91

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APPLICATION OF GEOMAGNETIC MEASUREMENTS IN DETERMINING COMPENSATION AREAS AT MILITARY AERODROMES IN THE REPUBLIC OF SERBIA

Abstract:

Knowledge of geomagnetic characteristics, particularly magnetic declination, is essential for aviation safety, and military operations. This paper presents the methodology and results of geomagnetic surveys conducted at military aerodromes in the Republic of Serbia using the EDA DIM 100 declination–inclination magnetometer paired with a Carl Zeiss Theo 020 theodolite (DIM instrument). Absolute measurements were carried out following international standards defined by the International Association of Geomagnetism and Aeronomy (IAGA), including multiple series of observations to mitigate short-term geomagnetic variations. The paper demonstrates the practical implementation of fluxgate-theodolite systems in calibration areas and highlights the importance of magnetic hygiene, precise time registration in controlled environmental conditions. A constant secular fluctuation in magnetic declination congruent with accepted geomagnetic observation procedures is confirmed by the multi-epoch results obtained at the "Morava" military airport. Over 16.5 years, the declination increased from 3° 28.4′ in 2007.5 to 5° 17.8′ in 2024.0, resulting in a total shift of 1° 49.4′. This translates to an average annual change of roughly 7.18′ annually, which is consistent with Serbia's regional geomagnetic models and validates the accuracy of repeated surveys. Periodic re-surveys are required to avoid accumulated heading errors that could compromise navigation precision.

Keywords: Geomagnetic survey, compesation fields, magnetic declination, magnetometer

ПРИМЕНА ГЕОМАГНЕТНИХ МЕРЕЊА ПРИ ОДРЕЂИВАЊУ КОМПЕНЗАЦИОНИХ ПОВРШИНА ВОЈНИХ АЕРОДРОМА У РЕПУБЛИЦИ СРБИЈИ

Сажетак:

Познавање геомагнетних карактеристика, посебно магнетне деклинације, је од суштинског значаја за безбедност ваздушног саобраћаја и војних операција. У овом раду приказана је методологија и резултати геомагнетног премера реализованих на војним аеродромима у Републици Србији помоћу деклинационо-инклинационог магнетометра EDA DIM100 упареног са теодолитом Carl Zeiss Theo 020 (DIM инструмент). Апсолутна мерења су спроведена у складу са међународним стандардима дефинисаним од стране Међународног удружења за геомагнетизам и аерономију (IAGA), укључујући више серија опажања за ублажавање краткорочних геомагнетних варијација. У раду је приказана практична примена система флуксгејт DIM за потребе калибрације навигационих уређаја ваздухоплова при чему је наглашен значај магнетне хигијене, прецизне регистрације времена у контролисаним условима околине. Константна секуларна флуктуација магнетне деклинације у складу са прихваћеним процедурама геомагнетног премера потврђују резултати добијени из више епоха на војном аеродрому „Морава". Током 16,5 година, деклинација се повећала са 3° 28,4′ у 2007.5 на 5° 17,8′ у 2024,0, што је резултирало укупним повећањем од 1° 49,4′. То значи просечну годишњу промену од отприлике 7,18′, што је у складу са регионалним геомагнетним моделима Србије и потврђује тачност поновљених мерења. Потребна су периодична поновна мерења да би се избегле акумулиране грешке у правцу које би могле да угрозе прецизност навигације.

Кључне ријечи: Геомагнетни премер, компензационе површине, магнетна деклинација, магнетометар.

1. INTRODUCTION

The understanding of magnetic phenomena dates back to antiquity; however, systematic investigation of the Earth's magnetic field has become essential with the development of navigation, geodesy, and aviation. Today, knowledge of the geomagnetic characteristics of a specific area remains a matter of operational necessity rather than purely scientific interest. Among the elements of the Earth's magnetic field (see Figure 1), magnetic declination represents one of the most operationally significant parameters [1].

Magnetic declination, defined as the horizontal angle between true (astronomical) north and magnetic north at a given location and time, plays a crucial role in navigation and orientation [1], [2]. In aviation, accurate knowledge of declination is directly related to flight safety and aircraft airworthiness. Aircraft magnetic compass systems require periodic verification and calibration, particularly at designated calibration areas located at aerodromes [3].

From a methodological standpoint, absolute geomagnetic measurements must be conducted in accordance with internationally accepted standards. The procedures for magnetic measurements and observatory practice are defined by the International Association of Geomagnetism and Aeronomy (IAGA), which established guidelines for repeat station surveys and absolute observations [4]. These standards define the principles of determining declination, instrument requirements, observation procedures, and data reduction to base values and epochs [5].

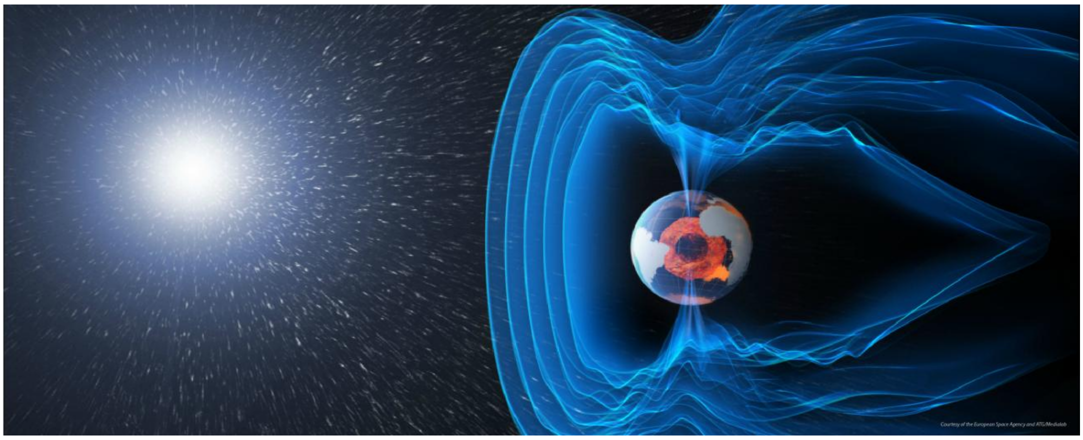

Figure 1. Representation of the Earth's magnetic field [6].

For more than five decades, the Military Geographical Institute "General Stevan Bošković" has conducted geomagnetic surveys for the needs of the Serbian Armed Forces. A significant portion of these activities includes surveys of magnetic compass calibration areas at military aerodromes. The primary objective is the determination of accurate magnetic declination values required for aircraft compass calibration and other operational applications where precise knowledge of the relationship between true and magnetic north is necessary [7].

Given the temporal variability of the Earth's magnetic field, known as secular variation, regular geomagnetic surveys and reduction of measured values to defined epochs are required to maintain the validity of geomagnetic documentation [8].

The Earth's magnetic field varies in both time and space; therefore, absolute measurements of its components are performed at defined time intervals. This vector field can be defined by three elements: declination (D), inclination (I), and total field intensity (F). Additionally, the horizontal component (H), vertical component (Z), and the north (X) and east (Y) components are used [9] (see Figure 2).

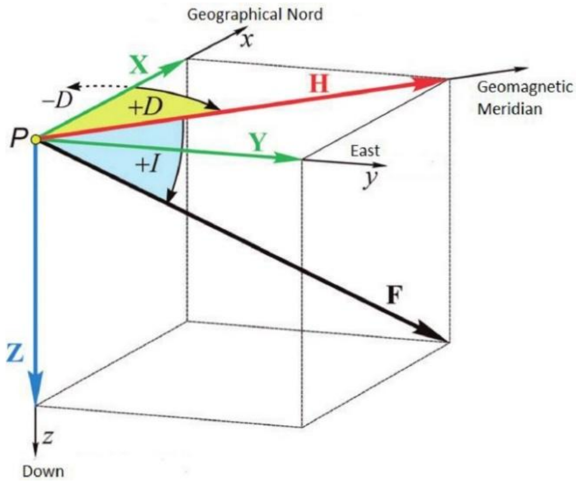

Figure 2. Elements of the Earth's magnetic field [10].

As shown in Figure 2, magnetic declination is the angle in the horizontal plane between the direction of astronomical (geographic) north and the direction of the magnetic meridian at the observation point [10].

2. MATERIALS AND METHODOLOGY

2.1. MAGNETIC COMPASS CALIBRATION AREA

A magnetic compass calibration area (compass swing area or compass calibration pad) is a designated surface located within or near a military or civil aerodrome and is used for the verification and calibration of aircraft navigation instruments.

Each aerodrome must possess official documentation (Geomagnetic Survey Report/Elaborate) representing a valid document with a maximum validity period of two years.

The selected location must meet the following basic requirements [3]:

- Homogeneity of the magnetic field;
- Sufficient distance from objects or devices emitting electromagnetic radiation (radio relay systems, high-voltage power lines and transformers, ferromagnetic objects, etc.);
- Suitability for conducting measurements (terrain configuration, personnel safety, accessibility for positioning aircraft during calibration).

The calibration area is designed according to the type of aircraft for which calibration will be performed. The only variable is the size of the calibration circle and the spacing between points.

The calibration circle consists of 25 points: one central point (usually designated A0) and three points along each principal and intercardinal direction (Figure 3). Points are labeled accordingly (e.g., N1, N2, N3 along the north direction; SW1, SW2, SW3 along the southwest direction).

Figure 3. Magnetic calibration area shown on satellite imagery (created by author).

2.2. INSTRUMENTS FOR MEASURING MAGNETIC DECLINATION

Magnetic declination represents the angle between the planes of the geographic (astronomical) and magnetic meridians at a given location and time. Its determination is reduced to calculating the difference between measured horizontal circle readings of astronomical and magnetic azimuths toward a fixed orientation point [1].

For this reason, the magnetometer used for absolute declination measurements is structurally based on a non-magnetic theodolite. A fluxgate sensor is mounted along the optical axis of the telescope to detect the direction of the magnetic meridian [11].

The Military Geographical Institute uses the EDA DIM 100 paired with the Carl Zeiss Theo 020 (see Figure 4).

a)

b)

Figure 4. a) DIM instrument EDA DIM 100; b) DIM instrument (photography by author).

2.3. METHOD OF DETERMINING MAGNETIC DECLINATION

Magnetic declination represents the angle between the planes of the geographic (astronomical) and magnetic meridians at a given location and time. Its determination is reduced to calculating the difference between measured horizontal circle readings of astronomical and magnetic azimuths toward a fixed orientation point [12].

The procedure includes:

- Metrological assurance of measuring equipment;
- Determination of magnetic field homogeneity;
- Determination of geographic azimuth;
- Absolute magnetic measurements using a declination–inclination magnetometer (DIM);
- Processing of measurement results and reduction of magnetic declination to base values and the selected epoch;
- Preparation of technical documentation.

2.4. DETERMINATION OF GEOGRAPHIC AZIMUTH

Before the widespread application of Global Navigation Satellite Systems (GNSS), geographic azimuth was determined by solar observations near the first vertical. This indirect method required precise timing and atmospheric corrections and was limited by daylight and weather conditions.

Today, the optimal method is GNSS positioning. Geographic azimuths are computed from obtained coordinates using the inverse geodetic problem. For this purpose, real-time kinematic (RTK) GNSS positioning relative positioning may be applied, such as RTK VRS (Virtual Reference Stations), supported in Serbia by AGROS (Active Geodetic Reference Network of Serbia). Observation duration per point is approximately 180 epochs, sufficient for centimeter-level accuracy.

2.5. MEASUREMENT OF MAGNETIC NORTH DIRECTIONS

Geomagnetic measurements are performed in two series at each point of the calibration area.

Before measurements, the instrument must satisfy specific requirements [9]:

- Magnetic cleanliness (<1 nT at 1 cm distance);
- Angular reading resolution of 0.1′ or better;
- Proper mechanical and optical adjustment of the theodolite;
- Stable magnetometer scale offset throughout the measurement series.

Magnetic contamination from vehicles, equipment, or personal metallic items must be avoided.

The accuracy of absolute magnetic declination measurements largely depends on the level of geomagnetic disturbances [7]. For this reason, it is essential that observations be conducted during magnetically quiet periods, i.e., when increased solar activity and geomagnetic storms are not present. Elevated geomagnetic activity may introduce short-term variations in the magnetic field that can significantly affect declination measurements [7]. Therefore, prior to fieldwork, it is recommended to verify whether a nearby geomagnetic observatory that distributes real-time data reports enhanced geomagnetic activity [8].

Geomagnetic measurements are performed by observing and reading horizontal circle values of the theodolite in four fluxgate sensor positions: “sensor up” oriented toward North (N) and South (S), and “sensor down” also oriented toward N and S. During the measurement of horizontal directions, precise Coordinated Universal Time (UTC) is recorded. UTC is typically obtained from reliable time servers (e.g., www.time.nist.gov). Although time can be recorded to the nearest second, minute-level time registration is generally sufficient for this purpose.

The obtained horizontal direction readings are averaged in order to eliminate the influence of non-parallelism between the fluxgate sensor and the telescope axis, as well as to compensate collimation error of the theodolite [8].

All readings are entered into the corresponding geomagnetic observation record, which is subsequently used for the computation of absolute magnetic declination values. Upon completion of measurements at all points of the calibration area, one measurement series is considered completed. As previously stated, declination measurements are typically performed in two series, preferably at different times of day (e.g., one in the morning and one in the afternoon), in order to minimize systematic effects and improve reliability [13].

After calculating the absolute declination values, they must be reduced to base values for the day of observation. The reduction data are obtained from the competent geomagnetic observatory. In the Republic of Serbia, this function is performed by the Centre for Aeronomy and Geomagnetism "Milutin Milanković" (GCK).

The reduction to the daily base value is performed according to [14]:

$$D_{red} = D_{abs} - [D_{obs(t)} - D_{obs,day}] \tag{1}$$

Let:

- $D_{abs}D$– measured absolute declination at time t.
- $D_{obs(t)}$– observatory declination at time t.
- $D_{obs,day}$– observatory daily mean declination.

This correction removes the short-period variation component and refers the measured value to the observatory daily mean [8].

Subsequently, the measured values are reduced to the selected epoch (reference year). In order to reduce absolute declination values to a given epoch, it is necessary to obtain mean monthly declination values from the geomagnetic observatory for a period covering six months before and six months after the selected epoch. For example, if measurements are reduced to epoch 2025.0, mean monthly declination values from July 2024 to July 2025 are required to ensure proper epoch reduction.

Because the Earth's magnetic field undergoes continuous secular variation, declination values must be reduced to a defined reference epoch (e.g., 2025.0) to ensure temporal consistency and comparability.

If:

- D_{red}– declination reduced to daily base value
- D_{epoch} – declination reduced to selected epoch
- ΔD_{sec} – secular variation between observation date and epoch

then:

$$D_{epoch} = D_{red} + \Delta D_{sec} \tag{2}$$

The secular variation term ΔD_{sec} is determined using mean monthly declination values from the reference observatory. For epoch reduction, monthly means for six months before and six months after the selected epoch are required. The epoch correction can be approximated as [15]:

$$\Delta D_{sec}=\Delta\delta \cdot \Delta t \tag{3}$$

where:

- $\Delta\delta$ – annual rate of change (arcminutes/year)
- Δt– time difference between observation date and selected epoch (in years)

or example, if the annual secular variation at the site is approximately 7.2′ per year and measurements are reduced to epoch 2025.0, the correction is computed proportionally to the fractional year difference (see Figure 5).

This procedure ensures that declination values presented in official geomagnetic reports are temporally harmonized and suitable for operational aeronautical use [5].

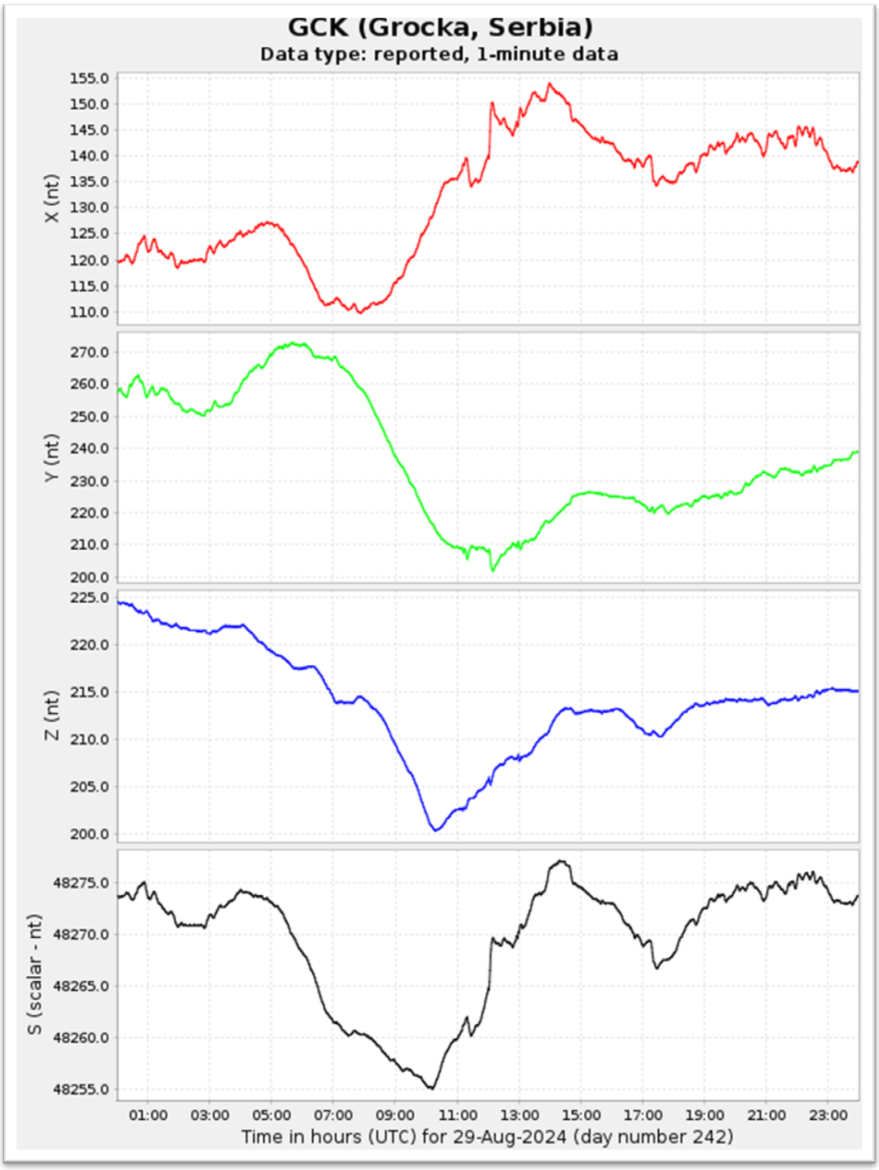

Figure 5. Daily Variations of Geomagnetic Field Components on 29 August 2024 [16].

3. RESULTS

The measurements of magnetic declination at each point of the calibration area (Table 1) indicate a high degree of spatial uniformity. The recorded values range from 5° 15.0′ at point S3 to 5° 20.4′ at point NE3, resulting in a maximum variation of 5.4′ across the entire calibration area. Considering the stated measurement uncertainty which is derivated from empiric standard deviation is $u_{d\_} = 1.2'$, represent about a 68% probability that the true declination at a measured point lies within ±1.2′ of the reported value. These relatively small variations confirming that the area is magnetically homogeneous, which is essential for aircraft compass calibration, where the required precision typically ranges between 0.3 to 0.5 arc degree.

Table 1. Magnetic Declination Values at Individual Points of the Calibration Area

Point ID	Magnetic Declination (° ′)	Point ID	Magnetic Declination (° ′)
A0	5° 18.3′	S1	5° 18.3′
N1	5° 18.7′	S2	5° 18.4′
N2	5° 17.2′	S3	5° 15.0′
N3	5° 18.0′	SW1	5° 18.0′
NE1	5° 17.8′	SW2	5° 18.2′
NE2	5° 18.2′	SW3	5° 17.4′
NE3	5° 20.4′	W1	5° 18.8′
E1	5° 17.6′	W2	5° 18.4′
E2	5° 18.4′	W3	5° 18.9′
E3	5° 17.7′	NW1	5° 16.8′
SE1	5° 17.8′	NW2	5° 17.9′
SE2	5° 15.2′	NW3	5° 18.3′
SE3	5° 15.1′		
Measurement Uncertainty:		**u_D = ± 1.2′ (k=1, standard uncertainty)**	

Mean magnetic declination of calibration area is 5° 17.8′. The central point (A0) has a declination of 5° 18.3′, which closely matches with mean value and with most peripheral points, indicating minimal localized anomalies. Slightly higher deviations are observed at NE3 (5° 20.4′) and lower values at SE2 (5° 15.2′) and SE3 (5° 15.1′). These deviations are within the expected range and generally may be caused by minor local ferromagnetic influences or soil heterogeneities [12].

The systematic arrangement of points along cardinal (N, E, S, W) and intercardinal axes (NE, SE, SW, NW) allows detailed mapping of the declination field. Such a layout ensures that all possible headings of an aircraft or navigation instrument can be checked against known magnetic declination values, enhancing the reliability of fluxgate-theodolite calibration procedures [4].

Overall, the dataset confirms that the Morava calibration area satisfies all criteria for a military aerodrome compensation field:

- Homogeneous magnetic field with variations within ±3′ of the mean declination.
- Central and peripheral points show minimal deviation, enabling consistent calibration across the area.
- The arrangement of 25 points (central plus peripheral axes) provides complete coverage for directional calibration test.

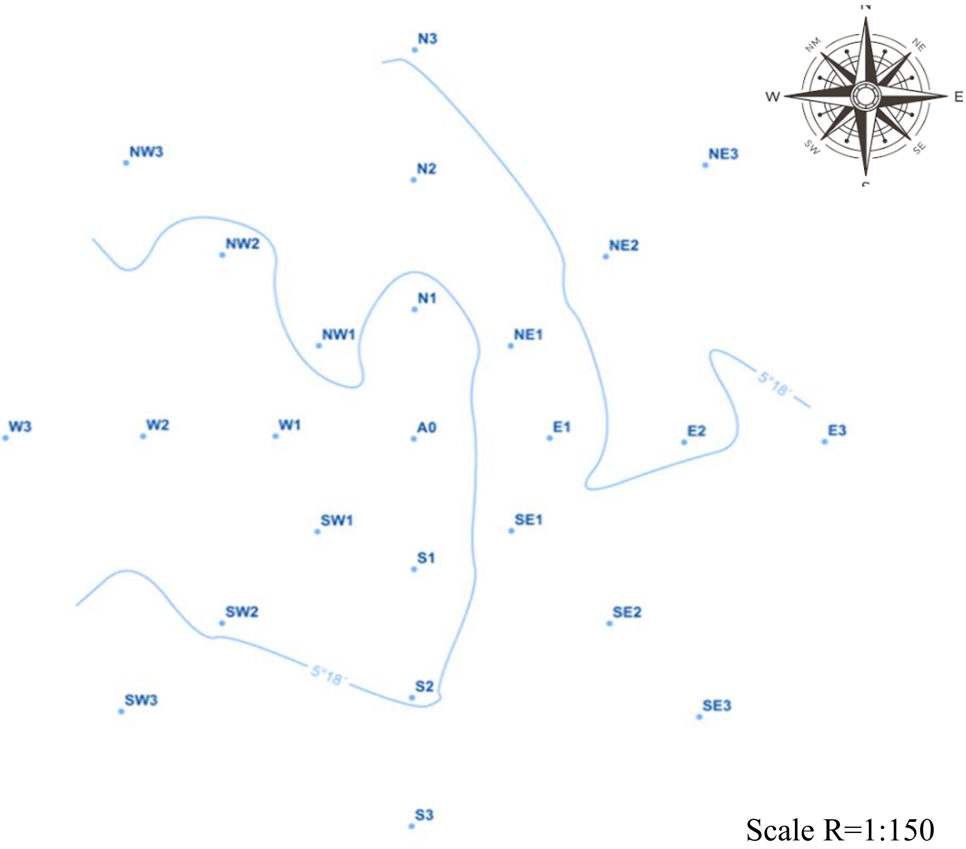

Figure 6. Map of the isogonic compensation surface for the military airport "Morava.", at scale R=1:150 (created by author).

Figure 6 shows a map of the isogonic compensation surface for the military airport "Morava." The map displays lines of equal magnetic deviation or compensation, which are used to correct navigational instruments at the airport. Isogonic lines indicate variations in the Earth's magnetic field and allow pilots and technicians to properly adjust compasses and other instruments to ensure accurate navigation [17].

Table 2 presents the magnetic declination measured at the calibration area for different epochs between 2007.5 and 2024.0. The values show a steady increase in declination over time, reflecting the secular variation of the Earth's magnetic field at this location [18].

Table 2. Absolute Magnetic Declination Values at the Calibration Area of “Morava”Aerodrome (2008–2024).

Epoch	Magnetic Declination (° ′)	Difference from Previous Epoch (′)
2007.5	3° 28.4′	–
2009.5	3° 42.4′	14.0′
2012.0	3° 56.4′	14.0′
2014.0	4° 11.7′	15.3′
2016.0	4° 22.0′	10.3′
2018.5	4° 38.6′	16.0′
2020.5	4° 54.4′	15.8′
2022.5	5° 05.5′	11.1′
2024.0	5° 17.8′	12.3′

The declination increased from 3° 28.4′ in 2007.5 to 5° 17.8′ in 2024.0, giving a total change of 1° 49.4′ over 16.5 years. This corresponds to an average annual change of approximately 7.18′ per year, which aligns closely with regional geomagnetic models for Serbia and confirms the reliability of repeated surveys.

While the overall trend is smooth, small differences between consecutive epochs are observed. For example, between 2014.0 and 2016.0 the change is 10.3′, whereas the largest observed difference, 16.0′, occurs between 2016.0 and 2018.5. These fluctuations may be attributed to short-term geomagnetic variations, measurement precision limits, or minor local magnetic anomalies.

The consistent long-term increase in declination demonstrates that the „Morava“ calibration area provides stable conditions for instrument calibration. By monitoring these changes, navigational instruments, including aircraft compasses and fluxgate systems, can be corrected for secular variation, ensuring accurate alignment with geographic north [2].

In conclusion, the table highlights the necessity of periodic geomagnetic surveys: they track secular variation, confirm homogeneity, and provide the data needed for precise calibration of navigation and orientation systems over time.

4. CONCLUSION

The geomagnetic survey of magnetic compass calibration areas represents a technically specialized and operationally significant activity within military aviation support. Accurate determination of magnetic declination ensures the reliability of aircraft navigation systems and contributes directly to aviation safety [3].

The applied methodology, based on absolute measurements using a declination–inclination magnetometer (DIM) combined with precise determination of geographic azimuth, follows internationally recognized standards for magnetic repeat station surveys [5]. Compliance with metrological requirements, magnetic hygiene procedures, and careful data processing is essential to achieve the accuracy necessary for operational use [10].

The results of the research in this article showed that the magnetic declination value changed by 1° 49.4′ during a period of 16.5 years, from 3° 28.4′ in 2007.5 to 5° 17.8′ in 2024.0. This translates to an average annual change of about 7.18′ annually, which is consistent with Serbia's regional geomagnetic models and validates the accuracy of repeated surveys.

The multi-epoch results obtained at the “Morava” military aerodrome confirm a continuous secular variation of magnetic declination consistent with established geomagnetic observation practices [8]. Considering that the annual change in declination at the study location is approximately 7′, periodic re-surveys are necessary to prevent cumulative heading errors that may affect navigation accuracy.

Therefore, systematic geomagnetic monitoring, strict adherence to international measurement standards, and timely reduction of observed values to defined epochs remain indispensable components of aeronautical safety and military geospatial support.

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