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D and E ionospheric layers as a source of remote sensing

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Abstract

The main problems of remote sensing of the Earth's surface in the range 1.2–1.6 GHz caused by the resonant quantum properties of the medium of propagation of radio waves in the lower ionosphere are discussed. It is shown that for the passive location, the main source is incoherent microwave radiation of the D and E layers of the ionosphere in the decimeter range. Since the source is located below the orbiting satellites, a fundamentally new method has been developed for the necessary measurements. The question is raised about the correct calibration of measuring equipment, depending on the current state of the ionosphere.

1. Introduction

Currently, considerable interest is being shown in the physicochemical processes taking place in the Earth's lower ionosphere with the participation of electronically excited states, which is primarily associated with the problems of remote passive location of the Earth's surface [1,2]. A spontaneous increase in solar activity is accompanied by a significant increase in electromagnetic radiation, which leads to noticeable perturbations of the propagation medium. One of these disturbances is the malfunctioning of the global navigation satellite system (GNSS) operating in the frequency range 1.2–1.6 GHz at altitudes of 60–110 km [3].

It was shown in [4] that incoherent microwave radiation is formed at an altitude from 60 up to 110 km as a result of solar flares. The intensity of this radiation is hundreds of times higher than the typical levels of microwave bursts of the Sun. Analysis of various possibilities for generating the detected radiation has shown that the greatest contribution to the resulting spectrum picture is made by transitions between orbitally degenerate Rydberg states of neutral components of a non-equilibrium two-temperature plasma excited by the action of a stream of sunlight or a stream of electrons ejected from the ionosphere [5,6].

Incoherent UHF radiation of Rydberg states during periods of geomagnetic disturbances is accompanied by intense long-wave infrared (IR) radiation (with a wavelength exceeding 15 microns), which was observed in [7]. Passive sensing involves the use of natural radiation to determine the properties of the Earth's surface, which is usually carried out with receivers operating at a frequency of 1.4 GHz, since at this frequency there is a one-parameter dependence of the signal power on the electronic concentration [8].

Previously researchers assumed that this source has a cosmic origin and corresponds to the radiation observed on radio telescopes of a hydrogen line with a wavelength of 21 cm and a transition frequency ν=1.4204 GHz, corresponding to an energy of $\omega=2\pi\nu$=5.86 10 eV. The upper sublevel corresponds to the parallel arrangement of the electron and proton spins, the lower one to the antiparallel one. The probability of a transition between them is equal to $2.85 \cdot 10^{-15}$ sec^{-1} (i.e., one transition takes place over 11 million years).

Estimates show that as a result of resonant rescattering of hydrogen radio emission at the Rydberg states in the D and E layers of the Earth's ionosphere for normal geomagnetic conditions and electron concentration $n_e=10^4$ cm^{-3}, and also taking into account the dependence given in [9], the power of the cosmic radiation flux coming to the radiometer is 10^{-32} W/cm^2. This value is several orders of magnitude less than the value of the flux density of the intrinsic incoherent UHF radiation of the lower ionosphere [10]. This is also confirmed by the fact that direct measurements with a radiometer under normal conditions have shown that the maximum effect is achieved only in the daytime, when the microwave radiation is caused by the influence of the Sun.

A large number of original articles, reviews, and monographs are devoted to remote sensing of the Earth's surface in the literature (see, for example, [1,2] and references therein). However, these publications do not take into account the attenuation and delay of radio waves during the passage of the D and E layers of the lower ionosphere at an altitude of 60–110 km as a result of resonant scattering in the orbitally degenerate Rydberg states, which leads to an uncontrolled failure of the group and phase velocities and time delay. In addition, they do not take into account the direct additional underground UHF radiation coming to the satellite from the upper atmosphere located below D and E layers, as well as the attenuation of signals due to interaction with charged aerosols [1,2].

2. The problem of attenuation of the UHF power flux

The key issue here is the problem of attenuation of the UHF power flux radiation during the passage of charged aerosol layers in the atmosphere. It is well known that when considering the propagation of radio waves, it is necessary to take into account the influence of not only atmospheric gases, but also aerosols of anthropogenic and natural origin. Although the concentration of substances in the aerosol state is small by weight, their influence on the propagation of electromagnetic radiation is significant due to the fact that aerosol particles can lead to the separation of charges in the atmosphere and create significant negatively charged zones. This phenomenon causes the formation of atmospheric electrical discharges.

Consideration of the charge kinetics of particles in the atmosphere is an extremely difficult task, which must be solved to account for the distortion and loss of satellite radio signals. The reason for the appearance of charges on aerosol particles is the appearance of free electrons as a result of air ionization by cosmic particle flows. Several dozen charged pairs are formed in the troposphere under normal conditions. Free electrons interact with oxygen, and the resulting negative ions are effectively deposited on submicron particles always present in the air, even under the purest conditions. Positive ions form heavy clusters when reacting with water molecules.

The complexity of considering particle charging is related to the fact that the free path length of an ion is comparable to the Coulomb length, i.e. the distance at which the energy of thermal motion becomes comparable to the molecular free path length. This means that even with very small particle sizes (large Knudsen numbers), it is not possible to apply the free-molecular approximation. An effective and fairly simple solution to this problem is described in [11].

The next important aspect is also the need to take into account the impact of acid emissions on the power of the radiation flux of the D and E layers in the lower ionosphere, which is an independent task. Many physical and chemical processes that affect the passage of a signal through the troposphere have now been studied in detail. However, there are still problems in chemical physics that have not yet been sufficiently studied. First of all, they include the hydration of aerosol ions. As is known, it determines their mobility and affects the rate of chemical reactions, including diffusion processes, where the mobility of ions should also be considered together with the hydrate shell. The latter also applies to the problem of incoherent microwave radiation passing through aerosol layers, where the processes occurring in the aerosols themselves are particularly significant [12,13].

3. Determination of nonequilibrium plasma parameters using the spectrum of IR radiation

The most promising method for monitoring the plasma parameters of the d and E layers of the atmosphere over time is their recovery by solving the inverse problem of the spectrum of long-wave IR radiation (in the wavelength range of 15-100 microns), measured on a low-orbit satellite [9]. This imposes certain restrictions on IR sensors, which, along with high resolution, must have a small size and weight. The sensor used in [7] did not have this resolution. A way out of this situation has emerged in recent years and is associated with the appearance of metamaterials with unique optical properties associated with abnormal reflection and refraction [14], which stimulated the development of fundamentally new IR sensors. The block scheme of such a sensor is shown in figure 1, where the filters are metasurfaces. The scheme is developed based on the requirements for the speed of the measuring device.

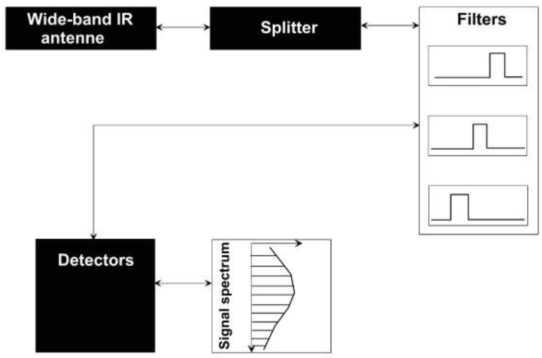

Figure 1. Simplified block-scheme of the sensor for measuring the spectrum of incoherent IR radiation.

Currently, Japan and the United States are actively involved in creating devices using such metasurfaces. For example, the GRES program of the Japanese Agency for science and technology has already implemented the latest single-photon detectors in the wavelength range of 10-50 microns, which are GaAs/ALGaAS charge-sensitive transistors with an equivalent noise level of $8.3\cdot10^{-19}$ W/Hz$^{1/2}$ and are ready for mass production. The total weight of the equipment does not exceed 200 grams. The next modification (with wavelengths up to 100 microns) is being developed at the University of Massachusetts in the United States under the CLAREO program, which have the same characteristic parameters and are designed with the requirements of their reliable operation in both normal and cryogenic conditions, as well as resistance to vibrations when putting the satellite into orbit.

4. The problem of calibration in passive remote sensing

The next fundamental scientific and technical problem is the calibration of measuring equipment (installed on a satellite or aircraft), which makes it possible to uniquely link the indicators of sensors with the determined physical parameters (humidity, structure and chemical composition, magnetic properties of the reflecting surface, etc.). In contrast to direct ground measurements, satellites receive both the reflected radiation from the Earth's surface and the radiation from the upper atmosphere at the same time. Therefore, calibration of the measured equipment and restoration of the physical parameters of the surface must be carried out on the basis of a detailed analysis of the interactions of the source radiation with the propagation medium and with the Earth's surface.

The traditional satellite calibration method is called indirect and consists of the following. The necessary relationships between the sensor output signals and the desired physical values are found by directly comparing the measured signals with the absolute standard of these values before satellite launch, i.e. calibration is performed directly on Earth [15]. It usually uses a spectral window with a central frequency of 1.413 GHz and a bandwidth of 27 MHz, which corresponds to cosmic radiation due to the lower forbidden transition in the hydrogen atom. At the same time, it is believed that the effect of the Faraday effect on the measurement results is insignificant [16]. A fundamental disadvantage of this calibration is that it completely ignores variations in sensor parameters over time due to the presence of incoherent additional background radiation from the D and E layers of the ionosphere over a wide frequency range (including the 1.4 GHz frequency [1,2], the intensity of which constantly changes over time [17]). It is also necessary to take into account the influence of the above-mentioned effects of attenuation of the radiation intensity due to inhomogeneities of the lower atmosphere. For this purpose, it is advisable to switch to a two-frequency measurement method and take advantage of the fact that at a frequency of 1.4 GHz, the intensity of microwave radiation is proportional to the square of the concentration of free electrons, and at a frequency of 5 GHz, its first degree [9].

It is impossible to solve the problem of calibration of measuring equipment without monitoring the parameters of two-temperature plasma in the D and E layers of the atmosphere. Therefore, the next important area of research is a detailed study of the features of the IR radiation spectrum (in which the main contribution is made by radiation $\Delta n \geq 1$ transitions, where n is the principal quantum number of the Rydberg state), which is directly related to the incoherent UHF radiation considered above. Since the shape of the radiation line of the Rydberg States is very critical to the distribution of the electron concentration and temperature inside these layers [9], the measurement of the IR spectrum on the satellite can serve as a basis for solving the inverse problem of restoring the dependence of the main plasma parameters and their height distribution on time. Reliable information about the shape of the IR spectrum will also allow us to calculate using the "Rydberg" program [8] depending on the height of population of the Rydberg states.

5. Conclusion

To conduct passive remote sensing of the Earth it is necessary to have a calibration technique for measuring equipment, which until now is absent in world practice. Attempts were made to solve this problem using the differential measurement method using two antennas located up and down at the same time. But this did not lead to success due to the specifics of incoherent UHF radiation. The problem is due to the fact that the radiation source is not a point one and is spatially widely distributed in the upper atmosphere. The next interfering factor is the mismatch between the viewing areas of the antennas used. To carry out the calibration of measuring equipment and measurements independent of time, it is necessary to know at any time the power of the flux coming to the surface of the radiation at two frequencies 1.4 GHz and 5 GHz.

Rydberg particles are the source of this radiation [1,2]. Therefore, knowledge of the distribution function of their concentration in the radiating layer (80–110 km) will allow to determine the power of the incoming flux in real time. Since these particles radiate simultaneously in the far IR range, it is most expedient to restore the distribution of their concentration using the infrared spectrum measured on satellites in the wavelength range of 20-50 μm, which will additionally require complex mathematical processing of the signals [18]. Moreover, the sensors in the indicated range must be vibration-proof and operate under cryogenic conditions, which is a rather complicated scientific and technical task.

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7. References

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