University of Tehran Press

Journal of the Earth and Space Physics

Homepage: https://jesphys.ut.ac.ir

Vol. 51, No. 4, Winter 2026, P. 65-73

(Research Article)

Geomagnetic Disturbance Impact on Magnetic Survey Tool Errors in High-Latitude Directional Drilling

Vorobev, A.V.[1] | Vorobeva, G.R.[2]

1. The Geophysical Center of the Russian Academy of Sciences, Moscow, Russia.
2. Department of Informatics, Ufa University of Science and Technology, Ufa, Russia.

Corresponding Author E-mail: geomagnet@list.ru

(Received: 2 Nov 2025, Revised: 11 Jan 2026, Accepted: 10 March 2026, Published online: 17 March 2026)

Abstract

This paper presents an approach to develop a proactive probabilistic model for assessing extreme errors in magnetic surveying tools caused by geomagnetic disturbances in the Arctic aurora zone, with the aim of enhancing the efficiency of directional drilling and accounting for risks that go beyond reactive compensation methods.

Analysis of high-resolution geomagnetic data (2004-2005) from 12 auroral observatories reveals that the absolute additional error in magnetic declination ($|\Delta D|$) follows a composite statistical law. The core of the distribution (~84% of data) is lognormal (shape parameter s = 0.87 for $|\Delta D_{mean}|$ and s = 1.02 for $|\Delta D_{max}|$), indicating error formation via multiplicative ionospheric processes. Critically, the tails (~16%) are heavy and obey a Pareto distribution, signaling a substantial risk of extreme events. We quantify that the maximum synchronous error ($|\Delta D_{max}|$) exceeds 5.67° with a 1% probability, even during the solar cycle's declining phase. A distinct diurnal pattern with dual maxima suggests an optimal time windows for precision drilling operations.

The established lognormal-Pareto model facilitates a paradigm shift towards proactive risk management in high-latitude drilling. Our findings underscore the statistical insufficiency of mean-error approaches and quantify a significant probability of extreme azimuthal errors due to space weather. This study provides a foundation for developing decision-support systems, optimizing operational schedules, and informing stricter metrological standards for Arctic drilling equipment.

Keywords: Space weather, Geomagnetic disturbances, Magnetic survey tool, Directional drilling, Risk assessment, Additional error, Extreme value statistics.

1. Introduction

The development of oil and gas fields in the Arctic region presents unique technological challenges due to extreme environmental and climatic conditions, which results in high costs and resource intensity for all production processes, including drilling. Modern directional drilling (DD) technologies require high-precision control of the wellbore trajectory, with azimuthal accuracy reaching up to 0.1° (Chang et al., 2025; Yang et al., 2025). Table 1 presents typical metrological characteristics of magnetic surveying tools.

The quality of these measurements significantly depends on the properties of the geomagnetic field (GMF) and the intensity of geomagnetic disturbances (GMDs), which are governed by space weather variations (Soloviev, 2024; Gvishiani et al., 2015; Kudin et al., 2024).

Table 1. Typical Metrological Characteristics of Magnetic Surveying Tools (Vorobev et al., 2017).

X_{basic} for Zenith Angle Measurement (Measurement Range)	X_{basic} for Azimuth Angle Measurement at θ > 3° (Measurement Range)	Temperature-Induced Error (Temperature Range)
±0.25° (from 0 to 180°)	±1.6° (from 0 to 360°)	$\pm 0.1 \cdot X_{basic}$ /10°C (from –10 to 120°C)

Cite this article: Vorobev, A.V., & Vorobeva, G.R., (2026). Geomagnetic Disturbance Impact on Magnetic Survey Tool Errors in High-Latitude Directional Drilling. *Journal of the Earth and Space Physics*, 51(4), 65-73. DOI: http//doi.org/10.22059/jesphys.2026.404857.1007734

E-mail: (2) gulnara.vorobeva@gmail.com

Publisher: University of Tehran Press.
DOI: http//doi.org/10.22059/jesphys.2026.404857.1007734

Print ISSN: 2538-371X
Online ISSN: 2538-3906

It is well-established that the highest risks associated with the adverse effects of space weather on magnetometric systems occur within the auroral ovals – zones surrounding the Earth's magnetic poles (Vorobev et al., 2022; Vorobev et al., 2024; Pilipenko et al., 2023). In these regions, GMDs, caused by the interaction of the solar wind with the Earth's magnetosphere, can induce extreme additional errors in magnetic surveying tools during the measurement of both zenith and azimuthal angles (Yang et al., 2023).

The primary physical cause of such errors is the distortion of the geomagnetic field vector at the measurement point. In high-latitude regions, these distortions are caused not so much by crustal magnetic anomalies, but by intense currents in the ionosphere (e.g., the electrojet), particularly during magnetic storms and sub-storms. These factors lead to a deviation of the actual GMF declination and inclination from the values predicted by global models like the IGRF, which is the direct cause of errors in calculating the wellbore azimuth.

This problem becomes particularly acute in high-latitude regions during periods of maximum solar activity. This is especially critical given that the Russian Arctic Zone holds approximately 30% of the world's hydrocarbon reserves. The issue is further exacerbated by the growing proportion of complex wells with high deviation from vertical (the projected share of such wells may reach ~60% by the end of 2025 (Zhang et al., 2024)), coupled with the limited applicability of standard global magnetic field models (such as IGRF (Beggan et al., 2021)) under extreme geomagnetic activity. Despite these challenges, expert estimates suggest that by 2050, 20–30% of Russian hydrocarbon production will come precisely from Arctic resources. Therefore, minimizing risks during the development of the Arctic shelf becomes a strategic priority (Kovalev et al., 2025).

Known methods for error mitigation, such as the use of hybrid surveying systems and real-time geomagnetic monitoring, can, to a certain extent, compensate for the arising angular measurement errors (Yang et al., 2024). However, these approaches are typically reactive in nature and do not allow for the advance quantitative assessment of the probability of extreme errors caused by the specific distribution of ionospheric currents in the polar cap and within the auroral oval.

Therefore, despite existing developments in magnetic interference compensation, proactive methods based on extreme value statistics and predictive risk assessment remain underdeveloped. The objective of this research is to develop statistical models that enable a probabilistic assessment of the occurrence of extreme errors based on the analysis of historical GMD data.

2. Sources of Additional Error in Magnetic Surveying Tools

Wellbore surveying typically involves measurements of the zenith angle (i.e., the angle between the tangent to the wellbore axis at a given point and the vertical passing through that point) and the azimuthal angle (i.e., the angle between the wellbore plane and the meridian plane) as functions of depth. These measurements are performed using surveying tools with either continuous or stationary measurement modes.

The *X*, *Y*, and *Z* coordinates of points along the wellbore axis are calculated from grid directions. This requires applying corrections for magnetic declination (*D*) and meridian convergence (γ) to the measured magnetic azimuths.

$$\alpha = A_i + \gamma, \tag{1}$$

where α is the grid direction (from the grid north meridian), A_i is the true azimuth ($A_i = A_m + D$, where A_m is the magnetic azimuth, and D is the magnetic declination), and γ is the meridian convergence angle.

The angular elements D [°] and I [°] are functions of the local geomagnetic field (GMF) components and are determined by the following expressions:

$$D = \arctan\left(\frac{B_Y}{B_X}\right); \tag{2}$$

$$I = \arctan\left(\frac{B_Z}{\sqrt{B_X^2 + B_Y^2}}\right), \tag{3}$$

where B_X, B_Y, and B_Z are the north, east, and vertical components of the GMF induction vector, respectively, measured in nT.

Under normal conditions, the primary source of error in surveying systems is instrumental error, which is specified in the technical documentation. However, in a changing external environment, an additional error (X_{add}) arises due to the deviation of influencing quantities from their normal values

$$X = X_{\text{basic}} + X_{\text{add}}, \quad (4)$$

where X, X_{basic}, and X_{add} are the total, basic, and additional errors of the magnetic surveying system, respectively.

Regulatory standards stipulate that normal measurement conditions are those under which the contribution to the total error from the combined effect of influencing quantities should not exceed 35% of the permissible limit of the basic error of the measuring instrument:

$$0.35 \cdot X_{\text{basic}} \leq X_{\text{add}}; \quad (5)$$

$$X_{\text{add}} = \sum_{i=1}^{n} X_{\text{add}i}, \quad (6)$$

where n is the number of factors contributing to the additional error of the magnetic surveying tool.

According to the technical instruction for geophysical research and wireline logging in oil and gas wells, the permissible basic error for zenith angle measurement is no more than ±0.5°, and for azimuthal angle measurement (for zenith angles greater than 3°) it is no more than ±2.0°.

For instance, it is known that additional errors in zenith angle measurement caused by changes in supply voltage or ambient temperature (per 10°C change from 20°C) should not exceed $0.2{\cdot}X_{\text{basic}}$ and $0.1{\cdot}X_{\text{basic}}$, respectively. Despite the direct dependence of measurement quality on the stability of the local GMF, official sources provide no information on the permissible level of its variations.

It is important to note that in the auroral zone, GMDs (due to the intensification of ionospheric currents, particularly the westward electrojet) primarily affect the horizontal component of the GMF. Since magnetic declination is a function of the ratio of east and north field components (Equation 2), even minor variations in these quantities, characteristic of sub-storms, cause significant angular deviations in *D*. In contrast, magnetic inclination is determined by the ratio of the stable vertical component to the total horizontal intensity of the magnetic field (Equation 2). Because the *Z*-component is dominant at high latitudes and less susceptible to relative changes, variations in I during disturbances are an order of magnitude smaller than the fluctuations in declination. For this reason, the subsequent analysis will focus on variations in the additional error of magnetic declination under the influence of geomagnetic activity (GMA) in the auroral zone.

3. Initial Data and Preprocessing

This study utilized geomagnetic time series from 2004-2005 (the declining phase of solar cycle 23) obtained from 12 magnetic observatories located in the auroral and sub-auroral zones, within a geomagnetic latitude range of approximately ~64°–73° (Figure 1, Table 2).

Access to the geomagnetic data was provided by the SuperMAG project, a global initiative that collaborates with leading scientific organizations in the field of Earth's magnetism (Gjerloev et al., 2012). SuperMAG currently provides access to minute and second resolution measurements from over 500 magnetic observatories and variometer stations, making it one of the most comprehensive and widely used sources of information on GMF dynamics.

Figure 1. Geographical distribution of the geomagnetic observatories used in this study.

For each station, reference values of magnetic declination (D_{IGRF}) were calculated using the 12th generation IGRF model (Thébault et al., 2015) and used subsequently as benchmarks.

The following metric was used in this work to assess the potential additional error of magnetic surveying tools:

$$\Delta D = |D - D_{IGRF}| \quad (7)$$

where D is the magnetic declination value recorded by the magnetic observatory, and D_{IGRF} is the magnetic declination value calculated using the IGRF model (for the epoch corresponding to the time of the *D* measurement), adopted in this work as the reference value.

Table 3 presents the results of the data completeness assessment for the 12 stations shown in Figure 1 (Vorobev et al., 2022). Analysis of gaps in the geomagnetic time series revealed a total of 11.34% missing values. These missing data points were excluded from the final dataset. Consequently, the number of elements in set *S*, which contains informative geomagnetic data points synchronously recorded by all magnetic stations (Equation 6) for each observed parameter, amounts to 133,212 values.

$$|S| = \cap S_X \text{ for } X \in \{\text{ABK, DIK, CCS, TIK, PBK, BRW, CMO, YKC, FCC, PBQ, NAQ, LRV}\} \quad (8)$$

Table 2. Geomagnetic Data Sources.

o.	IAGA Code	Magnetic Observatory	Geographic Coordinates		Geomagnetic Coordinates		Magnetic Declination D_{IGRF}	Magnetic Inclination I_{IGRF}
			Lat_N	Lng_E	Lat_N	Lng_E		
1	ABK	Abisko	68.35°	18.82°	65.2°	101.48°	5.725°	77.441°
2	DIK	Dixon	73.53°	73.53°	68.74°	156.03°	29.784°	84.281°
3	CCS	Chelyuskin	77.72°	104.28°	72.30°	175.81°	16.026°	87.155°
4	TIK	Tixie	71.59°	128.92°	66.18°	-162.07°	-17.142°	82.879°
5	PBK	Pebek	70.08°	170.90°	65.21°	-129.62°	-0.502°	78.464°
6	BRW	Barrow	71.32°	-156.62°	69.99°	-107.63°	20.984°	80.742°
7	CMO	College	64.87°	-147.86°	64.87°	-95.06°	22.816°	77.156°
8	YKC	Yellowknife	62.48°	-114.48°	69.13°	-58.42°	21.673°	81.464°
9	FCC	Fort Churchill	58.76°	-94.09°	67.90°	-31.49°	-1.520°	81.468°
10	PBQ	Poste de la Baleine	55.28°	-77.74°	65.25°	-0.96°	-18.286°	78.322°
11	NAQ	Narssarssuaq	61.16°	-45.44°	65.61°	42.91°	-27.143°	76.131°
12	LRV	Leirvogur	64.18°	-21.70°	64.64°	66.35°	-17.354°	75.616°

*Note: Quasi-dipole geomagnetic coordinates and reference values for magnetic declination and inclination are provided according to the IGRF model for epoch 2005.0.

Table 3. Completeness Analysis of the Geomagnetic Time Series.

No.	IAGA Code	T_F [min]	T_F[%]	N_{TF}	<*tf*1>[min]	Me(*tf*1)[min]
1	ABK	133	0.010	8	16.62	5.00
2	DIK	591329	56.17	330	1791.91	10.0
3	CCS	196306	18.649	931	210.85	12.0
4	TIK	35548	3.377	40	888.70	7.00
5	PBK	467005	44.37	736	634.52	6.00
6	BRW	16340	1.552	150	108.93	12.0
7	CMO	8521	0.809	114	74.75	12.0
8	YKC	80374	7.635	149	539.42	5.00
9	FCC	5170	0.491	34	152.06	4.50
10	PBQ	33806	3.212	61	554.20	11.0
11	NAQ	86	0.008	18	4.78	4.00
12	LRV	293	0.028	18	16.28	4.00

*Note: *T* = 1,052,640 min (731 days); T_F – number of missing values; N_{TF} – number of data gaps; 〈*tf*1〉 – mean gap duration; Me(*tf*1) – median gap duration.

Subsequently, the parameters $|\Delta D_{\max}|$ and $|\Delta D_{\text{mean}}|$ were calculated according to expressions in Equation (9):

$$|\Delta D_{\max}|_i = \max(|\Delta D|_i)\,; \quad |\Delta D_{\text{mean}}|_i = \frac{1}{N}\sum_{j=1}^{N}|\Delta D|_j \tag{9}$$

where ΔD represents the set of magnetic declination deviations from the corresponding reference value, synchronously recorded by all N=12 stations (Table 2) at the i-th time instant.

4. Statistical Analysis of Potential Additional Error in Magnetic Surveying Tools

To assess risks in high-latitude directional drilling, it is necessary to determine the statistical characteristics of the additional error in magnetic surveying tools caused by GMDs. Proper accounting for the "heavy tails" of the distribution is particularly important, as their underestimation can lead to an undervaluation of the probability of extreme events critical for drilling safety.

Figure 2 shows the distribution of the absolute potential average ($|\Delta D_{\text{mean}}|$) and maximum ($|\Delta D_{\max}|$) additional error in azimuthal angle measurement. Statistical analysis of the approximating functions using the Kolmogorov-Smirnov test (Daniel, 1990) showed that the values of $|\Delta D_{\text{mean}}|$ and $|\Delta D_{\max}|$ are best described by a lognormal distribution (Equation 10), which is consistent with previously obtained results.

$$\text{PDF}(x,s) = \frac{1}{sx\sqrt{2\pi}}\exp\left(-\frac{\log^2(x)}{2s^2}\right); \tag{10}$$

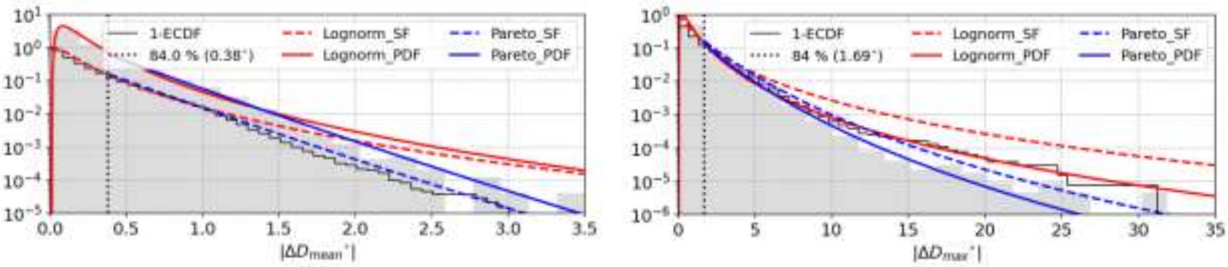
where s is the shape parameter (s = 0.87 for $|\Delta D_{\text{mean}}|$ and s = 1.02 for $|\Delta D_{\max}|$).

The quantile ratio method was applied to analyze the distribution tails (Farcomeni and Geraci, 2024). The tail boundary was defined at the 84th percentile, corresponding to the point where the empirical data begin to deviate significantly from the lognormal model. The Pareto distribution (11) provides the best approximation for the "heavy tails" (Figure 2, blue lines). Consequently, reliance solely on the mean values of $|\Delta D_{\text{mean}}|$ and $|\Delta D_{\max}|$ (0.23° and 0.99°, respectively) is statistically unjustified, and the probabilities of extreme deviations must be considered. For example, with a probability of 1%, $|\Delta D_{\text{mean}}| \geq 1.13°$ and $|\Delta D_{\max}| \geq 5.67°$. Given that this study covers only the declining phase of the solar cycle, it can be expected that the magnitude of extreme errors will be higher during solar maximum. A quantitative assessment of this effect requires a separate investigation.

$$\text{PDF}(x,c) = {(cx_m^c)}\Big/{(x^{c+1})}, \tag{11}$$

where c> 0 is the shape parameter (c = 57.6 for $|\Delta D_{\text{mean}}|$ and c = 9.1 for $|\Delta D_{\max}|$), and $x \geq x_m$ (where x_m is the minimum value of the random variable).

Figure 3 shows the diurnal variation of $|\Delta D_{\max}|$, revealing two distinct maxima – morning and evening. This pattern is the characteristic of GMA at high latitudes and is attributed to the asymmetry of large-scale magnetospheric convection and the drift dynamics of charged particles.



(a) (b)

Figure 2. Statistics of the magnetic declination measurement error within the auroral oval at the Earth's surface. The solid and dashed red lines correspond to the Probability Density Function (PDF) and Survival Function (SF) of the lognormal distribution, respectively. The solid and dashed blue lines correspond to the PDF and SF of the Pareto distribution, respectively. The solid black line corresponds to the empirical survival function (1-ECDF, where ECDF – Empirical Cumulative Distribution Function).

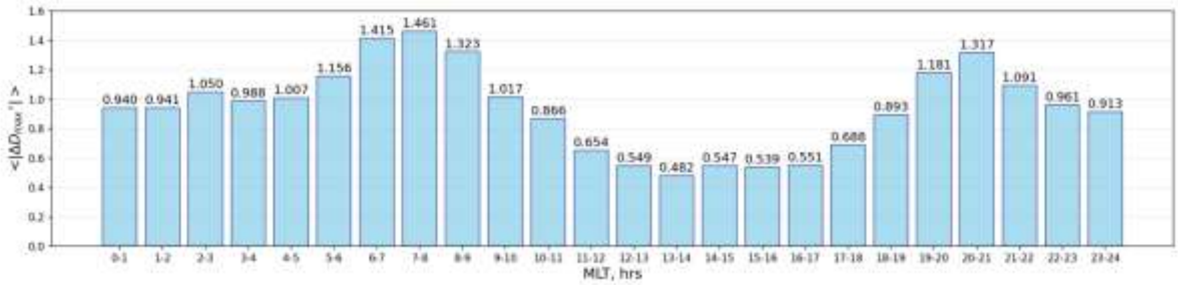


Figure 3. Diurnal variation of the potential additional error of magnetic surveying tools during azimuthal angle measurement in the auroral zone.

The presence of these maxima suggests that critical drilling operations should be scheduled during periods of minimum error, such as the afternoon hours.

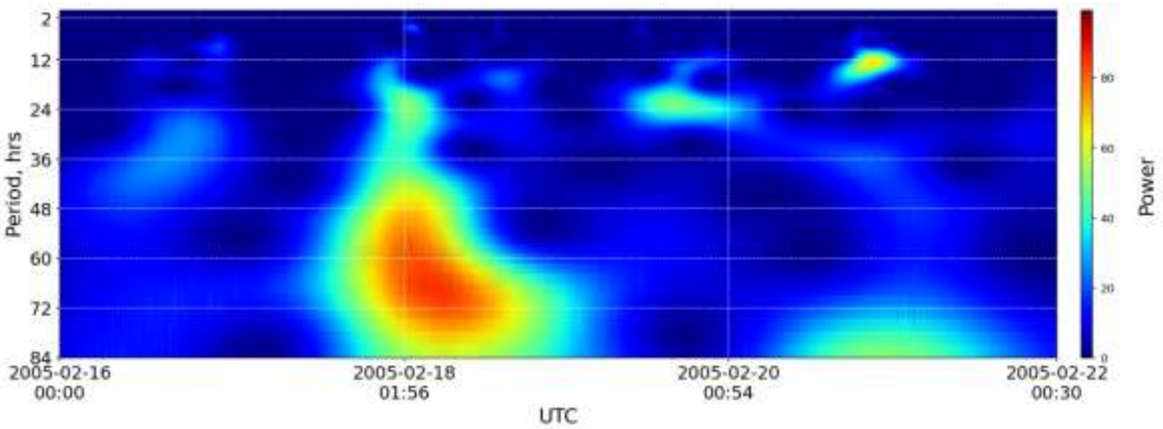
Figure 4a presents the wavelet periodogram of the $|\Delta D_{max}|$ parameter for the period from 2005-02-16 (00:00 UT) to 2005-02-23 (00:00 UT). This interval was selected as the most extensive continuous fragment with synchronous data from all 12 stations (see Table 3). The pattern of frequency packets, in addition to the factors considered earlier, may indicate a direct response of the measurement error to large-scale solar wind structures, particularly the sector structure of the interplanetary magnetic field (IMF) and associated shock waves. For comparison, Figure 4b shows the wavelet scalogram of the Dst-index for the same period.

5. Discussion

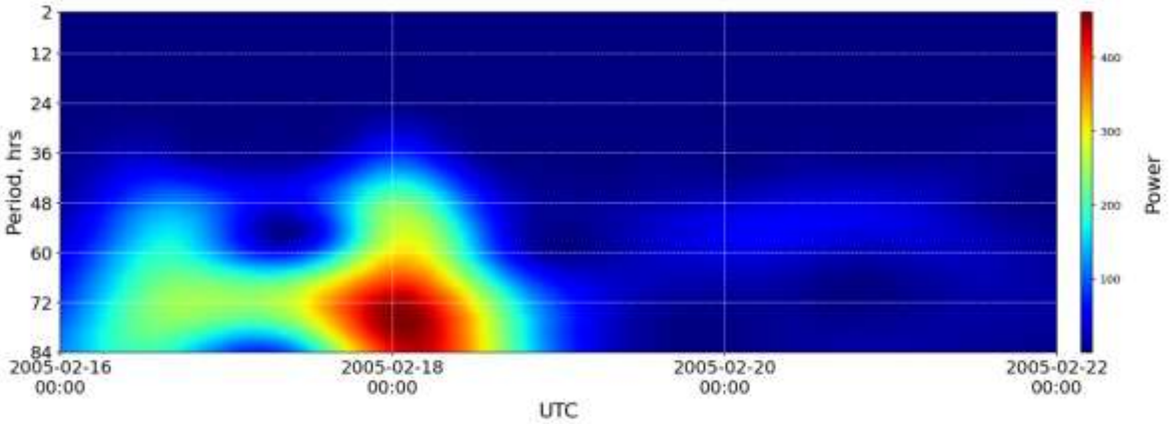
The observed lognormal distribution of $|\Delta D|$ errors is consistent with the hypothesis of their multiplicative nature, where the resultant error is the product of multiple factors related to ionospheric dynamics. In other words, this distribution suggests a complex process where random variations are proportional to the current state of the system. Within the context of this study, such variations may include local sub-storm activity, characterized by episodes of exponential growth in GMF induction governed by numerous stochastic factors, as well as large-scale solar wind structures, particularly the sector structure of the interplanetary magnetic field (IMF) and its associated shock waves.

Conversely, the heavy tails characterized by the Pareto distribution indicate the presence of extreme events. Typically, such a distribution signals that the system is in a critical state where even minor events can trigger processes leading to errors exceeding 31.8° (Figure 3). During solar maximum periods, the additional error is expected to substantially exceed this value.

When calibrating and verifying magnetic surveying tools, it is necessary to consider that the resultant level of additional error will also include components determined by variations in power supply voltage and ambient temperature. This situation imposes additional constraints on the conditions and timing of such metrological tests.



(a)



(b)

Figure 4. Wavelet analysis (periodograms) of time series for the period 2005-02-16 – 2005-02-23: (a) potential additional azimuthal error (|ΔDmax|) across the auroral observatory network; (b) the geomagnetic disturbance storm time (Dst) index.

The seasonal and 11-year variations of the additional error for magnetic surveying tools operating in the Russian Arctic Zone require further investigation. However, by analogy with the occurrence of extreme geomagnetically induced current (GIC) values in high-latitude power transmission lines (Švanda et al., 2021; Marshall et al., 2021), it can be hypothesized that the highest deviations of the additional error will be concentrated around local midnight during the spring and autumn equinoxes (Kataoka and Ngwira, 2016), which is explained by the specific configuration of the GMF relative to the interplanetary magnetic field.

The present study has two key limitations. First, the analysis is based on data from the declining phase of the solar cycle. Since the intensity of geomagnetic disturbances is highly dependent on the solar cycle phase, the quantitative estimates obtained should be considered a lower bound for periods of high solar activity. Second, the study assumes that the error recorded on the surface (Δ*D*) is equivalent to the error within the wellbore. While this assumption is reasonable for a first-order assessment, it does not account for the potential shielding effect of the surrounding rock formations. Quantifying this effect represents a separate and complex challenge. Furthermore, it should be noted that due to the substantial number of data gaps (Table 3), the analyzed sample contained only 133,212 values, constituting approximately 12.66% of the theoretically possible data volume for the study period. More complete datasets might slightly adjust the results presented here.

In the future, the $|\Delta D_{mean}|$ and $|\Delta D_{max}|$ metrics could potentially be utilized as specialized indices of geomagnetic activity, reflecting the degree of impact of geomagnetic disturbances on magnetometric equipment.

6. Conclusions

The statistical analysis of minute-resolution data from high-latitude magnetic observatories for the period 2004-2005 has yielded the following key results:

The analysis established that the error distribution followed a composite law. It was shown that the distribution of the absolute additional error in magnetic declination measurement (|ΔD|) during disturbed periods followed a lognormal law. This indicated a multiplicative nature of error formation, where its magnitude results from the product of numerous random factors, likely associated with the dynamics of ionospheric currents during magnetic storms and substorms.

It was found that the tails of the empirical distributions (~16% of the total sample) were characterized by a Pareto distribution. This indicated the presence of heavy tails and a high risk of extreme deviations, triggered by processes of intense energy release in the magnetosphere, such as magnetic reconnection.

It was demonstrated that the additional error of magnetic declination in the auroral zone did not follow a normal distribution. It was established that its main body was described by a lognormal law, while the extreme deviations (~16% of the sample) obeyed a Pareto distribution.

This fundamental observation enables the development of a probabilistic model for proactive risk assessment. Specifically, there is a 1% probability that the additional error can exceed 5.67°, even during the solar activity declining phase. The obtained results lay the foundation for creating decision support systems, planning drilling operations, and developing stricter metrological requirements for equipment operating in high-latitude regions.

Prospects for future research primarily involve refining the models by accounting for the seasonal variation of geomagnetic activity, integrating satellite data, and developing methods for short-term forecasting of extreme errors based on them. It also seems worthwhile to investigate the potential of using $|\Delta D_{mean}|$ and $|\Delta D_{max}|$ metrics as specialized indices of geomagnetic activity, reflecting the degree of influence of geomagnetic disturbances on magnetometric equipment.

Acknowledgments

This research was supported by the Russian Science Foundation (Project No. 21-77-30010-P)

References

Beggan, C. D., Brown, W. J., Cox, G. A., et al. (2021). The BGS candidate models for IGRF-13 with a retrospective analysis of IGRF-12 secular variation forecasts. *Earth, Planets and Space*, 73, 42. https://doi.org/10.1186/s40623-020-01301-3

Chang, J. L., & Jung, K. L. (2025). Highly accurate accelerometer- and magnetometer-based elevation and azimuth estimation procedure under stationary conditions. *Journal of Sensor Science and Technology*, 34(1), 8–18. https://doi.org/10.46670/JSST.2025.34.1.8

Daniel, Wayne W. (1990). Kolmogorov–Smirnov one-sample test. Applied Nonparametric Statistics (2nd ed.). Boston: PWS-Kent. pp. 319–330.

Farcomeni, A., & Geraci, M. (2024). Quantile ratio regression. *Statistics and Computing*, 34, 94. https://doi.org/10.1007/s11222-024-10406-8

Gjerloev, J. W. (2012). The SuperMAG data processing technique. *Journal of Geophysical Research: Space Physics*, 117(A9), A09213. https://doi.org/10.1029/2012JA017683

Gvishiani, A., Lukianova, R., & Soloviev, A. (2015). Geomagnetic field analysis and directional drilling problem in the Arctic region. *GornyiZhurnal*, (10), 94–99. https://doi.org/10.17580/gzh.2015.10.17

Kataoka, R., & Ngwira, C. (2016). Extreme geomagnetically induced currents. Progress in Earth and Planetary Science, 3, 23. https://doi.org/10.1186/s40645-016-0104-7

Kovalev, D. V., Vorobev, A. V., Valchuk, A. S., et al. (2025). Assessment of the Effects of Space Weather on the Reliability of Readings of Magnetic Inclinometers. *Cosmic Research*, 63(6), 582–590.https://doi.org/10.1134/S001095252560177X

Kudin, D. V., Gvishiani, A. D., Nikitina, L. V., et al. (2024). Storage and processing of big data for geomagnetic support of directional drilling. Applied Sciences, 14(21), 9730. https://doi.org/10.3390/app14219730

Marshall, R. A., Smith, E. A., Francis, M. J., Waters, C. L., &Sciffer, M. D. (2021). A preliminary risk assessment of the Australian region power network to space weather. *Space Weather*, 19(9), e2021SW002925. https://doi.org/10.1029/2021SW002925

Pilipenko, V. A., Chernikov, A. A., Soloviev, A. A., Yagova, N. V., Sakharov, Y. A., Kudin, D. V., Kostarev, D. V., Kozyreva, O. V., Vorobev, A. V., & Belov, A. V. (2023). Influence of space weather on the reliability of the transport system functioning at high latitudes. *Russian Journal of Earth Sciences*, 23(2), 1–34. https://doi.org/10.2205/2023ES000824

Soloviev, A. A. (2024). Geomagnetic support for directional drilling. *Herald of the Russian Academy of Sciences*, 94(10), 885–891. https://doi.org/10.31857/S0869587324100023

Švanda, M., Smičková, A., &Výbošťoková, T. (2021). Modelling of geomagnetically induced currents in the Czech transmission grid. *Earth, Planets and Space*, 73, 229. https://doi.org/10.1186/s40623-021-

01552-8

Thébault, E., Finlay, C. C., Toh, H., et al. (2015). International Geomagnetic Reference Field: the 12th generation. Earth, Planets and Space, 67, 158. https://doi.org/10.1186/s40623-015-0228-9

Vorobev, A. V. (2017). Assessment of the influence of geomagnetic activity on the metrological characteristics of inclinometric information-measuring systems. *Izmeritel'naya Tekhnika*, (6), 21–24.

Vorobev, A. V., Lapin, A. N., Soloviev, A. A., & Vorobeva, G. R. (2024). An approach to interpreting natural indicators of the state of space weather to assess the effects of its impact on high-latitude power systems. *Izvestiya*, *Physics of the Solid Earth*, (4), 100–110. https://doi.org/10.31857/S0002333724040071

Vorobev, A. V., Soloviev, A. A., Pilipenko, V. A., & Vorobeva, G. R. (2022). Interactive computer model for aurora forecast and analysis. *Solnechno-Zemnaya Fizika*, 8(2), 93–100. https://doi.org/10.12737/szf-82202213

Vorobev, A., Soloviev, A., Pilipenko, V., Vorobeva, G., & Sakharov, Y. (2022). An approach to diagnostics of geomagnetically induced currents based on ground magnetometers data. *Applied Sciences*, 12(3), 1522. https://doi.org/10.3390/app12031522

Yang, C., Zeng, Q., Xiong, Z., & Yang, J. (2024). IMU/Magnetometer-based azimuth estimation with norm constraint filtering. *Sensors*, 24(10), 2982. https://doi.org/10.3390/s24102982

Yang, J., Cai, J., & Wang, S. (2024). Online compensation of geomagnetic measurement errors while drilling. *IEEE Transactions on Instrumentation and Measurement*, 73, 1–9. https://doi.org/10.1109/TIM.2024.3379082

Zhang, Y., Msangi, S., Edmonds, J., & Waldhoff, S. (2024). Limited increases in Arctic offshore oil and gas production with climate change and the implications for energy markets. *Scientific Reports*, 14, 6699. https://doi.org/10.1038/s41598-024-54007-x