Tatuoca Project: Automated data extraction from magnetogram images

Keanu Frota Sales*, Raissa Moraes Baldez‡, Pericles Lopes Machado*,
Vinicius Augusto Carvalho de Abreu*, Jacquelin Teresa Camperos-Reyes†,
Cristian Berrío Zapata†, Cristiano Mendel Martins‡
* Institute of Exact and Natural Sciences – Federal University of Pará
(UFPA), P.O. Box 479 – 66.075-110 – Belém – PA – Brazil
† Institute of Applied Social Sciences – Federal University of Pará
(UFPA), P.O. Box 479 – 66.075-110 – Belém – PA – Brazil
‡ Institute of Geo-sciences – Federal University of Pará (UFPA),
P.O. Box 479 – 66.075-110 – Belém – PA – Brazil
keanu.sales@icen.ufpa.br, raissa.baldez@ig.ufpa.br, pericles.machado@seequent.com,
{vabreu, jacquelin, berriozapata, mendel}@ufpa.br

***Abstract*—The Earth's magnetic field acts as a natural shield against solar radiation, with several magnetic observatories established around the world. Among them, the Tatuoca Magnetic Observatory, located in the equatorial region, stands out for the intense variations of the field in this area. Its 50 years of historical records are fundamental to the study of the Earth's magnetic field. However, preserving these records faces significant challenges, as they degrade over time. To prevent this loss, the Tatuoca Project proposes the computerized extraction of data from these records and making this information available to the global scientific community. Using image processing and data analysis techniques, including clustering methods such as DBSCAN, the project aims to transform the physical records into accurate and accessible digital formats, as well as enabling automatic extraction, replacing the time-consuming manual work of data extraction.**

I. Introduction

The Earth's magnetic field is a complex phenomenon, generated by the contribution of sources both internal and external to the planet, which vary both in time and space. Studying the magnetic field not only makes it possible to understand the physical processes taking place inside the planet, but it is also an important tool for navigation, space weather, and the exploitation of natural resources. One of the main ways of collecting data on the field is through magnetic observatories, which are fixed places where the magnetic field is continuously observed. Considering the Cartesian system, the Earth's magnetic field can be expressed in 7 different components: X is the north component of the field; Y is the east component; H is the horizontal field; Z is the vertical component; F is the total intensity of the field; D is the angle between the North and Horizontal components and I is the inclination between the H and F components as shown in Figure 1.

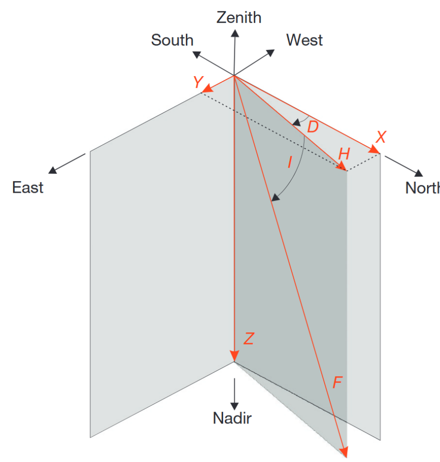

Fig. 1. Components of the Magnetic Field. Source: [1]

Observatories have two types of observations: relative and absolute. Relative measurements are automatic; three pieces of equipment record the variations of the field over time in three different components (H, D, and Z, for example) at a fixed frequency. Absolute measurements are made at least once a week by trained technicians. These absolute measurements are essential because they constitute the baselines that serve as a reference for the variations observed in the relative measurements. Before the digitalization of observatories, the equipment responsible for relative field measurements was mechanical, known as variometers. They used a set of magnets, mirrors, a flashlight, and quartz wires to record the field variations on photographic paper (Figure 2); this record is known as a magnetogram [2], [3] (Figure 3). This operation created a magnetogram for each day, so observatories have created vast collections of magnetograms, many of which exist only on physical media and are susceptible to degradation over time. Therefore, it poses a problem as the loss of such a record harms the understanding of Earth's magnetic field, which requires long time series to study some of its characteristics, as well as science production and communication associated with the observatory. Thus, some observatories have begun to develop plans to digitize these collections and make the data available to the community. Another incentive to develop a strategy to digitize and extract data from magnetograms is to increase data resolution, as the original operation provided magnetic values at hourly intervals for each component, known as *Hourly Mean Values* (HMV). Therefore, the possibility of acquiring data at minute intervals (as is common now in many observatories using modern equipment such as DI Fluxgates) for this record will allow an large dataset with better resolution the study of magnetic phenomena such as magnetics storms with better precision.

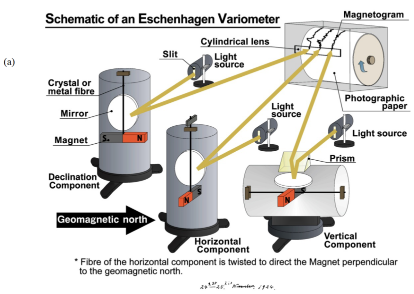

Fig. 2. Classical variometer schematic. Source: [4].

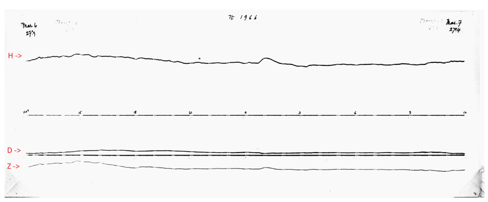

Fig. 3. Magnetogram of Tatuoca showing the H, D and Z components. The other lines are time measurement baselines. Source: the author himself.

In this context, the project "Archive of the Tatuoca Magnetic Observatory: preservation and digitization of physical record data generated between 1957 and 2007" [5], [6] aims to rescue, organize, preserve, digitize and disseminate the physical archives of the Tatuoca observatory in Belém of Pará (TTB acronym in the INTERMAGNET), Brazil. TTB is considered an important data source for the scientific community for two reasons: its location and proximity to two different magnetic field phenomena. TTB lies near the Magnetic Equator, a region where the magnetic field has zero inclination, and is under the influence of the Equatorial Electrojet, a feature of the field originating from the complex interactions between electric current systems, the magnetic field geometry, and solar radiation in the region. South of the observatory lies the South Atlantic Anomaly, a region over Brazil where the field shows low intensity to the point where it poses risks to radio communication, satellites, and space missions that go through it. Nowadays, most observatories are in the Northern Hemisphere, creating an inhomogeneous geographical distribution of data that hurts magnetic field modeling and secular variation studies.

Thus, TTB data is invaluable to help fill this gap. Therefore, for TTB records, the digitization guarantees the preservation of this magnetic knowledge, benefiting the scientific community and society. In addition, the project will modernize access to this data, facilitating research and analysis that was previously limited to the physical format of the records. To this end, this large-scale project relies on a multidisciplinary team specialized in Archival Science, Computer Science and Geophysics. The union of different areas of knowledge allows each aspect of the project to be supported by a specialized technical team, thus generating an exchange of knowledge between these areas and enriching the educational value of the project as a whole.

II. Previous works on data extraction from magnetograms

One of the earliest attempts to digitize and extract data from magnetograms is the work of [7]. The authors scanned the magnetograms with an A4 scanner at 150 DPI, which they judged sufficient to recover minute-resolution measurements. They implemented a semi-automatic pipeline (in Turbo C and Basic) to use after scanning, required an operator to mark the start and end of each trace. Trace detection used a moving-window strategy to balance points above and below and thus define a midpoint, taken as the curve location. Because magnetograms often show discontinuities — from mechanical faults, magnetic storms, or maintenance — the software flagged segments for later manual handling. Crossings between different traces also prevented full automation: the algorithm could not reliably decide which line to follow, so the operator manually tracked the correct curve to continue extraction.

In Japan, [8] created a digital magnetogram database by manually writing Hourly Mean Value (HMV) tables and scanning or photographing the records. Later, [9] used 600 ppi scans and an algorithm capable of extracting one-minute data, reaching a 7.5-second resolution, much higher than the usual hourly HMVs. Their method detected baselines and time marks through pixel brightness and position, as by rule they must form a straight line, then found midpoints for extraction. As for trace curves, which naturally vary vertically, were identified by fitting into a small elliptical locus progressing forward in time with minor up-and-down deviations. For line-crossing events, the algorithm still requires manual action to mark the lines, so the algorithm knows where to go next.

In Canada, [10] showed how they approached this by framing the magnetic record as a convolution of the signals from the point light source and its modified path by the variometer, thus creating a record as an Airy Disk. The deconvolution of these signals would, in theory, reveal the original record. Their process scanned TIFF images with a resolution of 1964 x 6236 pixels. With that, their methodology employs 4 steps: (i) image preprocessing, (ii) tracing and pattern detection, (iii) trace interpretation and (iv) baseline subtraction and stitching. This methodology works well for the majority of magnetograms, but it also fails in line-crossing events. When this happens, the algorithm flags the magnetograms to be run into a series of custom algorithms made for specific events for each type of crossing. This approach allows a semi-automatic processing.

In the UK, [11] explains how observatories started the digitization and data extraction for their records. They used an open-source software called Engauge Digitizer to reconstruct the magnetogram curves from a scanned photo, where they manually input the image and axes coordinates to reconstruct digitally the magnetogram into the software. Then, the software outputs a file with all the curves coordinates. Besides the extraction process, the UK team also made publicly available all the scanned images and associated Yearbooks on a web service. These are just a few examples to show how the digitization process is long because it is semi-manual, with only a few steps being fully automated, characterizing a time-consuming process.

III. Image processing

Several libraries for image processing are available nowadays. For this work, we used OpenCV, a library written in C++ that, in the Python environment, operates with multidimensional NumPy arrays, expanding the processing possibilities, since several libraries use NumPy as a base.

The computational process involves several steps, from standardization of image size to automatically extracting the measurement curves. Techniques such as Gaussian-Binary Thresholding, Gaussian Blurring, and edge detection via Canny improve the image quality and make it easier to identify the relevant data. Subsequently, the DBScan (Density-Based Scan) algorithm [12] is used to identify and group points on the measurement curves, allowing meaningful information to be segmented. First, the algorithm extracts the curves, and then a set of calculations is done to convert the extracted data into magnetic units, such as gammas or nanoTesla. This conversion step involves converting the differences in pixels to millimeters and then applying the equations in the Tatuoca Observatory yearbooks. These equations make it possible to determine precise values for the geomagnetic variables, ensuring that the digitized data retains its scientific validity. After listing the necessary steps, it is possible to plan the code structure responsible for this processing.

A. Standardization of image size

First, the magnetogram image is modified to give it a standard size in terms of height and width. The purpose of this is to ensure that differences in size in the input image do not impact the image processing result. This modification is performed using the cv2.resize [13] function in OpenCV.

B. Removing noises from images

A common challenge in magnetograms, as already mentioned, is the degradation of the paper over time, requiring specific treatment to remove imperfections. OpenCV stands out in this respect, offering various noise reduction functions. After a detailed analysis, we applied the following:

- Gaussian-Binary Threshold: Clearly highlight objects in the image.
- Gaussian Blur: Smooth the image by eliminating small noises.
- Canny edge detector: Identify and refine the contours of objects.
- Skeletonization: Simplify the image by extracting only its skeleton.

The Gaussian-Binary Threshold implementation uses OpenCV's cv2.adaptiveThreshold function [14]. This function binarizes the image by comparing the current pixel values with the weighted sum of their neighbors, determined by a Gaussian kernel. As a result, element identification in the image, such as measurement curves and reference lines, is improved, providing a clear distinction from the background. The code is in [15]. For Gaussian blur, we use the cv2.GaussianBlur function [16], which blurs the image to smooth it out and reduce noise and imperfections. This technique applies a convolution with a low-pass filter (Gaussian filter). The main advantage of using this function is that it improves the continuity and detection of elements in the image, an advantage for the Canny filter stage. Like the previous one, the code is in [15]. Figure 4 shows the magnetogram in its original form. In contrast, Figure 5 shows the magnetogram after applying the two Gaussian processes, including Threshold and Blur. A better explanation of both algorithms can be found in [17].

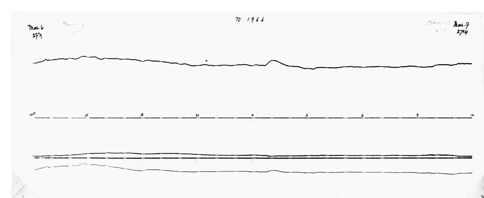

Fig. 4. Image before any kind of processing. Source: [18]

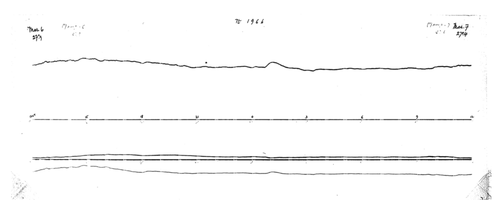

Fig. 5. Image after both Gaussian processes. Source: the author himself.

The central processing includes the Canny filter [19], whose function is to identify the edges present in the image using cv2.Canny. This filter detects contours and significantly reduces image noise. This step simplifies the task of skeletonizing the image by identification of the contour lines of the elements. Figure 6 illustrates the result of Canny processing, while the code is available in [20]. As with the previous algorithms, a better explanation can be seen at [17]. The skeletonization function, on the other hand, is custom-made. Written in Cython, a mix between C and Python, it does not depend on external libraries. The logic behind this function is straightforward, as illustrated in the Skeletonize Algorithm [21]. The algorithm goes through the image columns searching for white pixels. When it finds one, it checks for the presence of another white pixel at a predefined distance. If both are detected, it calculates the midpoint between them, thus determining the skeleton. The skeletonization could introduce some millimetric errors in the result, but it is a very small error when compared to the manual extraction process, making it irrelevant. The result of this process can be seen in Figure 7.

Fig. 6. Image after the Canny filter applied. Zoom applied. Source: the author himself.

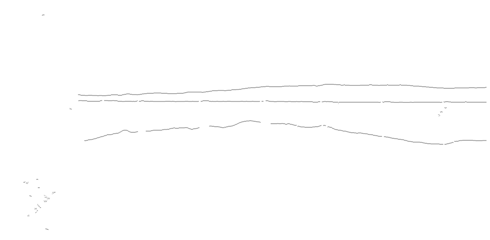

Fig. 7. Image after skeletonization. Zoom applied. Source: the author himself.

C. *Extraction of curves*

The skeletonization processing generates an image similar to a point cloud that initially has no meaning. The following processing stage requires the identification of relevant pixels to serve as magnetogram measurement data and then its grouping. To do this task, we selected the DBScan (Density-Based Scan) algorithm [12], a well-known machine learning and data mining algorithm, with its implementation available at [22]. It identifies densely clustered points within a set, forming organized subsets. When applying DBScan in Tatuoca data, identifying grouped points means locating the reference lines and measurement curves of the magnetograms, making it possible to filter out useful information from irrelevant information. In order to work, the algorithm requires a few parameters: the set of points to be clustered, an anisotropy to adjust the distribution of the points, and two tolerances, one in radius and the other angular, which helps in the search for neighbors. These parameters are:

- The set of points is the image points resulting from the skeletonization for clusterization.
- Anisotropy is an ellipsoid that distorts the space of the points, bringing them closer together or further apart in different directions, depending on the parameters defined.
- The radius tolerance defines the maximum radius for considering neighboring pixels as part of the same cluster and is essential for forming groupings.
- The angle tolerance sets the maximum angle allowed between neighbors for them to be part of the same cluster, a crucial parameter for adequate clustering.

Based on these factors, adjusting the DBScan parameters is strictly necessary to ensure the correct processing of the magnetogram data, especially when the goal is to use DBScan automatically, without human intervention. However, doing this without the problem of crossing lines is proving to be quite a challenge, as we have some TTB magnetograms with this issue. We will discuss this issue further in the Next Steps section. For now, the adjustment works well on some test images, with the measurement curves identified by DBScan shown in Figure 8.

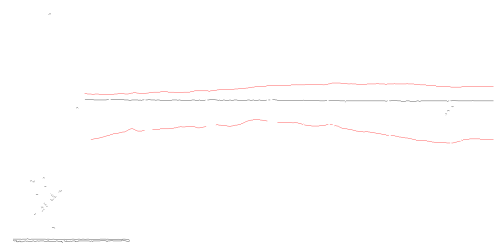

Fig. 8. Image detailing the DBScan detection. Zoom applied. Source: the author himself.

D. *Converting pixels into units of measure*

The data obtained by the DBScan goes through another processing stage to become useful magnetic information, which consists of archiving the knowledge. Along with the magnetograms, magnetic observatories produce *Yearbooks*, books containing the metadata needed to process the magnetograms and other records of the observatory's activity. It is through these books that the information extracted from the magnetograms can be converted from pixel information to degrees or nanoTesla. Therefore, in order for the algorithm to provide the correct values converted into magnetic units, it is necessary to know the standard dimensions in millimeters of the sheets and the conversion parameters from to magnetic units available in the book in the year. In this way, the algorithm must follow the steps below:

- First, based on the reference lines and the measurement curves extracted by DBScan, the algorithm calculates the difference in pixels between them and stores the results for later use.
- Second, the differences in pixels are converted to millimeters, taking the total dimensions of the image in millimeters, and pixels as the basis for the conversion.
- Third, with the differences in millimeters, the algorithm determines the corresponding value in magnetic units using the formulas and parameters available in the yearbooks.

That said, in order for the conversion to be carried out properly, we first need to have the dimensions of the magnetogram on paper and standardize the size of the image. From the files we have, each of the magnetograms is 510 by 200 millimeters.

From there, we adopted a multiple of this size for the image, with 2000 rows by 5100 columns being the chosen size. This means that each pixel is worth 0.1 mm of the original image.

With this information, we can make the conversions using the formulas described in the yearbook. As shown in the Figure 3, Tatuoca's magnetograms have the components H, D and Z, and the yearbook contains a conversion equation for each component. Thus, the formulas presented for the H, D, Z components and the temperature are as follows: $H = H_0 + S_H n_H - q_H(T - T_s)$; $D = D_0 + S_D n_D$; $Z = Z_0 + S_Z n_Z - q_Z(T - T_s)$ and $T = T_0 + S_T n_T$. From this, we can see that all the variables follow the equation

$$X = X_0 + S_X n_X - q_X(T - T_0), \quad (1)$$

where X is the variable under analysis (H, D, Z or T), X_0 is the base value of the variable, S_X is the conversion from millimeters to the unit of measurement of the variable, n_X is the variation of the variable in millimeters, q_X is the temperature coefficient of the variable, T is the base temperature and T_s is the temperature variation. Declination and temperature do not depend on thermal variation to be measured ($q_X = 0$), eliminating the final term from the equation. Based on this general formula, it is possible to create an algorithm that converts the pixel differences into millimeters and then into the desired unit for each variable. The algorithm [23] demonstrates this conversion, implemented as a vectorized function in terms of NumPy arrays.

IV. Next steps

Future steps include testing the entire algorithm extensively in various use cases once a large part of Tatuoca's magnetograms finish the scanning process. The tests include magnetograms with few flaws, as seen in Figure 4, and many flaws, as seen in Figure 9. The algorithm works well in images like the first case, but it is not very accurate for ones in the second case because there are crossed lines, with the processing results shown in Figure 10. To do this, the processing pipeline must be modified. In the Skeletonization part, the processing must be modified to make line detection more continuous. In the DBScan part, the process must be adjusted more precisely to detect the lines being crossed in order to separate them. This hasn't been done yet because we don't yet have enough images of Tatuoca to adjust the algorithm. As more images are scanned, more adjustments will be made.

The Tatuoca project started interviews with the technicians at the Tatuoca and Vassouras magnetic observatories. These interviews are fundamental to understanding how manual data extraction was done in the past, thus making it easier to understand the steps the algorithm must follow to extract the data automatically. In addition, the identification of the different data sources needed to process the magnetogram data is underway, with sources that go beyond yearbooks. In addition, work is underway to identify the different data sources needed to process the magnetogram data, with sources that go beyond yearbooks. This includes processing the information in the yearbooks, organizing it into tables and cataloging it. This data in tabular form will serve as the basis for the automatic processing of the algorithm described here, since the conversion of the data to magnetic units requires it. This cataloging will also be done with the results of the manual extractions that we have and with the data that IAGA (International Association of Geomagnetism and Aeronomy [24]) has, precisely so that we can conflate the information and adjust the algorithm as necessary.

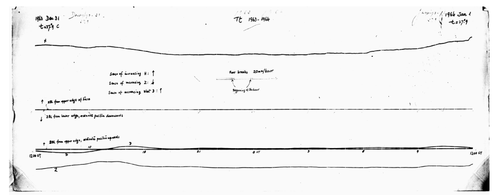

Fig. 9. Magnetogram with the crossing lines problem. Source: [18]

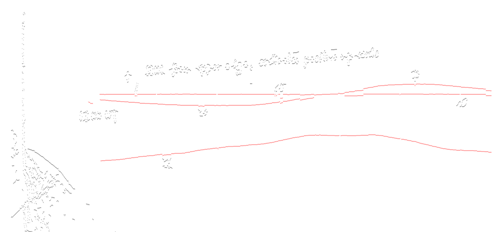

Fig. 10. Detection on the magnetogram with crossing lines. Zoom applied. Source: the author himself.

After testing and correcting the code for the most varied types of use, the next step is to make the data from all the magnetograms available to the public. The data resulted from the conversion of units will be stored according to the IAGA output standard, and all images must include the structuring and configuration of the metadata layers needed to document all their source information, so as not to lose the context of the data and its archival validity. All of this will be done with the aim of increasing the amount of data we have from the Tatuoca paper magnetograms in the IAGA repository, since the current amount is very low, as the Figure 11 shows.

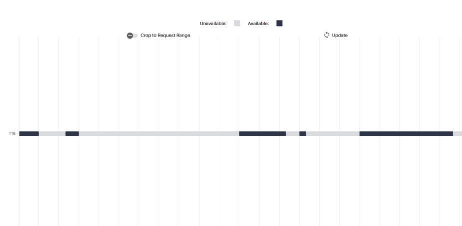

Fig. 11. Availability of TTB magnetograms in WDC of Geomagnetism. Source: [25]

V. Conclusions

The Tatuoca Project proposes the use of computational techniques for the extraction and digitization of geomagnetic data, in which our study of the state of the art at the observatories showed that only Kakioka and Tatuoca have developed automation that seems to be considerable [5], [6]. Compared to [7], Tatuoca uses a more modern language and has more automated steps, while compared to [10] we are using image processing instead of signal deconvolution processes, and our software is open. Finally, compared to [11] we are developing our own software instead of using a existing software, in addition to having more automated processes.

The project transforms analog records into structured digital information using libraries such as OpenCV for image processing and the DBScan as a clustering algorithm. The computational pipeline involves removing noise, segmenting key elements of the magnetograms, and converting measurements into standardized units, ensuring accuracy and reliability in the processed data.

The application of these methodologies aims not only to improve the quality of digitization but also to enable automation of the process, reducing the need for manual intervention and increasing the efficiency of data extraction, with the aim of even improving the granularity of data, from one data per hour to one data per minute. The integration of image analysis algorithms and mathematical modeling will allow the reconstruction of geomagnetic measurements digitally, benefiting other Observatories in the INTERMAGNET - IAGA network. This step would release a significant amount of data recorded over the last 100 years, which would be unprecedented.

Acknowledgments

The Tatuoca Project is part of the global research network Interpares Trust AI, and has received funding from the Federal University of Pará, the International Council on Archives (ICA) and CAPES under the PROCAD AMAZÔNIA RTCIC-DS project. We thank them for their financial support and for making this project possible.

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