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Teoloyucan Geomagnetic Observatory operation over a Quality Management System ISO 9001:2015

Ana Caccavari-Garza [1]; Gerardo Cifuentes-Nava[1]; Armando Carrillo-Vargas[1], Adriana Elizabeth Gonzalez-Cabrera[2], Charbeth López-Urías[1], and Juan Esteban Hernandez-Quintero 🎗.

[1]Magnetic Service, Universidad Nacional Autónoma de México, Mexico City, 04510, Mexico
[2]Mexican Solarimetric Service, Universidad Nacional Autónoma de México, Mexico City, 04510, Mexico
🎗Deceased

Corresponding author to: Ana Caccavari-Garza (anacg@igeofisica.unam.mx)

Abstract. Geomagnetic Observatories are essential for the study of the Earth's magnetic phenomena, they allow the precise and continuous measurement of the geomagnetic field. They are built and operated according to rigorous international standards to ensure the acquisition of high-quality geomagnetic data. Given the nature of Quality Management Systems based on ISO 9001:2015, we consider that their implementation in a Geomagnetic Observatory, can be a valuable tool that allows monitoring the follow-up of international standards and ensuring their correct operation, thus guaranteeing high quality geomagnetic data.

Some of the main advantages of implementing a Quality Management System and obtaining an ISO 9001:2015 certification include setting clear objectives, systematically analyzing risks that could affect both functionality and data quality, fostering a culture of continuous improvement, promoting of context analysis through a Strengths, Weaknesses, Opportunities, and Threats analysis; and strategic planning based on this knowledge. In addition, involving the senior management of the institution responsible can help raise awareness of the operation characteristics and needs. It also facilitates the continuous monitoring of user's requirements and satisfaction, as well as the correct documentation of all procedures carried out for its operation.

This study presents the registered experience in the implementation of a Quality Management System in the only Magnetic Observatory in Mexico: Teoloyucan. It details the operation of the observatory, including data acquisition platforms, transmission, reduction, management, and data publication. It also describes the Quality Management System implementation process in the data deployment procedures, highlighting its advantages, disadvantages, and challenges during its adoption.

Keywords: Geomagnetic Observatories, Quality Management Systems, quality data, improvement, geomagnetism

1. Introduction

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The objective of geomagnetic observatories is to record, continuously and in the long term, the temporal variations of the magnetic field vector; maintaining the absolute standard of accuracy of the measurements (Brake, 2025; Jankowski and Sucksdorff, 1996).

INTERMAGNET (International Real-time Magnetic Observatory Network) is a worldwide network of Geomagnetic Observatories that is managed by the IAGA (International Association of Geomagnetism and Aeronomy). It establishes guidelines and verifies that the observatories belonging to this network generate high quality data. These observatories are important because they provide data for both scientific research and practical applications (Rasson et al, 2011).

In Mexico, the only existing Geomagnetic Observatory is managed by the Magnetic Service of the Geophysics Institute of the National Autonomous University of Mexico. It had previous locations (1879-1912) and has been operating since August 1914 in the town of Teoloyucan, State of Mexico. On that date it began its operation with Mascart variographs that belonged to the previous site. In 1923, the magnetometer Dover 123 and the inclination compasses Fauth 73, Negretti- Zambra 65 and Chasselon 64 were incorporated. Later, in 1931 the set of Eschenhagen photographic recording variometers was acquired, from the Askania House (Figure 3), which worked until the change to the digital era (Hernandez Quintero et al., 2018). In 1950 the first publication of the Observatory's Magnetic Values was made (Sandoval, 1950).

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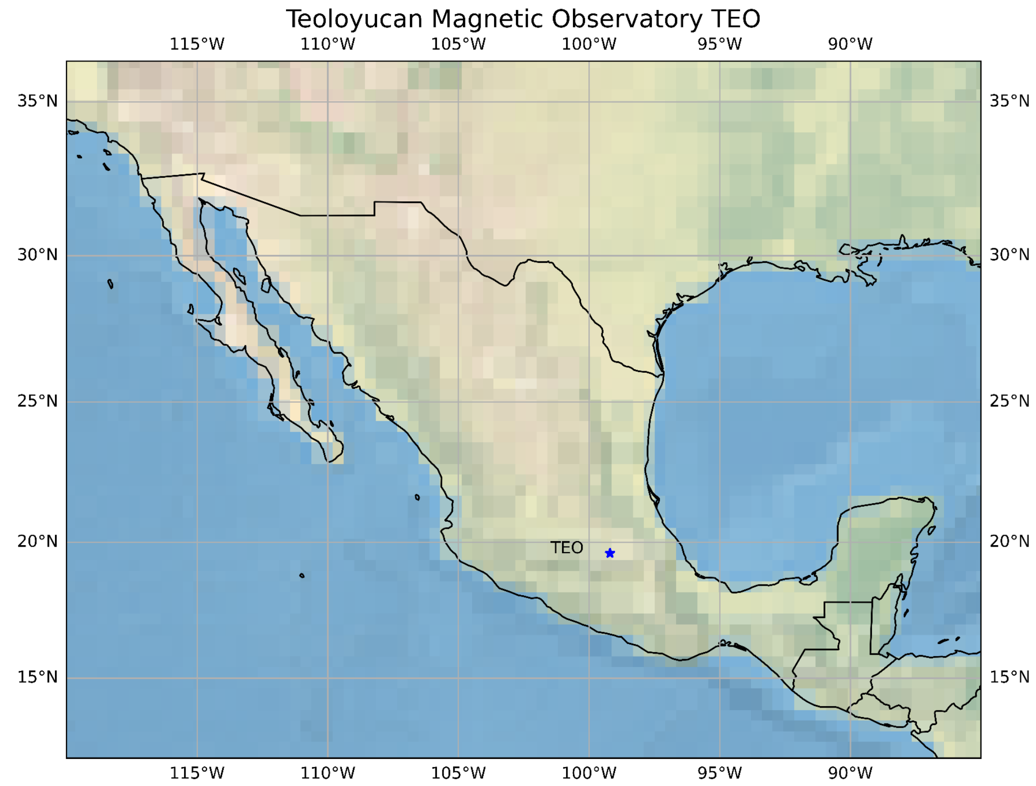

Figure 1: Observatory location map (Made with Cartopy and Natural Earth. Free vector and raster map data @ naturalearthdata.com)

In 1978, it had to be relocated, moving 700 m to the southwest, to the position where it is currently located (99° 11' 35.735" W, 19° 44' 45.100" N, 2280 masl). It was at this time that the current operating huts were built.

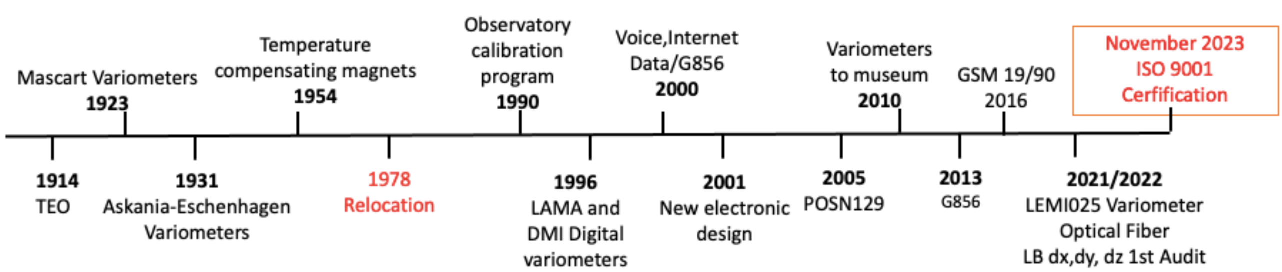

Figure 2: TEO timeline

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In 1993, it was calibrated for the first time with a first-class standard observatory (Friedericksburg, USA). And in 1996, after the first Latin American Congress of Geomagnetic Instrumentation held at the Magnetic Observatory of Teoloyucan (1996), it entered the digital era, with a three-component fluxgate variograph (DFI, baptized as LAMA, from the Royal Meteorological Institute of Belgium, RMI) and a three-component fluxgate variograph FGE (DHZ, from the Danish Meteorological Institute DMI), along with a PPM Geometrics G856 magnetometer and a RUSKA non-magnetic theodolite converted to a DI-flux magnetometer for absolute observations. Also starting in the year 2000, the Internet was available for data transmission (Hernandez-Quintero et al., 2018).

From this date, it continued operating without major changes until 2021, when after an electrical failure that affected the installation of the variographs, they were replaced by the LEMI025 variograph. In addition to this change, and following the new Quality Management guidelines of the National Autonomous University of Mexico, it was decided to incorporate the "Geomagnetic data deployment in near real time" procedure, to the Quality Management System of the Geophysical Services of the Institute of Geophysics of UNAM.

TEO currently operates with a ukrainian LEMI025 fluxgate (XYZ) variograph (by Lviv Center of Space Research Institute), a GSM90 Total Intensity (F) magnetometer (by GEM Systems) and a Theo 020B Di-Flux (DI) theodolite (ZEISS/RMI/USGS), following Intermagnet standards (Brake, 2025; Jankowski and Sucksdorff, 1996), and relying on a QMS to verify the implementation of these standards.

It is important to emphasize that implementing a QMS does not define the operating guidelines themselves, these are given by the international standards already mentioned: the purpose of a QMS is to verify that these guidelines, which are described throughout the QMS, are rigorously followed.

This paper will present the aspects that we consider relevant when implementing a Quality Management System focused on the operation of a magnetic observatory: what a QMS is, how to adapt the work with a Management System (define scope, objective and quality policy), staff participation (experience, adaptation, profiles, distribution of responsibilities), continuous review of Strengths, Weaknesses, Opportunities and Threats, risk analysis, maintenance scheduling. Also, the participation in the QMS of both top management and users and the advantage of having annual audits to have a revision of the entire system. Finally, we present some points that we consider disadvantages or points against a QMS.

2 Methodology

From the analysis of the ISO 9001:2015 Standard of the International Organization for Standardization, a Quality Management System is a set of principles that allow improving the performance of an organization to meet the needs of its customers (Godinez-Mendez, 2023, International Organization for Standardization, 2015).

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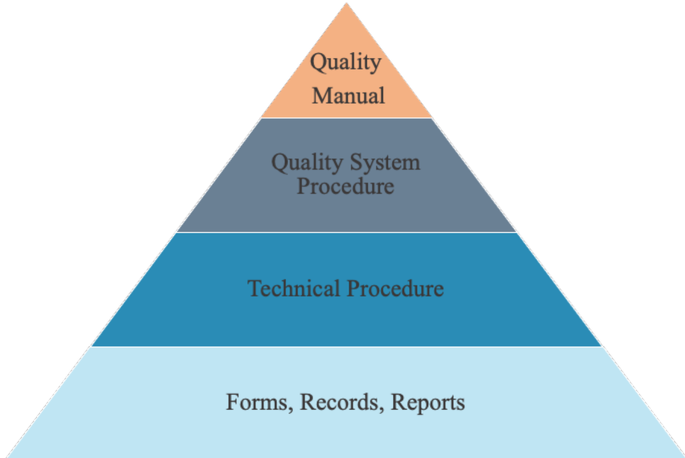

Figure. 3: Structure of a Quality Management System (Adapted from Berte and Nevalainen,1996)

2.1 Work Adaptation with a Quality Management System

Performing a work task within a QMS does not change the work performed, but the vision one has about it. One becomes aware of the importance of each step to achieve the provision of a service (Godinez-Mendez, 2023). In this case, as mentioned above, the Observatory has been operating since 1914 following the established international standards (Brake, 2025; Jankowski and Sucksdorff, 1996). Implementing a QMS does not change its operation, but allows incorporating continuous analysis of its operation, systematizing the actions carried out, such as preventive maintenance, better defining the roles of each member and seeking continuous improvement, among other things.

The *Quality Manual* is a fundamental document that consolidates and clearly communicates the structure, scope and essential elements of the QMS. Although its development is no longer a mandatory requirement under ISO 9001:2015, it remains a valuable tool to facilitate internal understanding of the system, support staff training, and serve as a reference point for audits and external stakeholders. Its usefulness lies in its ability to integrate key processes, reflect the organization's commitment to quality, and contribute to the standardization and continual improvement of activities, thus strengthening the effectiveness of the management system.

2.2 Organization and top management context analysis: defining policies, objectives, and system scope.

The context of the organization in which the Observatory is located is described within the QMS *Quality Manual*. The Magnetic Observatory of Teoloyucan is managed by the Magnetic Service of the Institute of Geophysics of the National Autonomous University of Mexico (UNAM), which is one of the six Geophysical Services of the Institute of Geophysics. The senior management role consists of the Geophysics Institute Director and the Director's Representative.

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The Quality Management System was implemented for five of the six Geophysical Services, which jointly defined the following *quality policy*:

"Geophysical Services are committed to ensure quality in the services they provide by offering truthful and reliable results, based on what is stated in the International Standard ISO 9001:2015 Quality Management Systems, to meet the needs and expectations of our customers and users with the ongoing commitment of the Management to support the continuous improvement of processes as well as the effectiveness of the QMS with a risk-based approach."

The Magnetic Service defined the scope in the QMS, based on the importance of having a correct operation of the Observatory in order to obtain and deploy high quality geomagnetic data. This scope includes data acquisition (infrastructure, instrumentation, operation), data reduction, transmission, and deployment.

Scope: Publication on the web page of the geomagnetic data recorded at the Magnetic Observatory of Teoloyucan, State of Mexico. Under the requirements of ISO 9001.

Quality Objective: To publish on the web page the geomagnetic data recorded at the Magnetic Observatory of Teoloyucan, State of Mexico, with at least 90% data completeness.

As mentioned above, QMS systems encourage senior management to become involved in and committed to the system. The *Quality Manual* establishes the commitments it makes annual review of the QMS to update objectives, processes, equipment and whatever is required for accountability in relation to the effectiveness of the QMS, ensure that quality policies and objectives are established for the QMS, and that these are compatible with the Institute's context and strategic direction, and ensure that all the resources required for the QMS are available.

The *Quality Manual* also describes roles, responsibilities and authorities, risk management and *SWOT*; however, as these topics are of special interest, they will be developed further below.

2.3 SWOT and risk analysis

Beyond the QMS, *SWOT* analysis is known to be a powerful tool for the analysis of an organization (Otero and Gache, 2006). The *SWOT* analysis consists of an evaluation of the strengths and weaknesses that together diagnose the internal situation of an organization, as well as its external evaluation, i.e., opportunities and threats. It is also a tool that can be considered simple and provides an overview of the strategic situation of a given organization (Novy and Wahab, 2020).

The *SWOT* analysis carried out for the Magnetic Service:

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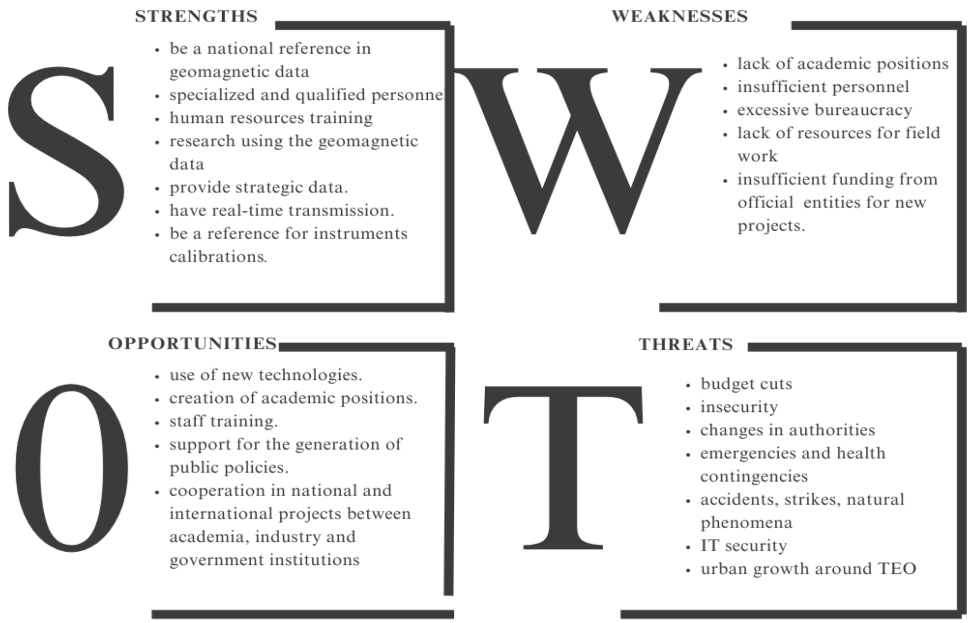

Figure 4: SWOT: Strengths, Opportunities, Weaknesses Threats analysis for the Magnetic Service

This analysis offers different possibilities, among them, it allows us to know the Strengths and through the Opportunities, seek to make them bigger, but also, one of the greatest contributions of this analysis is that, through the analysis of the Weaknesses together with the *Threats*, it helps us to identify the risks that we can face in our system, so that, from this, we can establish mitigation actions for these risks. An example of this in the case of TEO, is the *Threat* of lack of replacement instruments, with the *Weakness* of long times in the purchasing processes, this can strongly affect the operation of the observatory. From these analyses, the *Risk Matrix* is constructed, which includes the risks, the probability of their occurrence, the severity in case of occurrence, and the mitigation actions. This matrix is analyzed periodically, and it is observed whether the proposed risks occurred and whether the actions were relevant to mitigate them, and if not, new actions are proposed. Figure 5 shows a reduced version of the *Risk Matrix* obtained for TEO.

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Probability	Negligible	Marginal	Critical	Catastrophic
Frequent	4	8	12	16
Probable	3	6	9	12
			Failure in internet connection. Lack of electrical energy. Logical or physical failures on the server that prevent real-time reporting of data	Extreme phenomena. Theft. Vandalism Urbanization-Magnetic Noise
Occasional	2	4	6	8
			Change of authorities Emergencies and health contingencies incendios Lack of supplier inventory Long purchasing process times	
Improbable	1	2	3	4
		Temporal absence of staff		Accidents, strikes, natural phenomena
	Severity			

Figure 5: Risk Matrix of the Magnetic Service

2.4 The knowledge, experience and skills of the personnel that will be integrated into the system.

It is of utmost importance to consider the experience and knowledge of the personnel working in the Magnetic Observatory. All this knowledge must be documented. One of the main advantages of implementing a QMS is to document the procedures performed, in order to preserve all the knowledge and experience of the personnel involved. In many cases this knowledge belongs to a single person, who, when absent or retired, takes it with him/her, making it difficult to continue with the operation of the Observatory. Later on, the document where the whole operation is depicted will be described: the *technical procedure* for the deployment of TEO geomagnetic data, where the responsibilities of the members of the QMS are described, and the

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job profiles specify the functions and requirements of each member of the group. Defining this, contributes to a better organization, performance, and commitment to the tasks. For the operation of the Magnetic Observatory of Teoloyucan, the Magnetic Service defined the following organization chart:

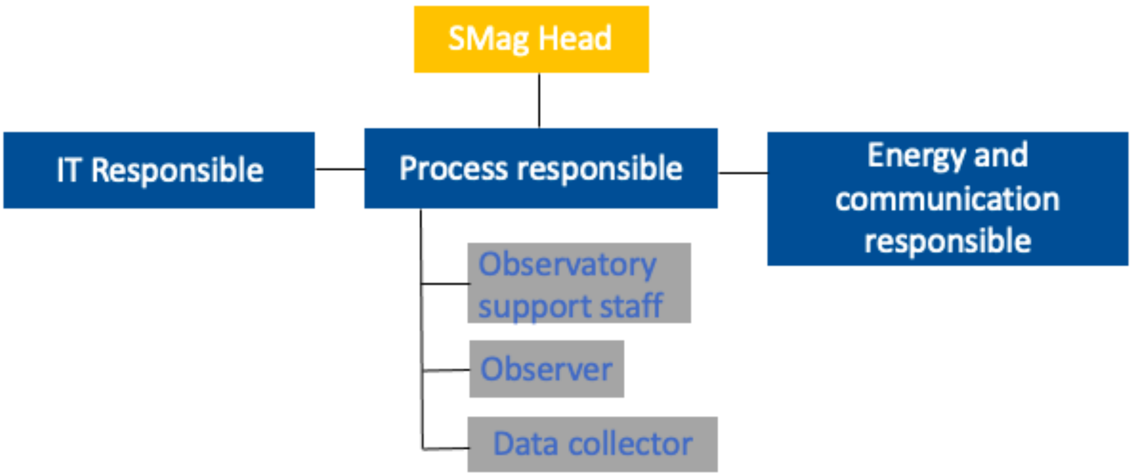

Figure 6: Magnetic Service organizational chart

2.5 Instrumentation and maintenance. Records

Within the *Management Documents*, in the part corresponding to *Instrument Control,* there is a format (SMag IGEF-FPG02-01) which contains the inventory of instruments and servers, their characteristics and location. There is also a format (SMag IGEF-FPG02-03) that tracks instrument maintenance, such as routine cleaning of servers, antivirus revision, delta F measurement, theodolite maintenance, cleaning, verification and adjustment, internal cleaning of LEMI025 memory, among others.

Complementary to the records of the equipment and its maintenance, there is a logbook to record failures that occur in the equipment or systems, record any maintenance activity either preventive or corrective, and to record changes or events that produce disturbances in data that affect data quality.

Keeping this control, allows to carry out another key point in the QMS: the *planning of changes*, *corrective actions* and *improvements*.

2.6 Corrective and preventive actions: keys to continuous improvement

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One of the relevant approaches of QMS is that of continuous improvement; organizations should focus on optimizing their processes, eliminating nonconformities and preventing problems before they happen. *Planning changes*, *corrective actions* and *improvements* are essential processes for the growth and efficiency of any organization.

Corrective actions are focused on fixing existing problems, addressing the root cause to prevent recurrence. The implementation stages consist of identifying the nonconformity or problem, analyzing the root cause, making a corrective action plan, implementing this plan and verifying its effectiveness (Summer, 2025). An example of a *corrective action* in the Magnetic Service (AC-SMag-2024-05) was carried out due to a lack of personnel in the work areas, in the Magnetic Service Chief, due to the decease of the department head. These actions were implemented, and their effectiveness verified.

Improvements, on the other hand, seek to optimize processes, products, or services, generating added value for the organization. An example of this in the Observatory's QMS corresponds to the fact that during the first year of implementation it was considered convenient to incorporate expert personnel in the design of energy and transmission systems. Therefore, the planning of this change was carried out, this improvement was recorded (MM-SMag-2023-02), and subsequently incorporated. Upon verifying the effectiveness of the change, it was considered that it contributes to the better operation of the Observatory, so it was a positive improvement.

In both corrective actions and improvements, once the problem or possible improvement has been identified, the changes are carried out in a planned manner, defining the following stages in change planning: analyze what impact this change may have, resources and possible risks, define the objective, develop a concise action plan that details activities, responsible parties, deadlines, and evaluates the effectiveness of this change. All this documented and recorded in the corresponding formats.

2.7 Stakeholders. Users and focus groups

Another advantage to consider when implementing a QMS is the monitoring of stakeholders and users: stakeholders are not just people, but also groups and organizations that have an interest in, or are affected by, the organization's activities associated with the QMS. An example of this can be suppliers, administrative systems, managers, as well as the users themselves. The QMS shall assess the relevance of each of these stakeholders and shall follow up on whether stakeholder requirements are met over time.

In the case of users, the QMS seeks to follow up on the satisfaction of their needs, to know their requirements and to know their opinion about the products or services offered by the QMS. In the case of the Magnetic Observatory and its geomagnetic data deployment procedure, users are those who consult the page or use the data generated by the Observatory. The effectiveness of the system, the availability of data and points that are considered of interest to improve the system are discussed annually through meetings with different users that make up a focus group. This evaluation can also be carried out through a user satisfaction survey.

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2.8 Audits

In addition to being a requirement of the standard, audits allow verifying whether the QMS conforms to its own requirements and to the requirements of the standard, and whether its implementation and operation is effective. Although it may initially seem a cumbersome procedure, having these systematic evaluations makes it possible to check that all the points described in the QMS and, in particular, in the *technical procedure* are punctually covered, which contributes to the correct Observatory operation. In the case of the Magnetic Service QMS, two annual audits are carried out: an internal one, performed by a University agency, and an external one performed by national certifying companies with international validity, which allows obtaining the ISO 9001:2015 certification. Our QMS has had 3 internal audits, and 2 external audits. Certification was obtained in November 2023 and has been renewed annually.

2.9 Disadvantages

Undoubtedly one of the points against implementing a QMS, is all the necessary documents, although this article describes most of them, there are also others whose function may be considered not so necessary, and still must be done. This may require time on the part of the personnel. However, it is important to mention that once the whole system is integrated, the documents that must be updated or created are linked to the *technical procedure*, and contribute, in this case, to the correct functioning of the observatory.

It is also important to mention that certification has a cost, in this case the cost is covered by the Management, considering the benefits of operating with a QMS and certification. Although it is an important point to consider. One way to solve this, in case of not wanting to allocate this resource, can be to implement a QMS without obtaining the Certification, since it gives structure to the operation.

3 Results

3.1 Technical Procedure

The most relevant document of the QMS is the *technical procedure*, which is where the way the Observatory operates is documented, starting from the definition of the most important concepts, personnel responsibilities, infrastructure, instruments and power and communication equipment, description of the activities to be performed, including the formats to perform absolute measurements and data reduction. The following is a general description of the main points of the Observatory's *technical procedure*: “Graphical display of geomagnetic data”.

The Teoloyucan Magnetic Observatory consists of a variograph hut, an absolute measurement hut, two auxiliary huts and an office (Fig. 5)

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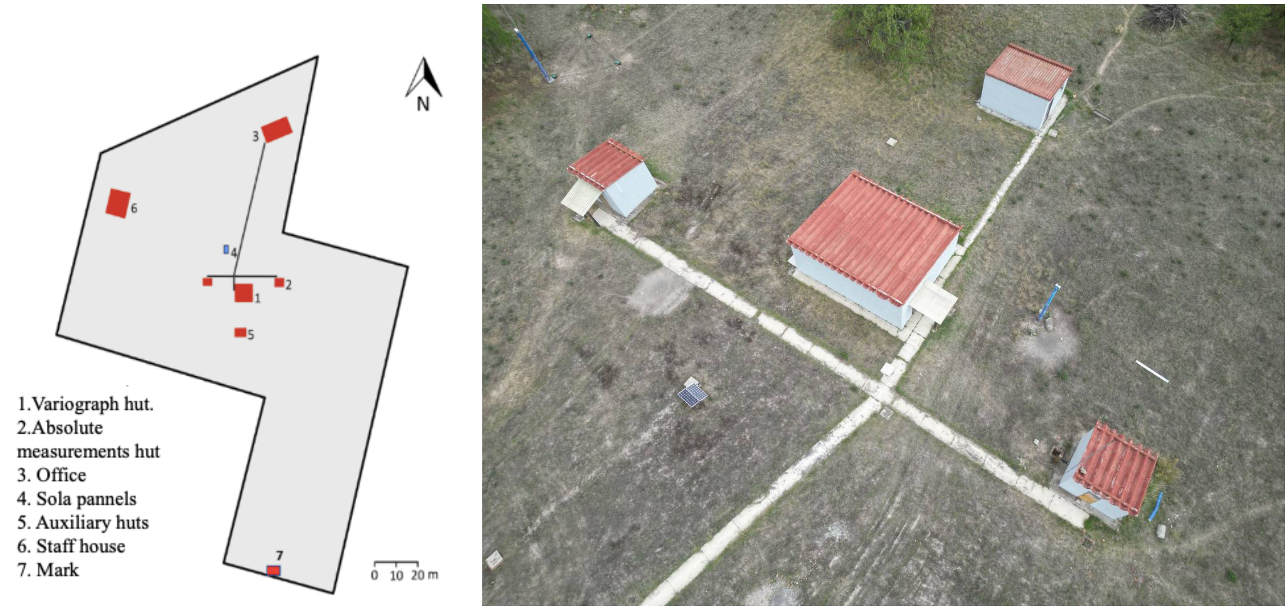

Figure 7: a) TEO sketch and b) aerial photo

The huts were built following the established standards: the absolute observations hut has two pillars for measurements, is built of non-magnetic materials and has a window to observe the sight, which is 70 m away; the variograph hut, has a double wall for thermal control, is built of non-magnetic materials, and has 5 pillars for instruments, inside is the LEMI025 sensor and in the intermediate part between the walls is the GSM90, the LEMI025 console and the power and transmission systems. The instruments are powered by solar panels. Between the variograph hut and the office, data is transmitted via fiber optics. As already mentioned, there is a LEMI025 variograph, a GSM90 total intensity magnetometer and a Diflux Theo 20B for absolute measurements (Fig 8).

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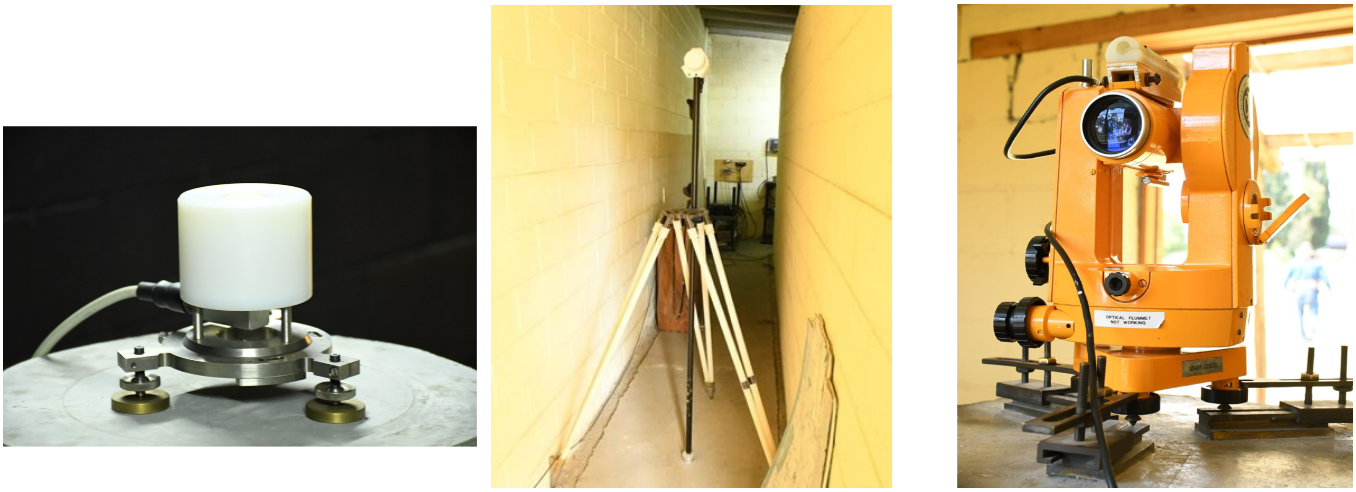

Figure 8: TEO instrumentation: a) LEMI025 Variograph, b) GSM90 Magnetometer, c) Diflux THEO20B

The operation and distribution of instruments and systems as well as personnel activities are described in the operation diagram (Fig. 9).

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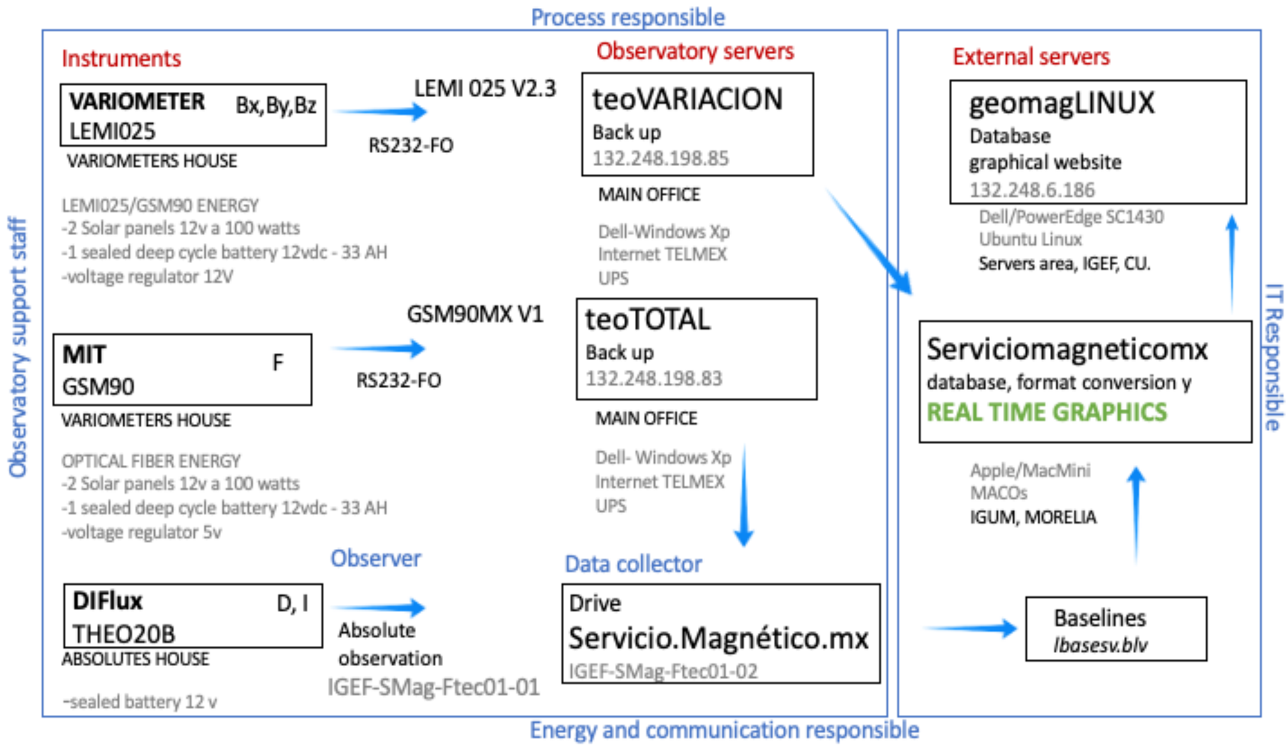

Figure 9. TEO operation scheme

240 The *technical procedure* describes in detail the type of files generated, their location, power supply systems, form of data transmission, and servers, it also describes how to perform absolute measurements (Rasson, 2004), and the format (IGEF-SMag-Ftec01-01) where the measurement is recorded, then this information is captured in the format (IGEF-SMag-Ftec01-02) from which the baseline of the Observatory will be generated. These formats and their location within the Magnetic Service documentation can be found in the *technical procedure*.

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Universidad Nacional Autónoma de México

Servicio Magnético

GEOFISICA UNAM

FORMATO: IGEF-SMag-Ftec01-01				FOLIO 0	
Estación		Fecha		Az. "A"	183°32'40"
Instumento		Az.-marca		Az. "B"	184°51'56"
Pilar		Observador			

Serie-A	DECLINACIÓN						
	Marca-arriba			Meridiano-Mag.			
	Marca-abajo						
				LEMI			MIT
Telescopio-Sensor	Hora	Grados	Minutos	ΔX	ΔY	ΔZ	F
EU Este-Arriba							
WD Oeste-Abajo							
ED Este-Abajo							
WU Oeste-Arriba							
	Marca-arriba						
	Marca-abajo						

INCLINACIÓN					LEMI	MIT
Telescopio-Sensor	Hora	Grados	Minutos		ΔZ	F
NU Norte-Arriba						
SD Sur-Abajo						
ND Norte-Abajo						
SU Sur-Arriba						

Notas:

Fig. 10. IGEF-SMag-Ftec01-01 form for absolute measurements. Serie A

The programs that allow data display and the servers where they are executed are also described: those for acquisition, GSM90MX 1.0 (Cifuentes-Nava, 2016) (Fig. 11), LEMI V 2.3 and the cron that executes the transmission codes, generation of data in IAGA2002x format, generation of graphs, daily, weekly and 27-day (Carrington rotation), and their subsequent display on the Magnetic Service web page.

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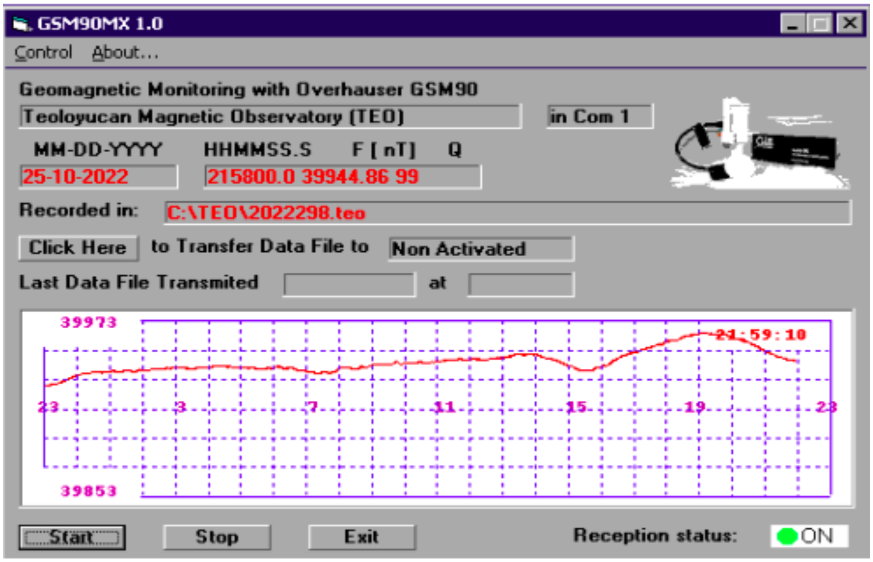

Figure 11. GSM90MX 1.0 software deployment window of the GSM90 Magnetometer recording Total Intensity data (Cifuentes-Nava, 2016).

The final products generated are also shown:

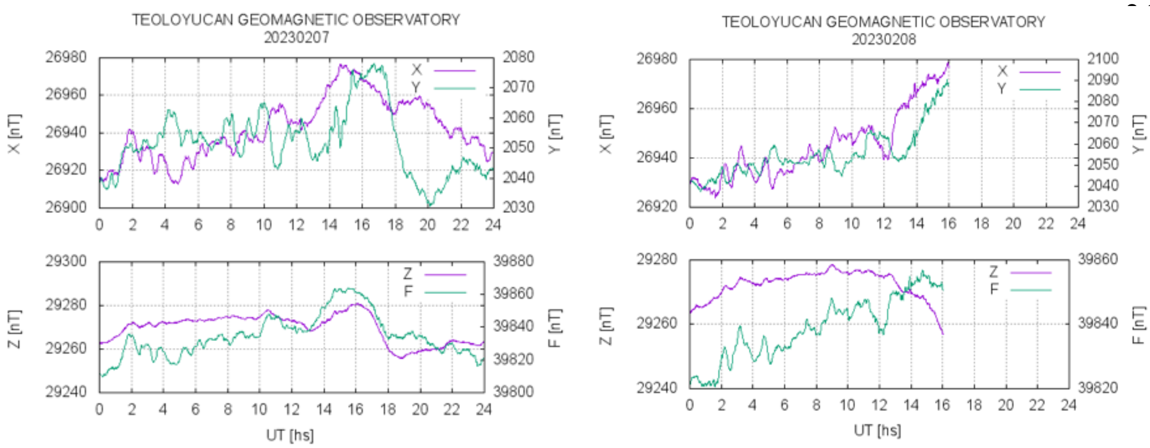

Figure 12: Plots of the X, Y, Z, F components displayed on the web page: a) previous day, b) current day.

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Figure 13: a) Plot of the last 7 days of the X, Y, Z, F components. b) Plot of the last 27 days (Carrington Rotation) of the X, Y, Z, F components.

In the following QR codes, Graphical geomagnetic data display on the website and the ISO 9001:2015 certification document of the geomagnetic data display process in the Magnetic Observatory of Teoloyucan are shown.

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a) b)

Figure 14. a) QR Code of the Graphical geomagnetic data display in Teoloyucan Geomagnetic Observatory (TEO). b) QR Code of the ISO 9001:2015 Certification.

4. Conclusions

Certification under the ISO 9001:2015 standard has been designed for industry and business; however it can be used in academic and research environments as has been seen in this case. Its usefulness for this case has been mainly to document in detail the operation and generation of a final product under quality standards such as TEO's Graphic Display of Geomagnetic Data (Fig.14a) and for more information about the Certificate or the QMS consult the QR code (Fig. 14b).

There are several advantages of implementing a QMS and obtaining an ISO 9001:2015 certification include setting clear objectives, systematically analyzing risks, culture of continuous improvement, promoting of context analysis through a SWOT; and strategic planning based on this knowledge. Elaboration of all the documents associated with the operating procedures of a Geomagnetic Observatory and the continuity of the processes mentioned above guarantee TEO's Operation, including both production of data and its availability in real time for users.

The experience of implementing a QMS in the Teoloyucan Magnetic Observatory was satisfactory and contributes to the produce quality data and systematize the operation of the Observatory.

Data Availability

Data sharing not applicable to this article as no data sets were generated o analyzed during the current work.

Authors Contributions

Conceptualization: Ana Caccavari-Garza; Formal Analysis: Ana Caccavari-Garza, Gerardo Cifuentes-Nava, Armando Carrillo-Vargas, Juan Esteban Hernandez-Quintero; Methodology: Ana Caccavari-Garza, Gerardo Cifuentes-Nava, Armando Carrillo-Vargas, Juan Esteban Hernandez-Quintero. Project Administration: Adriana Elizabeth González-Cabrera, Ana Caccavari Garza;Software: Gerardo Cifuentes-Nava; Supervision: Ana Caccavari-Garza Validation: Gerardo Cifuentes-Nava. Visualization: Gerardo Cifuentes-Nava. Writing - Original Draft: Ana Caccavari-Garza; Writing - Review & Editing: Ana

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Competing interests

The authors declare that they have no conflict of interest.

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