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HF-Induced Artificial Injection of Energetic Electrons from the Earth's Radiation Belt as a Powerful Source for Modification of Ionized and Neutral Components of the Earth's Atmosphere

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Abstract: It has been found in experiments at the SURA mid-latitude heating facility that the modification of the ionospheric F_2 layer by powerful HF radio waves gives rise to artificial injection of energetic electrons from the Earth's radiation belt into the atmosphere. The spectral, energy, and spatial characteristics of such an injection are presented in the paper. It is significant that the energetic electrons excite the atoms and molecules of the atmosphere to Rydberg energy levels, followed by the transition of the excited atoms and molecules to lower energy states, accompanied by the radiation of the microwave electromagnetic emissions. It has been shown that the artificial injection of energetic electrons can be considered as an independent powerful source of generation of secondary artificial turbulence, the effect of which manifests itself at ionospheric and mesospheric heights both near the heating facility and at a large distance from it up to a thousand or more kilometers. Examples of such generation are given.

Keywords: mesosphere; ionosphere; magnetosphere; modification of ionospheric plasma; high-power radio waves; artificial ionospheric turbulence; energetic electrons; microwave electromagnetic emissions

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1. Introduction

Investigations related to modification of the Earth's ionosphere by high-power HF radio waves, radiated vertically or almost vertically upward by specially constructed heating facilities, have a history of more than half a century. During this time, studies have investigated the features of instabilities, generated in the upper ionosphere under an influence of a powerful radio wave (pump wave, PW), and the main characteristics of various types of electromagnetic and plasma disturbances developing in this case within the SURA antenna beam pattern near a height of PW reflection in the ionospheric F_2 layer known as artificial ionospheric turbulence (AIT). The area of turbulence generation in the horizontal plane at the level of the PW reflection has a size of about 50–100 km, which is determined by the width of the beam directive pattern and threshold power of generation of different AIT components. Its vertical size varies from a fraction of a kilometer to 20–100 km, depending on the type of the turbulence. This region over the SURA facility with strongly developed high-frequency and low-frequency plasma disturbances, in which the strongest heating of plasma electrons, acceleration of background plasma electrons to superthermal energies, and generation of artificial optical glows are also observed, is referred to as the central part of the ionosphere disturbed volume (IDV_c). The turbulence generated in the IDV_c during the direct interaction of powerful HF radio waves with plasma is referred to by us as the primary AIT; its characteristics were considered in detail in [1–6] (see also the numerous references therein).

In recent years, a number of studies have been carried out at the SURA mid-latitude heating facility (Radiophysical Research Institute (NIRFI) at Lobachevsky State University, Nizhny Novgorod, Russia), the results of which have significantly expanded our understanding of AIT properties. This concerns the study of the spatial structure of plasma density irregularities of various scale lengths inside IDV_c and far from it, the generation of travel ionospheric disturbances (TIDs) during periodic heating of the ionosphere by high-power HF radio waves, the generation of field-aligned electric currents during the development of artificial large-scale plasma density irregularities, the formation of ducts in the outer ionosphere with increased plasma concentration, the injection of energetic electrons from the Earth's radiation belt to ionospheric heights, etc. Plasma disturbances, excitation of which is often observed far outside IDV_c, can be considered as a result of the development of secondary artificial ionospheric turbulence. In this case, as below, the most important source of secondary turbulence generation is the artificial injection of energetic electrons (AIEEs) from the Earth's radiation belt to ionospheric heights, which is caused by the modification of the ionosphere by means of powerful HF radio waves. This is determined by its high energy and different influences on features of AIT generation registered in a large area of space, not only in the vicinity of the SURA facility but very far from it, including the ionosphere magnetically conjugate (MC) to IDV_c over the facility.

The purpose of this paper to consider AIEE properties in detail, as well as the influence of energetic electrons on numerous processes occurring in the Earth's atmosphere. Section 2 of the paper discusses the dependence of AIEE properties on ionospheric conditions and PW characteristics, along with daily, spatial, and energy variations of the electron injection. Section 3 considers possible mechanisms of the influence of energetic electrons on the development of the interaction of PW with ionospheric plasma, as well as characteristics of secondary plasma disturbances (secondary AIT) HF-induced in the ionosphere; furthermore, possible channels of influence of AIEE on features of the ionized and neutral components of the Earth's atmosphere are presented. These studies have shown that, as a result of the external impact of PW on the Earth's magnetospheric–ionospheric system, a powerful source of the secondary AIT generation is formed, which is based on the injection of energetic electrons from the Earth's radiation belt into the ionosphere. Section 4 summarizes the results of the research discussed in the paper and provides a list of agents of possible influence of AIEE on the Earth's atmosphere, including their impact on chemical–physical processes in different atmospheric regions.

All experiments discussed in the paper were conducted at the SURA heating facility (Russia), which is located approximately 100 km east of Nizhny Novgorod (its coordinates are 56.15° N, 46.1° E; McIlwain parameter $L \approx 2.7$). The facility has a three-module structure. Each module consists of an HF broadcast transmitter (PKV-250) generating an HF signal with power up to 250 kW within a frequency range from 4 to 25 MHz, which is loaded on its sub-antenna array, consisting of 12 × 4 broadband crossed dipoles having a biconical form. The size of such a sub-antenna array is 100 m in the north–south direction and 300 m in the east–west direction. The facility can radiate ordinary (*O*) and extraordinary (*X*) polarized waves from 4.3 to 9.5 MHz, covering a frequency range from slightly above the third to above the seventh electron cyclotron harmonic. Each module can operate independently (with independent frequency, power, polarization, and timing) or coherently, combining any two or all three of its modules. In the latter case, the full antenna array consists of 144 dipoles occupying a site of 300 m × 300 m. The effective radiated power (ERP) by the SURA facility in this case is $P_{\rm eff} = P_0 G \approx 80$ MW at $f_{\rm PW} \approx 4300$ kHz ($P_0 \approx 500$–700 kW is the maximal power generated by all three transmitters; G is the gain of the facility transmitting antenna). $P_{\rm eff}$ increases with increasing PW frequency up to ~280 MW ERP at 9500 kHz. The HF beam can be scanned in the geomagnetic meridian plane over the range of ±40° from the vertical. To increase the efficiency of the interaction of *O*-mode powerful HF radio waves with the ionospheric plasma due to the "magnetic zenith" effect [5,7], the ionosphere is often illuminated not by the vertical PW beam, but that inclined by 12–14° south. A comprehensive description of the SURA facility can be found in [8].

The SURA facility is currently the only operating facility in the world located in mid-latitudes, where strong natural geomagnetic disturbances are a rather rare event, in contrast to higher latitudes, where the EISCAT Heating (Northern Norway) and HAARP (Gakona, AK, USA) facilities are located, in which strong natural ionospheric and magnetospheric disturbances significantly complicate experimental conditions and, thus, interpretations of phenomena observed. This makes experiments at the SURA mid-latitude facility for modifying the ionosphere with high-power HF radio waves more preferable than measurements conducted in the high-latitude ionosphere.

It should be noted that a large number of studies of artificial injection of energetic electrons from the Earth's radiation belt to ionospheric heights have been performed in the USA, using the radiation from powerful ground-based VLF transmitters [9–11], as well as at the HAARP heating facility (Gakona, AK, USA) [5,12,13]. Experiments on stimulating the injection of energetic electrons were repeatedly carried out at the EISCAT Heating facility [3,6], which is located at auroral latitudes, in a region with a high level of natural plasma disturbances. It should be pointed out that all experiments at the EISCAT Heating and HAARP facilities were carried out under conditions when amplitude-modulated high-power HF radio waves with modulation frequencies lying in the ELF–VLF ranges (from several hertz to 30 kHz) were used to modify the ionosphere. As a result of nonlinear demodulation of a powerful radio wave, ELF–VLF waves are generated at the lower ionosphere heights and propagate into the magnetosphere, where, in the equatorial region of the HF-disturbed magnetic flux tube, they interact with energetic electrons of the Earth's radiation belt and change electron pitch-angle distribution. In contrast to these experiments, all measurements carried out at the SURA facility were conducted with the modification of the ionosphere by high-power HF radio waves that were not modulated in amplitude and radiated in the "continuous wave" (CW) mode. In this case, in the region of the upper-hybrid resonance for an *O*-mode powerful radio wave, lower-hybrid plasma oscillations are generated because of thermal parametric instability development, which, due to scattering from plasma density irregularities, can transform into VLF waves. Such generation of ELF–VLF waves during the modification of the ionospheric plasma by continuously radiated high-power HF radio waves was confirmed experimentally [14–17]. The VLF electromagnetic waves, as above, propagate into the magnetosphere, where they interact with energetic electrons from the Earth's radiation belt, causing their injection at ionospheric heights (see, for example, [5,18–21]).

2. Characteristics of Energetic Electron Injection

The study of AIEE was performed at the SURA facility employing onboard instruments of several satellites. In 2005–2010, these studies were conducted by means of the French microsatellite DEMETER, which flew at 660 km height in a sun-synchronous orbit. The satellite flew through the HF-disturbed flux tube over the SURA facility at 18:00–18:30 UT in the late evening or night hours, depending on a measurement season, and in the daytime ionosphere at 07:30–08:00 UT. Note that, for the SURA facility, the local time (LT), equivalent to the Moscow time (MT), is $T_{LT/MT} = T_{UT} + 3$ or 4 h depending on the year of measurements. Furthermore, DEMETER flew in the ionospheric region, MC to IDV_c over the SURA facility, at about 18:30 UT, in which measurements of plasma disturbances were often also conducted. The description of all measuring instruments placed on board the satellite DEMETER is given in detail in [22]. One of them is an IDP spectrometer [23], which detects energetic electrons in a range from 70 keV to 2.5 MeV, together with their flux density. The peculiarity of placing this device on board the satellite was that it measured electron fluxes in a direction close to orthogonal with respect to the plane of its orbit, or with pitch angles lying in the region of $90^\circ \pm 16^\circ$ relative to the direction of the geomagnetic field, which, in the case of measurements at the SURA facility, corresponded to the registration of electrons trapped in the HF-disturbed magnetic flux tube and did not register electrons that moved in the direction close to the geomagnetic field lines. However, due to the low altitude of the satellite orbit (~660 km), the pitch angles for such electrons in the equatorial region of the HF-perturbed magnetic flux tube only slightly (by several degrees) exceed the loss cone angle, which provides a condition for the transition of these electrons into the loss cone and their penetration (injection) to ionospheric heights. Since these electrons are absorbed in the plasma of the lower ionosphere (in its *D* and *E* layers) and do not return to the outer ionosphere, such an *injection* of energetic electrons to ionospheric heights can also be considered as electron *precipitation* into the Earth's ionosphere, as it was accepted, for example, in [24].

In 2019–2021, the study of AIEE properties in the morning, afternoon, and evening hours was carried out using the USA weather satellites NOAA-18 and -19 flying at about 850 km height in sun-synchronous orbits with an inclination of ~99°. The satellites flew over the SURA facility through the heated flux tube at about 07:00 UT and 13:00 UT (T_{MT} = T_{UT} + 3 h during the years of measurements), i.e., close to noon or in the early evening, or in evening hours depending on local time and a measurement season. In the ionosphere magnetically conjugate to IDV_c over the facility, the satellites flew through the HF-disturbed magnetic flux tube at about 13:30 UT, which, in different seasons, corresponds to daytime or early evening conditions. A detailed description of the NOAA Polar-Orbiting Operational Environmental Satellite (NOAA POES) onboard instruments can be found on the website of the National Oceanic and Atmospheric Administration (NOAA): www.noaa.gov/ (accessed on 7 March 2023).

For the NOAA satellites, data on the characteristics of energetic electrons were taken from two onboard detectors. Due to their different orientation in space, the detector at 0° (denoted as D-0 for brevity) at the latitudes of interest to us measured electron fluxes inside the loss cone, corresponding to the flow of energetic electrons precipitating from the Earth's radiation belt into the ionosphere, and the detector at 90° (or D-90) measured outside this cone, corresponding to electrons trapped in a magnetic flux tube. From the results presented below, it can be seen that the fluxes of such precipitating electrons measured at mid-latitudes are more than two orders of magnitude weaker in relation to the fluxes of trapped electrons, remaining in most cases below the threshold for their detection by the satellite onboard IDP spectrometer. A similar situation usually takes place for measuring the natural fluxes of "precipitating" and "trapped" electrons at mid-latitudes under conditions of low geomagnetic activity [25]. For the NOAA satellites, the increase in the flux of energetic electrons measured at 850 km height by D-90 can be considered, similar to DEMETER measurements, as a result of their artificial injection from the Earth's radiation belt to ionospheric heights, stimulated by the modification of the ionospheric F_2 region by high-power HF radio waves.

It is important to note that measurements in the daytime and early evening hours are usually conducted at a high level of the regular absorption of radio waves in the lower ionosphere (in its *D* and *E* layers) and at low heights of the F_2 layer. In addition, at a sufficiently high effective radiated power of the PW ($P_{eff} \geq 30$ MW ERP), the formation of a defocusing lens in the daytime at altitudes of 130–170 km takes place, which can significantly reduce the PW energy flux in the F_2 region [1,2]. The measurement results are also often affected by the presence of natural sporadic E_s layers at 100–110 km heights. All these factors taken together can lead to the strong (by 20–30 dB) decrease in the PW power transported to the upper ionosphere compared to measurements at night in a quiet ionosphere, thereby determining low efficiency of the interaction of powerful HF radio waves with ionospheric plasma under daytime conditions and, thus, weak intensity of the AIT generated in this case. An exception here may be the winter months, when the regular absorption of radio waves in the mid-latitude lower ionosphere noticeably decreases, E_s sharply weakens, and measurements using the modification of the F_2 region can be carried out in the dimly sunlit ionosphere.

During the experiments, we make some estimations of the level of AIT generation according to the characteristics of vertical sounder ionograms, which demonstrate some features of ionosphere pumping by high-power HF radio waves. Therefore, we took into account the appearance of artificial *F*-scattering (known as the F_{spread} phenomenon on ionograms) and its magnitude, the value of the anomalous absorption (AA) of the *O*-mode traces on ionograms at frequencies close to a PW frequency, features of scattering of radio waves at frequencies far from a PW frequency, variations in the intensity of the ionogram traces at low frequencies (1.5–2.5 MHz), and the results of changing the intensities of multiple reflections of sounding signals. We return to such effects of ionosphere pumping in Section 2.3.

Below, on the basis of the results obtained in [26–28], we briefly consider the main AIEE characteristics, which have been found in ionosphere heating experiments as a result of F_2 region pumping by high-power HF radio waves. It is clear that features of AIEE (and AIT also) should strongly depend on the following:

(a) characteristics of the radiation of a powerful radio wave (through its frequency, polarization, effective radiated power, and timing);
(b) time of day and ionospheric conditions for measurements (through the value of regular absorption of high-power radio waves in the lower ionosphere, the critical frequency of the F_2 layer (f_{0F2}), the shape of a F_2 layer vertical profile and its diurnal variation, the height of PW reflection, and the presence of a sporadic E_s layer);
(c) the level of current geomagnetic activity and the time after a last substorm (through the level of residual natural disturbance of the ionospheric plasma and the level of radiation belt filling by energetic electrons);
(d) the distance of the satellite orbit to the center of the HF-disturbed magnetic flux tube (through spatial characteristics of HF-induced plasma disturbances);
(e) other reasons affecting the features of such an injection.

The cumulative effect of all these causes sets up the large spread in experimental data obtained.

It should be noted that when measurements of the AIEE intensity were carried out in the ionosphere over the SURA facility, the facility was switched on approximately 15 min before the satellite passed through the HF-disturbed magnetic flux tube rested on IDV_c, in which the most strongly developed AIT was observed. In measurements in the region of the ionosphere magnetically conjugate to IDV_c, we used in some cases plasma pumping longer than 30–40 min to ensure more complete generation of plasma disturbances into a magnetic flux tube.

We also note that, in heating experiments, the optimal conditions for their implementation, from the point of view of more intense AIT generation and stronger heating of the ionospheric plasma, should fulfill the following conditions [2]:

(a) experiments have to be carried out in the late evening or night hours;
(b) the ionosphere has to be heated by *O*-polarized powerful waves;
(c) PW frequency must not be higher than 6 MHz, and its value has to be 0.3–0.5 MHz below the critical frequency of the ionospheric F_2 layer f_{0F2};
(d) the PW reflection height has to be higher than 200 km, for which collisions of electrons with ions, and not with neutral atoms and molecules, play the main role;
(e) measurements have to be carried out at $P_{eff} \geq 20$ MW ERP in a quiet or only slightly disturbed ionosphere with the low level of the regular absorption of radio waves in the ionospheric *D* and *E* regions;
(f) the tilt of the beam pattern of the SURA transmitting antenna by ~12° to the south is preferable to enhance the AIT generation because of the "magnetic zenith" effect [5,7].

Before research on AIEE properties began, the features of natural energetic electron precipitations in the vicinity of the SURA facility were previously investigated in the absence of ionosphere modifications by powerful HF radio waves [26–28]. In particular, we analyzed the relationship between the intensity of natural precipitations and the value of the geomagnetic activity index K_p (or its daily value ΣK_p), as well as the connection of precipitations with both aurora electro jet index *AE* and the geomagnetic activity development stage. The results of such an analysis were used to find the necessary criteria to distinguish of AIEE against the background of natural components of energetic electron precipitations.

When analyzing the experimental data, we took into account several factors. It is usually believed that energetic electrons in near-Earth outer space form the inner and outer radiation belts, which, under quiet geomagnetic conditions, are separated by a region with a low content of energetic electrons; its position corresponds to the value $L \approx 2.2$–3.5, and it is more pronounced for particles with energies $E \geq 300$ keV. For the SURA facility with $L \approx 2.7$, this corresponds to filling the gap between these radiation belts. However, for electrons with energies $E < 200$ keV, for which our studies were performed, the decrease in the flux density of energetic electrons in this gap is weakly expressed under quiet geomagnetic conditions and even more weakly expressed under disturbed conditions. In our case, it is permissible to say that a single radiation belt is observed around of the Earth without dividing it into the inner and outer belts (see, for example, [29]).

The conducted studies of the AIEE properties make it possible to come to the following conclusions:

(1) With a low level of auroral activity (with $K_p \leq 2$ for several days preceding measurements, and with the *AE* index not exceeding 100–200 nT on the day of the measurements), the southern boundary of natural intense precipitations at the longitude of the SURA facility for time T $\approx$ 18:00 UT does not fall below geographic latitudes 62°–65° N, whereas the latitude of the center of the HF-disturbed magnetic flux tube φ_c is of about 54.6° N if the satellite orbit height ~660 km and a PW reflection height $h \approx 240$ km.

(2) With an increase in the value of the *AE* index, the southern boundary of a natural precipitation region shifts toward the equator, and, at $AE \approx 300$–800 nT, it can already reach the latitude $\varphi_c \approx 54.6°$ N, descending to latitudes 46–52° N at $AE = 800$–1200 nT. It should be noted that the position of the southern boundary of the electron precipitation region is controlled to a greater extent not by the value of the K_p index, but by the average value of the *AE* index, the magnitude of which is taken within a few hours before precipitation measurements.

(3) The *AE* index has maximum values at the stage of attenuation of geomagnetic disturbances, usually observed 1–2 days after the maximum value of the K_p index.

2.1. Measurements of AIEE Properties over the SURA Facility in the Late Evening and Night Hours

These measurements were carried out in 2005–2010 within the framework of the SURA–DEMETER program in experiments on modifications of the ionospheric F_2 region by high-power HF radio waves. The satellite flew over the SURA facility at T $\approx$ 18:15 UT. Depending on the season, this time corresponded to measurements in the late evening hours or at night.

To perform these experiments, the coordinates of the HF-disturbed magnetic flux tube resting on the IDV_c were calculated. If the antenna pattern of the SURA facility is tilted by 12° to the south and the height of the PW reflection is 250 km, the coordinates of the DEMETER satellite, when crossing the center of this flux tube at the altitude of 660 km, are $\varphi_c = 54.6°$ N and $\lambda = 45.6°$ E in the northern hemisphere.

According to the results obtained during the ionosphere pumping by the SURA facility, the following characteristics of AIEE have been found:

(1) the maximum of the AIEE intensity is observed, as a rule, inside the HF-disturbed magnetic flux tube resting on IDV_c, where the most intense generation of AIT and the strongest heating of the ionospheric plasma take place near PW reflection height;

(2) the injection intensity increases with the growth of the geomagnetic activity, which ensures the filling of the Earth's radiation belt with energetic electrons;

(3) weak intensity of AIEE after a long period of very weak geomagnetic activity (more than 10–14 days) or even its absence is determined by the low content of energetic electrons in the HF-disturbed magnetic flux tube with $L \approx 2.7$ during experiments;

(4) maximum fluxes of injected energetic electrons with $F \approx 100$–200 el/(cm^2·s·sr·keV) were observed for their energies $E \approx 100$ keV;

(5) when the duct with increased electron concentration relative to the background plasma density is formed in the HF-disturbed magnetic flux tube, a severalfold local increase in the flux of injected electrons into the duct is observed;
(6) at the height of the satellite orbit $h \approx 660$ km, the area of electron injection along a geomagnetic meridian in the northern hemisphere has dimensions up to 900 km north of the center of the HF-disturbed magnetic flux tube and up to 400 km south of it, far exceeding the IDV_c horizontal dimension of about of 60–100 km; the dimension of the injection area in the direction orthogonal to the meridian is estimated as 400–500 km, which also significantly exceeds the horizontal dimension of the HF-disturbed magnetic flux tube.

Such a large area of registration of artificial injection of energetic electrons from the Earth's radiation belt into the ionosphere is determined by the width of the beam of radiated VLF radio waves (whistlers) at the heights of the magnetosphere. For example, in [30], at an altitude of $h \approx 1000$ km, a region with a high level of plasma disturbances and VLF waves was registered, the size of which was of up to 700 km along a satellite orbit, i.e., much larger than the size of the IDV_c where VLF waves are generated. It was shown in [31–33] that, in the presence of ducts with increased plasma density on the inside and with dimensions $l_\perp \geq 50$ km across the geomagnetic field lines, which are usually excited when the mid-latitude F_2 ionospheric region is modified at night by high-power HF radio waves [16], there is a significant change in the propagation trajectories of VLF waves leading to a strong increase in the width of their initial beam to the observed sizes. The greater broadening of the beam of injected electrons toward the north pole for the northern hemisphere is determined by both the properties of the propagation of VLF waves and the higher content of energetic electrons in shells with larger L. As shown in [34], the broadening of the VLF beam can also be related to their multiple reflections from the Earth's surface and their propagation in the Earth ionosphere waveguide with gradual radiation of waves through its boundary into the outer ionosphere. In the latter case, the most intense central part of the VLF beam is singled out. Such a situation apparently took place in experiments performed using low-orbit satellites [15,16].

Three examples of the artificial injection with different levels, i.e., weak (when K_p = 0–1 and $AE \approx 25$ nT during the measurements, which were carried out on 27 May 2010, 25 days after a geomagnetic substorm with K_p up to 5–6), moderate (when $K_p \approx 1$ and $AE \approx 200$ nT during the measurements, which were carried out on 14 May 2010, 12 days after the geomagnetic substorm with K_p up to 5–6), and strong (when $K_p \approx 1$ and $AE \approx 100$ nT during the measurements, which were carried out on 25 May 2005, 10 days after the very strong geomagnetic substorm with K_p up to 8 and 5 days after the subsequent repeated substorm with K_p up to 5), are shown in the left, central, and right panels of Figure 1, respectively. The black triangles under the abscissa mark the location of the heated magnetic flux tube center at the satellite orbit height of 660 km. It should be stressed that all these measurements were conducted in quiet geomagnetic conditions but at a different number of days since the last substorm.

It is clearly seen from Figure 1 that the intensity of the flow of energetic electrons is determined by the level of geomagnetic activity and the time after the last substorm, because both have an influence on filling the Earth's radiation belt with energetic electrons. It can be concluded also that the maximum value of AIEE is detected inside the HF-disturbed magnetic flux tube. Moreover, Figure 1 clearly demonstrates that the AIEE intensity shows a connection with the intensity of the natural precipitation of energetic electrons in the auroral ionosphere (at $\varphi \geq 65°$ N), from which it can be also concluded that the value of the injected electron flux is largely determined by the level of filling the HF-disturbed magnetic flux tube with energetic electrons. This conclusion was confirmed by many other examples obtained in our measurements.

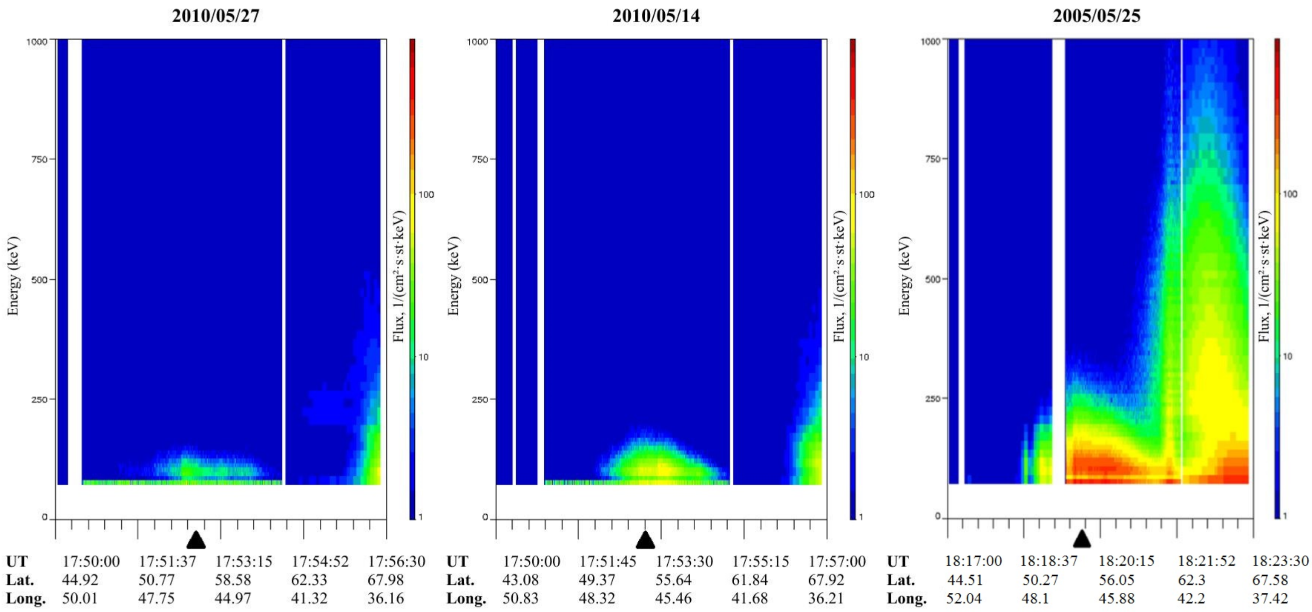


Figure 1. Three examples of AIEE with their different levels, i.e., **weak** (when K_p = 0–1 and $AE \approx 25$ nT during the measurements, which were carried out on 27 May 2010, 25 days after a geomagnetic substorm with K_p up to 5–6), **moderate** (when $K_p \approx 1$ and $AE \approx 200$ nT during the measurements, which were carried out on 14 May 2010, 12 days after the geomagnetic substorm with K_p up to 5–6), and **strong** (when $K_p \approx 1$ and $AE \approx 100$ nT during the measurements, which were carried out on 25 May 2005, 10 days after the very strong geomagnetic substorm with K_p up to 8 and 5 days after the subsequent repeated substorm with K_p up to 5), are shown in the left, central, and right panels, respectively. The black triangles under the abscissa mark the coordinates of the heated magnetic flux tube center at the satellite orbit height of 660 km.

It should be stressed that the measurements conducted on 27 May 2010 were carried out under the condition when a duct was HF-produced during this heating session. Results of these measurements demonstrate that the intensity of energetic electron injection has a prominent maximum inside the duct simultaneously with an increase in VLF electromagnetic radiation intensities. Such an increase in energetic electrons and VLF signals inside such ducts were also observed in [16,31].

The performed studies made it possible to establish that the development of thermal (or resonant) parametric instability [1,5] plays a decisive role in the mechanism of AIEE generation. In this case, as noted above, in the region of instability development (or in IDV_c), the generation of lower hybrid plasma oscillations takes place, which can transform into VLF waves when they are scattered from artificial ionospheric irregularities [5,18–21]. Such a scheme for the generation of VLF waves during the modification of ionospheric plasma by high-power HF radio waves supplements the schemes of their direct generation due to radiation from ground-based VLF transmitters [9–11,35] or due to nonlinear demodulation of amplitude-modulated high-power HF radio waves (because of the Getmantsev effect) [6,12,13,36]. It is important that, in our case, it is possible to use the PW radiation in the "continuous wave" (CW) mode to stimulate the injection of energetic electrons from the Earth's radiation belt into the ionosphere. As stated in [37], the lifetime of injected energetic electrons is about 2–3 s and corresponds to the decay time of VLF waves in the HF-disturbed magnetic field flux tube after PW switching off. A similar result with a lifetime of about 4–6 s was recently obtained in [38].

It follows from the results considered that any turn on of PW for a time longer than several minutes is accompanied by the artificial injection of energetic electrons from the Earth's radiation belt into the ionosphere, which should be taken into account when setting up experiments and interpreting the obtained results.

2.2. Measurements in Late Evening and Night Hours Conducted with Onboard Satellite Instruments in the Ionosphere Region Magnetically Conjugate to IDV_c over the SURA Facility

As part of the experiments conducted in the framework of the SURA–DEMETER program, measurements of AIEE characteristics were conducted in the ionosphere region MC to IDV_c. This region is located in the southern hemisphere, the coordinates of its center at the height of the satellite orbit $h \approx 660$ km were determined as $\varphi^* \approx 41.1°$ S and $\lambda^* \approx 61.2°$ E, taking into account model calculations of the geometry of the geomagnetic field and the results of our measurements of injection features of energetic electrons [28].

According to the experiments conducted, AIEE into the ionospheric region magnetically conjugate to IDV_c has the following characteristics:

(1) under quiet geomagnetic conditions, the maximum value of the energy flux F of injected electrons with $E \approx 100$–150 keV is about (100–200) el/(cm^2·s·sr·keV);
(2) the maximum injection intensity is observed, as a rule, inside the HF-perturbed magnetic flux tube resting on IDV_c;
(3) in the injection region (in a latitude range 46°–53° S), rapid decreases in the energy of injected electrons and in the intensity of their flux are observed by the displacement of a point of measurements from the center of MC region toward the equator rather than by its displacement toward the south pole;
(4) into the MC ionosphere, the spatial dimension of the region of AIEE can reach 2200 km along the geomagnetic meridian (this is somewhat large in the comparison with the northern hemisphere) and about 500 km across it.

Comparative measurements of AIEE characteristics in both hemispheres under the same conditions of the ionosphere modification showed that the intensity of the injection in the southern hemisphere is several times higher than in the northern hemisphere. This conclusion is demonstrated in Figure 2, which shows the results of measurements when, in one measurement session, the satellite flew close to the center of the HF-disturbed magnetic flux tube both over the SURA facility and in the MC ionosphere. This difference can be explained by the influence of the South Atlantic Magnetic Anomaly (SAMA), in which there is a local decrease in the strength of the geomagnetic field and, consequently, a weaker keeping of energetic electrons in a magnetic flux tube. As follows from the data presented in [39], the MC region for the SURA facility is located close to its eastern boundary. As this takes place, the geomagnetic field strength in the HF-disturbed magnetic flux tube is about 35,000 nT at its southern end and about 55,000 nT at its northern end.

2.3. AIEE Characteristics Obtained in Measurements in the Daytime and Evening Hours Employing Onboard Instruments of NOAA Satellites

Compared with the night hours of measurements, the results of which are given above, experiments in the daytime and evening hours are usually carried out under conditions of noticeable regular absorption of the PW energy in the lower ionosphere (in its D and E regions), which is not related to HF-induced nonlinear effects and has the strongest value at midday hours [40]. The absorption value determines the PW power transmitted to the ionospheric F_2 region. In the late evening and night hours under quiet geomagnetic conditions, the regular absorption is small and, in most cases, shows little influence on measurement results. In this case, the effective radiated power of the PW radiation, when all three modules of the SURA facility operate in a coherent mode, is $P_{\mathrm{eff}} = P_0 \cdot G$, where $P_0 \approx 500$–700 kW is the HF power generated by all three transmitters of the facility, and $G \approx 130$–400 is the gain of the entire radiating complete antenna array, the value of which increases with growth of a PW frequency f_{PW} from 4.3 to 9.5 MHz. In our experiments, the value of the regular absorption of radio waves was not measured, and data available in literature were used in order to estimate a reduced PW effective radiated power $P_{\mathrm{eff}}{}^*$. In the daytime, the absorption value from the Earth's surface to a PW reflection height under quiet geomagnetic conditions is approximately 5–10 dB at f_{PW} = 4.3–5.8 MHz; higher absorption occurs in the summer months in the midday hours and at a lower PW frequency. This corresponds to a decrease in the value of the reduced PW power $P_{\mathrm{eff}}{}^*$ in this frequency range to 10–30 MW ERP compared to $P_{eff} \approx$ 80–120 MW ERP for night measurements in the absence of the regular absorption. In the morning and early evening hours, the absorption value is 3–5 dB and $P_{eff}^* \approx$ 20–50 MW ERP. In the natural ionosphere under disturbed geomagnetic conditions, the regular absorption of HF radio waves can increase significantly by 20 dB or even more depending on the level of ionospheric disturbances and stage of their development, as well as on f_{PW}. As a result, a reduction in P_{eff}^* to a value of several megawatts takes place. When carrying out measurements in the daytime ionosphere, it is necessary to take into account the possibility of defocusing lens formation at heights of 130–170 km and the presence of natural sporadic E_s layers. Therefore, an additional decrease in the HF energy flux in the upper ionosphere and, consequently, weakening of the AIT intensity are observed [1,2]. Lastly, due to the development of a nonlinear interaction of PW with the plasma of the lower ionosphere, which appears at a power $P_{eff} \geq$ 30–50 MW ERP as a result of heating of plasma electrons in the field of powerful radio waves, the limitation of the flux density of its energy passing upward at a certain level can be observed [1,31,41]. At such PW intensity, the development of AIT in the lower ionosphere is also possible, particularly the generation of artificial irregularities and, thus, the appearance of E_{spread} on ionograms [4,6,42]. This demonstrates that, without detailed measurements, it is difficult to quantify the value of P_{eff}^* and the level of the ionospheric plasma disturbances when it is modified by high-power HF radio waves.

For a qualitative assessment of the level of HF-induced turbulence, we use, as a rule, the following simplified criteria: it is believed that AIT has a very low level of development if F_{spread} is not almost detected on the ionograms or, in other words, the broadening of ionogram traces at frequencies close to a PW frequency does not exceed 0.1 MHz; moreover, the effect of the anomalous absorption (AA) of probing waves sounding IDV_c is not observed. AIT has a moderate level of development if broadening of the *O*-mode trace on ionograms is about 0.2–0.4 MHz and a slight decrease in the intensity of the *O*-mode trace at frequencies close to f_{PW} because of its AA begins to be registered on ionograms. At strong development of AIT, the broadening of both traces on the ionograms is observed up to a value of 0.5–1 MHz, along with a strong decrease in intensity of the *O*-mode trace due to the AA effect. Lastly, a very strong development of AIT is registered if the broadening of both traces on the ionograms becomes more than 1 MHz, and the traces of both polarizations overlap each other, whereby the *O*- and *X*-modes become indistinguishable. The *Z*-mode is often registered on the ionograms and, in addition to strong AA, weakening of the intensity of the *O*- and *X*-traces is observed in a wide frequency range due to the appearance of scattering in this mode. An increase in the level of the AIT development is accompanied by a decrease in the intensity of multiple reflections of both traces or their complete disappearance. As shown in [2], the analysis of ionograms makes it possible to estimate the intensity of plasma concentration of artificial irregularities in the large range of their scale-lengths across the geomagnetic field, from several meters to several kilometers. It is important that the proposed approach to assessing the level of AIT, according to the analysis of visible changes in ionograms, is applicable directly during the experiments, which allows controlling the progress of experiments making some changes in research programs.

To determine AIEE characteristics in the daytime and evening hours, the USA weather satellites NOAA-18 and -19, flying at altitudes of 850–860 km in sun-synchronous orbits, were used in the experiments at the SURA facility. For them, the fluxes of energetic electrons were measured using two detectors (D-0 and D-90) orthogonally located onboard the satellite, which allowed conducting measurements in four ranges of electron energy: E_1 = 40–130 keV, E_2 = 130–287 keV, E_3 = 287–612 keV, and $E_4 \geq$ 612 keV. The measurements at the SURA facility showed that, in the HF-disturbed magnetic flux tube, the energetic electrons with $E \geq$ 287 keV were never detected, or their energy was always below a threshold of the electron flux detection $F_{thr} \approx$ 100 el/(cm^2·s·sr). In view of this fact, we consider below the results of measurements only for the two lowest ranges of the electron energies, E_1 and E_2.

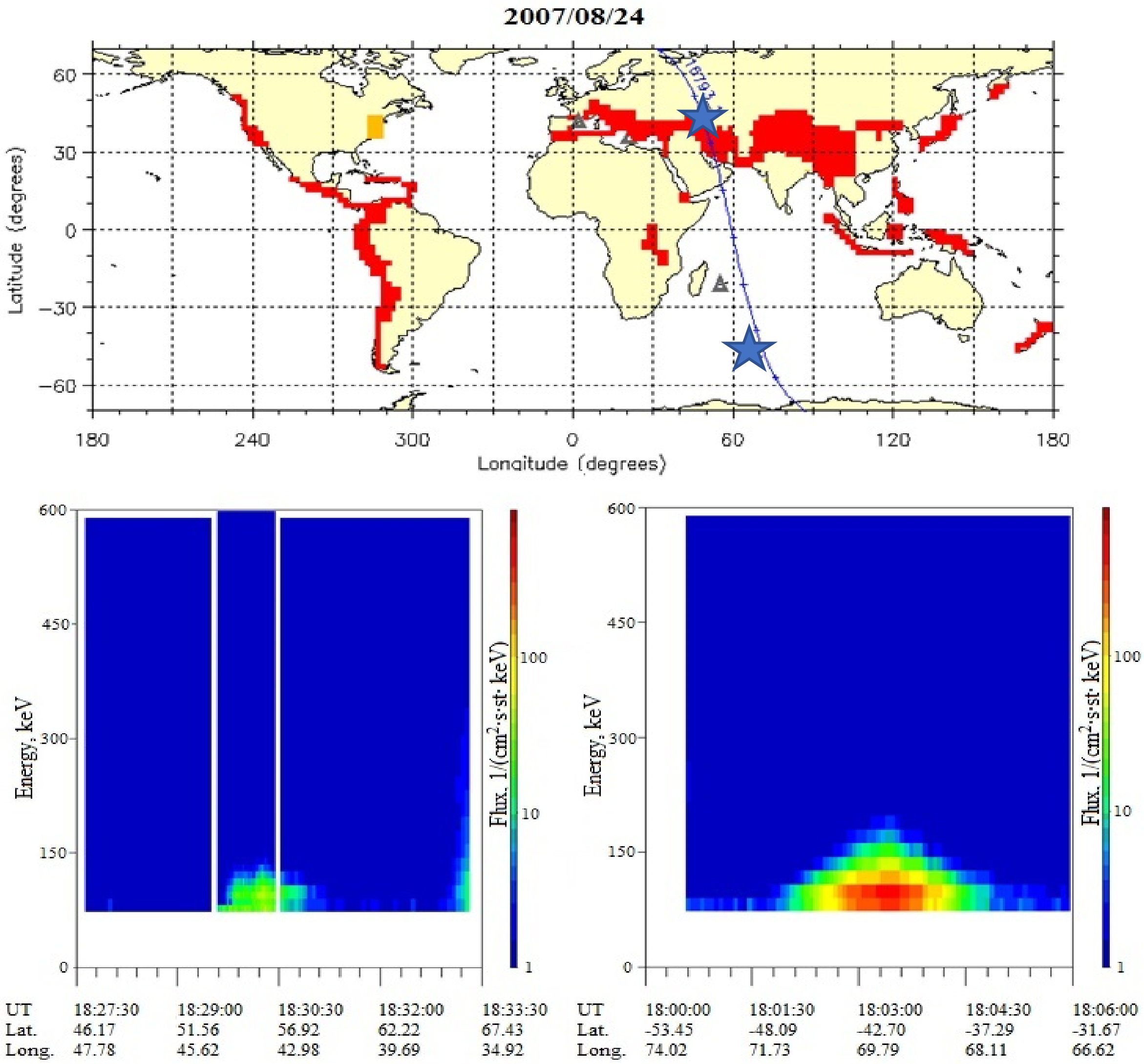


Figure 2. An example of the onboard DEMETER satellite measurements on 24 August 2007, when the satellite orbit passed close to the center of the HF-disturbed magnetic flux tube in both the northern (above the SURA facility) and the southern (in the ionosphere region MC to IDV_c) hemispheres marked by blue stars. The lower panels show the spectral densities of AIEE in the northern hemisphere (**left panel**) and in the southern hemisphere (**right panel**).

As an example, Figure 3 shows the results of a measurement session employing the NOAA-19 satellite, which was conducted on 3 June 2019 under quiet geomagnetic conditions (K_p = 0–1, $AE \leq 50$ nT; the last rather strong substorm registered before the measurements was on 29 May with $K_p \geq 4$). The upper and middle panels of the figure show latitude dependences and values of energetic electron fluxes measured with D-90 and D-0, marked as 90° and 0°, for the energy ranges E_1 = 40–130 keV (top panel) and E_2 = 130–287 keV (middle panel), respectively. The lower panel shows the latitude–time dependence of the satellite orbit. The satellite at T^* = 12:57:12 UT = 15:57:12 MT (this time is marked in the figure by a vertical line) flew very close to the center of the HF-disturbed magnetic flux tube in the daytime ionosphere, when there was a high linear absorption of HF waves in its *D* and *E* regions. The facility in this session operated in *O*-mode at the PW frequency f_{PW} = 4300 kHz with a fairly low effective radiated power of PW $P_{eff} \approx 25$ MW ERP at a *O*-mode critical frequency $f_{oF2} \approx 4.4$ MHz. Taking into account the conditions for these measurements, the value of the reduced power P_{eff}* did not exceed 5 MW ERP. An even greater decrease in the power of the PW radiation passing into the upper ionosphere in this session was affected by the presence of an E_s layer with a critical frequency up to 4 MHz. Therefore, vertical sounding ionograms showed that development of E_{spread} was observed after PW turn on, which indicates the generation of artificial plasma density irregularities in the E_s layer with $l_\perp$ on the order of several hundred meters. From this, we can conclude that, in addition to the expected effect of partial screening, an additional nonlinear absorption of the PW energy in E_s should have been associated with its nonlinear interaction with the plasma. Taking into account all of the above, the value of the reduced PW power should be estimated as not higher than 3 MW ERP. At such a low power P_{eff}*, as expected, the generation of an artificial layer of F_{spread} on ionograms of the vertical sounding was not observed, determined by the generation of intense medium-scale ionospheric irregularities with $l_\perp \approx$ 0.5–2 km as a result of the development of the self-focusing instability of a powerful e–m wave in IDV$_c$, as well as the anomalous absorption effect (AA), associated with the generation of small-scale irregularities with $l_\perp \leq$ 50 m because of the development of the thermal (resonant) parametric instability; the scattering of *O*- and *X*-mode probing waves in their own modes was also not observed from irregularities with $l_\perp \approx$ 100–200 m [2,5,6]. Altogether, this shows a low level of AIT development. However, as follows from Figure 3, even under such experimental conditions and with such a weak interaction of PW with the ionospheric plasma, D-90 registered AIEE in the energy range E_1 = 40–130 keV with a sufficiently high flux density of $F(1) \approx 3 \times 10^3$ el/(cm^2·s·sr); only slightly above the detection threshold, electrons were registered with energies E_2 = 130–287 keV with $F(2) \approx 2 \times 10^2$ el/(cm^2 s sr). In this session, the southern boundary of recording of natural auroral precipitation was at a latitude of ~62° N, near which the presence of AIEE could still be observed.

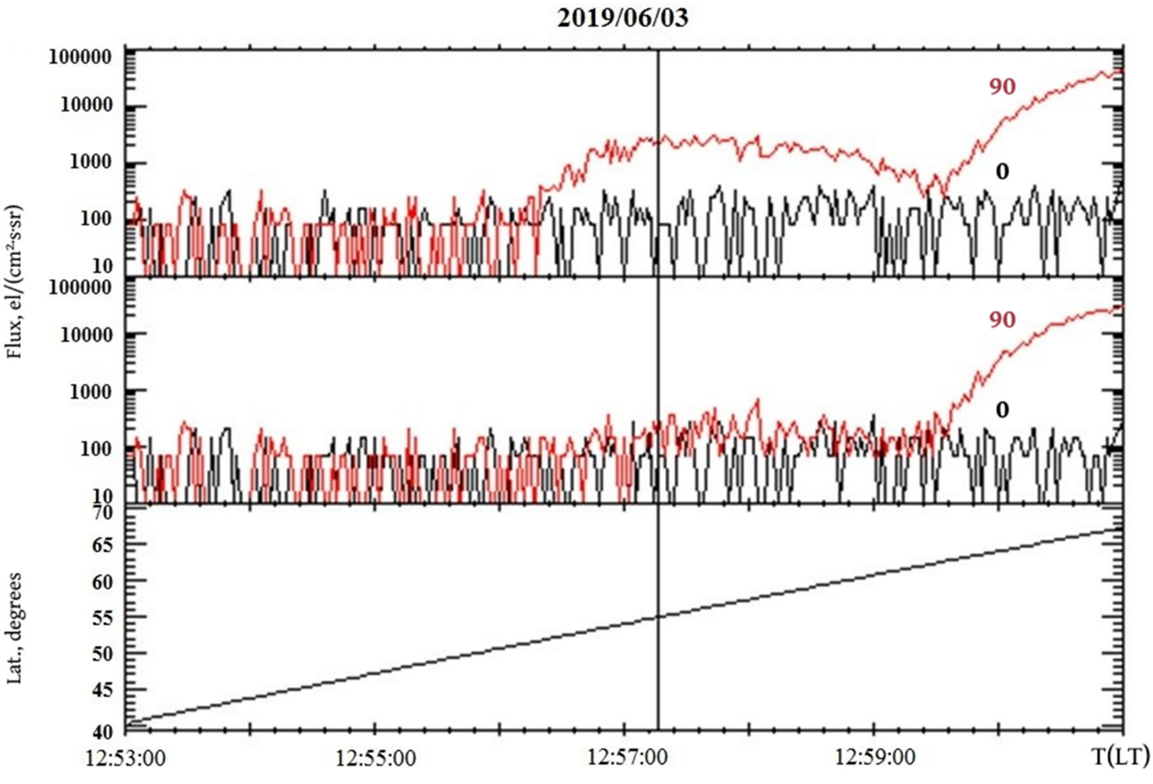


Figure 3. An example of the registration of AIEE performed on 3 June 2019 using the NOAA-19 satellite. The two upper panels of the figure demonstrate the intensity-time dependences of energetic electron fluxes measured with D-90 and D-0, marked as 90 and 0, for the energy range E_1 = 40–130 keV (**top panel**) and E_2 =130–287 keV (**middle panel**). The **lower panel** shows the variation of the latitude of the satellite's orbit with time. The vertical line near T = 12:57:12 LT marks the time of the satellite's flight through the center of the HF-disturbed magnetic flux tube.

On the basis of all experimental data obtained, it can be concluded that the AIEE intensity is determined to a greater extent by the level of filling the radiation belt with energetic electrons than by the AIT intensity.

The value of the flux $F \approx 2 \times 10^2$ el/(cm^2·s·sr), obtained under conditions of the daytime ionosphere, is almost two orders of magnitude lower, on average, than the flux of AIEE in the evening or late evening hours. In such a situation, AIEE could only be registered (or be detected above the threshold level) at an enhanced energetic electron content in the Earth's radiation belt after a burst of geomagnetic activity.

2.4. Energy Characteristics of AIEE

The results of experimental studies considered in this paper make it possible to estimate the total power introduced into the ionosphere of each hemisphere during the artificial injection of energetic electrons from the Earth's radiation belt. The estimates given below take into account electrons with energies exceeding E = 20 keV, for which the maximum of their spectral density is observed at mid-latitudes [25,43,44]. On the basis of the available data, the power law of the spectrum for electrons with $E \geq 20$ keV is assumed with the value of the spectrum index ~1 and ~2.5, respectively, for the night and midday hours of measurements. It is also believed that the measurements are carried out under optimal conditions for ionospheric plasma heating with a sufficiently high content of energetic electrons in the Earth's radiation belt after previous geomagnetic disturbances, when the artificial injection is still at a sufficiently high level, which is actually unknown to us and can strongly change from heating session to session and from day to day. Knowing the characteristics of energetic electrons injected as a result of the modification of the ionosphere by powerful HF radio waves, and assuming dimensions of their injection areas on the order of 500 km × 1000 km = 5 × 10^{15} cm^2 in the northern and 500 km × 1500 km = 7.5 × 10^{15} cm^2 in the southern hemispheres, while also taking into account the severalfold higher injection intensity in the southern hemisphere, it is possible to estimate the total power introduced by these electrons into the ionosphere. The results presented below are, of course, estimates in nature, since, as noted above, many factors have a strong influence on the injection intensity, which is difficult to take into account correctly.

According to the estimates made from the data obtained with the NOAA satellites under quiet geomagnetic conditions in the morning and early evening hours (or at times close to the times of sunrise and sunset) using optimal modification of the ionosphere by high-power HF radio waves with $P_{\text{eff}}^* \approx 20$ MW, the power introduced into the northern hemisphere by energetic electrons is about 0.3–1 kW. It can reach a value of 3–10 kW under disturbed geomagnetic conditions with increased content of energetic electrons in the Earth's radiation belt. In the midday hours, this power under quite ionospheric conditions does not exceed, as a rule, 0.1 kW. It should be emphasized that measurements in the early evening and especially in the daytime are carried out with a high level of the regular absorption of the PW energy in the lower ionosphere, when low-intensity AIT develops. In this case, as noted earlier, intense injection of energetic electrons can be solely observed at a high level of filling the Earth's radiation belt with such electrons.

On the basis of the results of measurements of the spectral characteristics of the injection for electrons with energies $E \geq 20$ keV at night in quiet geomagnetic conditions and under the optimal conditions for the interaction of PW with ionospheric plasma, estimation of the total power of high-energy electrons injected from the Earth's radiation belt into the northern hemisphere can be up to 20–50 kW; under disturbed geomagnetic conditions, the injection power can be several times greater, up to 100–200 kW. In the southern hemisphere, the power introduced into the ionosphere by artificially injected electrons somewhat exceeds the above values, amounting to ~150 and ~600 kW, respectively, under quiet and disturbed geomagnetic conditions. Then, under conditions just after strong geomagnetic activity, the total power introduced into both hemispheres can be up to 800 kW or even more. Such a large power injected into the Earth's ionosphere by the energetic electrons is on the order of the HF power 500–700 kW generated by the SURA facility transmitters or even slightly exceeds it. Such a result can be considered as an indicator of the possible strong influence of the modification of the mid-latitude ionosphere by high-power HF radio waves on ionospheric–magnetospheric coupling.

The conclusions made in Section 2 clearly demonstrate that AIEE, owing to its high energy and the possibility of its application under various geophysical conditions, can be successfully used to influence processes occurring in the magnetosphere and for studying their properties. In addition, it can also be successfully used as a powerful independent source for the generation of secondary disturbances in the ionospheric plasma and in the neutral atmosphere. It is important that, in this case, the region of secondary turbulence generation extends far beyond the IDV_c dimensions.

It is possible to estimate the energy injected by energetic electrons from the Earth's radiation belt into the ionosphere when it is modified by high-power VLF radio waves radiated by ground-based VLF transmitters. The first such estimates were made using the VLF station NAA (Washington, DC, USA), the effective radiation power of which is about 1.8 MW. In these experiments, the S81-1 satellite measured precipitated electrons in an energy range 2–1000 keV by means of an onboard electron spectrometer [37]. The measurements were carried out on 17 August 1982 in the morning hours under conditions of an increased level of geomagnetic activity. They showed that an energy flux *F*, introduced in the northern hemisphere due to AIEE, was about 10^{-4} ergs/cm^2·s (or ~10^{-11} W/cm^2). Estimating the area of energetic electron precipitation as $S \approx 300 \times 300$ km^2 [37], we obtain the value of injected VLF power of ~10 kW, which is close to estimations made for the SURA facility, although its HF-generated power was more than 2.5 times lower than the VLF-generated power for the NAA station. From this, we can conclude that the efficiency of HF-stimulated injection using CW pumping is somewhat higher than for VLF stations with close ERP.

In experiments with the DEMETER satellite with the powerful VLF station NWC (Sydney, Australia) [45], it was stated that, due to the electron and ion heating, the generation of strong plasma temperature and density variations can be observed over the VLF transmitter, as well as the precipitation of energetic electrons. It was also shown that strong plasma perturbations are induced in the ionosphere MC to NWS [46].

3. Mechanisms of Possible Action of AIEE on the State of Ionized and Neutral Components of the Earth's Atmosphere

In this section, it is considered how energetic electrons injected into the ionospheric plasma because of the modification of the ionospheric F_2 region by high-power HF radio waves can affect the state of the ionized and neutral components of the Earth's atmosphere, as well as any related consequences.

3.1. Additional Ionization of the Earth's Atmosphere by AIEE

It is known (see, for example, [24,25,43,47]) that electrons with $E \approx$ 20–200 keV, injected into the atmosphere, are strongly absorbed at 60–100 km heights and do not return to the outer ionosphere and magnetosphere. In particular, this gives us grounds to talk about the *precipitation* of energetic electrons into the ionosphere. Due to such an injection, higher-energy electrons penetrate into the *D* and *E* ionospheric regions, causing additional ionization of neutral atoms and molecules in the Earth's atmosphere. This leads to an increase in the plasma concentration in the lower ionosphere at heights of about 70–90 km and, as a result, an increase in radio wave absorption in LW, MW, and HF bands up to 10–20 dB, especially under disturbed geomagnetic conditions. Under natural conditions, the effect of the additional ionization of the lower ionosphere by energetic electrons during an increase in the level of solar activity is easily registered using various diagnostic tools [25,47]. In [48], it was shown that the fluxes of precipitating electrons with energies higher than 40 keV vary within wide limits at geographic mid-latitudes similar to the changes in the radio wave absorption, demonstrating good correlation between the level of energetic electron fluxes and the value of f_{min} on ionograms ($f_{min} \approx$ 1–3 MHz is the minimum frequency registered in *D* and *E* regions for typical ionosondes). During the artificial injection of energetic electrons, when the modification of the ionosphere by the high-power HF radio waves radiated by the SURA facility is employed, the effect of the MW and HF wave absorption was well observed in experiments [27,28], in which the suppression of *O*- and *X*-mode traces on ionograms at their low frequencies, corresponding to the reflection of sounding waves from *D* and *E* ionospheric layers, as well as the decrease in the intensity of multiple reflections of sounding waves on ionograms in a wide frequency range, was observed by means of the vertical ionosonde located near Kazan, 180 km east of the SURA facility. It is clear that the region of manifestation of the ionospheric effects related to the additional ionization has to be observed in the zone of the artificial injection (precipitation) of energetic electrons from the Earth's radiation belt into the ionosphere.

Registration of the effect of AIEE with the help of the Kazan vertically radiated ionosonde, in contrast to satellite measurements, makes it possible to obtain some information not only about the conditions for the appearance of the atmosphere additional ionization and the size of the artificial injection region, but also, importantly, about the characteristic times of development and decay of such phenomena. It was stated that, in the evening and at night, the characteristic time for the development of absorption of ionosonde signals due to the injection of energetic electrons after the first of PW turn on (or under the "cold start" conditions) varies from several minutes to 10–12 min; however, such absorption begins to be detected much more quickly (within 1–2 min) after PW is switched on in a periodical mode of pumping, if the pause between PW pulses does not exceed 10–15 min. Note that the time of 10–20 min corresponds to the decay time of the additional ionized plasma change going from the HF-disturbed ionosphere to its preheating state at about 80 km height [49]. It was found that, for sufficiently short times of PW radiation with short off intervals (for example, when the facility operates in a cyclic mode [1–5 min on, 1–5 min off] or [$\pm$(1–5 min)] for brevity), a superposition of the effects of accumulation and aftereffect from different PW pulses is registered. The results obtained allow us to conclude that the evolution of plasma disturbances diagnosed during measurements around times up to 10–20 min after PW turn off is determined not only by their decay processes and the plasma removal from the IDV_c due to its natural drift, which are usually taken into account, but also by the temporal evolution of the additional ionization of the ionospheric plasma.

Unfortunately, measurements by means of typical ionosondes, due to the high nonlinear and noncalibrated nature of their receiver-recording path, do not allow conducting quantitative measurements of the radio wave absorption value in the lower ionosphere and their evolutionary characteristics. Therefore, we are not able to obtain the necessary information about the real magnitude of the increase in plasma concentration in the lower ionosphere during its heating by powerful HF radio waves. The estimates showed that, under quiet ionospheric conditions, this increase can reach tens of percent; they strongly depend on both PW power and ionospheric conditions during experiments. According to available estimates (see, for example, [50]), such an increase in plasma concentration in the mid-latitude *D* region of the ionosphere by 10% at 80 km height takes place at a flux density of 100 keV electrons with $F \approx 10^3$ el/(cm^2 s) and 60% with $F \approx 10^5$ el/(cm^2 s). Notice that the maximum increase in the plasma concentration is observed at an initial stage of geomagnetic substorm recovery.

It was shown in [50] that, at heights $h \leq 120$ km, the additional artificial ionization of the atmosphere by energetic electrons injected into the ionosphere during the operation of the SURA facility can be detected at a distance up to 1000 km or more from the facility. In this case, to ensure the required degree of ionization of the plasma at lower ionosphere heights, the density of the electron flux with energies $E \approx 100$ keV should be greater than 10^3 el/(cm^2·s). From this, it directly follows that the total power contributed by energetic electrons to the Earth's ionosphere in the northern hemisphere is W $\geq$ 170 kW. This estimation is in good agreement with the similar estimation given in Section 2.4.

The results obtained in this paper about the AIEE features and their influence on the lower ionosphere allow us to interpret the hitherto unexplained effect, which was revealed in the first heating experiments at the facility in Platteville (CO, USA) in measurements of the HF-induced absorption of radio waves in the ionospheric *D* region [51]. In this work, it was demonstrated that, after long-term ionosphere heating by high-power radio waves (of about of 10 min), a long-term (up to 10 min) relaxation of the absorption of probe radio waves in the lower ionosphere was observed. Such a long-term relaxation has never been registered for short (40 ms) PW radiation pulses, for which the characteristic growth and decay times of absorption in the *D* region were shorter than 40 ms, corresponding to the typical results of measurements under natural conditions. In addition, the heating of the ionosphere by high-power *O*-polarized radio waves was more efficient compared to *X*-mode heating in terms of obtaining a stronger absorption of probe radio waves, although the effect should be the opposite in the case of the ohmic plasma heating [40]. These results did not fit into the framework of the accepted ideas about the modification of the lower ionosphere by powerful HF radio waves. It has now become clear that such results are easily explained taking into account the additional ionization of the lower ionosphere by AIEE. The data obtained in these experiments demonstrate also that the AIEE absorption of radio waves in the lower ionosphere exceeds the absorption caused here by the ohmic heating of the plasma by high-power radio waves. However, this fact was never taken into account in digital models used for the HF-pumped lower ionosphere.

In addition to those noted above, in experiments at the Platteville facility, it was found that, when the ionospheric F_2 layer was heated by powerful HF radio waves, development of a sporadic E_s layer was observed in the morning at ~90 km heights. This phenomenon in [52] was associated with the HF-induced injection of energetic electrons from the Earth's radiation belt into the ionosphere. The nature of this phenomenon is currently not clear, and new research is required to clarify its essence. It is possible that the formation of E_s is associated here with the generation of a vortex component of the electric currents at ionospheric heights due to the development of artificial large-scale plasma density irregularities [53,54]. Their closure in the ionosphere *E* region, at the heights of the dynamo region, is usable for *E* region modification.

3.2. Generation of Plasma Disturbances in the Outer Ionosphere and in the Ionosphere Magnetically Conjugate to IDV$_c$

Measurements of the properties and characteristics of plasma disturbances in the HF-disturbed magnetic flux tube in the outer ionosphere and in the region MC to the IDV$_c$ were rather rarely performed at the SURA facility. It is only possible to indicate a few publications that present the results of such studies. In [14], the influence of the PW operation on the passage of VLF waves (whistlers) to MC ionosphere and back was studied; in [30], the generation of artificial plasma disturbances and ELF–VLF radiations at 960 km heights was registered in a region of 500–700 km in size using equipment placed onboard the Kosmos-1809 satellite, in the same regions where the development of plasma density irregularities with their scale lengths along the satellite orbit ~ 80 km was observed; in [15], using the equipment placed onboard the Interkosmos-24 satellite, the generation of VLF waves was detected at altitudes of 500–1000 km with a maximum of their intensity at frequencies of 8–10 kHz, when the satellite crossed an HF-disturbed magnetic flux tube; in [16], the features of the generation of ELF and VLF waves were studied using the equipment placed onboard the French microsatellite DEMETER. In these studies, the generation of VLF waves was explained by the transformation of lower-hybrid plasma oscillations, excited by the development of the thermal (resonance) parametric instability in the interaction region of a powerful *O*-polarized radio wave with ionospheric plasma into a whistler propagation mode (into VLF waves) due to their scattering from small-scale plasma density irregularities, which are also generated during the development of this instability. Such a mechanism was noted above. Lastly, in [28], with the help of equipment placed onboard the DEMETER satellite, in the ionospheric region MC to the

IDV_c over the SURA facility, variations in the electron concentration δN_e and temperature δT_e with their relative values up to 10% and 2–3%, respectively, were first registered in heating experiments. The scale- length of these variations was about 90 km along a satellite orbit. It was found that such artificial variations in δN_e and δT_e were observed only under conditions when intense AIEE from the Earth's radiation belt into the ionosphere took place in this region. Therefore, it can be assumed that their generation is determined by the presence of large fluxes of energetic electrons. Since energetic electrons are simultaneously injected into the ionosphere of both hemispheres, it would appear reasonable that they can cause the development of similar plasma density and temperature perturbations in them. It is possible also that the enhancement of large-scale natural ionospheric irregularities, already existing in the outer ionosphere, could be observed in these measurements.

In support of the conclusion made about a possible connection between the generation of plasma density disturbances and the precipitation of energetic electrons from the Earth's radiation belt, we highlight [55], in which such a connection was revealed for the generation of natural irregularities in the ionospheric F_2 layer. The development of a natural intense radio aurora upon intrusion of energetic electrons into the ionosphere was also discussed in [56]. It is quite reasonable to expect the development of similar processes in the case of intense artificial injection of energetic electrons into the ionosphere from the Earth's radiation belt, stimulated by heating of the ionosphere by powerful HF radio waves.

In concluding this section, we note that the numerical simulation of plasma modification in HF-disturbed magnetic flux tube over its entire length, performed on the basis of the SAMI2 digital model for the mid-latitude ionosphere (see, for example, [57]), showed that (a) heating of a magnetic flux tube is more efficient at a lower background plasma concentration and is accompanied by the formation of the duct with an increased plasma density, (b) heating of an entire tube lasts from several tens of minutes to 1 h and the relaxation of plasma disturbances in it lasts up to 3 h, strongly dependent on geophysical conditions, and (c) in the MC ionosphere, the magnitude of the relative variations in the plasma density greatly exceeds the variations in the electron temperature. Verification of these numerical simulations has yet to be performed in ionospheric experiments.

3.3. Generation of Microwave Electromagnetic Emissions under Influence of AIEE: Effect of These Emissions on Features of Neutral Components of the Earth's Atmosphere at Ionospheric, Mesospheric, and Tropospheric Heights

In recent years, in the NIRFI NNSU, a study was conducted of the generation of microwave electromagnetic emissions at ionospheric heights with wavelengths from millimeters to decimeters. These emissions were produced under an influence of AIEE, which is a result of the modification of the ionospheric F_2 region by means of powerful HF radio waves radiated by the SURA facility. Such electromagnetic emissions are similar to the natural sporadic microwave radio emissions generated in a wide range of centimeter and decimeter wavelengths, the intensity of which was tens of degrees in the brightness temperature [58–60]. These natural emissions correlated with bursts of solar activity and associated geomagnetic disturbances. The nature of these emissions was explained in [61] on the basis of the "Rydberg mechanism" of the radiation of neutral atoms and molecules at ionospheric heights. This mechanism includes electron transitions between highly excited (with principal quantum number $n > 10$) Rydberg levels of neutral atoms and molecules of the ionosphere due to their collisions with high-energy solar particles. Energy transitions from Rydberg states fill the entire range of the electromagnetic spectrum of upper atmospheric emissions from decimeter radio waves to hard ultraviolet (UV) radiations. A similar mechanism, but under the influence of superthermal electrons accelerated in the ionospheric plasma modified by powerful HF radio waves, was used in [62] to interpret the detected artificial electromagnetic radiation HF-induced in the decimeter wavelength range.

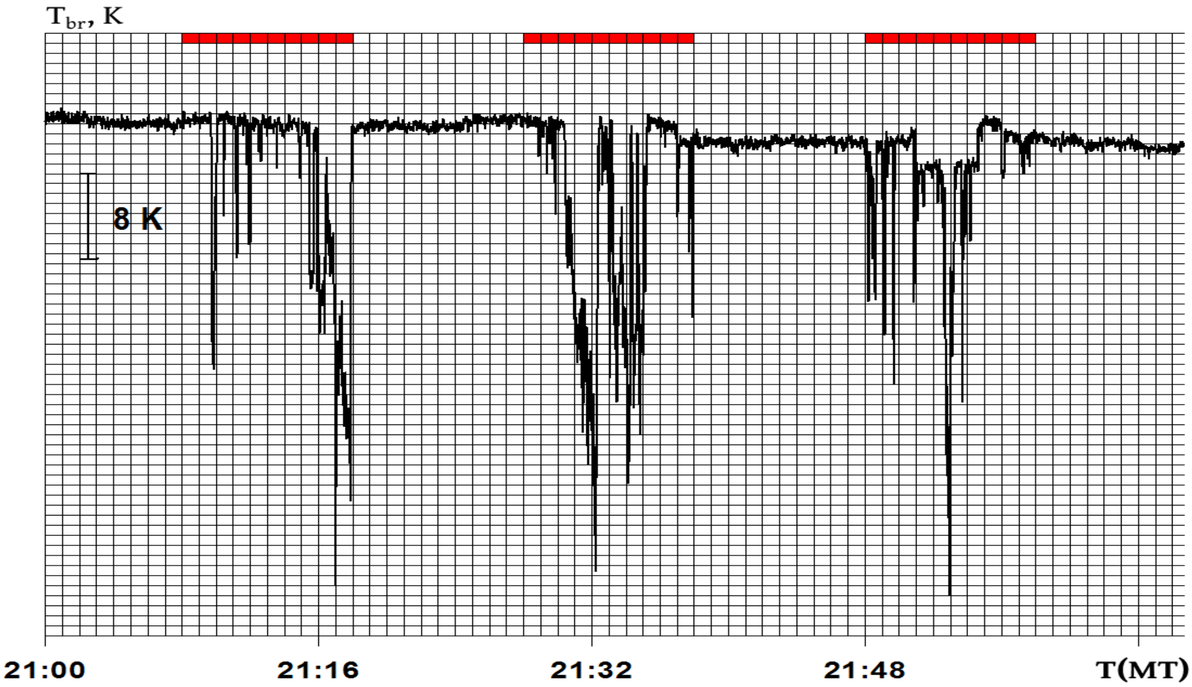
The natural mechanism for the formation of Rydberg states at ionospheric heights includes the processes of photoexcitation upon absorption of solar hard UV radiation, excitation upon collision of energetic electrons of solar flares with atoms and molecules of the Earth's atmosphere and energetic electrons precipitating from the Earth's radiation belts, and the process of dissociative excitation. Since, at ionospheric heights, the ionization potentials of the main atoms and molecules of the atmosphere N_2, O_2, and O are 15.5, 12.2, and 13.62 eV, respectively, which is much less than the energy released in these processes, the energetic electrons can easily excite atoms and molecules up to pre-ionization levels and even ionize them. Furthermore, during the transition of Rydberg atoms and molecules to lower states, a wide spectrum of electromagnetic waves is produced. According to experimental data [58–60], the intensity of this emission in the decimeter wavelength range is comparable to or even exceeds the typical levels of bursts of solar radio emissions during solar flares.

As follows from Section 2 of the paper, high-energy electrons with $E \approx 100$ keV can appear at ionospheric heights due to their artificial injection from the Earth's radiation belt when the ionospheric F_2 region is modified by powerful HF radio waves. These electrons, because of multiple collisions with atoms and molecules of the atmosphere, can also transfer them to highly excited Rydberg states, as in the case of solar radiation. At the next stage, as in the natural mechanism considered above, their transitions to lower energy states with the emission generation in a wide spectrum of electromagnetic waves occur.

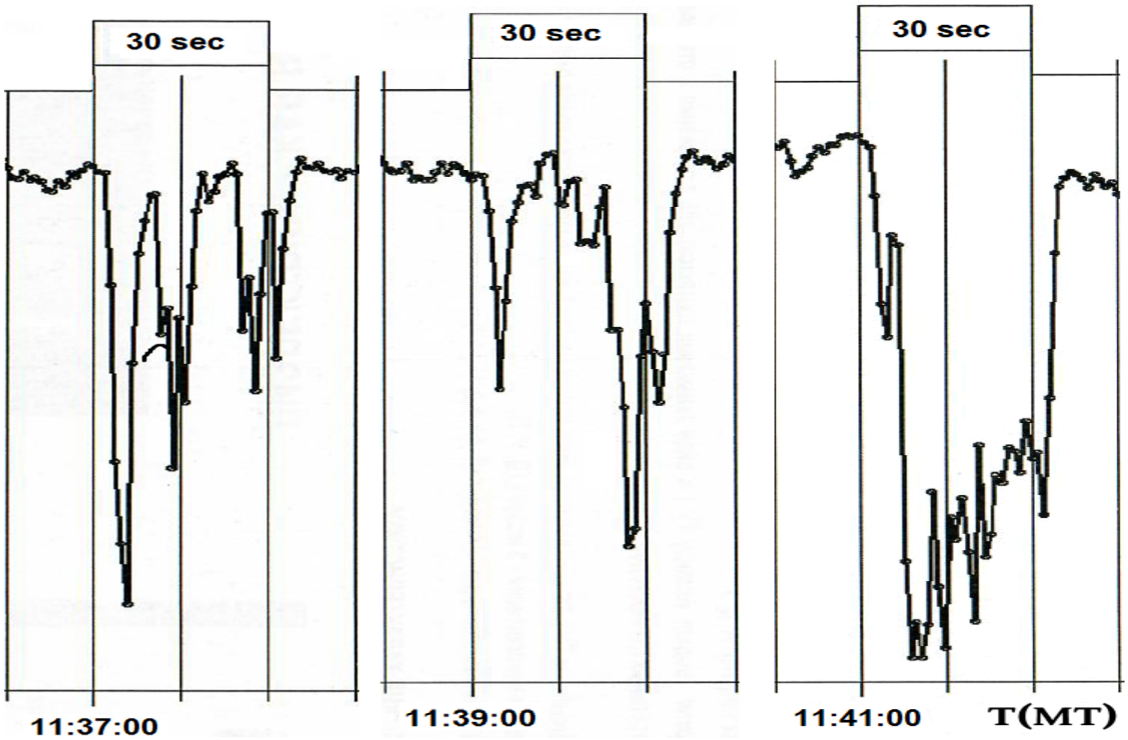
The study of the characteristics of the microwave emissions, generated at ionospheric heights because of the modification of the ionosphere by the high-power HF radio waves radiated by the SURA mid-latitude heating facility, was carried out in 2014–2018 [63]. The facility radiated *O*-polarized waves in a frequency range 4.3–6.8 MHz with P_{eff} = 80–180 MW ERP and [±(10–15 min] duty cycle. In most experiments, the HF beam was directed to the "magnetic zenith", at the angle of 12° to the south of the vertical, in order to increase the efficiency of AIT generation. Measurements of the intensity of the microwave electromagnetic emissions generated at ionospheric heights were carried out using spectral radiometric receivers of the modulation type (radiometers) tuned to frequencies f_1 = 1°–2° GHz and f_2 = 574 MHz; the radiation patterns of their received antennas were directed to IDV_c. The receiving complex was co-located with the SURA facility.

The conducted experiments made it possible to detect the Rydberg radiations of atoms and molecules HF-induced in the upper atmosphere in the decimeter wave range. Their peak intensity in the brightness temperature was $\Delta T_{\text{br}} \approx$ 10–26 K in the morning and afternoon hours and up to $\Delta T_{\text{br}} \approx$ 30–43 K in the late evening and night hours. The values of ΔT_{br} are in good agreement with the results obtained in the measurements of the intensity of natural sporadic ionospheric emissions registered during solar flares [58–60], therefore, they significantly exceed the results of measurements of the intensity of artificial radio emissions from the ionosphere found in [62].

Figure 4a shows a fragment of the recorded microwave emission in a spectral channel band 1450 ± 8 MHz on the scale of brightness temperatures, increasing downward in the figure. The measurements were carried out at the PW frequency f_{PW} = 4300 kHz on 28 March 2014 in the late evening hours from 21:00 to 22:07 MT, or in the ionosphere unlit by the Sun when a low level of the regular absorption of radio waves was observed in the lower ionosphere. In this session, PW was cycled [±10 min]. The time intervals of the SURA facility operation are shown on the time axis with bold line segments. The maximum peak intensity of the Rydberg radiation with $\Delta T_{\text{br}} \approx 43$ °K was registered in this experiment. From the measurement data presented in Figure 4a, we can also conclude that the intensity of the detected emission fluctuates strongly in time. Furthermore, after the start of facility pumping in the mode [±10 min] at 20:28 MT, the microwave emission appears only in the third pulse of the PW radiation (at 21:15 MT, in 7 min after PW turn on at 21:08 MT). In the fourth pulse, this delay is only ~2 min, and the emission begins to be registered almost immediately after PW turn on in the fifth pulse of pumping. It should be pointed out that similar dynamics of the development of the absorption was observed for low-frequency ranges of an ionogram in [26,28], associated with the additional ionization of the atmosphere due to AIEE. Therefore, these times can be attributed to the appearance of energetic electrons.



(a)



(b)

Figure 4. (**a**) Intensity of the microwave radio emission of the atmosphere in the band of the spectral channel f = (1450 ± 8) MHz on 28 March 2014. (**b**) Intensity–time variations of the microwave emission at a frequency f = 1450 MHz, when the ionosphere was modified from 10:01 until 12:50 MT in HF mode [±30 s], for 14 min, followed by a 16 min pause in the SURA facility operation. In the figure, oscillograms are shown for the microwave emission intensity in T_{br} with 1 s resolution for the seventh, ninth, and eleventh pumping pulses beginning at 11:37, 11:39, and 11:41 MT, respectively.

The generation of the microwave emissions makes it possible to measure the lifetime of the artificially injected energetic electrons as a function of their decay time after PW turn off. Such studies were performed on 29 August 2018 from 07:01 until 09:50 UT (10:01–12:50 MT, i.e., at hours close to noon), 3 days after the start of strong geomagnetic activity with $K_p \approx 7$. The powerful *O*-polarized radio wave was radiated with $P_{\rm eff}$ = 45 MW ERP at a frequency of 4300 kHz ($f_{0F2} \approx 5$ MHz) with the PW beam tilted 12° south of the vertical. The geomagnetic conditions were quiet judging by the index $K_{\rm p}$ = 1–2, or slightly disturbed judging by the index *AE* = 100–200 nT. All this makes it possible to estimate the reduced effective radiation power as $P^*_{\rm eff} \leq 5$ MW. Under such conditions, as expected, the ionograms of the ionosonde placed at the SURA facility do not show the development of artificial $F_{\rm spread}$, indicating a very weak level of interaction of the powerful HF radio wave with the plasma of the ionospheric F_2 layer, as well as the development of low-level AIT. A distinctive feature of this session is also that the Earth's radiation belt should have a high degree of filling with energetic electrons due to the high level of geomagnetic activity observed just before the measurements.

Figure 4b shows three fragments of recording the intensity of the microwave emission at the frequency f = 1450 MHz, when the ionosphere was modified in the PW mode [±30 s] for 14 min, followed by a 16 min pause in the SURA facility operation. Such a 30 min periodicity of the PW radiation was repeated six times during the considered measurement session from 10:01 until 12:50 MT. Figure 4b demonstrates oscillograms of microwave emission with 1 s resolution for the seventh, ninth, and 11th pumping pulses beginning at 11:37, 11:39, and 11:41 MT, respectively. The superimposition of the time scheme of the PW radiation on the received oscillograms of the microwave emission was performed visually, according to the principles that the emission does not appear before PW turn on and that they begin to disappear only after turn off. The estimates made show that the alignment accuracy was not worse than ±1 s. It follows from these and other measurements that, in the first 2–3 pulses of such a 30 s scheme of PW radiations after a 16 min pause, the intensity of the generated microwave emission was less than in subsequent pulses, and only the most powerful emission bursts appeared in them. The received oscillograms also demonstrate that, starting from the third pulse of the PW radiation, the time of appearance of the microwave emission was 3–4.5 s (4.5–7.5 s for the first two pulses), while the time of their disappearance was 4.5–6 s. These times are in agreement with the results of measurements and a numerical simulation of the characteristic times of development and relaxation of precipitation of energetic electrons from the Earth's radiation belt when modified by signals from powerful VLF transmitters [37,64]. In the latter experiments, an operating mode of the NAA powerful VLF transmitter, radiated with $P_{\rm eff}$ = 1 MW ERP, was [3 s–on, 2 s–off]. Similar conclusions can also be drawn from the measurements [17,34,65]. Unfortunately, experiments similar to the above on the generation of ELF/VLF radiations due to the Getmantsev effect could not be carried out at the SURA facility due to the low amplitude of horizontal electric currents in the mid-latitude dynamo region (as a rule) and, consequently, the low efficiency of the generation of such VLF radiations.

From the data presented in Figure 4b, we can also conclude that the intensity of the flux of the electromagnetic microwave emissions stimulated due to ionosphere modification by the powerful HF radio waves had a pronounced pulsating character with a pulse duration of 6–15 s. It is conceivable that high irregularity of spatial distribution of energetic electron flows takes place at ionospheric heights in the form of separate energetic electron beams with dimensions of about of 300–500 m in the direction transverse to the geomagnetic field.

Since microwave components of the Rydberg emissions propagate in the Earth's atmosphere almost without loss (except for a few distinguished absorption frequency bands), they can exert an influence on the processes taking place in the ionosphere, mesosphere, and troposphere. At tropospheric heights, this radiation can affect weather–climatic processes through the trigger mechanism of solar–magnetospheric–weather–climatic relationships [66–68]. This leads to an increase in the concentration of water clusters in the troposphere, forming from water vapor under the action of microwave emissions, which consequently has an influence on the development of atmospheric clouds. The existence of the impact of solar and geomagnetic activity on the properties of the troposphere and the surface layer of the atmosphere was discussed in detail, for example, in [24,69–72].

The results of the conducted experiments allow us to state that a new channel of influence on the Earth's neutral atmosphere through the generation of microwave emissions has been revealed in heating experiments. This is based on emissions of neutral atoms and molecules excited to Rydberg states by the energetic electrons artificially injected from the Earth's radiation belt to ionospheric heights. Therefore, AIEE can be considered a new HF-induced source, which can produce a secondary artificial ionospheric turbulence. It is important to emphasize that the intensity of HF-induced microwave radio emissions is comparable to the intensity of natural radio emissions generated during solar flares. The presence of such a powerful source, which is able to act upon the Earth's neutral atmosphere, opens up great opportunities for its application in heating experiments.

In conclusion, it should be noted that the collision of energetic electrons with atoms and molecules in the Earth's atmosphere can produce *X*-rays and gamma rays [24], which can transport electron-injected energy to even lower altitudes in comparison with HF-injected energetic electrons. Consideration of the effects associated with their influence on the atmosphere is outside the scope of this paper.

3.4. Influence of Ionospheric Plasma Heating by Powerful HF Radio Waves on the Ozone Content at Mesospheric Heights

The Earth's mesosphere, located at 50–90 km heights, is still a poorly understood part of the middle atmosphere. A distinctive feature of this region is a high density of neutral particles in a weakly ionized plasma, in which there are various positive and negative ions and heavy cluster ions, formed as a result of complex ionization and recombination physical–chemical processes. With the existing diversity and complexity of these processes, the number of methods for studying its properties and characteristics is very limited. Therefore, the search for new opportunities to study the mesospheric properties remains an urgent task today.

In this section of the paper, we briefly consider the results of ionosphere pumping by high-power HF radio waves on the characteristics of microwave emissions in the ozone line with its spectral maximum frequency of 110,836.04 MHz. In this case, ozone acts as an impurity; changes in its properties demonstrate the effect of ionosphere heating on the state of neutral components of the Earth's atmosphere at mesospheric heights of 50–60 km, at which the radiation of the mesospheric ozone gives the largest contribution to its spectral maximum. These experiments were carried out at the SURA facility in 2008–2016 using the method of ground-based microwave radiometry based on measuring the intensity of atmospheric thermal radiation in the ozone rotation transition line with subsequent analysis of the shape of its spectrum. In [73,74], the measurement technique, its technical characteristics, and the accuracy of measurements were described.

In the first ozone measurements, a noticeable decrease in the intensity of microwave emission was found at frequencies near the maximum of the ozone spectral line (110,836.04 MHz) [73,74]. The SURA facility radiated a powerful HF radio wave, as a rule, at the lowest possible frequency f_{PW} = 4300 kHz, since it was initially assumed that the heating of the lower ionosphere should have a major impact on the processes in the mesosphere. To heat the ionosphere, radio waves of both *X*- and *O*-polarizations were used with P_{eff} = 80 MW ERP. The PW radiation was cycled [15 or 30 min—on; 15 or 30 min—off]; such a scheme was determined by the 15 min time interval necessary for complete measurements of the ozone spectral line.

In Figure 5, an example of one measurement session carried out on 27 March 2011 from 07:00 until 21:00 UT (from10:00 till 24:00 MT) is shown. The horizontal lines show the averaged values of the spectral intensity of the received emissions obtained in measurements made before and after an ionospheric plasma modification conducted under daytime conditions, as well as the results from night measurements conducted without ionosphere pumping. The time of sunset for the considered day of measurements was 18:35 LT. The dotted lines show the decrease in the emission intensity in the ozone line during each PW pulse and its inverse increase during every pause in pumping.

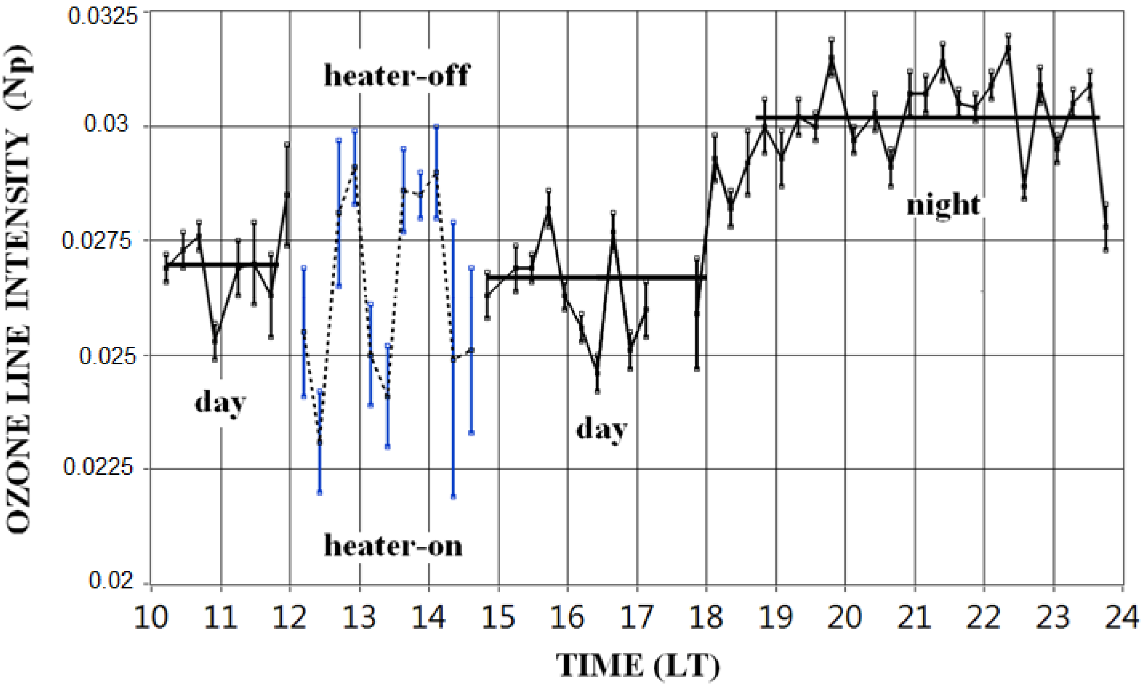


Figure 5. Diurnal variations of the microwave spectral intensity in the ozone line at its resonance frequency. The horizontal lines on Figure 5 show the averaged values of spectral intensities obtained in the daytime before and after séances of pumping, as well as under nighttime conditions. The sunset time for this experiment was 18:35 LT ($T_{LT} = T_{MT}$). Dotted lines show variations of the ozone line spectral intensity during PW being switched on, (points with lower intensities) and during PW being switched off (points with higher intensities). The measurements were performed on 27 March 2011. The intensity is expressed in nepers (N_p) relative to the intensity of solar radiation at a height of the upper boundary of the neutral atmosphere.

The results of the measurements made it possible to conclude that (a) heating of the ionosphere leads to a noticeable decrease in the ozone emission intensity at small frequency shifts ($|\Delta f| \leq 40$ MHz) relative to the center frequency of the ozone line, whereby a smaller detuning value led to a greater decrease, (b) the decrease in the integrated intensity of microwave emissions in the ozone line, averaged over all measurement sessions, was ~10% (18% for the session shown in Figure 5), (c) the times of the decrease in the intensity of the microwave emissions after PW turn on and their recovery after the end of ionosphere pumping were much shorter than 15 min, and (d) this effect was observed not only in the HF-modified region of the mesosphere (in its PW-illuminated region), but also at a distance of ~110 km south of it [75]. It was also found in [75] that, when a powerful HF radio wave acted on the lower ionosphere, an increase in the intensity of electron density irregularities and a general increase AIT were observed starting from ~55 km heights, indicating the development of strong perturbations in the ionospheric plasma during such experiments.

When interpreting the observed decrease in the ozone line radiation intensity, it should be taken into account that the extremely low concentration of electrons in the *D* region compared to the concentration of neutrals (the degree of ionization here is ~10^{-9}) virtually eliminates the possibility of a direct influence of electron temperature rise in the electric field of a powerful radio wave on properties of the neutral component of the atmosphere. Here, an important circumstance is the detection of this effect 110 km south of the region of the modification of the lower ionosphere by high-power HF radio waves, from which it follows that the PW direct heating of the ionospheric *D* and *E* regions is not the cause of this effect.

Experimental studies carried out in recent years at the SURA facility made it possible to propose a model, related to the heating of the ionosphere, for suppressing the intensity of microwave emission generation in the ozone line at the mesospheric heights. Following [76–80], energetic electrons with $E \approx 100$–150 keV, when injected into the ionosphere, penetrate to mesospheric heights $h \approx 50$–80 km, where they, through collisions with neutral atoms and molecules, lead to the formation of nitric oxide molecules (NO) and hydroxyl molecules (HO). These molecules, reacting with ozone molecules, destroy them, thereby reducing their content at mesospheric heights. The decrease in the ozone concentration can then reach tens of percent in a wide region of space, subject to the influence of injected energetic electrons. Such a process is well known in the polar ionosphere as the nitrogen and hydrogen cycles of physical–chemical reactions affecting the ozone concentration at mesospheric heights (see, for example, [79,80]). In our case, energetic electrons with energies *E* up to 100–150 keV appear at mesospheric heights due to their artificial injection from the Earth's radiation belt when the ionospheric F_2 region is modified by powerful HF radio waves. Since the time of variations in the ozone concentration after PW turn on/off is much shorter than 15 min, the main influence should be exerted by HO molecules, which dominate at 40–60 km heights where the maximum of the ozone emission spectral line is formed. It is important that HO molecules have a short lifetime at ~50 km heights, ranging from seconds to several minutes, compared to the much longer-lived NO molecules [77,78].

To develop a detailed model of the influence of ionospheric plasma modification by high-power HF radio waves on the ozone content at mesospheric heights, further experimental and theoretical studies are required. In the experimental plan, in order to obtain necessary information, comparative measurements at different PW polarizations should be conducted; it is also necessary to determine the characteristics of the effect of ozone suppression at different times of the day, at different levels of the geomagnetic activity, and in different modes of PW pulsed radiation. It is also important to find a way to more accurately measure the values of the characteristic times for the decrease in and recovery of the emission intensity in the ozone line after PW turn on/off. This will make it possible to study in more detail the properties of the observed decrease in the ozone content at ~60 km heights during modification of the ionosphere by powerful HF radio waves, as well as to develop new methods for diagnosing the Earth's mesosphere. Heating experiments, due to their good repeatability and strict dosage of selected perturbations introduced into the atmosphere, can play an important role in solving these problems.

4. Concluding Remarks

The results presented in this paper convincingly demonstrate that the artificial injections of energetic electrons (AIEE) from the Earth's radiation belt to ionospheric heights have a strong and easily detectable effect on the characteristics of various AIT components. Such HF-induced injection and subsequent microwave emissions can be considered a powerful source for modification of the Earth's atmosphere to generate intense secondary artificial perturbations of its ionized and neutral components by employing the electron energy stored in the magnetosphere. Its power under favorable conditions for modifying the ionospheric F_2 region is comparable to the HF power generated by heating facility transmitters. It is very important that such a secondary ionospheric turbulence can be developed far from the heating facility, at a distance much larger than the dimensions of the central part of the IDV (IDV_c) as well as in the ionosphere magnetically conjugate (MC) to the IDV_c region. Some secondary turbulence properties open up wide opportunities for studying the effects of energetic electron on features of the surface layer of the Earth's atmosphere, the study of whose characteristics is still far from complete. As demonstrated in the work, some agents of such an influence are as follows:

(1) the additional ionization of atoms and molecules of the atmosphere at 60–120 km heights, which leads to an increase in the absorption of LF–MW–HF radio waves passing through this region, influencing the characteristics of physical–chemical processes in the mesosphere;
(2) the generation of artificial ionospheric irregularities at outer ionosphere heights;
(3) the change in the ozone content in the mesosphere and stratosphere, influencing the characteristics of the distribution of the solar ultraviolet radiation in the atmosphere and leading to a change in its heat balance;
(4) the generation of the microwave radio emissions, influencing the mechanisms of water vapor condensation in the surface atmosphere, including the formation of water clusters (this process is known as the condensation cluster mechanism);
(5) the perturbation of the global electric circuit due to the generation of electric currents at ionospheric heights, which can have various manifestations including cloud formation [79].

It is important that it is possible to use the PW radiation in the "continuous wave" (CW) mode to stimulate the injection of energetic electrons from the Earth's radiation belt into the ionosphere.

It should be mentioned that the authors of [12,24] considered the possibility of using the artificial injection of energetic electrons, stimulated by the operation of a heating facility, to remove them from the Earth's radiation belt if necessary. Furthermore, because the phenomenon of AIEE is usually observed in ionosphere heating experiments, any turn on of the powerful HF radio wave during measurements conducted in the upper ionosphere is accompanied by the artificial injection of energetic electrons from the Earth's radiation belt into the ionosphere. As it follows from the present paper, such an injection can significantly change the ionosphere's characteristics and conditions of plasma–wave interactions, which should be taken into account when setting up experiments and interpreting the results obtained in the measurements. Therefore, there should be clear differences in the AIT properties during the modification of the ionosphere under the "cold start" conditions and with a long sequence of radiation of high-power HF radio wave pulses, which was repeatedly observed in previous experiments.

Many other examples of the possible influence of HF-induced energetic electron injection into various regions of the Earth's atmosphere, including the impact on chemical–physical processes and climate, can be found in [43,45,63,71,72,81,82], in which possible influences of solar and geomagnetic activity on the weather and climate characteristics of the Earth's atmosphere were demonstrated. Many aspects of problems discussed in these papers have yet to be explored. Experiments connected with the modification of the ionosphere by high-power HF radio waves can make important contributions to this field of research.

In conclusion, we note that, in our paper, we did not consider the effect on the generation of HF-induced internal gravity waves (IGWs) or traveling ionospheric disturbances (TIDs) generated by periodic and pulsed pumping of the ionospheric plasma. These disturbances propagate for 1000 km or more from the heating facility and are also able to influence the features of the Earth's atmosphere. Some characteristics of both ionospheric plasma and neutral atmosphere perturbations produced by them were considered, for example, in [50,82]. On the basis of the results of the studies presented above in our paper, we can assume a new mechanism for the generation of IGWs due to periodic (with a period exceeding 10 min) or mono-pulse heating of ionospheric plasma, which may involve the artificial injection of energetic electrons from the Earth's belt into the ionosphere. In this case, the heating of the Earth's atmosphere is carried out because of the fluxes of energetic electrons and the electric currents excited by them. However, this hypothesis requires further comprehensive investigations.

It should also be noted that a separate detailed analysis also requires the results of experiments on the excitation of HF-induced electric currents in the ionospheric F_2 region modified by high-power HF radio waves, as well as their effect on the generation of AIT.

Such currents were revealed and studied in experiments at the SURA facility [53,54]. They can also contribute to the heating of the ionized and neutral components of the Earth's atmosphere. Consideration of these issues is beyond the scope of this paper and will be covered in future articles.

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