Solar-Terrestrial Physics. 2021. Vol. 8. Iss. 1. P. 39–50. DOI: 10.12737/stp-81202205. © 2022
O.V. Kozyreva, V.A. Pilipenko, M.N. Dobrovolsky, A.N. Zaitsev, E.E. Marshalko. Published by INFRA-M Academic Publishing House

DC 537.852.3
DOI: 10.12737/stp-81202205

Received October 19, 2021
Accepted December 26, 2021

DATABASE OF GEOMAGNETIC OBSERVATIONS IN RUSSIAN ARCTIC AND ITS APPLICATION FOR ESTIMATES OF THE SPACE WEATHER IMPACT ON TECHNOLOGICAL SYSTEMS

O.V. Kozyreva
Schmidt Institute of Physics of the Earth RAS,
Moscow, Russia, kozyreva@ifz.ru

V.A. Pilipenko
Schmidt Institute of Physics of the Earth RAS,
Moscow, Russia
Geophysical Center RAS,
Moscow, Russia, pilipenko_va@mail.ru

M.N. Dobrovolsky
Geophysical Center RAS,
Moscow, Russia, m.dobrovolsky@gcras.ru

A.N. Zaitsev
Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation RAS,
Moscow, Troitsk, Russia, alex.zaitsev1940@mail.ru

E.E. Marshalko
Finnish Meteorological Institute,
Helsinki, Finland, elena.e.marshalko@gmail.com

Abstract. An archive of digital 1-min data from Soviet/Russian Arctic magnetic stations has been created, starting from 1983 to the present. The archive includes data from stations deployed along the Arctic coast by various USSR/Russia institutes. All data are divided into daily files, converted into a standard IAGA2002 format, and provided with graphs for quick-look browsing. Some of the data are not included in the existing world data portals (SuperMAG, INTERMAGNET). We give examples of using the database for the Arctic: study of irregular disturbances and waves of the Pc5/Pi3 range exciting intense geomagnetically induced currents; distortion of the pipe-to-soil potential during magnetic storms; ground support for radar observations of the ionosphere. To assess the regions most susceptible to geomagnetic hazard, we calculated a map with normalized telluric fields for a uniform magnetic disturbance with a unit amplitude and periods 100–1000 s. This map shows that the geological structure significantly affects the magnitude of the geoelectric fields generated by magnetic disturbances. The database is made publicly available on the anonymous FTP site [ftp://door.gcras.ru/ftp_anonymous/ARCTICA_Rus].

Keywords: magnetic stations, Arctic, geomagnetic pulsations, databases, geomagnetically induced currents, telluric fields.

INTRODUCTION

The first magnetic observations in Russia were made as early as the 16th century during sea expeditions organized by English merchants in search of a northern route to China. In 1724, St. Petersburg Academy of Sciences was established, and the first observations of magnetic declination began in 1726. In 1830s, regular magnetic observations were expanded to eight locations, including China and Alaska. Digitized collection of data from the Main Physical Observatory in St. Petersburg for 1869–1914 comprises 70 thousand digital images and is available on the website [http://db.izmiran.nw.ru].

Geomagnetic observations were among the priorities during the First International Polar Year (1882–1883) and the second one (1932–1933). The turning point in planetary geophysics was the International Geophysical Year in 1957–1958, when in only the USSR and Antarctica 557 geophysical stations were deployed, the first satellite was launched, a system of world data centers was created, and the geomagnetic activity indices *AE* and *Dst* were introduced. In subsequent years, the era of great geographical discoveries began in understanding the structure and dynamics of near-Earth space. That time, satellite and ground-based magnetometers formed the basis of observational facilities.

More recently, after the 1989 Quebec energy disaster, it was discovered that space weather in near-Earth space is not only a giant natural plasma laboratory, but also a serious danger to the smooth functioning of space and ground-based technological systems. The most active manifestations of geomagnetic disturbances and geomagnetically induced currents (GICs) in conducting grounded systems occur at auroral latitudes. Research is being actively carried out in many countries into the GIC impact on terrestrial technological systems and into possible measures for mitigating negative effects. Since current space weather conditions depend on non-stationary and unpredictable solar activity, studies of mechanisms of solar-terrestrial relations have also led to a new area of research — space climate [Mursula et al., 2011]. For this area of research it is crucial to have long time series of geomagnetic observations.

The level and scope of domestic space weather research still lag behind the world ones in many respects. Moreover, the Russian Arctic does not have a sufficiently dense network of magnetic stations. Nevertheless, in severe Arctic conditions Russian scientific institutions perform regular observations of the geomagnetic field. Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy (SHICRA) of the Siberian Branch of the Russian Academy of Sciences and the Institute of Cosmophysical Research and Radio Wave Propagation (IKIR) of the

Far Eastern Branch of the Russian Academy of Sciences (RAS) make comprehensive observations at a network of stations in Eastern Siberia and the Far East. The Arctic and Antarctic Research Institute (AARI) has deployed magnetic stations along the Arctic coast as far as Chukotka. The Polar Geophysical Institute (PGI) KSC RAS conducts a set of observations on Kola Peninsula and Spitzbergen. New magnetic stations have been deployed by the Geophysical Center (GC) of the Russian Academy of Sciences [Gvishiani et al., 2018]. Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation (IZMIRAN) RAS has created a CD-ROM archive of data from Russian magnetic stations for 1984–2000 [Amiantov et al., 2001]. The data was written in binary format and accompanied by an MS DOS program to read the data. These efforts made it possible to save the archive of one-minute data from digital variational magnetic stations, including data on the project “Geomagnetic meridian 145°” [Zaitsev, 1974]. Nonetheless, the software tools developed that time for reading binary data cannot currently be used; therefore, the data appeared to be practically inaccessible to the scientific community. Recently, to monitor space weather effects on technological systems, IZMIRAN has deployed several magnetic stations in Yamal. However, these disparate observations have not been put in a user-friendly form yet.

While monitoring the geomagnetic field is extremely important for the Russian Arctic zone, the level of ongoing research is clearly insufficient. The territory of the Russian Federation covers approximately 1/3 of the auroral oval, but the number of works using data from Russian magnetic stations, according to the authors, is no more than a few percent of the total number of publications on physics of auroral phenomena in the world. This is largely due to the limited availability of data from Russian stations to the global community and domestic researchers [Pilipenko et al., 2019].

In this paper, we describe a new generalized database containing an archive of variational magnetic observations in the Russian Arctic and give some examples of its use for scientific and applied problems.

DATABASE DESCRIPTION

The database presented contains observations of geomagnetic variations with a 1 min resolution at stations in the Russian Arctic. Geographic and corrected geomagnetic (CGM) coordinates of the stations are listed in Table, and the map of the stations included in the database is given in Figure 1. Data from some station is available on the SuperMAG portal [https://supermag.jhuapl.edu], is part of the IMAGE [https://space.fmi.fi/image] and MAGDAS networks [http://www.serc.kyushu-u.ac.jp/magdas]. Some data was taken from the website of the Collective Use Center “Analytical Center for Geomagnetic Data” of GC RAS [http://ckp.gcras.ru]. However, these archives do not contain data from a number of stations, say, from Yamal. Naturally, in each of the archives listed above, data is stored in its own format.

Geographic and geomagnetic coordinates of the Russian Arctic stations computed using the algorithm [https://omniweb.gsfc.nasa.gov/vitmo/cgm.html] for 2015

Observation station	Code	Geographic coordinates		Geomagnetic coordinates		Organization	Network
		latitude	longitude	latitude	longitude		
Amderma	AMD	69.47	61.42	65.4	137.7	AARI	
Baranov	BRN	79.27	101.75	74.2	174.3	AARI	
Barentsburg	BBG	78.07	14.25	75.6	108.6	PGI	
White Sea	WSE	66.55	33.10	63.2	111.5	GC/MSU	
Bely	BEY	73.30	70.00	69.5	146.8	IZMIRAN	
Vize	VIZ	79.29	76.58	74.9	154.9	AARI	
Dikson	DIK	73.54	80.56	67.9	155.7	AARI	
Cape Kamenny	CKA	68.50	73.60	63.3	148.2	AARI	
Kotelny	KTN	75.94	137.71	69.9	201.2	SHICRA	MAGDAS
Lovozero	LOZ	67.97	35.08	64.1	114.9	PGI	IMAGE
Loparskaya	LOP	68.25	33. 08	64.1	114.1	PGI	
Nadym	NAD	65.53	72.50	61.8	145.6	IZMIRAN	
Norilsk	NOK	69.40	88.40	64.3	162.2	ISTP	
Sabetta	SAB	71.42	72.13	65.2	147.1	IZMIRAN	
Salekhard	SKD	66.52	66.67	63.0	141.7	IZMIRAN	
Seyakha	SEY	70.10	72.50	64.8	147.7	IZMIRAN	
Tiksi	TIK	71.59	128.78	65.7	196.9	SHICRA	MAGDAS
Cape Chelyuskin	CCS	77.72	104.28	71.3	175.0	AARI	
Cape Schmidt	CPS	68.88	180.63	64.2	235.1	IKIR	
Pebek	PBK	70.08	170.90	65.0	228.8	AARI	
Kharasavey	KHS	71.11	66.86	67.5	143.1	IZMIRAN	
Heiss Island	HIS	80.62	58.05	74.7	145.1	AARI	
Chokhurdakh	CHD	70.62	147.89	64.8	212.4	SHICRA	MAGDAS

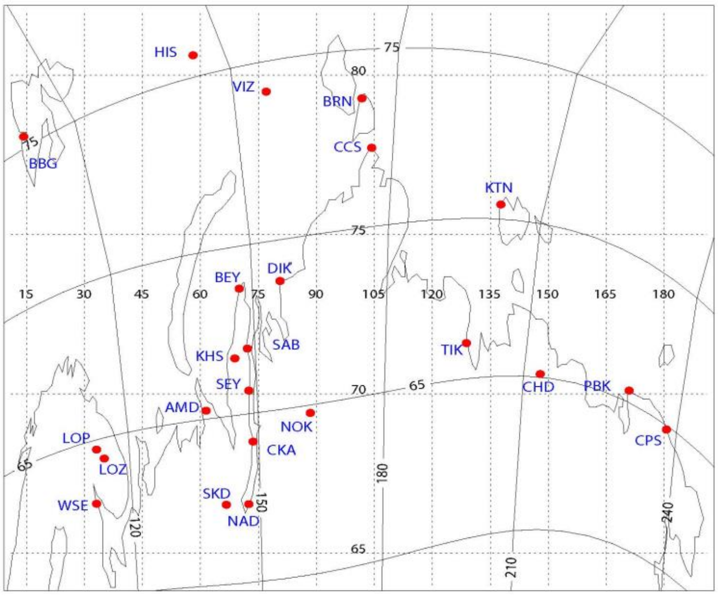

Figure 1. Magnetic stations in the Russian Arctic zone for monitoring adverse space weather effects on technological systems. Dashed lines show the geographic grid; solid lines, the geomagnetic grid. Station codes are given in Table

All gathered data was converted to the generally accepted ASCII format IAGA-2002 [https://www.ngdc.noaa.gov/IAGA/vdat/IAGA2002/iaga2002format.html]. The file names that make it easy to select the intervals needed for the analysis are STAYYYYMMDDvmin.min, where STA is the station code from Table; YYYY — year; MM — month; DD — day. The data files are arranged by years and stored in a compressed form (ZIP) to speed up the download process.

Most of the stations make variational observations, which do not require measurements of absolute values of the geomagnetic field. In the initial stages, the main component variometers at the magnetic stations were quartz-sensor devices [Amiantov et al., 1990]. Afterwards they began to be gradually replaced by fluxgate magnetometers with a flat frequency response. In recent years, some Russian stations are gradually switching to the INTERMAGNET [https://www.intermagnet.org] international network standard. In variational observations, only deviations from the base level are physically meaningful. Data in nanotesla (nT) is given in a three-column format in the geomagnetic coordinate system (H, E, Z): the H-axis is directed to the geomagnetic pole; the E-axis, to the geomagnetic east; the Z-axis, vertically down. Magnetograms from all the stations were visually examined, and defective files were discarded. However, some files have jumps in level, gaps in data, and short-term noise. Their correction requires special analysis.

To quickly view the data, check the availability of data for specific time intervals, and to select events, quick-look magnetograms were drawn. Below we present examples of files of the constructed *H*-component magnetograms in a graphical format. To generally characterize interplanetary space conditions from the OMNI database [https://omniweb.gsfc.nasa.gov], the same plots show variations in the solar wind plasma density N_p, solar wind velocity V, and vertical component of the interplanetary magnetic field B_z. These plots are given below for the events that are important for the problem of GIC excitation in power transmission lines (PTL) and pipelines, but their physical nature has not been fully elucidated.

EXAMPLES OF GEOMAGNETIC VARIATIONS GENERATING STRONG GICs

One of the most significant space weather factors is GICs in systems of technological conductors, caused by abrupt changes in the geomagnetic field dB/dt (see extensive literature in the review [Pilipenko, 2021]). While the largest magnetic disturbances on Earth's surface (magnetic bays) are caused by an extended auroral electrojet, the largest GIC bursts are generated by small-scale ionospheric current structures. The energy of such impulsive or quasi-periodic disturbances is much lower than the energy of magnetospheric storms or substorms; however, rapidly changing fields of such disturbances generate intense GIC bursts [Belakhovsky et al., 2019]. Examples of such disturbances are presented below from data collected in the DB. Figures for all the examples are given in the same format as the graphs for quick-look browsing included in the DB.

Russian industrial companies interested in determining possible effects of geomagnetic disturbances on the operation of technological systems at high latitudes may compare their failure archives with the presented DB. Furthermore, despite the deficiency of geomagnetic observations in the Russian Arctic zone there are periods when the coverage of observations is dense enough (for example, in the Yamal region) to study both the longitudinal and latitudinal structures of geomagnetic disturbances. Of course, the given examples are illustrative and far from exhausting the possible scientific problems for which the Arctic DB can be used.

Pi3/Ps6 pulsations

After the substorm expansion phase, irregular quasi-periodic Pi3 pulsations with characteristic time scales 3–15 min are often superimposed onto large-scale magnetic variations [Saito, 1978]. Figure 2 presents quick-look graphs for the substorms on February 09, 2019 (left panel) and March 02, 2019 (right panel) based on data from high-latitude stations included in the database. These pulsations are not harmonic oscillations, but a quasi-periodic series of nonlinear magnetic pulses with steep fronts. Pulsations morphologically close to Pi3 are Ps6 pulsations [Connors et al., 2003]. Due to steep fronts of Pi3/Ps6 pulsations, the *dB*/*dt* field variability during these pulsations is high and may exceed 20 nT/s.

The Pi3/Ps6 pulsations cause quasi-periodic GIC bursts. In many events, GICs were extreme (hundreds of amperes) not during the onset of a substorm, but during the subsequent series of Pi3 or Ps6 pulsations [Sakharov et al., 2021; Apatenkov et al., 2020; Chinkin et al., 2021].

Isolated magnetic impulses

When analyzing space weather effects, it is implicitly assumed that extreme geomagnetic fields are spatially homogeneous throughout the power system. However, isolated maxima are often observed in magnetic (with amplitudes >100 nT) and telluric (>1 V/km) fields against general field enhancement during substorms — magnetic perturbation events (MPEs) [Engebretson et al., 2019]. These maxima are highly localized, i.e. the amplitude peak at one station may be several times greater than the regional value of the field, on average, at distances around 500 km. Figure 3 presents examples of such pulse disturbances (at ~16 and ~05 UT) during moderate magnetic activity. The physical processes that determine the generation of these extreme disturbances are not well understood. The magnetic perturbation events are usually associated with local intensification of auroral luminosity.

Pc5 pulsations

While near-Earth space is a turbulent system, the presence of natural MHD resonators and waveguides gives rise to quasi-monochromatic oscillations in the ultra-low frequency (ULF) range (periods from seconds to tens of minutes). ULF waves and noise are an integral part of the electromagnetic environment of the planet. The ULF pulsations of the geomagnetic field

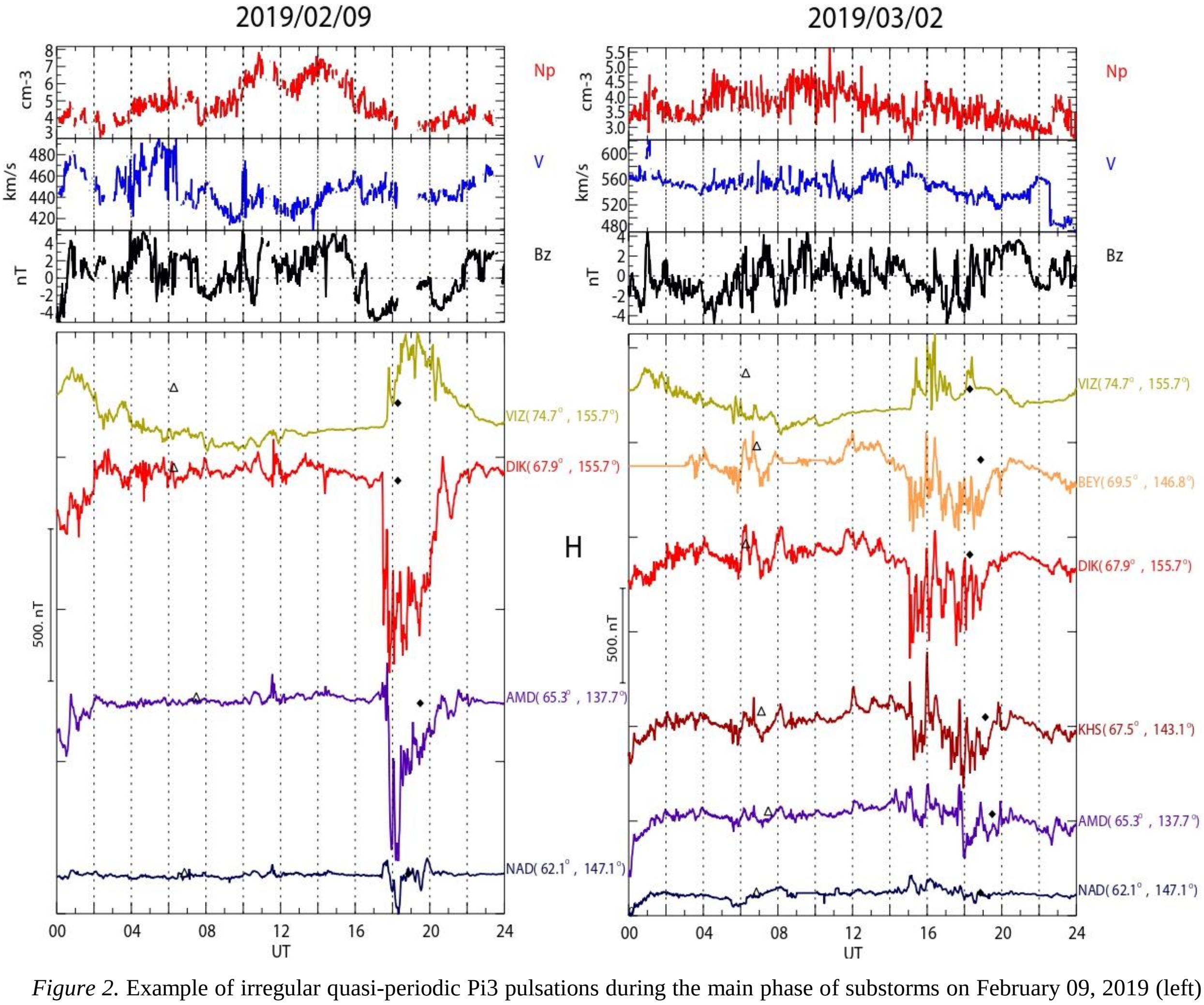

Figure 2. Example of irregular quasi-periodic Pi3 pulsations during the main phase of substorms on February 09, 2019 (left) and March 02, 2019 (right). The top panel on both plots shows variations in the solar wind plasma density N_p, solar wind velocity V, and vertical component of the interplanetary magnetic field B_z. Next to the station code in bottom panels are geomagnetic coordinates of the stations. Next to the magnetograms (*H* component), triangles mark the local noon at each station; rhombuses, the local midnight

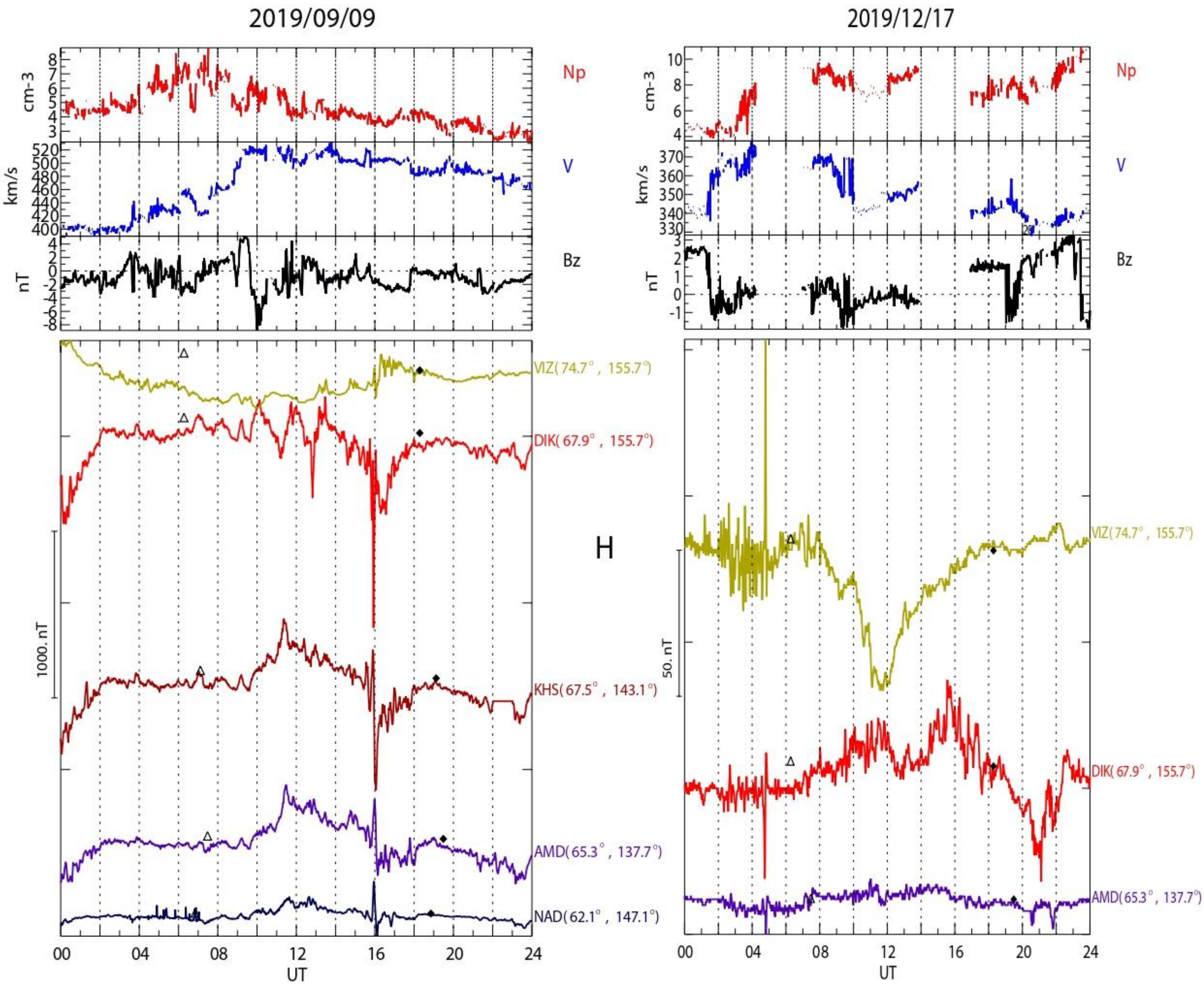

Figure 3. Example of localized magnetic perturbation events (MPE) recorded on September 9, 2019 (left) and December 17, 2019 (right). The format is the same as in Figure 2

observed on Earth's surface are predominantly a reflection of MHD waves in near-Earth space. These waves are excited by the solar plasma stream flowing around the magnetosphere or by energetic particle fluxes injected into the magnetosphere during magnetic storms and substorms. At the same time, ULF waves do not just indicate dynamic processes occurring in near-Earth space, but also actively influence their behavior: they modulate fluxes of trapped radiation, cause precipitation of trapped particles into the atmosphere, accelerate auroral electrons that excite auroras (Alfvenic aurora); transfer energy to relativistic "killer electrons" in the outer radiation belt posing a serious risk to satellite electronics.

At the low-frequency boundary of the ULF range are Pc5 waves (characteristic periods are 3–5 min). The Pc5 pulsations occur predominantly at auroral latitudes and are eigenmodes of Alfvén field line oscillations trapped between conjugate ionospheres. These Alfvén oscillations last for about several hours, are localized in latitude in a region with 200–300 km scales; their amplitude rapidly decreases to low latitudes. An example of long-term quasi-monochromatic Pc5 pulsations for February 22, 2019 is given in Figure 4.

Due to the high variability of the magnetic field of Pc5 pulsations, the GIC magnitude in PTLs when they appear increases and can exceed 10 A [Sakharov et al., 2021]. The long-term existence of the moderately intense GICs produced by geomagnetic Pc5 pulsations may be even more hazardous to long-term operation of electric networks and pipelines than short-term GIC bursts during the onset of substorms and storms owing to the cumulative effects —corrosion and premature aging of high-voltage transformers.

JOINT RADAR AND GEOMAGNETIC OBSERVATIONS

Magnetic stations in Yamal are in the field of view of the ISTP SB RAS decameter coherent radar, located on the territory of Arti Observatory [http://sdrus.iszf.irk.ru] [Bernhardt et al., 2020]. Arti observatory in the Sverdlovsk Region belongs to Bulashevich Institute of Geophysics UB RAS (geographic coordinates 56.41° E, 58.54° N). The radar's field of view and the magnetic stations falling into it are displayed in Figure 5. The experience of long-term operation of this radar has demonstrated its high sensitivity in detecting ionospheric plasma movements caused by magnetospheric pulses and waves [Chelpanov et al., 2019]. Therefore, the geomagnetic DB we describe will be useful

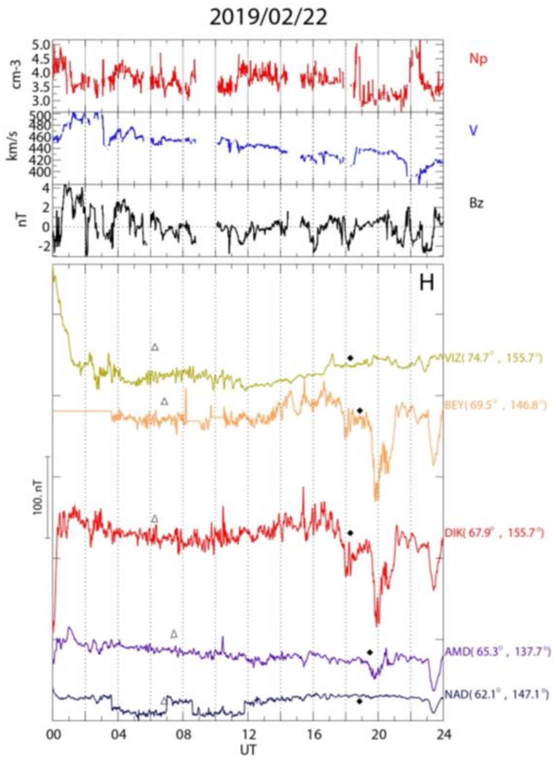

Figure 4. Example of quasi-monochromatic Pc5 pulsations (*H* component) recorded on February 22, 2019

for comparing ionospheric and geomagnetic ULF waves and pulses. The use of synchronous observations of ionospheric electric field and surface geomagnetic field variations provides important information about an additional physical parameter of disturbance — apparent impedance. Estimating the disturbance impedance makes it possible in principle to determine its physical nature [Pilipenko et al., 2012].

VARIATIONS IN GEOMAGNETIC AND TELLURIC FIELDS AS A GIC SOURCE: SIMULATION OF GEOELECTRIC FIELD DISTURBANCES

Modern power systems are a huge network with complex topology that covers vast areas of Earth's surface whose local geoelectric properties may vary by up to five orders of magnitude. The specific conductivity in Earth's surface layers ranges from ~10^{-4} S/m on granite bases to ~3 S/m in the ocean. Geoelectric fields induced in Earth's surface layers during magnetic substorms can disrupt the operation of electric networks, and the occurrence of an extremely intense magnetic storm in the future may even lead to a large-scale loss of energy capacity. In fact, a driver of GICs and its associated overloads in grounded electric power grids is the difference between electric field potentials in surface layers of the earth's crust. It is not, however, easy to get direct information about geoelectric fields. While geomagnetic variations are tracked by the global network of magnetometers, which consists of more than 300 stations and observatories [Gjerloev, 2012], regular observations of telluric fields are not yet so common. In principle, it is possible to calculate variations in electric fields and currents in the earth's crust from magnetometer data if information about the geoelectric section is available. To compute telluric fields with high accuracy, we can use the impedance ratio, which is valid on the assumption that the horizontal scale of disturbance is much greater than the skin depth in the earth's crust.

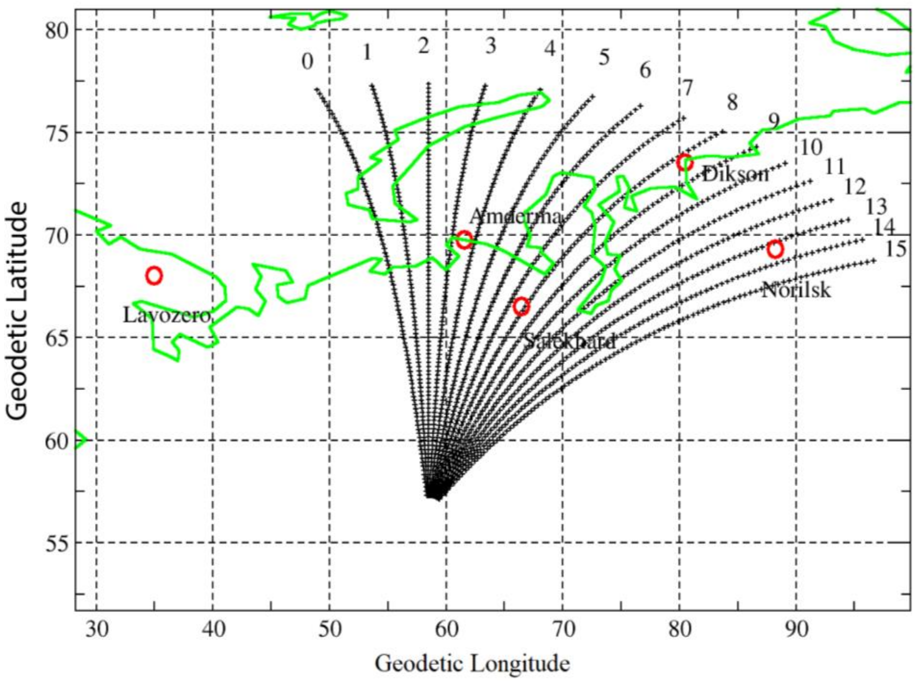

Figure 5. ISTP SB RAS Coherent Decameter Radar's field of view and position of magnetic stations. Numerals indicate numbers of beams

The situation is greatly simplified by the fact that practically important GIC calculations require integral values of the potential difference between nodes of an extended system (at least several hundred kilometers); therefore, necessary estimates can be made with sufficient accuracy even at a network of relatively widely spaced magnetometers and with a rough conductivity model.

The most intense GIC bursts occurred in electrical networks from geomagnetic disturbances with characteristic time scales 2–10 min [Belakhovsky et al., 2019]. Electromagnetic field disturbances with such periods penetrate into Earth's surface layers to a depth of the order of the skin depth ranging from units to several hundreds of kilometers. In low-conductivity media, the probability of negative effects of strong magnetic disturbances increases sharply since induced telluric fields *E* turn out to be greater and induced currents flow mainly through conductive elements of industrial networks. In the plane-wave approximation, on Earth's surface the impedance relation $\mathbf{E}=\mu_0^{-1}\mathbf{Z}\cdot\mathbf{B}$ holds between spectral amplitudes of vectors of horizontal electric $\mathbf{E}=\{E_x, E_y\}$ and magnetic components $\mathbf{B}=\{X, Y\}$, where $\mathbf{Z}$ is the impedance matrix [Berdichevsky, Dmitriev, 2009]. In this paper, we use the 1D impedance $Z(f)$

$$\begin{pmatrix} E_x(f) \\ E_y(f) \end{pmatrix} = \mu_0^{-1} \begin{pmatrix} 0 & Z(f) \\ -Z(f) & 0 \end{pmatrix} \begin{pmatrix} X(f) \\ Y(f) \end{pmatrix}. \quad (1)$$

For the homogeneous earth's crust with resistivity ρ the impedance $Z=\sqrt{-i\mu_0\omega\rho}$ depends on the period $T=2\pi/\omega$ of the incident disturbance in a power-law manner $Z(T)\propto T^{-1/2}$. However, near coastal zones with a sharp conductivity gradient 3D impedances should be used.

The GIC intensity *J* is usually assumed to be proportional to the time derivative of the geomagnetic field, $J\sim dB/dt$. In real situations, the circuit through which GICs flow is formed by PTL, ground contacts, final transformers, and ground, with electrical parameters of these elements and their frequency dependence known very approximately. The actual relationship of the spectral composition of magnetic variations $B(f)$ with the telluric electric field $E(f)$ and induced current $J(f)$ should be determined individually for each technological system. The frequency dependence of the impedance $Z(f)$ leads to the fact that geoelectric properties of seat rocks act as a filter that suppresses high frequencies in the geomagnetic variability dB/dt [Sokolova et al., 2019]. Thus, the geomagnetic variability dB/dt is not a sufficient characteristic of effectiveness of geomagnetic variations.

Determining the impedance of Earth's surface requires dedicated magnetotelluric sounding (MTS), which has been done only for certain areas of Earth's surface. For example, under the Earth Scope program, a magnetotelluric survey of the United States was carried out on a network of stations spaced by 70 km [Schultz, 2009]. Then, simultaneous measurements of geomagnetic and geoelectric fields were used to calculate the impedance tensor [Bedrosian, Love, 2015]. There is no equally detailed model of geoelectric conductivity for the entire territory of the Russian Federation; therefore, when calculating geoelectric fields, we have to apply different approximate models. We have used information about impedances of the earth's crust calculated by the global conductivity model [Alekseev et al., 2015] (depth range from 0 to 100 km) and the 1D conductivity model [Kuvshinov et al., 2021] (for depths greater than 100 km). The 3D model [Alekseev et al., 2015] comprises a great deal of data available in the world literature and obtained from MTS. The 3D model also includes data on the conductivity of the upper layer (the first 10 km) of the SMAP model for Fennoscandia [Korja et al., 2002], absent in the original model [Alekseev et al., 2015].

A map of the spatial distribution of averaged conductivity of the surface ten-kilometer layer of the earth's crust over the territory of the Russian Federation is presented in Figure 6. Rocks in the region of the Kola Peninsula, Karelia, the Urals, Novaya Zemlya, and Chukotka have the highest resistance, i.e. low conductivity ~10^{-5}–10^{-4} S /m. In Yamal, the conductivity is quite high.

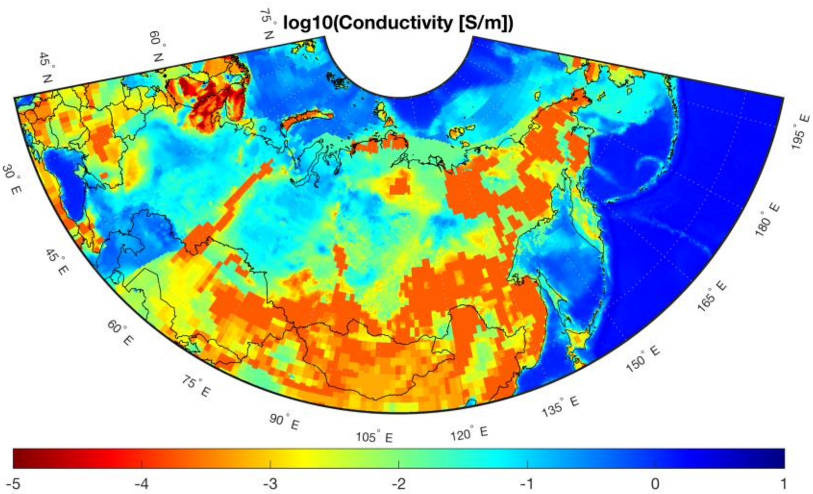

Figure 6. Map of spatial distribution of averaged conductivity of the upper ten-kilometer layer of the earth's crust σ [S/m] over the territory of the Russian Federation

To estimate geoelectric variations caused by the variable geomagnetic field, similarly to [Bedrosian, Love, 2015], we built a synthetic map of local geoelectric fields that would have been excited throughout the Russian Federation by spatially homogeneous field variations with |**B**(*f*)|=1 nT and *T*=100 s, using relationship (1) in the frequency domain between electric **E**(*f*) and magnetic **B**(*f*) fields through the complex impedance tensor *Z*(*f*). According to the telluric hazard map (Figure 7), the highest telluric fields up to *E*~5 mV/km during the same geomagnetic disturbance should be excited in the northwest of the Russian Federation and in the Urals. In this case, the difference between telluric field values *E* for different points in the northwest of the Russian Federation may be 3–4 times for the same amplitudes of the magnetic disturbance. In the Yamal region, telluric fields are rather weak, *E*~0.5 mV/km. The external magnetic disturbance with *T*=1000 s yields smaller amplitudes of telluric fields (Figure 8).

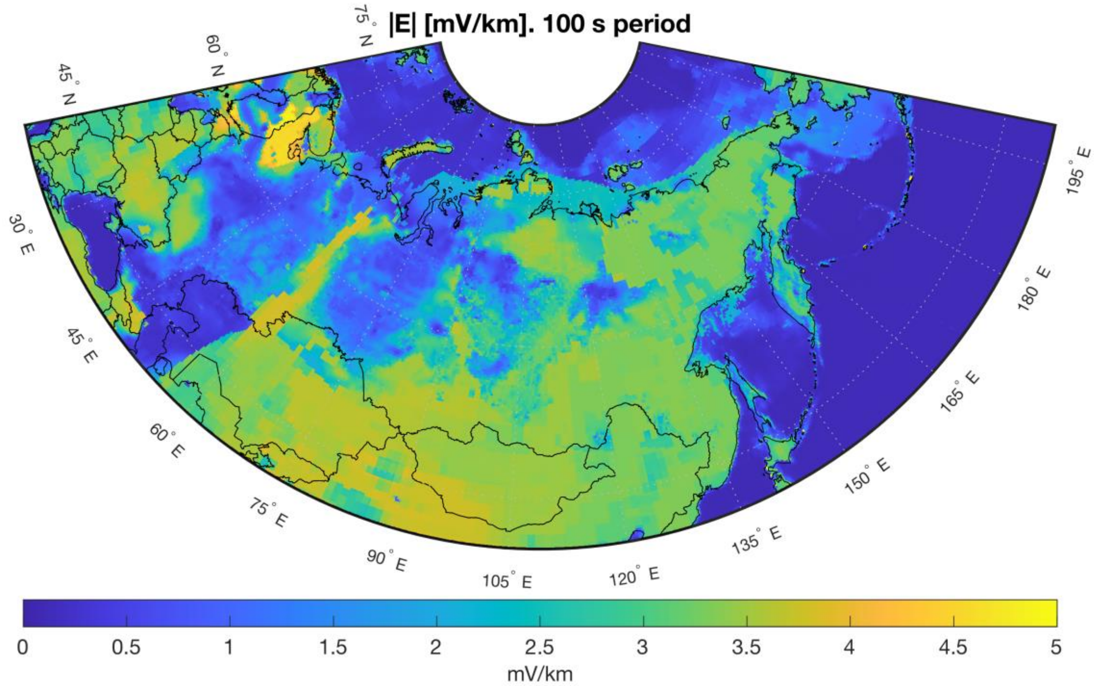

Figure 7. Map of telluric fields E[mV/km] excited by variations in a uniform magnetic field with a period *T*=100 s and an amplitude of 1 nT

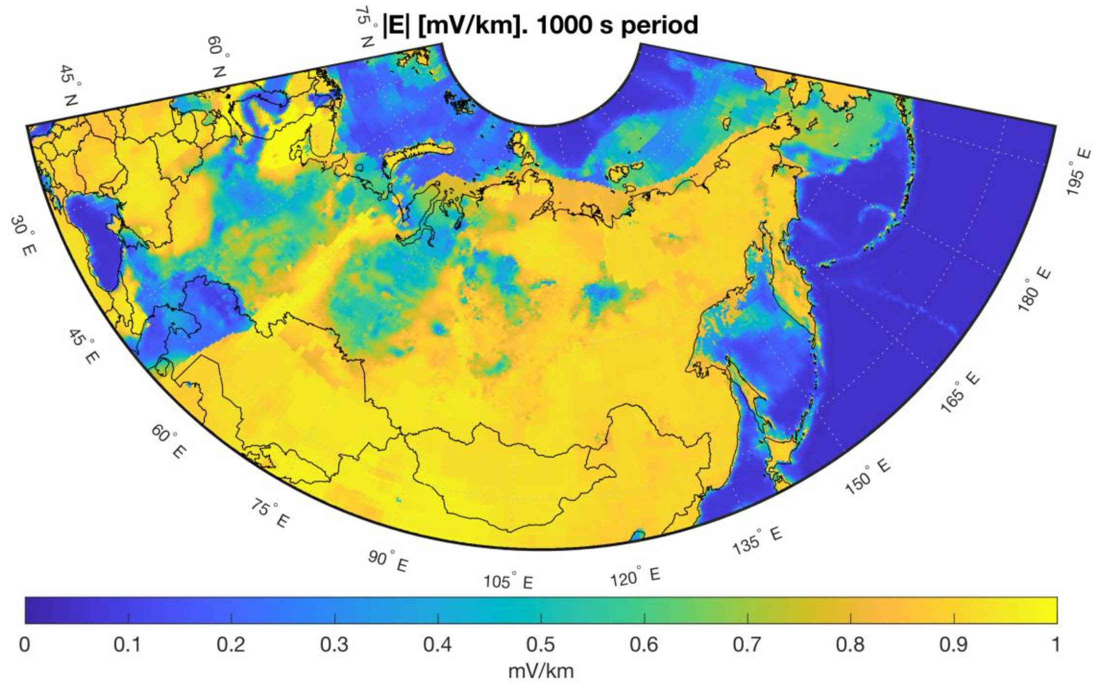

Figure 8. The same as in Figure 7 for *T*=1000 s

The calculations performed show that the geological structure significantly affects the intensity of geoelectric fields generated by magnetic storms. The map along with the geomagnetic DB allows us to assess, without any calculations, the possible risks from GICs during various geomagnetic disturbances for any region. To do this, it suffices to determine for the event of interest the magnitude of the maximum geomagnetic disturbance from the constructed magnetograms for the nearest magnetic station and to estimate the possible value of the telluric field from the map with a normalized response to a magnetic disturbance with a characteristic time scale (100 or 1000 s). This map allows industries to better anticipate the response to magnetic storms.

USE OF GEOMAGNETIC MONITORING DATA FOR REDUCING THE SPACE WEATHER RISK TO PIPELINES

Geomagnetic disturbances and associated geoelectric variations generate fluctuations in the pipe-to-soil potential (PSP), which bring the pipeline voltage out of the safe range of protection against electrocorrosion. Cathodic protection normally feeds a negative potential ~1–2 V. In case of malfunctions in the operation of cathodic protection in pipelines, corrosion at earthing points or insulation damage intensifies, and electronic control systems fail. These problems are especially relevant for Yamal and the Arctic shelf in the Barents and Kara seas since these regions are centers of production and transportation systems.

There is not much information on the impact of GICs on pipelines available to scientific community. Nevertheless, the collected information suggests that PSP changes during geomagnetic storms may be extensive enough to put the pipeline into the unprotected mode for a long period of time. For example, in a pipeline in Quebec (Canada), corrosion damage developed in one of the sections after five years of operation instead of expected 20–30 years [Trichtchenko, Boteler, 2002]. During strong storms in November 2004 in a pipeline in Australia for ~12 hrs, PSP fluctuations were approximately three times higher than the set limits [Boteler, Trichtchenko, 2015].

The longest studies of space weather effects were carried out in the Finnish gas pipeline in 1998–1999 [Pulkkinen et al., 2001]. According to the calculations made by Lehtinen and Pirjola [1985], for a 1.0 V/km electric field currents of ~50 A in this pipeline and up to 25 A in grounding should be excited which, if the insulation is broken, may lead to a noticeable change in the time of corrosion damage. Indeed, the number of occurrences of significant (>10 A) currents in the pipeline in southern Finland correlates well with the number of sunspots, which confirms the direct relationship of these currents with solar and magnetic activity [Viljanen et al., 2006]. In Alaska, it has been found that during strong magnetic disturbances current bursts up to 200 A occur in a pipeline [Campbell, 1980]. The pipeline in Alberta (Canada) experienced failures in the operation of cathodic protection associated with geomagnetic disturbances [Shapka, 1992]. In a pipeline in Norway, PSP was found to fluctuate with an amplitude of ~5 V during magnetic disturbances [Henriksen et al., 1978]. Strong geomagnetic disturbances can cause problems for technological systems even at midlatitudes. For a pipeline in northern Bavaria, peak currents in the pipeline at an average level of geomagnetic disturbance were as strong as 12 A, and during the magnetic storm main phase PSP variations were 3 V [Brasse, Junge, 1984]. In the Russian Federation, there are not many publications reflecting the results of measurements of induced currents in pipelines or PSP changes. A current up to 3.2 A was recorded by differential magnetometry in a gas pipeline near Yakutsk during a geomagnetic disturbance [Mullayarov et al., 2006]. At the section of the main gas pipeline Bovanenkovo–Ukhta during a geomagnetic disturbance, the potentials measured experienced changes in time with an amplitude up to 10 V [Ivonin, 2015].

Thus, the effect of geomagnetic variations generated by magnetospheric disturbances should be taken into account when organizing a cathodic protection system for pipelines. The impact of geomagnetic disturbances can manifest itself both directly (failure of control equipment) and be long-term cumulative (electrocorrosion) [Gummow, Eng, 2002]. To assess the degree of the impact of geomagnetic and geoelectric fields on a specific system, it seems appropriate, using the compiled database and the archive of registration of GICs or PSPs, to design a regression statistical model capable of estimating disturbances in a specific system for given geomagnetic variations [Vorobev et al., 2019].

The beginning of the development of hydrocarbon reserves in Yamal leads to the need to take into account the influence of space factors on all complex systems, from geophysical exploration to navigation and down-the-hole drilling. In particular, it is necessary to calculate the extent to which PSP is expected to change in the Yamal region during strong substorms and whether this effect should be taken into account when maintaining the cathodic potential for protection against electrocorrosion. From the constructed map of amplitudes of telluric fields we can estimate possible PSP variations during geomagnetic disturbances. In principle, this requires the calculation of a model of induction in a grounded conductor [Lehtinen, Pirjola, 1985; Boteler, 2013]. For rough estimates, we can restrict ourselves to a simpler approach. Analysis of the operation of cathodic protection in an oil pipeline [Hejda, Bochnicek, 2005] has shown that the calculated telluric field in the plane wave approximation and earth's homogeneous conductivity is linearly proportional to measured PSP. Transferring the relationship they derived to Yamal conditions, we find that the potential produced by telluric fields may exceed the ~2 V potential maintained between the pipeline and the ground at E>0.5 V/km. According to the constructed map (Figure 7), this requires a geomagnetic disturbance of ~500 nT with a time scale of ~100 s.

Although the Russian sector of INTERMAGNET is gradually expanding [Gvishiani, Lukyanova, 2015], there is still no magnetic observatory of this class in the Arctic zone of the Russian Federation. A new geomagnetic observatory should be part of the scientific complex of the International Arctic station Snezhinka, which is being built in the Yamalo-Nenets Autonomous Okrug, on eastern slopes of the Polar Urals [https://arctic-mipt.com]. In years ahead, the most important task of expanding geomagnetic observations in the Russian Arctic is to complete the transition of stations to real-time data transmission [Aleshin et al., 2020]. This will allow a continuous forecast of the expected level of GIC and PSP for key technological systems.

CONCLUSION

When creating the magnetic database for the Arctic zone of the Russian Federation, the authors pursued the following objectives: to make observations easily accessible to a wide range of users; to increase the efficiency of scientific and applied research through the massive use of data from magnetic stations; to partially fill gaps in the global network of geomagnetic observations; to increase the scientific return from many years of work on monitoring of the geomagnetic field at high latitudes. The entire DB, magnetograms, solar wind parameters, and the geoelectric model of the earth's crust are freely available on the anonymous FTP site [ftp://door.gcras.ru/ftp_anonymous/ARCTICA_Rus]. Using the magnetic DB and the geoelectric model, a researcher can either independently calculate a telluric disturbance in the Russian Arctic for any period or use the map of normalized disturbances and constructed magnetograms for rough estimates. Due to easy access to data, simple format, convenient graphics, and supporting material, this DB can be a useful adjunct to the global geomagnetic data portals INTERMAGNET, SuperMAG, IMAGE, MAGDAS. The DB is constantly updated, so the authors will be grateful for any suggestions for its improvement and development. In case of problems with access to the FTP server, please contact the authors. When using the database, please refer to [https://doi.org/10.2205/Rus-Arctic-1-min-DB].

The work was supported by government assignments of IPE RAS (PVA) and GC RAS (DVN), RFBR grant No. 20-05-00787 (KOV), and project No. 314670 of the Academy of Finland (MEE). We thank Sokolova E.Yu. for helpful discussions and both reviewers for constructive comments. We express our gratitude to all institutions that provided digital geomagnetic data.

REFERENCES

Alekseev D., Kuvshinov A. Palshin N. Compilation of 3D global conductivity model of the Earth for space weather applications. *Earth Planet Space*. 2015, vol. 67, no. 108. DOI: 10.1186/s40623-015-0272-5.

Aleshin I.M., Ivanov S.D., Koryagin V.N., Matveev I.V., Perederin F.V., Soloviev A.A., Kholodkov K.I. IT-infrastructure of geomagnetic observatory network. *Geophys. Res*. 2020, vol. 21, no. 3, pp. 50–65. DOI: 10.21455/gr2020.3-4. (In Russian).

Amiantov A.S., Odintsov V.I., Zaitzev A.N. The unmanned geophysical data collection platform based on the digital magnetometer CMVS-6. *Physics of Earth and planetary interiors*. 1990. Vol. 59. P. 61–65.

Amiantov A.S., Zaitsev A.N., Odintsov V.I., Petrov V.G. *Variatsii magnitnogo polya Zemli — baza tsifrovykh dannykh magnitnykh observatorii Rossii za period 1984–2000*. [Variations of the Earth's magnetic field — a digital database of magnetic observatories in Russia for the period 1984–2000]. On CD-ROM. M.: IZMIRAN, 2001, 52 p. (In Russian).

Apatenkov S.V., Pilipenko V.A., Gordeev E.I., Viljanen A., Juusola L., Belakhovsky V.B., Sakharov Ya.A., Selivanov V.N. Auroral omega bands are a significant cause of large geomagnetically induced currents. *Geophys. Res. Lett*. 2020, vol. 47, e2019GL086677. DOI: 10.1029/2019GL086677.

Bedrosian P.A., Love J.J. Mapping geoelectric fields during magnetic storms: Synthetic analysis of empirical United States impedances. *Geophys. Res. Lett*. 2015, vol. 42, iss. 23, pp. 10160–10170. DOI: 10.1002/2015GL066636.

Belakhovsky V., Pilipenko V., Engebretson M., Sakharov Ya., Selivanov V. Impulsive disturbances of the geomagnetic field as a cause of induced currents of electric power lines. *J. Space Weather and Space Climate*. 2019, vol. 9, no. A18. DOI: 10.1051/swsc/2019015.

Berdichevsky M.N., Dmitriev V.I. *Modeli i metody magnitotelluriki* [Models and methods of magnetotellurics]. Moscow, Nauchnyi Mir Publ., 2009, 680 p. (In Russian).

Berngardt O.I., Kurkin V.I., Kushnarev D.S., Grkovich K.V., Fedorov R.R., Orlov A.I., Kharchenko V.V. ISTP SB RAS decameter radars. *Solar-Terr. Phys*. 2020, vol. 6, no. 2, pp. 63–73. DOI: 10.12737/stp-62202006.

Boteler D.H. A new versatile method for modelling geomagnetic induction in pipelines. *Geophys. J. International*. 2013, vol. 193, pp. 98–109.

Boteler D.H., Trichtchenko L. Telluric influence on pipelines. *Oil and Gas Pipelines: Integrity and Safety Handbook*. Ed. R.W. Revie. John Wiley & Sons, Inc. 2015, pp. 275–285. DOI: 10.1002/9781119019213.ch21.

Brasse H., Junge A. The influence of geomagnetic variations on pipelines and an application for large-scale magnetotelluric depth sounding. *J. Geophys*. 1984, vol. 55, no. 1, pp. 31–36.

Campbell W.H. Observation of electric currents in the Alaska oil pipeline resulting from auroral electrojet current sources. *Geophys. J. Royal Astronomical Society*. 1980, vol. 61, pp. 437–449.

Chelpanov M.A., Mager P.N., Klimushkin D.J., Mager O.V. Observing magnetospheric waves propagating in the direction of electron drift with Ekaterinburg decameter coherent radar. *Solar-Terr. Phys*. 2019, vol. 5, iss. 1, pp. 51–57. DOI: 10.12737/stp-51201907.

Chinkin V.E., Soloviev A.A., Pilipenko V.A., Engebretson M.J., Sakharov Ya.A. Determination of vortex current structure in the high-latitude ionosphere with associated GIC bursts from ground magnetic data. *J. Atmos. Solar–Terr. Phys*. 2021, vol. 212, 105514. DOI: 10.1016/j.jastp.2020.105514.

Connors M., Rostoker G., Sofko G., McPherron R.L., Henderson M.G. Ps 6 disturbances: relation to substorms and the auroral oval. *Ann. Geophys*. 2003, vol. 21, pp. 493–508.

Engebretson M.J., Steinmetz E.S., Posch J.L., Pilipenko V.A., Moldwin M.B., Connors M.G., Boteler D.H., Mann I.R., Hartinger M.D., Weygand J.M., Lyons L.R., Nishimura Y., Singer H.J., Ohtani S., Russell C.T., Fazakerley A., Kistler L.M. Nighttime magnetic perturbation events observed in Arctic Canada: 2. Multiple-instrument observations. *J. Geophys. Res.: Space Phys*. 2019, vol. 124, pp. 7459–7476. DOI: 10.1029/2019JA026797.

Gjerloev J.W. The SuperMAG data processing technique. *J. Geophys. Res*. 2012, vol. 117, A09213. DOI: 10.1029/2012JA017683.

Gvishiani A.D., Lukyanova R.Yu. Geoinformatics and observations of the Earth's magnetic field: Russian segment. *Fizika Zemli* [Izvestiya, Physics of the Solid Earth]. 2015, no. 2, pp. 3–20. DOI: 10.7868/S0002333715020040. (In Russian).

Gvishiani A.D., Soloviev A.A., Sidorov R.V., Krasnoperov R.I., Grudnev A.A., Kudin D.V., Karapetyan J.K., Simonyan A.O. Successes of the organization of geomagnetic monitoring in Russia and the near abroad. *Vestnik Otdeleniya nauk o Zemle RAN* [Bull. of ONZ RAS]. 2018, vol. 10, NZ4001. DOI: 10.2205/2018NZ000357. (In Russian).

Gummow R., Eng P. GIC effects on pipeline corrosion and corrosion control systems. *J. Atmos. Solar-Terr. Phys*. 2002, vol. 64, pp. 1755–1764. DOI: 10.1016/s1364-6826(02)00125-6.

Hejda P., Bochnicek J. Geomagnetically induced pipe-to-soil voltages in the Czech oil pipelines during October–November 2003. *Ann. Geophys*. 2005, vol. 23, pp. 3089–3093.

Henriksen J.F., Elvik R., Gransen L. Telluric currents corrosion on buried pipelines, *Proc. 8th Scandinavien Corrosion Congress*. Helsinki, 1978, vol. II, pp. 167–176.

Ivonin A.A. Influence of the Earth's geomagnetic field on corrosion protection at MGP of GAZPROM. *Korroziya "Territorii Neftegaz"* [Corrosion of "Neftegaz Territory"], 2015, no. 1, pp. 88–89. (In Russian).

Korja T., Engels M., Zhamaletdinov A.A., Kovtun A.A., Palshin N.A., Smirnov M.Yu., Tokarev A.D., Asming V.E., Vanyan L.L., Vardaniants I.L., BEAR Working Group. Crustal conductivity in Fennoscandia — a compilation of a database on crustal conductance in the Fennoscandian Shield. *Earth, Planets and Space*. 2002, vol. 54, pp. 535–558. DOI: 10.1186/BF03353044.

Kuvshinov A., Grayver A., Tøffner-Clausen L., Olsen N. Probing 3-D electrical conductivity of the mantle using 6 years of Swarm, CryoSat-2 and observatory magnetic data and exploiting matrix Q-responses approach. *Earth, Planets and Space*. 2021, vol. 73, p. 67. DOI: 10.1186/s40623-020-01341-9.

Lehtinen M., Pirjola R. Currents produced in earthed conductor networks by geomagnetically induced electric fields. *Ann. Geophys*. 1985, vol. 3, pp. 479–484.

Mullayarov V.A., Kozlov V.I., Grigoriev Yu.M., Romashchenko Yu.A. The current induced in the gas pipeline from a large magnetic disturbance 01.21.05. *Science and Education*. 2006, no. 1 (41), pp. 53–55. (In Russian).

Mursula K., Marsh D., Nandy D., Usoskin I. A review of Space Climate and an introduction to the papers of the JASTP special issue on Space Climate. *J. Atmos. Solar-Terr. Phys*. 2011, vol. 73, pp. 179–181. DOI: 10.1016/j.jastp.2010.11.002.

Pilipenko V.A. Space weather impact on ground-based technological systems. *Solar-Terr. Phys*. 2021, vol. 7, no. 3, pp. 68–104. DOI: 10.12737/stp-73202106.

Pilipenko V., Belakhovsky V., Kozlovsky A., Fedorov E., Kauristie K. Determination of the wave mode contribution into the ULF pulsations from combined radar and magnetometer data: Method of apparent impedance. *J. Atmos. Solar-Terr. Phys.* 2012, vol. 77, pp. 85–95. DOI: 10.1016/j.jastp.2011.11.013.

Pilipenko V.A., Krasnoperov R.A., Soloviev A.A. Problems and prospects of geomagnetic research in Russia. *Vestnik Otdeleniya nauk o Zemle RAN* [Bull. of ONZ RAS]. 2019, vol. 11, NZ1103. DOI: 10.2205/2019NZ000362. (In Russian).

Pulkkinen A., Viljanen A., Pajunpaa K., Pirjola R. Recordings and occurrence of geomagnetically induced currents in the Finnish natural gas pipeline network. *J. Applied Geophys*. 2001, vol. 48, pp. 219–231.

Saito T. Long-period irregular magnetic pulsation Pi3. Space Sci. Rev. 1978, vol. 21, pp. 427–467.

Sakharov Ya.A., Yagova N.V., Pilipenko V.A. Pc5/Pi3 geomagnetic pulsations and geoinduced currents. *Izvestiya RAN. Seriya fizicheskaya* [Bull. of the Russian Academy of Sciences: Physics]. 2021, vol. 85, no. 3, pp. 445–450. DOI: 10.31857/ s0367676521030236. (In Russian).

Schultz A. EMScope: A continental scale magnetotelluric observatory and data discovery resource. *Data Sci. J*. 2009, vol. 8, IGY6–IGY20. DOI: 10.2481/dsj.SS_IGY-009.

Shapka R. Geomagnetic effects on modern pipeline systems. *Proc. Solar-Terrestrial Predictions Workshop*. May 18–22, Ottawa, 1992, vol. 1, pp. 163–170.

Sokolova E.Yu., Kozyreva O.V., Pilipenko V.A., Sakharov Ya.A., Epishkin D.V. Variations in geomagnetic and telluric fields in the northwestern regions of Russia under space weather disturbances: Relationship with the geoelectric structure and induced currents in power transmission lines. *Geofizicheskie protsessy i biosfera* [Geophysical Processes and Biosphere]. 2019, vol. 18, no. 4, pp. 66–85. DOI: 10.21455/GPB2019.4-7. (In Russian).

Trichtchenko L., Boteler D.H. Modelling of geomagnetic induction in pipelines. *Ann. Geophys*. 2002, vol. 20, pp. 1063–1072. DOI: 10.5194/angeo-20-1063-2002.

Viljanen A., Pulkkinen A., Pirjola R., Pajunpaa K., Posio P., Koistinen A. Recordings of geomagnetically induced currents and a nowcasting service of the Finnish natural gas pipeline. *Space Weather*, 2006, vol. 4, S10004. DOI: 10.1029/2006SW000234.

Vorobev A.V., Pilipenko V.A., Sakharov Ya.A., Selivanov V.N. Statistical relationships between variations of the geomagnetic field, auroral electrojet and geomagnetically induced currents. *Solar-Terr. Phys*. 2019, vol. 5, no. 1, pp. 35–42. DOI: 10.12737/stp-512019052018.

Zaitsev A.N. Project "Geomagnetic Meridian". *Vestnik Akademii nauk SSSR* [Bull. the Academy of Sciences of the USSR]. 1974, No. 4, pp. 92–94. (In Russian).

URL: ftp://door.gcras.ru/ftp_anonymous/ARCTICA_Rus (accessed February 10, 2022).

URL: http://db.izmiran.nw.ru (accessed February 10, 2022).

URL: https://supermag.jhuapl.edu (accessed February 10, 2022).

URL: https://space.fmi.fi/image (accessed February 10, 2022).

URL: http://www.serc.kyushu-u.ac.jp/magdas (accessed February 10, 2022).

URL: http://ckp.gcras.ru (accessed February 10, 2022).

URL: https://omniweb.gsfc.nasa.gov/vitmo/cgm.html (accessed February 10, 2022).

URL: https://www.ngdc.noaa.gov/IAGA/vdat/IAGA2002/iaga2002format.html (accessed February 10, 2022).

URL: https://www.intermagnet.org (accessed February 10, 2022).

URL: https://omniweb.gsfc.nasa.gov (accessed February 10, 2022).

URL: http://sdrus.iszf.irk.ru (accessed February 10, 2022).

URL: https://arctic-mipt.com (accessed February 10, 2022).

URL: https://doi.org/10.2205/Rus-Arctic-1-min-DB (accessed February 10, 2022).

Original Russian version: O.V. Kozyreva, V.A. Pilipenko, M.N. Dobrovolsky, A.N. Zaitsev, E.E. Marshalko, published in Solnechno-zemnaya fizika. 2022. Vol. 8. Iss. 1. P. 39–50. DOI: 10.12737/szf-81202205. © 2022 INFRA-M Academic Publishing House (Nauchno-Izdatelskii Tsentr INFRA-M).

How to cite this article

Kozyreva O.V., Pilipenko V.A., Dobrovolsky M.N., Zaitsev A.N., Marshalko E.E. Database of geomagnetic observations in Russian Arctic and its application for estimates of the space weather impact on technological systems. *Solar-Terrestrial Physics.* 2022. Vol. 8. Iss. 1. P. 39–50. DOI: 10.12737/stp-81202205.