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Earth Sciences

Review article

The Fúquene National Geomagnetic Observatory: A journey through its past, present, and future

El Observatorio Geomagnético Nacional de Fúquene: un recorrido por su pasado, su presente y su futuro

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Abstract

This paper offers a comprehensive analysis of the Fúquene National Geomagnetic Observatory's pivotal role in the history of geomagnetic research and its renewed significance in the study of geomagnetism and space weather monitoring. Geomagnetism plays a crucial role in understanding Earth's magnetic field, its internal dynamics, and its interaction with solar activity, which can impact satellite operations, power grids, and communication systems. A key focus of the document is the recent upgrade of the observatory's equipment, which has significantly enhanced its ability to detect and analyze geomagnetic phenomena, especially as solar activity intensifies with the approach of Solar Cycle 25's peak. It also highlights the technical improvements to the observatory's measurement systems to increase accuracy and data collection frequency, as shown by the detection and monitoring of recent geomagnetic storms triggered by intense solar flares and coronal mass ejections, underscoring Fúquene's role in providing real-time data during major space weather events. With these upgrades, the observatory is poised to become an integral part of global networks like the International Real-time Magnetic Observatory Network-INTERMAGNET and a key reference for future research on solar-terrestrial interactions. Its enhanced capabilities will significantly advance geomagnetic modeling and space weather forecasting, particularly in regions near the magnetic equator, where the impact of solar activity is a source of increased interest.

Keywords: Geomagnetism; Space weather; Observatorio Geomagnético Nacional de Fúquene.

Resumen

Ofrecemos aquí un análisis detallado del papel crucial del Observatorio Geomagnético Nacional de Fúquene en la historia de la investigación geomagnética y su renovada importancia en el estudio del geomagnetismo y el monitoreo del clima espacial. El geomagnetismo desempeña un papel clave en la comprensión del campo magnético de la Tierra, sus dinámicas internas y su interacción con la actividad solar, la cual puede afectar las operaciones de los satélites, las redes eléctricas y los sistemas de comunicación. Un tema de especial interés es la reciente mejora en el equipamiento del observatorio, lo que ha incrementado significativamente su capacidad para detectar y analizar fenómenos geomagnéticos, especialmente a medida que la actividad solar se intensifica con el acercamiento al pico del Ciclo Solar 25. Se destacan, asimismo, las mejoras técnicas realizadas en los sistemas de medición del observatorio, lo que ha resultado en una mayor precisión y frecuencia en la recopilación de datos, lo que se evidencia en la detección y el monitoreo exitosos de recientes tormentas geomagnéticas provocadas por intensas erupciones solares y eyecciones de masa coronal, lo que resalta el papel del Observatorio de Fúquene en la provisión de datos en tiempo real durante

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eventos significativos del clima espacial. Con estas actualizaciones, el observatorio está en una posición ideal para convertirse en una parte integral de redes globales como INTERMAGNET y una referencia clave para la investigación futura sobre las interacciones entre el Sol y la Tierra. Sus capacidades mejoradas servirán para avanzar en el modelado geomagnético y las predicciones del clima espacial, especialmente en las regiones cercanas al ecuador magnético, donde el impacto de la actividad solar es una fuente de creciente interés.

Palabras clave: Geomagnetismo; Clima espacial; Observatorio Geomagnético Nacional de Fúquene.

Introduction

The study of geomagnetism has deep roots in the history of science, tracing back to ancient civilizations that observed the magnetic properties of naturally occurring materials such as lodestone. However, it was not until the 16th century that systematic investigations into the Earth's magnetic field (EMF) began, largely thanks to the pioneering work of scientists such as William Gilbert. In 1600, Gilbert published *De Magnete* (**Gilbert**, 1958), a seminal work in which he proposed that the Earth itself acts as a giant magnet. This laid the foundation for centuries of research aimed at understanding EMF's origins, behavior, and variations. Over the centuries, numerous breakthroughs have expanded our understanding of geomagnetism. In the early 19th century, Carl Friedrich Gauss developed the mathematical framework necessary for analyzing geomagnetic data, allowing for the quantification of the EMF and its variation over time. His work led to the establishment of the first geomagnetic observatories, such as those in Göttingen and Munich, which began continuous monitoring of magnetic variations (**Barraclough *et al.***, 1992).

In the mid-19th century, the discovery of geomagnetic secular variation (slow, long-term changes in the EMF) further advanced the field. Simultaneously, the connection between geomagnetic storms and solar activity, first identified by Richard Carrington during the 1859 solar storm, highlighted the dynamic relationship between the Sun and the Earth's magnetic environment. This event, known as the Carrington Event, demonstrated the potentially devastating effects of space weather on terrestrial technology, making it clear that understanding geomagnetic phenomena had practical as well as scientific significance (**Tsuratani *et al.***, 2003). By the 20th century, geomagnetic research had become a global effort, with the establishment of a network of geomagnetic observatories worldwide. These observatories, including the Fúquene National Geomagnetic Observatory (FUQ), established in 1953, began to contribute invaluable data to international geomagnetic models. The introduction of satellite technology in the latter half of the century allowed for the mapping of the EMF from space, offering a global view of geomagnetic processes and enhancing the accuracy of geomagnetic models such as the International Geomagnetic Reference Field (IGRF) (**Thébault *et al.***, 2015).

The importance of understanding the geomagnetic field

Geomagnetic observatories play a vital role in monitoring variations in the EMF caused by both internal sources (e.g., the Earth's core) and external sources (e.g., solar activity). The study of the EMF field is not only essential for understanding our planet's internal dynamics but also for investigating the complex interactions between the Earth and space. The geomagnetic field acts as a shield, protecting the Earth from harmful solar and cosmic radiation. It plays a crucial role in maintaining the habitability of the planet by preventing solar wind and charged particles from directly impacting the atmosphere. However, when this shield is disturbed, as during geomagnetic storms caused by solar flares or coronal mass ejections, the effects can be profound. The principles of space physics provide a framework for understanding the interactions between the geomagnetic field and solar wind (**Kivelson & Russell**, 1995).

Geomagnetic storms can disrupt communication systems, navigation satellites, and power grids, making geomagnetism a vital area of study for mitigating the risks posed by space weather. Additionally, understanding the geomagnetic field provides insight into the Earth's interior, particularly the dynamics of the liquid outer core, which generates the magnetic field through the geodynamo process. The study of geomagnetic secular variation and pole reversals also helps geophysicists explore the history of the EMF and its evolution over geological time scales. Thus, geomagnetism serves as a crucial bridge between Earth sciences and space physics, offering essential knowledge for both planetary studies and the emerging field of space weather. **Figure 1** shows the global distribution of geomagnetic observatories, including those that are part of the International Real-time Magnetic Observatory Network (INTERMAGNET), a global network of magnetic observatories that monitor and share data on the EMF. The observatories are densely clustered in Europe, North America, and parts of Asia, as shown in the figure. This reflects the historical concentration of scientific infrastructure and observatories in developed regions, especially during the 20th and 21st centuries. These areas have long traditions in geomagnetic monitoring and scientific research. The latitudinal distribution of geomagnetic variations and their relationship with circumpolar currents has been well-documented (**Pogrebnoi *et al.***, 2009). Near-Equatorial observatories are less common, although their placement is critical because the equatorial region is highly dynamic geomagnetically, where phenomena such as the Equatorial Electrojet (EEJ) occur (**MacDougall**, 1978). With its strategic location in the equatorial region, the FUQ has played an important role in this global effort to monitor and understand the Earth's magnetic environment and is due to contribute to both scientific advancement and practical applications in a world increasingly reliant on technology vulnerable to space weather phenomena.

Advancements in geomagnetic observatories in Latin America

During colonial times, geomagnetic research in Latin America was primarily limited to declination measurements used for cartography and defining territorial boundaries (**Barreto**, 2007). A notable early survey was conducted in 1700 by Edmond Halley, who produced a magnetic chart of the South Atlantic. However, significant geomagnetic exploration in the region did not resume until 1880, when Dutch scientist Van Rickjervosel carried out an extensive field survey along Brazil's coastline, which culminated in the publication of the first Brazilian magnetic chart. Since no permanent geomagnetic observatories existed at the time, these early efforts can be considered the prehistory of geomagnetic studies in Latin America.

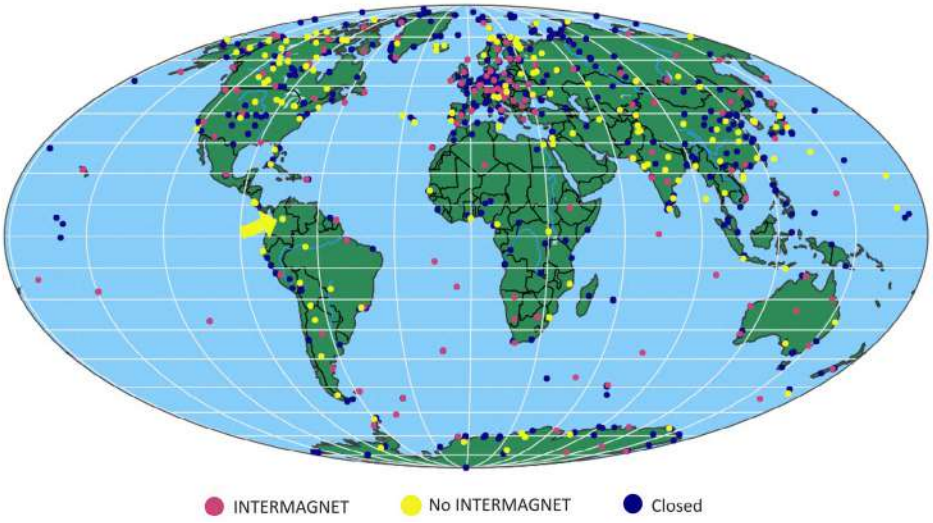

Figure 1. Global distribution of geomagnetic observatories, including those that are part of INTERMAGNET and those no longer operational, as labeled

In the first half of the 20th century, significant efforts were made by the Carnegie Institution of Washington, particularly through its Department of Terrestrial Magnetism, to advance the study of geomagnetism in South America. As part of this initiative, observatories were established in Perú and Argentina. Various countries also made local efforts, sometimes with the support of the Inter-American Geodetic Survey and the Pan-American Institute of Geography and History (PAIGH), to install additional observatories. This period of development spanned from 1920 to 1960, with the observatory in Costa Rica standing out as a prime example of international cooperation (**Randall**, 1989).

In recent decades, the Peruvian observatories at Huancayo and Ancón have benefited significantly from collaboration with Japanese institutions, particularly Tokyo University. Despite a promising start, however, some observatories eventually declined in quality, leading to the closure of several facilities. In 1980, the PAIGH launched a campaign, spearheaded by the National Observatory of Brazil, to reorganize and modernize geomagnetic observatories across Latin America. A key component of this campaign was the establishment of Latin American geomagnetic schools, which provided essential training for technicians and facilitated the installation of modern instruments. This initiative revitalized many previously inactive or underperforming observatories, transforming them into fully operational research centers (**Jankowski & Sucksdorff**, 1996).

International support played a crucial role in these advancements, notably through the efforts of two divisions of the International Association of Geomagnetism and Aeronomy (IAGA): Division V (focused on observatories, instruments, surveys, and analyses) and the Interdivision Commission on Developing Countries. Thanks to these collaborations, observatories such as those in Trelew, Argentina, and La Habana, Cuba, received state-of-the-art magnetic instruments, including digital fluxgate variometers and modern absolute instruments.

Besides the primary observatories mentioned, several variation stations (facilities where absolute observations are not conducted) operate for specific research projects. Some of the most important of these stations are located in Brazil, Perú, and México. The Latin American magnetic observatories play a critical role not only because of their broad latitudinal coverage, which spans a significant range of geomagnetic latitudes (from near the equator to the southern tip of the continent), but also because they monitor two significant geomagnetic phenomena: the EEJ and the South Atlantic magnetic anomaly. These observatories are vital for understanding geomagnetic variations and contributing to global geomagnetic research.

The evolution of geomagnetic research in Colombia

In the local context, geomagnetic research in Colombia has a long and evolving history, beginning with the early observations made during the expeditions of Alexander von Humboldt in the early 19th century. Von Humboldt, a renowned German naturalist and geographer, was one of the first scientists to systematically measure the EMF in the region during his travels through South America between 1799 and 1804. His measurements, taken with magnetic compasses and other instruments of the time, laid the foundation for the study of geomagnetism in the Colombian Andes and helped establish a global understanding of the EMF (**Jankowski & Sucksdorff**, 1996).

During his travels in the current Colombian territory, von Humboldt conducted some of the earliest geomagnetic measurements, particularly focusing on the Earth's magnetic declination, which is the angular difference between magnetic north and true north. His pioneering work included observations made in locations such as Bogotá and Popayán, contributing to early efforts to map the geomagnetic field across the continent. Von Humboldt's contributions were groundbreaking, as they provided data for what was then an emerging field of geomagnetic science, one that sought to understand the variations in the EMF and its global behavior. Linear magnetic anomalies in the Colombian Basin provide valuable insights into the region's tectonic and geomagnetic history (**Cristofferson**, 1973).

Overview of the Fúquene National Geomagnetic Observatory (FUQ)

The Fúquene National Geomagnetic Observatory, located in the department of Cundinamarca, Colombia, 130 kilometers north of Bogotá (**Figure 2**), is an institution of considerable scientific importance in the field of geomagnetic research. Established in 1953, the observatory was created as part of an international effort to better understand the EMF and its variations over time. Its establishment was driven by the need for a reliable station in the region to contribute to the global network of geomagnetic observatories. At the time, the increased interest in geomagnetic studies was largely influenced by the growing understanding of the connections between geomagnetic phenomena, solar activity, and their implications for technological systems such as telecommunications and navigation.

The observatory's location near Lake Fúquene was chosen strategically due to the area's relative geomagnetic stability and low interference from industrial activities. This location (**Figure 2**) also serves as a key reference point for the study and conservation of the Fúquene ecosystem. The construction of FUQ was part of a broader initiative of the IPGH (**Randall**, 1989), following the agreement of the Fourth Pan American Cartographic Consultation Meeting held in Buenos Aires in 1948, where the Instituto Geográfico Agustín Codazzi-IGAC was in charge of its creation.

Since its inception, the observatory has been equipped with highly specialized instruments to measure the EMF with great precision. This includes magnetometers, which record variations in the geomagnetic field, and other sensors designed to monitor magnetic anomalies and diurnal variations. Data from Fúquene has been used in a number of studies on geomagnetic storms, secular variations, and other space weather phenomena. The observatory's records have contributed to models of the EMF, such as the International Geomagnetic Reference Field (IGRF), which is used globally in various applications ranging from mineral exploration to satellite navigation.

The role of FUQ in monitoring equatorial geomagnetic variations

The FUQ has a very strategic geographic position since it is one of the few observatories located close to the dip equator (5°24′18″N), and its data is a significant contribution to understanding the global magnetic field (**Medina *et al.***, 2012). Fúquene's equatorial proximity allows it to capture key electromagnetic phenomena, making it valuable for the study of the EMF and its variations. Equatorial electromagnetic phenomena, such as the EEJ, the solar quiet variation (Sq), the ring current, and geomagnetic storms, are often analyzed by comparing data from pairs of observatories. Simultaneous eastward and westward flowing EEJ currents have been observed under specific conditions (**Rastogi & Kumar**, 1975). In the Americas, the pair Huancayo-Fúquene has been one of the most frequent pairs of observatories used for such studies, as Fúquene lies in a tropical latitude while Huancayo is near the dip equator. One key finding is that Sq in the horizontal

Figure 2. Location of the FUQ Geomagnetic Observatory on El Santuario Island. The left panel shows the map of Colombia with the departments of Cundinamarca and Boyacá highlighted in dark gray, bordering Lake Fúquene. The orange outline marks El Santuario Island, home to the observatory. The right panel provides a satellite image of the island

component (H) is abnormally large at the Huancayo Observatory compared to Fúquene. This is attributed to the influence of the EEJ, a strong eastward current that flows directly over the magnetic equator (**Chapman**, 1951; **Bhardwaj & Subba Rao**, 2017).

The FUQ has also played a crucial role in international geomagnetic monitoring. It was part of the initial set of five low-latitude observatories, alongside Honolulu (HON), M'Bour (MBO), Alibag (ABG), and Port Moresby (PMG), used for the Service of Rapid Magnetic Variations (SRMV) managed by the Ebro Observatory (**Curto *et al.,*** 2022). The SRMV provides critical real-time geomagnetic data to study rapid changes in the EMF. While FUQ was initially part of this network, it was replaced by other observatories over time, such as San Juan (SJG), Guimar (GUI), Alibag (ABG), and Kanoya (KNY). Nevertheless, low-latitude observatories like FUQ remain essential because disturbances from the auroral and EEJ are largely eliminated, allowing for clearer observations of geomagnetic variations (**Curto *et al.***, 2007). The strength of the EEJ has been a focus of critical appraisal and methodological refinement (**Kane**, 1973).

Several studies using FUQ's geomagnetic data have been conducted, including those by **Ladino** (2001), **Pinzón-Cortes *et al.*** (2025), and **Cortés-Rojas** (2024), focusing on the Sq and other geomagnetic phenomena. According to **Ladino** (2001), the hourly mean values observed in the three components of the EMF (H, D, Z) are affected by local current variations, as seen in the differences between the 0-1 and 23-24 UTC intervals. These differences suggest the influence of local currents and the variation of the EMF. The author also noted (**Ladino**, 2001) that by using the correction for non-cyclic variation method (CVNC), the effect of the ring current on Sq, particularly in the H component, was minimized. Fúquene's geomagnetic data showed that the minimum Sq current range occurred in December and January, during both high and low solar activity periods, while the maximum value of the quiet solar variation occurred in the afternoon, reflecting the greatest impact of solar activity.

Fúquene's seasonal variation was found to peak during the equinox, with a maximum value of 38 gammas and a minimum of 2 gammas in the H and Z components, except for the Z component at low activity levels, where the maximum variation occurred during the winter solstice, with an amplitude of 2.7 gammas (**Ladino**, 2001). Fourier analysis was employed by **Ladino** (2001) to examine annual and semiannual Sq variations, revealing changes in amplitude and phase for each month. Graphical representations of the quiet solar variation (Sq) for the magnetic components H, D, and Z at high, medium, and low activity levels have provided key insights into the geomagnetic behavior of Fúquene, enhancing its contribution to global geomagnetic research. **Macdougall** (1978) carried out a study to determine why the electrojet current was not similar to the Sq current. He analyzed the magnetic variations that affect Sq and observed from FUQ observatory data that it does not present variations in the H component at midday associated with the EEJ. The horizontal daily variation of FUQ is generated by low-intensity ionospheric currents that will have an impact on the equatorial increase of the electrojet. **Richmond** (1989) compared H and D components under conditions of magnetic disturbance. Data from the FUQ were used to determine these changes through simulations with tide impacts, or not included they were able to find variations from the local magnetic time instead of those of each observatory. Likewise, the study determined important characteristics of the Sq current from models of the geodynamo using thermospheric winds. These simulations have been able to demonstrate patterns of the Sq current at the equinox and solstice represented in asymmetric winds.

According to **Siddiqui** (2018), studies on EEJ variability in stratosphere high-heating events used data from the magnetometer located in the Fuquene and Huancayo observatories. Likewise, the calmest days in monthly periods were used to determine the magnetic effects that propagate in the primary field of the Earth. The variation of the horizontal fields is found from the residues of the daily values with the Sq current system and magnetospheric ring currents used to obtain the strength of the EEJ.

Shazana ***et al.*** (2014, 2015) conducted several studies to determine the correlation between the EEJ and SQ from geomagnetic observatory data, including Fúquene, based on criteria of geomagnetic quiet days. They found a weak correlation of negative character in South American observatories and concluded that the relationship is independent of the hemisphere and its change is slight due to periods of low geomagnetic activity. For this reason they recommend not to use the combined or total currents for future studies. **Pinzón-Cort**és ***et al.*** (2025) calculated local disturbance indices using data from the FUQ as a proxy of the DST index to analyze the impact of geomagnetic storms. They found that the intensity depends on the local time of the observatory and on whether it is noon or midnight. However, they concluded that this index is not enough to determine the impact of storms and that a better input to obtain results is the use of an ionospheric model, in this case, Sq, to subtract the calculated proxy and assess the risk of storms more accurately.

Cortés-Rojas (2024) is currently conducting research to compare the predictions of the ionospheric model DIFI-7 developed by NOAA with the ionospheric component derived from data collected at the FUQ under varying geomagnetic activity conditions. The study aims to quantify the impact of the Sq ionospheric current on the horizontal component of the local disturbance index (LDi) proxy developed by **Pinzón-Cort**és ***et al.*** (2025) using geomagnetic measurements.

Geomagnetic measurements

According to the IAGA guidelines, a geomagnetic observatory is expected to provide the following data:

Vector magnetic field components: Minute, hourly, and annual mean values of the magnetic field's vector components—commonly denoted as X, Y, Z, or D (declination), H (horizontal intensity), and Z (vertical intensity). These measurements should be calibrated through regular absolute observations to ensure accuracy.

Total field intensity (F): Continuous monitoring of the Earth's total magnetic field intensity using a proton precession magnetometer known for its precision in measuring scalar magnetic fields.

Geomagnetic activity days: Identification and reporting of geomagnetic activity by selecting five internationally designated quiet days and five disturbed days each month. This classification aids in distinguishing between regular geomagnetic variations and anomalies caused by solar or magnetic disturbances. Advanced techniques, such as complex demodulation, have proven effective for analyzing geomagnetic data and conductivity anomalies (**Agarwal,** ***et al.***, 1980).

Regarding global magnetic field variations, typical fluctuations are approximately ±3,000 nanoteslas (nT). However, at higher latitudes, these variations can escalate to around ±4,000 nT, reflecting the increased geomagnetic activity in polar regions (**IGAC**, 2020). These standards ensure that observatories maintain consistent and precise geomagnetic data, facilitating effective monitoring and analysis of Earth's magnetic environment. The daily disturbance variations have also been correlated with interplanetary plasma parameters in previous studies (**Kane**, 1974). The FUQ has recorded geomagnetic daily variations since 1955. The variations recorded in the relative measurements were represented in paper products called analogue magnetograms until 2022, which are revealed in 24-hour periods.

Generally, geomagnetic measurements at observatories are divided into two types: absolute and relative measurements. Absolute measurements are made using a non-magnetic theodolite equipped with a fluxgate sensor and a proton magnetometer, which measures the field intensity in the absolute measurement cabin. On the other hand, relative measurements are done in a separate room, where equipment such as triaxial variometers and a proton precession magnetometer is used to measure the three components of the field. Additionally, the entire system includes a computer setup used to convert the variometer's analog signals into digital data.

For absolute measurements, declination and inclination values are obtained from the DIflux theodolite, along with the exact time of the measurements. After determining declination and inclination, a set of five geomagnetic intensity field values is taken. In the FUQ, absolute observations are taken twice per week. They allow calibrating relative measurements, and they are useful to compute the reference baseline value for every component (D, H, Z). The baseline values are computed by using the data collected from the variometer and taking a relative measurement of the declination at the moment the first absolute declination measurement is made. We proceed in the same way for the dH, dZ, and F components. With these values, the baseline, consisting of the parameters (D0, H0, Z0, F0, and I0), can be calculated. These components allow to unify the absolute and relative measurements and obtain the final annual values for each component at FUQ. According to **St-Louis *et al.*** (2024), changes in baseline should be 5 nT per year maximum using modern instruments.

To ensure the quality of each measurement, the ESO, ESI, and EAZ errors are calculated, which allows for the verification of measurement precision and the correction of potential errors during data digitization. ESO (probe error) evaluates the quality of the measuring equipment; ESI (site error) describes the lack of parallelism between the sensor and the telescope's optical axis, and, finally, EAZ (azimuth error) refers to the possible angular deviation in the direction of the observation object.

Furthermore, when there is no single facility for both relative and absolute measurements as in the FUQ, it is necessary to calculate the gradient between the absolute and the variometer's huts. This calculation is called site difference (SD) and it is performed monthly by placing two magnetometers in each cabin that measure for at least five hours. This SD value factor is also used in the baseline computation. Final data are reported on component variations of the geographic north (X), geographic east (Y), vertical intensity (Z), declination (D), inclination (I), horizontal intensity (H), and total intensity field (F).

Data records have been reported up to 2013 in the World Data Center (WDC) of Geomagnetism, complying with international standards. Data can be found in different formats, the most prominent being the IAGA2002, designed to represent geomagnetic data in regular time series, and the WDC's own.

The FUQ is currently performing quality control on data collected between 2014 and 2022 to submit them to the WDC, a process that involves verifying both variometer data and baseline accuracy.

Previously, the baseline computation relied on scalar factors and a single average baseline value per month. However, this approach revealed inconsistencies (top plot in **Figure 3**), which were addressed by improving the baseline calculation process. The revised methodology for the 2014–2022 baseline involves fitting a polynomial equation to a set of absolute observations spanning approximately three months (middle plot in **Figure 3**). These polynomial segments are subsequently combined to construct the baseline. After establishing the yearly baseline, adjustments are applied to correct for baseline jumps observed at year transitions (highlighted by the arrows in the top plot in **Figure 3**). With this updated approach, we successfully produced a corrected dataset for the period from 2013 to 2015 (bottom plot in **Figure 3**).

Repeat station surveys: IGAC's implementation and applications

The observatories are responsible for providing the most accurate source of information on secular variation. However, the network of observatories does not offer adequate territorial coverage across the entire globe. This spatial limitation is compensated by repeat stations, i.e., marked points on the Earth's surface, either at ground level, near it, or on a specially constructed pillar. These temporary stations are low-cost, easy to install, and complement geomagnetic observatories, which require greater financial effort from the entities responsible for collecting geomagnetic data (**Newitt *et al.***, 1996).

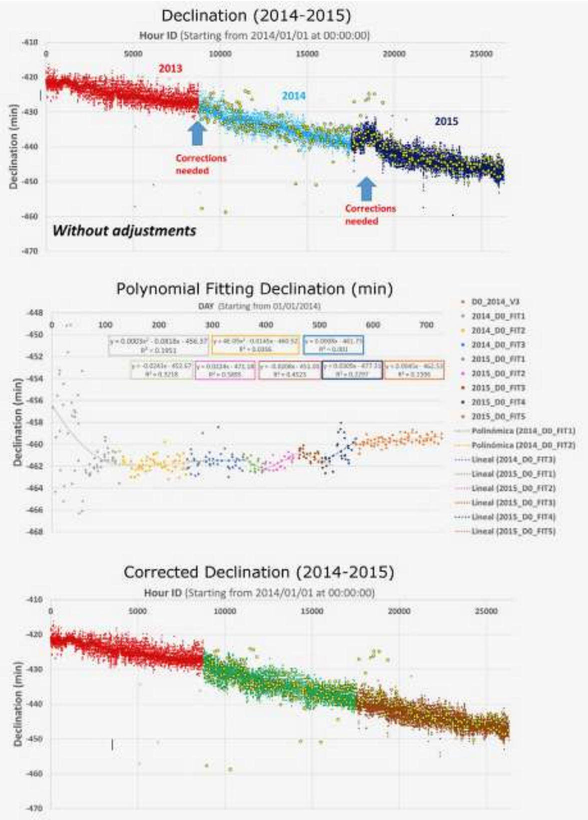

Figure 3. Declination (D) data correction process for 2014-2015. Top panel: Raw D from 2014-2015 displaying steps and inconsistencies due to the old baseline, required corrections highlighted. Middle panel: Polynomial baseline fitting for absolute observation spots in D, with segmented fits applied for 2014 and 2015 data. Bottom panel: Corrected D data after applying the adjusted baseline, showing improved consistency and accuracy

For data collection at repeat stations, a DI fluxgate magnetometer, a proton precession magnetometer, and a triaxial flux variometer are used; the latter is located at the geomagnetic observatory (**Figure 1S,** https://www.raccefyn.co/index.php/raccefyn/article/view/3166/4526). This combination is the most used in this methodology, as it ensures accurate results. Although any well-calibrated version of these instruments can be employed, the most up-to-date versions are recommended as they are easy to use and require less technical skill from the observer.

In Colombia, IGAC has made magnetic data acquisition efforts in various periods, mainly from FUQ. However, at different times, it has also worked on building a geomagnetic network covering the entire Colombian territory to generate geomagnetic charts that contribute to national navigation. Historically, these geomagnetic network surveying and measurement campaigns have been conducted in four distinct periods between 1968 and 1997, with an estimated total of 447 stations constructed and measured throughout the country (Period I: 1968 to 1974 (**Figure 4**); Period II: 1975 to 1987; Period III: 1988 to 1992, and Period IV: 1993 to 1997). During these periods, the IGAC produced isogonic, isoclinic, and isodynamic charts for each component: D, I, Z. The last update of these charts was in 2000, when a trial digital map was created using software tools for polynomial adjustment (**IGAC**, 2022).

Declination: Historically, magnetic declination in Colombian territory has varied in a NE-SW direction, with a greater degree of declination in the southwesternmost part of the country and a lesser degree in the northwest. Over time, the declination has taken on negative values according to the trend shown by the charts produced by IGAC.

Inclination: The temporal and spatial variation of inclination in Colombian territory is evident, increasing from south to north. The highest inclination is observed in the northern coastal departments, while the lowest inclination occurs in the southern part of the country.

Horizontal component: The horizontal component of the magnetic field varies in an E-W direction, with the highest values found in the western regions of Colombia and the lowest in the easternmost parts of the departments of Guainía, Vaupés, and Amazonas.

Data processing: Limited information was found regarding historical repeat station data processing. However, for quality control purposes, the acquired data were compared with the International Geomagnetic Reference Field (IGRF) model to verify their accuracy. According to internal reports from the IGAC's Geodetic Management (GIT), the data were discarded if differences were above 30% compared to the model. Additionally, the daily average of the EMF's three components was calculated, as the observation time was not always included in the provided formats.

Evolution and challenges of instrumentation at FUQ

The first instruments used at the observatory for absolute measurements were: an Askania magnetometer, a Ruska inductor, and an oscillation magnetometer to detect D, I, and the scalar field (F), respectively (**Figure 1S,** https://www.raccefyn.co/index.php/raccefyn/article/view/3166/4526). A few years later, a quartz horizontal magnetometer (QHM) was implemented to measure the H component and a proton precession magnetometer (PPM) to measure the scalar field, F (**IGAC**, 2022). However, this proton magnetometer failed in mid-2020 (it was very old and got damaged), and no absolute data was recorded until mid-2021, when Dr. J. Rasson donated a proton precession magnetometer (Geometrics 816) from the Dourbes Observatory Instrument Pool. Until 2022, the absolute house had two Ruska DIflux magnetometers to measure D and I, and a Geometrics 816 proton magnetometer for measuring F. The two Ruska DIflux were used at every absolute measurement, but only one was working properly.

Since its creation, the FUQ has conducted three significant instrument calibrations to ensure measurement accuracy. The first calibration took place in 1953, facilitated by a team from the U.S. Coast and Geodetic Survey. The second one was in 1993, during

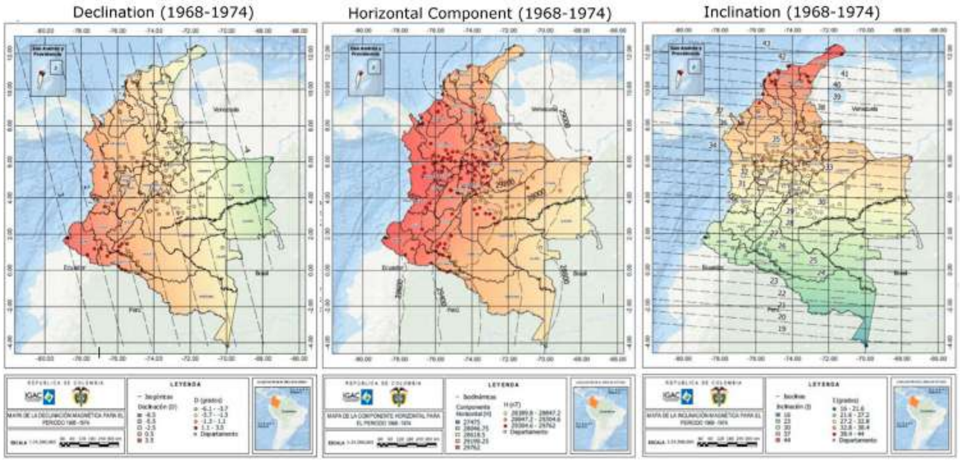
Declination (1968-1974)
Horizontal Component (1968-1974)
Inclination (1968-1974)

Figure 4. Magnetic field maps of Colombia (1968–1974). The figure displays three maps representing different aspects of the geomagnetic field in Colombia during the period 1968–1974. The left panel shows the magnetic declination map with isogonic lines and variations in declination (D). The center panel illustrates the magnetic inclination map, highlighting isoclinic lines and variations in inclination (I). The right panel presents the horizontal component map, featuring isodynamic lines and horizontal field strength (H) in nanoteslas (nT). Together, these maps provide a comprehensive overview of the geomagnetic field distribution across the region

the First Latin American Geomagnetism School (ELAG). The most recent was in 1996, following the installation of an automatic observatory equipped with instruments provided by the Royal Meteorological Institute of Belgium and Dr. Jean Rasson.

In 2022, the instruments at the FUQ experienced significant issues that halted observations. First, the declination variometer's mirror, an outdated model, became so blurred that measuring declination at the variometer house was unfeasible from March 2022 onward. The manufacturer confirmed it was beyond repair. Then, on October 13 and 26, 2022, two lightning strikes impacted the observatory. The first strike damaged the electrical system and the meteorological station at El Santuario island in Fúquene. The second strike, occurring 15 meters from the variometer house, destroyed all instruments within.

Enhancement and modernization of magnetic field measurement equipment

In 2023, IGAC undertook a comprehensive renovation of the FUQ, enhancing both its facilities and instrumentation (**Figures 2S and 3S,** https://www.raccefyn.co/index.php/raccefyn/article/view/3166/4526). The variometer house, which includes a "dark room" previously used for printing analog magnetograms, underwent significant refurbishment: complete roof replacement, facade varnishing, and repair of humidity affecting the structure. Similarly, the absolute observation house received a new roof and general maintenance, encompassing varnishing and the removal of debris and weeds (**Figure 4S,** https://www.raccefyn.co/index.php/raccefyn/article/view/3166/4526).

Between 2022 and 2023, the observatory's instrumentation was significantly upgraded. A notable enhancement was the integration of a British Geological Survey (BGS) FGE triaxial fluxgate variometer, which became fully operational in January 2024. This instrument provides high-precision geomagnetic data from FUQ at 1-second intervals. To further bolster geomagnetic monitoring capabilities, IGAC procured a LEMI-025 variometer, slated for installation by the end of 2024. The LEMI-025 is renowned for its high resolution and precision in measuring EMF variations. Maintaining dual variometers is crucial for ensuring continuous data acquisition. This redundancy allows for uninterrupted monitoring during calibration periods or unforeseen equipment issues, thereby enhancing the reliability of geomagnetic observations at the observatory.

IGAC also acquired two DI-flux theodolites from the Royal Meteorological Institute (RMI) of Belgium for absolute measurements—one in October 2022 and the other in October 2023. Additionally, a MAGREC data collector, an ObsDaq converter (acquired in October 2022), and three GSM-19 proton precession magnetometers (acquired in October 2023) were added to the observatory's suite of instruments. The three magnetometers are essential: one for absolute measurements, another for placement in the variometer house, and the third to update measurements for repeat stations in Colombia in 2025.

The instrumental configuration of the variometer house at FUQ is detailed in **Figure 2S,** https://www.raccefyn.co/index.php/raccefyn/article/view/3166/4526. It comprises the following components: an FGE fluxgate triaxial variometer and its electronic box; an analog-to-digital converter module (ObsDaq); two rechargeable 12V DC batteries; a set of screen, mouse, and keyboard for visualizing HDZ data at 1-second intervals; a MAGREC-4C with MAGLIN software; a GPS antenna; and a modem. Additionally, a GEM Systems Overhauser magnetometer was installed atop the cabin, adapted with a special cable designed to bypass its internal battery in favor of an external one, ensuring a continuous power supply.

These comprehensive upgrades have significantly enhanced FUQ's capacity to monitor geomagnetic phenomena with greater accuracy and reliability, positioning it as a pivotal facility for geomagnetic research in the region.

The importance of the FUQ in geomagnetism and space weather research

As we approach the peak of the current solar cycle, expected to culminate in the coming years, the Fúquene National Geomagnetic Observatory is poised to become an even more critical asset in the field of space weather research. The activity of the Sun follows an approximately 11-year cycle, alternating between periods of low and high solar activity. During solar maximum, the frequency and intensity of solar flares, coronal mass ejections (CMEs), and other solar phenomena significantly increase, directly impacting the Earth's magnetosphere and generating powerful geomagnetic storms.

The latest Decadal Survey for Solar and Space Physics (2024–2033) (**National Academies of Sciences, Engineering, and Medicine,** 2024) underscores a transformative vision for understanding the Sun, the heliosphere, and space weather in the coming decade. This roadmap, developed by a global community of scientists, engineers, and policymakers, identifies high-priority research areas and strategies for addressing critical questions about the Sun-Earth connection and its impact on society. It highlights the growing relevance of space weather research as humanity ventures further into space and becomes increasingly dependent on space-based technologies. Among the key themes is the integration of ground- and space-based observatories to achieve high-resolution, continuous monitoring of solar and geomagnetic activity. This aligns with the mission of the FUQ, which plays a vital role in observing and interpreting variations in Earth's magnetic field, particularly at equatorial latitudes. The observatory's contributions to space weather research are critical for improving models of ionospheric and magnetospheric interactions, which are central to forecasting space weather events that can affect communication, navigation, and power systems on Earth.

As the Sun enters this phase of heightened activity, the FUQ's role in real-time geomagnetic monitoring will be especially important. By observing sudden changes in EMF, the observatory will help detect the arrival of CMEs and other solar wind disturbances that could trigger geomagnetic storms. This early warning system will allow industries reliant on satellite communication, aviation, and power distribution to implement protective measures in advance.

Addressing the growing challenges of the solar maximum

The next few months of increased solar activity will bring new challenges to global infrastructure, including the potential for widespread disruptions to power grids, satellite navigation, and even the internet. One of the most significant risks during solar maximum is the possibility of a large-scale geomagnetic storm, comparable to the famous Carrington Event of 1859, which caused widespread telegraph outages and auroras visible near the equator (**Moreno-Cárdenas *et al.***, 2016). Today, with the global reliance on interconnected technological systems, such an event could be devastating.

The FUQ's continuous monitoring will be crucial in mitigating these risks. By contributing to global networks such as INTERMAGNET, its data will help build predictive models of geomagnetic storms and allow governments and industries to better prepare for potential disruptions. Additionally, the observatory's data will be used to improve EMF models, which are essential for maintaining accurate satellite navigation systems, especially during periods of geomagnetic disruptions.

Looking ahead, the FUQ's significance in space weather research will only grow as our reliance on space-based technology and interconnected communication systems expands. The observatory's ability to detect and monitor geomagnetic disturbances makes it an essential tool for studying how space weather events will impact emerging technologies, such as the increasing number of low Earth orbit satellites (LEOs), which are particularly vulnerable to solar storms. Furthermore, as the space economy continues to grow, with more nations and private companies launching satellites, and new plans for space exploration and even human settlement, accurate space weather predictions will be critical for protecting both assets in orbit and space travelers. The FUQ's precise measurements will be invaluable in understanding how geomagnetic storms influence satellite drag, ionospheric disturbances, and radiation levels in space. The years of high solar activity ahead will also allow researchers at FUQ to study how solar events shape the EMF over time, improving our understanding of secular variation and potentially aiding in the prediction of magnetic pole shifts. This research will contribute to a better understanding of EMF's long-term behavior, which is critical for navigating space weather challenges and preparing for future solar cycles.

Enhancing global collaboration in space weather research

As the Decadal Survey emphasizes a collaborative, interdisciplinary approach, the FUQ stands out as a key node in a global network of geomagnetic monitoring stations. Its technological advancements and long-term datasets position it as an essential contributor to the international effort to safeguard humanity's technological infrastructure and explore the fundamental processes governing our habitable cosmic neighborhood. The observatory's work will help bridge the gap between fundamental solar physics research and its applications in mitigating the risks posed by space weather, reinforcing its importance in the context of the survey's vision for the future. The international significance of the FUQ's data is another factor that will elevate its importance in the coming solar maximum. Space weather is a global phenomenon, and understanding its impacts requires coordinated efforts across multiple observatories. As part of a global network of geomagnetic stations, Fúquene and its data can contribute to the collective scientific effort to monitor and predict space weather.

As the Sun has become more active in the last few months while approaching to solar maximum, and it will remain active in the coming years during the declining phase of Solar Cycle 25, Fúquene's contributions to international space weather monitoring networks will ensure that researchers and decision-makers access to accurate, real-time data on geomagnetic activity. This collaborative approach will allow governments, industries, and the scientific community to better understand and respond to the dynamic challenges posed by the solar maximum.

With the implementation of new equipment, the FUQ has significantly enhanced its capacity for monitoring geomagnetic activity. These improvements were critical in detecting and closely tracking the geomagnetic storms that occurred in March and May of 2024, as the Sun approached the peak of Solar Cycle 25, which commenced in December 2019.

The FUQ detection of May 2024 geomagnetic storms

In May 2024, intense solar activity originating from the active region AR 13664 caused significant geomagnetic disturbances. This region, rapidly evolving between May 4 and May 14, produced 12 X-class solar flares and multiple interplanetary coronal mass ejections (ICMEs). These ICMEs interacted, creating complex structures that led to a severe geomagnetic storm on May 11, with a Dst index of -412 nT, making it the sixth-largest storm since 1957 (**Hayakawa *et al.***, 2024). The geomagnetic storm was also captured by broadband seismic sensors worldwide. Magnetic signals generated by the solar storm are distinctly visible in seismic data over a period exceeding 55 hours, making it one of the most prolonged geomagnetic storms ever detected by seismic instruments (**Diaz**, 2024).

The storm compressed Earth's magnetosphere, recorded at approximately 5.04 Earth radii. Observations confirmed auroral extensions as far as 29.8° invariant latitude. Ground-based neutron monitors and GOES satellite data captured a ground-level enhancement of cosmic rays and a Forbush decrease. The storm significantly impacted the ionosphere, with enhanced densities observed globally (**Hayakawa *et al.***, 2024).

The May 2024 geomagnetic storm was one of the most intense solar events recorded as we near the solar maximum. The FUQ's new equipment was able to detect the onset of this storm in real-time, capturing high-resolution data across the three main geomagnetic components (D, H, and Z). The observatory recorded pronounced fluctuations, particularly in the H component, which exhibited sharp increases in intensity during the storm's peak, as seen in **Figure 5**. These measurements have provided key insights into the behavior of geomagnetic fields in equatorial regions, where the effects of solar storms can differ from those at higher latitudes.

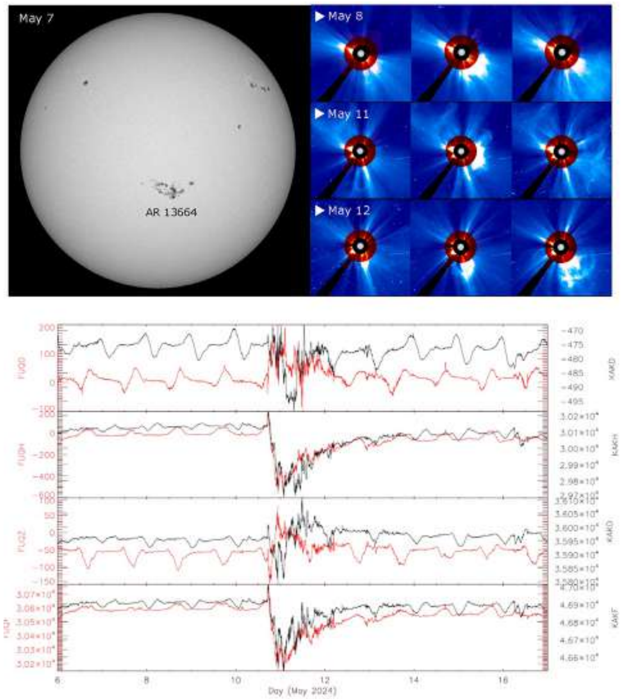

Figure 5. The figure illustrates the May 2024 solar and geomagnetic activity. The top-left panel shows a white-light image of the Sun taken on May 7 (Solar Dynamics Observatory, SDO), highlighting active region AR 13664 near the central meridian. The sequence on the right shows LASCO coronagraph images from the SOHO mission, depicting three of the coronal mass ejections (CMEs) that occurred on May 8, 11, and 12, as labeled. The bottom plot compares the magnetic variations recorded by the Fúquene National Geomagnetic Observatory (FUQ, red) and the Kakioka Magnetic Observatory (KAK, black) from May 6 to May 17, 2024, showcasing the pronounced geomagnetic disturbances associated with the solar events

Previously, in March 2024, another significant geomagnetic storm had been detected. Once again, the FUQ tracked the storm's progress, capturing detailed hourly variations in the EMF. These data can be compared with observations from other geomagnetic observatories worldwide, which will be critical for understanding the global nature of these events and their localized effects near the magnetic equator. One of the most significant implications of these storms is their potential impact on equatorial regions. While high-latitude regions are more typically associated with geomagnetic disturbances, equatorial areas like those near the FUQ also experience substantial effects, particularly during periods of heightened solar activity. The observatory's data from these recent storms indicate a stronger-than-expected response in the geomagnetic field near the equator, which could have implications for satellite communication, GNSS accuracy, and power grid stability in these regions.

Conclusions and discussion

Throughout its history, the FUQ has stood out due to its systematic and consistent geomagnetic measurements, making significant contributions to regional and global research. However, in previous years, the observatory had faced delays in adopting the most modern equipment and technologies used in other parts of the world. This technological lag limited its ability to fully integrate into contemporary research frameworks such as INTERMAGNET, the global network of geomagnetic observatories.

With the recent upgrades and modernization of its equipment, the observatory is now positioned to regain its prominence in the field of geomagnetic research. These new tools will enhance the precision and frequency of the data collected, making it a key player once again in space weather monitoring and geomagnetic modeling. Importantly, the data obtained from Fúquene's strategic geographical location will soon be incorporated into INTERMAGNET, marking a significant step forward in the observatory's contributions to the global scientific community.

As the FUQ becomes more integrated into international monitoring networks, its data will serve as a critical reference for studies on geomagnetic phenomena and solar activity. This includes its potential role in refining EMF models, such as those used for predicting space weather and understanding the South Atlantic Anomaly. The observatory's enhanced capacity will also allow for more detailed studies on solar-related events, such as coronal mass ejections and geomagnetic storms, improving our ability to forecast and mitigate the effects of space weather on technology and infrastructure.

The FUQ's role in detecting and analyzing recent major geomagnetic storms highlights the importance of its newly modernized equipment. The March and May 2024 geomagnetic storms have demonstrated that FUQ, equipped with its updated technology, is ready to play a leading role in the study of geomagnetism and space weather, offering invaluable data for both local and global scientific investigations. The data collected from these events will not only contribute to a deeper understanding of geomagnetic responses in equatorial regions but will also position the observatory as a key contributor to the global scientific community's efforts to monitor space weather. The observatory's contributions will become a crucial reference point for geomagnetic modeling and space weather forecasting, especially as Solar Cycle 25 reaches its peak. IGAC will continue working to ensure the operation of the FUQ and its contribution to the study of the global geomagnetic field.

Supplementary information

See the supplementary information https://www.raccefyn.co/index.php/raccefyn/article/view/3166/4526

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Author contributions

MRAC and SVD were responsible for structuring the work, conducting the analysis, and drafting the text. JV, EC, SP, NGP, ETM, and CAFP carried out research tasks, actively participated in discussions, and contributed to text editing. All authors have thoroughly reviewed and approved the final version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest associated with the research process leading up to the drafting of this manuscript.

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