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Geodetic Observations at Geomagnetic Observatories

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Abstract—Geodetic observations at geomagnetic observatories are used to orient reference directions in relation to a common coordinate grid. This problem is solved with the use of the measuring tools of global navigation satellite systems (GNSS). The results of experimental GNSS determinations at the St. Petersburg Geomagnetic Observatory, Russia, are presented. Combination of magnetic and GNSS observations is proposed in order to reveal the cause–effect relationships between magnetic field variations and global geodynamic processes.

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1. INTRODUCTION

An important element of the complex of geomagnetic studies is their geodetic support, which determines the position of the pillars of the unit with measuring instruments, as well as the azimuths of reference directions. This is necessary to bring territorially distributed observations into a common coordinate medium in order to study the spatiotemporal regularities of changes in the Earth's magnetic field.

Astronomical methods were previously used for this purpose; they made it possible to evaluate the nature of magnetic-field spatial changes in the geographical coordinate system realized by optical observations of the Sun and stars (Jankowski and Sucksdorff, 1996; Nechaev, 2006). This method has drawbacks since it is impossible to obtain a geometrically rigorous coordinate grid due to the orientation of the reading scales of measuring instruments using vertical lines. The implementation of a geographical coordinate system based on astronomical observations used to result in a distorted coordinate grid. Moreover, astronomical observations require significant time (a series of observations may take up to several days), favorable weather conditions, and highly skilled observers.

With the development of the GNSS technologies, it became possible to coordinate referencing of magnetic observatories without the above drawback. The constellation of GNSS satellites ensures a geometrically rigorous global coordinate system not related to the gravity field.

This particular method of setting coordinates was recommended in a guide (Newitt et al., 1996) that noted that the necessary accuracy in determining the position could be obtained using two high-accuracy GPS receivers in a differential (relative) mode. This allows us to position a station within a 2-cm accuracy, which is acceptable even in regions with very high magnetic-field gradients.

Astronomical methods (observations of the Sun and stars), measurements using a gyrotheodolite, and, in recent years, GNSS measurements are used to determine the azimuths of reference directions. Azimuth determination from Sun observations ensure an astronomical azimuth with an error of about dozens of arc seconds. Azimuth determination based on North Star observations improves accuracy to several arc seconds, but this method is very labor consuming and requires skilled observers, who are rare at present due to the wide dissemination of radio astronomical observations and satellite technologies. Determinations using a gyrotheodolite make it possible to obtain an azimuth with an accuracy of 15–30 arc seconds. The comparison of methods used in various physicogeographical conditions is given, for example, in (Barreto, 1996).

The relative methods of satellite geodesy make it possible to obtain coordinates at any point on the earth surface with an accuracy of about one centimeter; the accuracy of azimuth determination depends on the length of the reference direction. Thus, the shorter the length of the orienting direction section, the rougher the accuracy of azimuth determination. Today GNSS make it possible to determine geodetic azimuths for distances of several hundred meters with an accuracy of several seconds. This method is already implemented at magnetic stations abroad (Lalanne et al., 2013). It has not yet acquired a wide use at Russia's geomagnetic observatories, as it requires testing.

The purpose of this work is to describe the solution to a problem of georeferencing (by the example of the St. Petersburg observatory) and orienting this magnetic station's observation points using GNSS.

2. THE SCHEME OF THE EXPERIMENT

The experiment on joint magnetic and geodetic determinations was conducted at the St. Petersburg Geomagnetic Observatory (its three-character code, SPG), a new Russian INTERMAGNET observatory deployed on the base of the Ozero Krasnoe geomagnetic station of the St. Petersburg Branch of the Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation, Russian Academy of Sciences (RAS). The station is located on the shore of Lake Krasnoe in Leningrad oblast. The station's geographical coordinates are 60°32′ N and 29°43′ E.

Thanks to the current development of advanced satellite technologies, the International Association of Geodesy (IAG) of the International Union of Geodesy and Geophysics (IUGG) has created and maintains a common and highly accurate International Terrestrial Reference Frame (ITRF) in order to solve global-scale geospatial problems. It represents a single network of global permanent stations that observe the GNSS and Laser Ranging System (LRS) satellites and the extragalactic radio sources of the Very Long Baseline Interferometry (VLBI) system. The institutes and organizations involved in international collaboration within the activities of the International Association of Geodesy (IAG) and the International Earth Rotation and Reference System Service (IERS) conduct observations at stations and submit their measurement data and results for open use on the Internet. The highest density of such stations is in Europe, Japan, and the United States. They are slightly over 15 on Russian territory.

Note that the Svetloe VLBI station (its international code, SVTL) of the RAS Institute of Applied Astronomy functions near the Ozero Krasnoe station. Along with VLBI observations, the station conducts GNSS measurements. Another two similar permanent GNSS observation stations function near St. Petersburg.

Thus, two stations included into the ITRF, Svetloe (SVTL) and Pulkovo (PULK), can be used for coordinate support of geomagnetic observations at the St. Petersburg observatory. This is sufficient to determine an exact geodetic azimuth and, in fact, the coordinates of the magnetic observatory's points.

Today, the latest and user-available realization of the International Terrestrial Reference System (ITRS) is the ITRF08 coordinate catalog. This network is also directly connected to other coordinate frames, for example, the regional European Terrestrial Reference Frame (ETRF) and the global International GNSS Service (IGS). The coordinates of the catalogs of the above frames differ from one another by small values because of their individual functional specifics.

To date, the PULK station is not yet included into the ITRF08 catalog because of the short duration (about three years) of continuous observations there. Nevertheless, this station, as well as the SVTL station,

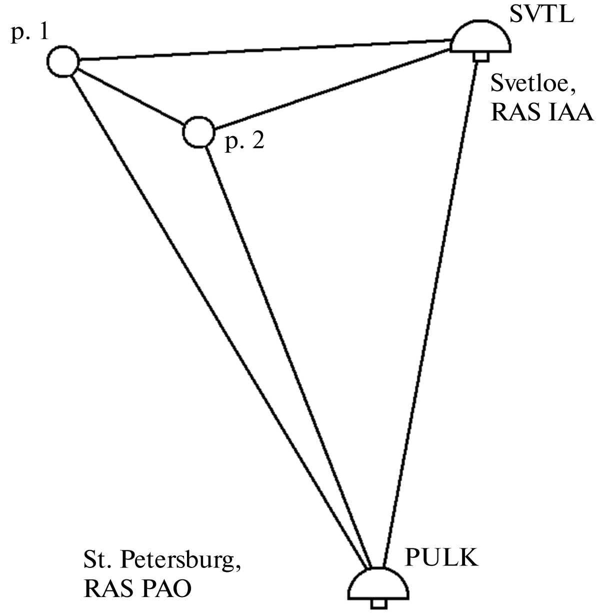

Fig. 1. Chart of the vectors of the baselines of GNSS observations.

were included into the IGS08 catalog. This coordinate frame is the main GNSS component of the general complex ITRF08 frame. Thus, it is now possible to use the coordinates of the SVTL and PULK stations obtained from the unified reference system, which is very close to the ITRF08 system. The data of the IGS08 catalog, as well as of other reference systems that account for a specific observation epoch, can be obtained on the web site of the European Permanent Network (http://www.epncb.oma.be/).

The IGS08 coordinates were used for the coordinate and azimuthal gridding of the Ozero Krasnoe station.

The main stage of geodetic measurements at the St. Petersburg magnetic observatory was the determination of the geodetic azimuth. This is necessary for the absolute determinations of magnetic declination and inclination in the common coordinate space, i.e., using a common terrestrial reference frame.

The GPS equipment manufactured by the Javad Navigation Systems was used to solve this problem: two sets of GPS Maxor receivers with Legant antennae. Because of the heavy forestation of the pillars of the pavilion for geomagnetic observations, auxiliary observation points 1 and 2 (Fig. 1) were established in places where satellite signals were best received. The final evaluations have shown that the ranging direction was obtained with an accuracy of 2″.

Temporary auxiliary point 2 was also established 150 m away from point 1 for accurate determination of the astronomic azimuth under the conditions of the best receiving of GPS satellite signals, which slightly improves the possibilities of increasing the accuracy of

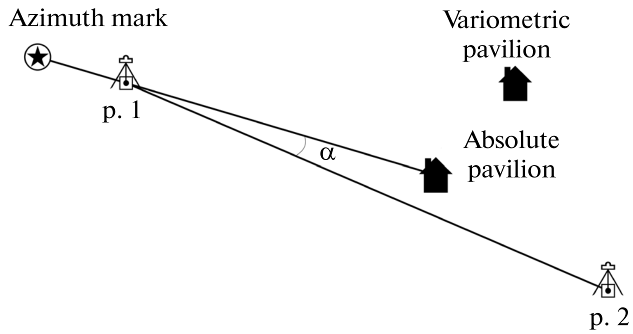

Fig. 2. Chart of the geodetic azimuth transmission from the 1–2 reference direction to the azimuth mark–pillar no. 4 (Pavilion) direction.

azimuth determinations using a longer segment than the pillar no. 4–azimuth mark segment.

The determination of the geodetic azimuth using the GPS system was performed for the point 1–point 2 direction. To this end, two sessions of repeat GPS measurements, lasting four hours each, were performed. To reduce errors in determining the positions of the phase centers of the satellite antennae in horizontal plane (which is important for azimuthal determinations), the orientation of the antennae in the second session was changed to the opposite. This technique ensures error compensation in the horizontal position of the phase centers of the GNSS antennae.

The discrete interval of satellite signal recording was set beforehand at 5 s. The elevation mask (the vertical angle of the satellite position below which the reception of radio signals is neglected) of satellites above the horizon was 5°.

The points of the global reference frame nearest to the geomagnetic station, Svetloe (SVTL) and Pulkovo (PULK), were used to obtain the geodetic azimuth in the common global reference system. Thus, a geodetic network of four points, SVTL, PULK, 1, and 2 (see Fig. 1), was formed. The mathematical treatment of the observations was done using the commercial software MAGNET™ Office Tools (MAGNET Tools, 2013). The files of measurements at the global network stations were obtained from the archives of international GNSS data centers in the compact RINEX Hatanaka format (http://sopac.ucsd.edu/dataArchive/hatanaka.html), which compresses files to save the memory of storage devices.

The measurements were processed mathematically in static mode with the determination of double differences and ionospheric-free combinations for baselines longer than 5 km using the MAGNET™ Tools software (MAGNET Tools, 2013).

The processing yielded fixed ambiguity resolutions for all the six baselines between the four observation stations. The stations SVTL and PULK participated in the processing as reference (initial) stations to determine the coordinates and geodetic azimuth of the 1–2 baseline.

3. EXPERIMENTAL RESULTS

As the result of the mathematical processing of the obtained geodetic network by the least squares method, the coordinates of the determined points 1 and 2, as well as the azimuth and distance between them, were obtained.

The root mean-square errors (RMS) of the determination of the plane coordinates of points 1 and 2 were about 2 mm; the RMS of the determination of the geodetic azimuth was 2″. Such accuracy is characteristic of GPS measurements at relatively short baselines of about several hundred meters and approaches marginal estimations.

Azimuth determination is also possible with an accuracy of about 1″ and higher; to this end, the length of the reference baseline must be increased, for example, to kilometers. However, in the conditions of forestation and other obstacles for mutual visibility between the points on the territory of the Ozero Krasnoe geomagnetic station and in its vicinity, it was impossible to obtain a baseline longer than 150 m.

A Trimble M3 DR5" electronic laser total station and a standard sighting mark with a prism reflector were used to transmit the geodetic azimuth to the reference direction.

To transmit a geodetic azimuth from auxiliary point 1 to pillar no. 4, located inside the absolute pavilion, it would be sufficient to measure the point 1–point 2–pillar no. 4 horizontal angle using a high-precision theodolite with an RMS of one-step angle determination of no less than 2″ (Fig. 2). However, since it is necessary to determine the coordinates of the points where measuring equipment was installed inside the absolute pavilion in order to bring the points of geomagnetic observations to a common coordinate system, the coordinates were transmitted from auxiliary point 1 to pillar no. 4 and subsequently to all pillars of the pavilion (Fig. 3).

The laser tachometer was installed at point 1, from where the coordinates of the azimuth mark and pillar no. 4 were determined. Four complete steps of repetitive coordinate determinations were performed. In addition, the coordinates of point 1 and the 1–2 direction angle, obtained from GPS measurement processing, were taken as references. The calculations were performed automatically with the total station software using the coordinates in the UTM projection.

As a result, the coordinates of pillar no. 4 and the azimuth mark were obtained four times. In addition, the largest discrepancies in the coordinates were 6 and 3 mm for axes *X* and *Y*, respectively. In one case, determination overdiscrepancies reached 3 cm for elevations. This value is insignificant for the posed, mainly, planar (horizontal) task. The direction angles of the measured directions were calculated automatically. The deviations from the mean were used to obtain the values of root mean square errors during one-step angle measurement. They were 5″ and 7.5″ for each direction, which is close to the announced accuracy of angle measurements by the 5″ total station used. Thus, the root mean square errors of the mean final value $M = \frac{m}{\sqrt{n}}$ were 2.5″ and 3.8″, respectively.

After obtaining the geodetic coordinates of pillar no. 4, it became possible to transmit them to all of the remaining pillars of the pavilion. The coordinates were determined in four steps of angle and distance measurements, which ensured the control and estimation of accuracy. The chart for determination of the pillar coordinates by the polar method is given in Fig. 3.

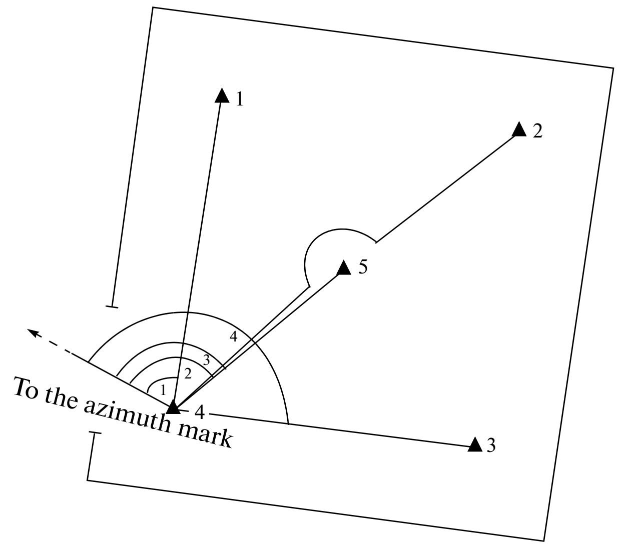

Fig. 3. Chart of determining the coordinates of the absolute pavilion's coordinates.

The experimental geodetic determinations resulted in obtaining the coordinates of the reference points of the magnetic observatory. Thus, this ensured the implementation of absolute magnetic observations and the obtaining of the characteristics of the Earth's magnetic field in the common coordinate space with the use of the international reference frame.

The major element of geodetic support for magnetic stations and observatories is the accurate determination of the azimuth mark geodetic azimuth to perform periodic absolute declination and inclination determinations in line with the requirements for the INTERMAGNET magnetic observatories, as stated in the manuals (*INTERMAGNET* ..., 2012; Jankowski and Sucksdorff, 1996; Newitt et al., 1996). Therefore, the main focus in the above experiments was on the operation of obtaining the reference geodetic azimuth of direction to the observatory's azimuth mark. The accuracy of determining the azimuth of the reference direction was 2″–3″.

4. RESULTS AND DISCUSSION

The coordinates of all the pillar centers in the absolute pavilion of the St. Petersburg Geomagnetic Observatory were obtained for the first time with reference to the common international coordinate frame. The results of the geodetic observations at the geomagnetic observatory have an applied character, but today the current level of science and technology requires regular and permanent geodetic observations in a common complex with other geophysical, particularly geomagnetic, observations.

There is an urgent need to activate observations over the earth system, especially in Russian conditions. Obtainment of authentic knowledge of global changes in the natural environment is a topical scientific problem.

Existing geodetic observation tools, such as GNSS, allow us to obtain integral characteristics of the condition of atmospheric layers along the paths of radio wave propagation from satellites to earth-based receivers (Awange, 2012). The study of the ionosphere with GNSS tools is of interest not only for meteorology but also for basic geomagnetic research. An example of the use of permanent GNSS stations to solve meteorological and geophysical problems can be seen in the efforts of the Russian Federal Service on Hydrometeorology and Monitoring of the Environment (Roshydromet) to develop a network of ionospheric GNSS observations (Aleshin et al. 2013; Aleshin et al., 2014; Alpatov et al., 2012; Tertyshnikov and Bol'shakov, 2010) and create a specialized service of high-orbital 3-D tomography. Moreover, GNSS observations are viewed as recorders of explosions in the atmosphere (Tertyshnikov et al., 2013), as well as tools to monitor the ionosphere of not only natural but also anthropogenic origin (Perevalova, 2011; Tertyshnikov, 2012).

Another important circumstance that attracts attention to geodetic observations in relation to studies on the Earth's magnetic field is its **relation to global geodynamic phenomena**. Today, researchers pay serious attention to the relationship between changes in the parameters of the earth's rotation in the determination of which GNSSs play an important role. For example, Gorshkov et al. (2012) compared changes in the coordinates of the earth's pole and the velocity of the Earth's rotation with variations in the magnetic field, in particular, with the INTERMAGNET network data, as well as geomagnetic and solar activity indices. An attempt is made to identify the relationship between the free nutation of the earth's core, expressed by changes in the parameters of the Earth's rotation, and geomagnetic activity (Malkin, 2013). The parameters of the Earth's rotation and mutual movements in its upper solid shells are recorded by earth-based astronomical–geodetic observatories, where GNSS observations play a major role. Geomag-

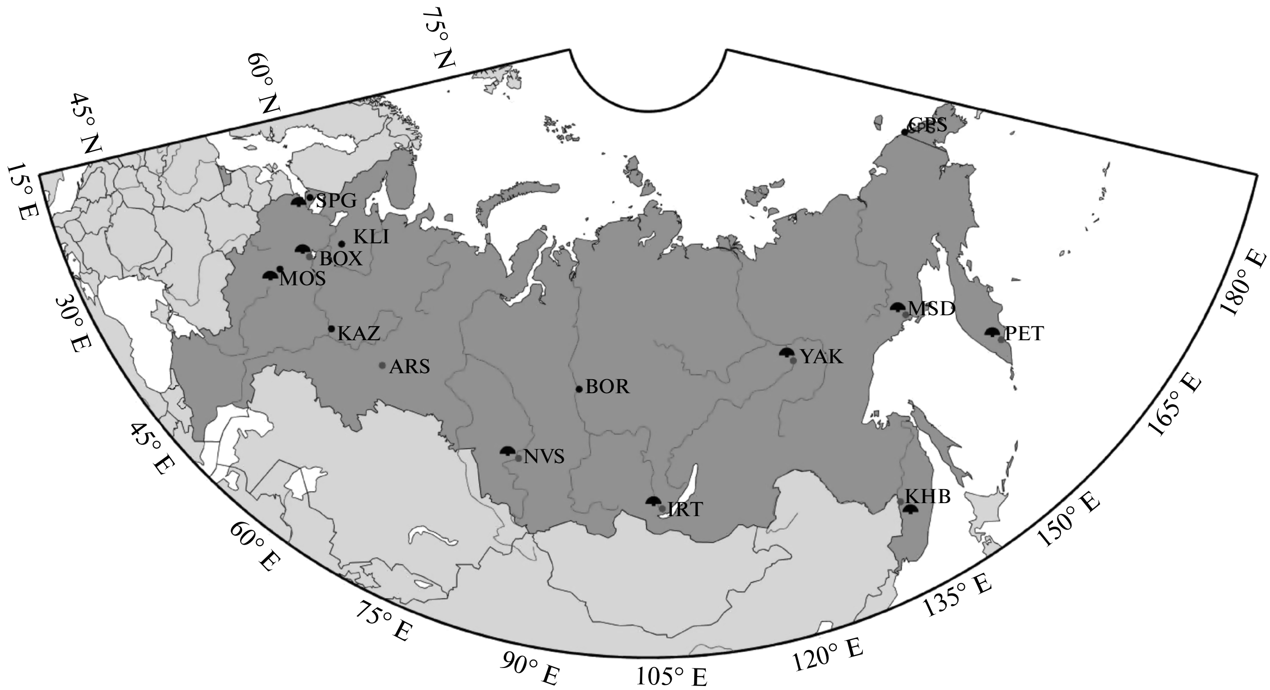

Fig. 4. The Russian INTERMAGNET segment and GNSS observation stations.

netic activity is studied for the most part independently from studies on global geodynamic processes.

The results considered above precondition research with the help of GNSS equipment installed at magnetic stations and observatories. Such a complex of simultaneous observations will make it possible to have more reliable knowledge of the degree and nature of the interaction between the Earth's main variables.

Figure 4 shows the Russian segment of the INTERMAGNET network with magnetic observatories that have already (black circles) and have not yet (gray circles) acquired the INTERMAGNET certification (Soloviev et al., 2013). Most magnetic stations are located in the direct vicinity of permanent GNSS observation posts (the black symbol of the GNSS antenna). This ensures the convenience of the joint analysis of the observations of the magnetic field, ionosphere, and geodynamic characteristics. Most GNSS observation points belong to various organizations. Nevertheless, observation data at most points can be accessed freely and used in joint analysis within the framework of various agreements, for example, within the International Commission on Regional Terrestrial Reference Frame for North-East Eurasia (Savinykh et al., 2013), initiated by the RAS National Geophysical Committee.

5. CONCLUSIONS

The obtained results of the experiment to test the technology of geodetic observations at geomagnetic observatories indicate the technological possibility of studying the magnetosphere, ionosphere, and geodynamic processes in a single observation complex.

The presented technology of geodetic observations at magnetic observatories can be proposed as a model for geomagnetic observation networks.

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