Automated information technology for ionosphere monitoring of low-orbit navigation satellite signals

Alexander Romanov, Sergey Trusov and Alexey Romanov

Federal State Unitary Enterprise Russian Institute of Space Device Engineering (FSUE “RISDE”), Moscow, Russia
E-mail: romanov@rniikp.ru

Introduction

In the last couple of decades ionospheric radio tomography by navigation low earth orbit satellite signal methods has been intensively evaluated. This kind of tomography consists of the synchronous registration of one satellite signal by a number of receiving stations and is followed by an ionosphere electron content distribution reconstruction based on a set of integral values (signal phase delay). Setting receivers along a satellite pass allows us to obtain height–latitude ionosphere cross-sections. The horizontal size of such sections is commonly a few thousand kilometres, and the vertical size is about 1000 km. The first radio tomography experiments were processed about 20 years ago (Kunitsyn and Tereshchenko, 2001) and the theoretical part has been well investigated, but the approaches to data acquisition and processing have been less well studied.

Usually the time gap between satellite signal registration at the receiving stations and the end of thematic data processing is weeks, or even months. The main reason for such a time delay in most modern tomography systems is because manual procedures are used in the process of acquiring and processing data which constrains the speed of the information being transmitted to the receiver. Consequently, data processing requiring visual analysis or qualitative assessment for decision making needs to be modified to reduce output time. At the same time, it is necessary to organize the high-speed data acquisition.

The process of tomography data acquisition and processing consists of several stages: (1) data acquisition from the receiving stations, (2) analysis of data characteristics, (3) different transformations necessitating decision making, and (4) reconstruction of problem solving quality assessments. Thus, it is necessary to develop an automated system of the tomography data acquisition and processing in order to increase the capability of the data receiving operation.

The automated ionospheric tomography data processing technique, the processing center and data acquisition receiving station interaction algorithm and the special software for information acquisition, processing, storing and representing are needed to develop such a system.

The automated ionospheric tomography data processing technique

The technique is based on the phase-difference tomography method (Kunitsyn and Tereshchenko, 2001). The technique parameters were obtained as a result of numeric modeling carried out for the geometry of the receiving stations’ network, located on Sakhalin Island. The network consists of three receiving stations spaced about 250 km apart.

The technique consists of three stages:

1. Useful signals allocated from data are received from the stations on the basis of empirically obtained boundary conditions (dispersion of the differential phase values in running average window $N = 10$ is less than 1 and the length of the signal part is longer than 60 s).
2. The systematization of the existing data is realized by radio sounding sessions. The data belonging to one session are characterized by a common satellite identifier and the time difference between registering data on the receiving stations of the chain is less than 35 min.
3. The high-frequency signal component (greater than 0.1 Hz) is eliminated and then the phase derivative with respect to time is calculated. The data are decimated and only every eighth measurement is used for further research.
4. The orbit satellite location row is calculated using the SGP4 orbit model (Kelso, 1996) for the satellite communication session according to the procedure of signal decimation. Thus, the satellite

location is calculated for every conformed measurement from the data files.

5. The redundant data for tomography task solving are rejected as soon as the locations of the radio signals in the area of interest are defined. For example, it is necessary to discard part of the received initial data from the southern station if the smallest satellite latitudes, fixed for it, are the smallest for all the tomography chain stations. It is also necessary to reject the data of the southern station if the satellite latitudes characterizing this information are also less than the minimum latitudes for the northern stations. The analogous but opposite conditions are used for culling data of the northern stations.
6. The projecting operator matrix is formed on the basis of the signals' path locations and piece-planar approximation function for the grid dimensions 50×25 km and 1000 km height. The vertical grid size is defined by the current session geometry.
7. An optimal initial guess is picked up by forming the finite set of the model electron concentration distributions and by correspondence analysis of the integral measurements calculated on their (model distribution sets) basis to experimental data.
8. The linear equation system (SLE) is formed using the created projecting operator matrix, the initial guess and measurement vectors $Ax = b$. The SLE solving procedure is realized by the algebraic reconstruction technique (ART) with the relaxation iteration algorithm. The iteration procedure ends if the velocity of the SLE right part of the reconstruction error change becomes less than 0.001, otherwise, it will end after 50 iterations. Thus, the electron concentration reconstruction is completed as soon as the values in regular grid nodes are calculated.

Consequently, the numerical parameters of every stage of the proposed technique were formalized and defined as a result of our research. The special software for automated ionospheric tomography operative data processing was developed.

Remote receiving station network administration

The task of operative data transfer is solved by means of receiving stations connected to the Internet. The transfer time of the data from one satellite communication session (220 Kb) is 14 s, with a typical connection speed of 128 Kb/s to a local Internet provider.

It is necessary to provide the receiving station with an actual schedule of satellite radio visibility sessions used. The proposed decision is based on the satellite orbit parameters, and the radio visibility zone calculation on the basis of the SGP4 model. If the communication session is invisible even for one receiving station in the tomography chain, the records of satellite communication sessions need to be culled after the communication schedule is formed. Thus, the files with the communication schedule are formed in the way represented above to transmit to the receiving station.

The remote control problem is solved by checking the accessibility of the receiver stations via the Internet and analyzing the retrieved log files periodically.

The proposed approaches were realized in the algorithm consisting of three procedures: the calculation of the satellite radio visibility zone, schedules, new data receiving, and receiving station administration. The execution of the procedure is determined by the task manager in accordance with pre-defined rules. The task manager works permanently and checks the schedule periodically. If the current time corresponds to the time of some procedural execution, the special process in charge for this procedure is initiated.

Special software for ionospheric tomography data acquisition and processing

To automate tomography data processing, it is necessary to solve a number of supplementary tasks such as ballistic data acquisition and managing the studies of the data processing. Special software was developed to solve the whole spectrum of the ionospheric tomography system data processing problems revealed above.

The special software structure consists of functional segments in charge of acquiring, processing, storing and representing information, and management and administration of the acquisition and processing information processes (Fig. 1). The basic functionality of each segment is provided with the execution of one, or more often, several program modules. A user web-interface allows the user to access data processing results and manage the acquisition and processing data procedures interactively using any computer with an Internet connection (Fig. 2).

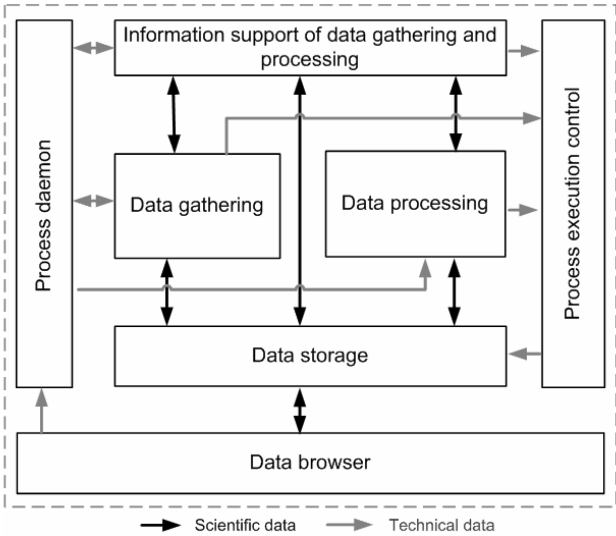

Fig. 1 Flowchart of special software developed for ionospheric tomography data acquisition and processing.

Information storage in the system consists of managing information acquisition and processing from a set of tomography chains realized with the provision for further possible enlargement of the receiving system segment.

This approach is based on special metadata structure usage where each receiving station is characterized by the set of the hierarchical and geographical characteristics, and allows the system to work with a single tomography chain as a set element.

Numerical Modeling Results

The reconstruction of the ionosphere electron concentration model distribution was carried out by developing special software according to conditions identical to real experiment geometry described in Romanov *et al.* (2008) for thematic processing quality assessment. The reconstruction errors were obtained by calculating the discrepancy between initial and reconstructed functions, and defined by the following relations (Kunitsyn and Tereshchenko, 2001):

$$\delta_2 = \frac{\sqrt{\sum_i (F_i - \tilde{F}_i)^2}}{\sqrt{\sum_i F_i^2}};$$

$$\delta_m = \frac{\max_i |F_i - \tilde{F}_i|}{\max_i |F_i|},$$

where F is the initial value and $\tilde{F}$ is the reconstructed one.

Results showed that the errors of the model distribution reconstruction, describing the disturbed ionosphere state (the existence of the irregularities and the horizontal gradient of electron concentration), are characterized by δ_2 = 0.08 and δ_m = 0.10 and become less with the regulating of the ionosphere structure.

Experiment Results

Experimental research on the quality of the developed system of ionospheric tomography data acquisition and processing was carried out using real ionospheric tomography data from stations located on Sakhalin Island.

The system of ionospheric tomography data acquisition and processing working results are the height–latitude distribution of electron concentration (Fig. 3). Figure 4 represents the results of the comparison between the data from the ionosonde in Wakkanai city (Hokkaido Island, Japan), located approximately in 150 km to the south of Yuzhno-Sakhalinsk city (Sakhalin Island, Russia) and the information reconstructed with the aid of the specially developed software. The ionosonde data were provided by "WDC for Ionosphere, Tokyo, National Institute of Information and Communications Technology". Data from the reconstruction of 90 ionosphere states were used: 50 were received in summer period of 2007 (July–August) and 40 in January 2008.

The maximum values of ionosphere electron concentration in the region of the ionosonde location were recalculated to the critical frequency foF2 terms for the further comparison. Good agreement was shown, with a mean discrepancy of 15% and δ_2 = 0.13. Maximum discrepancies of 41% and 46% were obtained for two reconstructions.

The correlation ration for two data rows was 84% (R = 0.84). These results are in good accordance with quality assessments of the ionosphere tomography reconstructions represented in independent research (δ_2 = 0.9–0.11) (Kunitsyn *et al.*, 2007). However, it is necessary to note that independent assessments were obtained using the phase difference tomography approach, but without any automation technique.

The correspondence of these results shows that the new technique proposed in this research allows us to automatically reconstruct the electron concentration distribution in the ionosphere with typical accuracy as for the phase difference tomography approach.

The operational speed of the ionospheric tomography reconstruction using this system is 5–15 min. The speed of this automated data acquisition and processing has no analogue in Russia, and has not yielded the best foreign samples.

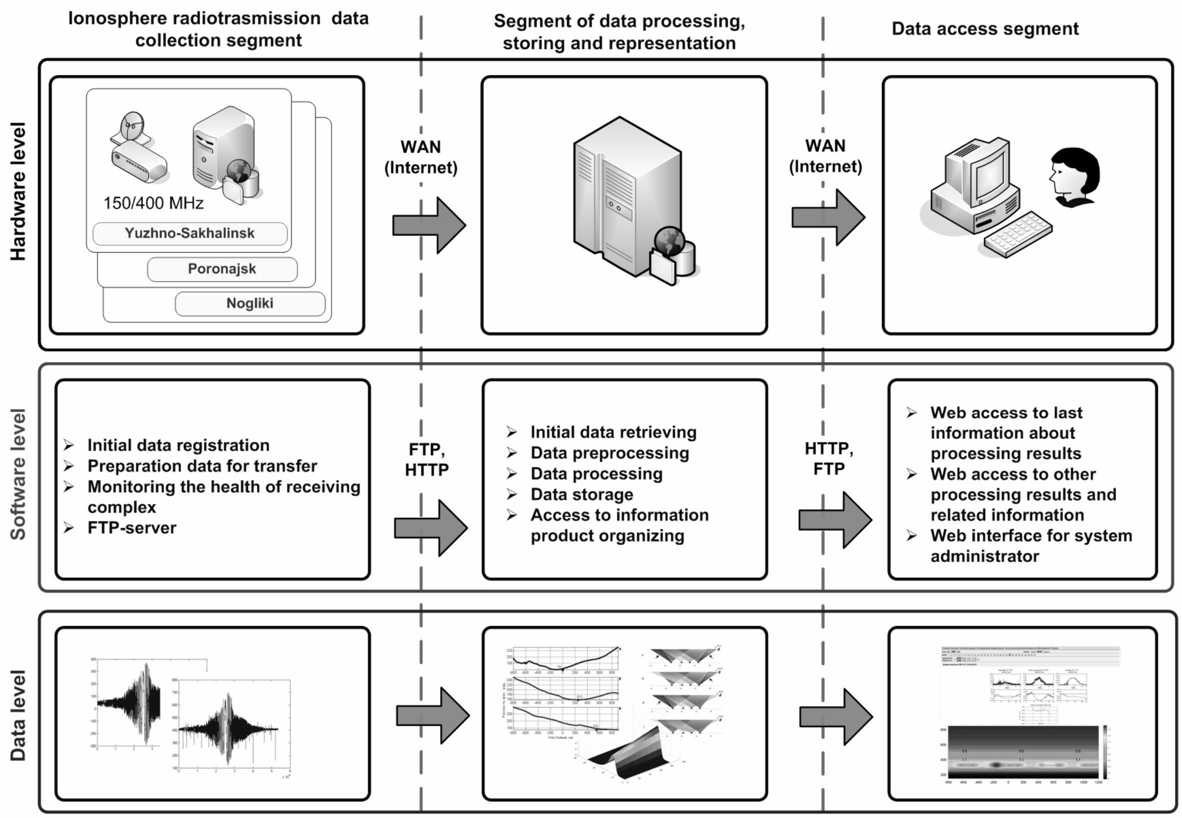

Fig. 2 The structure of ionospheric tomography data acquisition and processing automated system.

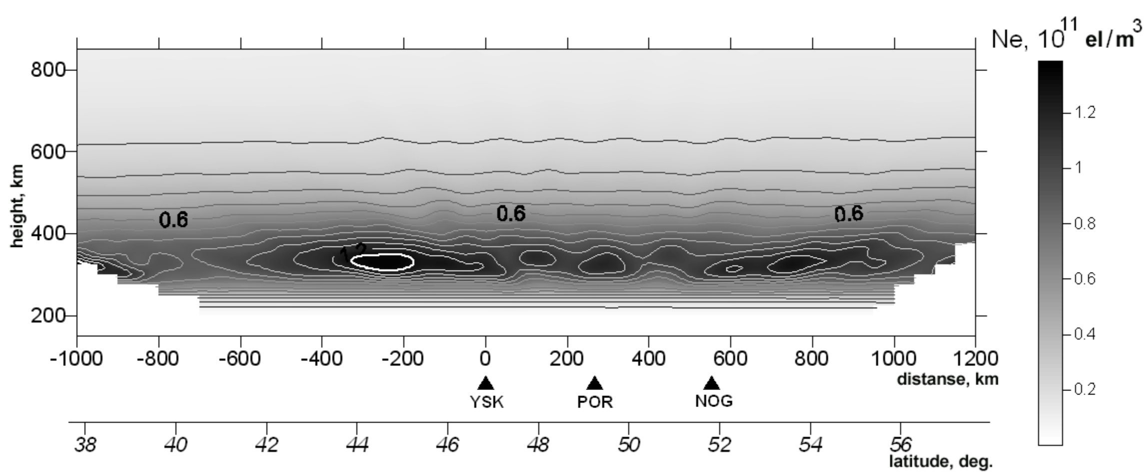

Fig. 3 Electron concentration distribution on July 29, 2007, 0:30 (local time) on Sakhalin Island.

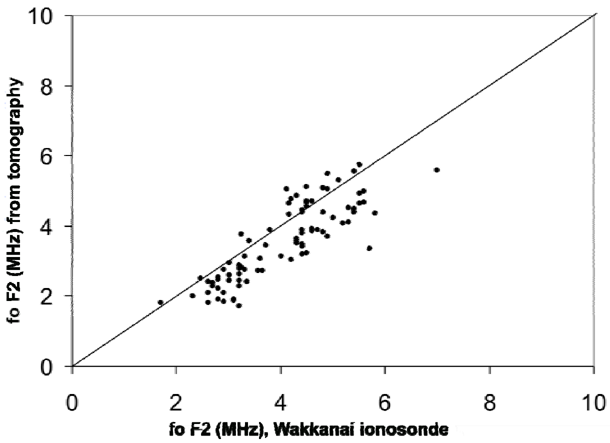

Fig. 4 The scatter plot of the values of critical frequency (foF2 calculated from tomography reconstruction and measured by ionosonde in Wakkanai (Hokkaido Island, Japan).

Conclusions

In the current research, the following results were achieved. The technique of automated ionospheric tomography data processing was developed. The automated ionosphere reconstruction has an accuracy about 15%.

A remote network management algorithm was developed which allows tasks to be solved automatically for ionospheric tomography data acquisition, dataware and workability administration of the receiving stations.

The special software for automated ionospheric phase difference tomography data acquisition and processing was developed. It allows the reconstruction of the ionosphere vertical electron concentration distribution in 5–15 min after the satellite communication session ends.

References

Kelso, T.S. 1996. Real-world benchmarking. *Satellite Times* **3** (November/December): 80–82.

Kunitsyn, V.E. and Tereshchenko, E.D. 2001. Ionosphere Tomography. Springer, Berlin.

Kunitsyn, V.E., Tereshchenko, E.D. and Anreeva E.S. 2007. Ionosphere Radiotomography. 336 pp. (in Russian).

Romanov, A.A., Trusov, S.V., Romanov, A.A. *et al.*, 2008. Researching of ionosphere disturbances on phase-difference tomography method at Russian Far East region. *Earth Remote Sensing* **2**: 14–20 (in Russian).