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Modification of the earth's ionosphere by high-power high-frequency radio waves

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1. Introduction

The ionosphere, being the upper part of the terrestrial atmosphere, has a decisive effect on both the nature of vital functions on Earth and the properties of different tele- and radio communication channels. In this connection, it has attracted the close attention of researchers already for many decades. The range of ionospheric research is extremely wide and embraces problems such as the physics of plasma formation, plasma dynamics and the mechanisms of plasma turbulization, ionospheric chemistry, and the propagation of radio waves in different ranges. The capabilities of conventional methods of ionospheric research were greatly enhanced when active ionospheric experiments were started. These include plasma modification by high-power radio wave beams produced by ground-based and space-borne high-frequency (HF) radio transmitters, as well as the injection of charged particle beams and chemical reagents from aboard artificial earth satellites (AESs) and geophysical rockets. The success achieved in active experiments allowed considering the ionosphere as a natural space laboratory for modeling different processes occurring in plasmas [1]. The relatively high stability and the practically infinite volume of the ionospheric plasma, as well as the variation over a wide range in its possible parameter values, permit a broad class of currently topical problems to be solved on an experimental basis.

The variation in ionospheric properties in the field of high-power radio waves was first encountered over 70 years ago in connection with the discovery of the Luxemburg–Gorky effect in 1933 [2]. The decisive roles in the theoretical interpretation of this effect were played by Ginzburg, Gurevich, and Vilenskii. The explanation of the Luxemburg–Gorky effect led to the understanding of the role of the nonlinear properties of ionospheric plasma, which show up under heating by a high-power radio wave and were considered at length by Ginzburg and Gurevich in Ref. [3]. The investigations conducted lent impetus to the construction of special-purpose high-power heater facilities for the modification of the ionosphere. In the USSR, the first facility was put into operation in the Scientific Research Radio Institute (Moscow) in 1961. More recently, constructed in the USA were the facilities Boulder in 1970 and Arecibo in 1971. At the Radiophysical Research Institute (NIRFI), this line of investigation was initiated by Getmantsev. Under his supervision, the Zimenki facility was constructed in 1973 near Nizhnii Novgorod (formerly the city of Gorky). In 1976, the Polar Geophysical Institute (PGI) of the Kola Branch of the USSR Academy of Sciences succeeded in its efforts to construct the Monchegorsk facility in polar latitudes near Murmansk.

Already in the first experiments on ionospheric modification by high-power radio waves carried out in the 1960s–1970s, apart from the expected large-scale variations in plasma temperature and density, several new phenomena related to the generation of artificial plasma oscillations and artificial plasma density irregularities with scale lengths ranging from fractions of a meter to several kilometers transversely to the geomagnetic field were discovered [4, 5], the Getmantsev effect was discovered [6], and the formation of artificial periodic irregularities of ionospheric plasma density in the field of a high-power standing radio wave was experimentally borne out [7]. There emerged a new line of research, which soon became one of high-priority areas in radiophysics and found diversified uses in geophysics, plasma physics, and space physics. An important point is that modifying the ionosphere by high-power radio waves does not pollute the environment and has no undesirable ecological consequences, because this action on the ionosphere is negligible in power in comparison with natural actions. At the same time, the possibility exists of conducting repeated measurements of the characteristics of the upper terrestrial atmosphere on a regular basis by using the thoroughly elaborated radiophysical techniques for the remote diagnostics of artificially produced plasma perturbations.

The results achieved fostered the construction of new, more powerful heaters in northern Norway (Tromsø, 1980) and in the USSR (Sura, 1981). More recently, in the 1990s, a start was made on the construction of a facility in Alaska (USA) in the framework of the High Frequency Active Auroral Research Program (HAARP); its first stage was put into service in the late 1990s. To this day, efforts are directed towards upgrading the potentialities of the facility. Among other facilities constructed in the 1980s–1990s are Gissar (Tadjikistan, 1981), a facility near Kharkov (Ukraine, 1987), and the High Power Auroral Simulation (HIPAS) facility (USA, 1990). Today, experiments in the modification of the ionosphere are conducted primarily at three facilities: HAARP and Tromsø in polar latitudes and Sura in middle latitudes. The remaining facilities either have fallen apart or are no longer in active use. In recent years, the British have undertaken the construction of the SPEAR (Space Plasma Exploration by Active Radar) facility on the island of Spitsbergen, in the polar cap zone. In 2004, the first stage of SPEAR was put into operation and heater experiments were started.

In this report, we briefly outline the results of experiments in artificial influence on the ionosphere by high-power HF radiation from ground-based transmitters. They were performed at NIRFI in cooperation with many Russian and foreign institutions and include investigations of the properties of artificial ionospheric turbulence (AIT), of the generation of combination-frequency signals by an ionospheric source in the very low frequency (VLF), superlow frequency (SLF), and ultralow frequency (ULF) ranges, and of different ionospheric layers with the help of artificial periodic irregularities. These investigations commenced at the Zimenki facility and continued at the Sura facility.

The Sura facility (NIRFI), which has received the status of a unique Russian facility (registration No. 06-30), comprises three high-frequency PKV-250 transmitters with the cw output power 3×250 kW in the 4 – 25 MHz frequency range. Each transmitter is loaded on its own antenna array with a 4.3 – 9.5 MHz frequency band. The three facility modules can work independently and emit a wave with ordinary or extraordinary polarization at its frequency, in its own timing, with the pulse duration ranging from 50 μs up to the cw output. In the regime of coherent radiation by all three heater modules (in this case, the total dimension of the antenna field is 300 by 300 m), the maximum effective output power is 80 – 280 MW, increasing with the frequency of the radiated wave. The heater beam can be deflected in the range $\pm 40°$ from the vertical in the plane of the geomagnetic meridian. Different diagnostic facilities are deployed around the Sura heater, which fulfill the function of probing the ionosphere and detecting plasma perturbations induced by a high-power radio wave.

2. Artificial ionospheric turbulence

The interaction between a powerful HF radio wave with ordinary polarization and a plasma is accompanied by the excitation of AIT of different types, which is determined by the development of several nonlinear effects: (1) the generation of high-frequency (different plasma oscillations and waves) and low-frequency (first and foremost, plasma temperature and density irregularities with different scale lengths) plasma turbulence; (2) modification of the plasma density profile under the action of striction and thermal pressure forces, which results in the formation of focusing (in the F_2 region) and defocusing (in the E and F_1 regions) lenses, as well as of artificial periodic irregularities under the action of a high-power standing radio wave; (3) electron acceleration to suprathermal energies, which leads to additional plasma ionization and the glow of neutral gas in the optical and decimeter wavelength ranges; (4) the generation of secondary electromagnetic radiation (in particular, artificial radio-frequency ionospheric radiation); (5) the excitation of electric and magnetic fluctuation fields, etc. It is significant that the wide-ranging experimental and theoretical investigations performed during the last three decades, which are summarized in several dedicated journal issues [4, 8 – 13], have enabled a detailed study of the features of high-power wave interaction with different ionospheric plasma regions, an investigation of the production features and properties of AIT, and an elaboration of new methods for diagnosing the processes occurring in magnetoactive plasmas.

In Sections 2.1 – 2.4, we briefly formulate the main properties of AIT excited by a high-power radio wave of ordinary polarization in its reflection from the F_2 ionospheric region.

2.1 Development stages of the interaction between high-power radio-frequency radiation and plasma

Four stages may be distinguished in the development of the interaction of a high-power radio o-wave and the plasma of the F_2 ionospheric region [14]. During the first stage, which lasts 5 – 20 ms from the onset of the action and is characterized by a 10 – 20 dB intensity lowering of the signal of the pump wave (PW) reflected from the ionosphere, a striction parametric instability [15] develops near the level of reflection of the high-power radio wave, resulting in the generation of Langmuir plasma turbulence and electron acceleration to suprathermal energies. At the second stage, which lasts 0.5 – 3 s (up to the onset of the development of the anomalous attenuation effect), the signal of the reflected PW is observed to regain its intensity level, which is accompanied by the emergence of its characteristic quasiperiodic oscillations. So far, this effect has not been adequately explained. At the third stage, 0.5 – 10 s after the onset of the PW, the generation of upper-hybrid plasma turbulence and small-scale field-aligned ionospheric irregularities (SFAIIs) of size $l_\perp \leqslant 30-50$ m in the direction orthogonal to the terrestrial magnetic field is observed due to the development of a thermal (resonance) parametric instability [16, 17]. The scattering of the high-power radio wave from the SFAIIs leads to its anomalous attenuation (AA) — a lowering of the signal reflected from the ionosphere by 10 – 30 dB. The fourth stage, which sets in 10 – 30 s after the PW engagement, is characterized by the development of a self-focusing instability of the high-power radio wave [17, 18]. This leads to an increase in medium-scale ($l_\perp \approx 0.1-1$ km) field-aligned ionospheric irregularities (FAIIs), which are responsible for strong fluctuations in the radio waves reflected from the perturbed region of the ionosphere and for the formation of spreading $F_{\rm spread}$ on the ionograms for the traces of probing transmitter signals reflected from the ionosphere, which is characteristic of radio wave propagation through a turbulent medium. The generation of larger-scale irregularities with $l_\perp \geqslant 1-2$ km is attributed to the intensification of natural plasma density irregularities.

The ionosphere modification effects are markedly intensified when the conditions are fulfilled for the propagation of a high-power radio wave beam along the magnetic field in the region of resonance PW – plasma interaction (the 'magnetic zenith' effect) [19]. In this case, as a result of PW self-focusing by the irregularities elongating along the geomagnetic terrestrial field, which measure several hundred meters in the direction transverse to the geomagnetic field and which are filled with SFAIIs with $l_\perp \approx 1-10$ m, a strong local plasma heating occurs due to the anomalous absorption of the energy of the high-power ordinary radio wave in its scattering by the SFAIIs into upper-hybrid plasma waves. This leads to the formation of caverns, such that the high-power radio-frequency radiation flux splits into narrow beams and is confined to these caverns.

2.2 Dynamic and spectral characteristics of artificial ionospheric irregularities

The development times $\tau_{\rm dev}$ of the FAIIs with $l_\perp \approx 1-10^3$ m depend strongly on their scale length (as $l_\perp^{0.5}$), the PW power (as $P_{\rm eff}^{-1}$), and its schedule (via aftereffects), as well as the ionospheric conditions [14]. On average, $\tau_{\rm dev} \approx 2-5$ s for $l_\perp \approx 10$ m and $P_{\rm eff} \approx 20$ MW. The FAII relaxation times $\tau_{\rm rel}$ are determined by the irregularity scale length $l_\perp$ [14]: a quadratic dependence $\tau_{\rm rel}(l_\perp) \propto l_\perp^2$ occurs for $l_\perp \leqslant l_\perp^*$, a weaker dependence $\tau_{rel}(l_\perp) \propto l_\perp^{0.5}$ occurs for $l_\perp \geqslant l_\perp^*$ ($l_\perp^* \approx 3-20$ m is some characteristic irregularity scale length, the quantity $l_\perp^*$ decreases in moving from daytime to nighttime observation conditions). It is believed that the SFAII relaxation in the domain of the quadratic $\tau_{rel}(l_\perp)$ dependence is due to the transverse ambipolar diffusion and is caused by longitudinal ambipolar plasma diffusion for $l_\perp > l_\perp^*$. The specific irregularity relaxation times also depend on the hour of the day, the PW reflection altitude h_{refl}, the location of the irregularities inside the disturbed region, the PW radiation regime, the degree of ionospheric perturbation, etc. For $l_\perp \approx 10$ m and $h_{refl} \approx 240$ km, the relaxation times in quiet geomagnetic conditions are 5 – 10 s in the daytime and lengthen to 15 – 20 s in the evening and to 20 – 40 s in the nighttime.

On the basis of cross section measurement data for the aspect scattering of radio waves in the high-frequency and very-high-frequency (VHF) ranges by anisotropic SFAIIs and measurements of AES signal flicker in radio wave transit through the disturbed region of the ionosphere, it was possible to measure the plasma density fluctuation spectrum in the $l_\perp \approx 1-4 \times 10^3$ m scale length range [14, 20, 21]. For a piece-wise power-law approximation of the dependence $\Phi_N(l_\perp) \propto l_\perp^p$, it was determined that $p \approx 4-5$ for $l_\perp \approx 1-3$ m, $p \sim 2-3$ for $l_\perp \approx 3-20$ m, $p \sim -(0.5-1)$ for $l_\perp \approx 50-200$ m, $p \sim 3$ for $l_\perp \approx 200-400$ m, $p \sim 1.5-2$ for $l_\perp \approx 600-800$ m, and $p \sim 3-4$ for $l_\perp \approx 0.8-4$ km. The peak of $\Phi_N(l_\perp)$ for scale lengths $l_\perp \approx 50$ m, which are close to the free-space wavelength of the high-power wave, is caused by the irregularity generation mechanism due to the development of a thermal (resonance) parametric instability. The second peak, which was observed for scale lengths $l_\perp \approx 400-600$ m, is attributable to the manifestation of the PW self-focusing instability in the plasma. On average, the characteristic magnitudes of the relative plasma density fluctuations at the stationary AIT development stage are $\delta N \approx 5\times10^{-3}-10^{-2}$ for $l_\perp \approx 1-2$ km, $\delta N \sim 10^{-3}-2\times10^{-3}$ for $l_\perp \approx 200-600$ m, and $\delta N \sim 5\times10^{-4}-10^{-3}$ for $l_\perp \approx 3-30$ m. During the first several seconds after PW engagement, owing to the faster growth of the irregularities with $l_\perp \approx 1-3$ m, the SAIT spectrum is inverted in form, peaking for scale lengths $l_\perp \approx 2-3$ m [14]. Measurements performed for different tilt angles of the high-power radio wave beam in the plane of the geomagnetic meridian enabled determining that SAITs are most intensively generated for tilt angles $\sim 12°-16°$ south of the vertical [21].

Therefore, by varying the power, frequency, polarization, and schedule of the PW radiation, it is possible to control the spectral FAII characteristics, which is important for the use of AIT in solving research and applied problems [22].

Doppler measurements of the spectrum of HF and VHF radio waves scattered by SAIT permit obtaining information about the motion of scattering irregularities inside the perturbed ionospheric region. On the basis of the measurements of the Doppler spectra of the scattered signals, it was determined in Ref. [23] that radial SAIT motions from the center of the perturbed ionospheric region to its periphery are induced during its heating. Furthermore, this method allows studying the characteristics of moving ionospheric perturbations [24] and local geomagnetic pulsations [25] as well as measuring the electric field strength in the F_2 ionospheric region [26]. The authors of Refs [27, 28] investigated the effect of broadening of the Doppler spectrum of the scattered signal in conditions where the PW frequency is of the order of or slightly higher than a gyroresonance harmonic frequency in the PW — plasma interaction region. This may be an indication that a significant role in the processes of determining the dynamics of decametric SAITs is played by the electron Bernstein plasma oscillations driven by a high-power radio wave.

2.3 Artificial ionospheric radio-frequency radiation

It the more than 30 years since the discovery of stimulated electromagnetic emission (SEE) in the ionosphere [29, 30], intensive investigations of its properties have been pursued. This radiation emerges due to all kinds of interactions of electromagnetic waves and high-frequency plasma oscillations with low-frequency plasma turbulence whose production and evolution are governed by SFAIIs. The interplay and interference of different plasma processes in the generation of SEE in magnetoactive plasma underlie its broad diagnostic potential for studying the properties of both artificial and natural plasma turbulence. More than 15 SEE components are presently known; their comprehensive description is given in review Ref. [31]. Among its components whose spectral and dynamic characteristics have been studied in greatest detail are

(1) the main SEE spectral maximum, or down-shifted maximum (DM);

(2) broadband down-shifted radiation, or broad continuum (BC);

(3) the up-shifted maximum (UM);

(4) the broad up-shifted maximum (BUM). The generation of this maximum is observed when the PW frequency is close to or slightly higher than the frequency of a gyroresonance harmonic in the region of the interaction between the high-power radio wave and the plasma (under the conditions of measurements performed at the Sura facility, the electron gyrofrequency is $f_{ce} \approx 1.3-1.35$ MHz);

(5) the striction narrow-band radiation component, or the ponderomotive narrow continuum (NC_p), observed at the development stage of a striction parametric instability;

(6) the thermal narrow continuum (NC_{th}) observed at the development stage of a thermal (resonance) parametric instability;

(7) the BUM-like broad up-shifted structure (BUS), which shows up in the frequency ranges between the gyroharmonics.

The generation of different components in the SEE spectrum depends heavily on the frequency and power of the PW, as well as on the ionospheric conditions. The investigations carried out at the Sura facility [32] in its entire frequency range 4.3 – 9.5 MHz showed (Fig. 1) that (i) the shape of the SEE spectrum changes radically in a narrow range of PW frequencies, when $f_{BH} \approx nf_{ce}$, where n is the gyroharmonic number; (ii) the radiation is most intense in the frequency range between the fourth and fifth gyroharmonics; and (iii) the effect of gyroresonances also manifests itself outside the regions where $f_{BH} \approx nf_{ce}$.

Methods for diagnosing the high- and low-frequency turbulence were developed on the basis of SEE, which enabled carrying out measurements of the characteristic buildup and relaxation times of the Langmuir and upper-hybrid plasma waves [33], studying the SFAII effect on the generation of different SEE components [34], and investigating the effects observed in the nonlinear interaction of two high-power radio waves in a magnetoactive plasma [35]. The diagnostic SEE method was employed to study the transport properties in the upper ionosphere [36]. The characteristic

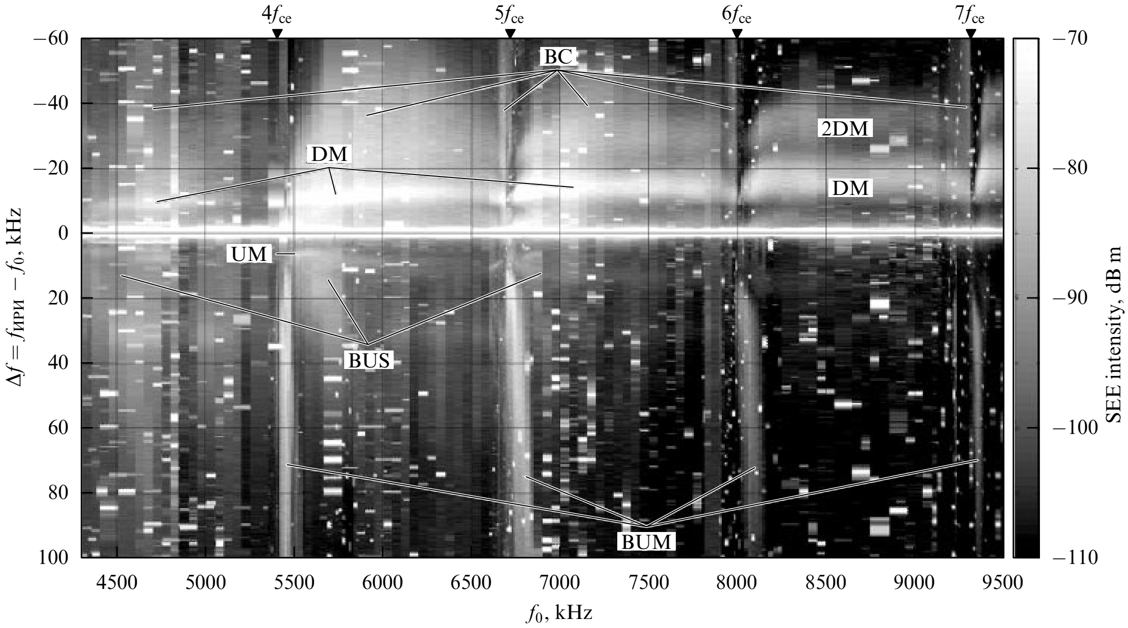

Figure 1. Dependence of the spectral SEE structure on the pump wave frequency in the 4.3 – 9.5 MHz range.

velocities $V_{\|}$ of the plasma perturbation propagation along the geomagnetic field were found to be of the order of or appreciably higher than the electron thermal velocity $V_{Te} \approx 2 \times 10^7$ cm s^{-1} under the typical conditions of our experiments conducted in the F_2 ionospheric layer. This may testify to the importance of inclusion of thermal- and accelerated-electron fluxes, as well as of short-circuit currents through the background plasma in the mechanisms of AIT generation outside the regions of resonance high-power wave – plasma interaction [36 – 38].

In recent years, the generation of artificial radio-frequency radiation in the decimetric wavelength range (at frequencies ~ 600 MHz) [39] has been revealed. It is assumed that the SEE emerges in this case in the electron transitions between the high Rydberg levels of the molecules of neutral ionospheric plasma components excited by accelerated electrons.

2.4 Spatial structure of the perturbed ionospheric region

Measurements of the spatial structure of the perturbed ionospheric region above the Sura facility using the satellite radio tomography technique were first performed in August 2002 [40] and repeated in August 2005. Figure 2 shows the tomograms obtained in the evening (Figs 2a and 2b) and night (Figs 2c and 2d) observation hours, when the PW was reflected near the maximum of the F_2 ionospheric layer at altitudes $\sim 270-300$ km. Shown are the tomograms for both the plasma density (Figs 2a, 2c) and the difference reconstruction (Figs 2b, 2d), which demonstrates the fluctuations of the plasma density with regard to its average value. The experimental data were processed with the use of the Bayes probabilistic approach to ray (phase) tomography relying on the theory of stochastic inversion [41].

It is easy to see from Fig. 2 that the plasma density perturbations exhibit a strongly pronounced orientation along the geomagnetic field lines, are observed throughout the altitude range possible under the given geometry of the experiment, from ~ 200 km to $\sim 600-700$km, and are excited in a broader horizontal region (± 200 km relative to the center of the high-power radio wave beam) than the ionospheric region irradiated by the main lobe of the heater antenna directivity ($\sim 60-100$ km). The radiation pattern of the main antenna lobe of the heater is shown by dashed lines, and the direction of the geomagnetic field for the Sura facility location is shown with a solid line. From the tomograms presented it is also clear that cavities with a strong (up to 20%) plasma depletion develop in the southern sector of the antenna pattern of the heater. With the use of heating by oblique high-power radio wave beams it was determined that such structures are most efficiently produced when the radiation direction of the high-power radio wave in the ionosphere is close to the direction of geomagnetic field lines and are a manifestation of the 'magnetic zenith' effect [19]. It was also determined that the plasma density irregularities with $l_{\perp} \approx 100-1000$ m, which are responsible for the scintillation of a signal transmitted through the perturbed ionospheric region, are confined primarily within the large-scale regions with a strong decrease in the plasma density.

Our attention is caught by the occurrence of regions with a pronounced wave-like form of plasma density perturbation, which appear at the altitude of PW reflection and extend upwards along the geomagnetic field to altitudes $\sim 500-600$ km. Referring to Fig. 2, these perturbations are confined to narrow geomagnetic field tubes with transverse dimensions ~ 30 km and their typical scale lengths along the field direction are ~ 75 km for the evening ionosphere and ~ 55 km for the night one. The nature underlying the formation of these perturbations is still unclear.

Modification under daytime ionospheric conditions, when the PW is reflected at altitudes $\sim 200-220$ km, does not give rise to regions with strong plasma depletion; the plasma density perturbations are smaller in magnitude and longer ($\geqslant 50-100$ km) in scale lengths than at nighttime. The aforementioned wave-like structures extended along the geomagnetic field are not observed at these altitudes, either.

In 2005, the investigation of plasma perturbations induced by the Sura heater at altitudes ~ 710 km began at

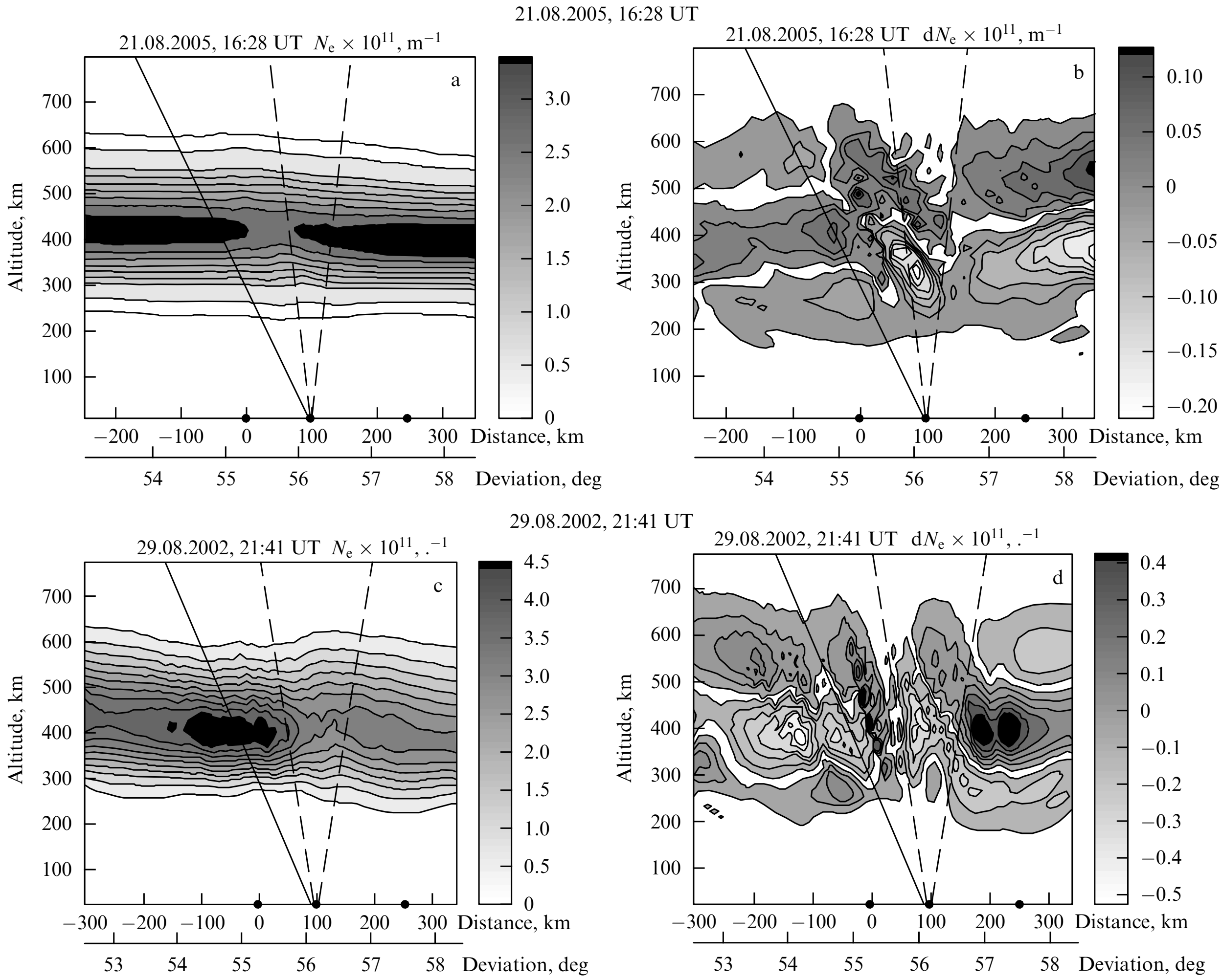

Figure 2. Tomographic reconstruction of the plasma density profile (a, c) and the density variations (b, d) in evening ionospheric conditions (a, b) and night ionospheric conditions (c, d).

NIRFI. The investigations were conducted with the help of the French microsatellite DEMETER (named from the 'Detection of Electromagnetic Emissions Transmitted from Earthquake Regions'), which has a unique set of instruments enabling measurements of different plasma perturbation parameters. The first measurements performed in the framework of the Sura – DEMETER program in the heating of the nighttime F_2 ionospheric region by an unmodulated PW, reflected near the maximum of the F_2 ionospheric layer, allowed the following conclusions [42]:

(i) strong (up to 5 – 10%) artificial fluctuations in the electron temperature (T_e) and density (N_e) and in the ion density (N_i) are observed at the altitude $\sim$ 710 km; variations in the ion temperature (T_i) are within the natural background fluctuation level of 1 – 2 %;

(ii) artificial fluctuations in T_e, N_e, and N_i are recorded at distances up to 400 km from the center of the perturbed geomagnetic tube that rests on the ionospheric region illuminated by a high-power radio-wave beam;

(iii) the excitation of electric field oscillations at frequencies $f \leqslant 1$ kHz is observed in the central part of the perturbed geomagnetic tube.

It is easily seen that on the whole, there is good agreement between plasma density variations measured by radio tomographic and satellite techniques.

In concluding this section, we note that despite the wealth of investigations made into AIT properties, several basic problems remain unexplored. In particular, the absence of adequate theoretical models of the generation of different SEE components hinders the development of SEE-based techniques for the diagnostics of natural and artificial plasma turbulence. It remains to elucidate the reasons underlying the generation of AIT far beyond the limits of the central part of the perturbed region, which sees the development of striction and thermal (resonance) parametric instabilities and intense plasma heating. The problems related to the nature of drift and wave-like motions induced by high-power radio waves in the perturbed ionospheric region also invite further investigation. Different manifestations of the effect of electrons accelerated by plasma turbulence on the high-power radio-wave — plasma interaction dynamics and the generation of different AIT components must be studied further.

In this report, we did not set ourselves the task of outlining the results of investigations into control of the propagation channel for HF and VHF radio waves via their refraction in large-scale FAIIs or scattering from SFAIIs. These investigations make up a separate important field of experiments carried out at the Sura heater; a substantial fraction of this field pertains to the study of the mechanisms of long-distance propagation of HF waves under controllable conditions. We only note that Uryadov et al. [46] experimentally demonstrated the feasibility of controlling the long-distance propagation of HF waves via extraction of waveguide modes from the ionospheric channel due to aspect scattering from SFAIIs. In Ref. [26], a sporadic E layer was shown to have a pronounced effect on the emergence of signals with a frequency exceeding the highest applicable frequency (HAF) of the F region, when their extraction to the terrestrial surface may be effected by aspect scattering from the SFAIIs. The Sura — HAARP experiment, performed under Grant No. RPO-1334-NO-02 from the Civilian Research and Development Foundation (USA) in 2006, was an important milestone in the pursuance of research in this area. For HF waves, the path of their long-distance propagation controllable on both ends was created in this experiment. The waveguide modes of the ionospheric waveguide path were excited in the radio-wave scattering from the SFAIIs induced in the ionosphere by HAARP radiation, and the path modes were extracted by their aspect scattering from the SFAIIs induced by the Sura heater [44]. The existence of this path opens up new possibilities for investigating the properties of channel radio wave propagation.

3. Progress in the investigation of the effect of low-frequency radio-wave generation in the ionosphere under the action of high-power modulated short-wave radio-frequency radiation

From the outset of research at the relatively low-power Zimenki heater (transmitter output 100 kW), the head of research Getmantsev took on the task of discovering the effect of low-frequency radio-wave generation in the ionosphere irradiated by modulated high-power HF radio waves. The formulation of this problem was based on the theory of nonlinear phenomena in plasma developed by Ginzburg and Gurevich [3] back in the 1950s. According to this theory, irradiation of the ionospheric plasma by an electromagnetic signal containing two carrier frequencies in its spectrum must lead to signals at the combination frequencies $f_1 \pm f_2$. Upon several attempts, the effect of combination-frequency signal (CFS) generation was discovered at the frequency $\Omega = f_1 - f_2$ [6, 45]. Closer investigation of CFS properties (spectral and polarization measurements and determination of the altitude of the low-frequency radiation source) led to an unambiguous conclusion about the nature of this radio-frequency radiation. It was determined that the mechanism of the observed CFS generation was directly related to the modulation of quasistationary ionospheric currents constantly present in the ionosphere at dynamo-region altitudes ($\approx 70-130$ km, the site of the strongest ionospheric currents) [46, 47]. In 1981, the discovery was registered as 'The phenomenon of electromagnetic wave generation by ionospheric currents under irradiation of the ionosphere by modulated short-wave radio-frequency radiation.' The effect discovered has come to be known as the Getmantsev effect [48]. For modern heater capabilities ($P_{\text{eff}} \approx 100-300$ MW) and the diagnostic techniques developed, low-frequency radiation is detected not only in the VLF range at the frequencies 0.5 – 10 kHz but also in the geomagnetic pulsation range at frequencies $\leqslant 10$ Hz.

Putting the Sura heater (the total output power of HF heater transmitters is $P = 750$ kW) into operation in 1981 opened up the possibility of carrying out research on a qualitatively new level, because the level of the ionospheric signal increased several-fold. This allowed more carefully verifying the propositions of the CFS generation theory, which had been developed by that time [49, 50]. Furthermore, two transmitters (with the total power $P = 200$ kW) were additionally constructed on the basis of the Sura heater in 1985 specifically for the pursuance of research into lower ionospheric effects. The transmitters were loaded on an 8-element antenna array for the zenith radiation of circularly polarized waves at a frequency close to the gyrofrequency of ionospheric electrons. This afforded a higher-efficiency ohmic plasma heating and substantially broadened the possibilities of the research conducted. The results of experiments performed on the Sura facility and their comparison with theoretical notions are summarized in review Ref. [51].

The experiments carried out at the Zimenki and Sura facilities enabled studies of

- the spectral characteristics of the CFS;
- the daily CFS variation and its dependence on the frequency, polarization, and power of the PW;
- polarization CFS characteristics;
- the fine structure of ionospheric currents;
- dependence of the low-frequency signal parameters on the source altitude.

To date, the methods of receiving and processing CFSs have been adequately elaborated, and the optimal conditions for their generation have been found. This allows using the Getmantsev effect for the diagnostics of the parameters of the lower ionosphere (the dynamo region) and the magnetosphere, as well as for deep probing of the earth's core. In this case, it is possible to gain information about

- the electric fields and currents in the terrestrial ionosphere and magnetosphere;
- the waveguide and resonance properties of the ionosphere and the conditions of low-frequency radiation propagation through the earth — ionosphere waveguide, radiation transmission through the ionosphere, and its propagation in the terrestrial magnetosphere;
- the characteristics of low-frequency wave interaction with energetic protons in terrestrial radiation belts;
- the effect of seismic activity and internal gravitational waves on the dynamics of the upper atmosphere;
- the distribution of the terrestrial surface conductivity with depth, which yields information about its geological structure.

Using the possibilities for the spatial control of a high-power radio wave beam furnished by the Sura heater, an investigation was made of a new type of ionospheric source, a traveling-wave antenna in the range of several kilohertz, and a study was made of the radiation pattern of the traveling ionospheric source [52]. This is, in essence, the Vavilov – Cherenkov radiation of a superluminal 'light spot' produced in the ionosphere by the tilting antenna pattern. The capability of the facility to operate simultaneously at two frequencies ω_1 and ω_2 also enabled investigating the cubic thermal nonlinearity, which in turn allowed generating a signal in the ionosphere with the low frequency $\Omega = 2\omega_1 - \omega_2$ without resorting to the amplitude modulation of waves directed to the ionosphere [53].

It was predicted in [54] that a natural resonance structure — an ionospheric Alfven resonator (IAR) located at altitudes of 100 – 1000 km — must exist in the ionosphere; it was experimentally discovered in [55]. At present, measurements of its parameters are widely used for diagnostics of the upper atmosphere.

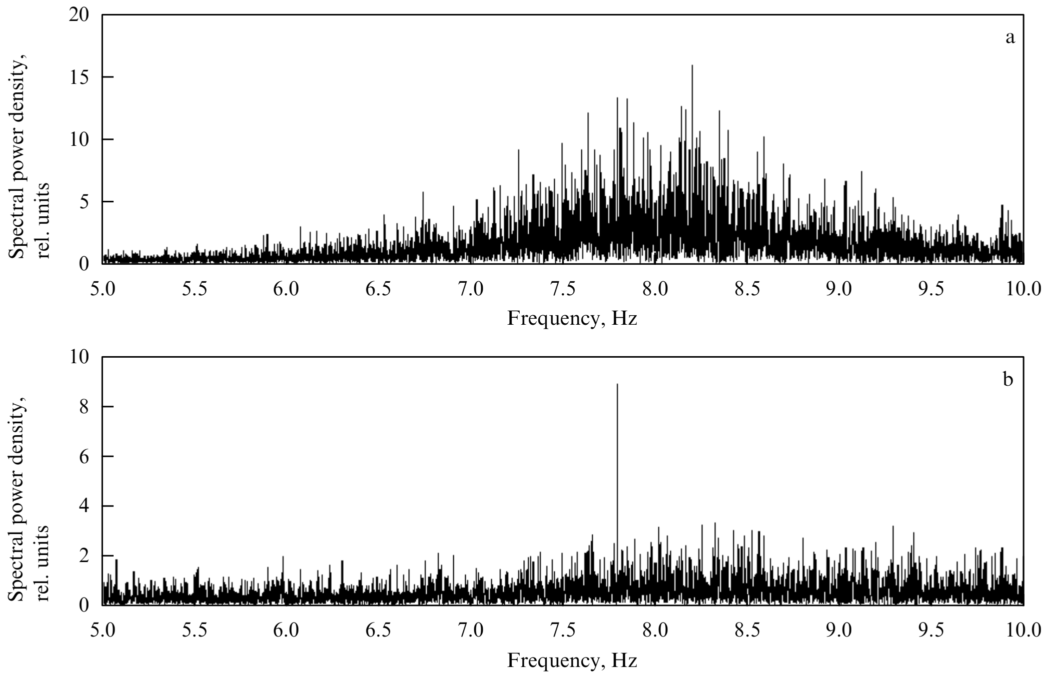

Figure 3. Spectral power densities of the signals from two detection devices (a) and spectral power density of the difference signal (b), where a 7.8 Hz signal is seen quite clearly.

The equipment and methods for measuring weak low-frequency electromagnetic radiation developed in the course of investigations are validly used for the study of the natural noise background in the $10^{-3} - 10$ Hz frequency range. This range occupies a special place in geophysical research because it comprises the frequencies of the main resonances of near-earth space: the magnetohydrodynamic (MHD) resonances of the terrestrial magnetosphere, the Alfven resonances of individual geomagnetic field tubes, the Schumann resonances of the earth – ionosphere cavity, the frequencies of Alfven masers (the generators of short-pulse geomagnetic pulsations) and the ionospheric Alfven resonator frequencies. This permits investigating the dynamics of terrestrial magnetospheric processes, studying the properties of MHD waves in the IAR region at altitudes of the F ionospheric domain, studying the efficiency of IAR excitation by different sources (magnetospheric, VLF heater radiation, and energetic particle fluxes), and diagnosing the upper ionosphere at altitudes of 300 – 3000 km from the spatio-temporal behavior of the spectrum of atmospheric noise background, whose variations are related to variations in the geophysical conditions and to the large-scale structure of the electron density profile in the upper part of the F region.

The low-frequency signals generated in the ionosphere by the Sura heater in the extremely low frequency (ELF) range are used as a controllable source for the development of new methods for measuring the spatial characteristics of radio waves with frequencies below 30 kHz. In particular, a differential gradiometering method [56] was tested in 2005. The method relies on the possibility of detecting weak signals against the high-power noise background by recording the amplitude at two spatially separated points with the subsequent subtraction of the signals. For instance, because the noise from a thunderstorm is uniform on a large spatial scale, synchronous recordings made at two locations spaced several dozen or even hundreds of kilometers apart have a high degree of coherence. This enables weak emissions with small-scale coherence to be extracted and experimentally investigated (Fig. 3).

At present, research into the effect of low-frequency radio wave generation by an ionospheric source is being intensively pursued in the USA in experiments at the HAARP and HIPAS heaters. The aim of these experiments is to find possibilities for increasing the ionospheric source intensity and reliability to the level required for the solution of communication problems and for probing the earth's interior and the magnetosphere. As regards the Sura heater, the prospects of its employment rely on (i) the development of modern automated control over its parameters and operating mode; (ii) the recovery of the transmitting complex with the radiation frequency close to the electron gyrofrequency, whose operation substantially broadens the heater potentials for the CFS generation; and (iii) the development of new pulsed superpower final stages. This will furnish the possibility of continuing, at a new level, research aimed at the elaboration of practical applications of low-frequency radio wave ionospheric generation.

4. Artificial periodic irregularities

The action of high-power radio waves on ionospheric plasma is accompanied not only by the development of AIT but also by the production of ordered structures. These primarily include artificial periodic irregularities (APIs), which are produced in the field of a high-power standing radio wave resulting from the interference of an incident wave and a wave reflected from the ionosphere. In 1970, Vilenskii predicted [57] that the electron gas in the antinode of a standing wave must warm up to give rise to a periodic temperature structure with the spatial period equal to half the wavelength of the high-power radio wave. The temperature irregularities, in turn, must produce electron density irregularities.

Experiments aimed at discovering APIs were pioneered by Getmantsev early in the execution of the Zimenki heater (NIRFI) research program. These irregularities were discovered in 1975 [7]. Further investigations showed that the APIs were formed in the altitude range from 60 km to the altitude of high-power wave reflection in the ionosphere. Based on experimental and theoretical research, it was determined that the API production and relaxation mechanisms, which turned out to be substantially more complicated than predicted by Vilenskii, had a different physical nature in different ionospheric layers. In particular, the production of APIs in the altitude range D ($h \approx 50-90$ km) is due to the temperature dependence of the coefficient of electron attachment to oxygen molecules; in the E region ($h \approx 90-130$ km), the irregularities are produced due to diffusive plasma redistribution under the excess pressure of the electron component heated in the antinodes of the standing radio wave; lastly, the APIs in the F region ($h \approx 200-350$ km) are produced under the action of the ponderomotive striction force with the excitation of ion – sound oscillations [58].

Because APIs are ordered in space, the radio waves they scatter have an appreciable amplitude only if the signals arising from all irregularities in the volume under investigation are added up in phase. This imposes certain constraints on the wavelengths of a high-power transmitter and pulsed radar. The resonance scattering condition (the Bragg condition) in the case of backscattering from the APIs implies the equality $\lambda_1 = \lambda_2$, where λ_1 and λ_2 are the respective wavelengths of the high-power radiation producing the APIs in the plasma and of the radar. This circumstance gave rise to the other frequently used name of this method: resonance radio wave scattering. The condition $\lambda_1 = \lambda_2$ can be satisfied in two cases, which in fact define two possible ways of observing and recording the APIs. The first, which has been used in the majority of experiments, involves the API production and radar by waves with the same frequency and polarization. In this case, the API recording condition is the equality $f_1 = f_2$ and the scattered signal is observed from all altitudes at which the APIs are sufficiently high in amplitude. The second way requires using radio waves with different frequencies and polarizations for the production of the APIs and their radar. Then, the condition for recording the scattering from the APIs is the relation $f_1 n_1^{\mathrm{o,x}} = f_2 n_2^{\mathrm{x,o}}$, where n_1 and n_2 are the refractive indices for the ordinary (the superscript '0') and extraordinary (the superscript 'x') waves at the corresponding frequencies. For given frequencies f_1 and f_2, this condition virtually uniquely determines the electron density, which underlies the method of determining the altitude dependence of the electron density $N(h)$.

Obtaining the altitude electron density profile $N_e(h)$ requires varying the ~ 1 MHz radar frequency about the heater transmitter frequency and recording the altitudes of the signals scattered from the APIs. An important feature of the method is the possibility of measuring the profile $N_e(h)$ in the valley (the interlayer trough) between the regions E and F. The upper measurement limit (in altitude) is due to the altitude of high-power wave reflection and the lower limit is due to the spectral width Δf_2 of the probing pulse. For $f_1 - f_2 < \Delta f_2$, the spatial matching between the API-producing wave and its diagnostic wave is satisfied for almost all altitudes of the D region, making it difficult to determine the altitude of signal scattering. This difficulty may be overcome by measuring the phase of the scattered signal, because the phase increment with altitude is proportional to the integral electron density. This underlies the phase technique for measuring the electron density [58].

Waves with extraordinary polarization are typically used for generating APIs because such waves do not excite ionospheric plasma instabilities and therefore experience lower losses in the reflection from the F ionospheric region, with the reflected wave having more regular characteristics. As a rule, the high-power wave is radiated at frequencies $\sim 4-6$ MHz. Measurements using the resonance scattering technique are performed as follows. The action on the ionosphere is effected with the period of several dozen seconds. In each measurement cycle, to produce the APIs, the high-power transmitter operates in the cw mode for several seconds to emit waves with extraordinary polarization vertically upwards. Subsequently, the transmitter is converted to the pulsed mode to emit short (20 – 30 μs long) pulses with the same frequency and polarization. The radio pulse repetition rate is several dozen Hertz. The signals scattered from each of the probing pulses are received by an auxiliary antenna array. The requisite circularly polarized wave is extracted from the signals received and is amplified by the receiver. The amplitude of this wave is recorded in the digital form with the aid of an analog-to-digital converter in the form of sine and cosine components in the 50 – 400 km altitude range. The experiment is schematized in Fig. 4, and Fig. 5 exemplifies the recording of the signals.

The primary data processing involves calculating the signal phase and amplitude at each altitude for each heating cycle and approximating their time dependences by linear functions of the form $\ln A(t) = \ln A_0 - t/\tau$, where τ characterizes the API lifetime after switching off the heating transmitter. The understanding of the mechanisms of API formation at different altitudes has enabled developing new methods of determining the main parameters of the atmosphere and ionospheric plasma. All these methods rely on the production of APIs, their radar by probing radio ways, the reception of signals scattered by the irregularities, and the determination of altitude – temporal characteristics of the scattered signals.

The theory of API formation and the main results of the experimental ionosphere research by this technique are detailed in monograph Ref. [58]. By using APIs, it is possible to determine

- the electron density distribution with altitude, including the interlayer E-F valley (altitudes 60 – 250 km);
- the temperature and density of the atmosphere at E-region altitudes (100 – 130 km);
- the velocity of vertical motion in the D and E regions (60 – 130 km);
- the characteristic turbulent velocity at turbopause altitudes and the height of the turbopause (90 – 100 km);
- the relative density of negative oxygen ions, the density of atomic oxygen and excited molecular oxygen in the $^1\Delta_g$ state in the D region (60 – 90 km);
- the ionic composition of the sporadic E layer (85 – 130 km);
- the electron and ion temperatures in the F region (200 – 300 km).

Apart from the characteristics listed above, the method of resonance signal scattering from the APIs also permits determining the parameters of internal gravity waves and their spectral characteristics; investigating the nonuniform structure of the lower ionosphere, including the stratification of the regular E layer; discovering weak sporadic ionization

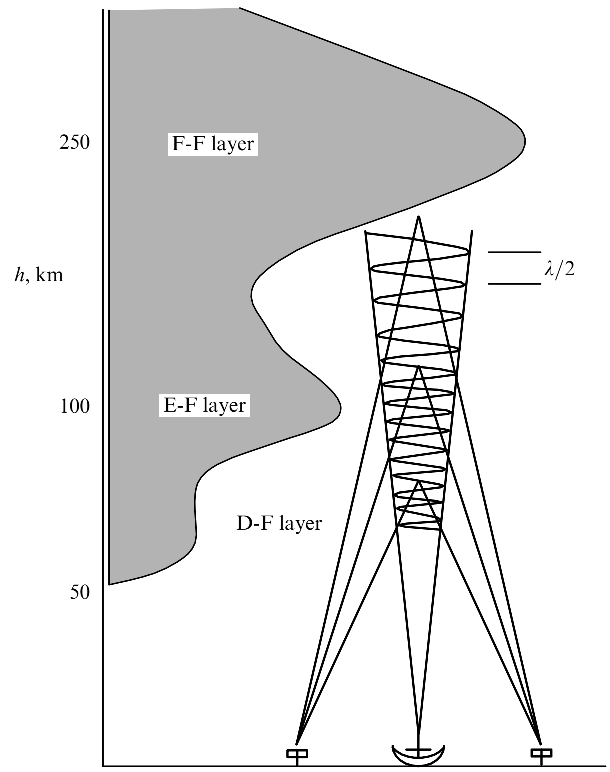

Figure 4. Scheme for the production of artificial periodic irregularities of ionospheric plasma and their radar by pulsed signals.

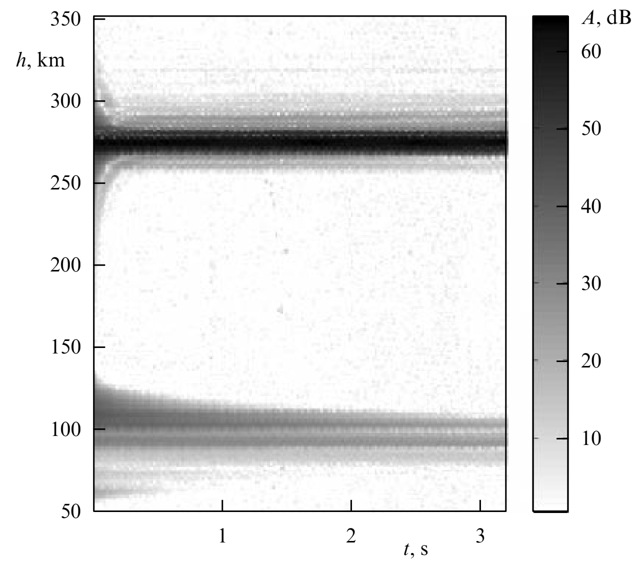

Figure 5. Example of the recording of a signal scattered from APIs. The maximum signal arises from the E region at the altitudes 100 – 130 km and the weak signal from the D region (60 – 80 km). At the altitude 270 km is the specularly reflected signal from the F layer and below a rapidly decaying ion sound.

layers, which escape detection by ordinary ionosondes, and additional layers in electron density profiles, beginning with the lower part of the D region and up to the altitude of the F-layer maximum; and investigating the features of sunrise and sunset phenomena in the D region.

The ionosphere investigation method with the help of APIs continues to develop. Proposed recently was a new way of determining the electron density from API relaxation time measurements at two sufficiently spaced frequencies [59]. This opens the way to a more precise measurement of the altitude profile of the electron density in the E region, as well as the temperature and density of the neutral atmosphere at the altitudes 90 – 115 km. This also opens up the possibility of determining the ambipolar diffusion coefficient and the turbulent motion velocity independently of one another.

By comparing the API method with other methods of remote ionospheric probing, it may be concluded that this method is vastly superior to them in information value. The API-based methods of plasma parameter determination afford high temporal resolution, which favorably distinguishes them, e.g., from the method of incoherent scattering, and may rival rocket research, substantially exceeding it in economy. The method is environmentally clean, because it does not introduce additional impurities into the atmosphere. In the measurements, the heating of the electron plasma component is insignificant and does not disturb the thermal balance of the neutral atmosphere. It is significant that all API-based methods of plasma diagnostics are easily combined into a common complex technique, making it possible to pursue research and monitor the ionosphere in a wide altitude range, from the D region to the F region [58].

5. Conclusion

Our report outlines the main findings of research involving the modification of the ionosphere by high-power HF radio waves, which was carried out from 1973 to 2006, first using the Zimenki heater and then, since 1981, the Sura heater. The new effects discovered in these experiments have far exceeded the expected phenomena due to ohmic plasma heating by high-power radio waves. The experiments conducted have enabled investigating the properties of different instabilities responsible for the generation of artificial ionospheric turbulence; studying the generation mechanisms of combination frequency signals and pointing out the areas of their practical use; and developing new radiophysical methods for the measurement of ionosphere parameters and plasma turbulence with the help of artificial periodic irregularities, stimulated electromagnetic emission, and aspect scattering of HF and VHF radio waves. This has opened up new vistas for research in which the ionosphere will be harnessed as a natural plasma laboratory that allows the pursuance of experiments to study a wide range of problems in plasma physics, geophysics, and space physics.

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