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DYNAMICS OF NATURAL IRREGULARITIES AND STIMULATED IONOSPHERIC IRREGULARITIES CAUSED BY A POWERFUL RADIO EMISSION WITH SCALES OF 5÷50 KM TO THE DATA OBTAINED RADIO AND OPTICAL MEASUREMENTS

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Phd supervisor: candidate of physical and mathematical sciences, associate professor
Nasyrov I. A.

Official opponents: **Krasheninnikov Igor' Vasil'evich,**
doctor of physical and mathematical sciences, senior researcher (associate professor)
Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation Russian Academy of Sciences,
head of the laboratory of wave field modeling in the ionosphere, leading scientific researcher

Padokhin Artem Mihajlovich,
candidate of physical and mathematical sciences,
Lomonosov Moscow State University,
senior researcher chair of Physics of Atmosphere

Leading organization: Polar geophysical institute

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Scientific Secretary
of the dissertation council
D 212.081.18
cand. sc., associate professor

A. D. Akchurin

GENERAL DESCRIPTION OF WORK

Motivation for the Study. The study of the physical mechanisms of development and relaxation of plasma turbulence in a magnetically active plasma, responsible for the formation of electron concentration fluctuations, using various, including combined diagnostic methods, is one of the urgent problems of the physics of the upper atmosphere. At present, a sufficiently large number of events, both natural and artificial, are known that can affect the distribution of electron concentration in the upper ionosphere, thus creating local electron concentration perturbations leading to the development of plasma instabilities and a number of other events. Such disturbances can also have a significant impact on the propagation of radio waves in a wide frequency range and lead to a decrease in the reliability of terrestrial and space-based radio systems. In the past two decades, for the study of ionospheric irregularities of electron concentration with scales of $5 \div 50$ km, they actively use radio sounding signals from global navigation satellite systems (GNSS): GLONASS and GPS. This method has been widely used in studies carried out during active experiments on the effects on the ionosphere by powerful short-wave radio emission, in studies of ionospheric effects and their precursors during extreme heliogeophysical events, such as magnetic storms, solar flares, eclipses, as well as regular events, for example , movement of the solar terminator (ST), etc. Currently, this method is actively developing, new global (GALILEO; BeiDou) and regional (IRNSS; QZSS) navigation satellite systems are being deployed, the number of stations equipped with GNSS receivers and coverage is increasing, the instrumental base of data is being improved and improved.

Experiments on the effects on the ionosphere by powerful short-wave radio emission on the «Sura» and «HAARP» stands [1–4] were found to be wave disturbances diverging from the center of the disturbed region to large distances (100 – 900 km). The frequency of the pump wave in these experiments was lower than the characteristic Brunt-Vaisala frequency of the neutral atmosphere at the corresponding altitudes. The authors of [2, 4] put forward the hypothesis that the observed perturbations can be acoustic-gravity waves generated due to the formation of sharp temperature gradients inside disturbed region, when the radiation of the pump wave occurs at a frequency less than or on the order of the Brunt-Vaisala frequency. At the same time, when the ST moves in connection with its violation of the ionization balance and dynamic equilibrium caused by a rapid change in the degree of illumination, an area of sharp gradient of the main ionosphere moving at the height of the F-region of the ionosphere is formed in the frontal zone parameters-electron concentration, electron and ion temperature, recombination coefficient, ion formation rate, etc. This, in turn, can lead to the generation in the F-region of the ionosphere of a solitary wave, the soliton [5]. The study of the physical processes occurring in the region of temperature gradients inside disturbed region, when exposed to powerful radio waves, and with regular events such as the movement of STs, is a hot topic of modern studies of the Earth's upper ionosphere (F-region), since nonlinear turbulent processes in a magnetoactive plasma from various sources of excitement may have common patterns and have similarities. In general, such studies are of undoubted interest, since they contribute to a deeper understanding of the terror-atmospheric-ionospheric connections, solar radiation generation processes, the behavior of the Earth's ionosphere and the Earth's magnetosphere under various natural and artificial perturbations.

The state of the investigated question. The ascertaining of physical mechanisms of the development of plasma irregularities responsible for electron density fluctuations is one of the fundamental problems in the physics of the upper atmosphere (altitudes from 80 to 1000 km). When the ionosphere is irradiated by high-power ground-based radiation, ionospheric disturbances develop due either to plasma displacement from the region of its heating or to additional ionization of the neutral component by electrons accelerated by plasma waves. The resulted electron concentration inhomogeneities are from tens of centimeters to tens of kilometers in size [6]. The electron concentration inhomogeneities on 5÷50 km scales can be effectively studied with dual-frequency radio transmission of GPS and GLONASS navigation satellites. When propagating through the disturbed region of the ionosphere, such signals have an additional phase shift due to the dispersion of radio waves in the ionospheric plasma and is linearly related to the total electronic content (TEC) on the signal propagation path. Since the GPS/GLONASS is moving rather slowly across the sky (the linear speed of movement is approximately 1.75 km/min (at an altitude of $h = 200$ km), the ionospheric penetration point remains within the considered area for 25 — 35 minutes , which allows to obtain information on both spatial and temporal characteristics of inhomogeneities, given their low speed of movement in the resonant layer.

To date, in the field of research of nonlinear effects arising from exposure to the ionosphere by powerful short-wave radio emission focused in the vertical or oblique direction, using the signals emitted from the GPS / GLONASS, the following main results have been achieved:

1. in the experiments carried out in the daytime [7–9], the TEC variations were± 0.05 TECU (Total Electron Content Unit – общепринятая единица измерения ПЭС, 1 TECU=10^{16} эл./м^2), which is significantly lower (by 3-10 times) the level of TEC variations observed in experiments conducted during evening and night hours. The scattering of the GPS signal on super small striations has been registered during the emission of a pump wave with a frequency in the region of the 4th harmonic of the electronic gyroresonance [8–10], which, apparently, are associated with the Bershtein modes, as

well as strong GPS scattering The signal indicates the presence of BUM components (Broad Upshifted Maximum - Wide Positive Maximum) in the spectrum of artificial radio emission from the ionosphere. According to wavelet analysis [1, 7], both even (2 and 4) and odd (1, 3 and 5) harmonics of the main periodic component equal to the duration of one cycle of exposure to the ionosphere by powerful radio emission were detected in the TEC series;

2. during observations mainly after sunset, the TEC variations were $0.2 \div 0.4$ TECU. Ultra-fine-scale inhomogeneities in the region of the 3rd harmonic of the electronic gyroresonance [11] have been recorded. Small-scale irregularities of [2, 12] were found inside the region with a reduced electron concentration limited by the bottoms of the "Sura" stand. Wave-shaped disturbances were detected, diverging from the center of HE over long distances (100—900 km) [1–4] when using the frequency of the pump wave, set below the characteristic Brunt–Väisälä frequency of the neutral atmosphere at the corresponding heights;

3. when tilting the bottom of the "Sura" stand at 12° in the plane of the geomagnetic meridian, the most striking manifestations of the generation of ionospheric disturbances are observed in the magnetic zenith [13] (see also the publications [14, 15]). The amplitudes of the TEC variations observed in this case are 20% larger compared with the amplitudes of the TEC variations recorded when the pump wave is emitted in the vertical direction;

4. experiments on the "Sura" stand, carried out with powerful radio waves with extraordinary polarization [16] on the ionosphere with an effective radiated power of $100 \div 150$ MW, showed that the generation of ionospheric irregularities detected by radio sounding by GNSS signals, in this case it is an order of magnitude less effective (the amplitude of TEC variations was $0.02 \div 0.03$ TECU) than when the ordinary polarization was modified by radio waves ($0.2 \div 0.4$ TECU). The strongest variations of TEC are observed at the edge of the disturbed region, which is limited by the main lobe of the directivity pattern of the stand. One of the possible explanations of the observed "edge effect" is the occurrence of solenoidal currents in the field of powerful radio waves emitted by the stand.

Dual-frequency radiosonding with GPS/GLONASS signals also effectively used to study such a phenomenon as solar terminator. In the work [17] the results of the analysis of TEC variations, measured according to the global network of GPS receivers, were presented. Two main types of disturbances observed in the TEC data were found: long-period (about 60 minutes) variations with an amplitude of about $0.5 \div 1$ TECU and short-period (about 15 minutes) variations with an amplitude of $0.05 \div 0.1$ TECU. The second type of observed disturbances, called wave packets (VP), has a duration of about 1-2 hours and a shift in time of about 1.5-2.5 hours after the appearance of the ST at an altitude of 100 km. The study of disturbances generated during the motion of the ST using the measurement of TEC variations was continued in [18], in which it was shown that the period and wavelength of running EPs are about 10–20 minutes and 100–300 km, respectively. The speed of movement of the phase front of the observed EP is about 300 m/s. The observations made in [19] confirm that ST is a stable and repetitive source of ionospheric wave disturbances. The authors of the work [19] obtained the first experimental evidence in favor of the magnetohydrodynamic (MHD) nature of the generation of nighttime medium-scale traveling ionospheric disturbances (TIDs) (including medium-scale TIDs generated by the ST motion), which in summer, for example, are detected as 1.5 -3 hours before evening ST at an altitude of 100 km above the observation point

Another effective method for studying the structure of a disturbed region with dimensions across the $l_\perp \gtrsim 0{,}5$ km geomagnetic field is to measure the artificial optical glow of the ionosphere in the red line of atomic oxygen ($\lambda =$ 630 nm) associated with level $\mathrm{O}(^1D)$ to the ground state $\mathrm{O}(^3P)$. The excitation potential of the $\mathrm{O}(^1D)$ level, the lowest of all observed lines of artificial optical luminescence, is 1.96 eV, and its radiative lifetime is $\tau_r(\mathrm{O}(^1D) = 107$ s. Optical emission arises when electrons transfer from excited levels of atoms, molecules and ions of the ionosphere to lower energy levels.The corresponding levels are excited when atoms collide with electrons whose energy exceeds the excitation potential of these levels, and as a result of ion-molecular reactions, de energy appears sufficient to excite one of the atoms, in particular when molecules are dissociatively recombined. The images of the disturbed region of the ionosphere in the 630 nm line, recorded using CCD cameras with the corresponding light filters, the structure of glow spots with an angular size of the order of 1–10° (this corresponds to $\sim$ 5–50 км at altitudes of 250–280 km above the Earth's surface), often moving in space with prolonged heating [15, 20–23].

The magnitudes of the irregularities in the disturbed region of the ionosphere, which are determined by means of TEC measurements, and the characteristic dimensions of the artificial airglow patches are thus close. In this connection, the problem of comparing the magnitude of TEC variations when flying navigation satellites and the brightness of an artificial gairlow in a disturbed region is of undoubted interest. In particular, this concerns the question of whether artificial luminescence is generated in the region of increased or decreased electron concentration and, therefore, electron acceleration occurs.

In the experiments conducted on the "Sura" booth at exposure powers ($\sim$60–120 MW), scanning the disturbed area with GPS signals revealed variations in TECs with observed characteristic periods $\sim$ 300–1200 s and magnitudes up to $\sim$ 0.6 TECU, which do not correlate with the cycles of the impact of the pump wave on the ionosphere [7, 14, 24]. These experimental results indicate that during exposure to the ionosphere within the DN of a heating stand, ionospheric heterogeneity is formed with a scale across the line of sight $\sim$ 10–60 km. Since with such powers no noticeable additional ionization is observed, we should expect the pump wave to refract to a region of low concentration, and therefore, more efficient acceleration of electrons and the generation of artificial airglow in this region. The first attempt to analyze the simultaneous measurements of the TEC and the brightness of the optical glow was made in [23].

Object of the research is the irregularities of the electron concentration of the Earth's ionosphere, with scales of $5 \div 50$ km, stimulated by both natural and artificial factors recorded using measurements of the GPS/GLONASS NS signals and joint analysis of the TEC behavior and the brightness of the artificial airglow in the 630 nm line in the direction of the satellite passing through the field of view of the CCD camera.

Purpose of the research: experimental studies of the mechanisms of development, relaxation and transfer of electron concentration perturbations in the Earth's ionosphere, arising from artificial and natural influences on it, in particular, such as radiation of high-power radio waves and movement solar terminator using measurements in radio - and optical wavelength range.

Achieving the stated goal required solving the following **tasks:**

1. conducting a series of experiments to measure TEC variations stimulated by the powerful short-wave radiation of the "Sura" facility, using dual-frequency radiosonding with GPS/GLONASS signals on the GNSS network of stations. To do this, it was necessary to develop software that allows: to process navigation messages from GNSS GPS and GLONASS, presented in the RINEX format; predict the orbital motion of the satellites GPS/GLONASS; calculate TEC by pseudo-range and phase measurements;

2. performing a detailed analysis and interpretation of data obtained in experiments on the measurement of TEC variations, stimulated by powerful radio emission from the "Sura" stand in the period 2010–2017. Determine the conditions for the generation of recorded disturbances depending on the state of space weather and the used modes of exposure to a powerful radio wave. Perform an assessment of the spatial dimensions and speed of traveling of such disturbances;

3. registration of the response of the ionosphere to the motion of the solar terminator in the mid-latitude ionosphere conditions by using dual-frequency radiosonding with GPS/GLONASS signals on the GNSS network of stations. Determination of characteristic periods and speeds of movement of the observed disturbances;

4. improvements in the methods of conducting and processing the data of joint synchronous measurements of variations of artificial airglow in 630-nm line and TEC along the line of sight on the GPS/GLONASS satellites passing through the disturbed region of the ionosphere by powerful radio emission. Development of software that allows for a joint analysis of the spatial behavior of the TEC on the GPS signal path and the artificial airglow in 630-nm line in experiments on the “Sura” facility.

Original Contribution. The results presented in the dissertation are based on a series of experiments carried out on the “Sura” facility, as well as a series of measurements of TEC variations for natural conditions performed on the GNSS network of stations (Kazan - EAO - Zelenodolsk - Vasil’sursk), located along geomagnetic latitude of the “Sura” facility in the period from 2010 to 2017 years. In the course of the dissertation, new results were obtained, including:

1. it was found that under the influence of a powerful radio wave in the ionosphere, irregularities with transverse scales of about 30–60 km are formed, which can propagate across the lines of force of the Earth’s magnetic field with horizontal velocities of about 300–370 m/s. The size of the stimulated ionospheric irregularities seems to be related to the linear scale of the main lobe of the antenna pattern of the “Sura” stand at the F- region of the ionosphere, where the maximum perturbation of the electron density due to the wave effect should occur pumping;

2. it is shown that when the antenna pattern of the “Sura” facility is inclined to the south by 12° (in the direction of the “magnetic zenith”), there is a more confident excitation of TEC variations compared with the case of radiation strictly to the zenith. The amplitude of the TEC variations becomes larger by 15–20%, which confirms the results published earlier in [2, 13, 14];

3. a decrease in the TEC (up to 0.55 TECU) was registered, due to the passage of the solar terminator along the Kazan-Zelenodolsk-Vasil’sursk line. The estimation of the scales of ionospheric irregularities (∼65–80 km across the direction of movement of the ST), generated during the passage of the solar terminator;

4. improved methodology and conducted a series of experiments on synchronous observations of the disturbed region structure using signals emitted from GPS satellites and measurements of the artificial airglow in the 630 nm line, carried out on the Sura stand in 2010—2017;

5. it is established that artificial airglow in the 630 nm line is generated in a region with a lower electron concentration. It is in this region that the population of energetic electrons accelerated by plasma waves to the excitation potential of optical levels turns out to be more intense.

Practical significance of the work is to study the artificial and natural disturbances in the electron concentration of the Earth's upper ionosphere, which can influence the propagation of radio waves in a wide frequency range and reduce the reliability and noise immunity of ground-based and space-based radio systems. Such studies can also be useful in the search for precursors of the processes occurring in the Earth's atmosphere and lithosphere.

The main arguments of a dissertation to be defended:

1. In a series of experiments on the effects on the ionosphere by powerful radio emission from the "Sura" facility, the generation of electron concentration irregularities in the Earth's ionosphere with characteristic transverse scales of $D \sim 29 \div 62$ km and the direction of propagation west-east with a speed of $\sim 300 \div 370$ m/s, which is confirmed by measurements of TEC variations on the GNSS network — stations located along the geomagnetic latitude.

2. It was established that during the passage of the solar terminator along the Kazan-Zelenodolsk-Vasilsursk line in the Earth's ionosphere, there are moving ionospheric disturbances (a decrease in the TEC to 0.55 TECU) was recorded, the period of which is ~ 23 m.

3. The technique has been improved and a full analysis of the experimental data obtained at the "Sura" facility in 2010–2015 years, in the joint registration of artificial airglow in the 630 nm line and parameters of navigation satellite signals passing through the disturbed region of the ionosphere.

4. Based on the analysis of the behavior of the TEC and the brightness of the artificial airglow in the 630 nm line in the direction of the satellite, as well as the spatial position of the glow spots and their behavior in time on the recorded images of the night sky, it was established that the positions of the artificial airglow spots correspond to the minimum values of the TEC, that is airglow is generated in the region of low electron concentration, and it is here that the population of energetic electrons accelerated by plasma waves to the excitation potential of optical levels is the most intense.

The authenticity of the results obtained is ensured by the application of generally accepted methods and algorithms that have emerged in the past two decades in studies of ionospheric disturbances, using radio sounding signals emitted from the GPS/GLONASS satellite. Experimental results obtained by joint analysis of the spatial behavior of the TEC on the GPS signal path and the artificial airglow in the 630 nm line in experiments on the « Surah stand are in accordance with the theoretical results obtained by other authors.

Approbation of work. The main results of the work were repeatedly reported and discussed at russian and international conferences and symposium. Including personally, oral presentations were made on: XXIV and XXV Russian

Open Conferences «Radio Wave Propagation» (Irkutsk, 2014; Tomsk, 2016); The 40th Scientific Assembly of COSPAR (Moscow, 2014); International scientific conferences «Radiation and scattering of electromagnetic waves» — RSEMW-2013, RSEMW-2015, RSEMW-2017 (Divnomorskoe, Taganrog 2013, 2015 and 2017); XII, XIII, XIV Conferences of Young Scientists «Interaction of fields and radiation with matter» (Irkutsk, 2011, 2013, 2015); X, XI, XII, XIII annual conferences «Plasma Physics in the Solar System» (IKI RAS, Moscow, 2015, 2016, 2017, 2018); Annual final conferences of Kazan (Volga Region) Federal University (Kazan, 2015, 2016, 2017, 2018); International Conference « Nonlinear wave structures in complex continuous media, including the atmosphere, hydrosphere and cosmic plasma » (Kazan, 2017); International Science Conference «Astrophysics and Particle Physics » (Dallas, USA, 2016).

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Personal contribution of the author. In the period from 2011 to 2017 with the participation of the author, 15 experimental campaigns were conducted to study the effects of the impact of high-power radio emission from the "Sura" facility on the ionospheric plasma. The main task of the author was: forecasting the orbital motion of the GPS/GLONASS navigation satellites; collection and processing of experimental data received from various GNSS receivers; measurements of TEC and brightness of artificial airglow in the 630 nm line in the direction of the navigation satellite. A total of 33 TEC registration sessions were conducted and processed during the GPS/GLONASS navigation satellites flight through the "Sura" facility and 5 sessions of simultaneous TEC measurements and artificial airglow of the ionosphere in the red line of the optical spectrum on the GPS signal propagation path when exposed to powerful radio emission. Considering that conducting experiments requires the simultaneous, integrated use of various diagnostic tools, the author's publications on the topic of research are co-authored. The dissertation includes only those results that were obtained with the direct participation of the author.

Publications. The main results on the topic of the dissertation are presented in 22 publications, 6 of which were published in peer-reviewed scientific journals recommended by the Higher Attestation Commission. Of these, 5 are indexed in the international citation systems Scopus and Web of Science.

Structure and scope of dissertation. The structure of the dissertation is justified by the accumulated to date data obtained in the course of experiments on the effects on the ionosphere by the powerful radio emission from the "Sura" booth from 2010 to 2017, as well as a series of measurements of TEC variations on the GNSS stations during the ST passage.

The dissertation consists of an introduction, three chapters, a conclusion, a list of abbreviations and conventions, a list of references and one application. The full volume of the thesis is 145 pages with 34 pictures 8 tables and 1 application. References contains 133 source.

BRIEF CONTENT OF WORK

The introduction shows the relevance of the topic, which the dissertation is devoted to, describes the current state of the research question, formulates the goal and scientific novelty, defines the practical value, presents the main points to be defended.

In the first chapter in section 1.1 briefly reviewed the history of the formation and development of satellite navigation systems. Section 1.2 provides the current classification of artificial Earth satellites operating in near-Earth space. Methods of dual-frequency sounding of the ionosphere by satellite signals are discussed in section 1.3. It is shown that according to the measurement of the angle of rotation of the polarization plane of radio waves emitted by the satellite transmitters, the integral concentration of electrons in the ionosphere can be measured (the number of electrons in a column of unit cross section and a given height). Section 1.4 of the thesis is devoted to a brief description of the hardware - independent format for the exchange of navigation data RINEX. The method used for processing navigation data and the procedure for calculating the total electronic content is presented in Section 1.5.

Small variations in TEC were studied in-depth by the described technique, in particular, in [14]. A trend was removed from the initial time dependence of *I(t)* (рис. 2) by the moving average subtraction with a linear weight function:

$$dI\left(j\right) = I\left(j\right) - \frac{1}{N}\sum_{n=j-N}^{j+N}\left(\frac{I\left[n\right]\left(N-\left|n-j\right|\right)}{N}\right), \tag{1}$$

where $dI\left(j\right)$ – is the TEC variation about the mean level, and N is the averaging parameter and the total number of summation points

The second possible way to remove a trend from the initial time dependence of the TEC ($I(j)$) is to subtract a second-degree polynomial (parabola) that approximates the original function at a given interval. This function describes with sufficient accuracy the course of the distance-frequency characteristic of the satellite in the absence of electron concentration perturbations associated with the operation of the “Sura” facility transmitters in the considered time interval. This method of studying small variations of the TEC ($dI\left(j\right)$) is applied when processing the combined measurements of the TEC and the brightness of the artificial optical airglow of the ionosphere in the red line 630 nm in the direction of the GPS satellite located in the field of view of the CCD camera work powerful transmitters “Sura” facility.

Section 1.6 provides an overview of the current state in the field of research on electron concentration perturbations stimulated by the powerful radio emission observed in the Earth’s ionosphere using dual frequency radio-sounding GPS and GLONASS satellite signals. Section 1.7 presents a description of the possibility of conducting an experiment on simultaneous measurement of TEC variations on the path navigational satellites and the brightness of an artificial airglow in the red line of atomic oxygen (630 nm) in experiments on the “Sura” facility.

In the second chapter presents the results of measurements of TEC in the mid-latitude ionosphere on the GNSS network of stations located along the geomagnetic latitude, performed from 2010 to 2017 years, with the emission of high-power radio waves and movement of solar terminator.

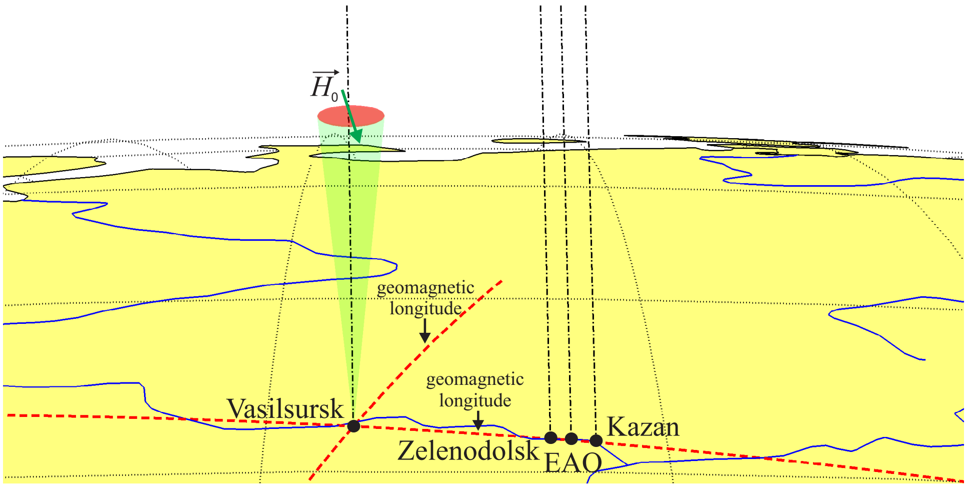

Figure 1: Geometry of the experiment on measurements of TEC variations in the ionosphere irradiated by high power radio waves radiation. The geomagnetic latitude and longitude of “Sura” facility are shown by the dashed lines; dots show Vasilsursk (56.13° N, 46.08° E), Zelenodolsk (55.86° N, 48.55° E), EAO (55.83° N, 48.91° E) and Kazan 55.80° N, 49.13° E) measuring sites, which are included in the GNSS network. The vertical dashed-dotted lines show the satellite–GNSS station radio paths at the time when the satellite was exactly over the center of the disturbed ionospheric region. The magnetic field strength vector H0 is shown by the heavy arrow. The spacing between the measuring sites is ∼ 160 km (Vasilsursk–Zelenodolsk), ∼ 170 km (Vasilsursk–Zelenodolsk) and ∼ 200 km (Vasilsursk–Kazan).

Section 2.1 describes the formulation of the experiment (see Fig. 1). A condition for selecting the frequency of the pump wave action is given, the power characteristics of the “Sura” facility are given, the parameters of the used GNSS receiver network located along the geomagnetic latitude are described, the parameters of each of the experiments under consideration and the state of space weather are estimated based on geomagnetic activity indices (D_{st} и k_p), the index of the auroral electrojet (AE) and the planetary W_p - the index of the state of the ionospheric weather. Section 2.2 presents the results of measurements of TEC variations obtained during the operation of the powerful transmitters of the "Sura" facility in 2010–2017. Several experimental days from the total array of data accumulated during this period were considered, the measurement conditions were described, the flight paths of the GPS and GLONASS satellites over the "Sura" facility were presented, the TEC variations and characteristic transverse scales of the observed disturbances were calculated, and the cross-correlation functions of the series were constructed TEC for each measuring point.

An example of a TEC recording before removing the trend associated with a change in the satellite zenith angle for GPS satellite № 08 March 15, 2010 for Kazan, is shown in fig. 2. It can be seen from the figure that at the moment when the satellite is located in the antenna pattern of the "Sura" facility (between the vertical dashed lines 17:16-17:42 UTC), electron concentration perturbations occur, reaching their maximum when the satellite is strictly above Vasil'sursk.

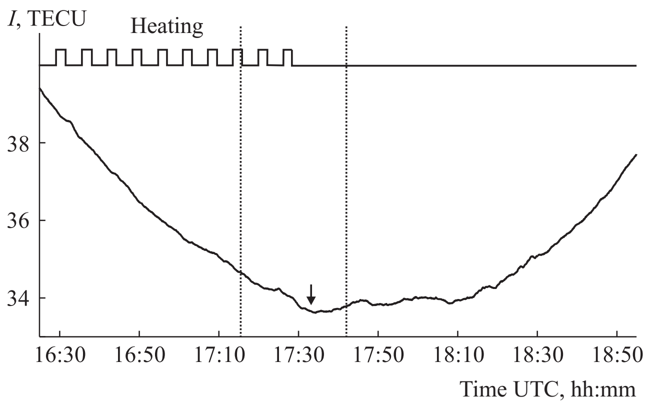

Figure 2: TEC for Kazan received from GPS№ 08 satellite on March 15, 2010. The vertical dashed lines show the time interval of the GPS № 08 satellite flight over the "Sura" facility. The squares in the upper part show the pump wave mode. The vertical arrow shows the instant when the satellite was exactly over the "Sura" facility center. The origination of large-scale disturbance of TEC is evident at the instant when the satellite was within the antenna pattern of the "Sura" facility (between vertical dashed lines); the disturbances attained the maximum value when the satellite was exactly over Vasilsursk.

TEC variations after the removal of the trend for GPS GPS № 08 on March 15, 2010 for Kazan and Vasilsursk are shown in fig. 3. The vertical dashed lines on the top panel of fig. 3a indicate the time when the satellite crossed the Sura antenna pattern (AP) (flying over AP interval). The high-power shortwave radiation mode is shown in by rectangles.The vertical arrows in fig. 3a show the time points where the satellite was exactly in zenith over the measuring sites (hereinafter, local zeniths), i.e., 17:34 UTC for Vasilsursk and 17:42 UTC for Kazan.

A discussion of the results of measurements of TECs variations obtained when the ionosphere was exposed to powerful radio emission was performed in Section 2.3. Based on the distance between the measuring points (between Vasilsury and Kazan $\sim$ 200 km) and the relative shift between the observed variations of the TEC, the propagation velocity of the ionospheric disturbance, stimulated by a powerful radio wave along the geomagnetic latitude, was $\sim 300 \div 370$ m/s. According to the data of the cross-correlation analysis of the TEC series for Vasil'sursk and Kazan points, it has been established that the propagation of an artificial ionospheric disturbance occurs from Vasil'sursk to Kazan i.e. from west to east.

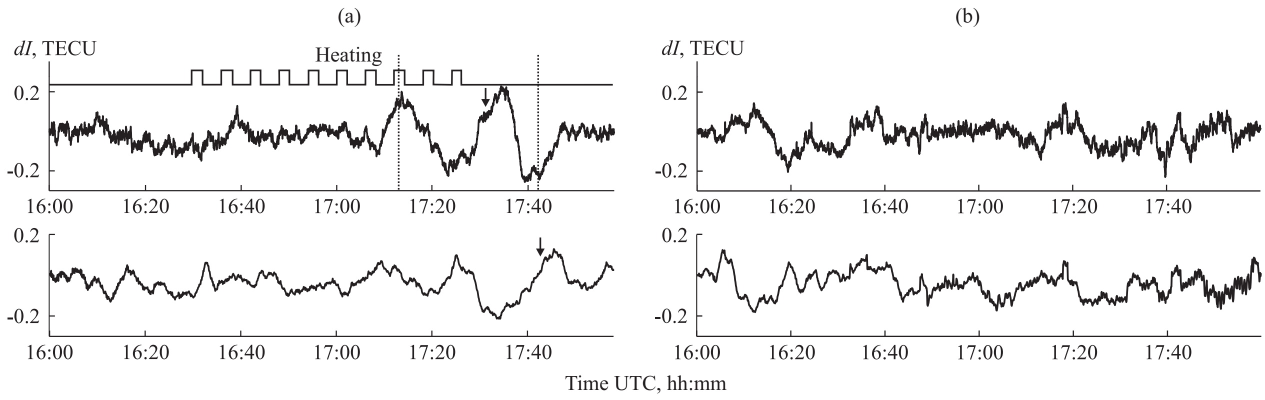

Figure 3: TEC variations in recorded in Vasilsursk (upper panels) and Kazan (lower panels) on March 15, 2010: (a) GPS 08 satellite (vertical dashed lines show the interval of satellite flying over Sura, which corresponds to the large ellipse in Fig. 3; squares in the upper panel show the high-power SW irradiation mode (2-min heating and 4-min pause); vertical arrows show the time points where the satellite was exactly in zenith over Vasilsursk and Kazan measuring sites) and (b) GPS 07 satellite (which did not fly over Sura AP during the experiment).

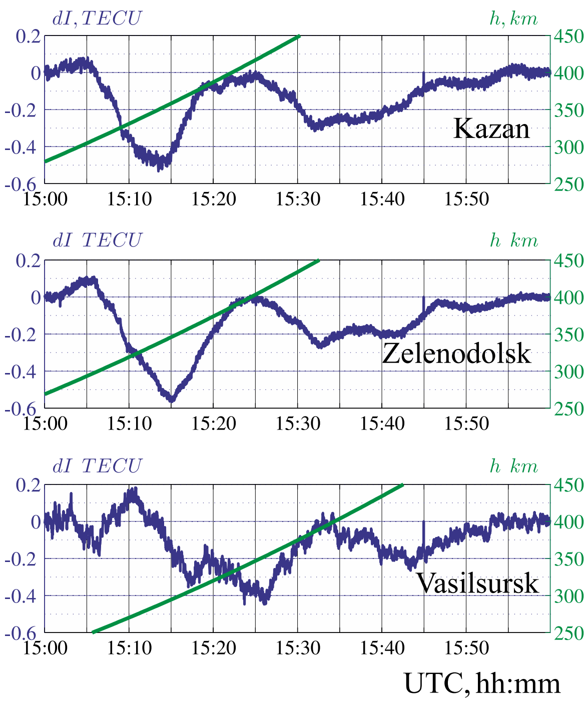

Figure 4: Solid line - TEC variations for GPS № 20 satellite recorded for three observation points (Kazan (upper panels), Zelenodolsk (middle panels), Vasilsursk (lower panels)) November 07, 2013; dotted line - the time of passage of the solar terminator for at altitudes of 250–450 km

The characteristic transverse scale of the observed ionospheric irregularities, which was estimated according to the procedure described in [14], was $\sim 29 \div 62$ km. It is noted that when the "Sura" facility is tilted by 12° from the zenith to the south in the plane of the magnetic meridian, the magnitude of TEC variations becomes $\sim 20\%$ larger.

Based on the speed and direction of propagation of the ionospheric disturbance, stimulated by a powerful radio wave along the geomagnetic latitude, as well as on the basis of estimates given in [2, 4], it was concluded that the effect of a powerful ground radio wave leads to the generation of acoustic-gravitational waves responsible for the modulation of the electron concentration of the F layer of the Earth's ionosphere.

Section 2.4 is devoted to the description of several sessions of measurements of TEC variations during the passage of the evening sector ST. As an example in fig.4 TEC variations for GPS satellite № 20 are presented, registered for three observation points - Kazan, Zelenodolsk, Vasilsursk November 07, 2013.

A discussion of the results of measurements of TECs variations obtained from the ST motion is performed in Section 2.5. For example, the data presented in fig. 4 shows that the difference in the time of passage of the ionospheric disturbance between Kazan and Vasilssursk is $\sim$ 11–12 min, which corresponds to the difference in local times (ΔLT) of the specified observation points. According to the analysis of the mutual correlation functions of the TEC series registered during the ST motion, a conclusion was drawn about the direction of motion of the registered ionospheric disturbance from east to west (from Kazan to Vasil'sursk). The maximum period of the observed TEC variations due to the passage of a terminator is $\sim$ 23 min (1365 s) for all observation points. The magnitudes of ionospheric irregularities generated during the passage of the ST were estimated using the methodology presented in [14] and amounted to $\sim$65–80 km across the direction of movement of the ST. It should be noted that all estimates given in Chapter 2 are valid only for the west-east component of the velocity of displacement of the irregularities. The final conclusions of chapter 2 are made in section 2.6.

The third chapter presents the results of simultaneous measurements of TEC variations on the GPS signal path and the brightness of the ionospheric artificial airglow in the red line of atomic oxygen (630 nm) performed when the radio emission of the "Sura" facility affected the ionosphere in 2010-2017 years. In total, 5 successful experiments were carried out during this period. Section 3.1 describes the experiment, specifies the complexity of its formulation, the parameters of the measurement sessions and the characteristics of the measuring equipment (GNSS receiver, CCD camera, ionosondes). The radius of the first Fresnel zone for the frequencies at which radio sounding is performed using GPS signals and the speed of the ionospheric penetration point are determined. In section 3.2 considered the main stages of data processing, which are as follows:

1. mutual spatial and temporal correlation of images of the night sky, obtained with the help of a CCD camera and the trajectory of the GPS satellite;
2. highlighting the area of artificial airglow on the received portraits of the night sky;
3. calculates the average intensity of the glow from the image area (11×11 pixels) corresponding to the location of the satellite at a given time;
4. distance of the regular trend introduced by the satellite movement from the initial TEC dependence on time;
5. comparison variations of TEC and artificial airglow in the red line of atomic oxygen (630 nm).

Section 3.3 presents the results of processing experimental data and their interpretation, with a detailed description of each experimental day: March 15, 2010 in subsection 3.3.1; March 17, 2010 in subsection 3.3.2; March 12, 2013 in subsection 3.3.3; August 24, 2014 in subsection 3.3.4; August 26, 2014 in subsection 3.3.5. An example of data from joint measurements of TEC and artificial optical luminescence of the ionosphere during the experiment on March 17, 2010 presented in fig.5.

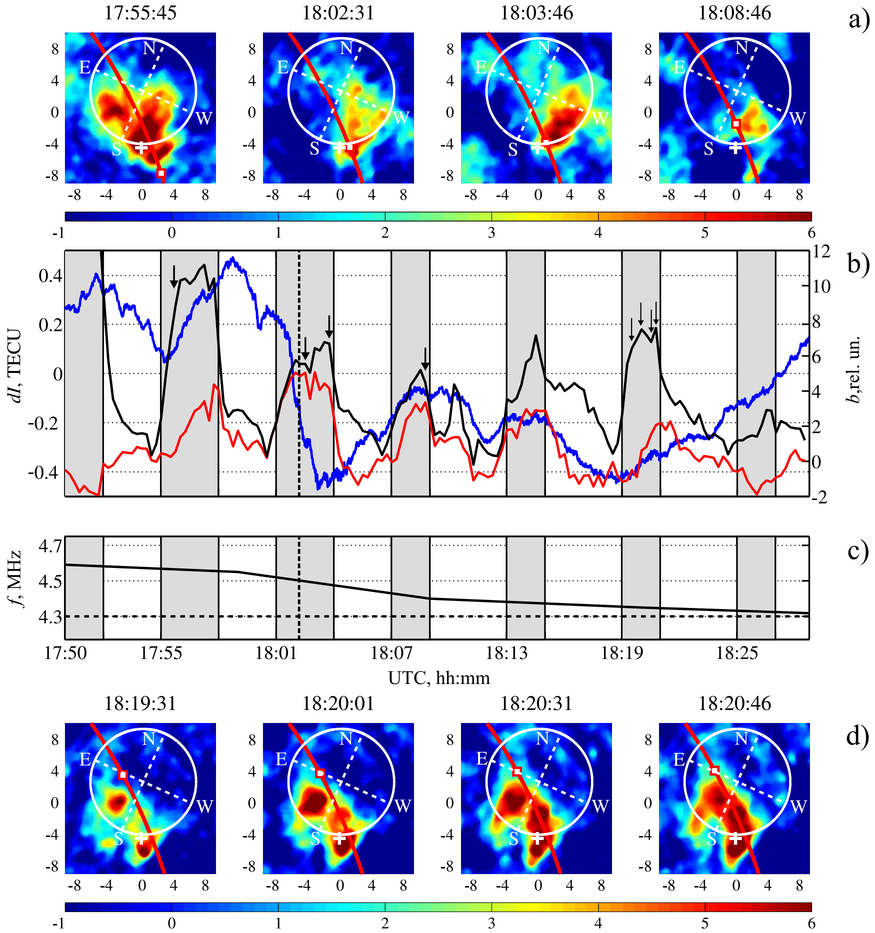

Figure 5: The results of joint measurements of TEC and artificial airglow on March 17, 2010. The heating direction is the magnetic zenith. The magnetic zenith position is marked by a white cross. Upper panel: *a* series of night-sky portraits obtained during the pump-wave radiation. The image shows the path (red line) and location (marker) of the GPS №28 at times indicated on panel *b* by vertical arrows. The white circle shows the projection of the main lobe of the Sura beam on the plane of the frame. The coordinates are given in angular degrees of the field of view of the camera and the airglow brightness, in relative units of the ADC of the camera. Panel *b* shows TEC variations after the trend removal (blue line), the dynamics of the airglow intensity from the region corresponding to the location of the satellite at the specified time (red line), and the dynamics of the maximum brightness of the airglow spot (black line). Panel *c* shows time variations of the cutoff frequency f_oF2 of the ionosphere according to the Tsyklon-GPS ionosonde located 170 km east of the facility. The horizontal dotted line indicates the frequency $f_0 = 4.3$ MHz of the pump wave. Gray vertical rectangles show the operating mode of the transmitters of the Sura facility and vertical dashed lines, the instants of the satellite's entry into and exit from the beam. A panel *d* with night-sky portraits in the 630 nm line was added.

From the analysis of the night sky images shown in fig.5, it follows that from the cycle to the pumping cycle, a spot of artificial airglow occurs in the same spatial coordinates, that is, it remains almost stationary relative to the west-east directions on the trajectory of the navigational satellite during the "heating" sessions. Thus, it can be considered that the ionospheric irregularities recorded in the TEC variations are "frozen" within the main lobe of antenna pattern "Sura" facility.

To conduct a joint analysis of the experimental data obtained during the session on March 17, 2010, a time interval of 17:55–18:29 UTC was chosen, corresponding to the time of six pump cycles. Taking into account the characteristic times of development and relaxation of the modulation of the background sky glow (see [25]), stimulated by the powerful radio emission from the "Sura" facility on the ionosphere, the averaging times of variations in the average intensity of the artificial airglow (b) and TEC (dI) were chosen for heating and pause periods.

The parameters of dI and b were averaged over the following time intervals: first period — 17:57–17:58 UTC heating, 18:00–18:01 UTC pause; the second period — 18:03–18:04 UTC heating, 18:06–18:07 UTC pause; the third period — 18:08–18:09, 18:14–18:15 и 18:20–18:21 UTC heating, 18:12–18:13, 18:18–18:19 и 18:24–18:25 UTC pause, then the average of the values obtained for each exposure cycle was calculated; fourth period — 18:26–18:27 UTC heating, 18:24–18:25 UTC pause. Due to the fact that the work of the CCD camera was terminated at 6:29 PM, UTC, when the transient processes associated with the "tail" after airglow of the ionosphere were not over, the averaging of the parameters dI and b in the pause for the fourth period was carried out in the time interval preceding the moment of switching on the pump wave (18: 25 UTC). The processing results are presented in the table 1. Here, the columns correspond to the selected periods, and the rows are the difference values of the parameters $(\Delta I, \Delta b, \Delta f)$, given by the relations (2).

$$\begin{cases} \Delta b = \overline{b_{\mathrm{h}}} - \overline{b_{\mathrm{p}}} \text{ (rel. un.)}, \\ \Delta I = \overline{dI_{\mathrm{h}}} - \overline{dI_{\mathrm{p}}} \text{ (TECU)}, \\ \Delta f = \overline{f_o F2 - f_0} \text{ (MHz)}, \end{cases} \tag{2}$$

here $\overline{dI_{\mathrm{h}}}$ и $\overline{b_{\mathrm{p}}}$ — the average values of the TEC and the intensity of the artificial airglow over a period of time taken during heating, and $\overline{dI_{\mathrm{h}}}$ и $\overline{b_{\mathrm{p}}}$ — mean values over a period of time taken during the pause, respectively; Δf — is the average difference between the critical frequency of the $F2$ layer of the ionosphere and the frequency of the pump wave (f_0) calculated for a specified period of time.

In Section 3.4, the final conclusions of Chapter 3 were made. Based on the analysis of the behavior of the TEC and the brightness of the artificial airglow in the 630 nm line toward the satellite, as well as the spatial position of the glow spots and their behavior over time in the recorded portraits of the night sky, that in all five experiments the position of the spot of artificial optical luminescence corresponded to the minimum values of the TEC, i.e. the artificial airglow in the

630 nm is generated in the region of reduced electron concentration, and it is in this region that the population of energetic electrons accelerated by plasma waves to the excitation potential of optical levels is more intense.

Table 1: Results of data processing for March 17, 2010

Time (UTC)	17:55–18:01	18:01–18:07	18:07–18:25	18:25–18:29
Δb (rel. un.)	2.40	4.40	3.11	−1.21
ΔI (TECU)	0.10	−0.20	0.10	0.10
Δf (MHz)	0.30	0.28	0.14	0.05

In conclusion of the dissertation, the main scientific results obtained during its implementation are briefly formulated.

In appendix presents a summary table of all experiments conducted on the "Sura" facility in 2010-2017 years during the passage of the GPS/GLONASS satellites over the "Sura" facility during the impact of powerful radio emission on the ionosphere.

THE MAIN RESULTS

According to the analysis of a series of experiments on dual-frequency radiosonde sounding of the ionosphere using the GPS/GLONASS satellites signals on the GNSS network - stations located along the geomagnetic latitude:

1. irregularities of the electron concentration in the Earth's ionosphere with characteristic transverse scales of $D \sim 29 \div 62$ km and the direction of propagation west-east with a speed of $\sim 300 \div 370$ m/s were found, which was confirmed by measurements of TEC variations in the Earth's ionosphere in a series of experiments on the impact on the ionosphere by the powerful terrestrial radio emission from the heating stand "Sura";
2. a decrease in TEC (up to 0.55 TECU) was found, associated with the ST movement along the Kazan-Zelenodolsk-EAO-Vasilsursk line. The transfer of disturbance in this case occurs in the east-west direction. The period of such disturbances is $\sim$ 23 23 min, the characteristic scale is $D \sim 66 \div 77$ km;
3. it is shown that when the antenna pattern of "Sura" facility tilts at 12° from zenith to the south in the plane of the magnetic meridian (at "magnetic zenith"), more confident excitation of TEC variations occurs compared to the case of radiation strictly in zenith. The amplitude of TEC variations becomes larger by $\sim 15 \div 20$ %.

According to the results of the analysis of the spatial behavior of the TEC variations on the GPS signal path and the ionospheric artificial airglow in the 630 nm in experiments on the "Sura" facility:

1. it was found that when the "navigation satellite—GPS receiver" path of a signal crosses the artificial airglow spot, the maximum brightness of the latter

on the line of sight of the optical device at the navigation satellite was observed in the region of the TEC minimum;

2. it was found that the decrease in the brightness of the background luminescence of the ionosphere during the switching on of the pump wave, in cases where the luminous enhancement mechanism due to electron acceleration by plasma turbulence no longer works, occurs in areas with high electron concentration;

3. the condition that, at $\Delta f < 0.5\,\text{MHz}$, the mechanism for enhancing the brightness of artificial airglow in the 630 nm due to the shock excitation of oxygen atoms by energetic electrons stops its operation, apparently, is necessary but not sufficient. As in a series of experiments, the excitation of artificial airglow occurs in those cases when $\Delta f \sim 0.30 \div 0.15\,\text{MHz}$;

4. the method of simultaneous measurements of TEC variations on the GPS signal path and the artificial airglow in the red line of atomic oxygen, performed with the strong radio emission from the "Sura" facility, was improved.

AUTHOR'S PUBLICATIONS ON THE THEME OF THE DISSERTATION

The research materials are presented in 22 publications published on the topic of the thesis, including 6 articles in leading peer-reviewed scientific journals, including international (Advances in Space Research, IEEE Xplore Digital Library) and central Russian (Geomagnetism and aeronomy, Radiophysics and Quantum Electronics, Russian Physics Journal) from the list of publications recommended by Higher Attestation Commission of Russia and indexed in international citation systems Scopus and Web of Science:

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