Physics of Earth and Space Environments

Vladimir L. Bychkov
Gennady V. Golubkov
Anatoly I. Nikitin *Editors*

The Atmosphere and Ionosphere

Elementary Processes, Monitoring, and Ball Lightning

Springer

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Physics of Earth and Space Environments

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Preface

Chapter 1 discusses the mechanisms of Rydberg state settlement and quenching processes in nonequilibrium two-temperature plasma in the D and E layers of the ionosphere during periods of increased solar activity. The most important of these is the process of l mixing, which leads to the formation of Rydberg particles in orbital degenerated states. Rydberg quasi-molecules are formed from these particles and neutral molecules of the medium. Radiative transitions between states of these quasi-molecules give rise to incoherent additional ultra-high frequency (UHF) radiation over background. The power flux of this radiation is the irregular complicated function of frequency, which depends on plasma parameters. This allows the consideration of such as background noise for satellite-positioning signals. Possible solutions to the elimination of errors in global-positioning satellite systems are discussed.

Chapter 2 is devoted to the analysis of electron ionization and elimination processes at early stages of electric discharges in air at altitudes between 0 at 90 km. In this chapter, ionization processes in an external electric field and background ionization by fast particles, as well as electron attachment and detachment with participation of atomic and molecular oxygen, are considered. Analysis of analytic ionization models allowing simplified approaches to detailed computation models is presented. It is shown that the electric breakdown process in air under the influence of an external electric field represents a complex of several stages that are differently realized with respect to different altitudes over the Earth. In numerical modeling on the basis of the detailed plasma chemical model, it is shown that relaxation processes lead to a nonlinear stage of electric breakdown. The ionization phenomena considered can be realized at natural high-altitude discharges in fields of thunderstorm clouds.

Chapter 3 discusses the physical principles of active and passive methods of remote detection of radioactive substances and toxic agents in the atmosphere as well as the measurement of parameters of regular and/or emergency gas-aerosol emissions and clusters of radioactive and poisoning fragments and microparticles on various surfaces, which provide the means to solve a range of unique problems in environmental monitoring. The analytical possibilities of currently available active and passive methods of remote control of radioactive and highly toxic substances—which are based on the achievements of infrared (IR) absorption spectroscopy, Raman spectroscopy, fluorescence, laser-induced breakdown spectrometry, THz (sub-THz) spectroscopy, *etc*.—are discussed. Modern trends in the development of active and passive methods of remote detection of radioactive substances and toxic agents for various spectral ranges are analyzed.

Chapters 4 and 5 are devoted to objects that naturally originate in the atmosphere. In Chap. 4, the latest research results on ball lightning (BL) are presented. Descriptions of 46 cases of BL affecting people are presented. Fifty cases of BL occurring inside and near airplanes are described. Cases of BL's interaction with different types of glass (widow, mirror) are analyzed, and experimental modeling of BL's influence on different types of glass are presented. Photographic and video data showing traces of natural BL are presented. Theoretical and experimental analysis of a new BL model connected with the oxidation of finely disperse silicon inside the silicon oxide cover is discussed. The results of experiments on the creation of long-lived fiery spheres on application of erosive capillary discharge at high pressures, in which exploding balls have occurred, is discussed. Computer modeling of "Gatchina" discharge, *i.e.*, discharge above a surface of water, is presented. Chapter 5 considers objects that often appear under the same conditions as BL. These are gelatinous meteors or "star jelly," *i.e.*, Pwdre Ser. Observation data of these natural objects are presented. Hypotheses of their origination is connected with the bacteria blue-green algae and *Pseudomonas* found in clouds.

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Editor Bios and Contributors

Editor Bios

Vladimir L. Bychkov is lead researcher in the Department of Physics at Lomonosov Moscow State University. He is also a laboratory head in FSUE "Moscow Radiotechnical Institute, RAS." He has 37 years of experience in plasma physics studies, the physics of elementary processes, gas discharges, plasma chemistry, and ball lightning. He is elected Academician of the Russian Academy of Natural Sciences.

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Introduction

Note: It was a rather complex task to choose the reviews for the present issue. With this respect to this, we chose topics containing mainly new information that has not been discussed previously or information that was published in sources not readily available.

In the city of Zelenogradsk, Russia, located on the coast of the Baltic Sea close to the Kushskaya spit (the Kaliningrad area of Russia), the 3rd International Conference "Atmosphere, Ionosphere, Safety" (AIS-2012) took place from 24 to 30 June 2012. Simultaneously as the section on electrochemical and electromagnetic phenomena in the atmosphere, the 12th International Symposium on Ball Lightning (ISBL12) also took place. Both were organized by the I. Kant Baltic Federal University (BFU), the N. N. Semenov Institute of Chemical Physics of the Russian Academy of Science, the N. V. Pushkov Institute of Terrestrial Magnetism and Distribution of Radio Wave Propagation of the Russian Academy of Science, the Noncommercial Partnership on Scientific, Educational and Innovative Activity "Center of Chemical Physics of the atmosphere," the Lomonosov Moscow State University, and the Russian Committee on Ball Lightning. Financial support was provided by I. Kant BFU, the Russian Foundation for Basic Research, the Presidium of the Russian Academy of Science, and the European Office of Aerospace Research and Development. Scientists from some foreign countries, various regions of Russia, and scientific centers of Commonwealth of Independent States (CIS) countries participated in the work of the conference. Twelve plenary and 59 section reports and >40 poster presentations devoted to analysis of the dynamics of physical and chemical processes in the "atmosphere–ionosphere" interaction taking place under conditions of natural and anthropogenic disturbances were given.

The attention of the conference participants was directed at studying the reasons for and examples of various geophysical and atmospheric phenomena, as well as giving an estimation of their influence on the Earth's biosphere and technological systems, in order to develop monitoring systems and decrease the risk of some natural processes to pose a negative influence on human life. These problems are of interest for a wide range of experts working in various scientific and technical fields.

The Earth's ionosphere is subject to the influence of complex physical and chemical processes caused by the absorption of sunlight, dynamic processes in the lower atmosphere, and seismic and volcanic activity. As a result of these processes, *e.g.*, powerful atmospheric disturbances, electrical currents, electromagnetic disturbances in various spectral ranges, plasma and optical heterogeneities, and increased levels of radioactivity, have changed the manner in which ionic and molecular compositions are formed. Moreover, microwave radiation of highly excited particles of the ionosphere accompanying the processes of solar activity increases the occurrence of magnetic storms, thus negatively influencing the Earth's biosphere.

Knowledge of the nature of influencing factors allows us to use them as indicators of catastrophic processes and to create corresponding monitoring systems. Additional research must be undertaken, the necessity of which is indicated by the significant expansion of human activity in the ionosphere, thus leading to the occurrence of new risks. These risks are posed by the development of manned and unmanned orbital systems, aviation using the altitudes of the middle atmosphere, and new methods of communication.

The fundamental direction of research was widely discussed by the conference participants. Disordered positioning of global satellite systems during periods of increased solar activity and the origination of magnetic storms were topics of concern. The development of modern technology increases the requirement to maintain positioning accuracy and reliability. This is dictated by the safety and profitability needs of ground-, sea-, and air-based objects movement and the need to solve particular problems (air photography, search and rescue of vehicles in distress, synchronization of work of extended electric networks, *etc*.). The key problem is the need to incorporate the quantum resonance properties of medium which affect to radio wave propagation that leads to fail of signals and disruption of positioning accuracy in conditions of geomagnetic disturbances.

Elementary Chemical Processes in the Upper Atmosphere and Ionosphere

Sixty-two participants at the conference took part in the work of this section. They were from the CIS countries, *i.e.*, Russia, Belarus, and Ukraine, and some foreign countries, *i.e.*, the United States of America, Germany, Great Britain, the Netherlands, Belgium, Switzerland, Japan, India, and China. From these countries there were 2 plenary and 12 oral reports and poster presentations.

The work of this section was opened by the plenary lecture, in which it was shown that nonequilibrium two-temperature plasma is formed during periods of increased solar activity in the E and D layers of the ionosphere at altitudes from 50 to 120 km. Interaction with the neutral environment leads to the filling of highly excited (Rydberg) states of quasi-molecules $A^{**}N_2$ and $A^{**}O_2$, the presence of which is the principal cause of the delayed propagation of global-navigating satellite system signals and increased positioning errors. Radiation transitions between Rydberg states of quasi-molecules also results in the appearance of noncoherent super background radiation in the decimeter range leading to decreased signal-to-noise ratio.

Another plenary lecture was devoted to a discussion of the technical problems connected with the use of Born-Oppenheimer approximation in the calculation of electron wave functions and surfaces of potential energy. A new computer program for the calculation of wave function phases, which is especially important for the calculation of nuclear collision and photo-dissociation processes, was discussed. Spin effects at interactions of oxygen-containing complexes with a medium were also discussed.

A special report was devoted to the analysis of main elementary processes (collisional ionization of molecules by electrons, dissociating attachment of electrons, *etc*.) in the atmosphere (lower atmosphere to the mesosphere). These were considered along with an account of the influence of atmospheric electricity or imposed external electric fields. There was discussion regarding the calculation of the dynamics of highly vibrationally excited small molecules in terms of dynamic potential. The influence of solar activity on radio-signal propagation in the D layer was also discussed.

An explanation for the shining layers nature of the stratosphere during storm activity observed from the satellites "Tatyana-1" and "Tatyana-2", moving at the altitude of approximately 850 km, was presented. Expressions for the polarization tensor and the electronic propagator were also presented; these were constructed under perturbation theory on the basis of finite molecular orbitals. The calculation of transition energies from the ground into electronically excited states of small molecules and their ions was proposed. A report devoted to the description of a new algorithm for calculating poles and residues of the polarization propagator executed under first-order perturbation theory was presented.

Results of calculations of auto-ionizing states of molecules executed within the limits of the stabilized-spheres method were presented. Calculations of the lower resonant state of the ion H (1S) in context of the stabilization method was also discussed. The theoretical model of oxygen molecule vibrational levels filling in the mesosphere and lower thermosphere was presented.

The method of the compound system (Rydberg atom + neutral particle of the environment) was presented in detail, and wave functions of the impact and quenching of Rydberg atom processes in the upper atmosphere were discussed.

Electrochemical and Electromagnetic Phenomena in the Atmosphere

This section and the 12th International Symposium on Ball Lightning (ISBL12) were devoted to research on plasma structures, plasmoids, BL, and nonlinear effects in an atmosphere. The work of the sessions involved 67 participants from Belgium, Switzerland, Japan, the Netherlands, the USA, Russia, Belarus, Ukraine, and

Kazakhstan. Plenary reports in this section were devoted to a discussion of current research on BL.

A report on the investigation of long-lived BL analogues by means of electric discharges, a topic studied extensively by S. E. Emelin at St. Petersburg State University, was presented. Emelin died in 2011. He was the author of many successful pioneering works on the modeling of artificial BL by means of different gas discharges using various materials (polymers, metals, dielectrics) and an expert in the generation of Gatchina discharge plasmoids. A report on the results of chiral wave-front calculation for laboratory plasmoids of Gatchina-type discharge, as well as spherical formations obtained at electric discharge in water, was given.

An analysis of reasons constraining the development of works on BL theory was presented. It was shown that these reasons contradict a set of myths about the structure of BL based on erroneous interpretation of previous observations. Thus, there is still a need to publish detailed descriptions of BL as well as detailed analyses of artifacts left by BL.

Interesting information was presented in a series of reports involving photographic and video data of observed BL. A report on the nature of jelly-like clots (star jelly) sometimes falling from clouds during thunderstorms was presented. These objects can be considered a product of vital functions of the bacteria living in clouds.

A report on studying traces that appeared after the influence of a fireball on a mirror was given. In addition, a theoretical model of this influence was presented. A report on the unusual properties of plasmoids in high-speed gaseous streams was given. Separation of the plasma into a core and a halo was revealed; their gas-dynamic characteristics strongly differ. A report on cases of complex traces of dust particles appearing on the surface of a mirror and a windowpane during a thunderstorm is presented. In addition, a mathematical model of electric phenomena on the basis of hydrodynamic equations was proposed. Comparison of its results with known experimental data proves its adequacy.

Dynamics of the Ionosphere and Atmosphere–Ionosphere

Sixty-nine participants took part in this section. Scientific researchers presented the results of experiments performed in Russia, Germany, France, and China. At the plenary sessions of the conference, 38 reports were heard and considered. The subjects of plenary reports concerned actual problems of experimental and theoretical research of the ionosphere and the upper atmosphere.

The plenary report was devoted to a discussion of atmospheric precursor mechanisms of earthquake formation in the ionosphere on the basis of a concept called a "global electric circuit." In analyzing the problem, various physical processes in the ground layer of the atmosphere that influence the electric conductivity of an environment were considered, and their experimental and theoretical substantiation was presented. In an example of current modeling research, it was shown that a change of electric conductivity in the lower atmosphere leads to excitation of vertical electric currents, thus effectively influencing the ionosphere.

A review of the results of experimental research on ionosphere modification due to the influence of powerful high-frequency radio waves executed in a heating facility, “Sura,” was presented. In particular, features of temporary evolution of generated ionosphere disturbances at various altitudes, spatial structure of ionosphere nonuniformities, features of stimulated electromagnetic radiations from the ionosphere, and generation of acoustic waves at periodic heating, *etc*., were considered.

A separate presentation was devoted to research on the influence of dynamic processes in the Earth’s lower atmosphere that affect the ionosphere. In a research example of the formation mechanisms of ionosphere effects, which are caused by sudden stratospheric warming, various statements of modeling problems within the context of problematic theoretical research were discussed. Results of research performed using an application of the global self-consistent model, *i.e*., the thermosphere, ionosphere, and protonosphere (GSM TIP) model, were presented.

In subsequent reports, results of experiments on the ionosphere’s active influence on the study of spatial and temporary characteristics of atmospheric nonuniformities were considered. Results of theoretical research, within the limits of modeling experiments of the influence of such disturbance mechanisms on the ionosphere, were presented.

A significant portion of the work in this section was directed to experimental and theoretical research of ionosphere disturbances during increased seismic activity, *i.e*., ionospheric precursors of earthquakes. Some reports were entirely devoted to this problem. Experimental evidence of the origination of ionospheric precursors of earthquakes and theoretical research results of their excitation mechanisms were presented.

Geomagnetic storms are one of the important factors influencing the dynamics of the ionosphere. Some reports were devoted to theoretical research of ionosphere dynamics under the conditions of geomagnetic storms. By observation of total electron content (TEC), a comparative analysis on the ionospheric effects of geomagnetic storms during various seasons was given. Much attention was given to a discussion of theoretical and experimental research results of the spatially nonuniform structure of the ionosphere.

In a separate report, results of observation of the zonal ionosphere’s nonuniformities in the area of equatorial anomaly, *i.e*., those of the middle-latitude, magneto-coupled Yakut and Weddell seas, were presented. Based on modeling research, a physical interpretation of the formation of their features was proposed. Observations of 27-day variations of parameters of the ionosphere were discussed. Analysis of the observations showed that the most probable reason for this phenomenon are corresponding variations in radiation from the sun.

In subsequent reports, questions of interaction among various atmospheric layers were considered. An example of modeling research showed that thermosphere dynamics significantly influence the mesosphere. An assumption was stated that in the context of a global electric circuit, it is possible to explain a connection between disturbances of solar activity and strong meteorological events. Questions about the theoretical and experimental study of the interrelation between tropospheric and ionospheric processes were considered.

In a separate report, results of ionosphere variations during solar eclipses and at passage of the solar terminator are presented. These results were obtained both by TEC observations and those in the short-wave range on inclined radio paths. Results of the development of methods of ionosphere vertical probing were presented. Statistical approaches to the analysis of daily variations of TEC were discussed. Improvement of vertical-probing, data-processing algorithms improvement were examined. Conference participants further discussed research directions in the field of mathematical modeling of ionosphere processes, and the opportunity for collective research on subjects of the ionosphere took place in the final meeting of this section.

Information Systems of Environment Monitoring and Safety Insurance

The basic topics of this section were devoted to the problem of decision-making monitoring of high-energy anthropogenic, geophysical, and social processes developing in time. Fifty-eight participants from various regions of Russia took part in this section. In the plenary report, there was an attempt to classify monitoring systems for coordinated radiation-reception gauge resolution as well as the analysis of process features registered in time over frequency or in the analytical continuation of time sequence. In the next report for systems of object protection, information levels of safety analysis on the object's protective cover were proposed.

Monitoring of the anthropogenic phenomena of the large power is presented by a set of the works describing existing space technical systems of monitoring, questions of generation, screening by the conductivity of the electromagnetic pulses, generated by the isotropic gamma pulses of the large power. Time was devoted to a report in which questions of the technical realization of an onboard space receiver intended to detect and determine the physical time of arrival of electromagnetic pulses passing through the ionosphere.

The problem of passive control of the structure of electronic concentration was considered. A presentation on the formation of electric currents created by radioactive plasma electrons was given. Discussion of a problem on the correlation of changes of Volf numbers with the dynamics of solar activity was entertained. Determining the influence of geophysical and anthropogenic phenomena on the unsuccessful startup of space vehicles intended for research on Mars was another topic in this section of the conference.

Burning and Environmental Contamination: Influence on the Environment

Fifty-five participants took part in this section, in which scientific results obtained in Russia, Germany, France, China, the Netherlands, and Austria were presented. Reports were heard and discussed at plenary sessions of the conference and the sessions of it. Other scientists took part in the plenary session.

The plenary report included the concept of a jet propulsion engine capable of controlled detonation burning of an air-hydrogen mixture and included the results of numerical modeling of the working process in a flow-through cylindrical combustion chamber. It was shown that replacement of existing combustion chambers with continuous burning by detonation-combustion chambers could yield great benefits in aerospace technology thanks to the detonation cycle's possible great thermodynamic efficiency. Similar combustion chambers possess important advantages: increased full pressure, decreased fuel expense, and decreased harmful emissions due to the small residence time of the gaseous mixture in the combustion chamber.

Among this section's reports, special interest invoked a report devoted to problems of soot-emission control in piston engines. From 2012 onward in the European ecological standard Euro-VI, a new restriction has been introduced, *i.e.*, the number of condensed-phase particles in automobile engine exhaust gases should not exceed a certain norm for a distance of 1 km. Therefore, developers of the engines are designing filters, converters, and afterburners of particles as well as further perfection of the working process aimed to substantially decrease soot emissions.

In a separate report, topics of discussion involved the results of computation and experimental research directed toward perfection of the working process for burning devices, internal-combustion engines, and jet propulsion engines to maintain energy efficiency and decrease the emission of harmful substances (soot, nitrous oxide, *etc*.).

A report on the application of electric discharges for combustion control was delivered. A report on monitoring air pollution under city conditions along with industrial enterprises was given. A unique database for the calculation of soot-particle distribution functions with reference to internal combustion engines was presented.

A model of smoke-particle coagulation in the outlet system of the piston engine, including different mechanisms of coagulation, was proposed. It was shown that the dominating mechanism of particle coagulation in the outlet system of a diesel engine is the Brownian mechanism.

An additional interesting report was devoted to the perspective of using ecologically clean cryogenic fuel, *i.e.*, methane, for aerospace applications. In this presentation, a new equation of state of methane in the supercritical area across pressure and temperature was proposed.

New Physical and Chemical Methods for Environmental Control and Monitoring

This section is new to the AIS conference. Thirty-nine scientists from the Austria and Russian federation, Germany, and Japan took parting this section, and 6 oral reports were presented.

The plenary report was devoted to the application of new methods of nuclear magnetic resonance for research of diffusion mobility in flexible polymers. This perspective requires qualitative mathematical processing of the results.

A report on thin-layers structure diagnostics for spintronics using magneto-resonant methods sparked interest and a long discussion. A detailed analysis of a role for new types of organo-metallic compounds—*e.g.*, alkyl complexes of bivalent copper—as prospective catalysts of metathesis reactions (interaction of alkanes with four-chloride carbon) was presented. Possibilities of using quantum-chemical calculations to interpret the experimental results of studies regarding the nature of intermediate compounds arising from the interaction of copper chloride complexes with alkyl radicals were considered. Opportunities and some results of dynamic spin-exchange methods in chemical and biological research were analyzed.

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Chapter 1
Optical Quantum Properties of GPS Signal Propagation Medium—D Layer

Gennady V. Golubkov, M.G. Golubkov, M.I. Manzhelii, and I.V. Karpov

Abstract Uncontrollable sporadic distortions of global positioning system (GPS) satellite signals, caused by phase and group delays in the propagation of electromagnetic radiation through a medium, take place during periods of high solar activity and formation of geomagnetic disturbances in the Earth's ionosphere. Determining ways of ensuring sustainability of GPS systems is a fundamental scientific and technical challenge.

Above-background incoherent ultra-high frequency (UHF) radiation is formed at altitudes of the E and D layers of the Earth's ionosphere. Wavelengths of this radiation correspond to a range from 1 dm to 1 mm. This emission is caused by transitions between Rydberg states of atoms and molecules, which are excited by electrons in plasma and are surrounded by a neutral particle environment. Reliable information about UHF radiation flux power in this wavelength range is not currently available. The answer to this question depends entirely on the knowledge of impact and radiation quenching of Rydberg state dynamics and the kinetics of their location in a lower ionosphere, *i.e.*, on the quantum optical properties of a perturbed environment. Analysis of existing experimental data has shown that UHF radiation is formed in the atmospheric layer located at altitudes of 60–110 km. A physical mechanism of satellite signal delay is caused by cascade resonance re-emissions of electromagnetic waves in the decimeter range while passing through this layer over a set of Rydberg states. The most promising approach to studies of medium optical quantum properties can be a simultaneous analysis of background additional noise and GPS signal propagation time delay, which determines a positioning error. Using standard methods of noise measurement, one cannot detect physical and

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chemical processes responsible for noise formation and errors affecting positioning. Therefore, the problem can be solved if the level of a background noise is considered as a noise of the measured GPS signal because propagation delays of the latter are caused by one of the most important atmospheric collisional process, *i.e*., the orbital degeneracy of highly excited states. For this purpose, it is advisable to use the *S*/*N* ratio where a signal corresponds to a level of a signal obtained by the GPS receiver and a noise corresponds to a GPS signal fluctuation.

In this chapter, a current state theory is examined, and manners of its further development are discussed. These are associated with the progress of theoretical methods for describing medium neutral particle impact effects on the dynamics of collision and radiation quenching focusing primarily on elementary processes involving molecules of nitrogen and oxygen. It has been shown that preliminary calculations of nonadiabatic transition dynamics between potential energy surfaces (PES) of Rydberg complexes, construction of appropriate electronic wave functions, calculations of allowed transition dipole moments, and determination of emission line shapes are necessary for the quantitative estimation of the influence of excited particles on a spectrum of incoherent UHF radiation of the atmosphere. These results should be included in the total kinetic scheme, which establishes the dependence of UHF radiation on temperature and density of the lower ionosphere. Then satellite-monitoring data of infrared (IR) radiation, which accompanies UHF radiation, can be directly used for the detection of Rydberg states and diagnostics of plasma parameters.

Keywords Highly excited states of atoms and molecules • D and E layers of lower Earth's ionosphere • Neutral particles of medium • Rydberg complexes • *l* mixing • Nonequilibrium two-temperature plasma • UHF microwave radiation

1.1 Introduction

Experimental and theoretical studies of ionosphere states, as well as the physical–chemical processes occurring in them, are largely connected with the need for the reliable operation of Global Navigation Satellite System channels in different frequency ranges. In recent years, much attention has been paid to the improvement of satellite communication and navigation systems that use trans-ionospheric data channels. This has led to a necessity for the development of a special experimental technique that aims to further study the ionosphere structure to establish physical reasons for the delay of GPS signals.

Measurements of group delay and phase signals from navigation satellites, along with the total electron content (TEC), have been used for numerous studies of the irregularities in the ionosphere's structure and dynamics. To analyze the ionosphere's structure and dynamic disturbances, TEC-distribution maps with high temporal and spatial resolution have been created. This is impossible to realize on the basis of ground station's vertical sounding observations. In a monograph (Afraimovich and Perevalova 2006) are described the existing methods of ionosphere research based on the incoming satellite's GPS signals. On the basis of TEC analysis, the investigations greatly expanded our understanding of the ionosphere's physical structure and its dynamic irregularities of dynamics, which are associated with geomagnetic disturbances and perturbations of solar activity.

Reliability of communication and navigation systems using ionospheric communication channels depends on knowledge of the ionosphere's behavior under calm as well as disturbed conditions. Current trends in the development of communications technology are focused on increasing the carrier frequency. This fact determines a situation where irregularities should be considered not only to be ionospheric plasma perturbations associated with the dynamics of the atmosphere but also the processes associated with the interaction of propagating electromagnetic waves with neutral atoms and molecules of the medium. On one hand, this leads to a complicated description of electromagnetic wave propagation. On the other hand, the analysis of disturbances and disrupted operation of space communications systems using a UHF band, as well as the development of theoretical ideas about the physical processes responsible for these phenomena, provides new information about the environmental state and opens the possibility of further improvement of communication systems.

It is now established that during the periods of increased solar activity in the E and D layers of ionosphere at altitude 60–110 km above the Earth's surface UHF radiation is formed, the intensity of which is much greater than typical levels of microwave bursts from the sun (Avakyan 2008). In particular, UHF was observed using the radio-telescope Nizhny Novgorod Radiophysical Institute during geomagnetic disturbances at a wavelength range of 3–50 cm (Troitskii et al. 1975). Observations were noted simultaneously at several points during the project SETI. Analysis of different generating possibilities of detected UHF radiation has shown that the greatest contribution to the resulting picture of the spectrum are radiative transitions between Rydberg states of the nonequilibrium two-temperature plasma neutral component excited by a flux of a sunlight or electron flux emitted from the ionosphere (Golubkov et al. 2011a).

Such highly excited states, which are located near an ionization limit and are characterized by the presence of an infinite sequence of energy levels converging to the ionization threshold, are called "Rydberg states." They represent an intermediate between low-lying electronically excited states and ionized states. Microwave radiation at frequencies of 600 MHz, as well as additional luminescence emission of oxygen atom red lines (Grach et al. 2005), are generated in the ionosphere during the conduction of active experiments that consisted of heating the ionosphere by powerful pulses of radio waves at frequencies of 4.7–6.8 MHz. Transitions between oxygen atom Rydberg states were also recorded in the luminescence of the night sky in spectral range 394–927 nm (Slanger et al. 2004). Analysis of different generating possibilities of the observed microwave radiation showed that the greatest contribution to the resulting view of the spectrum comes from transitions between Rydberg levels of the ionospheric plasma neutral molecule's component, which is excited by collisions with electrons (Golubkov 2011).

Rydberg states of atoms and molecules are populated in conditions of nonequilibrium two-temperature recombination plasma formation. Their binding energy is above a certain characteristic value E_* of energy (Biberman et al. 1982). Such plasma is created in the upper atmosphere by fluxes of electrons spilling from the ionosphere during strong geomagnetic disturbances (Golubkov et al. 2012a). The distribution of population over levels E_n located near the ionization limit is practically at equilibrium and is characterized by a temperature close to the temperature T_e of free electrons. For larger binding energies, $E_n \sim E_*$ in the energy range $\Delta E \ll E_*$, the equilibrium distribution is strongly violated. This interval is called a "neck of flow" or "recombination flux bottleneck" (Gudzenko and Yakovlenko 1982). Above the neck of flow for the energy $E_n \leq E_*$, collisional transitions between the bound states and the continuum dominate. Below the neck of flow, radiative transitions dominate, thus leading to the equilibrium population of the medium molecule's low-lying states with a temperature equal to medium temperature T_a.

A neutral medium concentration varies in the range of $10^{12} < \rho_a < 10^{16}$ cm^{-3} for E and D layers. A concentration of highly excited particles formed here, as shown below, is defined by free electron temperature T_e and density of free electrons n_e and also depends on medium density. Therefore, for $\rho_a \geq 10^{16}$ cm^{-3}, their concentration should decrease sharply. One should also expect that states with principal quantum numbers in the range of $n \approx 20 \div 70$ will be most effectively populated.

Rydberg atoms and molecules possess an excited weakly bound electron, the state of which is characterized by an energy level and angular momentum l relative to ion core. Energy levels with large angular momenta do not depend on l (orbital degenerate states). Statistically, the most stable are these Rydberg states in which the electron spends most of the time at large distances from the ion core. The process leading to the formation of such states is called "l-mixing" (Hickman et al. 1983; Golubkov et al. 1998, 2010; Golubkov and Ivanov 2001a). In the upper atmosphere, this proceeds rapidly and is irreversible, *i.e.*, all Rydberg particles are orbitally degenerated. As a result, the differences between highly excited atoms and molecules are lost, and the emission spectrum should depend mainly on a composition of the upper atmosphere's neutral component.

During the origination of a magnetic storm in the E and D layers, a separation takes place of the electron temperature T_e and the medium temperature T_a, and two-temperature nonequilibrium weakly ionized plasma is formed. In the text below, we present the neck-of-flow E_* location calculation results, as well as the populations of the orbitally degenerated Rydberg states m_n, with respect to parameters characterizing a level of the magnetic storm (temperature T_e and free electron concentration n_e) and T_a, ρ_a of neutral medium (Golubkov et al. 2012b). Also indicated are emission bands $\Delta n = 0$ for transitions between the split-off and Coulomb-degenerated Rydberg states and quasi-molecules $A^{**}N_2$ and $A^{**}O_2$ located near energy E_* of the neck of flow. Three bands located in frequency ranges 1.17–1.71, 4.31–6.09, and 7.27–57.10 GHz, in which there is a strong attenuation of UHF radiation, are found.

Their appearance, as will be shown by us, is connected by differences in the characteristics of slow electron elastic scattering by molecules of nitrogen and oxygen. At an increased magnetic storm level, the UHF radiation profiles change dramatically, *i.e.*, grows on the right side of the range corresponding to the highest frequencies of transitions. Established non-monotonic behavior of the frequency profile in the middle of the lower range is connected with non-homogeneity of the emission spectrum (Golubkov et al. 2012b).

This review examines the possibilities of using distortion of GPS signals during periods of increased solar activity as a working tool for studies of quantum optical properties of their propagation medium. The possibility of reconstructing upper-atmosphere parameters and assessing positioning errors by simultaneously using GPS signal and IR radiation are discussed. For this goal, we consider the properties of incoherent UHF radiation spectrum of atmosphere D-layer Rydberg states in the range of 0.8–8.0 GHz for different levels of geomagnetic disturbances. The possibility of undertaking such assessments is connected with the following facts: (1) near frequencies of 1.44 and 5 GHz, the power flux of UHF radiation does not depend on electron temperature; and (2) the dependence of the GPS propagation delay is proportional to the population of Rydberg states near these typical frequencies and has a quadratic dependence on UHF radiation frequency.

1.2 Tools for the Registration of Lower-Ionosphere Disturbances During Periods of Enhanced Solar Activity

1.2.1 Influence of Solar and Geomagnetic Disturbances on the Quality of Satellite Navigation System Operation

It is known that during geomagnetic and solar disturbances, the operational quality of satellite signal receivers deteriorates, which is revealed by increased density and localization of faults. The accuracy of satellite navigation systems decreases, which significantly affects determination of the current location. These conditions produce a tendency toward an increased number of dual-frequency regime failures of current-location determination as well as difficulty in obtaining synchronization signals for GPS receivers. According to (Afraimovich et al. 2003), intense mid-latitude flickers of GPS signal amplitude at frequency $L_1 = 1.57542$ GHz with a depth of fading $\leq$20 dB were observed for the first time in the northeastern part of the United States during a geomagnetic disturbance on 25–26 September 2001. The flickers were registered at the receiving station of Cornell University with the help of a modified GPS receiver with a scan rate of 50 Hz. According to (Yizegaw et al. 2006), a sharp increase in positioning errors ($\leq$120–280 m) and failures in the determination of coordinates were observed during the same disturbance at a number of mid-latitude stations in the regions of North American and eastern Siberia equipped with ASHTECH receivers (Afraimovich et al. 2003; Yizegaw et al. 2006).

Experimental data have shown that signal fadings in the decimeter range were deeper than would be expected according to numerous measurements. In addition, these fadings were observed at mid-latitudes where they were not expected. These data support the assumption about GPS signal degradation and subsequent decreased accuracy and continuity of positioning. Similar phenomena were observed in measurements carried out by Orenburgenergo in 2009 (Krasnyshov et al. 2010). Crashes of dual-frequency mode positioning are more frequent than single-frequency faults.

Failures of a dual-frequency positioning regime are more frequent than those of a single-frequency positioning regime. The main reason for this could be decreased signal level at the secondary (closed) frequency $L_2 = 1.22760$ GHz with respect to the basic L_1 frequency. Thus, the received power at an elevation beam angle for NC 45° was 159 dB/W at L_1 frequency and 166 dB/W at closed frequency L_2. Anomalous fluctuations registered during 13 months of observations appeared predominantly at night. Their duration varied from 5 s to 2 min. These phenomena were observed during sporadic increases in solar activity (Afraimovich and Perevalova 2006).

The experiments were performed using Wide Area Augmentation System (WAAS) basic stations whose precise coordinates were known, GBAS ground transmitting stations whose precise coordinates were also known, and GPS satellite-transmitted positioning signals. Coordinates determined for base stations according to observations of flying satellites were compared with their exact coordinates. As a result, a correction signal was generated and sent to the satellite or the ground basic station. The correction signal, together with the positioning signal, is used by consumers (consumers can use a mobile station placed in a car).

Ionosphere delays of satellite signals are determined by the distribution of electron density along the satellite-receiver route. Extensive experimental data on the distribution of electron density below the maximum of the ionosphere F-2 layer (*i.e.*, below 300–400 km) were accumulated during long-term studies of the ionosphere vertical structure using ionosondes. The distribution of electrons above the maximum of the ionosphere is known to be much worse. Separate data on the structure of the ionosphere above the maximum of the F layer were obtained in experiments with ionospheric sounding (or probing) by satellites. However, these data were not sufficient for empirical modeling of the ionospheric structure above the upper limit of the F layer due to the absence of regular monitoring (Radievsky et al. 2010). Currently, observations—with the goal of reconstructing the structure of the upper ionosphere by GPS satellite signals received by stations in the circumterrestrial orbit (Cosmic, Leo, etc.) and by ground stations—are actively being carried out. Thus, the problem of reconstructing the electron-density profile in the ionosphere from observations of satellite GPS signals was considered in (Yizegaw et al. 2006). Reproduction of the concentration profile was performed in this work by tomography methods. As noted in (Yizegaw et al. 2006), this method was historically developed in Russia (see, for example, Kunitsyn and Tereshchenko 2003) and is presently widely used (Kunitsyn et al. 2010; Nesterov and Kunitsyn 2011).

In (Afraimovich et al. 2003), evaluation and correction of ionospheric delay signals that according to the authors should improve the accuracy of navigation, communication, and space weather forecasting, was carried out. These studies, the results of which contribute to the rapid development of studies in near-Earth space, are being performed both in Russia and abroad. In particular, these studies were conducted in West Branch Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, RAS (IZMIRAN) (Russian) (Yizegaw et al. 2006) where extensive data on various algorithms for electron-density profile reconstruction have been accumulated.

Observations of satellite signals give integral electron content along "satellite-receiver" routes. Reproduction of profiles requires solving the inverse problem on the basis of systematic *a priori* information, which is currently absent. As a rule, a model theoretical description is used that is based on simplified notions of electron ionization and diffusion processes in the ionosphere, *i.e.*, the "Chapman layer." The functional dependences of electron density over the altitude based on such conceptions are applied in almost all empirical models used in practice. In particular, in the International Reference Ionosphere models (international joint project of COSPAR with the Union of Radio Sciences), global distribution of electron density at altitudes from 50 to 2,000 km is determined on the basis of satellite- and ground-based ionospheric studies.

The accuracy of electron-density profile reconstruction is determined by reliable measurements of electron density at any high altitude point along with thermospheric temperature changes (along both horizontal coordinates and altitude). Due to inaccuracies of these data, errors in electron concentration appear at altitudes >400 km. According to (Yizegaw et al. 2006), the main reason is inaccurate tuning of Chapman-layer parameters in calculations using algorithms for profile reconstruction, *i.e.*, the scale of heights was estimated incorrectly using temperature and gas composition. A similar situation occurred in COSPAR, where the presented data of the empirical model were based only on theoretical concepts of electron-density behavior above the maximum of layer and did not contain any direct or indirect measurement data.

Developers in the United States have increased the number of ground-based stations and deployed an alternative ground station network that uses cellular signals. These activities are devoted to increasing the accuracy of positioning systems, particularly during geomagnetic disturbances. Thus, at present our understanding of the physical reasons for delayed radio signals in the upper atmosphere is limited by the lack of experimental data on the medium's parameters under disturbed conditions and simplified concepts of electromagnetic wave interaction with the propagation medium in the ionospheric plasma.

1.2.2 GPS Positioning Error

An increase in positioning errors of global navigation satellite systems during periods of increased solar activity can occur for both short (5–20 min) and long periods of time (several hours). In the first case, errors occur due to radiation coming from solar flares. The second case is realized 30–35 h after an outburst under the influence of the solar wind.

A concrete example is the time-dependence of GPS satellite system violations during periods of solar activity, which was published by Cornell University (http://gps.ece.cornell.edu/realtime.php). According to measurements carried out at real-time monitoring stations of Arecibo Observatory (Puerto Rico) daily from August 30 to September 02, 2011, between 03.00 and 04.00 (Coordinated Universal Time [UTC]), there was a 20-min failure of GPS systems. The horizontal positioning error reached $\geq$50 m.

More powerful geomagnetic disturbances lead to the complete disappearance of signal at the GPS receiver for a longer periods of time (http://gps.ece.cornell.edu/realtime.php). Thus, the data obtained at Sao Luis Observatory (Brazil) on September 15–16, 2011, showed that the loss of GPS signal occurred several times during the day. The signal at the receiver sporadically disappeared five times for 5–30 min each time between 16.00 UTC September 15 and 01.00 UTC September 16, 2011. Moreover, the horizontal positioning error during this time period exceeded 50 m.

No less interesting is the detection of high-power IR radiation in the range of 14–100 μm, which was first measured by the spectrometer FIRST on June 7, 2005 (Mlynczak et al. 2006). Particularly significant here is the presence of an intensity peak in the vicinity of 20 μm, which greatly decreased with decreasing wavelength $\leq$14 μm. Below we will give an explanation of these phenomena on the basis of physical and chemical processes in nonequilibrium two-temperature plasma, which is formed in the D and E layers of the Earth's atmosphere.

1.2.3 Registration of Changes in Signal/Noise Ratio

Strong geomagnetic disturbances of the Earth's ionosphere are formed as a result of a sharp increases in solar activity accompanied by the emission of particles and electromagnetic radiation. One of the most interesting and important manifestation of such disturbances is the failure of GPS caused by a significant decrease in the signal-to-noise (S/N) ratio as well as the inability to select the satellite signal during background noise. Because the reliable performance of satellite navigation systems is extremely important, researchers have carried out a number of special studies to determine the causes of emerging technology issues. An independent group of scientists carried out additional measurements of atmospheric radiation in the frequency range of 1–5 GHz. A GPS receiver with a sampling frequency of 50 Hz was used by investigators from Cornell University for simultaneous detection of the satellite signal (http://gps.ece.cornell.edu/realtime.php/Naval_Air_Systems_Symposium.ppt).

First, direct measurements of radio emission under quiet sun conditions in the frequency range of 1.5–18 GHz were carried out in September 2005. The noise

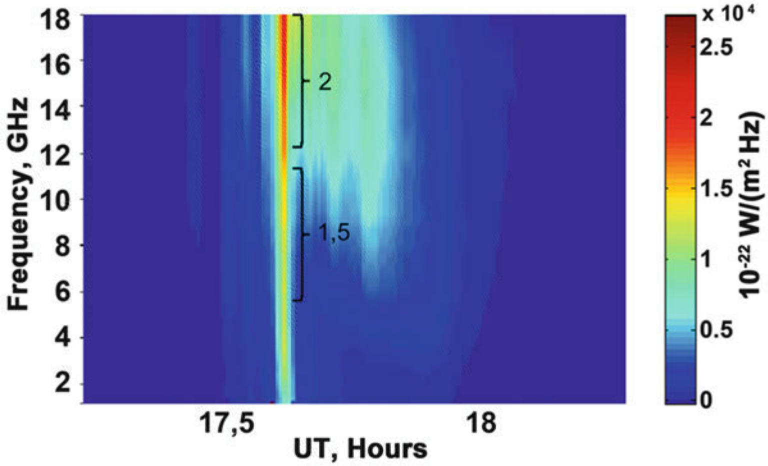

Fig. 1.1 The *f* frequency and power of the incident radiation dependence on time

power in the specified frequency band turned out to be negligible and reached only 2.7 dB (see Fig. 1.1). Radiofrequency power is weakly frequency dependent and is practically uniform over a wide range of its variation. Therefore, for the time moments 17.5 and 18.5 UT (where UT is medium-American time in hours and minutes), a constant value of *S*/*N* ratio should be observed in this frequency range.

The observations presented in Fig. 1.2 demonstrate the validity of this assumption. The upper graph shows the dependence of the *S*/*N* ratio obtained from the satellite PRN25 with an interval equal to 24 h. The circles on the graph denote the results of the measurements carried out for 2 h simultaneously with measurement of the incident radiation power, which is shown in Fig. 1.1.

It can be seen that the formation time of *S*/*N* ratio local minima (Fig. 1.2) and radiation power maxima (Fig. 1.1) strictly coincide. The dependence, which is illustrated in black, presents the results of measurements carried out exactly 1 day later at a lower emission power for the determination of a hardware error. With the exception of these local minima, comparison of the black curve with the circle-marked curve shows that the *S*/*N* ratio is constant during the entire period of observation. The latter indicates the stability of the measurement system. As follows from the data shown in Fig. 1.2, the values of local minima, which depend on radiation power, are <3 dB, *i.e*., they do not cause failure of the GPS.

The lower graph in Fig. 1.2 shows the time-dependence of the radio wave radiation power. The black line indicates the total power of the radio emission. Circles and dashed lines denote signals relating to the right and left circular polarization, respectively. Isolation of the two polarizations is performed to determine the overall capacity. The radiation power is given in units of SFU (1 SFU $= 10^{-22}$ W/m^2 Hz), which is applied to determine the density of radio

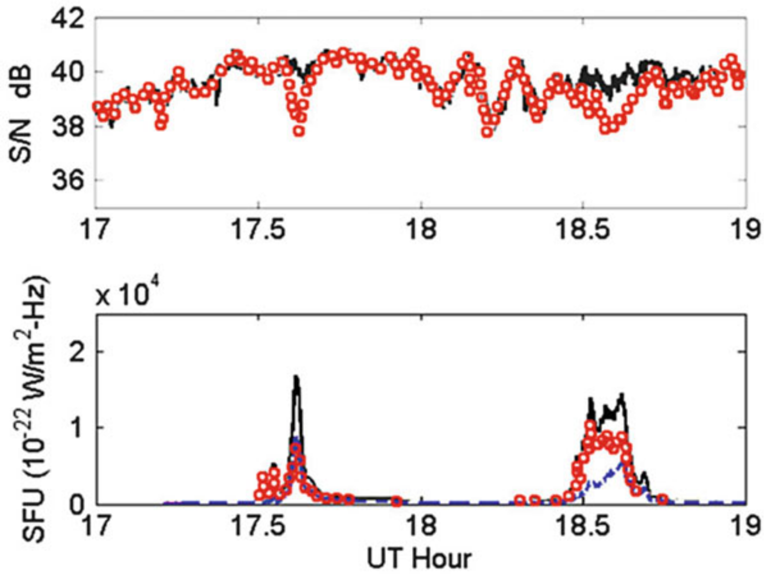

Fig. 1.2 Time dependence of *S*/*N* ratio and incident power on time obtained from GPS satellite PRN 25 (pseudo-random noise 25) by a receiver at frequency L_1

flux from the sun registered on Earth. $F_{10.7}$ index is the output radiation power at a wavelength of 10.7 cm corresponding to a frequency 2.8 GHz. Because radiation power (Fig. 1.1) is almost uniform in a wide frequency range, these measurements can be compared with those made at the frequency of the GPS.

In contrast to the results obtained under a quiescent sun (see Fig. 1.2), the following measurements were carried out at the time as the class X3 solar flare during a period of 2 h at L_2 frequency. This dependence of the *S*/*N* is shown in Fig. 1.3 where it is compared with the results obtained under a quiescent sun.

The black graph corresponds to measurements performed during a quiet sun. The black line with red circles corresponds to measurements carried out during the class X3 solar flare. During the sun flash, the *S*/*N* ratio decreased by 20 dB, which can lead to loss of the signal detected by a receiver. Moreover, as shown in Fig. 1.4, the observed effect does not depend on the type and band of filters used in the receiver. The upper dependence, marked by circles, represents the result of a filter with a bandwidth of 5 Hz. The lower black curve corresponds to a filter with a 15-Hz bandwidth. In both cases, the magnitude of pulsation is not less than 20 dB, meaning that the elimination of GPS signal failure based on circuit design is not feasible.

It has been shown in (http://gps.ece.cornell.edu/x6flare.php) that during solar flares of different power, there is a certain sequence of decreasing *C*/*N* ratio for frequencies L_1 and $L_2 = 1.22760$ GHz (see Fig. 1.5). During a class X1 solar flare (22.15 UTC; 15 December 2006), the *C*/*N* ratio for frequency L_1 became worse. At

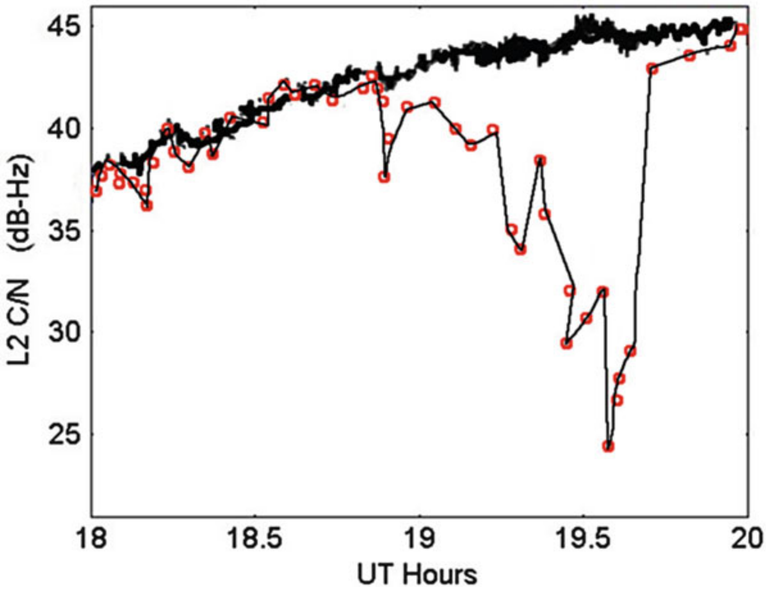

Fig. 1.3 Time dependencies of *S*/*N* ratio obtained at frequency L_2 by a receiver at active (class S6) and quiet sun. Time-averaged measurements for solar class S6 curve (o) and for quiet sun (●)

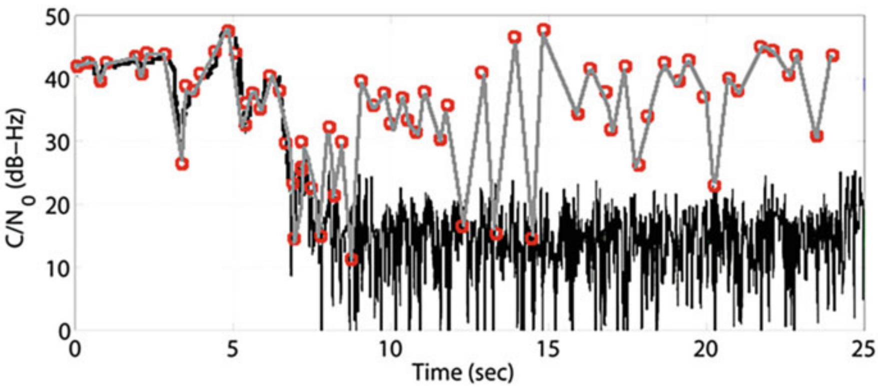

Fig. 1.4 Time dependence of *C*/*N* ratio for two types of filters. Results of adaptive Kalman filter ([KFPLL] *circles*) and band pass filter ([CBPLL] *black line*)

the same time, the *C*/*N* ratio for L_2 frequency remained unchanged (see Fig. 1.5a). The class X3 flare (02.40 UTC; 13 December 13) led to a simultaneous deterioration of *C*/*N* ratio for both frequencies (see Fig. 1.5b). In both cases, the duration of the observed phenomena was approximately 30 min. In principle, this behavior of *S*/*N* ratio cannot be explained by the impact of broadband solar radio emission.