10.1515/astro-2017-0144

Baltic Astronomy, vol. 22, 25–33, 2013

RADIO INTERFEROMETRIC RESEARCH OF IONOSPHERE BY SIGNALS OF SPACE SATELLITES

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Received: 2012 November 13; accepted: 2012 November 28

Abstract. Since 2012, the Radiophysical Research Institute and the Lobachevsky State University at Nizhny Novgorod, Russia and the Ventspils International Radio Astronomy Centre at Irbene, Latvia are making radio interferometric experiments on study of ionosphere parameters in a quiet (natural) state of medium and research of artificial turbulence of the ionosphere, heated by the emission from the SURA facility. Remote diagnostics of the ionosphere is implemented using a method of radio sounding by signals of navigation satellites in combination with the Very Long Baseline Interferometry (VLBI) method. As a result of spectral and correlation analysis, interferometric responses of the two-element (RRI–UNN) and three-element (RRI–UNN–Irbene) interferometers were received by observations of 12 satellites of the navigation systems GLONASS and GPS. Here the first results are reported.

Key words: instrumentation: interferometers, VLBI – Earth ionosphere – space vehicles – solar-terrestrial relations

1. INTRODUCTION

Increasing of the accuracy of radio astronomy techniques applied to the investigations of space media and objects are directly related to the study of radio wave propagation processes in the near-Earth environment and in the ionosphere. The research of the ionosphere is an independent task that is important for understanding the nature of the phenomena occurring in the atmosphere, as well as for solving various applied problems, such as: (a) determination of the impact of the atmosphere to signals of global navigation space systems (GLONASS, GPS) trying to improve their operation; (b) forecast of the behavior of the ionosphere to ensure reliable operation of terrestrial and space radio communication, including the selection of operating frequencies and the observation of frequency variations depending on the state of the ionosphere during a day and in different seasons; (3) study of the ionosphere effects on the operation of facilities for positioning, navigation and timing, and low-frequency radar systems intended for a deep ground probing and earthquake prediction.

Radio wave propagation is mainly predetermined by the distribution of electrons in the ionosphere. Turbulent irregularities and electron density fluctuations distort radio waves, passing through the environment, and lead to some random effects: the phase and group delay of signals, amplitude scintillations, frequency variation, rotation of the plane of polarization and other effects. The intensity of these effects depends on the state of the ionosphere at the moment of observation, which depends on the solar and geomagnetic activity, time of a day and the anthropogenic interference.

One of the most effective methods for remote diagnostics of the ionosphere is the method of radio sounding (Yakovlev 1998; Armstrong 1990), which probes the medium by radio signals and investigates their distortions caused by inhomogeneities in the propagation medium. In this paper we consider tasks of experimental research of the Earth's ionosphere radio raying it by a noise-frequency radio signals and using for reception the Very Long Baseline Interferometer (VLBI) method. This method is based on measuring of the mutual coherence of emission, passing through the disturbed medium on different paths from the radio source (natural or artificial) to the spaced antennas of the interferometer. Peculiar property of the method is that the diagnostics of the medium at the VLBI reception can be carried out radio raying it by a broad-band noise radiation from natural radio sources, as well as by monochromatic signals of artificial transmitters. The signal processing procedure, used in VLBI, allows to exclude the proper fluctuations of the source emission and examine only the relative perturbations, caused by the environment in two different propagation paths. The size of the baseline projection on the wave front determines the maximum scale of irregularities, which can be measured by this interferometer. Movement of irregularities or change in their intensity becomes apparent in the spectrum of the interferometer signal (Gavrilenko 2002, 2007; Alimov 2004). The case of weak phase fluctuations is the most informative, since the output signal of the interferometer allows to determine the velocity of irregularities and the index of spatial spectrum of electron density fluctuations on the scale, comparable to the length of the interferometer baseline.

Earlier we have used the VLBI technique to study the solar wind plasma. The experimental results and results of the theoretical analysis led to the conclusion, that this method may be applied for Earth's ionosphere research. In recent years, VLBI experiments on the ionosphere by raying by natural radio signals were started. The observations were carried out using multielement VLBI, including radio telescopes in Russia, Latvia and Ukraine. In 2011–2012, the VLBI-network was expanded after equipping antennas by a receiving facility on the frequency range 1.6 GHz, that made it possible to perform the research of the ionosphere sounding it by signals of navigation space satellites (NSS) of the global navigation systems GLONASS and GPS.

The use of navigation satellites as a source of sounding signals facilitates planning of the experiments, because a large number of NSS, distributed almost uniformly over the sky, are constantly situated in mutual visibility from several telescopes. The high power level of signal, emitted by the NSS, provides a high signal-to-noise ratio for the receiving antennas with a small effective area. Compound navigation signal of satellite navigation systems with a bandwidth of 10 MHz (GLONASS) and 20 MHz (GPS) makes it possible to use the standard procedure for VLBI signal processing. A significant advantage of work at a frequency of 1.6 GHz is the absence of interference at the VLBI stations, located near major industrial centers.

Modern techniques allow to study the ionosphere not only in its quiet (natural) state, but also in a state of artificial disturbance, which is created by a powerful transmitter radio emission on the medium. The information obtained will give a possibility to make predictions of the phenomena which can occur under conditions of high solar and geomagnetic activity and under the influence of anthropogenic factors.

2. EXPERIMENTS

In March and April of 2012 two experiments were carried out on the investigation of the Earth's ionosphere with radio raying it by signals of NSS. The RRI 12.1 experiment took place from March 19 to 23, and the RRI 12.2 experiment from April 5 to 10. The following radio telescopes were involved in the observations: parabolic radio telescope RT-2, installed on the building of UNN, a Horn antenna with the size of the aperture of 20 cm in RRI, and a parabolic radio telescope RT-32 at Irbene. The main scientific objective of the experiments was to obtain the dynamic characteristics of the electron density irregularities (such as spatial spectrum parameters and the direction of movement), as well as the examination of the dependence of the electron density fluctuations from the degree of medium disturbance at the artificial excitation by a powerful radio emission.

Previously, in 2011–2012 RT-32 at Irbene was equipped by a high frequency receiver unit and the antenna feed at 1.6 GHz. The feed, made on the basis of spiral antennas and designed for receiving emission in the right circular polarization, has been installed in the secondary focus of RT-32.

During the experiment of the artificial ionosphere turbulence (AIT), the impact on the environment was performed by the heating SURA facility (RRI), attended for monitoring the Earth's upper atmosphere (Belikovich 2007). The HF-heater consists of three independent transmitters, capable to radiate 250 kW and operated in a frequency range of 4–25 MHz, and the transmitting and receiving antenna of the size 300×300 m^2, operated in the range from 4.3 to 9.5 MHz. The antenna gain is $G = 200$–380 and the total effective radiation power is 150–300 MW.

The experiments were carried out in the following outline: the emission from the spacecraft propagates through the ionospheric layer and is received by a network of antennas in the VLBI mode. The region of artificial ionosphere turbulence with a transverse dimension of about 50 km was produced at an altitude of 250 km by the continuous radiation up to about 250 kW generated by the SURA facility. The NSS signals traversed AIT and were received by one of the interferometer telescopes. Other telescopes received the signals, passed through a zone of weak turbulence or through an undistorted area.

Figure 1 shows the relative position of the receiving antenna of the VLBI complex and the heating SURA facility. The first experiment (RRI 12.1) was performed on the radio interferometer UNN-RRI with a baseline 4 km and was coordinated with the work schedule of SURA. The second experiment was carried out with a three-element interferometer, including also the VLBI station at Irbene.

In these observations the ionosphere was studied in its natural state, and the SURA facility was not used (Figure 2). Since the size of the baseline projection on the wavefront determines the maximum scale of irregularities, to which this interferometer is sensitive, then this configuration of VLBI network (with bases from 4 to 1500 km) gives the opportunity to explore a wide range of spatial scales of electron density distributions, which strongly differ in the process of generation, dynamic characteristics and the time of occurrence.

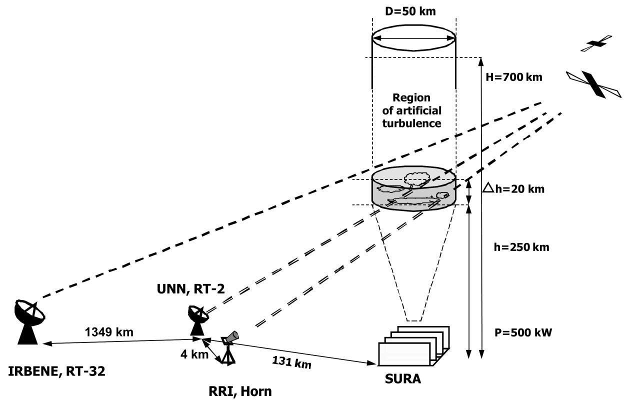

Fig. 1. The scheme of VLBI-experiment on receiving the satellite signals which pass through the artificial ionospheric turbulence produced by the heating SURA facility.

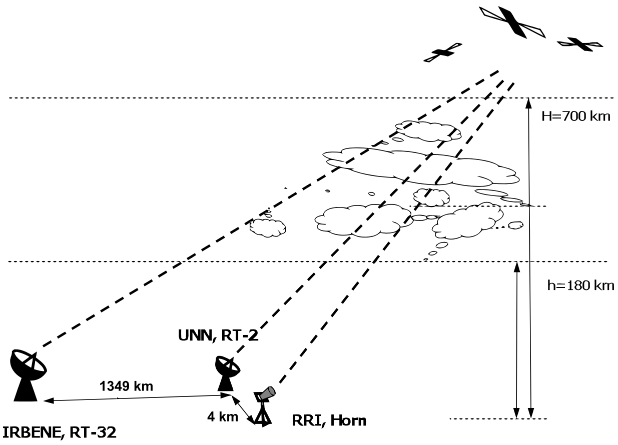

Fig. 2. The scheme of the VLBI experiment on radio raying of the ionosphere by a signal of space satellites.

The coordination of observations was performed by the Internet. During the observations, small portions of data recorded at each receiving station were transferred for the test processing in RRI.

The main difference of these experiments from the previous VLBI session in 2011 is the fact that antennas with small effective area were enabled in the observations. Using the antennas with a wide directional pattern (DP) gives a number of benefits, providing the cost savings, in comparison with the large full-circle expensive antennas, that require a permanent maintenance. Small antennas are mobile and can be quickly moved to a new location, that facilitates the creation of the desired configuration of the VLBI network, which is especially important in the study of artificial ionospheric turbulence. A wide view of the sky allows to perform tracking of a group of objects simultaneously.

Since the horn antennas on the building of RRI were rigidly fixed, the schedule of observations was determined by the moment of NSS entering in the DP of the horn. Recording of the signal from a horn antenna was implemented continuously. The antennas RT-2 (UNN) and the RT-32 (Irbene) performed tracking of NSS during 15–30 minutes.

The telescopes are equipped with specialized receiving and recording VLBI units: the frequency and time standard (hydrogen maser is used on the antennas of RRI and Irbene, rubidium standard is used on the antenna of UNN) with reference time by GPS signals, analogue frequency converters and digital base band converter (DBBC) (only at Irbene), high-frequency unit (low-noise amplifiers with noise temperature close to 100 K, a mixer and local oscillator unit at frequencies 1420 and 1500 MHz), clock frequency generator and control instrumentation. Signal generator, synchronized by hydrogen maser, is used as the second local oscillator. The main element of the registering system is the TN-16 unit, attended for recording of the quantized signal on computer and constructed in RRI. Signal recording was implemented in the frequency bands 2 MHz and 8 MHz, depending on selection of the converter in the Irbene antenna.

3. RESULTS

Processing of the experimental data has been started using the correlation RRI-4. At the first stage the cross-correlation function of the signals received by two antennas of the interferometer is calculated. A delay, which represents time difference of the arrival of signals in the two receiving antennas, is measured from the maximum of the correlation function. At the second stage of data processing, the multiplication of signals with previously included time shift, equal to the measured value of the delay, is performed. Further processing is the implementation of spectral analysis of the obtained series.

The output signal of the interferometer is represented as a two-dimensional correlation function on the axes amplitude – frequency – delay. Figure 3 demonstrates an example of the interferometer signal obtained on the baseline Horn (RRI) – RT-2 (UNN) for a signal of NSS GPS '26605' (date of the experiment: 2012-03-23, 06:00:30 UT).

The vertical axis shows the maximum amplitude of the output signal (in relative units), one of the horizontal axes shows the delay (in microseconds), another horizontal axis shows the frequency (in Hz).

The cross-correlation function of the interferometer signal is shown in Figure 3 by a thin dotted curve. The main and secondary peaks are clearly visible. These peaks are typical for the correlation function, when a noise signal with the flat spectrum is received. The cross-correlation function has a maximum with a delay of 11.8 ns, and this corresponds to the time difference of signal propagation from NSS to the two interferometer antennas.

The rich line in Figure 3 shows the power spectrum of the interferometer signal. The frequency of the maximum is 1.16 Hz, and this is the interference frequency (fringe rate) corresponding to the velocity of NSS, passing through the directional

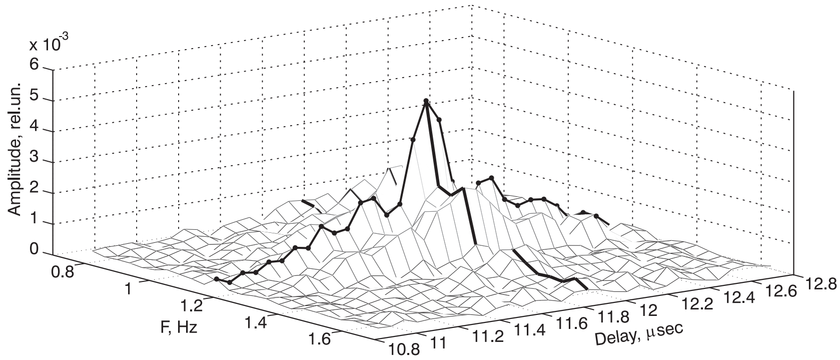

Fig. 3. The output signal of the interferometer RRI–UNN for a signal of the satellite GPS '26605'. The thin dotted curve denotes cross-correlation function for signals, received in two points of the interferometer; the rich curve shows the power spectrum for the result of multiplication of the signals, recorded with the antennas.

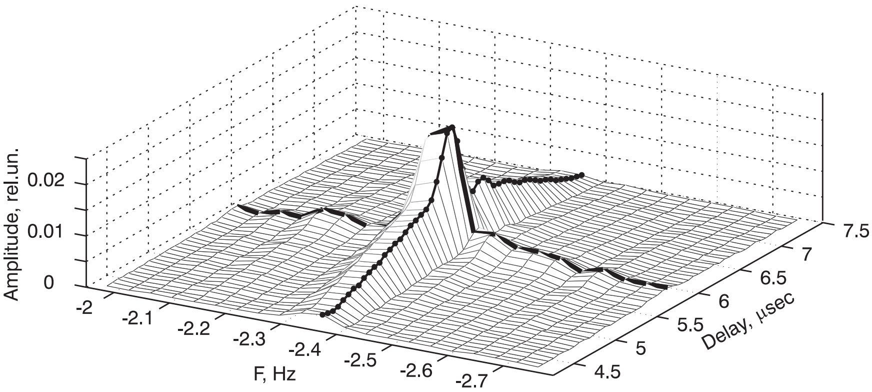

Fig. 4. The output signal of the interferometer Irbene–UNN observing the satellite GLONASS '37868'.

pattern of the interferometer.

Figure 4 demonstrates the response of the interferometer Irbene–UNN for a signal of NSS GLONASS '37868'. The correlation function (thin dotted curve) is typical for the GLONASS signal waveform: a narrow peak is clearly visible on the background of a broader part. The presence of this pedestal is explained by the fact, that the maximum power of the radiated signal is concentrated in a narrow frequency band. An example of the spectrum of a signal, emitted by GLONASS, is shown in Figure 5. The narrow peak in the correlation function in Figure 4 is defined by recording frequency band (8 MHz), and its width is 125 ns. The power spectrum of the interferometer output signal is indicated in Figure 4 by a rich curve.

One of the tasks of the experiments is to study the behavior of the interferometer signal depending on the mode of impact on the ionosphere. In the first phase of data processing we analyzed the amplitude changes and the pattern of the spectrum of the correlation response as a function of time. In this view, the observation of the NSS signal during its pass through a quiet ionosphere and the artificial turbulence was implemented.

Analysis of the interferometer response to the signal of NSS GPS '26605' at its transit behind the heating zone during 40 minutes showed, that the amplitude of the interferometer signal has abruptly changed at engaging the SURA device. At the same time the power spectrum width has increased, what was associated with strong phase fluctuations, arising in the received signals under the influence of the electron density fluctuation irregularities in the impact region.

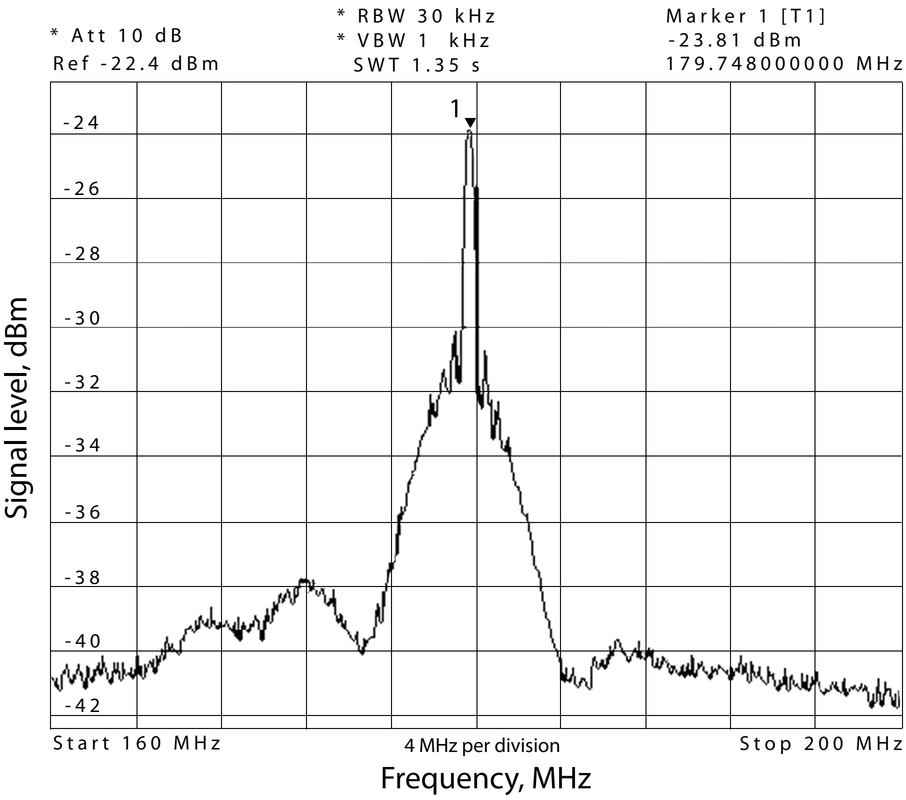

Fig. 5. The spectrum of the signal, emitted by a satellite of the navigation system GLONASS, recorded at Irbene after conversion to the intermediate frequency. The central frequency (in MHz) and the level (in dBm) of the signal emitted by the satellite is denoted by a marker 1.

The operation schedule of SURA is shown in Figure 6 by rich horizontal lines (line position above zero denotes the intervals, when the transmitter of the heating stand radiates). The effective radiation power of the transmitting antenna during the session reached 110 MW. The influence of the ionosphere was carried out with approximately 15 min long intervals with 15 min breaks between the intervals of radiation. In Figure 6 a thin line denotes the interferometer signal amplitude depending on time. The vertical axis shows the amplitude of the output interferometer signal with full delay compensation (in relative units), and the horizontal axis shows the time in minutes. The beginning of the time axis in Figure 6 corresponds to the first engaging of SURA transmitter in this day. The figure illustrates, that the amplitude fluctuations of the power spectrum have increased

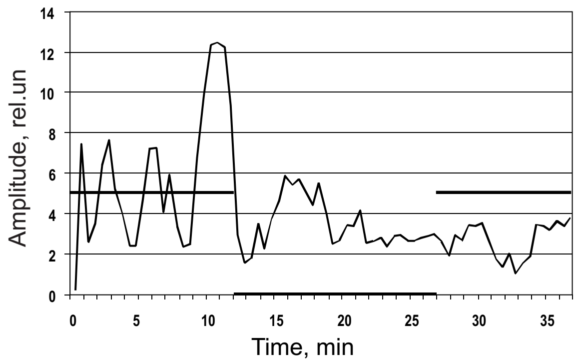

Fig. 6. The dependence of amplitude of the interferometer signal on the schedule of SURA during reception of the signal from the satellite NSS GPS '26605'; 2012-03-23; the interferometer UNN–RRI.

more than six times at the beginning of the impact, while the ionosphere is modified from the unperturbed state to the state of high electron density fluctuations. Then, the amplitude fluctuations has decreased at the transition of medium into the state of weak turbulence. The fluctuations are significantly reduced almost to a minimum after the end of the radiation. Since the next engaging of SURA after 15 minutes break, the satellite was out of zone of high turbulence, and the effect of the disturbed medium on the signal was difficult to determine from the preliminary data.

The analysis of previous experiments allowed us to evaluate the changes in the output signal amplitude, depending on the structure of the signal emitted by the NSS: the amplitude variations do not exceed 20%. This suggests that strong amplitude variations in Figure 6 are actually due to the influence of artificial perturbation of the ionosphere.

To summarize, in 2012 a number of successful experiments on Very Long Baseline Interferometry were implemented with the main task to study the turbulent medium at radio raying of signals of navigation satellites. As a result of the preliminary processing of the recorded data, spectral and correlation responses of the two-element interferometer RRI – UNN and the three-element interferometer RRI – UNN – Irbene were obtained for 12 satellites of the navigation systems GPS and GLONASS. The degree of the medium influence on two main parameters of the interferometer signal, the amplitude and the width of the power spectrum, was evaluated. Further plans include post processing of the experimental data to estimate the electron density fluctuations from phase spectrum of the interferometer signal. The purpose of data processing is to obtain a knowledge about the ionosphere parameters (index of spatial spectrum of electron density and its intensity), as well as to develop methods for measuring the coordinates of NSS.

ACKNOWLEDGMENTS. The researches were supported by grants of the Russian Foundation of Basic Research (project 10-02-00875 "Application of VLBI for investigations of space-time structure of solar wind turbulence and disturbed by high power radio emission ionosphere region"), European Social Fund (project 2009/0231/1DP/1.1.1.2.0/09/APIA/VIAA/151 "Receiving, transmitting and processing technologies of signals related to artificial Earth satellites") and State contract P683 20.05.2010 (registration number 01201061443, 2010-09-10).

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