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Modern Geodetic Methods for High-Accuracy Survey Coordination on the Example of Magnetic Exploration

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Abstract—The purposes and problems of the international network of geomagnetic observatories INTERMAGNET are briefly described in the work. The importance of the development of the Russian segment of the network as a part of a system for monitoring and estimating geomagnetic conditions on the Russian territory is emphasized. An example of the use of modern high-precision geodetic equipment for coordinate referencing of field geophysical observation is described. Factors that distort the referencing of field observations in problems of survey, engineering, and technical geophysics are listed, as well as those related to detail and high-resolution geophysical surveying and those that require a corresponding accuracy of observation point coordination. The magnetic exploration at the site of the Yamal INTERMAGNET-standard observatory serves an example to describe a technique for geodetic provision of a detailed geophysical survey by means of joint use of differential GNSS measurements and electronic tacheometry. The main advantages and disadvantages of the technique suggested are listed.

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1. INTRODUCTION

The International Real-Time Magnetic Observatory Network (INTERMAGNET) routinely records components of the Earth's magnetic field and provides the global scientific society with magnetic data recorded and processed according to highest standards. The INTERMAGNET network is a unique source of data for the interpolation and approximation of the magnetic field distribution with the goal of modeling the field and studying the geomagnetic activity (Berezko et al., 2011; Soloviev A. et al. 2012a; 2013b). In particular, such techniques allow a determination of the parameters of the Earth's magnetic field in hard-to-reach regions of the Russian Federation, where the deployment of geomagnetic observatories is impossible. The INTERMAGNET network today includes more than 130 magnetic observatories located at different places, from polar archipelagos to equatorial regions. The density and geographical coverage of the geomagnetic observatory network is the most important factor in the construction of adequate models of the Earth's magnetic field and the distribution of its variations. The density is quite high in Western Europe, and the coverage is quite homogeneous in Northern America, while the INTERMAGENT network is less dense in Asia and on the territory of USSR. In particular, only eight Russian, two Ukrainian, and one Kazakhstan observatories participate in the INTERMAGNET network. Thus, compensation for the lack of Russian magnetic observatories should contribute significantly to the development of a system for monitoring and estimating geomagnetic conditions on the Russian territory.

The first Russian magnetic observatories were renovated according to the INTERMAGENT standards with the support of the CRENEGON international project (The Creation of a Renewed Network of Basic Geomagnetic Observatories of NIS Countries). This project allowed five observatories of NIS countries to join the INTERMAGNET network. The Irkutsk magnetic observatory started transmitting data into the INTERGAMGNET geomagnetic information nodes in 1998 and became the first Russian magnetic observatory to officially enter the INTERMAGNET network in 1999 (Potapov et al., 2011). In 2002, an INTERMAGNET-standard magnetic observatory was deployed on the basis of the Borok geophysical observatory (Yaroslavskaya oblast) as part of the collaboration between the Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, and the Paris Institute of the Physics of Earth. This observatory received official INTERMAGNET status in April 2004 (Chulliat, 2008).

The development of a network of INTERMAGNET-standard magnetic observatories on the Russian territory is an important applied research task that can be implemented by joint efforts of institutes of the Federal Agency for Scientific Organizations and ROSHYDROMET (Gvishiani et al., 2014; Soloviev et al., 2013a). The deployment of new INTERMAGENT magnetic observatories includes the mounting and putting into operation of complexes of magnetic measuring instruments at existing and new geophysical stations and observatories. A complete set of magnetic measuring instruments at an observatory usually includes scalar and vector magnetometers, a declinometer/ inclinometer based on nonmagnetic theodolite, and a data acquisition and transmission system. When deploying a magnetic observatory, the magnetic situation at the site of deployment is important: there should be no significant anomalies of the strength of the magnetic field and its high gradients near observatory buildings and facilities. Thus, geomagnetic exploration at the planned magnetic observatory site is the most important and integral part of its deployment (Nechaev, 2006; Jankowski and Sucksdorff, 1996; Newitt et al., 1996).

This specific problem of magnetic exploration concerns the detailed study of the magnetic properties of the upper part of the section and the search for a observatory facility site that is free of magnetic disturbances of both natural and technogenic origin, which affect the quality of data recorded. Otherwise, uncommon mathematical methods for the recognition and removal of technogenic disturbances in magnetograms are required (Bogoutdinov et al., 2010; Soloviev et al., 2009; 2012b, 2012c; Sidorov et al., 2012). In this case, the problem of setting out a regular survey grid of a certain scale and coordinate referencing of the network arises. Ranging and use of squares, theodolites, and topographic measuring tape are common ways of solving this problem. However, stationing and coordinate referencing with the use of the above instruments require significant time. Approaches involving the use of electronic total stations (or electronic theodolites with laser rangers) and GNSS receivers are the most modern and effective. Let us further consider the advantages and disadvantages of these modern approaches.

2. USE OF GLOBAL NAVIGATION SATELLITE SYSTEMS

During geophysical works in the field, the setting out and coordinate referencing of observation points are often carried out with the use of mobile GPS trackers. These devices are relatively cheap, compact, and user-friendly. They allow the quite rapid setting out of survey grids and observation point referencing, as well as other types of geodetic support of geophysical works. However, the use of portable GNSS devices does not always provide sufficiently accurate coordinate referencing of observations, because such GNSS receivers usually determine positions only via a free open code (a pseudo-random sequence that modulates a satellite-transmitted signal), which is transmitted at one carrier frequency. These receivers are commonly called code. The accuracy of code measurements varies from 2 to 5–10 m, depending on the observation conditions (Antonovich, 2006). Comparable observation accuracy is ensured with built-in or plug-in GNSS modules, with which some common models of field magnetometers are equipped (e.g., GEM Systems GSM-19GW or MMPOS-1/2, NPC Quantum Magnetometry, magnetometer (Denisov et al., 2006)). This accuracy is evidently insufficient for such geophysical engineering problems, the solution of which requires surveying with 10-m spacing or less.

To increase the positioning accuracy of a single-frequency code GNSS receiver, the use of state and commercial augmentation systems is provided. The signals of these systems allow the code measurement accuracy to be increased to 0.5–1 m. However, their use has certain limitations. For example, the American WAAS (Wide Area Augmentation System) and European EGNOS (European Geostationary Navigation Overlay System) systems cover the territories of Northern America and Europe, respectively. The Russian SDCM (System for Differential Correction and Monitoring) has not been fully put into operation and it is not supported by all manufacturers of measuring instruments. Commercial services (e.g., OmniSTAR) require payment for their use and also have some geographical limitations.

The use of geodetic GNSS receivers, which allow phase measurements of satellite navigation signals, provides more accurate and reliable results. Real time kinematic (RTK) is the most common and rapid technique. It allows a navigation solution by field phase measurements. The GNSS complexes of two receivers are used in this technique. One of the receivers is stationary and mounted at a small distance (up to 10 km) from the worksite at a point with known or measured coordinates; it plays the role of a so-called base station or base. The direct stationing and coordinate referencing is carried out with a movable receiver—a so-called mobile station or rover. The two receivers carry out observation simultaneously, the base station transmits mobile corrections through a radio channel (GSM, VHF), which allow an increase in the accuracy and reliability of the navigation solution. The positioning error is about 10 cm in this case (Antonovich, 2006).

3. EXAMPLES OF USE OF GNSS MEASUREMENTS IN MAGNETIC EXPLORATION

A detailed magnetic gradiometer survey was carried out during deployment of the Klimovskaya magnetic observatory (Rotkovets geological and biological station of the Institute of Physiology of Natural Adaptation, Ural Branch, Russian Academy of Sciences, Konosha district, Arkhangelsk region, Russia) on the observatory project land. First, the territory was analyzed at a 10-m regular survey network to reveal the general character of the anomalous magnetic field. The survey stationing was carried out with the use of optical theodolite and a fiberglass topographic mea-

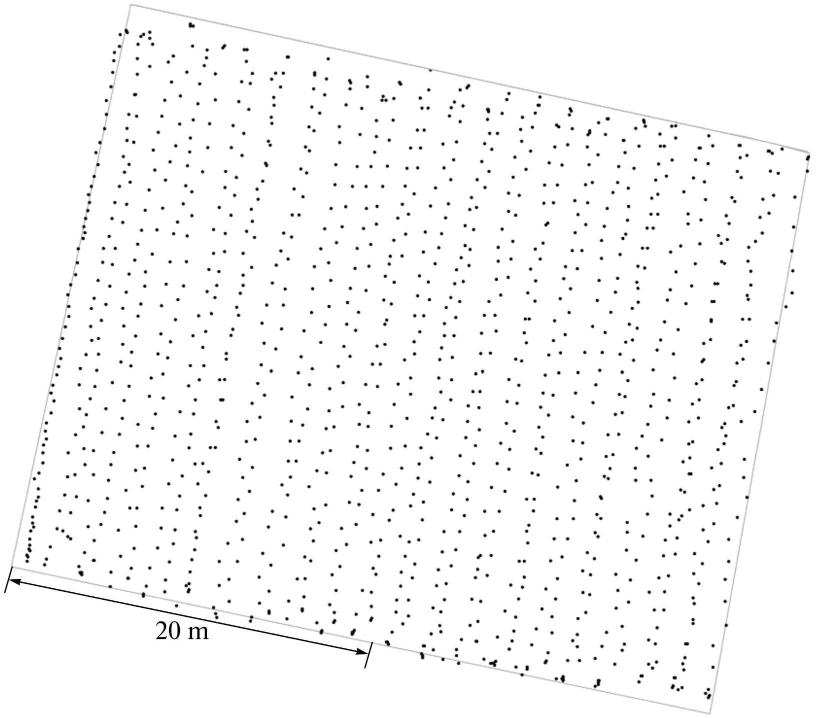

Fig. 1. Station arrangement for a detailed magnetic survey at the territory of Klimovskaya observatory. The referencing has been carried out with the use of the built-in GNSS receiver of the magnetic gradiometer. Gray lines show boundaries of the site under study. The dots show survey points.

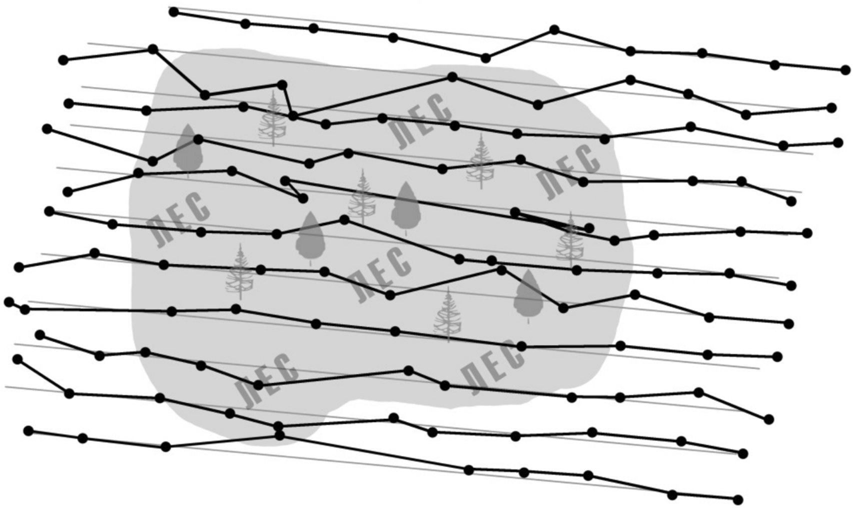

Fig. 2. Profiles of magnetometric survey on the territory of Moskva observatory. Gray lines show the actual direction of the profiles; dots show survey points for which the coordinates were measured with the GNSS receiver of the magnetic gradiometer.

suring tape. The coordinates of survey points were determined by a magnetic gradiometer's receiver at the instants of recording. To detail the areas for observatory buildings and fixing sites for pillars for observatory facilities, a micromagnetic survey with 1-m spacing was carried out automatically with a 1-s recording interval by a mobile proton magnetic gradiometer. The positions of survey points were determined with the magnetic gradiometer's receiver. Figure 1 shows that the coordinate referencing of observation points were often made with significant errors, though the observer moved along clearly marked profiles.

Another important factor which makes difficult the precise referencing of survey points with GNSS receivers is wooden vegetation at the project site. A signal from navigation satellite can be scattered and distorted due to dense foliage, which is shown in additional positioning errors. Figure 2 shows the arrangement of survey profiles during the magnetometric study of the territory around buildings of the Moskva magnetic observatory (IZMIRAN, Troitsk, Moscow). The survey area was partially covered with trees. The space between profiles and the survey spacing were chosen as equal to 10 m. The setting out of survey profiles and points was also carried out with the use of optical theodolite and a topographic measuring tape, and the coordinate referencing was conducted with a built-in GNSS receiver of a GSM-19GW magnetic gradiometer. It is seen from Fig. 2 that the measured positions of survey stations significantly differ from their actual positions at the marked survey profile.

Survey points positioning errors can cause false extremums and condensation of isolines during mapping, which will make it difficult to interpret the results. This applies especially to high-precision high-resolution geophysical surveys.

4. ELECTRONIC TOTAL STATION AND ITS USE

An electronic total station is intended for measurements of horizontal and vertical angles and distances and is an optical theodolite with an electronic system for measuring angles, a built-in laser range finder, and a field computer for processing the measurements. The operation of an electronic total station requires a reflector mounted at a measured point. Reflectors in the form of glass prisms mounted on a telescopic rod are the most common today. Modern electronic total stations with certain limits can measure without reflectors with guidance to different physical objects or with the use of special reflective film or retroreflectors.

The built-in software of modern electronic total station allows solving a wide range of geodetic problems in situ, including the positioning of points; the calculation of perimeters, areas, and volumes; the design of survey networks; and setting out of points (by angle and distance, by coordinates, by range between the points) to a specified horizontal or inclined plane. Some total stations are equipped with a laser target finder to increase the efficiency of setting out of points, and some are equipped with an optical track-light to simplify visual tracking of a bearing cross-section. Common interfaces (RS-232, USB, Bluetooth, Wi-Fi, etc.) are usually used in electronic total stations for data transmission to peripheral devices (Dement'ev et al., 2008).

Electronic total stations are widely used in different geodetic works; in particular, they can be effectively used for geodetic maintenance of field geological and geophysical explorations. With an electronic total station, a survey network of any desired configuration can be designed and set out. Necessary geophysical measurements can be carried out at set and fixed survey points. It should be noted that the precise coordinate referencing of geophysical measurements requires the presence of control points with known coordinates, relative to which the total station determines the coordinates of the survey points.

Local stations of the state geodetic network, stations of local landmark networks, and other fixed points with known coordinates can serve as control points. If such points are absent, a temporary control network can be deployed for these purposes. The coordinates of the control network points are easier to determine from GNSS observations. This requires the use of geodetic GNSS devices, which allow phase measurements at several carrier frequencies. The coordinate references in this case can be performed in the total station computer after setting out of the survey points. For this, it is necessary to input the coordinates of the total station point and specify the reference direction for its horizontal circle to be oriented correctly. If a territory under study is covered with dense vegetation and the GNSS receivers cannot be used at the survey site, one can set out the control network at an open area at a certain distance from the site (at a forest edge or clearing, along a road or railway) and then set out a temporary line-angle traverse. Thus, the use of an electronic total station along with GNSS receivers allows one to design a local survey network of a desired configuration and perform the coordinate referencing of survey points. The results of geodetic and geophysical measurements can then be easily jointly processed in a computer. Some examples of the use of high-precision geodetic instruments are described in (Kaftan and Krasnoperov, 2015).

5. EXAMPLE OF JOINT USE OF ELECTRONIC TOTAL STATION AND GNSS IN MEGNETIC EXPLORATION

The building of a new observatory at Yamal, in Sabetta settlement (Yamal-Nenets Autonomous Okrug) was planned within the development of the network of INTERMAGNET-standard observatories on the Russian territory (Soloviev et al., 2013c). Magnetic exploration of the project land was carried out by researchers of the Laboratory of Geoinformatics and Geomagnetic Studies of the Geophysical Center of the Russian Academy of Sciences during the expedition to Sabetta settlement The observatory was deployed within a project on the development of systems for monitoring and estimating the geomagnetic situation on the territory of the Russian Federation. The data which will be received at this observatory are expected to be used for solving the problems of interpolation and approximation the magnetic field distribution during the development of the South-Tambeyskoye gas-condensate field.

The region under study is located at the east of the Yamal Peninsula on the coast of the Gulf of Ob (Kara Sea). This region is arctic tundra with permafrost soils. When choosing the region for the study, both physico-geographical features (many tundra bogs and water reservoirs) and the arrangement of existing and projected industrial objects and service lines (natural-gas liquefaction plant, sea port, airport, projected settlement) were considered. Finally, a land area for detail magnetic exploration was chosen at a sufficient distance (no less than 3 km) from probable sources of noise.

The works included three sessions of areal magnetic survey of different scales. The first session was performed for an area of 250000 m^2 (500 × 500 m) marked with a 50-m survey network (121 points). Maps of the anomaly component of the total vector of the magnetic field and its vertical gradient were constructed on the basis of the survey results, and a site for the next session was chosen. The second session of magnetic survey was performed for an area of 10000 m^2 (100 × 100 m) marked with a 10-m survey network (121 points). It also resulted in maps of anomalous magnetic field and the vertical gradient of the total vector of magnetic field constructed in the GIS environment (Beriozko et al., 2011; Krasnoperov et al., 2012). On the basis of these measurement sessions, a square site of 24 × 24 m was chosen, on which a 2-m network for detail survey (169 points) was designed.

Three planned survey sessions, despite the redundancy of magnetic measurements during sequential refinement of the survey, are justified from the viewpoint of general principles of the geophysical research methodology. Thus, the guidance based on the experience of researchers of the Irkutsk geomagnetic observatory (Nechaev, 2006) suggests carrying out areal magnetometry on several scales when choosing an observatory site for a multilevel study of the character of magnetic field anomaly distribution and the selection of sites appropriate for building observatory facilities. A preliminary magnetic survey is carried out each 100–200 m within a radius of 1–2 km from the chosen site and a 10-m interval survey is carried out immediately at the building site. In our case, the reconnaissance problem (ascertaining the general character of magnetic field anomalies) was solved via a 50-m interval survey carried out during the first step. The reconnaissance survey was also very important under snow cover conditions, where visual detection of disturbing objects and obstacles was impossible.

The survey during the next step can be considered a task of detecting desired sites. The desired area, within which variations in horizontal and vertical gradients are minimal, was 24 × 24 m in size and, hence, this region could be found by three points in three neighboring profiles with a good probability (nine points in total), which evidently satisfies the well-known three-sigma and three-point rule (Magnetic Survey, 1990; Khmelevskoi et al., 2004).

The problem of refinement was solved during the third step on the basis of the results from the previous survey. According to the project, the magnetic observatory should include the construction of an observation pavilion, where scalar and vector magnetometer and fluxgate theodolite for absolute observations are to be mounted, and also an engineering building. The observation pavilion was 12 × 6 m in size; it was decided to choose an area 24 × 24 m for its location. Detailed mapping requires a step in the profiles of the object under study to be at least ten times smaller than its characteristic size (Magnetic survey, 1990); this implied that the resolution of 2 × 2 m was sufficient for the site refinement. A similar observatory project was successfully implemented earlier by the Geomagnetic Group of the USA Geological Service during deployment of the Deadhorse Observatory in Alaska (Deadhorse, 2014). We should note that there are no requirements for the absence of magnetic disturbances for the engineering building (a small building located at a distance from the measuring pavilion) in which the control and telecommunications facilities are mounted.

It was decided to select a square survey network (with the ratio of the profile step to the interprofile space 1 : 1) at all survey steps because of the peculiarity of the stated problem. In geophysical survey observations, profiles are projected across the course of target objects (Khmelevskoi et al., 2004), and the survey network is often constructed anisotropic, with a ratio of the profile step to interprofile space of 1 : 5 to 1 : 10. In the studied case, the location and orientation of the observatory building at a final site of 24 × 24 m were assumed arbitrary, and the target building sites could be considered equilateral. Therefore, it was decided to perform all of the survey steps on square survey grids. In addition, the survey results on isotropic (square) networks are more representative and obvious than on anisotropic networks, since magnetic anomalies are mapped from the results of the former without distortions caused by network inhomogeneity.

The magnetic survey was carried out with a GMS-19GW magnetic gradiometer. Magnetometer sensors were mounted 56 cm apart on a separate rod. The recorded data were referenced to the UTC timescale with a built-in GNSS receiver of the magnetic gradiometer. To consider daily variation, an additional GSM-19 proton magnetometer (magnetic-variation station, (Magnetic Survey, 1990)) was used fixed at a distance of 700 m to the southeast of the survey network center. The time scales of the magnetic gradiometer and the magnetic-variation system were synchronized. The logging interval of the magnetic-variation station was chosen to be equal to 10 s, which was accepted optimal for all of the survey steps.

A Trimble M3 DR 5" electronic total station and a set of two geodetic GNSS receivers Javad Maxor and were used for setting out the survey grid and coordinate referencing of the survey points. The receivers were installed at points T1 and T3 of the temporary control network. Their exact coordinates were found during processing the GNSS measurements. The total station was installed at T1 point. The horizontal circle

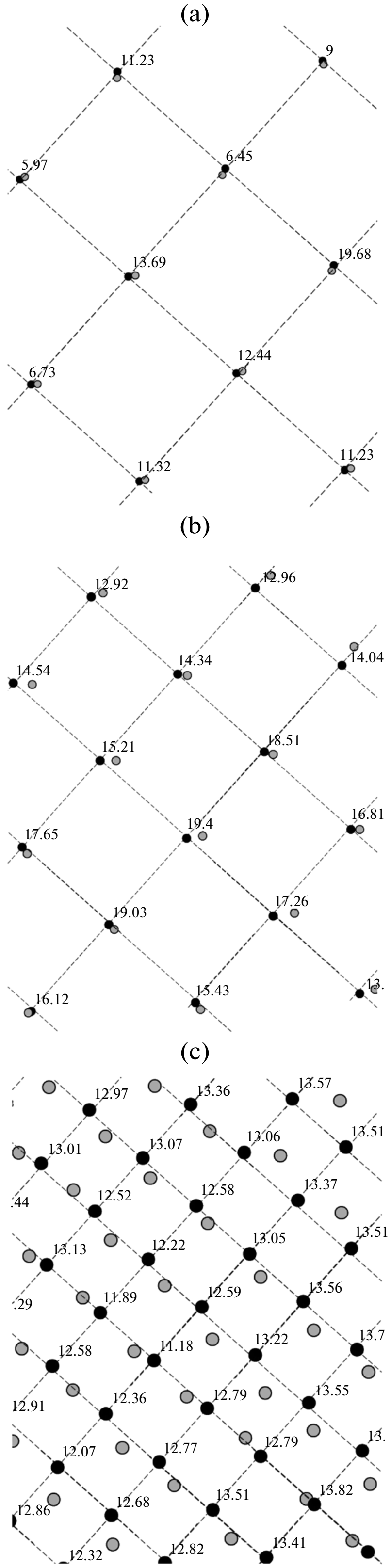

Fig. 3. Fragments of the magnetic survey networks near Sabetta settlement with a resolution of (a) 50 × 50 m, (b) 10 × 10 m, and (c) 2 × 2 m. Black dots show the set out points for which the coordinates were found from geodetic measurements; empty circles show the points for which the positions were determined with the GNSS receiver of the magnetic gradiometer. The network lines are dashed. The measured values of magnetic field anomalies are written.

of the total station was oriented along the T1–T4 reference direction, the azimuth of which was preliminary calculated. The T4 point was chosen during the reconnaissance of the survey site; it specified the T1–T4 reference direction, relative to which the stationing and survey network setting out were conducted. The survey network was then designed and calculated in the total station computer. The setting out of the survey network points was carried out using a prism reflector. The set out points were marked with nonmagnetic wooden pickets. The error of the survey points setting out didn't exceed 10 cm. The point coordinate referencing error using GNSS data, with the long range between the survey site (1.1–1.7 km) and the total station taken into account, did not exceed 20 cm. The coordinates of the control points and survey network points were determined on a plane in the UTM (Universal Transverse Mercator) coordinate system. The stationing and magnetic survey were carried out in such a way that the effects of ferromagnetic elements of a marker (clothes details, prism reflector rod) on magnetic measurements were minimal. For this, a space between the marker and a magnetometer operator were kept such that the effect of disturbances on the measurements could be considered negligible.

6. ANALYSIS OF THE DEVELOPED TECHNIQUE

During the survey, the total vector and vertical gradient of the magnetic field strength were measured at each survey point with the GNSS receiver of the magnetic gradiometer, as well as the coordinates and UTC time of measurements. This allowed the study of coordinate referencing errors through the comparison of observation point coordinates recorded with the magnetic gradiometer receiver with the corresponding coordinates found from geodetic measurements with GNSS receivers and the electronic total station. This comparison also allowed estimation of the efficiency of the magnetic gradiometer's built-in GNSS receiver during surveying with different resolution.

To estimate the coordinate referencing accuracy, the survey station coordinates found from geodetic measurements with the receivers and total station were considered as reference. Let us designate these coordinates in the UTM system as (X_i^G, Y_i^G), where $i = 1,\ldots,n$ is the station number (the total number of stations is $n = 121$ for the first and second survey sessions and $n = 169$ for the third session). There is also a set of coordinates for each station determined with the GNSS receiver of the magnetic gradiometer during magnetic measurements. Let us designate them as (X_i^M, Y_i^M). If the point set $M = \{(X_i^M, Y_i^M) | i = 1, \dots, n\}$ is considered as a sample from the entire assembly, then the GNSS-receiver measurement error of the coordinates relative to the reference coordinates from geodetic measurements (let us similarly designate them as the point set $G = \{(X_i^G, Y_i^G) | i = 1, \dots, n\})$ can be expressed as $\bar{r} \pm s$—the average with the standard deviation (Gmurman, 2003), where:

$$\bar{r} = \frac{1}{n}\sum_{i=1}^{n} r_i,$$

$$s = \sqrt{\frac{\sum_{i=1}^{n}(r_i - \bar{r})^2}{n-1}},$$

$$r_i = \sqrt{(X_i^G - X_i^M)^2 + (Y_i^G - Y_i^M)^2}.$$

The deviations for survey sites with resolutions 50 × 50, 10 × 10, and 2 × 2 m are 2.1 ± 0.6 m; 1.4 ± 0.6 m, and 1.7 ± 0.7 m, respectively. Thus, the coordinate error of the magnetic gradiometer receiver is 2 m on average. Though the error is constant in absolute value, the quality of the referencing of the survey points reduces with an increase in the survey network resolution, since the error of 2 m is 4, 20, and 100% for survey spacing of 50, 10, and 2 m, respectively. Figure 3 exemplifies the mutual arrangement of points of the *M* and *G* sets according to the survey results.

Thus, an electronic total station provides significantly more accurate coordinate referencing as compared to a code single-frequency built-in GNSS receiver of a magnetic gradiometer. The coordinate error of the latter is critical in the case of surveying with a resolution of 2 × 2 m or more, since it is comparable with the survey space. This undoubtedly implies that the importance of high-precision stationing and coordinate referencing of the points increases as the level of survey detail rises.

7. CONCLUSIONS

Using magnetic explorations at the project site of the Yamal magnetic observatory as an example, an effective technique for the coordinate provision of geophysical observations was developed with the use of modern geodetic technologies. The technique has several evident advantages, such as stationing efficiency (441 points were set out and surveyed for three working days at an area of 25 ha) and high accuracy of the coordinate referencing of the survey network. The survey network setting out was designed in situ, and the coordinates of designed and set out points and magnetic measurement results were digitized for mapping magnetic anomalies.

The possibility of setting out the survey network immediately during the magnetic surveying is a feature of the technique. However, implementation of this approach requires a certain time for a marker to set out the points according to instructions of a land surveyor (especially under a strong wind and poor visibility). A magnetometer operator carried out measurements with pauses; the main difficulty was the existence of ferromagnetic details of the reflector, which did not allow the operator and land surveyor to work simultaneously at close range. This approach is not always effective due to pauses between measurements at separate stations and measurement sessions as applied to the magnetic survey if a magnetometric base network is used for accounting for a daily magnetic variation (Magnetic Survey, 1990) instead of a magnetic-variation system. In this case, preliminary setting out of a geodetic survey network is recommended. In addition, if the works are carried out at one small site with a survey resolution of less than 10 × 10 m, the use of an electronic total station for setting out the survey points can require more time than, e.g., network setting with the use of a topographic measuring tape. In view of this, we recommend using an electronic total station for solving geodetic problems similar to the described above, where a series of surveys of different scales is supposed, including a detailed survey.

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