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Satellite radio probing and radio tomography of the ionosphere

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1. Introduction

Investigations of ionospheric spatial plasma distributions are necessary in order to study the ionosphere and the physics of its processes. The ionosphere, as a medium for radio wave propagation, essentially influences the operation of various navigation, positioning, and communication systems. Therefore, investigations of the ionosphere structure are of interest for many geophysical and radiophysical applications. The existing radars and ionosondes allow only local diagnostics of the ionosphere. The creation of a sufficiently dense network of traditional means of ionospheric sounding is quite difficult and expensive. Low-orbit (like the Russian Cicada and the American Transit systems) and high-orbit (GPS/GLONASS) satellite navigation systems and the network of receivers on Earth's surface allow conducting ionosphere sounding in various directions and using tomographic methods, i.e., allow revealing the spatial structure of the ionospheric electron concentration. Currently, satellite radio tomography (RT) methods for the ionosphere are being successfully developed [1 – 7]. Since the early 1990s, RT systems have been operating on the basis of low-orbit (LO) navigation systems. Recently, there have been active RT studies based on the data of high-orbit (HO) navigation systems [6, 7]. To identify the different RT types, the terms 'Low-Orbit RT' and 'High-Orbit RT' are used here (LORT and HORT).

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2. Low-orbit radio tomography of the ionosphere

Low-orbit navigation systems, having an almost circular orbit at the height about 1000 – 1150 km, and ground-based receiver chains give the opportunity to obtain series of RT data over various rays. In RT experiments, the reception of two coherent satellite signals at frequencies 150 and 400 MHz and recording of the phase difference between them (the reduced phase) is carried out on a network of several ground-based receiving stations located along a trajectory of satellites at distances of a few hundred kilometers. Measurements of the reduced phase φ at the receiving points are the data for the RT reconstruction. Integrals of the electron concentration N over the rays between a ground-based receiver and a satellite transmitter are proportional to the absolute (total) phase Φ [1, 2] that includes the unknown initial phase φ_0,

$$\alpha\lambda r_{\mathrm{e}} \int N \, \mathrm{d}\sigma = \Phi = \varphi_0 + \varphi \,, \tag{1}$$

where λ is the sounding wave length, $\mathrm{d}\sigma$ is the ray length element, r_{e} is the classical electron radius, and the proportionality coefficient α (of the order of unity) is determined by the selection of sounding frequencies.

We rewrite Eqn (1) in the operational form [4], taking a typical noncorrelated experimental noise ξ into account:

$$PN = \Phi + \xi \,. \tag{2}$$

Here, P is the projection operator transforming the two-dimensional distribution N into a set of one-dimensional projections Φ. The problem of tomographic reconstruction thus amounts to finding a solution of the set of linear integral equations (2) and finding the electron concentration N. One of the possible variants is discretization (approximation) of the projection operator P. We then obtain a corresponding set of linear equations with a discrete operator L:

$$LN = \Phi + \xi + E \,, \qquad E = LN - PN \,, \tag{3}$$

where E is the approximation error depending on the solution N. We note that Eqns (2) and (3) are equivalent if the approximation error is known. But in the data reconstruction of a real RT experiment, E is unknown and another system of linear equations is actually solved:

$$LN = \Phi + \xi\,. \tag{4}$$

System (4) is not equivalent to (3). In other words, the difference between the solutions of (3) and (4) is determined by a different quasinoise component ξ and by a correlated (in time and rays) approximation error E. To solve (4), the absolute phase Φ should be known together with φ_0. Estimation errors of φ_0 for different receivers can lead to contradictions and inconsistencies in data and, as a result, to poor quality of the RT reconstruction. Therefore, a phase difference RT method, or an RT of the difference of linear integrals on close rays [8], was developed that does not require finding the initial phase φ_0. The system of linear equations for the phase difference RT is determined by the corresponding difference:

$$AN = LN - L'N = \Phi - \Phi' = D + \xi\,, \tag{5}$$

where $LN = \Phi$ is the initial linear system, $L'N = \Phi'$ is the linear system formed in the set of close rays, and D is the difference in integrals (1) for close rays.

There are numerous direct and iterative algorithms to solve the systems of linear equations in (4) and (5). Currently, iterative algorithms are most often used for ionospheric RT ray problems, but noniterative algorithms are also used: the singular decomposition method and its modifications, regularization methods of root-mean-square deviation, orthogonal decomposition, maximum entropy, quadratic programming and its various versions, the Bayesian approach, and so on [3–7]. In the process of modeling and carrying out numerous experimental LORT reconstructions, effective combinations of various methods and algorithms have been found that provide the highest-quality reconstructions.

The phase difference LORT gives considerably better results and has a higher sensitivity in comparison with phase methods, which is confirmed by modeling results and experimental data [4, 7, 9]. The resolution in the LORT problem in the linear formulation is 20–30 km horizontally and 30–40 km vertically. If we take the refraction of sounding rays into account, the spatial resolution of the ionospheric LORT method can be improved up to 10–20 km [7].

The world's first LORT reconstructions were obtained during March–April 1990, by researchers from Moscow State University and the Polar Geophysical Institute (PGI) of the Kola Scientific Center, Russian Academy of Sciences [10]. As an example, Fig. 1 shows, in geographical latitude–altitude coordinates (in kilometers), one of the first RT sections of the ionosphere obtained, the ionospheric RT section (in units of 10^{12} m^{-3}) between Moscow and Murmansk with a well visible ionization trough at the latitudes 63°–65° containing a local extremum inside. Numerous subsequent experiments showed the complexity and the structural and dynamical variety of the trough [1–7]. Later, in 1992, preliminary results of the RT reconstruction of the ionosphere were obtained by foreign colleagues [11]. In 1994, experiments began on the Moscow–Arkhangelsk RT system created by the Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences (IZMIRAN) [12].

Studies on the ionosphere LORT and its applications attract appreciable interest throughout the world, with more than ten scientific groups in leading countries currently working in this area [3–7]. Within the last twenty years, series of successful LORT experiments [3–7] were conducted

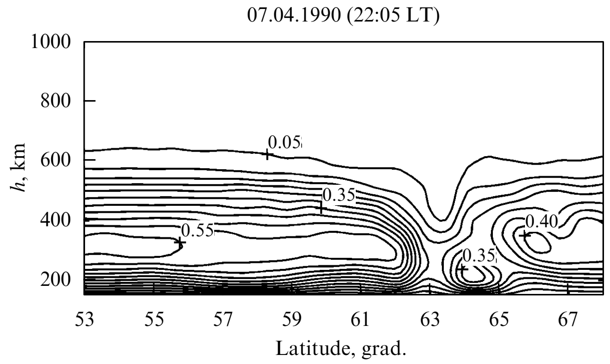

Figure 1. An example of one of the first LORT reconstructions of the ionospheric electron density (Moscow–Murmansk) in units of 10^{12} m^{-3} according to the data of April 7, 1990, 22:05 LT (local time).

in various regions of Europe, America, and Southeast Asia that demonstrated the wide opportunities of RT methods for the investigations of various ionospheric structures.

In RT cross sections in various regions, the known wave structures such as traveling ionospheric disturbances (TIDs) [3–7] were repeatedly observed. As an example, Fig. 2 presents the ionospheric RT reconstruction in which TIDs are clearly seen with the characteristic tilt angle about 45°, revealed over the Moscow–Arkhangelsk chain [12].

In the process of RT experiments in Southeast Asia on the low-latitude Manila–Shanghai chain, a number of structural features of the equatorial anomaly (EA) were revealed: the orientation of the formed EA 'core' (a region of the electron concentration close to the maximum level) at midday along Earth's magnetic field direction, an essential asymmetry of EA borders, and characteristic alternations of 'expansion and contraction' of the ionospheric F-layer [13–15]. The observable stable EA structural features can be interpreted by analyzing plasma fluxes and velocities in the EA region caused by the so-called fountain effect [7]. Reconstructing the ionospheric E-layer structure by RT methods is much more difficult, because the E-layer contribution to registered data is much smaller than the F-layer contribution. But if the RT system size allows the formation of a system of intersecting rays in the ionospheric F- and E-layers, it is possible to reconstruct the E-layer structure [16]. An example of the RT reconstruction of the F- and E-layer EA structures is given in Fig. 3. Terrestrial magnetic field lines are shown by dashed lines. The formed EA core is oriented along the direction of

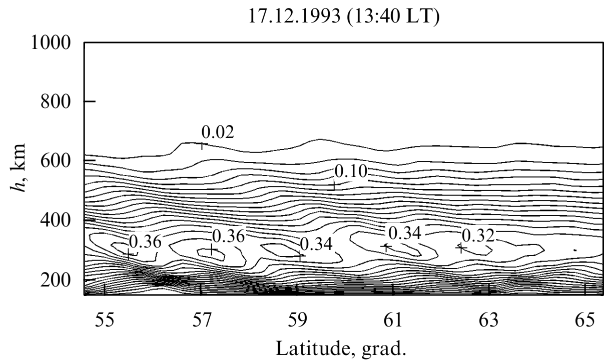

Figure 2. LORT reconstruction of traveling ionospheric disturbances (Moscow–Arkhangelsk) in units of 10^{12} m^{-3} according to the data of December 17, 1993, 13:40 LT.

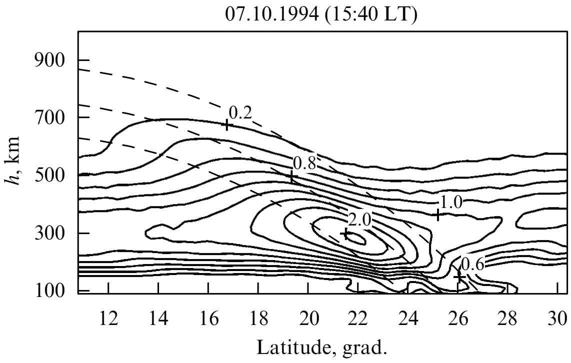

Figure 3. LORT reconstruction of the equatorial anomaly (Manila–Shanghai) in units of 10^{12} m^{-3} according to the data of October 7, 1994, 15 : 40 LT. Terrestrial magnetic field lines are shown by dashed lines.

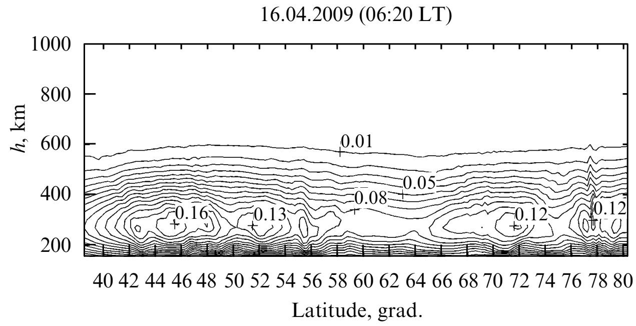

Figure 4. LORT reconstruction of the ionospheric electron density (Sochi — the Spitsbergen archipelago) in units of 10^{12} m^{-3} according to the data of April 16, 2009, 06 : 20 LT.

Earth's magnetic field; the asymmetry of the EA crest borders and the F-layer thickness variations are clearly seen. The 'forcing through' the F-layer bottom edge by the plasma flux along the field line is also observed, i.e., the plasma flow penetration from the F-layer into the lower layers of the E-region in the latitude range $24° - 26°$. In the region behind the EA core ($\approx 28° - 31°$), a constriction is formed.

In a series of experiments, the testing of ionospheric LORT and comparison of LORT reconstruction results with the incoherent scattering radar and ionosonde data [3 – 7] were done. One of the first such experiments was the 1993 autumnal Russian–American tomographic experiment (RATE'93), comparing the results of the ionospheric LORT cross sections with the incoherent scattering radar data in Millstone Hill (USA). The RATE'93 results demonstrated the high quality of LORT reconstructions and the agreement of results for radar LORT cross sections within the accuracy of both methods [17]. Similarly, the coincidence of the ionosonde and LORT data should be ascertained considering the restrictions of both methods [3 – 7, 14].

Currently, there are about ten operating chains (networks) of LORT receivers in various regions of the world (Russia, USA, Great Britain, Scandinavia and Finland, Alaska, Greenland, the Caribbean [2 – 7, 17 – 19]) that are actively used for research purposes. A LORT system has been created in India, and the LORT system in Southeast Asia is being updated. The Russian transcontinental RT system (Sochi — the Spitsbergen archipelago) consisting of nine receiving stations is the world's longest (about 4000 km) and has no analogues [20]. The uniqueness of the Russian LORT system is that the observation data cover the ionospheric region from auroral (polar cap zones) to low latitudes. This allows exploring the transfer of disturbances between the auroral, subauroral, and low-latitude ionospheres and studying the ionospheric plasma structure in various regions depending on various helio–geophysical conditions. As an example, Fig. 4 shows the ionospheric LORT cross section between Sochi and Spitsbergen for quiet geomagnetic conditions (the geomagnetic activity index $Kp < 1$). Around Spitsbergen ($78° – 79°$), quasiwave perturbations on the scale of the order of 50 km are detected. In the central reconstruction region ($59° – 65°$), the decrease in the electron concentration is appreciable. In the south of the RT cross section ($42° – 55°$), quasiwave structures on the scale of the order of 100 – 150 km are clearly seen, i.e., a complex ionospheric plasma structure is observed even in quiet conditions.

LORT allows not only revealing ionospheric inhomogeneities of a natural origin but also detecting ionospheric disturbances generated by anthropogenic sources, in particular, disturbances caused by rocket launches [7, 21, 22], industrial explosions [23], and powerful HF radiation [24 – 26]. For example, LORT allows the reconstruction of 'instantaneous' (10 – 15 min) two-dimensional cross sections of the electron concentration in the ionosphere. The time span between LORT reconstructions depends on the number of operating satellites and currently varies between 30 and 120 min. The LORT method also allows determining plasma fluxes by analyzing time-successive RT cross sections of the ionosphere [27]. If several receiving chains spaced by several hundred kilometers are available, then the three-dimensional structure of the ionosphere can be reconstructed. An essential limitation of the LORT technique is the necessity of constructing systems with many receiving chains.

3. High-orbit radio tomography of the ionosphere

With the development of global navigation systems in the USA and Russia (GPS, Global Positioning System and GLONASS, Global Navigation Satellite System), it has become possible to conduct continuous measurements of characteristics of ionosphere-propagating radio signals and to solve the inverse radio sounding problems [6, 7]. In the coming years, the development of other systems, in particular, the European (Galileo) and Chinese ones, is planned. We use the standard abbreviation GNSS (Global Navigation Satellite System) for all types of global navigation systems. Currently, the information constantly obtained by networks of GNSS receivers allows formulating the reconstruction problems for ionospheric electronic density distributions. There is a series of regional and global networks of GNSS receivers, in particular, the IGS (International Geodetic Service) network, totaling more than 1,500 receivers. The main feature of the inverse radio sounding problems based on GNSS data, related to the type of tomographic problems with incomplete data, is their high dimensionality. The comparatively low angular velocity of high-orbit GNSS satellites requires taking the temporal variability of the ionosphere into account, which leads to the formulation of a four-dimensional (three spatial coordinates and time) tomographic problem. Because of the four-dimensional character of the problem, the incompleteness of initial data becomes an essential issue; the satellite–receiver rays do not propagate through all points of space and in zones with a small number of receivers, regions of data absence appear that require the elaboration of special approaches [28].

For the purposes of ionospheric sounding, the measured phase values of radio signals propagating from a satellite to a ground-based receiver for two coherent and multiple operating frequencies are used. For example, for a GPS system, these are the frequencies $f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz. The corresponding data — the phase paths of radio signals measured at the wavelengths of the sounding waves — are usually denoted by L_1 and L_2. In addition, the pseudo ranges P_1 and P_2 (group paths of radio signals) measured according to the propagation time for wave trains at frequencies f_1 and f_2, can be used. The phase data L_1 and L_2 allow calculating the total electron content (TEC) — the integral along the ray connecting the transmitter and the receiver:

$$\mathrm{TEC} = \left(\frac{L_1}{f_1} - \frac{L_2}{f_2}\right) \frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\, \frac{c}{K} + \mathrm{const}\,, \qquad (6)$$

where the dimensional factor is $K = 40.308$ m^3 s^{-2} and $c = 3 \times 10^8$ m s^{-1} is the speed of light in the vacuum.

We note that by using the phase measurement data L_1 and L_2, it is possible to calculate the TEC only up to an unknown constant, which is specified in Eqn (6) as an extra additive term. Relation (6) is similar to (1) with an unknown constant in the right-hand side of the system of equations.

The pseudo ranges P_1 and P_2 also allow determining the TEC as [29]

$$\mathrm{TEC} = \frac{P_2 - P_1}{1/f_2^2 - 1/f_1^2}\,. \qquad (7)$$

However, such data are distorted and are much noisier than the phase data. The noise level in P_1 and P_2 is usually no less than 20% – 30%. At the same time, the noise in the phase data is typically less than 1% and rarely reaches a few percent. Therefore, it seems preferable to use the phase data for HORT.

In an overwhelming majority of studies (see, e.g., [6]), the HORT problems are solved by a set of linear integrals, i.e., it is supposed that TEC sets are determined with sufficient accuracy according to phase and group path data (6) and (7). However, the accuracy of the absolute TEC determination in (7) is low, and only the TEC differences in (6) are measured with high accuracy; therefore, the phase difference approach was also used here [28]. In other words, not the absolute TEC values but the corresponding differences or time derivatives $\mathrm{d(TEC)}/\mathrm{d}t$ were used as input data for the RT problem.

To solve the four-dimensional RT problem according to GNSS data, it is possible to use the approach developed in the two-dimensional LORT. The electron concentration distribution is represented as an expansion with respect to some local basic functions, and then the set of linear integrals or differences between linear integrals is transformed into a system of linear equations. However, the four-dimensional RT, unlike the two-dimensional one, requires an additional interpolation procedure for the solutions found in the region of absent data. Realization of this approach in regions with a dense network of stations (North America, Europe) gave good results on a sufficiently coarse network by choosing suitable splines with various smoothness [28, 30].

Another approach is based on the idea of seeking sufficiently smooth solutions of the problem, for which the algorithms used would provide good interpolation in regions of absent data. For example, we choose a Sobolev norm and seek a solution minimizing this norm over an infinite set of solutions of the initial (underdetermined) tomographic problem (5):

$$AN = D\,, \qquad \min_{AN=D} ||f - f_0||^2_{W_n^2}\,.$$

The difficulties encountered in the realization of this approach are related to the solution of a constrained minimization problem. The direct way to solve this problem, based on the Lagrange multiplier method, leads to a linear system with large-size matrices (due to a large number of rays), which, in addition, do not have a special structure that could simplify finding the solution. Therefore, an iterative method was suggested to solve the minimization problem, which is a variant of the SIRT (simultaneous iterative reconstruction technique) method with additional smoothing by filtration of iterative gains over spatial variables [28]. The method allows taking the a priori information into account expressed both in the initial approach for iterations and in the form of weight coefficients that set relative scales for the electron concentration variations at various heights.

Computer modeling demonstrated a reasonable reconstruction quality for quasistationary structures, although the HORT resolution is considerably lower than the LORT resolution. As a rule, in Europe and on the main part of the territory of the USA, the vertical and horizontal HORT resolutions are no better than 100 km. Only in the regions of the dense networks of southern California and Japan can the resolution reach 30 – 50 km.

To illustrate the results of applying the developed HORT methods, we give examples of reconstructions. In Fig. 5, an example of the ionospheric trough evolution over Europe on the evening of April 17, 2003 is shown. On the TEC maps and the meridional vertical cross sections (along 21° longitude), a trough expansion in the background of the electron concentration decrease during the night is seen. Figure 6 shows an anomalous electron concentration increase (up to 3×10^{12} m^{-3}) over the Arctic during the strongest magnetic storm on October 29 – 31, 2003. The increase in the electron concentration on the night side is related to plasma convection from the day side to the night side. The regions of increased ionization look like 'tongues' with an inhomogeneous spotted structure (Fig. 6a, b), which is also shown in the vertical sections (Fig. 6c, d). The sections are drawn along the lines shown on TEC maps (Fig. 6a, b). Apparently, this structure of inhomogeneities is related to the instability of the ionospheric plasma and the appearance of quasiwave structures.

4. Combination of radio tomography with other sounding methods

Systems using the radio occultation (RO) method (FORMOSAT-3/COSMIC and others registering GNSS signals with low-orbit satellites) allow obtaining quasitangential projections of the electron density N [31 – 33]. The RT method with ground-based reception implies ionospheric sounding in a wide range of various positions of receiving–transmitting systems. In this sense, the RO method giving integrals of N in the family of quasitangential rays (the

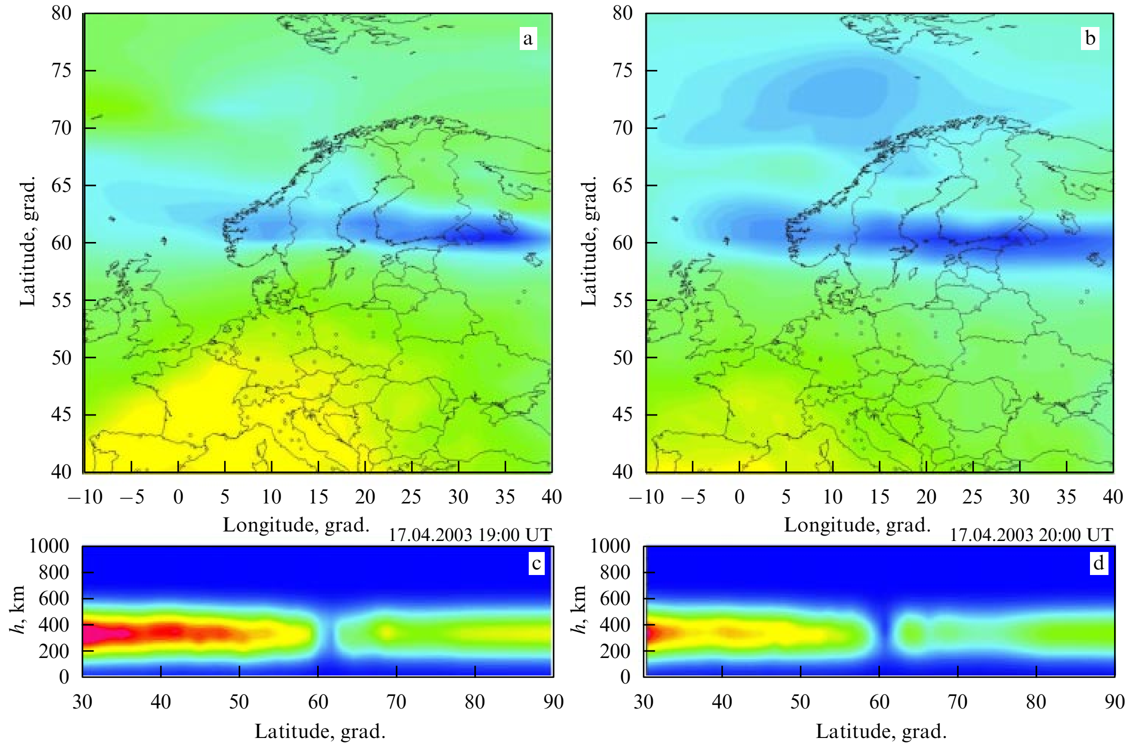

Figure 5. The ionospheric HORT reconstruction over Europe on April 17, 2003: (a, c) 19 : 00 UT, (b, d) 20 : 00 UT. (a, b): TEC maps in the latitude–longitude coordinates; the color scale is from 0 to 35 TECU (1 TECU = 10^{16} m^{-2}). (c, d): Vertical sections of the ionospheric electron density along 21° East in the latitude–altitude coordinates; the color scale is from 0 to 0.6 × 10^{12} m^{-3}.

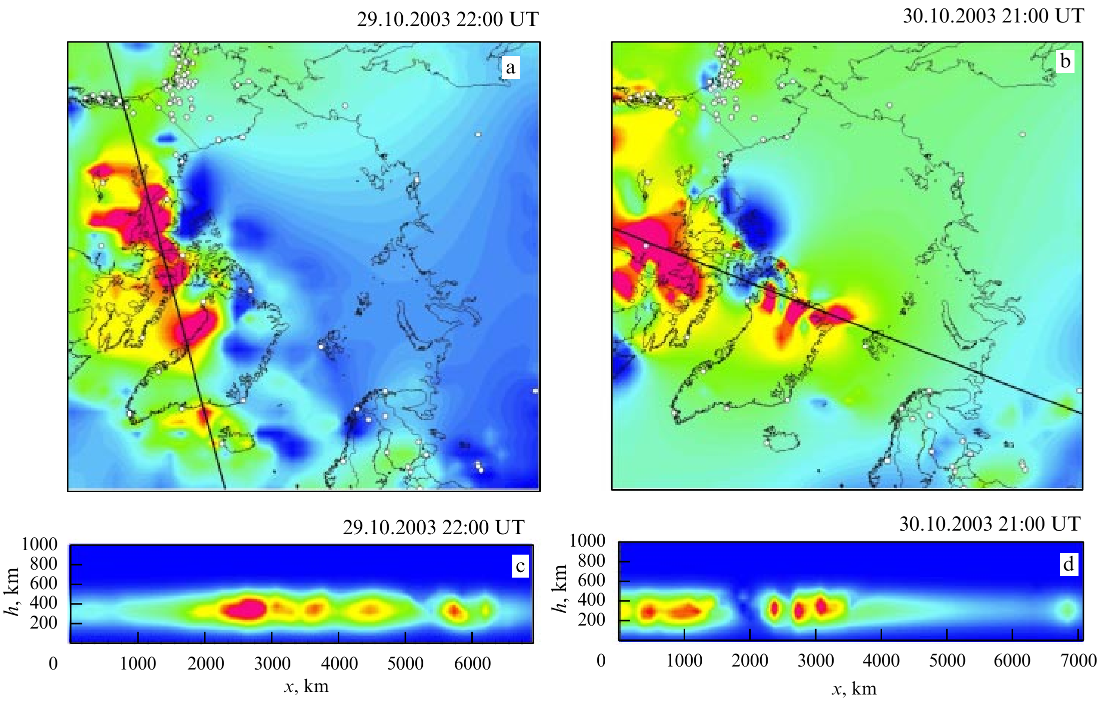

Figure 6. The ionospheric HORT reconstruction over the Arctic on October 29 and 30, 2003. (a, b): TEC maps; the color scale is from 0 to 60 TECU. (c, d): Vertical sections of the ionospheric electron density along lines shown on the TEC chart; x is the distance on Earth's surface along highlighted lines and h is the height; the color scale is from 0 to 2.5 × 10^{12} m^{-3}.

satellite–satellite paths) is a particular case of the RT method; therefore, a procedure to include RO data into a general tomographic scheme can be constructed [7, 34]. The combined application of the RT and RO methods, in which sounding data on the satellite–satellite paths (RO method data) are added to RT data of ground-based receivers, can lead to a noticeable refinement of the vertical resolution of RT reconstructions.

We note that the presented RT methods are related to ray tomography [1], in which diffraction effects can be neglected.

Earlier, we developed the diffraction and statistical RT methods [1, 2, 7]. The diffraction RT method allows reconstructing the structure of individual localized inhomogeneities with the diffraction effects taken into account. Statistical RT methods give an opportunity to obtain the spatial structure of the statistical characteristics of a stochastically nonuniform ionosphere [7, 35].

5. Conclusion

We have briefly reviewed the main results of tomographic ionospheric studies completed with our participation. A brief description of satellite radio tomography methods of the near-Earth plasma, including LORT and HORT, has been given. During the last two decades, numerous ionospheric RT studies of the near-equatorial, middle, sub-auroral, and auroral latitudes have been carried out in various regions of the world (Europe, USA, Southeast Asia). We have given examples of experimental RT reconstructions of the electron concentration distributions in the ionosphere.

The satellite RT system is a distributed sounding system: the moving artificial Earth satellites and a network of receivers give an opportunity to continuously sound the medium in various directions and to reconstruct the spatial structure of the ionosphere. The LORT systems allow obtaining 'instantaneous' (10 – 15 min) two-dimensional cross sections of the ionosphere at distances of a few thousand kilometers. The HORT systems, based on a network of independent receivers, together with traditional ionospheric sounding methods, allow realizing the regional and global monitoring of the near-Earth plasma.

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Space research at the Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences

V D Kuznetsov

1. Introduction

The space research at the Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, RAS (IZMIRAN) covers all the main areas of the institute activities: the study of the ionosphere and wave propagation, terrestrial and planetary magnetism, and solar–terrestrial physics. During the 70 years of its history, 50 of which are related to space research, IZMIRAN has participated in more than 50 space projects and conducted space research from the first artificial Earth satellite (AES) to modern complex space observatories like Interkosmos-19, APEX, CORONAS-F, and Compass-2. Substantial progress in the investigations pursued by the institute in recent years has been inseparably linked with spacecraft-borne measurements. Space research is an important constituent in the complex approach to the study of diversified and complex phenomena and physical processes in the Sun–Earth system, objects like the Sun, the terrestrial magnetosphere, the ionosphere, etc., which require dedicated experiments and a comprehensive analysis of observational data and their comparison with theoretical models.

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