MATHEMATICAL MODELLING OF RADIO TOMOGRAPHIC IONOSPHERIC MONITORING VIA SATELLITE CONSTELLATION

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The condition of an ionosphere defines the major vital processes on our planet. Currently, in all developed countries monitored the ionosphere, in many different ways using different satellite constellations. TEC (total electronic content) is one of the most important characteristics of an ionosphere of Earth, however, today, on the territory of Russia in its global monitoring isn't carried out. Analytical models give a good estimate of this parameter on condition of a quiet geomagnetic situation, but in case of the perturbed ionosphere the estimate of TEC becomes significantly less exact [1] that negatively affects work various (in particular navigation) satellite systems.

Ionospheric monitoring is implemented now, as a rule, with the help of ground stations of vertical sounding of the ionosphere (SVSI). SVSI possible to determine the number of significant characteristics of the ionosphere with high precision, but they have several drawbacks: significant weight and size, high power consumption and high cost of maintenance. A promising approach to monitoring the ionosphere is to determine the main parameters of the ionosphere on the results of processing the received radio signals of global navigation satellite systems GLONASS and GPS. Radio sounding of the atmosphere using the signals of satellite navigation systems [2] and a network of ground stations is readily available and does not require costly way to ionospheric monitoring in real time.

Despite all the advantages of modern monitoring systems, including the use GLONASS and GPS, these systems have one major drawback - the need to have a network of ground receiving stations. This deficiency deprived methods and systems using ionospheric sounding via satellite constellations [3.4]. In paper [3] proposed method radio tomographic ionospheric sounding using satellite constellation comprising satellites emitted coherent radio emission at frequencies f_1, f_2 and receivers satellites, detecting radiation of transmitters at these frequencies. Dual-frequency ionospheric sounding radio signals is based on the existence of the phenomenon of dispersion of radio waves in the microwave range electron plasma forming the Earth's ionosphere. Refractive index of radio signal while passing through the atmosphere from a transmitter located on the emitter satellite is determined by the formula:

$$N = (n-1)\cdot 10^6 = 77.6\frac{P}{T} + 3.73\cdot 10^5\frac{P_W}{T^2} - 40.3\frac{n_e}{f^2}, \tag{1}$$

where P - pressure of dry air in Pascals, P_w – water vapor pressure, T-temperature in Kelvin, f - carrier frequency, n_e - electron density, n - refractive index.

Thus, the total electron content (TEC) along the beam of sight from the antenna phase center of the receiver to the transmitter antenna is proportional to the difference between the phase shifts at two frequencies. Given that the phase velocity is equal in sign and opposite to the group velocity, it is easy to see that the TEC is proportional to the phase difference module or the difference between pseudoranges, determined from the navigation signals on two frequencies. However, not difficult to understand that the value of the TEC phase measurements can be determined only up to a fixed (within one session) constant.

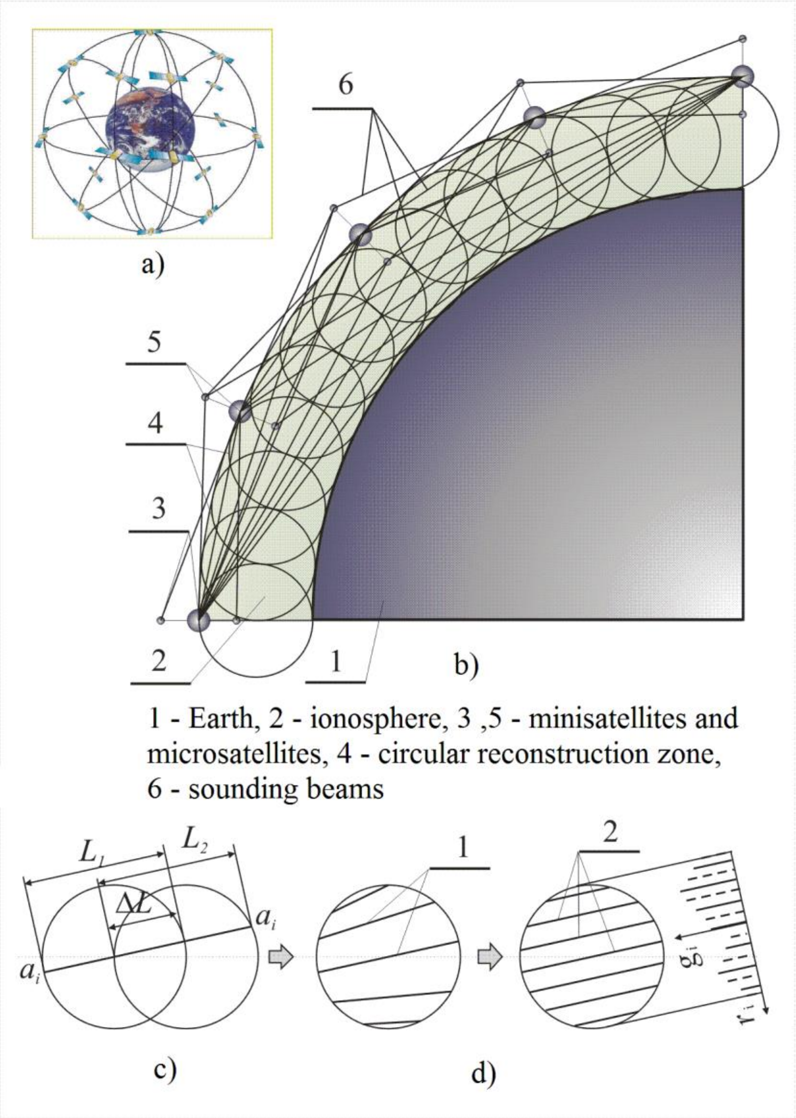
At the satellite receivers, the phase difference of emitted from electromagnetic radiation satellite emitters after propagation through the ionosphere, one can calculate the ionospheric total electronic content on the electromagnetic radiation propagation path in accordance with the following relation:

$$TEC \sim \Delta\phi = \lambda r_e \int N d\sigma, \tag{2}$$

where TEC - a total electronic content - the phase difference of coherent electromagnetic radiation after propagation through the ionosphere, λ - the wavelength of electromagnetic radiation with the lowest frequency f_1, r_e - electron radius, N - electron concentration and - $d\sigma$ - space bin along the beam of sight satellite - satellite, having a dimension of length [5].

It should be noted also that the phase shift measurements by several orders more precisely than pseudoranges code measurements, so to determine the absolute TEC most convenient to use code and phase measurements together. The next step is to move from the measured absolute or relative delays along the inclined beam of sight to the vertical delays. Are two approaches to solving this problem:

- the first is that it is necessary to characterize all simultaneous measurements of only one average value of the vertical TEC values tied to the coordinates of the receiver antenna;
- the second involves the calculation of "vertical" TEC values directly in the "underionospheric points" (points corresponding to the intersection of the beam of sight to the satellite with a hypothetical infinitely thin ionospheric layer located at a selected height).



1 - Earth, 2 - ionosphere, 3 ,5 - minisatellites and microsatellites, 4 - circular reconstruction zone, 6 - sounding beams

Fig. 1 - Satellite constellation geometry of the arrangement for radio tomography ionospheric sounding

The authors have developed a way to reconstruct the spatial distribution of the ionospheric electron density, which differs from the known methods, so that, using the simulation of the propagation of the radio pulse along the incident direction - distance between satellites tomography, radio tomography problem can be reduced to the usual problem of few-view reconstruction. This approach allows us to solve in the general case, the problem of direct 3D reconstruction of the TEC in a ionospheric spherical layer , or two-dimensional problem in its selected section.

The essence of this method is that the small satellites constellation arranged on several spatially located planar orbits deployed relative to one another, as shown in Figure 1 a). With this configuration, the satellite constellations can solve the problem of three-dimensional TEC reconstruction. We explain the contents of the proposed TEC reconstruction method by the example of 2D reconstruction distribution function of the electronic component to the ring carrier according to some - a given section of the ionosphere. To do this, you must put 24 minisatellite into a flat circular orbit, as shown by simulation experiments. Each minisatellite must contain receivers and transmitters operating on frequencies f_1, f_2. Moreover, for registering the phase components for each frequency, each minisatellite in its composition must have two nanosatellite provided with receivers for these frequencies. After separation from the microsatellites delivery device and their distribution along a circular orbit at equal distances from each other, each of them produces a "start" nanosatellites in the radial direction as shown in Figure 1 b). Nanosatellites moved from its carrier at distances (2 ÷ 5) km, and remain fixed at these distances. Hold nanosatellite - satellites by means of microcable locking systems. This satellite constellation configuration enables along this sound direction - 6 (Fig. 1 b)) register phase components of the sound pulse, the same way as it is done ground antenna devices detect radiation by navigation satellite constellation. In addition, each minisatellite contains a transceiver (ratings frequencies: 150, 400 MHz), it must have orientation engines (ion-plasma type), laser rangefinder, gyroscopic device, etc. In each minisatellite is also necessary to place the pre multiprocessor module processing raw data, and radio channels for communication between satellites and orbital or ground system support.

Inverse problem of the TEC reconstruction on the ring carrier can be reduced to the usual few-view reconstruction problem based on the convolution method with few-view kernel and back-projection procedure in two ways. The first is that it is possible to reformulate Radon Theorem for ring carrier, provided that the desired functions can be predetermine on the basis of experimental data on the circular area of reconstruction. However, due to the fact that the height of the ionosphere is taken equal to 1,500 km, and the radius of our planet 6300 km, ring reconstruction zone is too small, in the sense that the amount actually received, chord data is negligible compared with the number on a circular carrier radius 7800 km. Furthermore, it should be noted that chord data that must be subsequently result in the projection data, can be determined in a rather small angle of convergence. Taking into account, that the spatial resolution, even in the two-dimensional case, must determine the unit area of not less than (500 ÷ 500) m^2, i.e. each projection must contain 15600 counts and reconstructed format respectively (15600 ÷ 15600) elements, it becomes clear that this approach will require enormous computational cost, making it ineffective.

Another way proposed by the authors is that, for example, for the 2D reconstruction problems:

- The ring layer of the ionosphere is represented as a set of circular (elementary) carriers whose diameter is equal to the height of the ionosphere, overlapping, see Figure 1 b).
- Thus, the chord element between satellites emitting and receiving radio-frequency pulse can be represented by the sum of segments $a_i a_i$ (see Figure 1)).
- Each segment $a_i a_i$, in turn, is determined by chords of elementary circular reconstruction areas L_1, L_2, with an area of overlap ΔL.
- If the parameters are known a priori, such as the ionosphere air pressure, steam, temperature, etc. see equation (1), we can calculate the attenuation by modeling the radio emission at each frequency for chord directions L_1, L_2, taking into account the areas of overlap ΔL.
- Therefore, using data for the absorption in the directions of the probing beams - 6 (Figure 1 b) can create a set of chord data – 1, for each unit of the circular area reconstruction (Figure 1 g).

- Next recalculated chord data from fan geometry to orthogonal (Figure 1 g)), predetermine to the specified reconstruction format, i.e. formation of classical orthogonal projection.

However, as in the first case, with this approach, we can get a set of projection data in a rather small angle of convergence by the order of (15 ÷ 30)°. This is true for small satellites adjacent located in zones beam of sight with respect to each other (Figure 1 b)). For efficient reconstruction procedure using fast convolution algorithms and operations of back projection necessary to predetermine projection data in Fourier space, using the symmetry properties of the Fourier images and a priori data about air pressure, water vapor, etc. The calculation of the required number of intermediate projections made on circular harmonics in polar coordinates of Fourier space. Further, being transformed one-dimensional Fourier - images calculated wanting projections in signal space, and convolving projection functions with of few-view low-frequency kernel. After the operation of back projection and transform data in a Cartesian coordinate system, we obtain the desired reconstruction of elementary circular carrier - according to the geometry shown in Figure 1 b) of the 48 elementary carriers for ionospheric ring. Given additivity overlay zones crossing performed the final reconstruction of the desired distribution of the TEC on the ring area of the ionosphere.

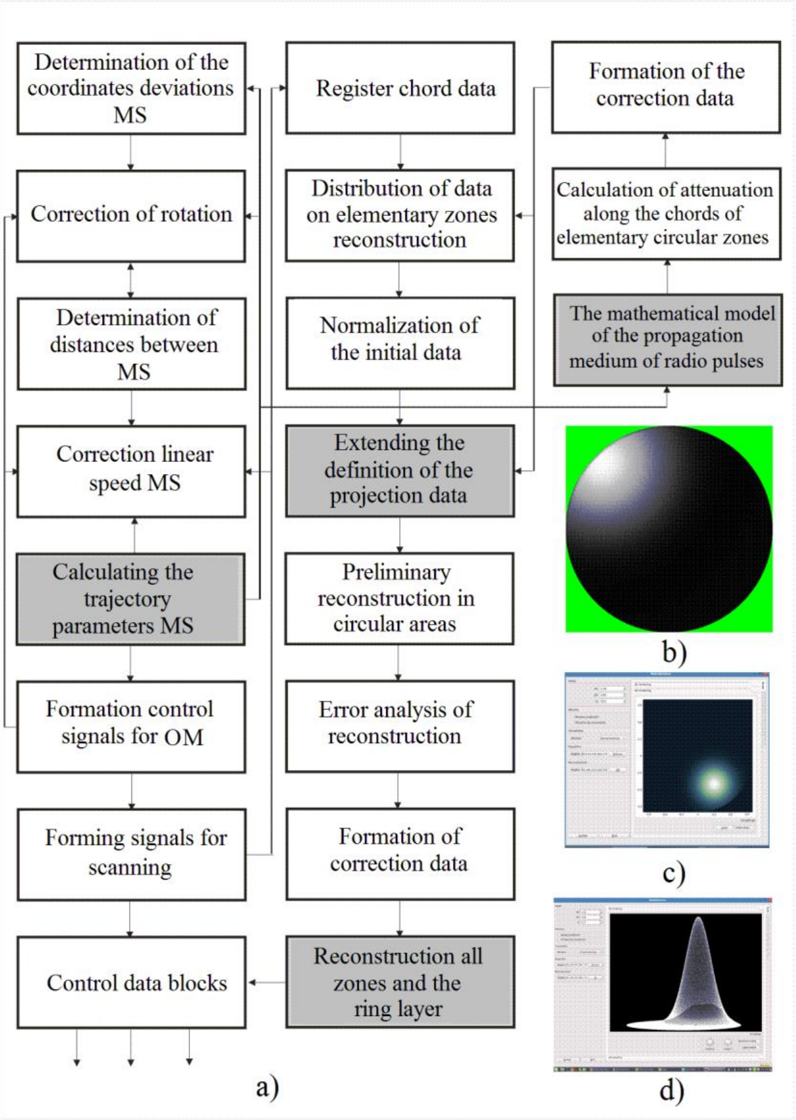


Fig. 2 - Block diagram of the application package for the reconstruction of the TEC on the ring carrier

Figure 2 a) shows a block diagram of the application package, which allows to simulate the two-dimensional reconstruction procedure of the TEC distribution functions in the ionospheric ring zone. For convenience, package program modules presented in three columns. The left column contains modules that are responsible for the location of small satellites into the orbit, their mutual orientation, and modules forming control signals to optimize the location of each MS into the orbit, using microengine orientation (EO). The middle column shows the modules responsible for the reconstruction of the desired TEC distribution in the ring section. The right column includes modules associated with process modeling attenuation of radio emission along each sound chord in elementary circular areas of reconstruction. This takes into account the functional distribution of air pressure, the partial pressure of water vapor with height. The grayed out modules, starring in its class. It is assumed that the considered control procedures, simulation and reconstruction can be performed multiprocessor computing system installed on board each MS.

Fig. 2 b) shows the model TEC distribution function according to [2], obtained by tomography of the ionosphere with the help of navigation satellites and a network of ground receiving stations. Fig. 2 c) is an example of reconstruction of the desired TEC distribution using the methods described above. Fig. 2 c) shows a display example of the required distribution functions as a projection image. In a model experiment reconstruction format has been selected (512 × 512) of the elements at 512 gradations in amplitude. Choosing this format is associated with time constraints standard quad-core processor PC. On multiprocessor systems, procedures implementing distributed computing environment in UNIX format, the reconstruction can be increased by an order that will make it possible to get the resolution (500 × 500) m^2 and above.

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