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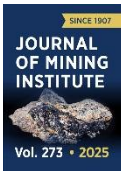

Review article | *Geotechnical Engineering and Engineering Geology*

Specifics of magnetotelluric studies in Antarctica

Tatyana V. Davydkina✉, **Andrei A. Yankilevich**, **Anna N. Naumova**

Empress Catherine II Saint Petersburg Mining University, Saint Petersburg, Russia

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Abstract

One of the priority areas of scientific research in Antarctica is the study of its deep structure. Most of the continent is covered with a thick ice sheet, so the main geoscientific data are acquired using geophysical methods, among which magnetotelluric (MT) ones have the greatest penetration depth and insignificant environmental impact. The possibility of acquiring high-quality MT data in the conditions of the sixth continent has long been questioned. The work is aimed at studying the specifics of magnetotelluric survey in Antarctica. The following tasks were set: to summarize the world experience of studying Antarctica using MT sounding methods; to identify factors that negatively affect the high-quality data acquisition; to determine methods for minimizing the influence of these factors. The article analyses geophysical studies conducted by the magnetotelluric sounding method in the Antarctic region from 1964 to the present. The application of the method is complicated by the following: extremely low temperature affects the drop in the batteries capacity, freezing of the non-polarizing electrodes solution, and changes in the strength properties of materials. Electromagnetic noise occurs during strong winds; proximity to the magnetotelluric field source can violate the plane wave principle on which the method is based. The ice sheet covering most of Antarctica does not allow acquiring optimal values of the contact resistance of the electrode grounding; the extended coastline distorts the acquired data. Studies of the influence of factors complicating the MT sounding method in the coastal and central parts of Antarctica made it possible to formulate recommendations for preparing equipment and adapting the work procedure, modifying the processing flow and a set of measures to ensure safety, the implementation of which will both allow safe performance of geophysical investigations and high-quality data acquisition.

Keywords

geophysical research; magnetotelluric sounding; electrojet; auroral zone; plane wave; contact resistance; ice sheet; Antarctica

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Introduction

Antarctica is the southernmost and most difficult to access continent. Logistical challenges, a short field season, and the fact that almost the entire surface is covered with a thick ice sheet, which in the central part of the continent exceeds 4 km [1], make this area difficult for geological study [2-4]. The bulk of information about the structure of Antarctica and glacial deposits is acquired through drilling [5-7] and geophysics [8].

One of the geophysical methods used to study Antarctica is the magnetotelluric sounding based on the study of variations in the natural alternating electromagnetic field of the Earth. The useful magnetotelluric signal sources are the processes in the ionosphere and magnetosphere that occur during the interaction of the Earth's magnetic field with solar wind plasma, when there is no need to use generators to excite the field. Due to its depth and environmental friendliness, various modifications of the MT sounding have become widespread throughout the world for studying the structure of sedimentary basins [9], the deep structure of the Earth's crust and upper mantle [10], as well as for the prospecting and exploration of hydrocarbons and solid mineral deposits [11, 12].

The Antarctic region has a specifics that complicates the geophysical survey using the MT method and affects the reliability of the acquired results: extreme climatic conditions, a thick resistive ice sheet, and proximity to the Earth's magnetic pole. To investigate the magnetotelluric methodology in Antarctic conditions, the following tasks were set: to summarize the world experience of studying Antarctica using MT sounding, to identify factors that negatively affect the high-quality data acquisition, and to determine methods for minimizing the influence of these factors.

Review of Antarctica investigations using MT methods

Despite the difficulties, a fairly large number of studies were conducted in various areas of Antarctica (Fig.1, *a*).

The first studies were conducted to determine the possibility in principal of recording a telluric signal in conditions of resistive Antarctic ice. In 1964, two orthogonal electric receiving lines, 200 m long each, were installed at Vostok Station. The electrodes were copper strips measuring 8×0.3 m, installed in a trench 0.3 m deep, which, together with the first layer of backfill, was impregnated with a 5 % aqueous solution of sodium chloride [13]. The total resistance of the receiving lines was 400 kOhm, which is several times higher than the values considered optimal for magnetotelluric methods. Strong noise was observed in the acquired records, but a correlation was found between the electric and magnetic field measurements [14]. For the same purpose, work was carried out in the Dome *C* area in East Antarctica in 1978-1980 [15]. In both cases, a conclusion was made about the possibility of conducting magnetotelluric measurements in similar conditions.

The aim of subsequent studies was to investigate the deep structure of Antarctica. The small number of measurements (2-4 stakes) before 1993 did not allow acquiring a detailed geological result. Nevertheless, these works were of great practical importance for the magnetotelluric sounding procedure development. In 1984, on the Priestley Glacier in the northern part of Victoria Land, the equipment was placed in a heat-insulated aluminium case, in which it was heated by its own heat [16]. The use of brass pins as electrodes did not give positive results. In addition, the daily recording of time series and the position of the auroral oval were analysed, and a connection with the signal amplitude intensity was noted.

On Ross Island in 1991-1992, measurements were made in areas practically free of ice cover [17]. Investigations carried out in 1992 and 1993 in the Changcheng (Fildes Peninsula) and Zhongshan (Prydz Bay) stations area noted that the vertical magnetic field H_z has a large amplitude, which is either the effect of the high electrical conductivity of sea water [18] or a distinction of the polar region [19].

Since 1994, the number of magnetotelluric measurements has increased significantly. In the 1994-1995 field season in the central part of West Antarctica, 12 MT sounding measurements were made above the Byrd subglacial basin (Fig.1, *b*). A specially developed electrometric system with preamplifiers was used to reduce the influence of the high contact resistance of the ice. Its preamplifiers were located in the immediate vicinity of the receiving electrodes [20]. This system is considered in detail in the article by P.E.Wannamaker, describing the results of works in 2004 in the South Pole region [21]. Their goal was to study the structure and thermal regime in the central part of Antarctica, as well as the possibility of acquiring magnetotelluric data in the extreme temperature conditions of the South Pole. When studying the effect of strong wind on data quality, it was suggested that noise during winds greater than 8 m/s is not associated with the movement of sensors or wires, but with the generation of electrical charges when ice crystals move in the air.

The mentioned preamplifier system or its modification was also used in later measurements, in 2007-2008 in the Wilkes subglacial basin area [22], in 2008-2009 in the Vestfold Hills and the Rauer Islands area in Prydz Bay (Fig.1, *g*) [23] and near the Neumayer III Station (Fig.1, *e*) [24]. The use of such preamplifier systems in MT sounding in Antarctica became standard after the successful large-scale investigations carried out from 2010 to 2012 along a 550 km line passing through the central part of the Transantarctic Mountains [25], and studies on Ross Island in 2014-2017 [26], the purpose of which was to investigate the deep geological structure of Antarctica.

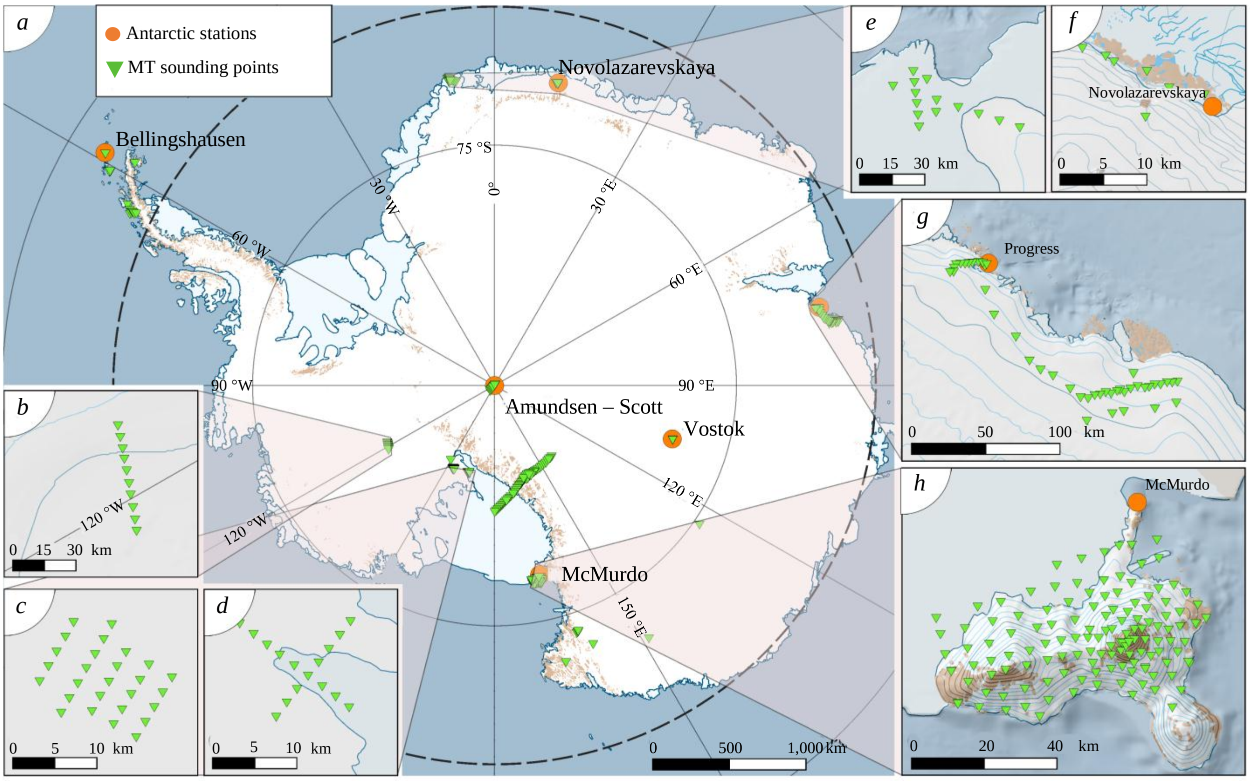

Fig.1. Areas of MT soundings in Antarctica:
a – location of magnetotelluric sounding points in the map of Antarctica; *b* – subglacial Byrd Basin area; *c* – subglacial Lake Whillans area; *d* – area of the supposed watercourse outlet from subglacial Lake Whillans into the ocean; *e* – Neumayer III Station area; *f* – Maitri Station area (Schirmacher Oasis); *g* – Vestfold Hills area; *h* – Ross Island area

In ice-free areas, no additional equipment modification (preamplifiers) is required. In 2004-2006, in the Schirmacher Oasis area (Fig.1, *f*), the Earth's crust structure was studied to confirm the continuity of the Mozambique mobile belt [27]. The stakes were located on the coastal nunatak. Satisfactory-quality magnetotelluric sounding curves were acquired in the 10^3-10^{-3} Hz range. Investigations were also carried out without preamplifiers in the Zhongshan Station area in 2019-2020 [28]. To reduce contact resistance, a saline solution was poured into the electrode holes, and non-polarizing electrodes were grouped to increase the contact area.

In 2002, a magnetotelluric monitoring station was installed at the Akademik Vernadsky Station to study the auroral electrojet influence [29]. During the winter months (from July to October), the electrode solution froze. After thawing, the potential difference between the matched pairs increased significantly, but this did not affect the measurement results. It was noted that the plane wave approximation is valid at a distance of at least 600 km from the auroral electrojet axis.

Magnetotelluric sounding data are sensitive to melts and elevated temperatures. In 2008, the correlation between the magma chamber and the structure of fractures associated with the caldera collapse was studied at the active volcano on Deception Island [30]. From 2014 to 2017, areal geophysical survey was carried out, the purpose of which was to study mantle magmatism and the Erebus and Terror volcanoes structure (Fig.1, *h*) on Ross Island [26].

In 2018-2019, a comprehensive geophysical survey studied the subglacial lake systems in the Lake Whillans area (Fig.1, *c*, *d*). The survey confirmed the results of modelling conducted to determine the sensitivity of the magnetotelluric method to lakes below ice sheets [31, 32]. It was suggested that Antarctic groundwater is interconnected and affects the behaviour of glacial flows.

Parameters characterizing the MT soundings, such as the number of sounding points, recording time, and grounding technologies for electrical receiving lines are given in Table 1.

Table 1

MT sounding parameters

Study area (physical sounding points)	Period	Recording time	Recording system	Electrodes	Preamplifier
Vostok Station (1)	1964	14 days	Medistor microvoltmeter Esterline Angus recorder	800×30 cm copper strips	*
Dome *C* (*)	1978-1980	~40 h	Microprocessor controlled system	*	*
Priestley Glacier (4)	1984-1985	4 days	Digital data acquisition system, two-channel electrograph	50×50 cm copper plates	No
James Ross Island (3)	1991-1992	*	*	Non-polarizing $Cu\text{-}CuSO_4$ electrodes	No
Changcheng Station (3)	1992	4-6 days	MMS-02 (Metronix)	*	*
Zhongshan Station (2)	1994	*	MMS-02 (Metronix)	Copper plates and non-polarizing $Cu\text{-}CuSO_4$ electrodes	*
Subglacial Byrd Basin (12)	1994-1995	*	*	50 cm titanium plates with perforation	Yes
Akademik Vernadsky Station (1)	2002	*	Two-component electrometer (LC ISR)	Non-polarizing electrodes	*
South Pole (10)	2004	3 days	University of Utah System	45×60 cm titanium plates	Yes
Schirmacher Oasis (9)	2004-2006	3-4 days	GMS-05 and ADU-06 (Metronix)	Non-polarizing electrodes with $Cd\text{-}CdCl_2$ solid-state electrolyte and titanium electrodes	No
Subglacial Wilkes Basin (3)	2007-2008	*	Narod Intelligent Magnetotelluric (NIMS)	100×100 cm copper plates	Yes
Deception Island (7)	2008	2-3 days	*	*	*
Vestfold Hills and Rauer Group (34)	2008-2009	5 days	AuScope MT	Stainless steel plates	Yes
Transantarctic Mountains (57)	2010-2012	4-11 days	V-5 and V-5a (Phoenix Geophysics Ltd.)	45×60 cm titanium plates	Yes
Mount Erebus and part of Ross Island (129)	2014-2017	3-12 days	V5-2000 MT (Phoenix Geophysics Ltd.)	45×60 cm titanium plates	Yes
Zhongshan Station (8)	2017-2018	6-7 days	Aether (Crystal Globe)	Non-polarizing electrodes	No
Subglacial Lake Whillans (44)	2018-2019	> 20 h	MTU-5C (Phoenix Geophysics Ltd.) Zen MT receiver (Zonge International Inc.)	Titanium electrodes (solid and perforated)	Yes
Neumayer III Station (14)	2019	3-13 days	SPAM4 (The University of Edinburgh and GFZ Potsdam)	Non-polarizing Ag-AgCl electrodes	Yes
Zhongshan Station (10)	2019-2020	1-6 days	MTU-5A (Phoenix Geophysics Ltd.)	Groups of non-polarizing electrodes with $Cd\text{-}CdCl_2$ solid-state electrolyte	No

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* No data.

The total number of magnetotelluric soundings performed in the Antarctic region from 1964 to 2022 exceeds 350 physical sounding points, most of which are of satisfactory quality. The main objectives of investigations were to study the possibility of using MT sounding in harsh Antarctic conditions and to improve the field work methodology, considering special requirements for logistics and safety. The study was performed using equipment and software developed in Australia, Argentina, Great Britain, Germany, Canada, and the USA. The existing Russian hardware and software systems for MT sounding are not inferior in technical specifications to modern foreign models and allow operation in various climatic conditions, but they require additional modernization for successful operation in Antarctica.

Discussion of results

The literature review identified the main issues encountered by the researchers in their work. The main factors influencing the performance of magnetotelluric sounding in Antarctica include (Fig.2):

- extremely low temperature (decrease in battery capacity, freezing of non-polarizing electrode solution, change in strength properties of materials);
- electromagnetic noise from the wind (thermoelectric effect in snow and ice particles);
- proximity to the MT field source (violation of the plane wave principle);
- a thick ice sheet covering most of Antarctica (high contact resistance);
- an extended coastline (coastline effect anomaly).

The tasks that researchers have to solve when using the MT sounding in Antarctica can be divided into three groups: ensuring the operability of the measuring equipment; developing a special data processing flow; and implementing safety measures.

Temperature and wind conditions. The ambient air temperature on the sixth continent varies greatly from the coastal zones to the central part. Table 2 shows the average monthly air temperature at six Antarctic stations. The stations in the central part of Antarctica are highlighted in light blue, and the stations on the coast are highlighted in indigo. The temperature indicators of coastal areas are several times higher than in the central part, where they reach extremely low values even in the summer months (December, January, February). The main part of precipitation in the form of snow (or rain) falls on the coast.

To assess the wind regime in different parts of Antarctica, a statistical analysis of the surface wind speed was performed using archived meteorological data[1] acquired over 11 summer seasons at Vostok and Progress stations located in the central part and on the coast, respectively. A wind speed of 7 m/s was used as a threshold value, since the MT sounding data acquired during the period when the wind exceeded 6-8 m/s were of low quality [21, 23]. A statistical sample (Fig.3) of the number of days in which at least one wind speed measurement exceeded the threshold shows that the wind

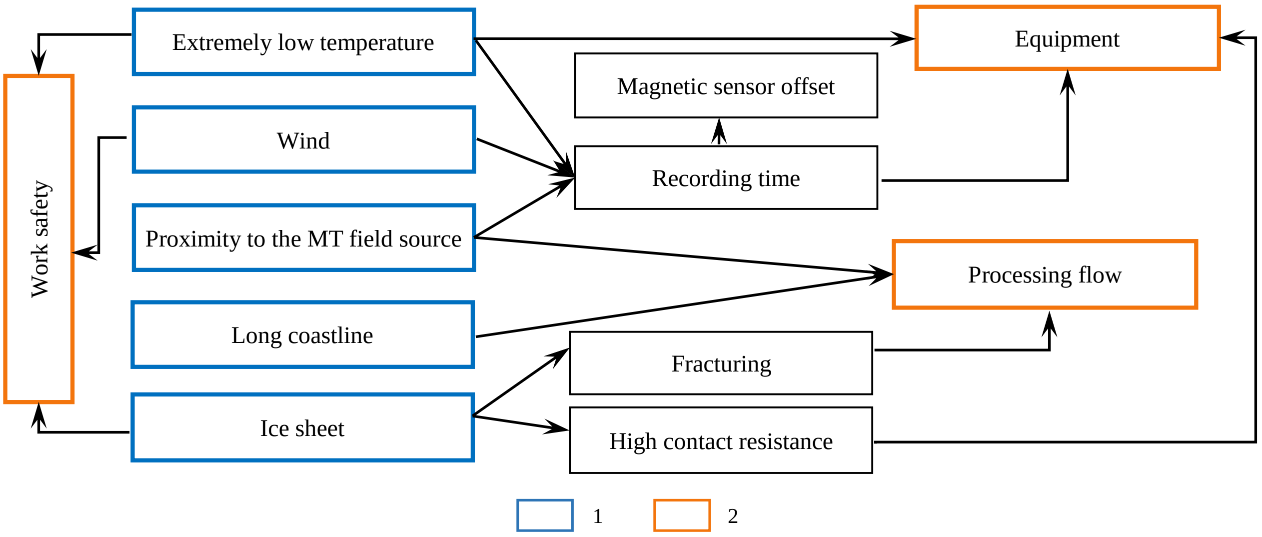

Fig.2. The main factors influencing the MT sounding studies in Antarctica

1 – generalized features that have a direct or indirect impact on magnetotelluric studies in the region;
2 – generalized study areas most susceptible to the influence of the Antarctic specifics

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[1] Weather and Climate reference portal. URL: www.pogodaiklimat.ru (accessed 31.10.2023).

regime in the central part is calmer compared to the coastal region. At Progress Station, blizzards lasting to 7-10 days were observed, while at Vostok Station, winds of such strength were recorded much less frequently, for example, 1-2 days during the entire summer season, or not at all, as in the 2017-2018 season.

Table 2

Average air temperature at Antarctic stations[2]

Month	Average temperature at stations, °C					
	Vostok	Amundsen-Scott	Progress	McMurdo	Bellingshausen	Novolazarevskaya
January	–31.8	–28.1	0.7	–2.6	1.6	–0.4
February	–43.8	–40.7	–2.7	–8.8	1.6	–3.2
March	–58.0	–53.6	–8.3	–17.4	0.5	–7.9
April	–64.8	–57.4	–12.3	–21.1	–1.4	–11.7
May	–65.7	–57.7	–14.3	–22.2	–3.0	–13.5
June	–65.5	–58.1	–14.6	–22.6	–5.1	–14.5
July	–66.0	–60.2	–15.9	–24.7	–6.0	–17.0
August	–66.8	–59.7	–15.5	–25.3	–5.7	–17.3
September	–65.7	–58.9	–14.8	–22.9	–4.3	–16.5
October	–56.5	–50.9	–11.5	–16.8	–2.6	–12.1
November	–41.5	–37.2	–4.5	–8.2	–1.1	–5.6
December	–31.4	–27.3	0.1	–2.6	0.3	–1.0

Interference arising during strong winds is associated not only with vibrations of wires, but also with the occurrence of electric charges in particles of ice and snow blown from the surface. G.J.Hill [33] describes three mechanisms of snowflake electrification (thermoelectric effect).

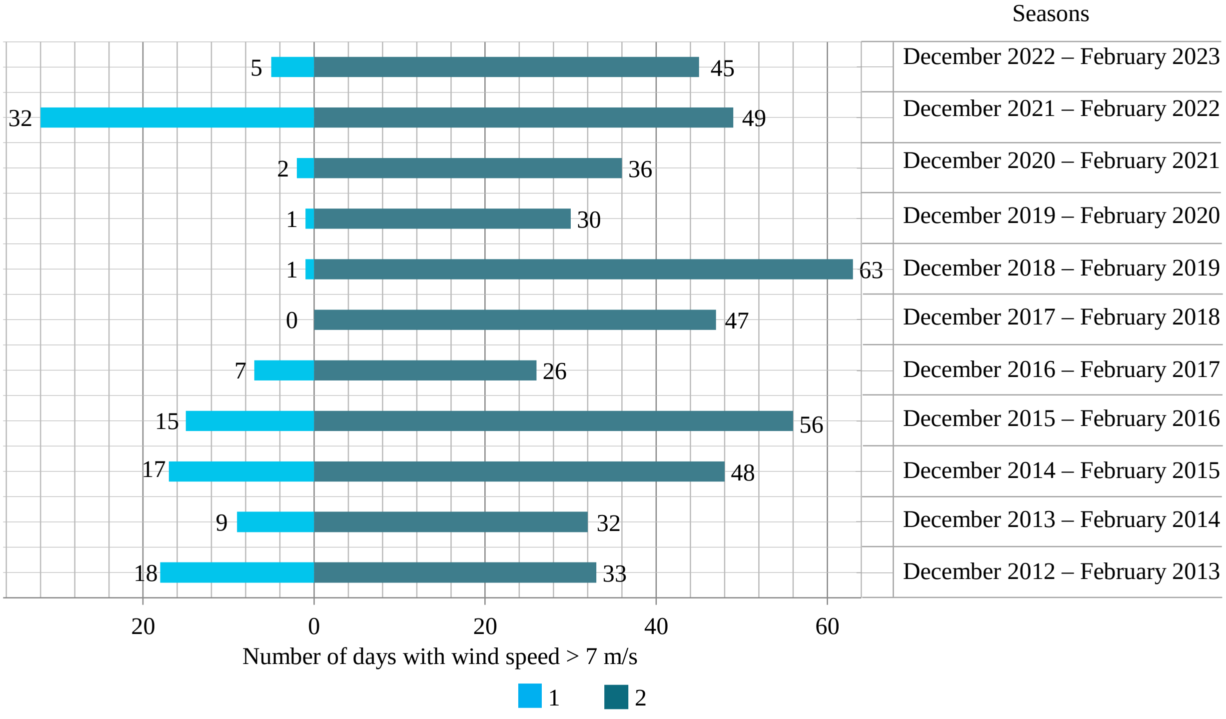

Fig.3. Number of days with wind speed over 7 m/s on the coast and continental part of Antarctica

1 – Vostok Station; 2 – Progress Station

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[2] Weather and Climate reference portal. URL: www.pogodaiklimat.ru (accessed 31.10.2023).

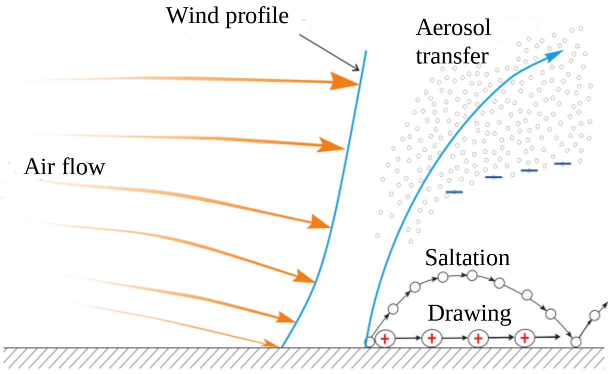

Fig.4. Movement of ice particles during a snowstorm

The first mechanism is related to the friction of ice particles during saltation. Small particles heat up more than the surface they rub against and acquire a negative charge, while the colder surface becomes positively charged.

The second mechanism is associated with the situation when the snowflake centre is warm, and the edges are cold. As a result of the collision, the cold positively charged edges are torn off, leaving a negatively charged central part.

The third mechanism is that the air may be colder or warmer compared to the ice sheet surface. Small particles in the air cool down or, conversely, heat up, and, depending on this, acquire a positive or a negative charge.

During strong winds in the summer months (when the air is warmer than the surface), larger particles settle and the ice sheet surface acquires a positive charge, while the cloud of small particles rising upward and carried by the wind becomes negatively charged (Fig.4). This results in an electrical potential gradient proportional to the wind speed.

According to P.E.Wannamaker et al. [21], the main source of wind interference to the electric field is large clouds of suspended particles, the width of which is comparable to the length of the receiving lines in the electric field, therefore increasing them to 300 m should have a positive effect on the signal/noise ratio. The observation results enabled to assume that wind interference is spatially limited and does not correlate either between observation points or between orthogonal north-south (X) and west-east (Y) electric dipoles. The range of noisy frequencies depends on the speed at which the charge moves: on the coast of Antarctica, where katabatic winds were observed, noise was recorded at frequencies of 5-0.01 Hz, in the Vestfold Hills areas, 4-0.05 Hz [23], on the Whillans Ice Plain, 75-0.02 Hz [31], and in the South Pole region, at frequencies of 0.1-0.01 Hz [21].

The issue associated with wind interference is solved by removing from the time series the sections of the record acquired at wind speeds exceeding 7 m/s. For this purpose, wind speeds are measured directly near the stake or at the base camp and the recording time for acquiring a sufficient amount of data is increased to 5-7 days or more depending on weather conditions [23, 25, 31]. Thus, when planning work in the coastal zone of Antarctica, data collection can take several times longer than in low and middle latitudes.

Extreme weather conditions affect the operation of geophysical equipment and complicate its application technique [34, 35]. Long-term recording tightens the requirements for power supply systems of measuring equipment. Two sets of batteries with a voltage of 12 V and a capacity of up to 65 A·h are usually used to power the MTU-5A recorder. In Antarctic conditions with a data recording duration of up to one week, it is necessary to use batteries with a higher capacity and/or other power sources (solar batteries), as well as to improve the temperature conditions of equipment operation (insulation and/or heating).

A better installation of magnetic sensors is required to prevent their displacement due to possible ice deformation.

For work in harsh conditions of Antarctica, it is necessary to provide for the use of special frost-resistant cables. Particular attention should be paid to such a characteristic as the minimum installation temperature (for example, for the central part of Antarctica –40 °C and below).

Traditional non-polarizing electrodes are a plastic vessel with a working surface in the form of a semi-permeable ceramic membrane (bottom) with a rod of exceptionally pure metal, filled with a solution of salts of the same metal. Under low temperature conditions, the electrode solution containing water can freeze [29].

Adding salts and antifreeze to the solution ensures stable operation of the electrodes for several days at temperatures down to –25 °C [24], which allows the electrodes to be used in the coastal part of Antarctica. In the central part of Antarctica, such weather conditions are unlikely even in the summer months; non-polarizing electrodes with solid-state electrolyte and metal electrodes should be used there (see Table 1).

Contact resistance on an ice sheet. The presence of a thick ice sheet over most of Antarctica requires special measures to reduce the contact resistance between the electrodes and the ice. The physical properties of firn can change depending on humidity and temperature. The lower the temperature, the higher the specific electrical resistivity of the ice. Specific electrical resistivity values reaching tens of megaohms in the central parts of Antarctica will inevitably lead to distortions of the MT sounding curves due to capacity leakage, especially in the high-frequency region. According to G.J.Hill and P.E.Wannamaker [26], the standard for magnetotelluric sounding in Antarctica is the use of preamplifiers with very high input resistance, such as the buffer preamplifier developed by J.A.Stodt from Numeric Resources LLC [21].

Buffer amplifiers have a single-ended output (signal output and ground) that is connected to the corresponding input terminal and ground of the receiver via a twisted pair. It is assumed that twisted pair wires insulated with polyethylene have a parasitic capacitance approximately half that of those insulated with polyvinyl chloride and tolerate low temperatures better. The screen ground wire is connected to ground at the receiver and remains unconnected at the buffer amplifier [25].

The buffer amplifiers are powered locally from AA batteries. For work in polar regions, it is preferable to use disposable lithium-iron-disulphide batteries, since their performance characteristics at low temperatures are better than that of other chemical elements, which for this design ensures continuous operation for 10-14 days. Power supply from a single source (battery or recorder) guarantees a single operating time of the preamplifiers and input voltage characteristics but requires the use of additional shielded cores in the electrical receiving wires.

Violation of the plane wave principle. One of the conditions for the MT sounding method applicability is the assumption that the distance to the source is much greater than the length of the electromagnetic wave on Earth. In this case, the magnetotelluric field at the observation point is a flat vertically incident electromagnetic wave in which the field vectors are located in the horizontal plane.

The external source of the magnetotelluric signal is considered to be current systems that form in near-Earth space during the interaction of the solar wind and the Earth's magnetosphere. In low and middle latitudes, with the exception of a narrow band in the equatorial region, the plane wave condition is met. In high latitudes, the proximity to constantly existing electrojets – currents flowing at an altitude of 100-150 km (Fig.5), can distort the MT sounding results, violating the distant source condition.

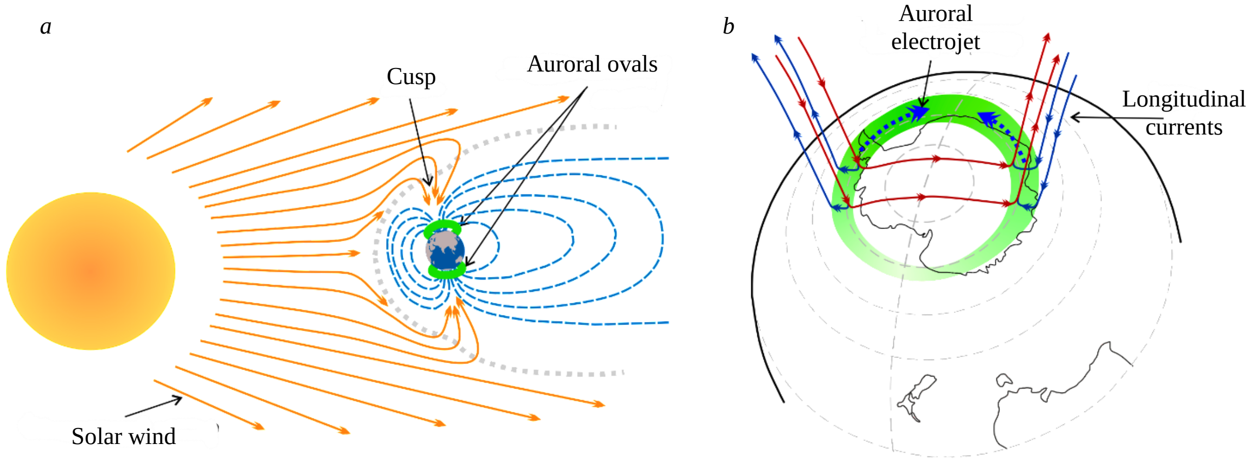

Fig.5. Schematic representation of the Earth's magnetic field (*a*) and longitudinal currents in the auroral zone (*b*)

To consider the influence of source effects on MT data, various approaches are used: modelling, determining the disturbed periods of the magnetosphere and comparing with the signal amplitude, identifying outliers in the vertical magnetic field values, and using various robust processing methods.

The physical processes occurring in the magnetosphere have not yet been studied to the extent allowing to construct an accurate mathematical model. A simplified model by I.L.Osipova et al. [36] showed that sections of the curves with frequencies less than 0.001 Hz depend weakly on the underlying medium. When comparing experimental data with practical ones, a sharp decrease in apparent resistance was noted at frequencies below $2.7 \cdot 10^{-4}$ Hz, which could be mistaken for a conductor in the upper mantle or as evidence of a phase transition at a depth of 410 km. Sections to 0.001 Hz may correspond to the plane-wave condition. More complex models show that violation of the Tikhonov – Cagniard conditions can be observed from frequencies below 1 Hz, with the effect being most noticeable in resistive media. Based on these considerations, E.Xiao et al. did not use data below 0.001 Hz during their work near Prydz Bay [37].

In the study by M.Beblo and V.Liebig [16], a connection between the electrojet and changes in signal amplitude was observed; however, despite its visible influence, the apparent resistivity computed in the work and the constructed geoelectric section do not contradict geological concepts.

In 1998, under the SVEKALAPKO international project, the BEAR (Baltic Electromagnetic Array Research) experiment [38] was conducted. One of its objectives was to study the influence of complex current systems on the deep magnetotelluric and magnetovariational sounding data. Analysis of the temporal variability of transfer functions showed that the sharp amplitude minima in individual segments of the record, accompanied by noticeable phase distortions, correspond to the multiple coherence minima. These segments correlate with the geomagnetic activity parameters. A large number of synchronous records in the experiment made it possible to develop a method of multi-point robust estimation of transfer operators – impedance and tipper (the multi-RR estimation method), which considers several remote points with synchronous magnetic observations and helps to suppress the distorting effects of an inhomogeneous electromagnetic field. Robust processing methods reject areas with minimum coherence, leaving records with moderate and low geomagnetic activity. The multi-RR estimation algorithm was later implemented in the PRC_MTMV software system [39].

In addition to the multi-RR method, positive examples of the robust processing application are also noted in other works. P.E.Wannamaker et al. [21] proposed removing interference from non-plane waves using the robust Jackknife technique, in which special attention is paid to removing outliers from vertical magnetic field records [21, 26]. After estimating the transfer functions, it is possible to reject biased estimates using the amplitude-phase data correction method [40].

The geomagnetic situation can be considered using geomagnetic indices, along with the transfer function analysis. A sign of a magnetic storm is a decrease in the horizontal and an increase in the vertical magnetic field. For a preliminary assessment, one can use auroral electrojet forecasts for the day[3].

N.L.B.Lauritsen [41] constructed hourly values of the real and imaginary parts of the impedance and compared them with geomagnetic indices: the planetary index of geomagnetic activity K_p and the index of geomagnetic activity of the auroral zone, which indicates substorm activity AE. There was no correlation between the parameters.

Analysis of the magnetic activity index A_p variation, the signal spectral power, the presence of substorms, and the division of records into 12-hour segments during the Mount Erebus study [26] led to the conclusion that either the influence of the non-plane (non-planar) wave was negligible, or such areas were removed using robust processing methods.

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[3] Aurora – 30 Minute Forecast. URL: https://www.swpc.noaa.gov/products/aurora-30-minute-forecast (accessed 31.10.2023).

A.G.Jones and J.Spratt used histograms of the vertical magnetic field distributions H_z and selected areas that remained within the specified limits [36]. This method is applicable to a one-dimensional medium when H_z tends to zero.

J.R.Peacock and K.Selway [23] evaluated data on four parameters alternating in time and frequency and rejected them in case of non-compliance with the conditions: apparent specific electrical resistivity – time invariance; number of principal components of the magnetic field ≤ 2; coherence between the measured electric field and estimated from the magnetic field > 0.5; modulus of the vertical magnetic field

$$1{,}5\sigma \le \frac{B_z(\omega,t)}{\sqrt{B_x(\omega,t)^2 + B_y(\omega,t)^2}},$$

where B_x, B_y, B_z are the magnetic field components; σ is the standard deviation of the amplitude B_z; ω is the angular frequency.

Based on the idea that using only one geomagnetic index considers only one aspect of activity in the magnetosphere, J.E.Borovsky and M.H.Denton [42] proposed using a composite index to describe magnetospheric events, the accuracy of which is significantly higher. However, at the moment, the experience in using composite indices is insufficient.

Without analysing the influence of complex current systems that are constantly present in the polar latitudes, unpredictable results can be acquired. The experience of previous researchers shows that working with one or several (preferably) remote base stations, modern robust processing methods (especially multi-RR estimation and the Jackknife technique), as well as the analysis of time series and transfer functions helps to successfully overcome source effects.

Ocean influence. Most magnetotelluric studies are concentrated on the coast of Antarctica (see Fig.1, *a*). The MT data quality can be affected by the coastline effect anomaly, arising under the influence of eddy currents excited by the magnetic field in the ocean due to the significant difference in resistance between the conductive ocean and the resistive continent. According to M.N.Berdichevsky and V.I.Dmitriev [43], this anomaly has two components.

The electric current directed perpendicular to the coast causes a galvanic anomaly and is divided into two components. One flows into the sedimentary cover and is channelled over a fairly large distance, slowly seeping into the deep layers of the lithosphere – the effect of a continental trap. The size of the continental trap depends on the average integral conductivity of the sedimentary cover and the average integral resistance of the resistive crust. The second seeps through the ocean floor into the deep conductive zones of the continent. The ratio of the two components determines the distortion degree and sensitivity of the transverse MT sounding curves (TM modes of the magnetotelluric field).

The electric current directed along the coast causes an induction anomaly, which is associated with the interaction of oceanic and continental longitudinal currents (horizontal skin effect). These currents create an intense magnetic field, as a result of which the vertical magnetic field can exceed the horizontal one in amplitude.

In Antarctica, the coastline effect manifests itself to varying degrees. The anomaly intensity depends on the coastal part depth and the land specific electrical resistivity value. The greater the resistivity contrast and the greater the depth, the more pronounced the coastline effect. When studying the geological structure of the Deception Island, the influence of the coastline effect on the MT curves is weak, since the difference in specific electrical resistivity between conductive volcanic rocks and seawater is small, and the topography of the underwater part of the caldera is smooth [30]. In the Prydz Bay area [37], the contrast between the specific electrical resistivity of saline seawater and the rocks that make up the coast is large, and the MT curves acquired in the northern part of the line differ from the others by five orders of magnitude. One of the possible causes of the distortion may be the coastline effect. The ocean influence on the transfer functions has been noted in other studies [23, 26, 41], with the effect being more pronounced for the TM mode [27]. Studying the influence of the coastline effect anomaly, N.L.B.Lauritsen [41] found that eddy currents strongly distort impedance curves and induction vectors.

The coastline effect is considered in the modelling by including a thin layer and bathymetry data with variable conductivity [43, 44].

Static shift in areas with fracturing. Horizontal inhomogeneities in the upper part of the section can introduce strong distortions into the impedance tensor in the entire frequency range, which are manifested in a conformal shift of the magnetotelluric sounding curves.

Ice core studies show that the ice sheet is heterogeneous in its physical properties [45-47]. Standard values of ice sheet resistivity range from $4 \cdot 10^4$ to $4 \cdot 10^5$ Ohm·m [31]. Depending on the surface firn temperature, admixtures, basal melting, ice density or the presence of fractures, the electrical properties of ice can vary. Heterogeneities are more likely to occur in the coastal part, where the temperature rises to zero values and fractures can be filled with a mixture of snow-firn mass and frozen seawater [32]. Heterogeneities can cause a static shift in the MT sounding curves. J.R.Peacock and K.Selway suggest using any of the standard procedures for correcting static shifts [23]. For example, they applied a spatial median filter, assuming that dust pollution would be similar at a distance of 20 km. Using additional information (magnetovariational sounding [48], phase tensor method), it is possible to localize near-surface inhomogeneities.

Work safety. Antarctica is the coldest and highest continent on the planet. Weather conditions here change very quickly. In the central part, temperatures drop to –89.2 °C in winter. The air in most of the area is very dry, thin, atmospheric pressure is low, and the solar radiation level is increased. Harsh conditions on the continent prompt considering safety regulations in highlands when planning and performing work [49]. Extreme climatic conditions affect the work safety (data collection can take significantly longer than when working in mid-latitudes).

Bad weather in Antarctica can last for more than a week, so if the group is far from the camp, it is necessary to be prepared for a situation where it will be physically impossible to return and there is a need to ensure autonomous life support for several days.

Expanding the study area by increasing the length of electric receiving lines increases the likelihood of fractures and other threats associated with the ice cover structure in the work area. In dangerous areas, it is necessary to organize a roped safety line (movement along a rope).

Researchers must undergo training in safe movement on an ice sheet, have special equipment and skills to rescue a person from a crevasse, recognize dangerous health conditions that arise in highlands and rapidly changing extreme weather conditions (frostbite, hypothermia, cerebral edema, pulmonary edema, injuries), and also be able to provide first aid [50].

Working in isolation affects both physical and psychological state of a person [51]. To minimize injury-prone behaviour, M.V.Tumanov et al. [52] propose assessing the psychophysiological indicators using a personal risk index.

Conclusion

Analysis of the conducted studies showed that the magnetotelluric sounding method is successfully used both to clarify the geological structure of the Earth's crust and upper mantle, and to solve hydrogeological issues.

A number of factors that complicate high-quality MT data acquisition were identified: extremely low temperatures, strong winds, proximity to the source, extended coastline, and ice sheet coverage of most of the area.

Methods were identified that, if implemented, will reduce the impact of the listed factors and acquire high-quality MT sounding data in Antarctica.

1. Preparation of equipment and adaptation of the work procedure, including:

- measures to minimize the impact of high contact resistance between the electrodes and the surface ice by using plate electrodes with preamplifiers with high input resistance;
- ensuring continuous operation of the equipment over a long period of time from several days to two weeks, considering low temperatures, using high-capacity batteries and solar panels;
- insulation of the equipment and the use of arctic-grade wires with an installation temperature of no higher than –40 °C;

- selection of the receiving electrical line length to ensure a sufficient level of useful signal;
- increasing the recording time to acquire a sufficient number of data accumulations.

2. Development or adaptation of a processing flow that includes:

- use of one or more remote base stations and robust processing methods solves the issue of proximity to the geomagnetic poles (violation of the plane wave principle);
- removal from time series of recording sections acquired at wind speeds exceeding 7 m/s reduces the impact of wind interference (broadband electromagnetic noise);
- consideration of the coastline effect and static shift.

3. Ensuring work safety involves a set of measures:

- supplying the Antarctic expedition with special equipment and gear for work on ice sheets and in highland areas;
- training personnel in safe movement on ice sheet, as well as skills in rescuing people from crevasses, recognizing dangerous health conditions that arise in highlands and rapidly changing extreme weather conditions, and providing first aid.

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Authors**: Tatyana V. Davydkina,** *Engineer of the 1st Category*, *davydkina_tv@pers.spmi.ru*, *https://orcid.org/0000-0001-8950-5555* (*Empress Catherine II Saint Petersburg Mining University*, *Saint Petersburg*, *Russia*), **Andrei A. Yankilevich,** *Candidate of Engineering Sciences*, *Leading Engineer*, *https://orcid.org/0000-0002-6677-0812* (*Empress Catherine II Saint Petersburg Mining University*, *Saint Petersburg*, *Russia*), **Anna N. Naumova,** *Engineer of the 2nd Category*, *https://orcid.org/0000-0003-1112-1679* (*Empress Catherine II Saint Petersburg Mining University*, *Saint Petersburg*, *Russia*).

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