (about 200 km). The first response appeared after $\Delta t \approx 3$ min, showing a narrower Doppler spectrum and greater amplitude of the dominant mode. The process repeated periodically, with $T \approx 6$ min. The delay time corresponded to $v \approx 20$ km/s.

The values characteristic of all the propagation paths of hectometer wavelength signals were $\Delta t \approx 24.5$ min, or $\Delta t' \approx 20$ min and $v' \approx 2.7$ km/s.

The underground explosions of 2 August, 1987 produced at the Semipalatinsk (01:00 UT) and Novaya Zemlya (02:00 UT) test sites ($E \sim 10^{14} - 10^{15}$ J) brought forth a 0.6 radian phase variation in the $f = 60$ kHz signal propagating between a UK transmitter and a receiver in Kharkov. The time delay Δt was ~0.5 hr for both explosions, which corresponded to $v \approx 1.7$ km/s. Compared with the reference dates of 1 August and 3 August, 1987, the morning sinking of the lower ionosphere (to be more exact, formation of the upper wall of the Earth-ionosphere waveguide) was delayed by roughly one hour.

Next, we will consider the results obtained with an ionosonde network. The observations were performed in Kharkov, Ukraine; Nizhny Novgorod, Russia; Moscow; Karaganda, Kazakhstan, and Paratunka, Kamchatka Region, Russia. Nearly 1000 ionograms have been treated to analyze the ionospheric response to 12 underground explosions of energies between $10^{14} - 10^{15}$ J. The range R varied from 750 km to 10 000 km. Following the explosion of 19 April, 1987 (04:00 UT, $E \approx 7 \cdot 10^{13}$ J and $R \approx 750$ km), the critical frequency f_0F2 varied by 0.2 to 0.3 MHz with $\Delta t \approx 15; 45; 105$ min. The corresponding velocities were $v' \approx 2.5; 0.4; 0.1$ km/s. The variations were absent on the reference dates of 18 April and 20 April, 1987. The $f_{\min}$ variations on the same data were characterized by $\Delta t \approx 30;90;135$ or $v' \approx 0.5; 0.15; 0.1$ km/s. Most probably, all the effects reflected the same disturbance process with $v' \approx 0.5$ km/s and $T \approx 60$ min. Besides, the explosion triggered the formation of a sporadic layer, E_s. In the experiment of 22 April, 1986 the explosion was performed in the state of Nevada (time: 15:30 UT; power: $E \sim 10^{14} - 10^{15}$ J). The observations were made at three sites, each at about 10 000 km from the source. Sites 1 and 2 were roughly at the same meridian, while 1 and 3 lay at the same latitude with the source. The minimum frequency $f_{\min}$ first increased by 0.3 to 0.4 MHz after $\Delta t \leq 15$ min, the corresponding estimate for v being $v \geq 10$ km/s. Apparently, the change in $f_{\min}$ resulted from an increase in the electron density of the lower ionosphere. Besides, the frequency showed a weakly pronounced oscillatory variation with $\Delta t \approx 90; 135; 180$ min. The corresponding velocity was $v' \approx 2$ km/s, and $T \approx 45$ min. The delay times in the F-region were $\Delta t \approx 30; 120; 150; 225$ min, accordingly $v' \approx 8; 1.5; 1.2\ 0.8$ km/s. At site 2 which was some 2500 km farther to the West than site 1, both $f_{\min}$ and f_0F2 increased sizably (up to 1.5 MHz) 15 to 30 minutes after the explosion. Besides, quasiperiodical ($T \approx 45 \div 60$ min) disturbances were also observed. Effects as strong as these hardly could be ascribed to the explosions. Most probably, the natural pre-dusk effects overlapped with some explosion stimulated processes. The latter were characterized by $\Delta t \approx 15; 75; 120; 195$ min (i.e. $v \geq 15; 2.5; 1.5; 0.8$ km/s, respectively) in the lower ionosphere and $\Delta t \approx 0; 30; 90; 195$ min ($v' \geq 10; 8; 2.5; 0.8$ km/s) in the F-region. The measurements at the third site gave $\Delta t \approx 30; 75; 135; 165$ min ($v' \approx 7; 2.5; 1.3; 1$ km/s, respectively) for the lower ionosphere and $\Delta t \approx 30; 90; 150$ min ($v' \approx 8; 2.5; 1.2$ km/s) for the F-region. As can be seen, the delay time estimates obtained at the three sites are generally in agreement. The apparent propagation velocities of the disturbances are therefore nearly equal in the meridional plane and along the latitude.

The statistical analysis of variations in $f_{\min}$ and f_0F2 and of their delay times for $R \approx 10000$ km [12, 42] showed $f_{\min}$ and f_0F2 to vary as 0.3 ± 0.1 MHz. The delay times fall into five groups, namely $\Delta t \approx 30 \pm 5; 80 \pm 5; 150 \pm 12; 250 \pm 14$ min, or $v' \approx 8.3 \pm 1.4; 2.4 \pm 0.1; 1.2 \pm 0.1; 0.69 \pm 0.04$ km/s. The estimated velocities do not contradict the results obtained in other methods.

Thus, powerful aerial or underground explosion can trigger the generation of AGWs, acoustic and seismic waves with apparent velocities $v' \sim 0.1 \div 0.2; 0.3 \div 0.7; 3 \div 4; 6 \div 8$ km/s. Both these and the faster waves, $v' \sim 1000$ km/s (fast MHD modes) were investigated by many workers backing 1960s. The generation of slow MHD waves ($v' \sim 1 - 2$ km/s) was studied somewhat later. The present authors discovered wave processes characterized by $v' \approx 30 \div 50$ km/s, admittedly related to magnetocoustic and gyrotropic waves propagating in the ionosphere.

Powerful radio waves.

The impact of powerful radio waves upon the geospace plasma is for the most part, of thermal and chemical character (change of chemical reaction rates). From the ecological point of view, radio waves represent the least polluting source of disturbances. It is responsible for radio physical, geophysical and weak optical effects in the ionosphere-magnetosphere system.

Anomalous effects. The ionospheric response to powerful radio waves has been studied at the University of Kharkov since early 1970s. Along with the familiar effects owing to heating of the medium, the very first experiments revealed some anomalies in the behavior of diagnostic radio signals [23]. They appeared preferably during the first "ON" period of the powerful transmitter in every given experiment. Their delay time was $\Delta t \approx 5 - 10$ min and duration $\Delta T \approx 1 - 2$ min. The intensity and probability of appearance of the effects depended on the geophysical conditions. The specific effects that were observed included an anomalously high amplitude cross-modulation factor, a 0.2 to 0.4 MHz increase of $f_{\min}$, greatly enhanced $\overline{A_{\pm}^2}$ and $\overline{A_{noise}^2}$, and abnormally attenuated diagnostic signals that passed through the disturbed region. All of these effects were observable within the radiation pattern of the powerful facility, however they cannot be explained straightforwardly in terms of the radiation impact on the ionospheric plasma. The powerful radiation rather seemed to trigger natural-like processes. As of 1983, the disturbances that manifest themselves rather far away from the heating facility have been studied. Such effect are known as large-scale disturbances. Currently, the data base that has been collected embraces the complete solar activity cycle and contains data for a variety of separations between the heater and diagnostic facilities (100 to 2700 km) and for different path orientations. The measurements have been done in different radio techniques [24-31].

Large scale disturbances in the lower ionosphere. First observation of large scale disturbances were performed on 31 May through 3 June, 1983. They were stimulated by the powerful transmitter Sura near Nizhny Novgorod, Russia that operated in the CW mode at $f = 4785$ kHz and 5828 kHz (without modulation). The effective radiated power was $PG = 300$ MW. The partial reflections diagnostics was done at the RPO separated from the modifying facility by $R \approx 1100$ km. The partially reflected echoes were averaged over one minute intervals with one-minute time shifts. A considerable increase in $\overline{A_{-}^2}$ (by a factor of 2 or 3) showed up at minute 14/15 after the heater switch-on. Short-term (1 to 2 minutes) surges of intensity correlated with the switch-on/ switch-off moments for the heating facility. The records of geomagnetic field fluctuations at 0.01 to 0.3 Hz (the 'h.f.' magnetometer channel, horizontal field components) taken at Borok, Yaroslavl Regio, Russia (magnetic observatory of the Institute for Earth Physics, Russian Academy of Sciences; $R \approx 400$ km) showed a 0.5 to 1 nT increase in amplitude at roughly the same time.

In the series of experiments performed in April, 1984, of special interest were those days when the heater was operated in short cycles ($T_c < 3$min) at $f = 4785$kHz and $f = 6815$kHz, with PG=300 MW. The amplitudes $\overline{A_{\pm}^2}$ increased by a factor of 1.5-2 for the first time at minute 7-8 upon the first switch-on of the heater and reached their highest values (increasing by a factor of 4) at minute 15 or 16. Such disturbances lasted for 5 or 6 minutes. The variations cannot be associated with every individual switch-on or switch-off, the disturbance being an integrated effect. Some 9 or 10 minutes upon the first switch-on, sizable fluctuations of the geomagnetic field appear (about 2 or 3 nT in magnitude). They are better pronounced for the North-South field component where their dominant periods are 4 to 6 min in the 'low frequency' channel (frequencies between 0.0015 and 0.02Hz) and 1 to 2min in the 'high frequency' channel. The highest amplitude of geomagnetic disturbances was detected during minutes 23 to 28 in the 'h.f.' channel (2nT) and minutes 40 to 45 in the 'low frequency' channel (4nT).

The unperturbed electron density profile, N_0, calculated from measured data and the profiles of relative disturbance N / N_0 for several time moments are evidence for the appearance of a layer of enhanced ionization $\Delta N / N_0 \leq 1$ at $z \approx 70 \div 80$ km.

In the experiments of 19 November through 21 November, 1986 the ionosphere was modified with a powerful radio wave of ordinary polarization radiated by the HF facility of NII Radio (Radio Research Institute, Moscow) at $R \approx 800$ km the radiation parameters were as follows: $PG = 80$ MW; $f = 5905$ kHz;

$T_c = 45$ min; and heating duration 30 min. The radiation was modulated by a single sinusoidal waveform of frequency 1 kHz, with the modulation depth of 60%. The radiated power was cut down by a factor of 2 in the middle of the 'heater ON' period. The characteristic observations of November 20, 1986 were as follows. Some 10 minutes after switching the heater on a 2 to 5-fold increase in $\overline{A_-^2}$ was registered at $z = 75 - 87$ km, the effect lasting for 15 minutes. Another increase of $\overline{A_-^2}$, of a shorter duration (5 to 8 min), followed 15 or 16 minutes after the first one. Admittedly, it was associated with the changes of the heater power. A third maximum was observed 16 minutes after complete cut down of the heating facility. The partial reflection enhancements produces by subsequent activations of the heater were but less pronounced. A similar behavior was shown by $\overline{A_-^2}$ in the experiments of November 19 and November 21, 1986. All the three records demonstrated practically zero levels of partial reflections (especially of $\overline{A_-^2}$) after about 1 hour of operation of the facility. The effect remains till the end of the experiment, apparently being due to an increased absorption of the radio waves. The extended steady-state intervals (15 min) between changes of the heater power permitted detecting increased fluctuation amplitudes of the geomagnetic field horizontal components at 0.01 to 0.3 Hz that followed 3 or 5 minutes after the switch of power. The enhancements were seen on magnetometer records for 5 to 7 minutes.

To investigate the dependence of large scale disturbance parameters upon the heater power, a special experiment was held on 12 December, 1987 in which the radiated power was changed in every active period. The power values were 0.8; 0.36 and 0.1 of the maximum. Other parameters of the Sura operation mode were $PG = 300$ MW; $f = 4802$ kHz; $T_c = 10$ min, and duration of the ON period 0.5 min. The effect detected for the range $R \approx 1100$ km was a 2 to 3-fold increase in the scattered intensity $\overline{A_-^2}$ from $z = 93$ km that was observed 10 to 14 minutes past switching the heater on at power levels $0.8P_{\max}$ or $0.36P_{\max}$. The disturbances lasted for 2 or 3 min. No response was detected to irradiation of the ionosphere at the power level $0.1P_{\max}$.

Active experiments on modification of the polar ionosphere were performed on 12 November through 15 November, 1991 near Troms, Norway ($R \approx 2700$ km). The ionosphere was heated by a powerful ($PG = 360$ MW) radio wave of ordinary polarization at $f = 7953$ MHz. The measurements of this series were of special interest because the ionosphere was modified in the high-latitude region where particle precipitations from the magnetosphere are greatly more intense than at mid-latitudes, while the trigger levels for geomagnetic or geoelectric field disturbances are sizably lower. The essential drawback of the experiments was that the observation were performed in the transition period when the ionosphere was disturbed by sunset effects. The effect common to all the days when ionospheric modification was attempted was the long-term (about 1 hr) increase in $\overline{A_\pm^2}$ that showed some 30 to 35 minutes after the Tromse heater was started. The time delay of this magnitude corresponds to $v \approx 1.3 \div 1.5$ km/s. On 12 November, 1991 it was observed at $z \approx 84 \div 93$ km, definitely after the sunset. Admittedly, it can be ascribed to an increase in the electron density at the height. Additional evidence in support of this is given by the considerable attenuation of the reflections from a sporadic E-layer at $96 \div 110$ km. Note that $\overline{A_-^2}$ was attenuated stronger than $\overline{A_+^2}$.

We have for the first time registered the response of the lower ionosphere to a periodic (5 minutes ON/5 minutes OFF) heating with powerful radio waves ($PG \approx 100 \div 300$ MW) from the transmitter near Nizhny Novgorod, Russia. Measurements along the propagation path between a transmitter in the Czech Republic and the receiver in Kharkov ($f = 50$ kHz) revealed quasiperiodic variations in the signal phase with $\Delta\varphi \approx 7^0$; $T \approx 5$ min or 20 min; $\Delta T \approx 40$ min and the delay time $\Delta t \approx 15$ min. The phase error was 3^0 [10].

Large scale disturbances in the middle ionosphere. Along with the partial reflections method and direct magnetometer measurements, the disturbances of this variety were investigated in the vertical sounding technique, using the ionosonde network of the former USSR, as well as in the vertical Doppler and multiple frequency (3 kHz to 30 MHz) oblique sounding [10, 13, 19, 20]. In addition, panoramic measurements of the ionospheric radio noise were made in the range of 1 to 30 MHz. E.g., the experiment of 29 January, 1987 resulted in simultaneous records of noise intensity in the ordinary and extraordinary components at $f = 2.2$ MHz (in a 50kHz band), Doppler frequency shift for the 2.4 MHz carrier (vertical sounding from RPO, Kharkov), and geomagnetic field variations (the magnetic observatory of Borok). The ionosphere was disturbed by a CW powerful radio wave of extraordinary polarization radiated near Nizhny Novgorod ($f = 1.35$ MHz and $PG = 10$ MW). As was found, noise intensity reduced by a greater factor than 2 some 7 to 10 minutes after the powerful transmitter had been switched on, while the ratio of intensities of the noise normal components changed from 1 or 1.1 to 0.5 or 0.7. These disturbances lasted for one hour or longer. The Doppler frequency shift increased by a factor of 1.2 to 1.5 upon $\Delta t_1 \approx 12 \div 15$ min, then (after $\Delta t_2 \approx 20$ min) it changed sign to reach values about –0.2 Hz. At the same time, the fluctuation amplitude of the geomagnetic field increased slightly in both frequency channels. The delay times as reported can be associated with $v_{1,2} \approx 1.2 - 1.5;\ 0.9$ km/s. In other experiments the ionospheric heating stimulated quasiperiodic disturbances (with $T \approx 5 \div 20$ minutes at $z \approx 100 \div 300$ km, and $\Delta T \leq 1$ hr), multiple mode propagation and even deterioration of the diagnostic Doppler spectra. The typical observational parameters were $\Delta t \approx 25 \div 30$ min, or $v \approx 0.7 - 0.6$ km/s for $f = 2 - 4$ MHz [25].

Statistical analysis of the ionograms taken by ionosondes at $R \approx 100$ km from the heating facilities shows the ionospheric disturbance to manifest itself through increased variations in $f_{\min}$ and f_0F2 (the critical frequency varies by 0.3 ± 0.1 MHz) that appear after a time delay $\Delta t < 15$ min and last for $\Delta T \approx 46 \pm 12$ min. In the case of ionosondes at $R \approx 1000$ km the magnitude and duration of variations in $f_{\min}$ and f_0F2 remains roughly the same, however two different delay times are detected, $\Delta t_1 < 15$ min and $\Delta t_2 \approx 30 \pm 11$ min, suggesting two mechanisms of disturbance [24].

To summarize, application of powerful radio waves to the ionosphere gives rise to a set of anomalous effects [23, 30, 31] manifesting themselves through sporadic ionized layers at $z \approx 70 \div 100$ km; generation or enhancement of the sporadic $E(E_s)$; increased absorption at $f \sim 1 - 10$ MHz; fluctuations in signal parameters at $f \sim 1 - 250$ MHz; elevated level of ionospheric radio noise at $f \sim 1 - 10$ MHz, and generation of wavelike disturbances of period $T \approx 5 \div 20$ min and velocity $v \approx 0.3 \div 0.7$ km/s. It should be emphasized that the effects developed 1 to 10 minutes after switching the powerful transmitter on and could either stop before it was switched off or continue (and even increase) beyond the moment when the disturbing agent ceased operation. The effects were not observable at shorter separations from the heater than 2700 km. In fact, their amplitude and appearance probability depended essentially on the current geophysical conditions. Thus we have collected evidence for activation by the powerful nonstationary radio waves of natural ionospheric processes.

Many of the effects described can be associated with particle precipitation from their stock in the geospace. As is well known, the corpuscular intrusions to the atmosphere may produce electron density enhancements, especially in the lower ionosphere, elevated radio emissions in a wide frequency range, and generation of acousto-gravity waves with $v \approx 0.3 \div 0.8$ km/s.

Stimulated particle precipitation is preceded by a variety of processes [30, 31]. The powerful nonstationary radio emission brings forth an enhanced electron density in the ionospheric D-region-either as an integrated effect of individual pulses of duration $\tau < t_N$ (where $t_N \approx 10 \div 100$ s is the formation scale time for N), or following a long time impact $\tau > t_N$. As a result, the ionospheric conductivity becomes inhomogeneous. The inhomogeneity is polarized in the presence of an external current, which brings forth generation of low frequency electromagnetic waves. When penetrating to the magnetosphere, this radiation may modify the pith-angle distribution of trapped particles and stimulate their precipitation. This results in another increase of the electron density, N, modulation of ionospheric conductivity and generation of electromagnetic radiation. In other words, the disturbance is amplified and repeated. Should the zone of precipitating particles at $z \approx 100$ km spread beyond the boundaries of the initially disturbed region, that would imply existence of some process of ionosphere-magnetosphere-ionosphere interaction extending beyond the radiation pattern of the heating facility. The propagating disturbances associated with this process attenuate but weakly because of power being pumped from the magnetosphere.

Chemical injections

The releases of chemical agents into the geospace (mostly by means of an explosion) exert gas-dynamical, chemical, ionizing and thermal actions. The active experiments of the kind may well be ecologically clean (say, with the mass of the substance released remaining below 1 to 10 kg). Such releases given rise to a variety of physical effects, including optical, geo- and radio physical, etc.

Chemical injections represent a convenient modeling method for a variety of natural ionospheric processes, like generation of quasistatic electric and magnetic fields, production of electron density irregularities, etc. Besides, the injection of plasma producing substances may prove useful in modeling the artificial ionized formations of a different origin (e.g., those produced by high altitude nuclear explosions). Plasma extinguishing materials are used to reduce the impact of the ionosphere – in particular, in the decameter and hectometer wave radio astronomy. Some of the related problems are discussed in papers [3, 4, 32-34].

Ionospheric 'holes'. Considerable amounts of plasma extinguishing materials are released during fuel burn-out at the active portion of a rocket trajectory at launch. As a result, an ionospheric 'hole', i.e. area of reduced electron density appears in the middle ionosphere. Such 'holes' were observed in the Doppler sounding technique at the Kapustin Yar launching site. The radio sounding facility was at 150 to 200 km off the active trajectory of a medium power rocket. The build-up of the reduced density area was monitored as of minute 10 after the launch and till minute 30, while the relaxation period lasted from minute 30 to minute 80. Fig.10 shows the Dopplerogram and variations of the effective reflection height at $f = 3.7$ MHz. As can be seen, the reflection height varied as much as 30 to 40 km, while the relative reduction in the electron density of the F-region plasma never exceeded 10 or 15%. Both the build-up and relaxation periods of the area of reduced electron density were marked by generation of wavelike disturbances of quasiperiods 10 to 15 minutes and $\Delta N / N_0 \approx 5\%$.

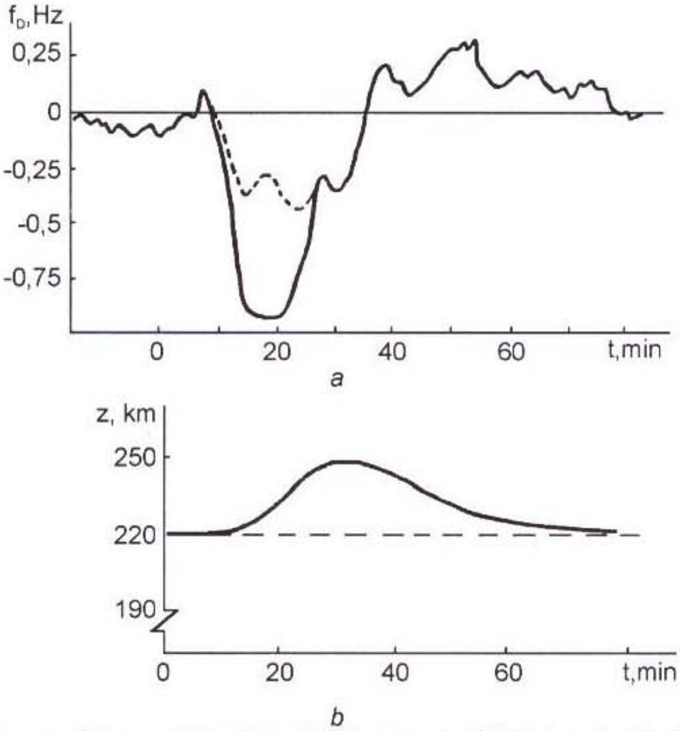

Fig.10. Time variations of the Doppler frequency shift (a) and effective reflection height (b) of radio waves $f = 3.7$ MHz at a vertical propagation path ($R \approx 150 - 200$ km). The measurements covered the periods of development and relaxation of an area of reduced electron density upon injection of plasma extinguishing agents. (The experiment at kapustin Yar, 18 September, 1985).

Plasma generation. Doppler sounding of artificial plasma structures was performed, as part of the 'Active experiments in space' program carried out at the Kapuspin Yar test site. The plasma generating agents were injected from the MP-12 meteorological rockets at a height about 150 km. The Doppler ionosonde was 50 km off the surface projection of the center of the artificial plasma area. Examples of the Dopplerograms are given in Fig.11. Prior to the chemical injection (mostly of caesium atoms) the only echo signal observed was that reflected from the F-region (the sounding frequency was $f = 3.7$ MHz and the range selected 260 to 335 km). About 2 minutes after the release, additional echo signals were recorded, first direct reflections from the area of artificial plasma (range of 110 to 185 km), and then those rebounding from the ionosphere (335 to 410 km). The signals reflected from the artificial plasma area could be observed for 45 minutes, with their Doppler shift reaching –0.5 Hz.

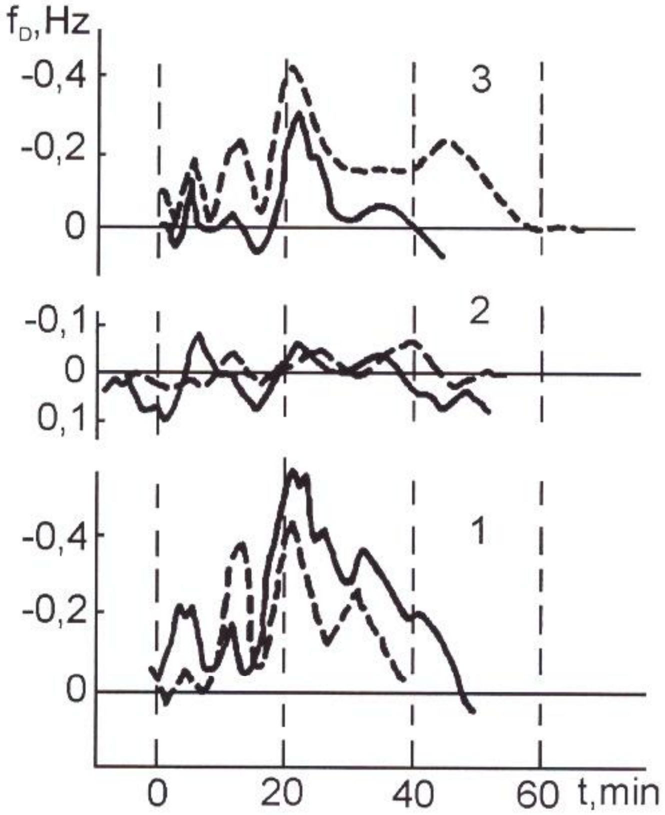

Fig. 11. Temporal variations of the Doppler frequency shift of vertically propagating signals ($f \approx 3.7$ MHz; $R \approx 50$ km) for several range bings (a plasma-generating material has been injected at a height about 150km). The solid line represents the data of 23 June, 1986; the dashed line is for 18 Okt., 1985: 1) ranges of 110 to 185km; 2) 260 to 335km and 3) 335 to 410km. The experiment was carried out at the Kapustin Yar launding site.

The Plasma generating agents released at $z \sim 150$ km brought forth a 5 to 10 fold increase in the $\overline{A_{\pm}^2}$ amplitudes of the signals partially reflected at $z \approx 70 \div 100$ km ($\Delta t \approx 1-2$ min and $\Delta T \approx 1-3$ min). Most probably, the experiment stimulated particle precipitation from the radiation belt.

Effect of ionospheric disturbances on radio signal parameters

The variations shown by radio wave characteristics are strongly dependent on the waveband and type of the energy releasing source [9, 10, 13, 35-37]. The general feature common to radio waves of all wavelengths is the increased depth and greater appearance frequency of fadings. These effects are evidence for enhanced turbulization of the ionospheric plasma during the period of disturbance.

Miriametric radio waves (3 to 30 kHz). These can penetrate the lower ionosphere (to heights about 80 or 100 km in the daytime and at night). Ionospheric disturbances produce amplitude fluctuations (4 to 5 times higher than under quiet conditions) and variations in phase, $\Delta\varphi$, up to 1 or 2 radians [9. 10]. The radio signal parameters are sensitive to variations in the level of ionozation in the lower ionosphere that may be caused, e.g. by the particles precipitating from the magnetosphere. Occasionally, the amplitude and phase variations (A and φ) are quasiperiodic with $T \approx 5-30$ min. The propagation velocity of such wavelike disturbances is $v \approx 10-300$ m/s. The duration ΔT of fluctuations in A or φ is dependent essentially on the kind of the primary source. In most cases it is $\Delta T \approx 1$ hr, while in the case of lightning discharges typical ΔT_s are a few seconds.

Kilometer radio waves (30-300 kHz). The magnitude and character of variations in the signal parameters of this range are quite similar to the previous case, in particular $\Delta\varphi \leq 0.5$ rad; $\Delta T \approx 1$ hr and $T \approx 5-20$ min. The fluctuations in A are less pronounced and normally remain below a fens percent [9, 10].

Hectometer radio waves (0.3 to 3 MHz). The measurement in this range were done both at quasivertical and oblique propagation paths (in the latter case the path lengths were $D \leq 1000$ km) [9, 10, 13]. Disturbed states of the ionosphere were characterized by fadings of the diagnostic signal, appearance of multiple propagation paths, detection of signals from parallel broadcasting stations (shifted by 0.1 or 0.2 Hz in the Doppler spectrum), and broadening of Doppler spectra. The quasiperiodic parameter variations occurred with periods $T \approx 10-30$ min and time delays corresponding to $v \approx 0.3$ km/s/ Occasionally these apperent velocities were $v \sim 10-30$ km/s.

Decameter waves (3-30 MHz, HF range). The measurements were done on radio paths of various geographic orientations and lengths D ranging from 100 km to 3000 km [9, 10, 13]. The radio physical effects detected were deep fadings of the signal, deterioration of the Doppler spectrum, and generation or suppression of ionospheric wavelike processes with $T \approx 5-40$ min. The associated apparent velocities were $v \sim 0.5-0.7; 1.0; 2-3; 10-30$ km/s. The effects lived for 1 or 2 hours.

Meter and decimeter wavelengths (30 to 3000 MHz). These measurements employed signals from satellite radio beacons [15, 16, 18]. The ionospheric disturbances were accompanied by deep fadings of the signal amplitudes and randomization of the ionospheric component f_{di} of the Doppler frequency shift.

Radio noise. The disturbed ionosphere is often characterized by variations in the level of radio noise over a broad frequency range (~1 kHz to ~ 1 GHz) [8, 38-40]. The variations occur over periods of a few seconds to a few minutes or tens of minutes. The mechanisms of noise generation have not been sufficiently understood. Low-frequency emissions ($f \sim 1-10$ kHz) apparently result from wave-particle interactions in the magnetosphere, while the higher frequency noise might be due to energetic particle precipitation in the atmosphere. Besides, the variations in the level of interference may result from alterations of the propagation conditions for signals from remote radio transmitters.

Models of processes and disturbances

As follows from many observations, the disturbances produced in the geospace by natural or technogenic energy releasing sources are extremely varied. The impact of sources upon the medium may be of gas-dynamic, thermal, chemical or electromagnetic kind, with observable effects of hydrodynamical, geophysical, radiophysical, optical and other nature. These may manifest themselves as motions in the medium, excitation of density waves, generation of quasistatic electric or magnetic fields or 'high' and 'low frequency' electromagnetic waves and noises, appearance of inhomogeneous structures with a broad spectrum of inhomogeneity scale sizes, change of chemical reaction rates, particle precipitation from radiation belts, etc. Hence, modeling such processes represents a complex and many-valued task that has not yet found its complete solution. The present authors have developed several empirical and theoretical models of processes and disturbances.

The empirical models represented sets of temporal and spatial characteristics of the processes, and their interdependences (e.g., magnitude and sign of deviation from the background value; duration; length of the quasiperiod; altitude range; propagation velocities of disturbances and their times of development or relaxation, etc.) [19, 20, 41-43].

The theoretical models reduced to formulation of the basic equations to describe the source and the process, and their solution. In most cases, preference was given to simple, while adequate models [44,48, 49]. Attempts of simulation were made with respect to the sources perturbations [46], as well as both primary [44, 48] and secondary [46, 49] disturbances in the geospace. The analytical models and computer simulation codes that have been developed allow calculating disturbed temperatures and particle concentrations, inhomogeneity intensities in irregular structures, amplitudes of the electromagnetic fields generated, fluxes of precipitating particles, etc. [45].

Conclusions

1. The powers of artificial (technogemic) sources of disturbances are comparable with and occasionally greater than the powers characteristic of natural sources. Therefore, localized sources often give rise to large-scale (100 to 1000 km) or global (1000 to 10 000 km) disturbances.
2. The lithosphere, atmosphere, ionosphere and magnetosphere comprise a unique open system. A powerful disturbance in the system results in energy and mass transfer between its subsystems, thereby stimulating their interaction. Beside the powerful action, there may exist control actions. These are case where a relatively weak initial effect starts processes characterized by sizable energy releases, i.e. the energy release is started by a trigger mechanism. The ready example is particle precipitation from the radiation belt, Generally, these are basic modes of interaction between various regions of the geospace responsible for space weather formation.
3. Transfer processes in the geospace are conditioned by the generation and propagation of waves of different kind (acoustic, seismic, magnetohydrodynamic or electromagnetic). The characteristic velocities are 0.1; 0.3 to 0.7; 1.0; 2 to 3; 6 to 8 and 30 to 50 km/s and more.
4. The lower ionosphere disturbance processes are, for the most part, aperiodic. They are stimulated by the particles precipitating from the radiation belt. Also, quasiperiodical processes are observed here, characterized by periods about 5 min and propagation velocities 0.1 to 0.3 km/s. The middle and the upper ionosphere normally demonstrate either generation (amplification) or suppression of quasiperiodic ($T \approx 1-40$ min) disturbances with propagation speeds of 0.1 to 0.7 km/s. The plasma turbulence is enhanced at all heights in the ionosphere.
5. Large scale and global disturbances follow energy releasing events in the ionosphere, atmosphere or earth crust characterized by energies of 10^7 to 10^8J,10^{11} to 10^{12}J and 10^{13} to 10^{14}J, respectively. The possibility of detecting such disturbances is conditioned, among other things, by the sensitivity of the methods employed.
6. Disturbances in the geospace and terrestrial environment have a sizable effect on the propagation of radio signal $f = 1$ kHz to 1 GHz. Characteristic manifestations are variations in the depth and occurrence frequency of the signal fadings, and phase fluctuations. These are associated with electron density inhomogeneities of different scale sized that are generated in the ionosphere.
7. The disturbances described normally are accompanied by variations in the parameters of radio noise in a broad frequency range (1 kHz to 1 1GHz).
8. Empirical models of the disturbances have been developed in gross features. Elements of theoretical models of the corresponding physical processes have been suggested.

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