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Fundamentals of Radio-Chemical Physics of the Earth's Atmosphere

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Abstract—Basics of the radiochemical physics of the Earth atmosphere are discussed. This area of science studies the resonance interactions of the electromagnetic waves with the gaseous media containing the Rydberg molecular complexes that occupy D and E layers of the upper atmosphere during solar flares. This interaction is responsible for the distortion of the signals from the satellite groups. The radiation transitions between orbitally degenerate states of these complexes form the non-coherent additional background radiation on the radio (UHV) and infrared (IR) ranges. The radiation in these wave ranges is of primary importance in a number of fundamental researches and is widely used in some technical applications. The areas considered in this paper include: the dynamics of processes in the upper atmosphere during increase of solar activity leading to the formation of incoherent additional background radiation; the distant passive location of the soil humidity and the salinity of the ocean waters; the distant radio sounding of the electromagnetic properties of the surface layers of the Earth for determining their structure and content; the technology of efficient and uninterrupted operation of energy networks by synchronizing the measuring equipment in view of the possible failures of the satellite signals; the use of the global positioning systems as a tool for monitoring the state of the atmosphere. In the present work the description is given of the most perspective applications of the above mentioned areas of the radiochemical physics of the atmosphere whose robustness is substantially depends on the current state of the upper atmosphere. We analyze the problems that arise here and provide their specific solutions. The prospects for the development of these applications are discussed, as well as those areas of research that are just coming up.

Keywords: atmosphere, solar activity, magnetic storms, Rydberg states, non-coherent and additional background radiation, charge aerosol layers, distortion and attenuation of signals, passive and active radiolocation of the Earth atmosphere, radio astronomy, monitoring of the atmosphere, management of the electric grid

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1. INTRODUCTION

Over the past few years, researchers at the Semenov Institute of Chemical Physics (ICP) of the RAS have carried out theoretical studies of the quantum optical properties of the D and E layers of the Earth's atmosphere that manifest themselves during strong geomagnetic disturbances of the ionosphere caused by increased solar activity. Under these conditions, additional background non-coherent decimeter waveband (UHF) and terahertz (IR) radiations arise, the intensity of which is a substantially non-monotonic function of the frequency and is strongly dependent on the level of the perturbation [1–7].

The physical source of this radiation are transitions between orbitally degenerate Rydberg states, which are populated in a nonequilibrium two-temperature plasma under the action of ionospheric electrons and radiation from solar flares. An important feature of the theory describing this effect is the interaction of Rydberg atoms and molecules with molecules of the neutral medium. The orbitally degenerate states are formed by an important atmospheric process l-mixing [8].

Studies of collisional and radiative processes involving Rydberg particles began at the ICP in the early 1980s [9]. The material accumulated during this time allowed to create a new direction of chemical physics: "radiochemical physics of the atmosphere," which covers a set of physicochemical processes responsible for the generation of additional background decimeter-waveband and long-wave infrared radiations in the atmosphere disturbed by solar activity [10]. This direction brings together a variety of fundamental and applied fields, which, at first glance, are not related with each other. In fact, they are largely linked to the specific features of the propagation of electromagnetic radiation through the Earth atmosphere and of the additional background radiation produced in the lower D and E layers of the ionosphere. The results depend strongly on the state of the atmosphere, which is determined by the dynamics of the processes occurring in the atmosphere–ionosphere system [11]. Efforts of researchers are aimed primarily at clarifying the role of these processes under different geophysical conditions and at studying their impact on the environment, biosphere, operability of infrastructure elements, such as energetics, transport, communication network, banking network, etc. [12]. The main problem of their proper functioning is related to the disruption of global satellite positioning and timing systems during solar activity and magnetic storms [13].

The Earth's atmosphere is influenced by a complex set of processes due to the absorption of solar radiation, dynamic phenomena in the lower ionosphere, and seismic and volcanic activity. These factors give rise to powerful atmospheric perturbations, electric currents, electromagnetic disturbances in different spectral ranges, plasma and optical inhomogeneities, elevated level of radioactivity, and changes in the ion and molecular composition of the atmosphere [14]. Microwave emission from highly excited particles of the ionosphere, arising during solar activity also produce a negative impact on the biosphere of the Earth [15].

Knowledge of the influencing factors makes it possible to use them as indicators of catastrophic processes and to create, on this basis, the corresponding monitoring system. At the same time it is necessary to carry out the additional recearches which are connected with the high activity in the atmosphere-ionosphere system, leading to occurence of new risks. They consern with an active development of the manned and uninhabited orbital systems, aircraft (including the using height of an average atmosphere), new kinds of communication, as well as operating at altitudes.

The development of modern technology imposes stringent requirements on the accuracy of positioning and reliability of navigation systems. This is dictated by the requirements of the safety and efficiency of land-, sea-, and air-based transport facilities, as well as by the need to solve some specific problems, such as aerial photography, search and rescue of accident-damaged vehicles, synchronization of extended electrical and power lines, etc. A key issue is to identify the optical characteristics of the radiowave propagation medium responsible for signal failure during geomagnetic disturbances, leading to a worsening of the positioning and timing accuracy. However, the interest of specialists is aimed here only at improving the radio equipment without of the phenomena underlying the disruption of satellite signal researching. Many still believe that the distortion of the signal occurs in the ionosphere, at an altitude of more than 200 km above the Earth's surface and that it is statistical in nature (Klobuchar model) [16].

It was theoretically proved and experimentally confirmed that these negative phenomena occur mainly in an atmospheric layer 60–110 km above the Earth surface, being caused by the multiple resonant scattering of the satellite signal on highly excited Rydberg states populated at these altitudes [6–8, 17]. It was also found that the additional background non-coherent radiation, including microwave and IR ranges, is generated namely in this region [3–5]. For most applications, especially satellite navigation, of greatest interest is UHF radiation in the decimeter waveband. The possibility of practical use of IR radiation has been intensely explored in recent years [18].

Another subfield of radio-chemical physics of the atmosphere, a variety of applications of which have independently developed over several decades in a number of areas of science and technology, is the remote sensing of the Earth surface at a frequency of $\nu_1 = 1.4$ GHz, including ocean salinity, soil moisture content, vegetation cover state, weather forecasting, etc. Such measurements are performed in the continental regions of Europe, South Asia, and the Middle East in the framework of international SMOS programs (soil moisture and ocean salinity; European Space Agency) and the "Living Nature" program in order to control the water balance of the Earth and biological resources. In our country, these issues also receive much attention, as evidenced by the proceedings of the international conference "Probing Earth Surface with Synthetic Aperture Radars and Radiometers" (Ulan-Ude, 2013). A key issue here is to identify the source of non-coherent decimeter-band radiation, to determine how the radiation intensity depends on the state of the atmosphere, and to clarify which factors hinder its propagation in the atmosphere (charged aerosol layers in the troposphere, their hydration, etc.). This leads to an uncontrolled behavior of the measured intensity and, consequently, to difficulties in calibration of the receiving equipment. The authors of the SMOS program believe that the frequency of $\nu_1 = 1.4$ GHz is most sensitive to changes in the soil moisture content and the salinity of the surface waters of the world ocean [19]. In fact, the use of this frequency makes the signal least dependent on unaccountable confounding factors in the process of measuring these quantities [10].

Similar serious problems are encountered in radio astronomy in measurements of cosmic radiation at the frequency of 1.4 GHz by means of a array of VLA radiotelescopes spanned over a large area, the results of which turn out to be time-dependent. To interpret such results, the ionosphere is considered, according to the Klobuchara model [16], as a simple refracting layer [20] that causes an error in phase (delay time) measurements of radio wave propagation, i.e., can be thought of as a simple single-phase homogeneous medium [21]. In reality, as shown in [11], this model is trivial, so the appropriate corrections should be introduced to account for the resonant quantum optical properties of the E and D layers of the atmosphere.

A promising direction of research concerns a number of fundamental and applied geophysical problems, including meteorology, oceanography, forecasting adverse natural phenomena, etc., which are solved by means of the active radio remote sensing the Earth surface using satellite signals in the UHF band at a frequency of 1.4 GHz. These primarily include the remote determination of the electromagnetic properties of subsurface layers (up to a depth of several tens of meters) and the study of gravitational irregularities in different areas. This makes it possible to overview large areas of the Earth to detect anomalies associated with mineral deposits, as well as oil and gas fields. Active sensing enables to measure various physical characteristics of substances, such as dielectric permittivity and absorption coefficient, which depend on the nature of the substance and its density and temperature. Measurements of the properties of electromagnetic waves interacting with a substance provide information on its composition, density, and temperature [22]. However, as in the case of positioning signal propagation, the issues of the distortion and attenuation of sent and reflected signals during the passage of the Earth atmosphere are ignored, which greatly complicates and, strictly speaking, casts doubt on the correctness of the interpretation of the results. Unresolved in full remains also the problem of how processes in the lithosphere produce disturbances in the atmosphere and ionosphere [23–26].

In recent years, the most topical problem is that of the safety of operation of power grids, which potentially can be disrupted due to the distortion of GPS/GLONASS signals in periods of increased solar activity. In this paper, we analyze the possibilities of the operation of power systems at the limit of their stability, which requires a fine balance of power and a strict global control of the entire system, a complex and large-scale scientific and technical challenge. It consists in finding the most efficient way of using power lines to increase their transmission capacity, determining the exact location of failures, and foreseeing measures to ensure the synchronization of the measuring equipment with view for possible disruptions of the satellite navigation system [13, 27].

Of great interest is to use GPS/GLONASS satellite systems and the sensors of additional background non-coherent infrared radiation installed on them as a tool for studying the state of the plasma in the D and E layers of the atmosphere and monitoring its main parameters in different geomagnetic conditions. These include the altitude distributions of the fluxes, and density, and temperature of free electrons. At present, in this country and abroad, signals of navigation satellites are used only to diagnose the Earth ionosphere in order to obtain information on variations of the total electron content [28].

The distinction of radio-chemical physics of the atmosphere from traditional radio physics consists in that the former explores natural phenomena occurring in the Earth's atmosphere under the influence of solar activity and external cosmic impacts as a result of physical and chemical processes involving Rydberg states. The latter examines the response of the medium to powerful electromagnetic radiation, focusing, in fact, on the propagation and reflection of radio waves as a tool for studying the ionosphere. The theoretical basis of radio physics has been developed by V.L. Ginzburg and A.V. Gurevich [29–31] in our country and by W. Utlaut, R. Cohen [32], and J. Feijer [33] abroad.

In the present work, we discuss the main sections of radio-chemical physics of the atmosphere that are directly related to the resonant quantum optical phenomena in the D and E layers in different geomagnetic conditions and give a detailed description of their possible scientific and technical applications. The mechanisms of the population of degenerate Rydberg states in these layers during increased solar activity, their influence on the propagation of radio waves, and specific features of the spectra of non-coherent decimeter-band and IR radiation are discussed in the second section. The third section describes a scheme of remote sensing at the frequency of 1.4 GHz, wherein the ionospheric D and E layers serve as a source of non-coherent radiation. The fourth section is devoted to the remote radio sounding of the Earth surface. The fifth considers modern technology of controlling power grids by means of the GPS/GLONASS system. Discussed in detail is the impact of targeted false signals on the performance of power grids. The sixth section examines the possibility of using these systems for monitoring the state of the atmosphere. Key problems in each of these application areas are identified examined, and optimal solutions are proposed. Particular attention is paid to the mechanisms of the formation of charged aerosol layers in the middle atmosphere and to the influence of these layers (including their hydration) on the effectiveness of the remote sounding of the Earth's surface. Finally, we discuss the prospects of further development of radio-chemical physics, as well as nascent research areas.

2. NON-COHERENT ADDITIONAL BACKGROUND RADIATION OF THE UPPER ATMOSPHERE

The modern development of space communication systems in our country and abroad have been traditionally aimed at upgrading the receiving equipment. In recent time, specialists have indicated interest in the nature of the ionospheric and atmospheric phenomena that develop during periods of increased solar activity. It became apparent that, in order to adequately account for the delay of satellite signals and correctly synchronize the measuring equipment, it is not enough, as is usually done, to take into account ionospheric plasma perturbations only [16]. There is a need to pay attention to the interaction of electromagnetic waves with the propagation medium, the optical properties of which are time-dependent and related to the dynamics of physicochemical processes in the Earth upper atmosphere [13].

Such an approach to this fundamental scientific and engineering problem is a new and requires a serious revision of the existing concepts of electromagnetic waves propagating in the upper atmosphere. Moreover, a detailed analysis of accidents associated with disruptions and failures in the functioning of space communication systems and refinement of the existing theory should provide additional information on the state of the medium and open up new opportunities for the further development of communication systems. To date, it has been shown convincingly that disruptions and failures in these systems occur mainly because of ionospheric disturbances at altitudes of 60–110 km above the Earth surface due to the resonance rescattering of satellite signals on the degenerate Rydberg states of molecular complexes [5–7, 17].

Rydberg States in the Upper Atmosphere

Rydberg states, located near the ionization threshold, arise due to the presence of a weakly bound electron with an orbit radius an order of magnitude larger than typical atomic dimensions. Therefore, the emissivity of such states depends on the density of the surrounding medium. The energy of a Rydberg level is determined by the principal quantum number n and angular momentum l of the electron with respect to the ion core. The energy of levels with large angular momenta is independent of l (orbitally degenerate states). These states are statistically most stable because the electron spends most of the time at large distances from the ion core.

The process leading to the formation of orbitally degenerate states (i.e., a superposition of states with large angular momenta of the electron) is known as l-mixing. In the upper atmosphere, this process is almost irreversible and has a characteristic time of 10^{-7} to 10^{-6} s [2]. As a result, the quantum difference between excited atoms and molecules disappear, so that the emission spectrum is independent of their chemical composition [11]. This process takes place in a dense neutral atmosphere with a density greater than 10^{12} cm^{-3}, which corresponds to altitudes of $h \leqslant 110$ km. The criterion for its effectiveness, directly related to the density of the medium, is the condition that the electron cloud of Rydberg particles A** (of radius $2n^2a_0$, where a_0 is the Bohr radius) contain on average at least one neutral molecule M. The interaction between A** and M results in the formation of quasi-molecules A**M, the potential energy surfaces of which are classified according to the angular momentum L of the weakly bound electron with respect to molecule M. The shapes of the potential surfaces are determined by the characteristics of the elastic scattering of the slow electron on this molecule [8, 9]. Optical transitions between split and degenerate states of quasi-molecules A**M that occur without changes in the principal quantum number, $\Delta n = 0$, corresponds to radiation in the decimeter-wave band. Transitions with a slight change $\Delta n \ll n$ in the principal quantum number correspond to infrared radiation.

At altitudes of $h \leqslant 60$ km, Rydberg states of particles A** are largely depopulated due to quenching, mainly in O_2–A** collisions, with the formation of the $A^+(nL)O_2^-(s)$ intermediate ionic complex via the harpoon mechanism. This occurs because the O_2^- anion has a number of resonant vibrationally excited autoionization s-levels located in the ionization continuum. In addition, the concentration of free electrons decreases with decreasing altitude [5]. As a result, an atmospheric layer radiating in the UHF band is formed at altitudes from 80 to 110 km [7].

Nonequilibrium Two-Temperature Plasma

Increased solar activity leads to the formation of two types of non-equilibrium plasma in the D and E layers of the atmosphere: recombination and photoionization plasma [3]. The first type is a nonequilibrium two-temperature plasma formed within ~10^{-10} s [1, 2]. Rydberg states are populated due to collisional transitions of free electrons into bound states as a result inelastic interactions with neutral components of the medium. The electron temperature T_e ranges from 1000 to 3500 K, whereas the neutral medium temperature T_a varies from 200 to 300 K. In the D and E layers, this mechanism of the population of Rydberg states is dominant [4]. The thermalization of electrons occurs mainly due to the vibrational excitation of nitrogen molecules through the formation of an intermediate negative ion [34]:

$$e^- + N_2(v = 0) \rightarrow N_2^- \rightarrow e^- + N_2(v \geq 1). \quad (1)$$

To determine the partial populations $m_{A^{**}X_2}(n, L)$ of degenerate Rydberg states of quasi-molecules $A^{**}N_2$ and $A^{**}O_2$, we modified the "Rydberg" software package [5], developed at the ICP, to include the dependence $n_e(\rho_a)$, which for altitudes of 60–110 km reads as [7]

$$n_e(\rho_a) = n_e(\rho_a^0)\left(\rho_a^0/\rho_a\right)^{0.89}, \quad (2)$$

where $n_e(\rho_a^0)$ and ρ_a^0 are the densities of electrons and medium at the upper boundary H^0 = 110 km. For example, the dependence of the population distribution on the medium density ρ_a in the D and E layers, calculated in [10] for a long-lived recombination plasma at $n_e(\rho_a^0) = 10^5$ cm^{-3} and $T_e = 2000$ K, is shown in Fig. 1 of [10].

Photoionization two-temperature plasma forms due to the joint action of a flow of electrons and broadband radiation from a solar flare and lasts for 20–30 min. This process involves the multiphoton excitation of electronic states of atoms and molecules, with spin prohibition for the corresponding radiative transitions being removed because of interaction with medium molecules M. In this case, the population of Rydberg states must differ substantially from that for plasma recombination. Indeed, since it occurs due to radiation absorption, no sink bottleneck arises [2]; i.e., low-lying Rydberg states are actively populated. For states with $n = 20$–40, the population must be two to three times higher than that in recombination plasma. The difference of the populations of high-lying Rydberg states here (for large values of n) from those formed in nonequilibrium recombination plasma is that they are additionally depleted by photoionization.

The formation of two-temperature plasma in the D layer of the atmosphere during increased solar activity should be accompanied by the generation of UHF radiation, the specific features of which in the range of 1.0–2.0 GHz are, as shown below, of most interest to us.

Spectrum of Above-Background Incoherent Radiation in the Ranges of 1.0–1.8 and 4.0–8.0 GHz

In normal daytime conditions (including periods of increased solar activity), the Earth surface receives additional background non-coherent radiation from the D layer, which occurs by the transitions between degenerate Rydberg states [7]. In the range of 1.0–2.0 GHz, the frequency dependence of the radiation flux I_{tot} exhibits a surprising effect: at the point $\nu_1 = 1.4$ GHz, a whole set of $I_{\text{tot}}(n_e, T_e)$ curves for different electron concentrations n_e and temperatures T_e intersect. Such dependence is called a waist point. The position of this point at the frequency axis is independent of n_e and T_e, while the radiation flux I_{tot} along the vertical axis increases quadratically with increasing n_e; i.e., there exists a one-parameter dependence on the electron density. The foregoing clearly is demonstrated in Fig. 2 of [10], where the solid and dashed lines represent families of $I_{\text{tot}}(\nu)$ curves for electron densities of $n_e(\rho_a^0) = 10^4$ cm^{-3} and 1.2×10^4 cm^{-3}, respectively. Note that this behavior around the frequency ν_1 was found experimentally in [35] and is now widely used for remote passive location of soil moisture and ocean salinity [10].

In the second frequency range, 4.0–8.0 GHz, around the $\nu_2 = 5.0$ GHz, another type of crowding of the $I_{\text{tot}}(\nu)$ curves for different electron temperatures T_e takes place Fig. 19 of [11]. These dependences were calculated using the "Rydberg" code at an electron density of 10^4 cm^{-3} [6, 7]. This kind of behavior is called the bottleneck. With increasing electron density up $n_e^0 = 5 \times 10^4$ cm^{-3}, the position of the bottleneck changes, the trajectory of which is described by a parabolic dependence of I_{tot} on the radiation frequency ν. In this case, at the point ν_2, I_{tot} increases linearly with the density of electrons [7]. Note that the frequency of 5.0 GHz, also discovered independently, is widely used in the ground-based facilities for controlling GPS satellites, because the transmission of information at this frequency is more reliable, although it requires a greater power of the transmitted signal [36].

Long-Wave Infrared Radiation from the D Layer of the Atmosphere

Another interesting phenomenon discovered is a powerful infrared radiation in the range of 10–100 μm, which was first measured with a FIRST spectrometer on June 7, 2005 [37]. Particularly important is the presence of the three characteristic dips in the frequency profile of the intensity, which decrease with increasing frequency. This special feature directly related to meteorology. At small n values, the depopulation of Rydberg and low-lying excited states occurs due to predissociation processes, including nonadiabatic transitions through intermediate valence configuration and the resonant (nonresonant) collisional transfer of internal energy followed by the thermalization of the medium. This is indicated by the increase of its temperature with the altitude in the range of 40–60 km. Note that, in these conditions, l-mixing and, consequently, the influence of the medium are markedly diminished [8]. The latter is especially important for the shaping of the frequency profile of the infrared radiation spectrum ($\Delta n = 1$) [38], measured in [37]. A direct indication of this fact is that the intensity characteristically declines with increasing radiation frequency from the position of the first peak (at a wavelength of ~20 μm) to a minimum (near 15 μm), which is caused by l-mixing. Note also that infrared radiation originating at altitudes above 110 km cannot have such a relief structure.

One of the feasible methods for monitoring the solar activity could be the satellite-based recording of infrared radiation in a given spectral range, which would enable to measure, along with the intensity and frequency profile of the radiation, the altitude distribution of the differential luminosity. On the other hand, based on the observed frequency profile of the IR spectrum and the position of the "bottleneck" within 4.5–8.0 GHz, the "Rydberg" code makes it possible to calculate the power flux of non-coherent decimeter-band radiation [8] and determine the concentration of electrons $n_e(\rho_a^0)$ at the altitude of 110 km at different levels of magnetic disturbances [11].

Thus, using the known electron density, it is possible to determine the dependence of the temperature T_e on the density of the medium at altitudes of 60–110 km, as well as the altitude distribution of the concentration of Rydberg particles, i.e., to solve the inverse problem. Moreover, based on the results of a theoretical analysis of the collisional and radiative quenching of Rydberg states and the data of subsequent satellite measurements, it is possible to come close to solving the fundamental problem of the distribution of the density of the atmosphere in this layer, for which reliable information is virtually absent.

Difficulties in solving these problems dictate, in the first place, the need to further refine the "Rydberg" code. Because of the substantial spatial extent of the electron cloud, the Rydberg states are influenced by interactions with neutral particles of the medium, which are not weak and, therefore, should be taken into account when calculating the relevant optical characteristics. To determine these characteristics, it is necessary to solve the quantum-mechanical problem of the radiation of Rydberg atoms or molecules subjected to the action of the field created by randomly arranged neutral particles. Calculation of the resultant intensity and frequency profile of the radiation is impossible without preliminary determining the characteristics of collisional quenching, which, in turn, requires, information on the potential energy surfaces (PES) of the quasimolecules for all the gas-phase components of the atmosphere (the composition and relative concentrations of the components are well known, being altitude-independent within the specified layer). The collisional quenching of Rydberg states can be carried out based on the calculated PES of the quasi-molecules in frame of the existing dynamic approach [39].

3. REMOTE SENSING OF THE EARTH AT THE FREQUENCY 1.4 GHz

As noted above, remote sensing at the frequency 1.4 GHz provides the least dependence of the signal on confounding factors and has a high sensitivity to changes in the soil moisture content and the salinity of ocean surface. It is intended for weather forecasting, as well as determining the state of vegetation, water balance of the Earth, and state of biological resources in different regions in real time. The latter is provided by a significant advantage of satellite systems, i.e. by the possibility of remotely sensing large areas, including inaccessible regions. The development of this type of location has made it possible to monitoring the scale of deforestation, evaluate the characteristic times of recovery, monitor the productivity of crops, predict the behavior of ice sheets, diagnose flows of water layers, and predict the volume of fishery resources in different parts of the Earth's oceans.

According to the current concept of the development of satellite radar remote sensing in Russia for the period up to 2025, it is planned to create and put into operation a number of spacecraft equipped with airborne radar systems with low and high resolution, with a view to solving the problems concerning hydrometeorology, monitoring of natural resources, and cartography. The main steps in the development of systems for Earth's remote sensing are to be implemented within the framework of the Federal Space Program of Russia.

The authors of the SMOS program believe that UHF radiation at this frequency is most sensitive to changes in soil moisture and ocean salinity [19]. Previously, they assumed that the radiation source has a cosmic origin [40]. However, direct measurements under standard conditions showed that the maximum effect takes place only in the daytime, when UHF radiation is generated by sunlight [41]. Consequently, the main source of radiation at the frequency of ν_1 = 1.4 GHz must be Rydberg states in the D layer of the atmosphere [1–7].

A key problem facing the experts in the field of satellite remote sensing is the complete absence of a clear understanding of the physical origin of this kind of radiation. In recent years, most of them have become convinced that the radiation source is the sun, since a reasonable measurement data are obtained only in the daytime. However, due to its remoteness from the Earth, the sun can safely be regarded as a point source. In this case, the received radiation should be polarized. Satellite measurements at an altitude of ~800 km confirmed this assumption. However, no polarization of the radiation at the Earth's surface has been detected, i.e., it appears to be non-coherent. Moreover, the measurement results turned out to be dependent not only on the time of the day (with the noticeable changes during the day), but also significantly dependent on the geomagnetic state of the ionosphere. This means that the receivers are inherently unable to ensure the stability of the measurements. In addition, in view of the assumption that the source of the radiation is the sun, not the D layer, the satellite-based measurement schemes have been and are intended to receive a single reflection. Since solar radiation is broadband [11], the formation of the experimentally observed waist point in the spectrum of additional background non-coherent radiation at the frequency 1.4 GHz can be explained only by the presence of an additional source. This source, as shown above, is the D and E layers of the upper atmosphere. Consequently, measurements carried out in our country and abroad cannot be considered reliable; therefore, a further development of satellite remote sensing is impossible without a detailed study of the resonant quantum properties of the upper atmosphere.

Since the D layer is a source of non-coherent UHF radiation, one possible measurement schemes can be constructed for the case where the emitting layer (80–110 km) is located between a satellite and an aircraft (airship). Then, the power fluxes of received and reflected radiation are given by the simple expressions

$$I_{\rm sat}^{(z)} = I_{\rm D}^{(z)} + I_{\rm D}^{(z)}(1 - f_w)^2 k_r, \quad (3)$$

$$I_{\rm aer}^{(z)} = I_{\rm D}^{(z)}(1 - f_w)^2 k_r, \quad (4)$$

$$I_{\rm E}^{(z\downarrow)} = I_{\rm D}^{(z)}(1 - f_w), \quad (5)$$

$$I_{\rm E}^{(z\uparrow)} = I_{\rm D}^{(z)}(1 - f_w)k_r, \quad (6)$$

where $I_{\rm D}^{(z)}$ is the time-averaged flux of UHF radiation incident from the D layer. The quantities $I_{\rm sat}^{(z)}$, $I_{\rm aer}^{(z)}$, $I_{\rm E}^{(z\downarrow)}$, and $I_{\rm E}^{(z\uparrow)}$ are, respectively, the fluxes of radiation received at the satellite (including direct radiation from the D layer and that reflected from the Earth surface), reflected radiation received at the aircraft, and incident and reflected radiation at the Earth surface. The quantity f_w is the factor of attenuation of incoherent UHF radiation by layers of charged aerosols. The factor k_r is defined as the reflection coefficient, $I_{\rm E}^{(z\uparrow)} / I_{\rm E}^{(z\downarrow)}$. Taking into account expressions (3)–(6), it is easy to obtain the following two expressions:

$$I_{\rm D}^{(z)} = \frac{\Delta[k_r(\eta - 1)]^{1/2}}{1 - k_r}, \quad (7)$$

$$f_w = 1 - \frac{1}{[k_r(\eta - 1)]^{1/2}}, \quad (8)$$

where the parameters η and Δ are read as

$$\eta = I_{\rm sat}^{(z)} / I_{\rm aer}^{(z)},\ \Delta = I_{\rm E}^{(z\downarrow)} - I_{\rm E}^{(z\uparrow)}.$$

The advantage of relationships (7) and (8) is that they are expressed through relative quantities. Note also that, for "mirror" reflection in the absence of weather disturbances, when $f_w \to 0$, the reflection coefficient $k_r \to 1$, so that $I_{\rm sat}^{(z)}$ tends to $2I_{\rm D}^{(z)}$, as it follows from expression (3).

Direct vertical measurements of the incident and reflected radiation fluxes (3)–(6) as functions of time t make it possible to monitor the evolution of the D layer under different geophysical conditions. This is a separate problem, the solution of which should contribute to studying the dynamics of the water balance of the Earth [42–58]. The time dependence of f_w (expression (8)) is important for meteorological studies. Relationships (3), (4), and (7), in turn, enable to uniquely determine the quantity $I_{\rm D}^{(z)} = I_{\rm sat}^{(z)} - I_{\rm aer}^{(z)}$ and, therefore, can serve as a criterion of accuracy of determination of the parameters of the nonequilibrium two-temperature plasma.

Measurements of the time evolution of the UHF radiation flux $I_{\rm D}^{(z)}$ in the framework of the proposed scheme will enable to address the fundamental problem of the dynamics of the heterogeneity of the D layer. Furthermore, the joint use of its quadratic dependence on the concentration n_e^0 at the frequency $\nu_1 = 1.4$ GHz and the frequency quadratic dependence of the position of the "bottleneck" in the frequency range of 10^4 to 5×10^4 cm^{-3} [10, 11] makes it possible to determine the depth distribution of soil moisture.

Another important issue is related to the time evolution of the factor $f_w(t)$, which characterizes how the reflection and absorption of radio waves at the frequency ν_1, depends on the composition and charge of the atmospheric aerosol. The key aspect here is how the radiation is attenuated while passing through charged atmospheric aerosol layers. It is well known that, when considering propagation of radio waves, it is necessary to consider not only the influence of atmospheric gases but also aerosols of anthropogenic and natural origin in the troposphere and lower atmosphere [59]. The weight fraction of aerosols is small, but their influence on the propagation of electromagnetic radiation is significant because aerosol particles can cause the separation of charges in the atmosphere and lead to the formation of large negatively charged areas. This phenomenon gives rise to atmospheric electrical discharges. The difficulties in describing the process of charging of the particles arise to the fact that the mean free path of the ion is comparable with the Coulomb length, i.e., the distance at which the thermal and Coulomb's energies become identical. An effective and relatively simple solution of the problem was described in [60–66]. The diffusion limit was studied in [67], wherein a possible chemical interaction of ions with molecular ion impurities in the carrier gas was also taken into account.

Another important factor to be further investigated is how the radiation flux from the D layer is attenuated because of the interaction with atmospheric emissions when it passes through the lower atmosphere, an issue that constitutes a separate problem. Many physicochemical processes that influence the propagation of the signal through the troposphere have been investigated in detail. Nevertheless, some physicochemical aspects remain insufficiently studied. Primarily, these include the hydration of ions, which is known to influence the mobility of ions and affects the rates of chemical reactions, including diffusion processes, for which the mobility of ions must also be considered in conjunction with the hydration shell. The latter is directly related to the problem of the passage of non-coherent UHF radiation through aerosol layers, for which processes occurring in aerosols themselves play an important role [68–79]. Despite a long history of studies in this field, many important issues remain poorly understood, whereas for some of them only tentative approaches have emerged.

4. ACTIVE REMOTE SENSING OF THE EARTH

The active remote sensing of the Earth has been covered in many monographs, reviews, and original articles; i.e., there is an extensive body of scientific and technical on the subject. As a rule, sensing is carried out sporadically, being limited to the observation of the atmosphere and Earth's surface, by means of air and space vehicles equipped with various types of instrumentation. The operation wavelength range here is from fractions of a micron (visible optical radiation) to meters (radio waves). In this section, we consider the radio range and discuss its specific features regarding the sensing of the Earth's atmosphere.

Radiophysical Methods for Studying of the Ionosphere

Radiophysical methods for studying the processes occurring in the Earth's ionosphere are widely used in our country and abroad. Currently, the lower ionosphere is studied using radar sensing at medium and short waves, the method of incoherent scattering, method of partial reflections, acoustic and laser sensing of the atmosphere, optical methods, including the transillumination of the atmosphere in the IR range, etc. A detailed analysis of the results for altitudes between 50 and 200–450 km is presented in the review [80], as well as in numerous works referred to therein. Along with these studies, recent years have seen considerable activity in radio occultation measurements of the altitude distributions of the density and temperature of free electrons (with a pair of orbiting satellites) [81] and in the diagnostics of the upper atmosphere by means of sounding rocket [82, 83]. However, when discussing the monitoring of the neutral atmosphere at altitudes 90–120 km, the authors of [80] (Section 5) assumed that, in normal geomagnetic conditions during the daytime, a thermal equilibrium is established between electrons, ions, and neutral gas, so that due to the cooling of the electrons and ions, the temperatures of all plasma components are identical. In reality, as has been established experimentally and justified theoretically, the electron temperature does not drop below 1000 K even in the nighttime, with electron density being 10^3 cm^{-3}. This means that, at these altitudes, a weakly ionized nonequilibrium two-temperature plasma is formed (see, e.g., [10, 11] and references therein). Moreover, in 1973, American scientists P.B. Hays and A.F. Nagy found a discrepancy between the results of radar and direct measurement of the electron density [84]. They developed rocket-borne sensors to measure the concentration of ~0.1-eV electrons in the upper atmosphere. The measurements revealed a significant difference between data obtained by means of radars and sensors. These two examples clearly show that a further progress in radiophysics of the ionosphere is impossible without developing an integrated approach based on the entire arsenal of research methods, including radio astronomy.

Remote Radio Sensing of the Earth's Surface

For the last decades, no less intensely has satellite radar remote sensing been applied, mainly to studying its natural resources and solving meteorological problems [85–101]. Natural resources have been explored using orbiting satellites equipped with optical and radar equipment. Satellite remote sensing is considered most informative for studying the near-surface layers of the Earth [101], the results of which are processed based on the following ideas. Firstly, due to the coherence and polarization of the reflected UHF radiation and the possibility of penetration of incident UHF radiation into the depth of the Earth's surface, radar images, unlike optical ones, must contain much more information. Secondly, it is believed that the main achievement of the satellite remote sensing is the use antennas with synthetic aperture, which is accomplished through a well-defined movement of the transceiver element.

The use of synthetic aperture antennas faces a number of problems, since it requires highly accurate information on the receiver (transmitter) position in the space at each reference point. Such antennas can be most conveniently used in radars mounted on in near-Earth orbiting satellites, since their orbits are strictly fixed. Radar images obtained in this way contain phase information, which can be used on a par with amplitude data. Indeed, the difference between the initial phases of the signals from elements of synthesized images in the scheme of interferometric mapping from repeating trajectories contains information about the surface topography and its small-scale changes. Therefore, such data can provide useful information on the Earth vegetation cover, which, in turn, affects hydrology, biochemistry, and climate processes. Additionally, these data can yield information on the soil moisture content and surface structure. The main areas of satellite remote sensing include [101]:

**glaciology*, studying the types of ice covers, dynamics of sea ice, glaciers, icebergs, boundaries and moisture content of snow covers;

**geology*, studying the morphology of the surface of the Earth's crust, tectonics, arid regions, deposits of minerals, oil and gas fields;

**hydrology*, studying soil moisture, Earth's surface roughness, soil erosion and salinization, boundaries of water bodies;

**ecology*, studying soil erosion, weathering, desertification, human impact on the environment;

**oceanography*, including the study of currents, fronts, internal and surface waves, bathymetry;

**cartography*, the task of which is to create and update maps of various scales, construction of detailed digital maps of the terrain;

**vegetation covers*: the classification of vegetation types, boundaries of forests and their state, biomass volume, humidity;

**monitoring of emergency areas*: floods, consequences of natural disasters, areas of crisis situations;

**commercial activity* involving navigation in ice-covered waters, monitoring of offshore zones and areas of mining, control of the state of oil pipelines, control of fisheries in the coastal zone and of marine pollution, agriculture, forestry, and transport.

According to experts, the advantage of satellite remote sensing lies in the fact that it makes it possible to observe the Earth's surface *at any time, regardless of the state of the atmosphere* [21]. Therefore, it makes sense to examine how the D and E layers influence the results of measurements. It is known that, during the daytime under standard conditions (by analogy with the GPS system), decimeter-band signals are substantially distorted when passing for the first time through these layers, so that their time delay on the Earth's surface become randomly distributed [102]. In the reverse transmission and reception of the reflected signal at the satellite, the pattern repeats itself. Moreover, during the day, the state of the nonequilibrium plasma in these layers varies continuously [11]; i.e., results of a repeated measurement do not necessarily coincide with the results of the first, which puts into question the operability of the calibration procedure developed in [100]. A further important consideration is the effect of the aforementioned layers of charged aerosols, which can cause not only an attenuation of the signal, but also an additional shift in its phase.

These difficulties can be overcome as follows. Under normal geomagnetic conditions, the nighttime D and E layers have little effect on GPS/GLONASS signals [11]. Therefore, satellite signals will be influenced only by aerosol layers, the effect of which is significantly smaller than the influence of the gaseous components. On the other hand, for practical purposes, it suffices to perform location by means of an aircraft moving in the lower troposphere, below the D and E layers. It really allows measurements at any time.

5. TECHNOLOGY OF MAINTAINING THE OPERABILITY OF POWER GRIDS

Production and distribution of electricity is the most critical part of the power infrastructure with respect to various external influences. Numerous experiments have shown that the power grid is vulnerable to both conventional natural disasters and deliberate actions aimed at disrupting the operation of the GPS/GLONASS systems, so-called cyber attacks (false signals), which have recently become quite common. Natural or technogenic disruptions in power supply entail certain economic costs. Interruptions caused by intentional malicious attacks can lead to catastrophic consequences. Therefore, continuous monitoring of the energy infrastructure, including electricity transmission, transportation of oil, gas, etc., is crucial for the security of each country [103].

Detection of the Fault Place in the Power Line

The accuracy of the instrumentation used in our country for detecting fault places should not exceed 700 m (three spans between power line supports). This can be achieved by using of synchronized measurement recorders and the wave method of bilateral measurements of the power line parameters using GPS synchronization. Positive results of detecting fault places in a high-voltage line obtained by using the developed recorders of emergency events and by synchronizing measurements at the ends of the power line may make the wave method effective in locating short-circuit and breakage of wires of high-voltage lines. To demonstrate the effectiveness of this method, it is instructive to recall that it was successfully applied to locate a single-phase short-circuit to ground in a power line at a distance of 29.3 km from the "Pugachev" substation. Later, this fault was confirmed by the emergency brigade [104].

An analysis of the list of emergency shutdowns in three years performed by the Orenburgenergo power company showed that the proportion of high-voltage transmission lines that accounted for 30% of all cases of emergency shutdowns of power lines was 10%. As a result, more than 25% of the losses of the company falls on the reduction in the supply of generated electricity [104].

Monitoring the Temperature of Power Lines

Time-synchronized comparative measurements of phasors (for definition is given below) of currents and voltages with phasor measurement units (PMUs) can be used to monitor the temperature of the power line and, consequently, its loading and to determine the maximum admissible dynamic loading. The results of such measurements may be used as snapshots of the dynamics of the system. Widely used systems of supervisory control and data acquisition (SCADA) intended for stabilizing of power networks operate much more slowly [13].

The phasor is a vector comprised of three components of three-phase current [26]. Measurements are carried out at each end of the power line, so that only the average temperature of the line is determined. A drawback of this method is that it is incapable of detecting local heatings of the line. An advantage of evaluating the dynamic loading of the line is the possibility of increasing its loading by 10–30%.

Preventing Emergency Shutdowns

Major emergency shutdowns occur infrequently and usually lead to severe economic and social consequences. The largest of these occurred in 2003 in the United States, affecting 50 million consumers in eight northeastern states and Ontario [105]. This shutdown occurred because of cascading failures in the power grid, in which small and local failures, in view of the control service, led to instability across the entire grid. Preventing such shutdowns is an important task, the solution of which requires the real-time monitoring of the state of the whole system. This is done using the wide area measurement system (WAMS), which is a set of separate, spaced-apart time-synchronized measuring modules. This procedure makes it possible to perform large-scale measurements and allows operators to better protect the power system from the most disastrous failures [13].

The WAMS includes communications networks, instrumentation, and software. The most important component here is the high-performance technology of time-synchronized vector measurements with PMUs. Synchronization of the devices enables to determine the characteristics of the voltage, current, and frequency at the key substations of the power grid, generating stations, and major electricity consumption sites (such as industrial facilities, cities). These parameters, along with the known characteristics of transmission lines should be used for calculating the instantaneous redistribution of currents across the network. Data provided by PMUs come in more frequently than data from traditional classical instrumentation of SCADA systems, which makes it possible to rapidly assess of the dynamics of the power system and take, if necessary, appropriate accident- preventing measures.

Intentional Interference with the Operation of Satellite Systems

In recent time, there appeared possibility of subjecting GPS/GLONASS system receivers to cyber attacks (known as “spoofing”), which is very dangerous, comparable in consequences with the results of using conventional weapons. In fact, such an attack is accomplished by replacing a true GPS signal by a more powerful false signal generated by a “spoofer,” which leads to a shift in the receiver timing. It can be most effectively carried out if the target receiver cannot distinguish the true GPS signal from a falsified version. Previously, each element of the critical infrastructure, including power grids, operated without an external timestamp generator. The past decade has seen a significant increase in using precise time synchronizers in industrial control networks. Therefore, the role of time synchronization has become extremely important, since the power system is an integrated set of interconnected networks, each part of which can directly influence the functioning of all the others. On the one hand, in most cases it helps successfully protect them from adverse events, since, if an accident has occurred, PMU-based technologies have a capability to execute preventive actions before it could spread throughout the network.

On the other hand, PMUs use GPS signals to provide an accurate time synchronization for all the parts of the power grid, whereby it becomes vulnerable to cyber attacks. At present, researchers abroad develop various methods for protecting against “spoofing” [106–110]. However, these methods ignore the nature of the aforementioned physicochemical properties of the ionosphere, which significantly influence the propagation of GPS satellite signals through the atmosphere, thereby potentially affecting their efficiency. Indeed, an external attack leads to tuning of the target receiver to a more powerful signal, i.e., to a rapid, almost instantaneous change in the position, speed, and absolute time data it decodes. Since the change of this dataset in the receiver occurs against the background of rather slow variations of the basic atmospheric parameters, the constant monitoring of the current state of the atmosphere becomes absolutely necessary in the development of effective anti-spoofing methods.

6. GPS-BASED MONITORING OF THE ATMOSPHERE

Current changes in the state of the D and E layers during periods of increased solar activity lead to the adjustment of the parameters of the nonequilibrium two-temperature plasma, and, accordingly, to changes (within $\sim 10^{-7}$–10^{-6} s) in the populations of the degenerate states of Rydberg orbital complexes. In turn, this will have an effect on the functioning of any of the aforementioned engineering systems based on the use of GPS/GLONASS signals, which pass through these layers. Since direct observation of the states of these layers is almost impossible, it comes to the fore the issue of using the GPS system for plasma diagnostics in these layers. More specifically, it is necessary to monitor changes in electron density and temperature at an altitude of 110 km and to determine their altitude profiles within 60–110 km, where GPS signals are known to undergo the greatest distortions [17]. To solve this problem, the satellite radio occultation technique can be applied, which has been widely used in recent years to address climate problems [111, 112]. Naturally, this method makes it possible to determine only the vertical profiles of GPS signal propagation delays, which, after solving the corresponding inverse problem, can expectedly yield qualitative altitude profiles of the indicated quantities from relative measurements. Therefore, the results obtained should be complemented by ground-based measurements of the power flux I_{tot} of non-coherent radiation at a frequency 1.4 GHz, which, in conjunction with the "Rydberg" code, can at least provide a control over the reliability of the values found [5, 7].

Monitoring the changes in the state of D and E layers by repeating GPS-measurements at regular intervals is also of considerable interest. It is expected to provide valuable information on the macroscopic dynamics of the D and E layers containing Rydberg complexes and free electrons, for example, on how the thickness of the emitting layer changes with time. Such changes must contribute to the error of GPS measurements. In this regard, the obvious question arises of how the power flux of non-coherent radiation changes with time. Note also that the entire radiating layer of thickness 80–110 km in vertical direction and up to 1000 km and more in horizontal direction, i.e., as a result of an integral contribution to the overall picture of the phenomenon. Therefore, particular details of the internal irregularities of the layer structure (such as those associated with changes in temperature and density in each individual sublayer due to modulation of natural processes [80], etc.) are unimportant. Naturally, they are of interest to some problems of radio physics and ionosphere dynamics, but produce no noticeable effect on GPS signals received on the Earth's surface.

7. CONCLUSIONS

In this article, we have combined seemingly disconnected areas of science and technology into a unified science studying the influence of physicochemical processes occurring in the D and E layers of the Earth's atmosphere on the operability of their various applications. The present work is an analytical review in which we analyzed key problems dealt with in each subfield of radio-chemical physics and discussed possible solutions. The first section covers passive remote sensing the Earth's surface at the frequency 1.4 GHz. We have proposed a completely new algorithm for sensing measurements, which is based on the fact that non-coherent radiation originates in an atmospheric layer 80–110 km above the Earth's surface and which takes into account the specifics of the frequency profile of the radiation. In addition, we focused on an important role of charged aerosol layers and discussed the problems encountered in calibration of the measurements because of the continuously changing state of the upper atmosphere.

Then (in Section 2), we discussed in detail the problems of the satellite radar remote sensing of the Earth's surface in order to determine its structure and composition, as well as to prospect oil and gas fields and deposits of other natural resources, which is under way in recent years [113–115]. According to the general concepts of radio-chemical physics, the most reliable measurement can be performed in the nighttime, when the D and E layers produce no noticeable effect on the propagation of satellite signals, so that only the effect of aerosol layers should be taken into account. At the same time, for civil applications, it suffices to perform sensing with the help of aircraft moving in the troposphere, below the D and E layers, which allows measurements at any time of the day.

In the third section, we discussed the reasons for the disruption of synchronization signals, a factor that affects the safe operation of power grids, and proposed measures to ensure the synchronization of the measuring equipment with a view to possible failures in the operation of the GPS/GLONASS systems because an external interference with the work of the grid ("spoofing").

The possibility of using the GPS system for monitoring the state of the atmosphere, examined in a great number of original articles and reviews, is discussed in the fourth section. Most of the authors of these works have not yet developed a clear understanding of the phenomena occurring in the D and E layers of the atmosphere. What's more, here we have a kind of "chaos" of views and approaches, practically unfounded. This is due to the fact that this branch of science is least developed and needs further studies. Of the existing approaches, we have tried to highlight the most reasonable.

Note also that very interesting and promising are the results of measurements with telescopes at a frequency 1.4 GHz [116], which are related with the impact of Rydberg states on the passage of cosmic rays through the D and E layers of the atmosphere. The development of the Square Kilometer Array (SKA) radio telescope [117] entails a serious problem of calibration in the presence of the Earth's atmosphere. The results of SKA measurements at a frequency 1.4 GHz are affected by a number of ionospheric phenomena that diminish the accuracy of measurements and, consequently, the resolution in the visualization of the sky. The influence of the ionosphere is normally taken into account on the stage of processing of the signals in order to eliminate possible errors. Clearly, the accuracy of telescopic observations cannot be achieved without applying the theory of radio signal propagation delays in the D and E atmospheric layers, which is the subject of radio-chemical physics.

To conclude, we would like to point out that any engineering solutions involving the propagation of radio waves through the ionosphere require the application of the theory presented in [11].

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