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Geophysical research in Spitsbergen Archipelago: status and prospects

V V Safargaleev, E D Tereshchenko

1. Spitsbergen — a geophysical site for space weather research

The geographic position of the Spitsbergen archipelago provides a unique opportunity to solve a number of geophysical questions having important scientific and applied value. First and foremost, these are questions related to forecasting space weather.

During daytime, geomagnetic field lines connect the ionosphere over Spitsbergen with magnetospheric regions through which the energy and plasma of solar wind enter the near-Earth space. The energy collected in the magnetospheric tail is released in the course of substorms, and continuous energy influx from solar wind supports the recurrence of these most striking manifestations of space weather. The solar wind plasma that appears inside the magnetosphere mixes with the background plasma, which has essentially different properties, thus creating favorable conditions for the development of various plasma instabilities. These disturbances are also elements of space weather.

To investigate space phenomena far from Earth, the most convenient tools are 'agents' transferring information along the geomagnetic field lines, i.e., charged particles and Alfvén waves. Electrons precipitating into the ionosphere generate aurora. During the winter months, the ionosphere over Spitsbergen is not exposed to sunlight, even in daytime; this provides a unique possibility to investigate magnetopause processes by observing the daytime aurora. Disturbances generated in the process of the ion–cyclotron instability development in an anisotropic plasma are attributed, in particular, to Alfvén-type waves. The plasma anisotropy and associated wave turbulence are observed by satellites in the solar wind region directly bordering the daytime magnetopause. When the anisotropic plasma appears inside the magnetosphere on the field lines leaning on the ionosphere above Spitsbergen, the wave activity is detected by induction magnetometers as short-period geomagnetic pulsations (Pc1). The interaction of the solar wind and the interplanetary magnetic field (IMF) frozen in it with the magnetosphere also appears as a large-scale convection of magnetospheric and ionospheric plasmas. In the daytime ionosphere over Spitsbergen, the character of convection can be studied by a set of incoherent scatter EISCAT (European Incoherent Scatter Radar Systems) radars in Tromsø (TRO, Norway) and Longyearbyen (LYR, Spitsbergen), as well as by one of the auroral SuperDARN (Super Dual Auroral Radar Network) radars in Hankasalmi (HANK, Finland).

Therefore, consistent optic, magnetic, and radar observations in Spitsbergen provide a comprehensive approach to the investigation of an important formation stage of space weather, the energy and plasma influx from interplanetary space (solar wind) into the near-Earth space (magnetosphere). We note in this regard that although satellite measurements are intensively used in solving space weather problems, an analysis of ground observation data is still an effective approach, especially from the standpoint of the balance between costs and efficiency, in experimental investigations of magnetopause processes. Indeed, even if a satellite crosses the magnetopause in the 'right' place at the 'right' time (which is quite improbable), the measurements that interest us last for a few minutes only. A lasting series of ground-based observations allow following the development of a phenomenon (e.g., an abrupt change in the IMF sign or a discontinuity of the solar wind plasma pressure) for longer time intervals covering its prehistory.

The use of the ionosphere as a kind of 'screen' on which magnetospheric processes are presented also stimulates investigations of the 'screen' itself. The high variability of the Arctic-latitude ionosphere requires continuous observation. It is ineffective to obtain regular data on electron content by expensive direct rocket or satellite measurements. Cheaper, but no less informative, are the methods of remote ground-based sensing and satellite radiography. These methods allow determining the ionospheric electron density by radio waves propagating through it. Ionosonde sounding is a comparatively inexpensive method; however, it can be

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used only for investigation of the lower layers of the ionosphere. The space resolution of an ionosonde is not high. Radars make measurements with a better space resolution than the ionosonde, but they have a narrow field of view and require high expenses for their regular use.

A relatively inexpensive way to estimate the state of the ionospheric electron concentration in a space region of a few thousand kilometers along the meridian and with a height of the order of 1000 km is the satellite radio tomography method [1]. An additional advantage of this method is that it does not depend on weather and geophysical factors. Currently, satellite radiotomography is practically the only available method of continuous diagnostics of global electron density formations in the ionosphere, including gravity waves. The method can also be effectively used for localization of artificial disturbances: rocket launches, industrial emissions, and ionospheric inhomogeneities appearing because of the action of a powerful radio wave on the ionosphere.

Ionospheric research methods based on the action of powerful short-wave (SW) beams have been intensively developed over the last two to three decades. Because of ionospheric absorption of the energy of radiated radio waves, various physical phenomena are generated in the ionosphere (see, e.g., review [2]). Investigation of heating effects allows better understanding the structure of the ionosphere and the character of its natural processes. In addition, ionosphere artificial modification experiments also have an applied value. For example, one of the manifestations of heating — the generation of artificial ionospheric inhomogeneities — is used to study the influence of natural ionospheric inhomogeneities on the performance of satellite radio navigation systems.

Concentration of various diagnostic tools in northern Scandinavia stimulated, in due time, the construction of a heating facility at the EISCAT radar near Tromsø (Norway). The range of problems that this facility can solve is wide; but the participation of Russian scientists in experiments conducted there is limited and reduces to episodic expeditions. The absence of necessary portable mobile equipment, poor financing, customs formalities — this is an incomplete list of problems explaining the low activity of domestic academic science in auroral ionospheric studies by active influence methods.

A tendency to improve the situation appeared after the 2004 launch of the SPEAR (Space Plasma Exploration by Active Radar) project. The SPEAR heating facility was constructed in the framework of a project at ESR (EISCAT Svalbard Radar) near Longyearbyen (Spitsbergen). The geography of heating experiments expanded into a cusp region (during daytime), which is extremely interesting from the geophysical standpoint, and the boundaries between closed and open field lines (during nighttime). A few years earlier, the Polar Geophysical Institute (PGI) of the Kola Scientific Center, RAS, had resumed scientific investigations in the Barentsburg Observatory (BAB), which is approximately 40 km west of SPEAR. The first joint experiment on the registration of possible ionosphere modification effects by the SPEAR heating facility was conducted in February–March 2007. By that time, the PGI Observatory had already had a set of measurement facilities, including various optical, magneto- and radiometric devices.

The ionosphere is associated with a set of factors significantly affecting radio wave propagation. The high-latitude ionosphere is a more changeable formation than the middle latitude ionosphere. The tomographic investigations of ionospheric inhomogeneities done in the Spitsbergen archipelago, as well as those of the characteristics of the generation and propagation of electromagnetic waves in extremely and super low frequency (ELF–SLF) ranges in the Earth–ionosphere waveguide, can be used in solving the problems of radio communication, radiolocation, and radionavigation in the Arctic.

All the above determines the interest of the international geophysical community in investigations in Spitsbergen, an interest that is currently being realized through the establishment in the archipelago of one of the best and most convenient international scientific sites in the Arctic, with developed infrastructure and strong international connections. A new stage in PGI studies in Spitsbergen began in 2000, after the Russian Federation governmental regulation "On Financing the Activity of Russian Organizations in the Spitsbergen Archipelago" and the creation of the Interdepartmental Commission on Securing Russian Interests and Industrial and Scientific Activity in the Archipelago. It was at that time that the foundations of the northernmost Russian geophysical observatory facility were laid. Nowadays, this observatory, equipped with an extensive armory of observation tools, is an integral part of the international geophysical platform (Fig. 1).

The basis for the PGI regular observations in Barentsburg is a facility including a magnetovariational station and inductive magnetometers, a radio–tomographic receiving station, a GPS (Global Positioning System) and GLONASS (Global Navigation Satellite System) signal receiver, various optical devices, an electric field sensor, a neutron monitor, and an ozonometer to measure tropospheric ozone variations. To conduct specific experiments, additional devices are used, specifically, an SW radio interferometer facility and a precision ELF broad-band receiver. On the basis of experimental data obtained at the PGI Observatory over the number of recent years of its existence, more than 40 publications and scientific communications have been prepared. In the next sections, we briefly review those that, in our opinion, constitute a significant step forward in the above three scientific areas: space weather research, artificial ionosphere modification by SW waves, and propagation of SLF waves in the ionospheric waveguide. To conclude this section, we note that the organization and conduction of observations in severe Arctic conditions require extensive efforts and determination of the researchers. Therefore, the authors use the opportunity provided by this paper to thank those PGI researchers whose professional activity facilitated the development of the observatory and the acquisition of high-quality data.

2. Comprehensive studies of ionospheric disturbances related to processes in the magnetopause and adjoining domains

A large part of the PGI scientific results obtained in Spitsbergen is based on the data of annual collaborative campaigns for the investigation of daytime aurora dynamics in the context of ionospheric convection. These campaigns are organized by Oulu University (Finland) and the Swedish Institute of Space Physics (Kiruna, Sweden). These scientific institutions are members of the International EISCAT Association, and have long-standing partner relations with the PGI.

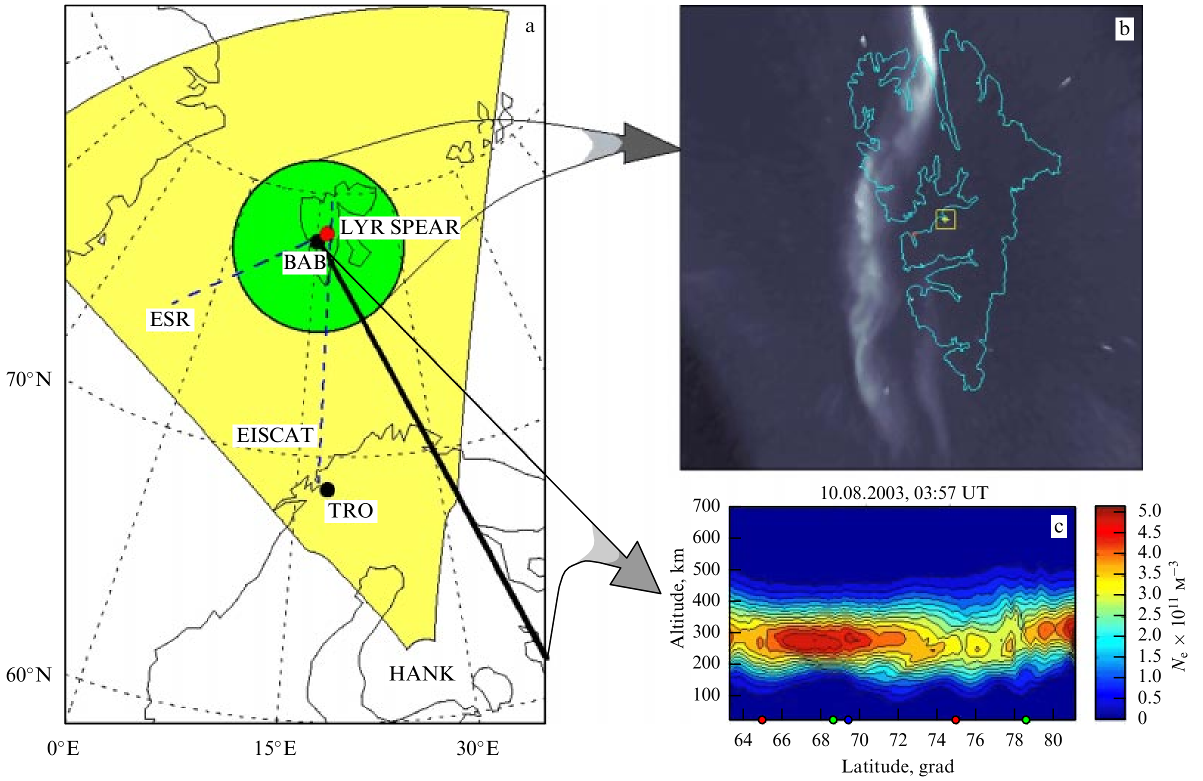

Figure 1. (a) The positions of the Barentsburg Observatory (BAB) and the SPEAR heating facility relative to the field of view of HANK, ESR, and EISCAT radars. The bold solid line shows the profile along which the points of the PGI tomographic chain are located. The circle corresponds to the field of view of the PGI TV camera. (b) The projected TV frame, with the square schematically showing the SPEAR heating facility. (c) An example of tomographic reconstruction of ionospheric disturbances; dots on the horizontal axis correspond to receiving points.

In the campaigns, both antennas of the ESR radar in Longyearbyen and the EISCAT radar in Tromsø are in operation. The movable ESR antenna that is oriented along the geomagnetic latitude or at a small angle to it measures the speed of plasma convection along the auroral arcs. The Tromsø radar antenna is tilted such that its beam crosses the vertical (or skewed, depending on the problem) beam of the ESR antenna at the height 120 – 150 km, and hence the measurements are within the field of view of the full sky observation camera in Barentsburg (Fig. 1a). In such experiments, an important role is played by the correct spatial matching of optical and radar measurements. With this aim, an exact positioning of a TV camera with respect to Earth is done with the help of a software package developed by Swedish colleagues (the so-called camera geometric calibration). As a result of the calibration procedure, each pixel of the image corresponds to a point on the ground with certain coordinates. After that, it is not difficult to match aurora images with radar and satellite measurements.

Solar wind interaction with the daytime magnetosphere is a continuous process; however, it appears especially clear during distinctive interplanetary medium parameter changes, such as an abrupt change of the IMF sign or a discontinuity in the solar wind pressure. Theoretically, energy and plasma influx into the magnetosphere are considered to occur at the time of reconnection of Earth's lines and those of the IMF. For the southern IMF, the reconnection occurs near the under solar point and the reconnected field lines are transported by solar wind through the polar cap to the tail, where their collection is interpreted as a magnetic energy increase. In this process, the number of closed field lines on the day side decreases, and the cusp is shifted to the lower-latitude region. For the northern IMF, the reconnection occurs behind the cusps. The solar wind plasma located on the field lines adjoining the magnetopause appears on the newly created closed field lines, which is interpreted as trapping of the transition layer plasma. An increase in the number of closed field lines in the daytime magnetosphere leads to a shift of the cusp toward the high latitudes.

The picture becomes more complex if we take the large-scale magnetospheric convection into account, which does not allow the field lines to 'accumulate' on the night side for the southern IMF, and transports the closed field line 'excess' from the day side to the night one for the northern IMF. The convection can also play a positive role. Because of the magnetic field frozen into plasma, the magnetospheric convection is reflected in large-scale motions of the ionospheric plasma. Therefore, the convection property of certain responses to IMF changes can be used as an additional information source in the studies of solar wind and magnetosphere interaction processes by ground means.

One of the most effective means for studying processes in the magnetopause and adjoining regions is, traditionally, the investigation of the structure and dynamics of the daytime aurora. In the above context, this is investigation of the auroral response to the change of the IMF sign. Theoretically, the solar wind interaction scheme looks understandable; but technical complications appear in attempting to investigate it experimentally. First, an abrupt change of the IMF sign typically occurs at the front of the solar wind inhomogeneity and is accompanied by a noticeable change in the plasma pressure. As a result, we see the combined effect of a field flip and a pressure jump in the auroras. Second, calculating the beginning time for the interaction of the inhomogeneity with the magnetopause involves an uncertainty because of the inaccuracy of time calculation for the inhomogeneity propagation, since ACE (Advanced Composition Explorer) satellite data for measurements at the distance 250 R_E (R_E is Earth's radius) are typically used. The third difficulty appears because the source of the daytime aurora is near the daytime cusp or the polar cap boundary (see, e.g., [3]). The magnetosphere there consists of layers whose sizes are small when projected on the ionosphere; this makes it more difficult to associate the auroral source with a magnetospheric domain. A wrong association can lead to a wrong interpretation of observed optical phenomena.

Typical forms for daytime aurora are the so-called poleward-moving auroral forms (PMAFs). In pioneering work on the investigation of daytime auroras in Spitsbergen, a hypothesis was put forward that the reconnection can be the reason for PMAF-type auroral activity [4]. Further use of this hypothesis by a Norwegian research group that has a developed network of optical observations in Spitsbergen led to the conclusion that almost every case of near-midday PMAF is an ionospheric manifestation of reconnected field tubes that drift into the magnetospheric tail, even though the interpretation is ambiguous due to the above reasons. An alternative approach was attempted in Refs [5, 6], where cases were described where the structures were observed on closed field lines, and their dynamics were not due to convection only. That work demonstrated the importance of optical studies combined with other measurements and initiated the idea of regular collaboration campaigns in Spitsbergen.

A phenomenon that is described below was detected during one of the campaigns; it represents a unique situation in which the above difficulties were almost absent. First, it turned out that we were dealing with a response to IMF changes only. Second, we used data from the Geotail satellite, which is not far from the magnetopause. This allowed relating the PMAF to just the IMF twist to the north with a sufficient degree of confidence; this was later confirmed by the ionospheric convection pattern recovered on the basis of radar data. Third, not long before the beginning of the phenomenon, a satellite of the DMSP (Defence Meteorogical Satellites Program) series was above the aurora; according to its data, the forms were on closed field lines.

To interpret the results of optical observations, HANK radar data (part of the SuperDARN network) were invoked, as were the data of the Finnish network of interference magnetometers complemented by the PGI's magnetometer in Barentsburg. As a result of such a comprehensive approach in the analysis of the phenomenon, we concluded the following (see also [7]). After the twist of the IMF B_z component to the north, the HANK radar detected an ionospheric inhomogeneity over Spitsbergen as an anomalous reflected signal. The anomaly was accompanied by an activity burst in the Hz range, and in Barentsburg only, i.e., it was detected by the highest high-latitude induction magnetometer (Fig. 2a). The anomalous echo and the geomagnetic activity burst were due to the trapping of anisotropic plasma of the transition layer, as is schematically shown in Fig. 2b. Drifting along the boundary between the BPS (boundary plasma sheet) and the LLBL (low-latitude boundary layer), the plasma bunch caused LLBL widening and, as a consequence, a shift of the source of three auroral arcs that had existed before that (Fig. 3b).

This optical phenomenon seems to be a typical PMAF in a keogram (Fig. 3a). We note that the IMF variation had the shape of a short-time positive pulse. By using data from far ACE and Wind satellites, it is quite possible to relate PMAFs in time with the back side of the inhomogeneity, i.e., with the IMF turned to the south, because of a large calculation error of the inhomogeneity propagation time to the magnetopause and in the absence of additional radar data on the character of the ionospheric convection. The arc dynamics can then be explained by the drift of the reconnected field lines to the tail, and the anomalous echo in the Hank data and the burst of magnetic activity in Barentsburg can be related to the cusp shifting toward low latitudes. Therefore, our investigation is methodologically important for diagnostics of the magnetopause processes by ground-based means.

3. Investigation of the ionosphere over Spitsbergen by the active modification method

Currently, scientific progress as a whole not only is determined by the development of observational techniques but also depends significantly on international cooperation. Along with space weather research, another impressive example of the international approach to solutions of important geophysical problems in Spitsbergen is the polar ionosphere modification experiments by powerful SW radiation.

Active ionosphere modification, with the aim to investigate the properties of this natural plasma shell, has been used in geophysics since the 1980s. But in Spitsbergen, in the cusp and the polar cap region, the SPEAR heating facility began operations only in 2004. Artificial ionospheric radiation (AIR) — a broadband noise-like radiation appearing as a result of ionospheric plasma excitation by powerful electromagnetic radiation — was discovered in EISCAT (Tromsø) heating experiments [8]. Although the interest in spatial characteristics of this radiation has existed from the moment of its discovery, the AIR observations have long been restricted to measuring the signal intensity, separating the spectral components of the radiation, studying the radiation dynamics, and so on. Localization of the AIR generation region remained an unsolved problem for a long time because of the high requirements for the equipment.

The SW radio interferometric facility capable of determining the direction of an incoming signal by the phase difference method was constructed at the PGI in 2002 – 2003. The interferometer works in the 1.5–32 MHz frequency range, with the 300 kHz bandwidth and a wide dynamic range (about 100 dB). The facility allows conducting phase difference and amplitude measurements of artificial as well as natural signals.

In February–March 2007, the PGI took part in the ionosphere heating experiment in Spitsbergen. To date, we have acquired considerable experience, and our equipment has been tested at middle and auroral latitudes during the Sura and EISCAT heating experiments. In the polar cap region, such observations were unprecedented. Although the heating facility power was only two thirds of the projected one (the effective radiation power only slightly exceeded 10 MW), we were able to confidently record artificial ionospheric radiation [9].

Artificial ionospheric radiation is a weak noise-like signal in the frequency range $\approx 200 - 300$ kHz whose amplitude is 60 dB less than the amplitude of the heating facility wave reflected by the ionosphere. The radiation and properties of its spectral characteristics significantly depend on nonlinear

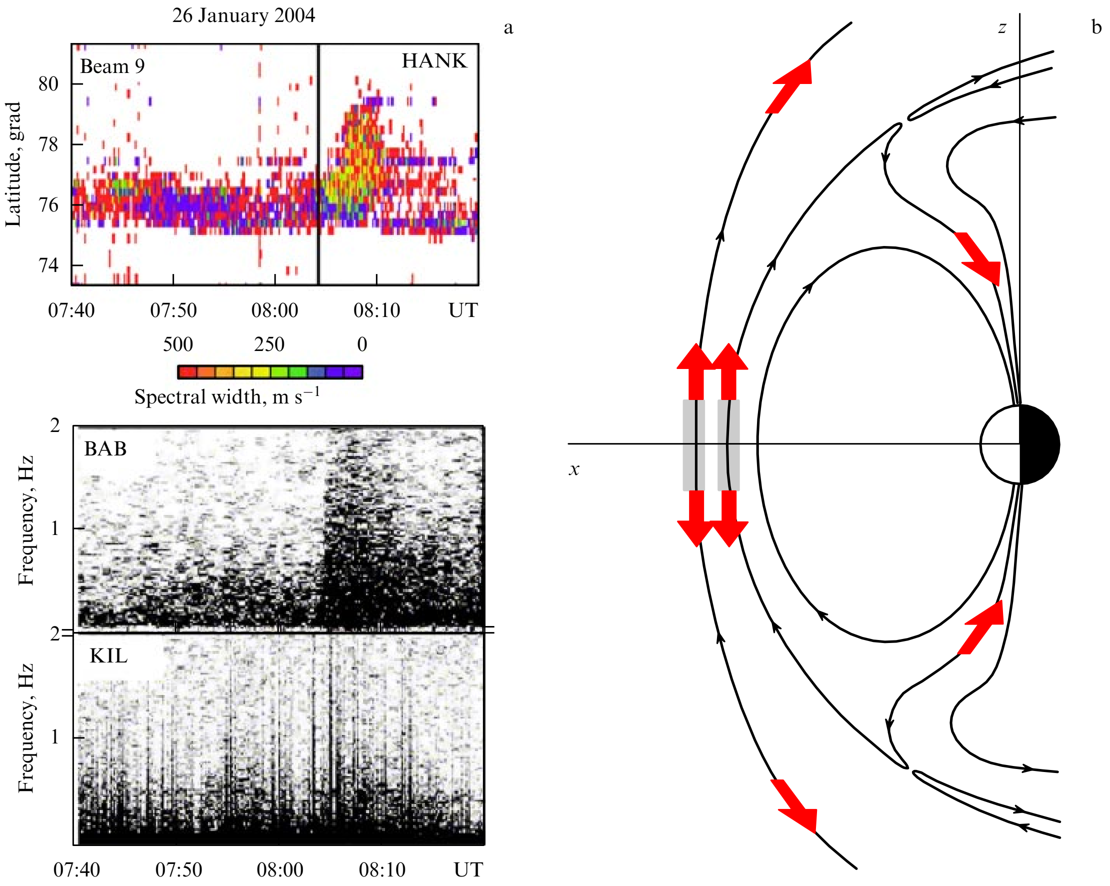

Figure 2. (a) The anomalous echo in the HANK radar data and wave activity in Barentsburg (BAB) and at the Kilpisjärvi (KIL) auroral station. (b) A scheme illustrating the 'trapping' of the solar wind anisotropic plasma (the grey area) and the appearance of Hz waves in the high-latitude ionosphere (bold arrows) in the reconnection process for the northern IMF.

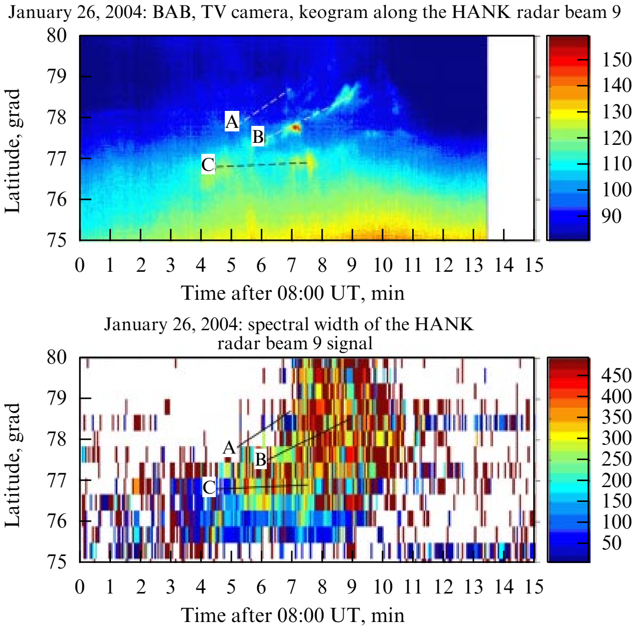

Figure 3. A keogram illustrating the dynamics of three auroral arcs, A, B, and C, along the ninth beam of the HANK radar (a), and the mutual motion of the arcs and the anomalous radar echo region (b).

processes excited in the ionospheric plasma as a result of heating, as well as on the value of the plasma frequency, the local gyrofrequency harmonic, and the orientation of geomagnetic field lines with respect to the heating facility.

As an example, Fig. 4a shows the spectrum of the artificial radiation recorded on March 9, 2007, for the heating frequency 4.45 MHz, the effective radiating power of the heating facility 13 MW, and radiation directed along the geomagnetic field lines. In this Figure, the characteristics of the artificial radiation stationary spectrum are clearly seen, such as the main downshifted maximum (DM) and its second harmonic 2DM, the broad continuum (BC) and broad upshifted maximum (BUM) signals in the region of negative and positive frequency shifts, respectively, as well as the upshifted maximum (UM) in the region of positive frequency shifts. The central part of the spectrum corresponding to heat waves reflected from the ionosphere is suppressed by a rejection filter set up at the intermediate frequency of the SW interferometer receiver.

The AIR registration by the PGI installation, which was incompletely integrated in Barentsburg at that time, demonstrated a possibility in principle of AIR generation by heating in the geophysical conditions of Spitsbergen. In its current modification, the facility is capable of not only recording the fact of AIR generation but also determining the direction to its source in the ionosphere (Fig. 4b), as was done in one of EISCAT heating facility experiments [10].

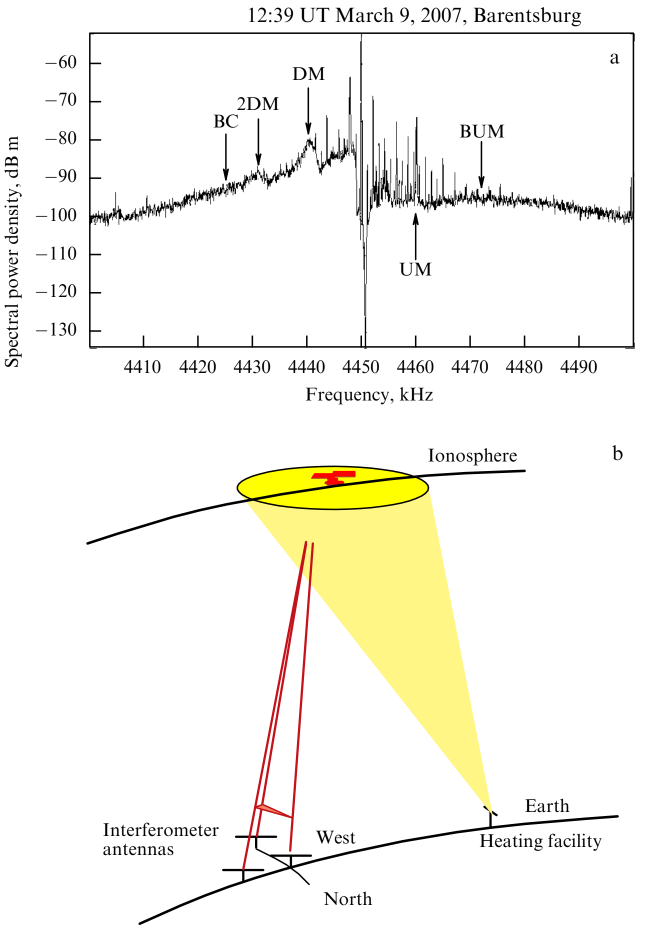

Figure 4. (a) The AIR spectral power density recorded at 12 : 39 UT on March 9, 2007 in the Barentsburg Observatory. (b) A scheme of the AIR source localization experiment by the PGI interferometer.

4. Characteristics of the high-latitude propagation of an artificial electromagnetic signal in the 0.1 – 10 Hz range

Wave propagation in various frequency ranges is studied by using theoretical (numerical) ionosphere models. Continuous improvement of the models, aiming to most adequately represent real situations, is important for applications. It is known that the spectrum of near-Earth background noise in the 0.1 – 10 Hz frequency range has a number of features related to the ionospheric structure. As is known from the theory [11], there are two reflecting ionospheric regions for a wave in the range from 0 to 10 Hz. The first reflecting region, where the electron concentration increases with increasing the height, is below the F-layer maximum, thus forming the Earth–lower ionosphere waveguide for such waves. The existence of the second reflecting region is due to a characteristic drop in the electron number density above the F-layer maximum. Together with the first region, this region forms the outer waveguide, the ionospheric Alfvén resonator (IAR). The interference of waves reflected from resonator walls leads to a nonmonotonic frequency dependence of their amplitudes and hence to the formation of so-called spectral resonance structures in the noise background. It is probable that IAR can also have a similar influence on signals of artificial origin in this frequency range.

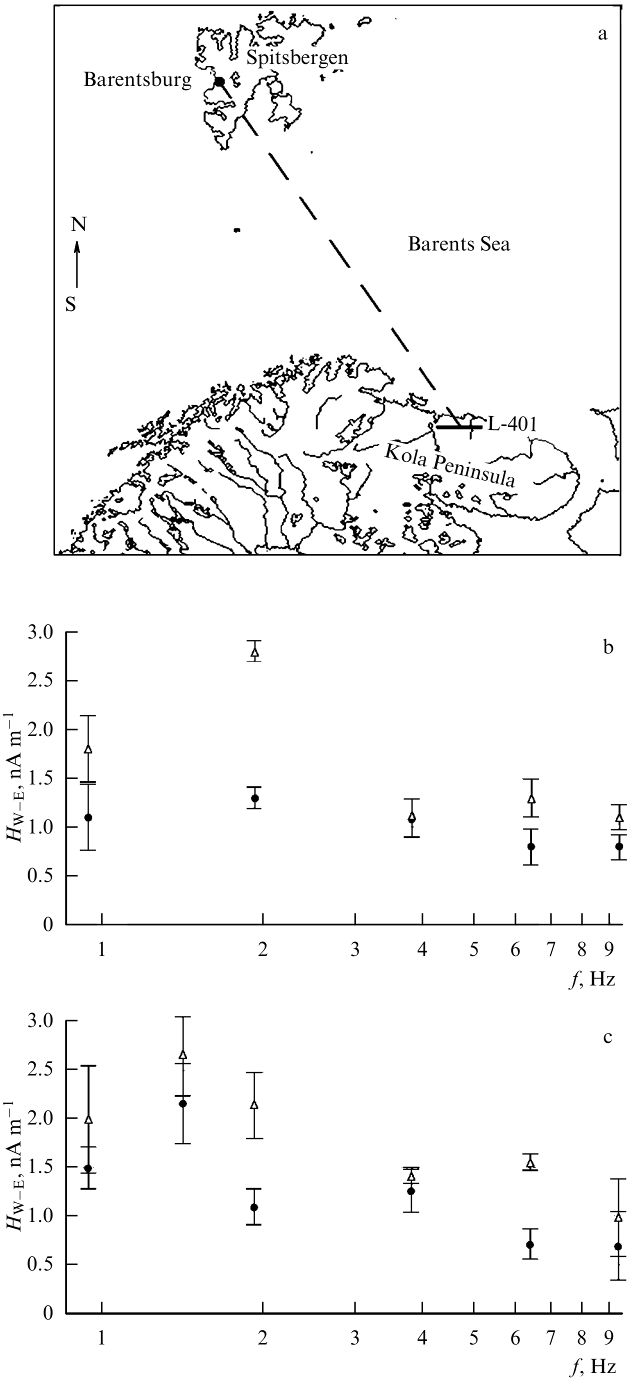

Figure 5. A scheme of ELF signal radiation and reception experiments (a), and results of signal amplitude measurements on September 5 and 6, 2007 (b) and on August 18 and 20, 2009 (c).

To check this hypothesis, a comprehensive experiment designed to generate and receive 0.1 – 200 Hz ELF electromagnetic radiation was conducted in September 2007. An L-401 transmission line 107 km in length, which was grounded at the ends, available in the northern part of the Kola Peninsula, and predominantly west–east oriented, was used as a radiating antenna (Fig. 5a). A quasimonochromatic current in the antenna was supported by an ELF transmitter with the power 100 kW. The radiation occurred at several frequencies in the 0.1 – 10 Hz range, and the current amplitude in this range was 150 – 180 A.

The magnetic field created by this antenna was measured at the distance 1200 km from the transmitter, in the Barentsburg Observatory, by a three-component induction magnetometer. The radiation experiments were conducted within a few days, mostly at night, when the IAR formation probability is high.

The main result of these experiments is that in a number of cases, a nonmonotonic dependence of the received signal on the frequency was detected for the horizontal magnetic field component (Fig. 5b, c). We believe that this is due to the IAR influence on the propagating signal, because the scheme of the experiment allowed investigating the field in the region with a significant contribution of the wave propagating in the outer waveguide (above the F-layer) to the total field.

We also estimated the effectiveness of various ionospheric models for interpretation of the results of the conducted measurements. We showed that the results of the international reference ionosphere (IRI) model calculations agree poorly with the experimental data. The upper atmosphere model (UAM) calculations better correspond to the experiment, but they are also imperfect. The results of experimental ionospheric studies (such as satellite tomography) should be used to refine the ionospheric characteristics obtained by model calculations.

5. The future of geophysical investigations in Spitsbergen

The future of geophysical investigations in Spitsbergen is seen, first, in increasing international cooperation. The times have passed when observations were made in isolation and only data from two or three instruments were used to analyze phenomena. Studies by Russian, Norwegian, Swedish, Finnish, and Chinese researchers clearly demonstrate the effectiveness of coordinated observations and a comprehensive approach to data analysis. Understanding that, in 2009 the Norwegian Research Council put forward an initiative to integrate the maximum possible number of observation points operating in Spitsbergen into a unified measurement–information system aimed at the global modeling of the Arctic atmosphere. This Svalbard Integrated Observing System (SIOS) project was financially supported by the European Union. The Polar Geophysical Institute is a member of the consortium running the preliminary stage of the project; it is part of a group researching the influence of magnetospheric processes on the Arctic climate.

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Results of solar wind and planetary ionosphere research using radiophysical methods

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1. Introduction

We describe the results of space plasma studies using remote methods developed at the Kotelnikov Institute of Radioengineering and Electronics (IRE) of the Russian Academy of Sciences. The main result of circumsolar plasma research is the determination of the radial velocity dependence for the motion of plasma fluxes and solar wind turbulence modes at various distances from the Sun. Priority data on altitude profiles of Martian and Venusian night ionospheres have been obtained using the radio sensing method. Two monitoring methods for Earth's ionosphere have been suggested and realized. In the first method, ionospheric radio sensing is done on the spacecraft–Earth's surface point path. In the realization of the second method, two Earth satellites are used, one of which is the source of radio waves sounding the ionosphere, and the other is the receiver of plasma-modified signals.

The aim of this contribution is to briefly describe the main results of various space plasma studies done at the IRE, Department of Space Radiophysics, from 1970 to 2009. The work performed was devoted to investigations of solar wind and Martian and Venusian ionospheres, and to the development of new monitoring methods of Earth's ionosphere by using spacecraft signals. In Figure 1, dashed lines show the radio wave propagation paths from spacecraft to points on Earth's surface. For solar wind research, we used signals of Soviet (Mars-2 and Venera-10 (-15,-16)), European (Helios and Ulysses), and American (Galileo and MGS (Mars Global Surveyor)) spacecraft. It was possible to investigate the plasma shells of Mars and Venus after the Soviet Mars-2 and Venus-9 (-10) spacecraft were launched into the first artificial satellite orbits of these planets. The monitoring of Earth's ionosphere by a new radio sensing method was realized on satellite–satellite paths. For this, we have used radio links between the Mir Station and geostationary satellites, as well as between GPS (Global Positioning System) satellites and the research CHAMP (Challenging Minisatellite Payload) and FORMOSAT-3 satellites. At the first stage, the influence of various media on the amplitude, phase, frequency, and spectrum of decimeter radio waves was

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