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DISSERTAÇÃO DE MESTRADO

Planning the new Brazilian Magnetic Repeat Station Network

RAISSA MORAES BALDEZ

Belém – Pará
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Dissertação apresentada ao Programa de Pós-Graduação em Geofísica do Instituto de Geociências da Universidade Federal do Pará para obtenção do título de Mestre em Geofísica.

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Linha de pesquisa:
Incorporação de vínculos no problema geofísico inverso

Orientador: Prof. Dr. Cristiano Mendel Martins

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Banca Examinadora:

Prof. Dr. Cristiano Mendel Martins (Orientador)
Universidade Federal do Pará

Profa. Dra. Katia Jasbinschek dos Reis Pinheiro (Coorientadora)
Observatório Nacional

Dr. Achim Morschhauser
GFZ German Research Centre for Geosciences

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RESUMO

Uma rede de estações de repetição magnética é uma coleção de pontos fixos onde o campo magnético da Terra é medido em intervalos de 2 a 5 anos. A pesquisa mostrou que a rede brasileira atual está em desordem. Por isso, este trabalho tem como objetivo oferecer ideias para o planejamento da nova rede de estações repetição. Para cumprir o objetivo definido, foram realizadas pesquisas sobre a rede de diferentes países, bem como a análise da atual rede brasileira. Isso permitiu a criação de três critérios de seleção para determinar quais estações serão incorporadas à nova rede. Os critérios são a distribuição geográfica, o número de ocupações de uma estação e o valor RMSE entre a estação e o modelo de campo global IGRF13. Os resultados mostram um resumo das redes que ofereceram ideias para o planejamento, a seleção de 50 estações de repetição para a nova rede e a criação de três modelos diferentes para a configuração da nova rede brasileria de estações de repetição

Palavras-chave: geomagnetismo; rede de estações de repetição; variação secular; Brasil.

ABSTRACT

A magnetic repeat station network is a collection of fixed points where the Earth's magnetic field is measured at intervals of 2 to 5 years. Research showed that the present-day Brazilian network is in disarray. Because of it, this work aims to offer ideas for the planning of the new repeat station network. To accomplish the defined objective, research about the network of different countries was conducted, as well as the analysis of the present-day Brazilian network. This allowed the creation of three selection criteria to determine which stations will be incorporated in the new network. The criteria are the geographical distribution, the number of occupations a station has, and the RMSE value between the station and the IGRF13 global field model. Results show a summary of the networks that offered ideas for the planning, the selection of 50 repeat stations to be in the new network, and the creation of three different models for the configuration of the new Brazilian repeat station network.

Keywords: geomagnetism; repeat station network; secular variation. Brazil.

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1 INTRODUCTION

1.1 EARTH'S MAGNETIC FIELD, AN OVERVIEW

The terrestrial magnetic field permeates all layers of the Earth system, from its interior to the atmosphere, exerting effects on various natural processes occurring on the planet. An example of this is its role as a protective shield, making it essential for the presence of life on Earth.

The Earth's magnetic field can be expressed at any point at the surface by its vector components. In the Cartesian coordinate system, they are the Total Field F, the Horizontal component H, the Vertical component Z, the North X component, the East Y component, and the angles of Declination D and Inclination I (1.1). To describe the field completely it is necessary to know at least three components, the others are derived through the mathematical expressions (1.6). In practice, this means that it is not necessary to observe all magnetic components during magnetic surveys for example, only three are needed.

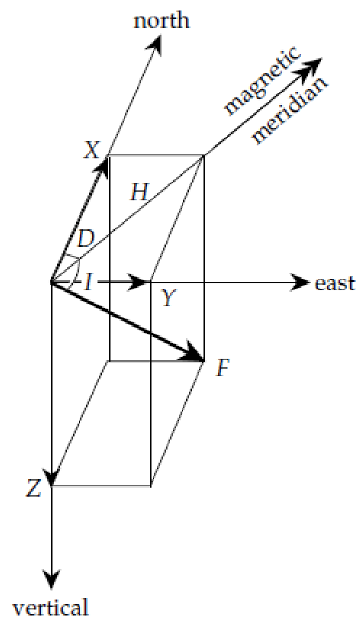

Figure 1.1: Representation of the vector components of the Earth's magnetic field in the Cartesian coordinate system. Source: Lowrie (2007).

$$X = F \cos(I) \cos(D) \tag{1.1}$$

$$Y = F \cos(I) \sin(D) \tag{1.2}$$

$$Z = F \sin(I) \tag{1.3}$$

$$F^2 = X^2 + Y^2 + Z^2 \tag{1.4}$$

$$D = \arctan\left(\frac{Y}{X}\right) \tag{1.5}$$

$$I = \arctan\left(\frac{Z}{\sqrt{X^2 + Y^2}}\right) \tag{1.6}$$

According to Hulot et al. (2015), the Earth's magnetic field can be defined as the sum of all fields produced by different magnetic sources. They extend from inside the planet to the boundary between the Earth's magnetic field and the interplanetary magnetic field created by the Sun. Following this definition, the sources responsible for creating the observed terrestrial magnetic field can be divided into two distinct natures: magnetized sources and electrical currents.

The magnetized sources correspond to rocks that have been magnetized in the past (e.g. igneous rocks recording the local magnetic field after their crystallization process) and the ones that are susceptible to magnetic induction effects. They occur into the so-called solid Earth, from regions above the Curie point in the planet's interior to the surface. On the other hand, the electrical currents represent a more dynamic source, as they are present in different environments within the planet (not only surface and interior as is the case for the rocks). In this category of source nature, the geodynamo process that takes place in the outer core of the planet is the most important one, since it is the biggest contributor to the generation of the magnetic field observed on the surface. However, magnetic fields generated by electrical currents are also present in electromagnetic interactions in the ionosphere, magnetosphere, earth's crust, mantle, and ocean. 1.2 shows the sources that contribute to the existence of the Earth's magnetic field.

When studying Earth's magnetic field, it is a common practice to divide the field into internal and external fields, according to their sources being located inside and outside the planet, respectively. The internal field comprises the core and crustal fields. The core field is created through the movement of electrical currents at the outer core due to its liquid metallic composition and the planet's rotation. This process is known as the geodynamo, and it is the greatest contributor to the magnetic field observed at the surface.

The crustal field arises from the magnetized rocks inside the planet and at its surface. This field is weaker than the core field in intensity, yet it shows variability in strength from place to place. This occurs due to the different ranges of magnetic susceptibility that rocks present. At Earth's surface, the internal field has an intensity of approximately 30

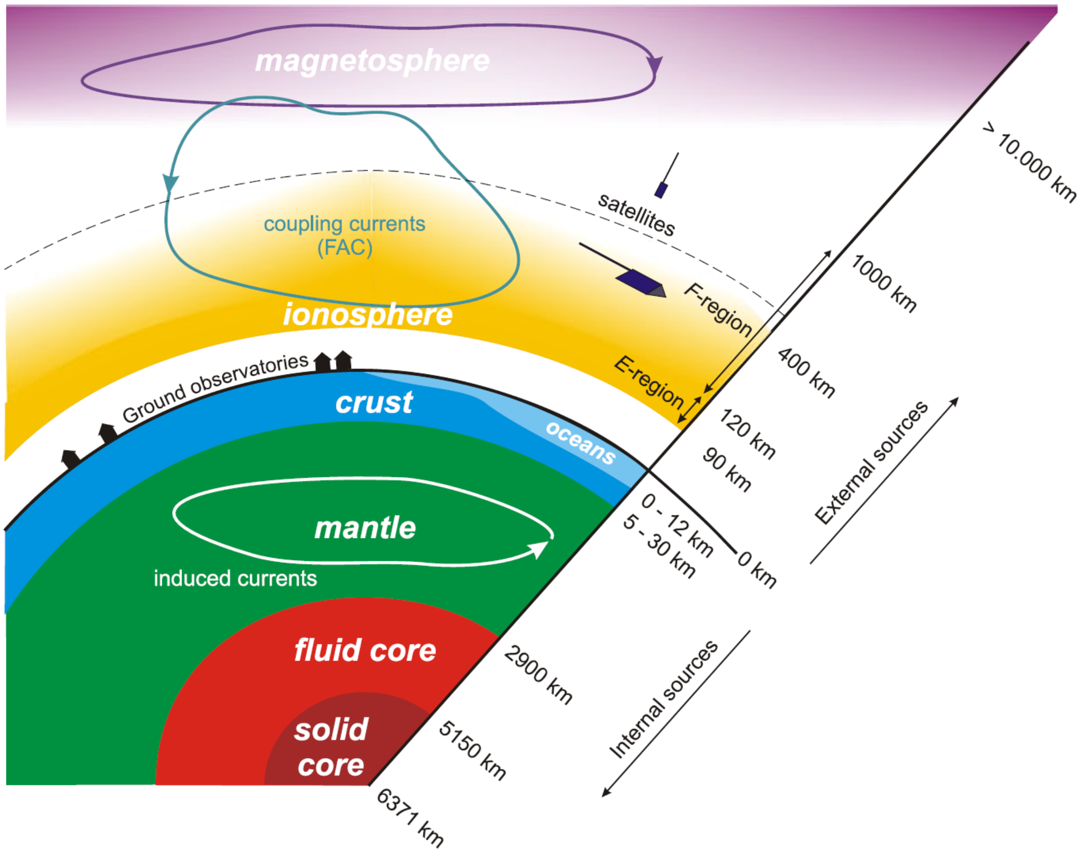

Figure 1.2: Representation of all the different sources that contribute to Earth's magnetic field and their spatial distribution along Earth's system. Source: Olsen et al. (2010).

000 nT at the Equator and 60 000 nT at the poles as is shown in the 1.3. Analyzing this figure, it is clear that the field is not uniform. An example of this is the case of the South Atlantic magnetic anomaly (SAA), a region where the field over South America has low intensity.

The external field comprehends the ionospheric and magnetospheric fields. The ionospheric field exists as a result of the movement of electrical currents in the ionosphere. The magnetospheric field has its origin attributed to electrical currents created by the movement of charged particles in the magnetosphere. Although they have different origins, these fields are coupled, which means they interact with each other. The external field usually has low amplitude when compared to the internal field of approximately 20 nT according to Hulot et al. (2015) but during magnetic storms, this intensity increases and can even cause damage to electrical grids in the surface. 1.4 shows the effects of solar radiation at the ionosphere, creating the Sq current system.

In the 19th century, Gauss developed a mathematical method to describe the field sources into internal and external types known as Spherical Harmonic Analysis. In spherical coordinates at Earth's surface and following specific conditions, the magnetic field can be expressed as the gradient of a scalar potential due to the internal (W_i) and external

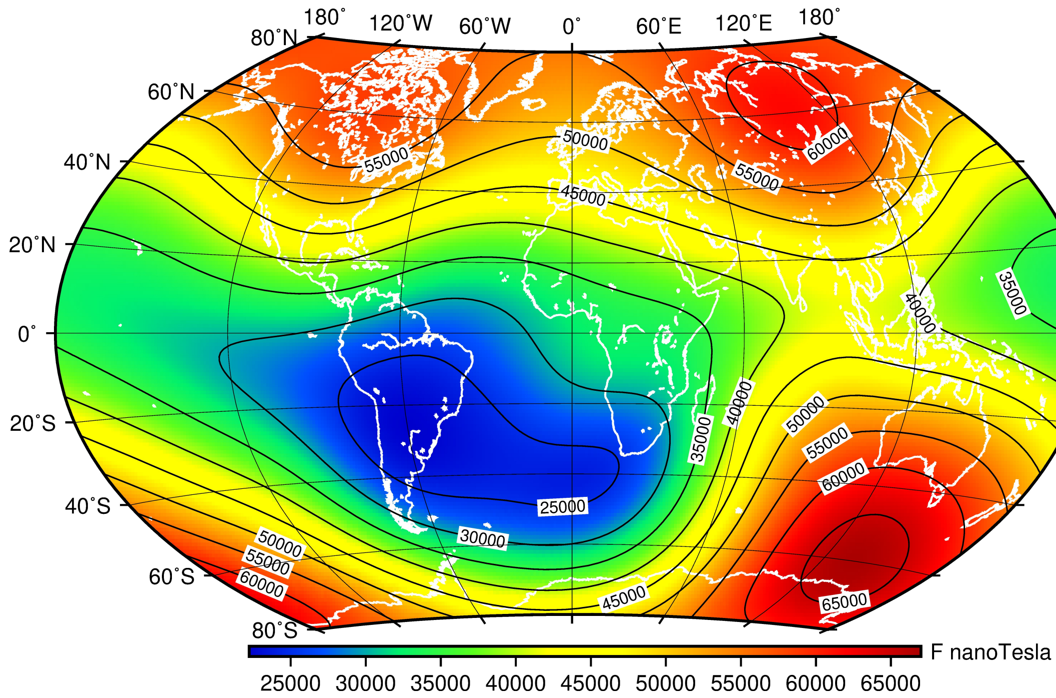

Figure 1.3: Representation of the total intensity of the terrestrial magnetic field calculated by the IGRF13 model. Source: British Geological survey site at `http://www.geomag.bgs.ac.uk/research/modelling/IGRF.html`.

sources (W_e) (Lowrie, 2011):

$$W = W_e + W_i \tag{1.7}$$

The external and internal potentials are given by:

$$W_e = R\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(\frac{r}{R}\right)^n \left(G_n^m cos\,(m\phi) + H_n^m sin\,(m\phi)\right) P_n^m(cos\,\theta),\ r > R \tag{1.8}$$

$$W_i = R\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(\frac{r}{R}\right)^n \left(g_n^m cos\,(m\phi) + h_n^m sin\,(m\phi)\right) P_n^m(cos\,\theta),\ r > R \tag{1.9}$$

Where R is the radius of Earth, θ is the co-latitude, ϕ is the longitude, (G_n^m), (H_n^m), (g_n^m) and (h_n^m) are the Gauss coefficients and P_l^m is the Schmidt normalization. Through this expression is possible to calculate the field components in spherical coordinates and then convert them to Cartesian coordinates (1.1), which are the more used coordinate system at magnetic observatories to express the field intensity values.

The observation of Earth's magnetic field is an ancient tradition, dating from a thousand years or so (Jonkers et al., 2003). The Chinese are considered to be the first civilization to employ the magnetic field as a way of navigation using the compass to measure the declination angle. During the 16th century, the recording of declination was standard

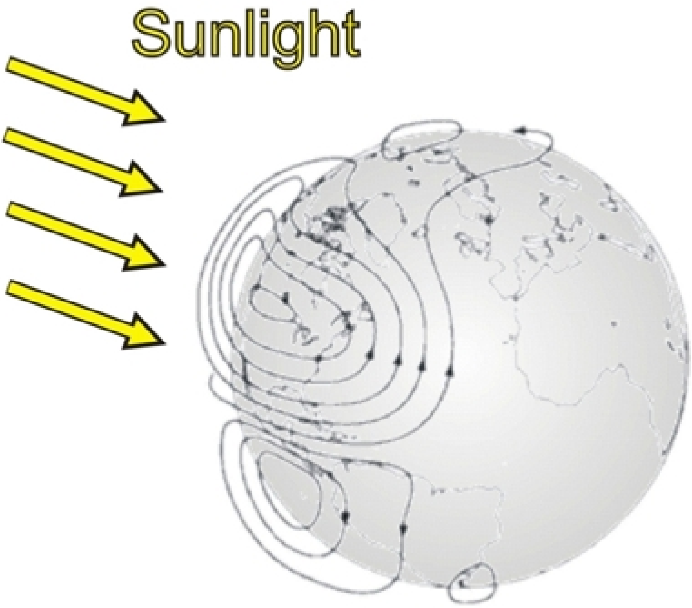

Figure 1.4: Representation of the ionospheric currents responsible for Sq variation during northern hemisphere summer. Source: British Geological survey site at this site `http://www.geomag.bgs.ac.uk/education/earthmag.html`.

practice for navigation (1.5), which created a vast database of measurements that allow the study of the field and its evolution through time (Jonkers et al., 2003). This kind of record is known as a historical record, and it contains information about declination and inclination values, in other words, directional data. It was through the analysis of the declination record at London that Henry Gellibrand discovered that the field had variations both in space and time (Kono, 2015).

Initially, the observations were in terms of the direction of the field, specifically the declination and inclination angles. However, during the 19th century, Gauss was responsible for developing an instrument capable of measuring field strength, allowing records of field strength to begin to be made in different places. This achievement and the conception of the Göttingen Geomagnetism Union by Gauss and Humboldt, which is considered to be the first international organization of geophysics, gave the necessary impetus for the creation of magnetic observatories and the beginning of the standardization of operations relevant to observing and studying the field terrestrial magnetic (Hulot et al., 2015).

Magnetic observatories are scientific stations where the components of the Earth's magnetic field are continuously measured with high accuracy. In addition to data collection, magnetic observatories are responsible for processing this data and making it available for the scientific community through the World Data Centers [1] and INTERMAGNET [2] websites. The observatory data is excellent for studying secular variation as it contains a time series at a fixed location. Besides, observatories follow specific guide-

[1] `http://www.wdc.bgs.ac.uk/`
[2] `http://www.intermagnet.org/`

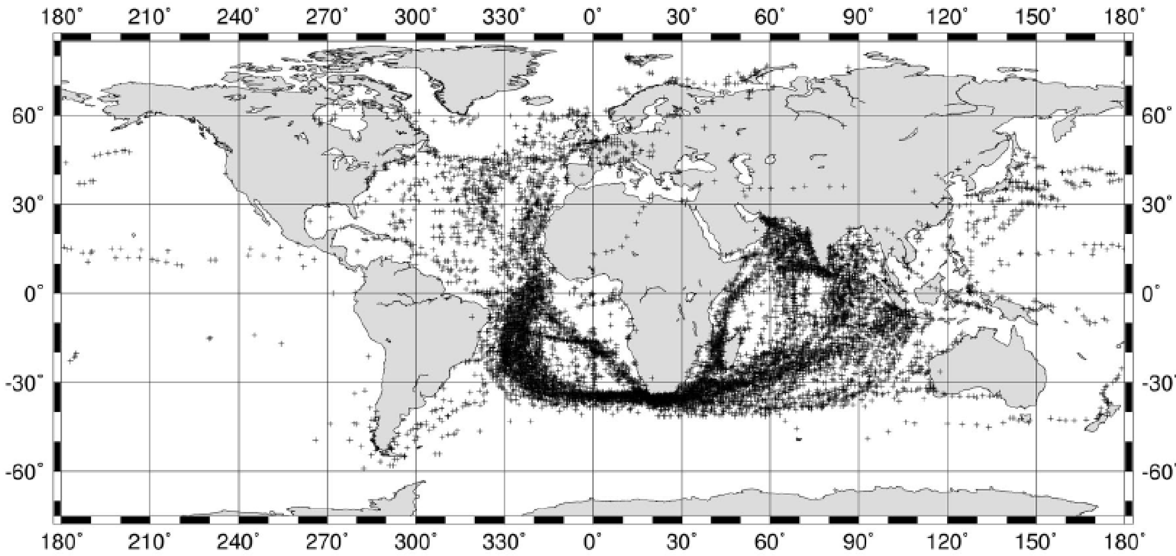

Figure 1.5: Geographical data distribution of declination observations made in 1590–1699. Source: (Jonkers et al., 2003).

lines to ensure that no other magnetic sources interfere with the Earth's magnetic field record. Today, magnetic observatories are one of the most important source of magnetic data, even if their geographical distribution is heterogeneous (Matzka et al., 2010; Rasson et al., 2011; Hulot et al., 2015; Chulliat et al., 2017). 1.6 shows the absolute house of the Magnetic Observatory of Tatuoca and its staff.

Another form of observation is the use of satellite missions. They are currently the most advanced form of field observation, capable of covering large areas, especially those where a good geographic distribution of magnetic observatories is not available. They can act for a few years, measuring the field at regular intervals and constant altitude, creating a homogeneous coverage in the data (Matzka et al., 2010). Currently, magnetic observatories and satellite missions are most responsible for the wide availability of high-quality data.

The historical record, magnetic observatory, and satellite data are extremely important to our continuous observation of the Earth's magnetic field, yet they only offer a glimpse into the field behavior over time, a recent one at that. Since the magnetic field is ancient, the earliest evidence of its existent points it to be around 3.4 Ga years old (Hale and Dunlop, 1984), the historical, observatory, and satellite data give information about its present and recent past. To better understand the field and its evolution, it is necessary to expand the time window of observation. Fortunately, this is possible with the paleomagnetic and archaeomagnetic data.

The paleomagnetic data extend the timescale to millions of years, using ancient rocks as a source of information about the past field (Kono, 2015). Rocks with specific magnetic properties are able to store magnetic field information during their formation period,

Figure 1.6: Magnetic Observatory of Tatuoca, Belém, Brazil. This image shows the absolute house and in front of it the observatory staff. Source: website about the magnetic observatories in Brazil at `https://observatoriosmagneticos.com/obsermagneticos/`.

creating a magnetic remanence. Usually, this process is more common in igneous rocks, but sedimentary rocks are also able to store information about the magnetic field through other processes. This type of record is the oldest available on the magnetic field, and it is capable of giving us information about large-scale variations such as reversals, periods of superchrons, and excursions, for example, besides being useful for the study of continental drift motion.

The archeomagnetic data covers the timescales of tens of thousands of years or less. It comes from the study of rocks and ancient artifacts made of ceramic, as such artifacts contain information about magnetic remanence. Because they are of human origin, the period they cover is much shorter than the geological record. Thus, it is noted that there is a large diversity in types of observation of the Earth's magnetic field.

The analysis of vast magnetic data of different origins showed that Earth's magnetic field has spatial and temporal variations in different scales (1.7). These variations manifest in short time scales like magnetic storms (which occur in hours) to long time scales, as is the case for polarity reversals, which are observable in the geological record, spanning millions of years.

Among the various forms of field variation that exist, the one of greatest interest in this work is the Secular variation, which Bloxham and Gubbins (1985) defined as field

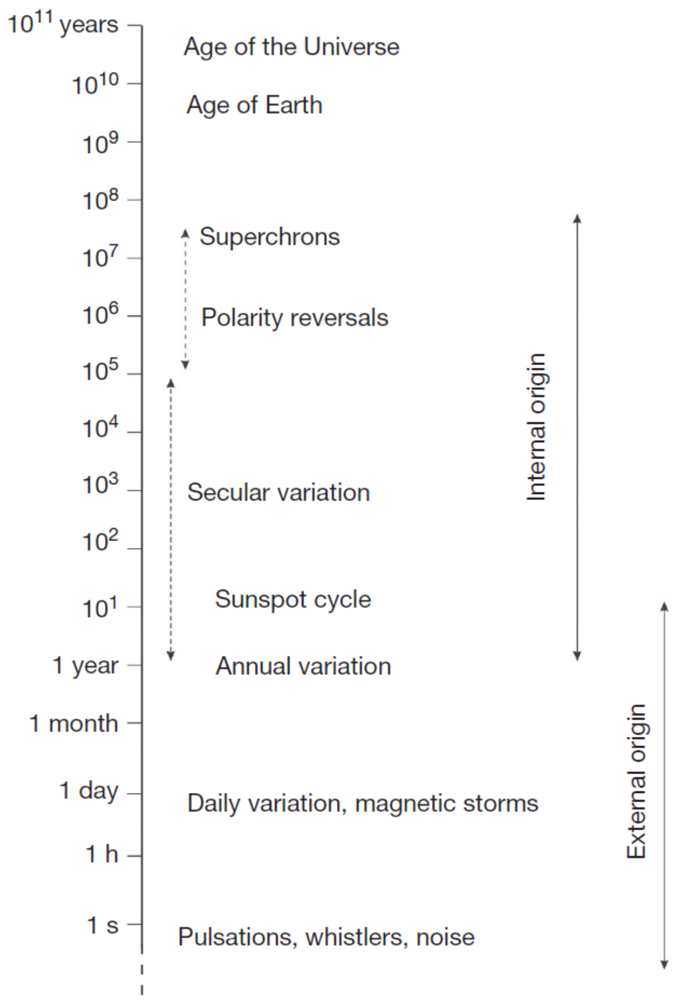

Figure 1.7: Comparison between Earth's age and the timescales of the terrestrial magnetic field. Source:Turner et al. (2015).

variations on a time scale of tens to hundreds of years, being associated with changes in core dynamics. Examples of this type of variation is the polar wandering (Amit and Olson, 2008), changes in the field intensity (Olson and Amit, 2006; Gubbins et al., 2006; Finlay, 2008; Terra-Nova et al., 2017), the westward drift (Bullard et al., 1950; Dumberry and Finlay, 2007; Livermore et al., 2013), and the geomagnetic jerks (Mandea et al., 2010; Pinheiro and Travassos, 2010; Brown et al., 2013; Torta et al., 2015; Aubert and Finlay, 2019).

As these facts show, the Earth's magnetic field is very complex. Nevertheless, its understanding is fundamental to humanity due to its impacts on society, from navigational purposes to environmental effects (Kerridge, 2019). Understanding the spatial and temporal variations of the field provide critical clues for understanding dynamic processes in the Earth system, which range from phenomena present inside the planet (the movement of the outer core, for example) to interactions between the external magnetic field and the solar wind, characterizing the space climate. Magnetic storms can cause severe damage to electrical networks, communication, and navigation systems, as well as damage to satellites. Therefore, to study and understand the dynamics of the field, it became essential to observe the magnetic field in a continuous and geographically well-distributed way as far as possible.

1.2 MAGNETIC REPEAT STATION

1.2.1 Definition

Another way to collect data about our planet's magnetic field is through magnetic repeat stations. A magnetic repeat station refers to the place where observations of the Earth's magnetic field are made periodically, at intervals of 2 or 5 years, depending on the station's objectives.

Usually, the repeat station network purpose is to supplement data from a magnetic observatory and study secular variation. This objective requires an occupation frequency of two years. For the production of magnetic charts, this frequency requirement can be relaxed to a five-year interval. Although, Santis et al. (2013) argue in favor of a reduced occupation frequency for the stations. Using concepts from chaos theory and ergodicity, they show how it is impossible to predict the field evolution by six years or more in the future. Therefore, for regions where the field experiences more changes, a reoccupation frequency of two years is better to minimize errors in the field prediction.

The repeat station location must be duly marked (through the construction of a non-magnetic pillar or tile) and registered to avoid positioning errors in future occupations. This procedure is necessary to minimize the effects of spatial variation in the field due to not being in the same location as the previous occupation (Barraclough and De Santis, 2011). 1.8 shows an example of a repeat station and the usual equipment used during its operation.

It is essential to pay attention to the definition of the repeat station so that there is no confusion with the magnetic ground survey practice. According to Newitt et al. (1996), the main difference between these two forms of observation is how the observations themselves are made.

Repeat station coordinates must be carefully marked so that there are no errors in the reoccupation. In addition, the removal of the effects caused by variations in the external magnetic field is fundamental, as these variations affect the study of the secular variation. Therefore, it is common for repeat station operations to occur when there is no magnetic disturbance caused by the external field, so observations are done mainly early in the morning or during the night, when there is no action of the Sun on the ionosphere.

Ground surveys do not require knowledge of the exact location of a station. Their main goal is to obtain scalar or vector field values representative of the region in question. The external field influences are corrected at the level of diurnal variation only. The book *IAGA*

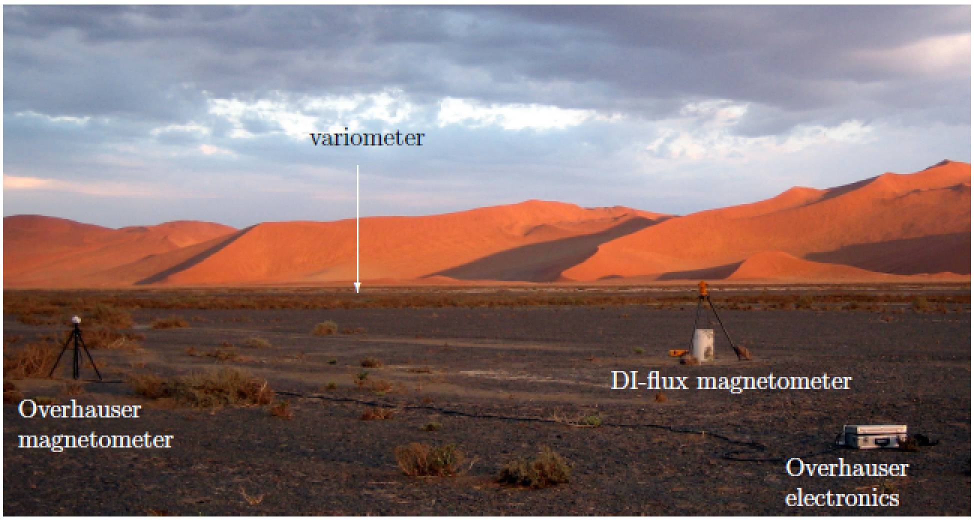

Figure 1.8: Magnetic Repeat Station localized at Sossusvley in the Namib desert, East Namibia. Source: Geese (2010).

Guide for Magnetic Repeat Station Surveys by L.R. Newitt, C.E. Barton, and J. Bitterly is the major reference about magnetic repeat stations. This book is publicly available at the INTERMAGNET website at `http://www.iaga-aiga.org/index.php?id=guides`.

1.2.2 Installation requirements

As is the case when planning the construction of a magnetic observatory, the choice of where to install a repeat station takes into account several factors. Among them are the following (Newitt et al., 1996):

- The magnetic field of the chosen location must be representative of the region
- The magnetic field of the site must not have disturbances due to magnetic anomalies of crustal origin
- The area around the station must be electrically homogeneous
- The magnetic field around the station marker must be uniform
- The area around the station must be free from external magnetic sources such as electrical rails, transmission lines, etc
- The chosen area must have ease of access
- The presence of landmarks that serve as a reference
- The station location must be carefully selected to ensure that it can meet all of the above requirements for a long time

A field representative of the region means that it must represent the field of the region where the station is located. This criterion is more used when the station has the function of observing the field for the purpose of creating magnetic charts of the regional field. In terms of studying secular variation, this criterion is not the most important.

A place with no magnetic disturbances implies a region free from external sources that could alter the registered field. For example, crustal anomalies are problematic in basaltic regions because the field gradient is high. This type of environment requires specific care when reoccupying the station so that the gradient does not affect the observations.

A homogeneous area around the station denotes that it should not be susceptible to induction effects. This is necessary to avoid magnetic fields that could disrupt regional field observations. Likewise, the absence of artificial sources is also an important criterion to avert contamination of the terrestrial field observation as removing the effect of these sources on the data is extremely difficult.

The ease of access requirement is essential for the maintenance of the station. Difficult access locations demand more financial support to maintain, which, in some cases, makes the repeat station operation too costly. This category also encompasses more general issues such as who is responsible for the land where the station is installed (governments, private entities, etc.), which in practice dictates the process for accessing and operating the station regularly, as well as the security to prevent the damage or loss of the station.

Reference marks help determine the azimuth and locate the station during field operations. It is advantageous in stations where the marking tiles are buried for safety reasons or when vegetation growth obscures the vision.

The station installation location must be well thought, as a change of location is undesirable after the station is built (it disrupts the time series for secular variation studies). It cannot be too close to cities, as its expansion would cause problems for the station data quality. For more details on the complete installation process, please consult Newitt et al. (1996).

1.2.3 Field operation

The operation of a repeat station is not a trivial task, so it is recommended that at least two people, a trained technician, and an assistant, are available to carry out an observation campaign on the repeat stations network.

Before the field operation summary, it is essential to define the two types of magnetic measurements performed at a repeat station: absolute and variometer measurements. Turner et al. (2015) states that it is necessary to register at least three different components to describe the magnetic field entirely. Unfortunately, the available instruments do not possess the ability to completely measure Earth's magnetic field in a continuous and automated format with the required accuracy. Therefore, a two-step observation process using absolute measurements and variometers is needed.

Turner et al. (2015) defines absolute measurements as declination, inclination, and total field observations that are done manually by a trained technician. Presently the DI flux and the proton magnetometer instruments are the most common equipment for absolute observations due to their high accuracy and ease of use. This type of measurement is critical because they establish the baseline needed for the variometer data.

The variometer objective is to monitor the time changes of a magnetic field component relative to a fixed baseline. The observed components are usually the North X, East Y, and vertical Z components. The state-of-the-art equipment used recently is the fluxgate. As stated previously, the merge between the baseline from the absolute measurements and variometer data produces a complete description of the field. This setup is the same for both magnetic observatories and repeat stations. The main difference between them is that an observatory measures the field continuously while a repeat station occupation occurs at a frequency of 2 or 5 years.

The first step in operating an already installed station is to perform a magnetic survey around the station location to guarantee that no artificial sources are present. Furthermore, it is essential to take notice of the environment, to check landmarks and station status to update the repeat station sheet if necessary. An organized repeat station sheet is helpful to find its location in future surveys, besides keeping its records accessible and updated.

After the repeat station installation, it is crucial to record the true north direction to measure the declination angle. In the past, this process required observation of the position of the Sun or another star. At present, the north direction is obtained using a gyroscope, which rotates around a horizontal axis until it is affected by the Earth's rotation and consequently changes its axis until it points to the north direction (Barraclough and De Santis, 2011). The presence of reference marks in the station also helps to determine the true north direction.

The next step is to install the instruments and start the observation. The standard equipment is DI fluxgate to measure Declination and Inclination and a proton precession magnetometer (PPM) to measure the Total Field intensity.Newitt et al. (1996) recommend using a variometer close to the repeat station to record the local variations for external effects removal during data reduction. This setup usually requires the staff to stay at least three days in the station so the variometer can stabilize well enough to acquire quality data. The presence of a variometer transforms the repeat station into a temporary magnetic observatory, which produces data with high quality.

If no variometer is present, the occupation time varies between a few hours and one day. It is best practice to perform the absolute measurements early in the morning and as late as possible in the afternoon/evening as a way to minimize the effects of the external variations in the recorded field (Newitt et al., 1996; Barraclough and De Santis, 2011).

Which instruments are available for the survey is decisive in the station classification. According to Newitt et al. (1996), the magnetic repeat stations surveys can be of two kinds: *First Order* and *Second Order* surveys.

A First Order survey has a DI flux, a PPM, and possibly a local variometer installed. In this survey, multiple sets of absolute measurements are made during the early morning and evening to avoid external field effects as much as possible. The resulting data is compared either to a close magnetic observatory or local variometer to minimize external field effects adequately.

A Second Order type survey also has a DI flux and a proton magnetometer. Instead, there is no close magnetic observatory to be used as a reference and neither is a variometer present at the station. The study of secular variation using Second Order repeat station data is complicated since the effects of the external field are present in the recorded data.

After the first sets of measurements are complete, it is important to plot them to verify if the readings of different sets are in accordance with each other. If not the survey can be stopped temporally while the staff searches for the possible causes of these errors. Besides, it is also recommended to always check the magnetic conditions in order to avoid further disturbances in the field.

Another fundamental aspect of station occupation is the occupation frequency. The IAGA [3] organization recommends that repeat stations should be reoccupied at 2-year intervals. However, the purpose of the network in question is the most relevant factor when deciding the occupation periodicity. The spacing between stations also depends on repeat station network purpose. In the case of regional field mapping, for example, a distance of approximately 200 km between stations is recommended (Newitt et al., 1996).

1.2.4 Data reduction

The result of the survey campaign is a collection of measurements for each repeat station. These measurements represent timed observations for each location. It is necessary to transform these spot readings into meaningful values representative of the local field around the station. The representativeness value of a station is expressed by its mean value over a period, usually a year. Therefore, the objective of the repeat station data processing is to transform those spot readings into annual mean values for each repeat station to use the data for secular variation studies (Turner et al., 2015).

The data reduction process encompasses two different tasks, removal of external field effects and annual mean values calculation.

The minimization of external field effects is a challenge due to source separation. The repeat station measurements contain influence from the internal and external fields. When the objective is to study secular variation, which is the main goal usually, it is necessary to

[3] `http://www.iaga-aiga.org/`

remove the external field influence and isolate the signal from the core field that represents the secular variation (Barraclough and De Santis, 2011).

As said earlier, marking the exact location of the repeat station is essential. This requirement exists because the crustal field is assumed to average out during several occupations as the location technically has not changed. On the other hand, the external field effects removal does not follow the same principle. The requirements of avoiding artificial sources close to the station, regions with induction effects, measurements in early morning or evening, and no surveys during magnetically disturbed times are all necessary precautions to minimize the external field influence.

There are different mathematical methods to remove the external effects besides the field operation requirements. The method of choice depends on several factors like the presence or not of a local variometer, the magnetic behavior of the region where the repeat station is, the proximity of magnetic observatories, and the magnetic conditions during the survey. Newitt et al. (1996) describes two different methods for First Order surveys: (i) Use of magnetic observatory as a reference and (ii) use of local variometer. Those are the most common methods, yet other researchers have been developing different approaches to account for their disadvantages (Schulz and Beblo, 1984; Andriambahoaka et al., 2007; Vujić et al., 2011; Vujić and Brkić, 2015; Šugar et al., 2015).

1.2.4.1 Magnetic observatory as reference

This method assumes that the rapid temporal variations (e.g diurnal variations) at the repeat station and the reference magnetic observatory are the same. The absolute measurements at the station are used to produce a baseline for a variometer in the reference magnetic observatory. Then, the baseline from the repeat station values is subtracted from the original baseline from the observatory. This difference in baselines represents the magnetic field variations between the repeat station and the reference observatory Turner et al. (2015). This results in the minimization of the external field effects and allows the calculation of the annual mean value at the station using the following expression:

$$E(t) - \boldsymbol{E} = \boldsymbol{E_o} - E_o(t) \tag{1.10}$$

$$\boldsymbol{E} = \boldsymbol{E_o} + E(t) - E_o(t) \tag{1.11}$$

where $\boldsymbol{E}$ is the annual mean value of a magnetic field element E at the repeat station, $\boldsymbol{E_o}$ is the annual mean value of the element E at the reference observatory, $E(t)$ is the value of element E at the repeat station at the moment the measurement is made and $E_o(t)$ is the value for the same element at the same time at the reference observatory.

This method shines in its simplicity since there is no need to use a local variometer. This means a reduced financial cost for the survey campaign and an easier and quicker field operation. Another benefit is that observatory data have higher accuracy, quality, and a long time series than a local variometer. This method produces excellent results when the reference observatory is close to the station or when the diurnal variation has a small amplitude at the station and observatory.

A disadvantage of this method is the presumption that the secular variation is the same at both locations. This is not always true. The difference in secular variation changes causes errors in the reduced data. These errors depend on the secular variation gradient and the distance between the locations. Newitt et al. (1996) elaborate further on the errors inherent from this method and how to minimize them.

1.2.4.2 Use of local variometer

The second method of external field effect removal is to use a local variometer during field operation. As stated previously, the presence of a local variometer transforms the repeat station into a temporary magnetic observatory. A local variometer is set up close to the station during the station occupation. It records the field for the entire occupation time. Then, the absolute measurements from the station produce a baseline for the variometer data. The merge of these two data sets provides the field values at the station, usually one minute values (depending on the variometer frequency).

From the combination of the absolute measurements and the variometer data at the station, precise daily means are calculated for the station. These daily mean values are subtracted from the observatory data, which makes now both observatory and station have the same external field variations, therefore removing the external field effects from the data. The next step then is to calculate the annual mean value at the station.

Newitt et al. (1996) affirms that to obtain the annual mean value at the repeat station is either necessary to have a long time series from the local variometer or a close magnetic observatory as reference. If an observatory is used, it follows the 1.10 equation with few alterations:

$$\boldsymbol{E} = \boldsymbol{E_o} + E(nt) - E_o(nt) \tag{1.12}$$

where $\boldsymbol{E}$ is the annual mean value of a magnetic element at the station and $\boldsymbol{E_o}$ is the annual mean for the same element at the observatory, $E(nt)$ and $E_o(nt)$ are the night time value (least disturbed field) for a magnetic element at the station and the observatory, respectively.

The main advantage of using a local variometer is to avoid the assumption of equal local field variations for the repeat station and the reference magnetic observatory. Although, the operation of a local variometer has additional sources of errors from temperature variations and stability. It usually does not have the same level of protection against temperature fluctuations as is present at an observatory (e.g. variometer house). Also, there is no pillar to guarantee its stability since they are mounted on tripods in the field.

1.2.5 Importance of repeat station networks

Although magnetic observatories provide the most accurate data for the secular variation studies, their installation and maintenance are costly. It contributes to making their global geographic distribution not extensive. Most observatories are located predominantly in the northern hemisphere, creating a gap in the coverage of the southern hemisphere, especially in oceanic regions as shown in 1.9.

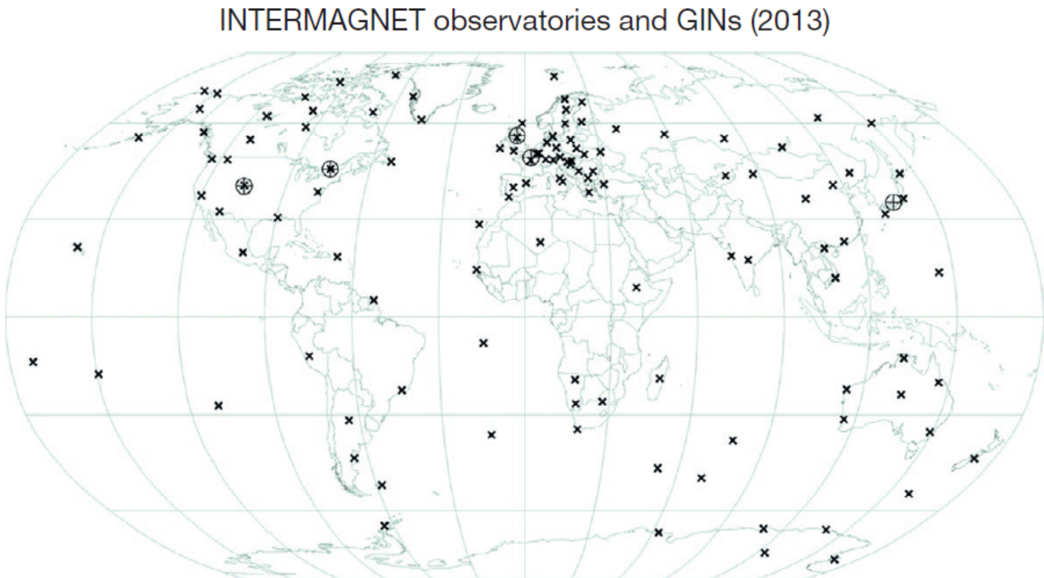

Figure 1.9: Map of INTERMAGNET observatories (crosses) and Geomagnetic Information Nodes (crossed-out circles) in 2013. Source: Turner et al. (2015).

Because of this non-uniform distribution, the repeat stations were conceived to supplement the magnetic observatories, covering distant regions of the existing magnetic observatories. 1.10 shows a map of the repeat stations occupied at least twice between 1975 and 2010.

The data provided by the stations are mostly used in modeling the global magnetic field and its secular variation. Although satellite data have become fundamental for global field models development, magnetic observatories and repeat stations play a fundamental role in the use of satellite data. Due to the complexity of the satellite operation (observation at high altitudes, greater influence of the external magnetic field, etc.), it requires the use of observatory and repeat station data during its processing (e.g through stabilization in the inversion process) (Matzka et al., 2010; Barraclough and De Santis, 2011; Chulliat et al., 2017).

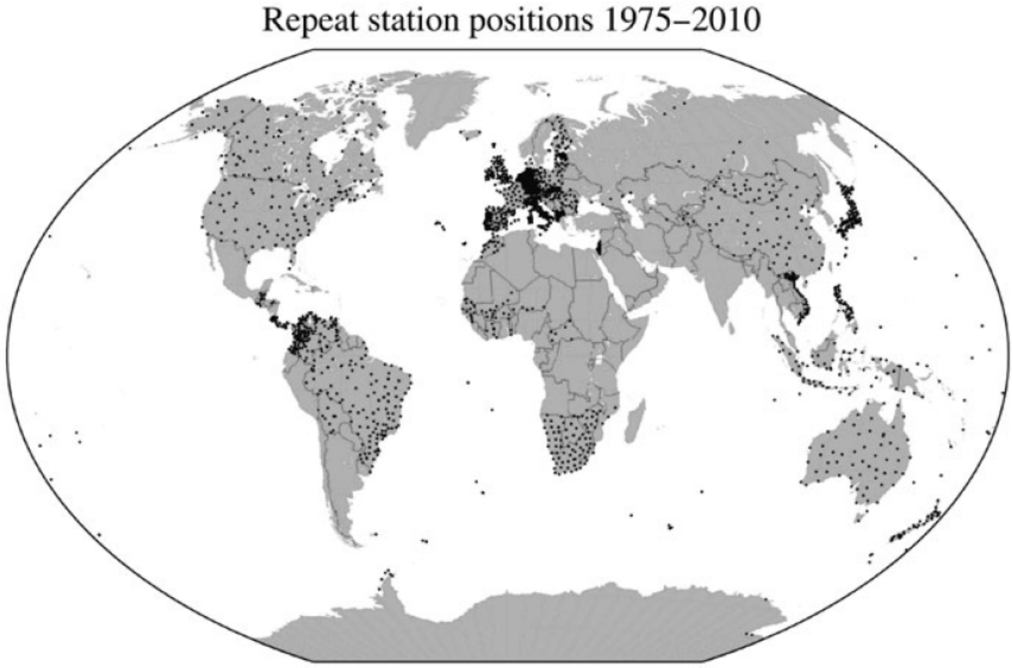

Figure 1.10: Map of repeat stations occupied at least 2 times between 1975 and 2010, whose data was sent to the World Data Center. Source: Barraclough and De Santis (2011).

Besides, satellite missions are costly endeavors that require high financial investment and continuous cooperation among different institutions and organizations. Therefore, when a satellite mission finishes, it is uncertain if another one will follow suit. In such a case, a repeat station network acts as a safety measure to keep the geomagnetic information updated (Lalanne et al., 2013).

Another use of repeat station data is the production of regional field models and magnetic charts for navigation. Welker et al. (2017) states that the use of geophysical fields as navigation tools has become more popular with time. Since the magnetic field changes in space and time, it is crucial to observe such changes to keep maps and navigation systems updated.

1.3 OBJECTIVES

The main objective of this work is to modernize the Brazilian network of magnetic repeat stations by:

- Defining the purpose of the new network: secular variation studies
- Decreasing the number of existing stations to facilitate network maintenance without compromising the data quality

To achieve the primary objective, a series of secondary objectives were established as a way to guide the network renewal process:

- Study of the repeat station networks of different countries
- Analysis of the current state of the Brazilian network of repeat stations
- Creation of criteria to define which repeat stations remain in the new network

The secondary objectives guided the progress of the research, as they are fundamental for the acquisition of the primary objective. The study of repeat stations networks in other countries served as a basis for understanding how to plan and maintain a national network. The analysis of the current state of the Brazilian network comprised the organization of the data recorded from all the available reoccupation campaigns into a comprehensive database, as well as reading any accessible documentation related to its operation.

To reduce the number of stations is essential to create criteria that will select the station that will be part of the new network. They should involve: the comparison of observations carried out at the stations with the values predicted by global magnetic field models, the analysis of characteristics such as accessibility of the station site, compliance with the standards defined by IAGA for station operation, and whether they will meet the new purpose of the new network.

2 METHODOLOGY

The methodology used in this work can be divided into three parts:

- Part I: Study of repeat station networks in other countries
- Part II: Analysis of the current status of the Brazilian repeat station network
- Part III: Planning of the new Brazilian repeat station network

2.1 STUDY OF REPEAT STATION NETWORKS IN OTHER COUNTRIES

This stage consisted in searching for reports, articles, books, and any documentation associated with the repeat station networks in other countries. Unfortunately, various publications about repeat stations originate from scientific conferences like the MagNetE workshops (Korte and Mandea, 2003; Duma et al., 2012). The problem is that such events usually do not provide the entire publication for consultation. Most of the time, only the abstracts are available. An example of this situation is the MagNetE workshop itself. The research about it managed to find only three active websites [1] [2] [3] with information about the event.

Besides that, only a few countries make their reports publicly available on the internet. Italy [4] and France [5] are the best examples of this behavior, with proper sites with easy access to information. A summary of the findings from repeat station networks of various countries is in the next chapter.

2.2 ANALYSIS OF THE CURRENT STATUS OF THE BRAZILIAN REPEAT STATION NETWORK

This section describes the methodology employed in the Brazilian repeat station network current status investigation. The methodology is divided into two steps: analysis of the available documentation about the Brazilian network and the network database creation to facilitate the visualization and study of the network.

The documentation investigation served to discover which stations had complications that denied their participation in the database. A discussion about the results of this investigation is presented in the next chapter.

[1] http://www.geodin.ro/MagNetE_2007/html/program.html

[2] https://space.fmi.fi/MagNetE2009/?page=welcome

[3] http://magnete2011.rm.ingv.it/

[4] https://www.annalsofgeophysics.eu/index.php/annals/search/search

[5] http://www.bcmt.fr/

The Observatório Nacional (ON) is the research institute responsible for the management of the Brazilian repeat station network. The staff provided the repeat station data necessary for the database development. The data is available in spreadsheet format.

The database production employed Python [6] programming language with the JupyterLab [7] development environment. Both tools are available for download using the Anaconda distribution [8]. The Anaconda environment setup file (with the name of all packages utilized) and the notebooks created in this process will be available at GitHub [9].

These tools were selected because they are open source and easy to use. In addition, they offer an excellent way to organize each processing step (using a single *Jupyter Notebook* for each task, which allows code execution and image manipulation in a single environment).

2.2.1 Pre-Processing

The original repeat station data file had information about the repeat station name (the closest city to the repeat station), the geographical position in latitude and longitude values in decimal degrees, the time of measurement in decimal years, and the magnetic components in decimal degrees and nT. It was decided then to complement the repeat station information by adding manually the columns *Code*, *State*, and *Region*.

The *Code* represent a standard abbreviated name for each station. In the original file the station names were the names from the cities they were installed on while the Code follow the order below:

> (State symbol) + (three letters to identify station name) + (one letter to identify possible station reallocation according to IAGA guidelines)

For example, the station at Cruzeiro do Sul city at Acre has the following code: `AC_CSZ`, where the *AC* symbol represents the Acre state and *CZS* is for Cruzeiro do Sul city.

The State column uses the official state symbol to mark the State where each station is. For example, to represent the Acre state, the column has the *AC* symbol to mark which stations are there. The Region column follows the same principle. It informs in which region the station is installed. The repeat station name column (*RS name*) is the column that contains the name of each station according to the original file.

After this, the pre-processing comprehended the conversion from comma to dot to separate decimal places, sorting the data in alphabetical order for station code and ascending order for the occupation period, and marking data gaps as NaN values.

---

[6] `https://www.python.org/`
[7] `https://jupyter.org/`
[8] `https://www.anaconda.com/`
[9] `https://github.com/raissamb/Master_thesis`

The last step was to check if the station's locations were correct by plotting their coordinates over the Brazil shapefile available at the IBGE site [10]. This resulted in the removal from further analysis of a few stations as they had their positions registered incorrectly.

2.2.2 Data processing

This phase encompasses the actual production of the database. It was divided into small steps: acquisition of altitude data, calculation of magnetic components, calculation of the distance of each station to the magnetic observatories of TTB-Tatuoca (Belém, Pará) and VSS-Vassouras (Vassouras, Rio de Janeiro), and the calculation of how many times each repeat station was occupied.

The altitude information addition was necessary since it was missing in the original file. This information was acquired using the ICGEM website calculation services [11]. The EIGEN-6C4 model was selected to provide the altitude values above the ellipsoid and the geoid. The altitude value over the geoid was used for the database creation and further analysis. 2.1 shows the parameters utilized for this step.

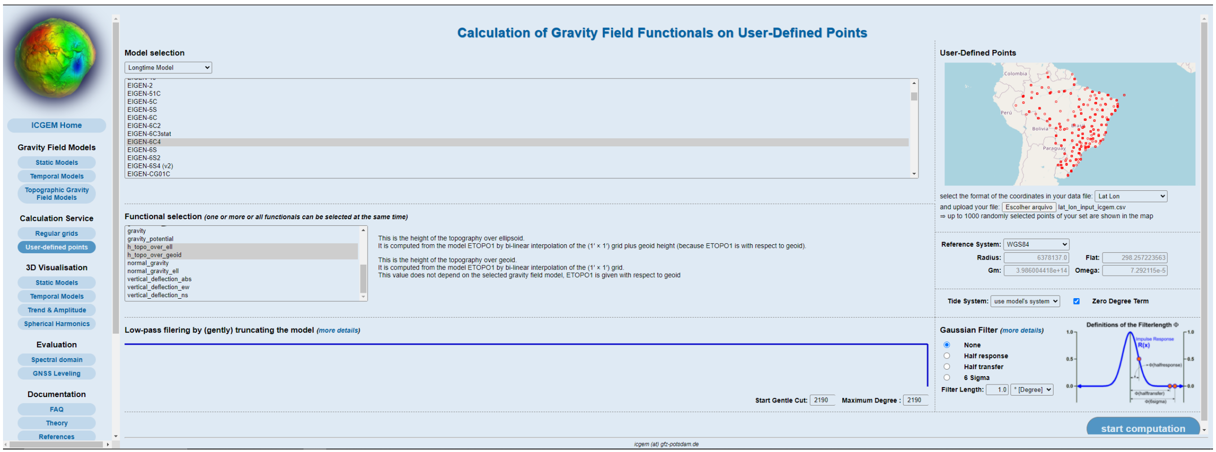

Figure 2.1: Print screen of the ICGEM calculation service used to acquire altitude information. Source: the author.

Only a few stations had the Y and Z magnetic components missing. Initially only the missing values for these components were calculated, but during the comparison between repeat station values and IGRF values (to be fully explained further in this session), it was noted that the X component for a few stations had values highly different from IGRF values (2.2). Because of this, it was decided to calculate the X, Y, and Z components for all repeat stations using the equations below. This way, all time series for the X, Y and Z components will display the original values and the calculated ones.

[10] https://www.ibge.gov.br/geociencias/organizacao-do-territorio/malhas-territoriais/15774-malhas.html?=&t=acesso-ao-produto

[11] http://icgem.gfz-potsdam.de/calcpoints

$$X = F\,\cos I\,\cos D \tag{2.1}$$
$$Y = F\,\cos I\,\sin D \tag{2.2}$$
$$Z = F\,\sin I \tag{2.3}$$

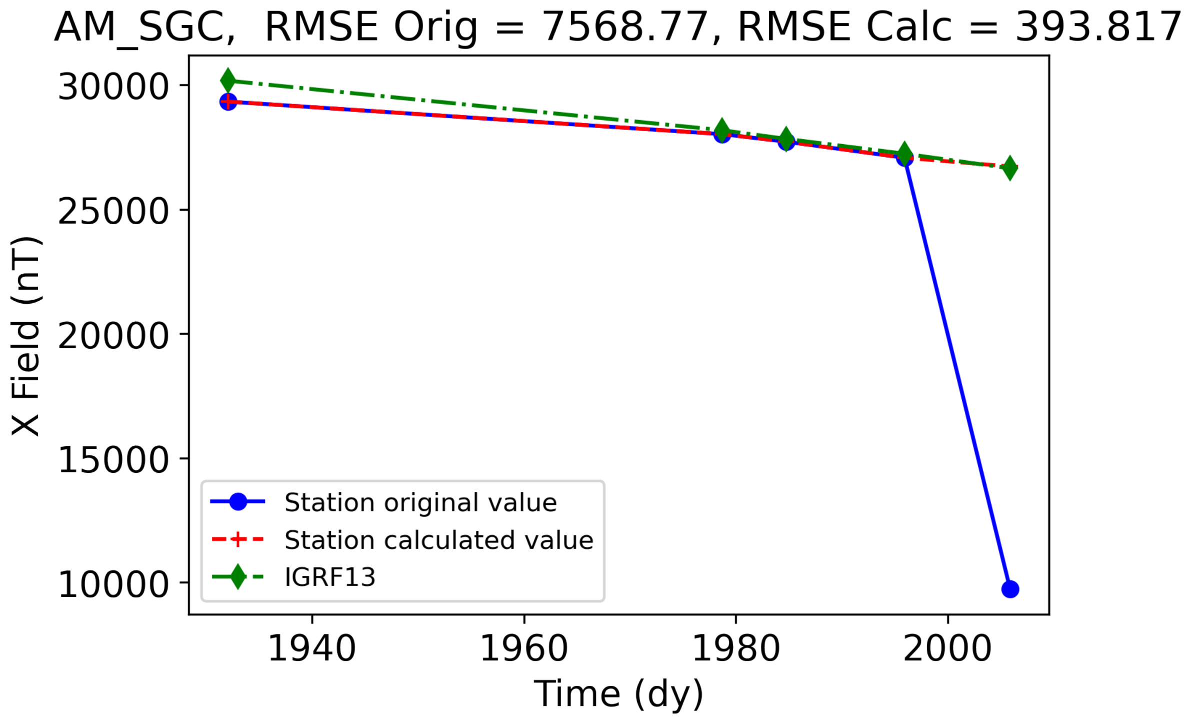

Figure 2.2: Comparison between the original value (blue circles), the calculated value (red plus symbol) and IGRF value (green diamond) time series and their RMSE values in relation to the IGRF for the X component at `AM_SGC` repeat station. Source: the author.

The distance between a repeat station and the available magnetic observatories in Brazil (TTB and VSS) is an important variable because it is a decisive characteristic when considering which reduction methods to use in the data reduction process. Therefore, the distances were calculated in kilometers using the Haversine formula (Great circle distance):

$$d = 2\,r\,\arcsin\left[\sqrt{\sin^2\left(\frac{\phi_2-\phi_1}{2}\right) + \cos(\phi_1)\,\cos(\phi_2)\,\sin^2\left(\frac{\lambda_2-\lambda_1}{2}\right)}\right] \tag{2.4}$$

Where r is the Earth's radius in km, ϕ_1 and λ_1 are the latitude and longitude coordinates in radians for the first location and ϕ_2 and λ_2 for the second location.

The last step in this phase is to count the occupation frequency of each station. The Pandas [12] tool for data analysis and manipulation provides a specific feature that is

[12]https://pandas.pydata.org/

capable of performing this task.

The database completion allowed the visualization of the geographical distribution of the repeat stations in the country. It is an essential source of information that contributed to the new network planning. These results are described in the next chapter.

2.3 PLANNING OF THE NEW BRAZILIAN REPEAT STATION NETWORK

With the information gathered from networks of different countries and the analysis of the current state of the Brazilian network, it was time to start the planning of the new network. The purpose of the new network is the study of secular variation. Therefore, the selection process must prioritize which stations better fit this purpose. The selection process presented here encompasses the creation of distinct criteria to select the stations.

The first and most important criteria is the geographical distribution of the repeat stations over the country. The analysis of the Italian network (Dominici et al., 2012; Dominici and Meloni, 2017), explained in the next chapter, showed the concept of an area of coverage for each station, a feature that in this work is called the *coverage radius*.

This coverage radius refers to the radius of a circular area (with the repeat station at its center) where the repeat station actively monitors the magnetic field during the occupation. This means that the station measurements will be representative of the field in that area.

After discussions and the analysis of the French (Lalanne et al., 2013) and Italian networks (Dominici et al., 2012; Dominici and Meloni, 2017), it was decided that the value of this parameter would be 300 km for the Brazilian repeat stations. It was agreed upon that this radius would be enough to give information about secular variation.

The establishment of the coverage radius is essential. The goal is to select 50 repeat stations capable of covering the national territory as best as possible using the coverage radius as a rule to determine the geographical distribution.

The second criteria is the number of occupations (meaning the time series size) analysis of each repeat station. Repeat stations with more occupations will have priority over stations with fewer occupations. At the same time, a station that has been occupied recently will have preference over a station that was last visited in 1970, for example. To this goal, six *occupations groups* were created. An occupation group divides the stations according to their number of occupations (2.1). This criteria prioritizes long temporal series since they are fundamental for secular variation study.

The third criteria is the comparison between the observed values at a repeat station and the ones given by the magnetic global field model IGRF13 (Alken et al., 2021). Alken et al. (2021) describe the IGRF (International Geomagnetic Reference Field) as a set of harmonic coefficients that can represent the large scale and time-varying parts of the Earth's magnetic field of internal origin. It spans the time series from 1900 A.D to the

Group	Number of occupations	Number of stations
01	12 or more	23
02	10 to 11	13
03	8 to 9	20
04	6 to 7	18
05	3 to 5	49
06	1 to 2	92

Table 2.1: Table describing the occupation groups. Source: the author.

present. The 13th generation is the newest one, it was launched at the end of 2019. The IGRF model uses in their calculations data from satellites, magnetic observatories and surveys. It is one of the most utilized global field model by the scientific community as well as the industry.

The IGRF13 data was acquired using the *Geomag 7.0* software [13] publicly available at the IAGA website. The decision to use this software instead of the Python package, also present at the site, is because it allows the calculation of values from a input file with the necessary information while the Python version did not offer this feature.

This comparison between repeat station data and IGRF13 model was done through the calculation of the *Root Mean Square Error* (Ω) given by the following equation:

$$\Omega = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y})^2}{n}} \tag{2.5}$$

where y is a magnetic element at the repeat station, $\hat{y}$ is the same magnetic element given by IGRF13, and n is the number of samples (meaning number of occupation) for a specific magnetic element for each repeat station.

At first it was considered the possibility of using different models like the CHAOS (Finlay et al., 2020), but its time series starts at 2000 A.D, so it would not produce data for stations that have been occupied for a long time. Nevertheless, this third criteria is not the most important in relation the geographical coverage and the time series. Therefore it was decided that the comparison with only the IGRF13 model would be enough.

After the three selection criteria establishment, it was time to select 50 stations to be part of the new network. After discussion, it was decided that a reduction from 218 present-day stations to 50 is a good fit. This number can still be reduced in the future.

Considering the coverage radius parameter value set to 300 km, the next step was to create a geographical distribution able to cover the national territory satisfactorily. This was possible with the use of the Folium [14] package for Python, which allowed the creation of an interactive map containing each repeat station.

[13]https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html
[14]https://python-visualization.github.io/folium/index.html

What makes the Folium map special is its interactivity. By separating the stations into occupations groups, the Folium map allowed the analysis in terms of the geographical distribution of each group separately. In other words, it was possible to visualize the group with 12 or more occupations and then the group with 10 to 11 reoccupations (and so on) through a layer control parameter. With different groups displayed on the map, it was feasible to see if any stations in the selected groups were near each other. At the same time, the Folium map exhibits station information (Code, localization, the nearest magnetic observatory, number of reoccupations, and last occupation) by hovering the mouse over the station sign. Furthermore, Folium plugins also have features like different zoom levels to allow awareness of the station location, a tool for measuring distances between points, a mini-map, and a full-screen mode for analysis.

2.3 shows the Folium map produced for the station selection. The red info signs represents the selected stations that have 12 or more occupations while the blue info signs refer to the group with 3 to 5 occupations. All the other elements present in the map are explained in the figure.

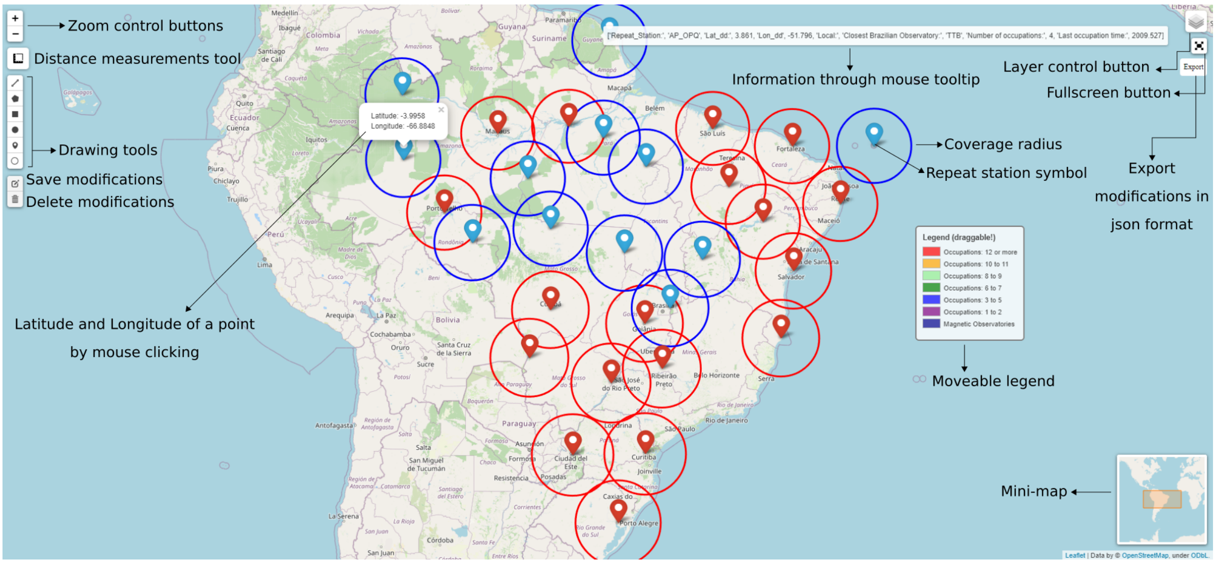

Figure 2.3: Screenshot of the selection process Folium map explaining each element present in the map. Red info signs are repeat stations that have 12 or more occupations while the blue info signs refer to the group with 3 to 5 occupations. Source: the author.

If there was any doubt in the station selection using the geographical distribution and number of occupations criteria, the decision was left to the RMSE (Ω) criteria. By consulting the table with the RMSE (Ω) values for each station, the station with the smaller number has priority.

3 RESULTS AND DISCUSSION

In this chapter, each section correspond to the results of each task explained in the Methodology.

3.1 REPEAT STATION NETWORKS FROM OTHER COUNTRIES

The research of how other countries manage their own repeat stations networks function was necessary since the documentation about the Brazilian network is scarce (a topic for the next section). Below, a few publications are summarized. They were selected considering how much information they provided to the planning of the new Brazilian network.

3.1.1 Network design process

The first step in the foreign countries' repeat stations network study was to search for scientific publications describing the network establishment. It resulted in the analysis of the three articles below.

Rasson and Delipetrov (2006) describes the establishment of the Macedonian network. The network was born from the necessity of acquiring knowledge about the magnetic field in the country. Due to political circumstances, it was decided to plan a network from the ground up instead of utilizing the old network created by the Yugoslavian government.

The creation of the new network came as part of an agreement among research institutes in Macedonia and Belgium. Later it was incorporated in a European project to further the geomagnetism research. This agreement encompassed the technical training of personnel to operate the network, the acquisition of instruments, and the necessary funding to establish the network. This represents a prime example of how partnerships among different countries are beneficial to scientific endeavors.

Their first concern was to define the stations' locations and how many would be necessary to provide the best possible geographical distribution. This task took into consideration Newitt et al. (1996) recommendations for repeat stations installation (e.g geological configuration, presence of external sources, transportation, etc) and management. After a series of campaigns, they found the best places to create the network. Since Macedon is a small country (compared to Brazil, for example), they decided that 15 stations would be enough to meet their objectives.

Another important observation about the Macedonian network is that the country had only one observatory to execute the data reduction. Therefore, it was decided to also utilize the data from observatories located in the nearby countries to avoid problems inherent to the distance between a station and the reference observatory. This practice seems very common among the different networks researched in this work. The actions of INTERMAGNET to provide easy access to high-quality observatory data play a fundamental role in it.

The authors listed a series of suggestions to check the measurements for possible errors while in the field since direct comparison with old values is not possible. Among them is the verification of the true north measurement, the analysis of instrument drift, the comparison with values from the nearby observatory, and the previous characterization of the local field.

Brkić et al. (2006) explains the Croatian repeat station network implementation. As was the case for Macedonia, this network was also developed to provide navigation information for the country. Partnerships were also essential in its development. The authors also comment on how they studied the networks from other European countries (Germany, Italy, and Hungary) to create their own.

They reported that no recent magnetic surveys were available at the time of the network planning. Therefore, they had to conduct magnetic surveys to map the areas with magnetic anomalies. Once again, the consideration of factors like easy access, presence of landmarks, lack of external sources, was fundamental to define the location of each station. A critical aspect of this process is to document all the information concerning the stations (field intensity, measurement process, terrain description, possible sources of contamination, etc). Being rigorous with documentation means that the status of each station is registered and available in case of need. In the end, the Croatian network had eight stations devoted to magnetic mapping.

Valach et al. (2004) explains the creation of repeat station network in Slovakia. A distinct feature in this work is the mentioning of the *MagNetE* program. The MagNetE is a workshop centered on the repeat station practices in Europe. Its main objectives are the standardization of repeat station operation over the continent, planning of new networks, improving the geographical distribution of stations, and further collaboration among its members (Korte and Mandea, 2003).

The conception of the Slovakian network follows clear guidelines: to have a regular geographical distribution, to avoid places with known magnetic anomalies and artificial magnetic sources, and the importance of long time series to facilitate secular variation studies. The stations for the new network were selected, following the guidelines, from a list of places where geomagnetic surveys were performed in the 18th and 19th centuries. In the end, they selected six locations to host the stations for the new network.

The analysis of these three publications served to showcase three main points when planning a network. The first is the relevance of creating partnerships to facilitate the development of a network, from its conception to operation. The second is the importance of following established guidelines in the network installation process to guarantee its success. The third is the necessity of having network documentation updated and easily available to avoid cases where station information is lost, compromising the network.

3.1.2 Networks located in regions with known magnetic field features

Brazil is one of the largest countries in the world. Therefore it is no surprise that different magnetic phenomena exist in its territory. One of the most known features of the Earth's magnetic field is the South Atlantic Anomaly (SAA). Terra-Nova et al. (2017) define it as a region of weak geomagnetic field intensity at the surface, which is attributed to reversed flux patches (RFPs) on the core-mantle boundary (CMB).

This region is dangerous to satellites flying over it since they are more susceptible to electrical failure due to interactions with high-energy particles present in the ionosphere and beyond. As the field is weaker, so is the protection it offers. The SAA is related to dynamic processes in the core. Hence, it is no surprise that the secular variation over Brazil is a rapid process compared to other countries. In turn, the presence of a repeat station network is fundamental to studying it.

Southern Africa is another region where the SAA is present. Korte et al. (2007) report that three magnetic observatories have been recording the field variations in the region for many years, yet their geographical distribution is not enough to fully cover the area. Therefore, they created a repeat station network to fix this gap. Recently, a partnership with the GFZ from Germany increased the network size from eight to forty stations. These actions resulted in high-quality data from the repeat stations that ensued in the application of the data in modeling studies (Kotzé and Korte, 2016; Kotzé, 2017).

The north region of Brazil is situated close to the equator. The equatorial region presents challenges for operation due to climatic and magnetic conditions. This region displays high temperatures in the summer, which can cause temperature fluctuations in instruments like the fluxgate. Besides, high solar radiation increases the effect of daily variation. Therefore it is recommended to make measurements in the evening or early morning. Another climate condition that affects the station operation is rain, so planning a survey must consider the rainy season.

For the magnetic conditions, the region is marked by the magnetic equator and the presence of the Equatorial Electrojet. The magnetic equator is the region where the field where has a zero inclination angle, making the field horizontal. Baumjohann and Nakamura (2007) explain the Equatorial Electrojet as an electrical current system created by the variations of the Sq current system due to intense solar radiation in the region. It covers an area of approximately 600 km across the equator and it causes a weakening effect in the observed horizontal field in the order of 50 to 100 nT at noon local time.

Because of this, it is essential to account for the external field variations. To use an observatory as a reference method, it is necessary that the observatory's latitude be similar to the station's latitude. Although, the use of a local variometer is strongly encouraged as making measurements at night when the external fluctuations are at a minimum. Newitt et al. (1996) have a chapter on how to operate in regions where the equatorial region is present.

Institut de Physique du Globe. Bureau Central de Magnétisme Terrestre (IPG BCMT et al., 2001(@) and Institut de Physique du Globe. Bureau Central de Magnétisme Terrestre (IPG BCMT et al., 2006(@) report the results of the Vietnamese network survey campaigns done through a partnership between France and Vietnam. The Vietnamese network is in an area under the influence of the Equatorial Electrojet. In the reports, the authors explain the difficulty in operating a network in the equatorial region and what precautions they took to produce high-quality data. The data reduction process is arduous due to the electrojet influence. Therefore, they adapted the reduction method using an observatory as a reference to account for the magnetic conditions of the region. This new approach relies on using observatories on both sides of the station to estimate the daily variation between them. Then, the station's daily variation is deduced from interpolation.

3.1.3 Influence of the reduction methods in the network operation

The section about repeat stations in the Introduction chapter summarized different methods of data reduction. In this subsection, three different configurations of data reduction operation is analyzed to show distinct approaches the new Brazilian repeat station network has available for consideration.

The first configuration for data reduction is to use only magnetic observatories. Valach et al. (2006) describes the results of the campaign of 2004 for Slovakia. The reduction process using magnetic observatories as reference is the same as explained by Newitt et al. (1996). For this, the authors used the Hurbanovo Magnetic Observatory (3.1). Considering that Slovakia is small coutry, the distances from the reference observatory to each station do not seem to cause much error for the assumption of same transient changes at both places as required by this method.

Shanahan et al. (2012) report the results of the UK network for the 2009-2010 survey campaign. In this article the authors describes how their 41 repeat stations use data from three magnetic observatories in the country. A key aspect of this configuration is the strategic localization of the observatories as each of them covers a specific region in the country. 3.2 shows that the Lerwick observatory covers the northern part of the country, Eskdalemuir the central part and Hartland the south. The approach in this configuration is that a station uses the two closes observatories in latitude for the data reduction. The Quiet time values used in this process are derived from a careful examination of the eleven day period (centered on the occupation day of the station) of magnetic record from the observatories.

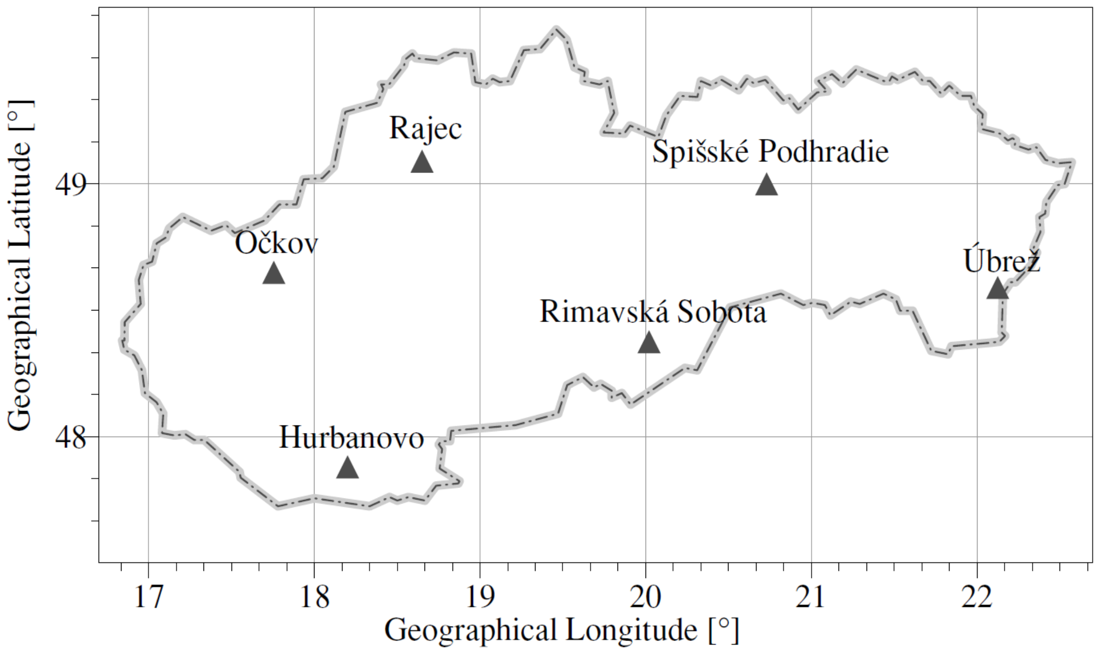

Figure 3.1: Map showing the Slovakian network. Source: Valach et al. (2006).

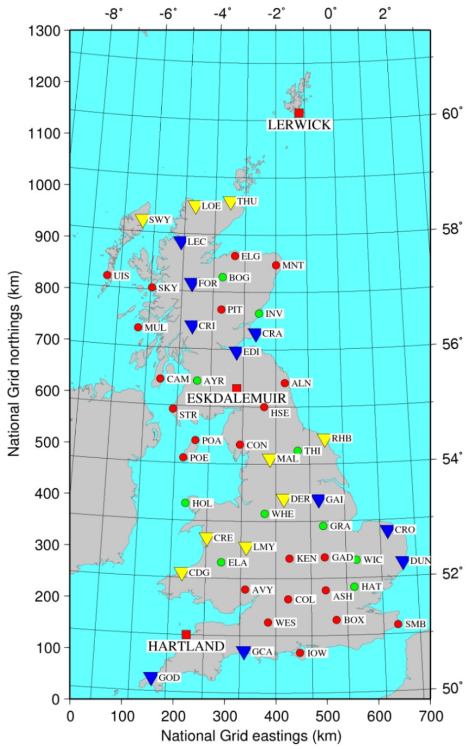

Figure 3.2: Map showing United Kingdom repeat station network (yellow triangles) and their magnetic observatories (red squares) in the campaign of 2009-2010. Source: Shanahan et al. (2012).

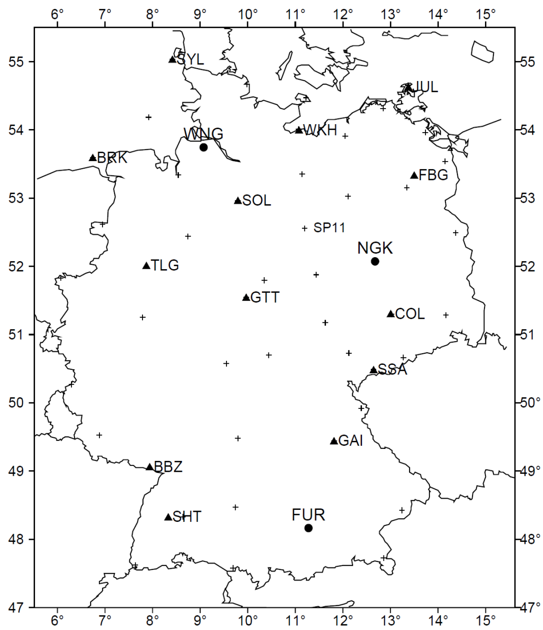

Figure 3.3: Locations of repeat stations (crosses), variometer repeat stations (triangles) and the three German geomagnetic observatories Wingst (WNG), Niemegk (NGK) and Fürstenfeldbruck (FUR) in the campaign of 2009-2010. Source: Korte and Fredow (2001).

The second configuration for the data reduction is the use of magnetic observatories and *central variometer stations*. Korte and Fredow (2001) define a central variometer station as the "local" variometer for a number of repeat stations close to it in a certain radius. The central variometer stays operational for several days while the nearby repeat stations are occupied. The authors then states that this set up creates two types of networks: first order type where the variometer is close enough to the station to guarantee excellent determination of external field effects and second order type when the station is far from the variometer position, although they limited the radius to 150 km, so no station would be farther than this distance. This configuration of central variometers helps to mitigate the problems from the assumption that the variations (internal and external) are the same for both the station and the observatory. The Italian network also uses this configuration (Dominici et al., 2017). 3.3 shows the German network for the survey of 1999-2000.

The third configuration is to use magnetic observatories and a local variometer in each repeat station. In fact, this what Newitt et al. (1996) recommends as standard procedure for field operation and data reduction. Korte et al. (2007) adopted this model in the African network, stating that this approach offer the best results over using only observatories or observatories and central variometer stations for data reduction. The problem with it is that a variometer needs to be active for days to register quiet field values, which puts pressure into the financial cost of the survey. Because of this, the authors decided to have the local variometer active for only a day for each station. 3.4

Figure 3.4: Southern African repeat station network in 2005. Red circles mark stations where measurements were impossible. Source: Korte et al. (2007).

shows the African network for the survey of 2005. Besides Africa, Australia (Paskos et al., 2018), and recently Hungary (Kovács et al., 2012) and Croatia (Šugar et al., 2015) started to use this configuration.

3.1.4 Network size reduction

Countries with extensive territory usually have a large number of repeat station in their network. However, to maintain a large network and at the same time ensure that they are appropriately occupied at regular frequency requires a grand financial commitment. Newitt et al. (1996) alert that is better to have a small number of stations occupied regularly and with the needed accuracy than to have a large network that produces low quality data. Therefore, the goal of reducing the size of a network while maintaining its quality became essential.

Lalanne et al. (2013) describes how the old French network with 32 stations in 2007 changed to a new network with only 11 stations (3.5) in 2012. The authors say that the decision to start a new network from scratch came from various complications in the old network (loss of stations due to city expansion, environment modification, loss of land-marks, etc) forced the institution responsible for the network maintenance to create a new one prioritizing the sustainability of the station sites and their magnetic characteristics

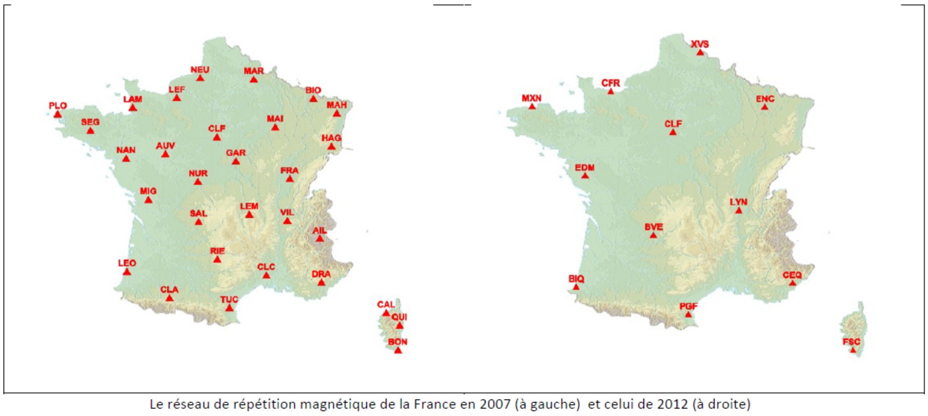

Figure 3.5: Comparison between the French network in 2007 and later in 2012. Source: Telali et al. (2018).

for an extended period of time.

Telali et al. (2018) shows the result of the new reduced French repeat station network. According to the authors, the reduced size did not interfered with the station ability to provide high quality data for secular variation studies and magnetic mapping for navigation. Besides, the new approach of using small airports as station sites proved to be a viable alternative for location, even if they impose challenges like time constraints on field operation.

The Italian network also went through a size reduction. Dominici et al. (2012) describe the results of the survey campaign of 2010 for Italy. At that moment, the network had 131 stations (3.6, left panel). Then, the authors commented that a network of that size is nonviable to keep with reduced financial support. Also, they noticed that a network does not need to be immense to properly register the field through the comparison of current repeat station data with older versions of the regional magnetic field model do not present great changes. Considering this, they planned another survey with a reduced size network to confirm their finding.

Dominici and Meloni (2017) present the results of the survey with the reduced network with 25 stations. 3.6 (right panel) shows a map with the reduced network where each colored sphere represents the area of coverage for each magnetic observatory and variometer station. They compared the regional field model derived from the complete network and the field model produced from the reduced network with the IGRF global field model. The results showed that the reduced network model did not introduce significant differences from the comparison with IGRF when the IGRF is compared to the regional model derived from the entire network.

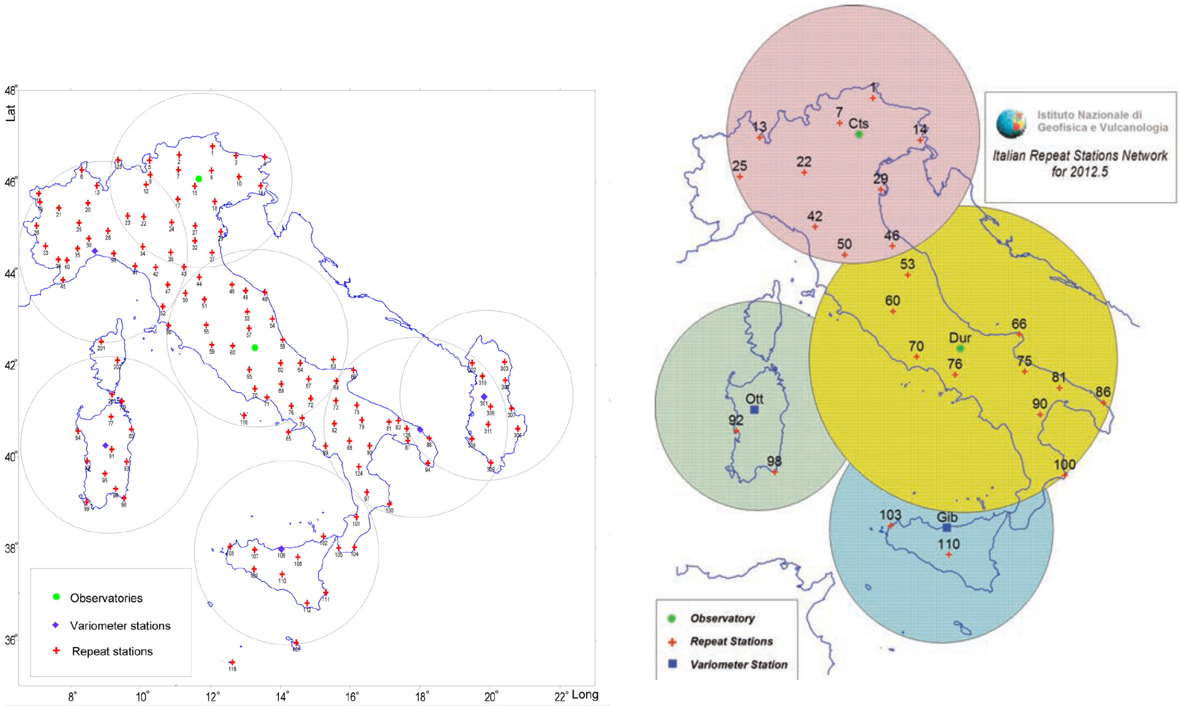

Figure 3.6: Comparison between the Italian Repeat Station Network size in 2010 (left panel) and in 2011-2012 (right panel). Source: Dominici et al. (2012) and Dominici and Meloni (2017).

3.2 CURRENT STATUS OF THE BRAZILIAN NETWORK

The present-day Brazilian network of repeat stations has 218 stations and a total of 1089 occupations, with most stations presenting observations of all vector components of the Earth's magnetic field. The first stations were implemented around 1903, and the most recent campaign took place in 2019. The research institute responsible for its establishment and operation is the Observatório Nacional (ON) [1].

The database production allowed better analysis of its current status through the:

- Identification of which stations had their position registered incorrectly
- Analysis of the geographical distribution of the stations in terms of the whole country, per Region and State
- Observation of the temporal series of each repeat station

3.7 shows the geographical distribution of the network in 2019, where each red circle represents a repeat station available at the database and the blue stars are the current operating magnetic observatories in the country. 3.8 displays the number of stations and the total occupations by Region and State. 3.9, 3.10, and 3.11 show the temporal series for all magnetic components at the `PA_SAN` repeat station (Santarém, Pará).

[1] https://www.gov.br/observatorio/pt-br

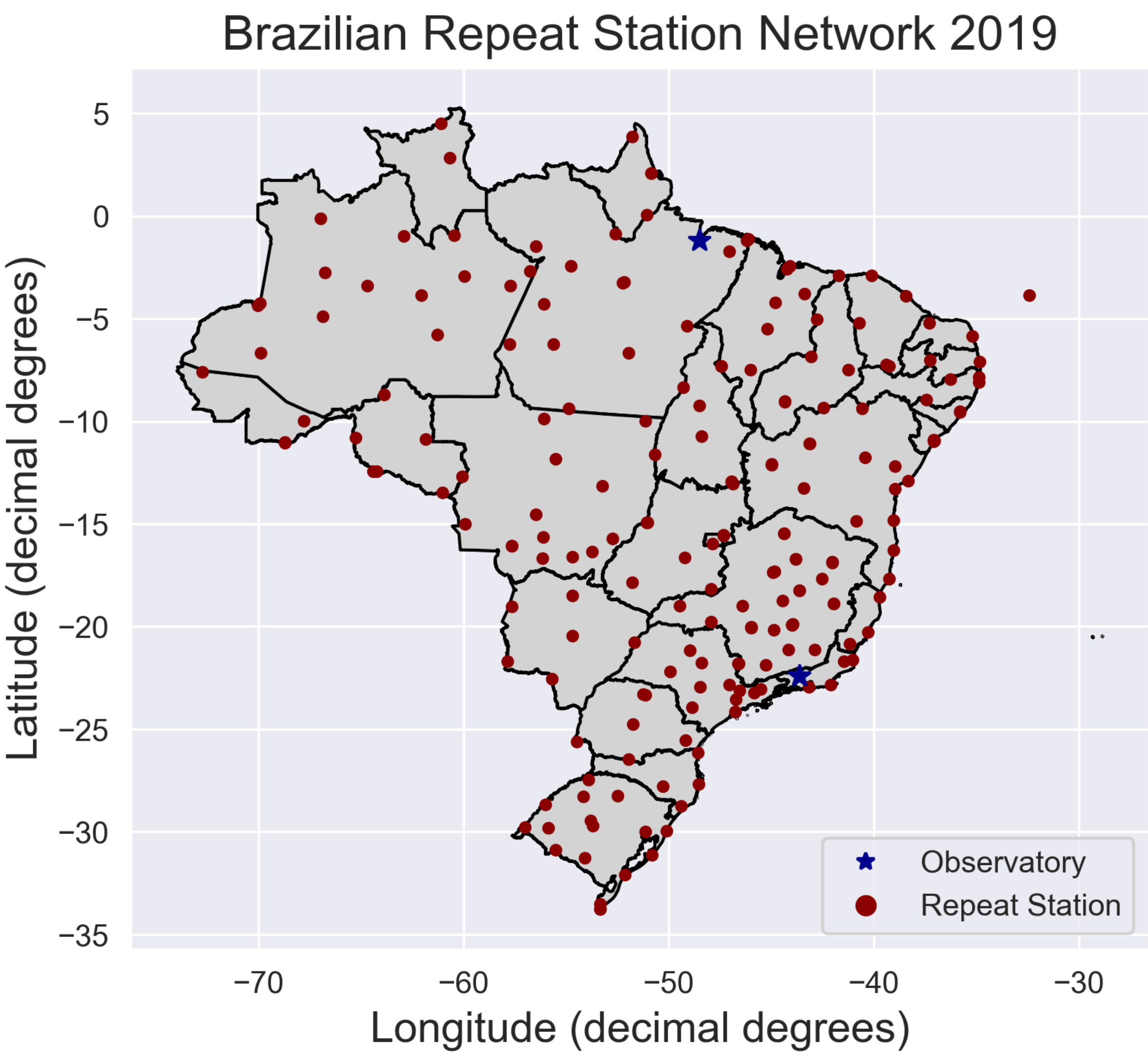

Figure 3.7: Map showing the present-day Brazilian network. Dark red circles are repeat stations and dark blue star are the Magnetic Observatories of Tatuoca and Vassouras. Source: the author.

However, the database development process encountered a severe problem that affected its effectiveness: lack of documentation about the repeat station activities in Brazil. Considering a situation where all the activities are documented and easily accessible, the database construction would have taken into account information regarding each individual repeat station status.

An example of this problem is the following: the `RS_LIV` station (Santana do Livramento, Rio Grande do Sul) has 15 occupations from 1953 to 2018, making it a good candidate to be part of the new network. Yet, reading the field report of the survey campaign of 2018 (Relatorio de Cartas Magnéticas 2018, personal communication with Carlos Roberto Germano, TTB observatory chief) states that this station has been magnetically polluted in the survey of 2018. Without having read this document, it would be impossible to know the exact current status of this station.

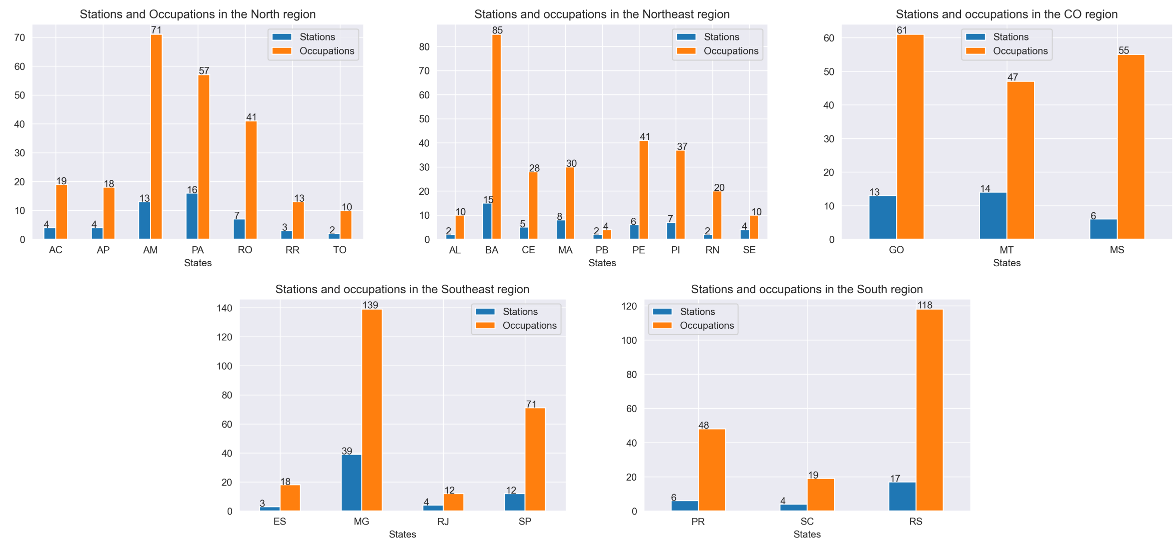

Figure 3.8: Number of stations and their occupations for each Region and State in Brazil. Source: the author.

To be precisely clear, the research into repeat stations activities in Brazil found reports for two distinct periods from 1960 to 1980 and the surveys of 2017 to 2020, all through personal communication with Carlos Roberto Germano. This shows how severe is the lack of documentation for the current Brazilian network.

Gama (1960) describes the data processing to create a regional magnetic field model and define the secular variation for the 1960.0 epoch using repeat station data from 78 stations occupied between 1953 to 1960. The author confirms that reduction data was done in terms of correcting for diurnal variation and the solar cycle. This is the first evidence that data processing has occurred.

Gama (1969) describes the production of the regional field model and its secular variation for the 1965.0 epoch using repeat station data from 85 stations occupied between 1953 and 1965. In this work, the author also explains that the data was processed to remove instrumental drift (reduction to The International Magnetic Standard), solar cycle, and daily variation effects. From these documents, it is safe to say that repeats station data from 1953 to 1965 received data processing and were reduced to an epoch.

Godoy (1993) gives a detailed account of the history of the Brazilian network until 1980. He established an organization system for the repeat station network data, although it is not possible to say if the system is currently in use. In terms of data reduction, the author states that data from:

- 1953 to 1980: instrumental corrections were done in relation to the International Magnetic Standard
- 1953 to 1974: solar cycle corrections were done
- 1979 to 1980: daily variation corrections were done

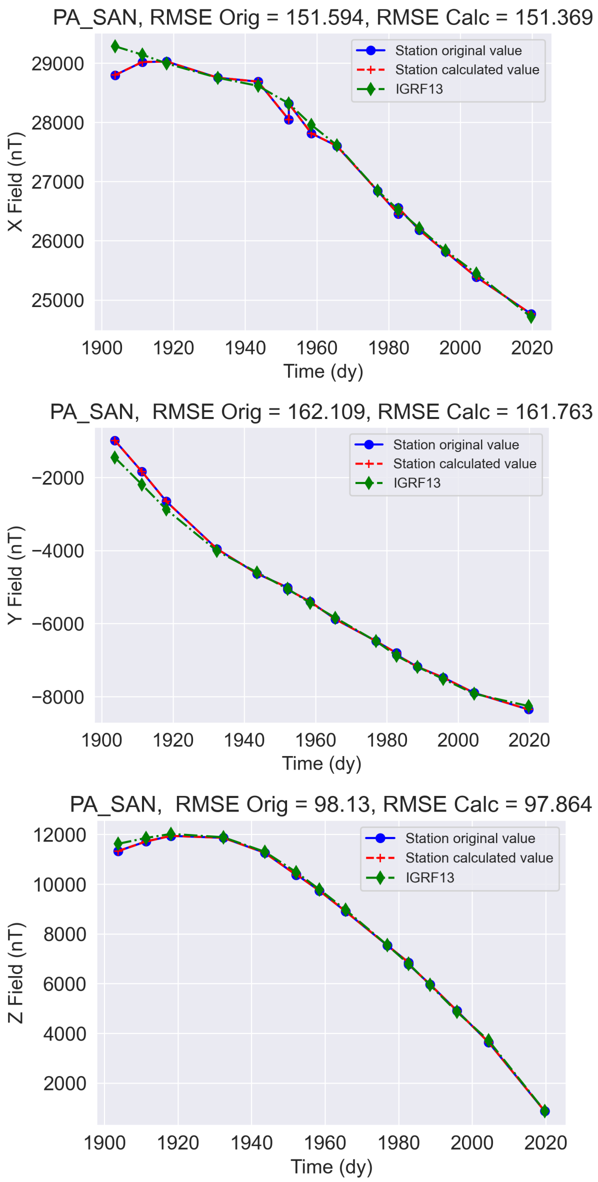

Figure 3.9: Temporal series of X, Y, Z, components at the `PA_SAN` repeat station (Santarém, Pará). Source: the author.

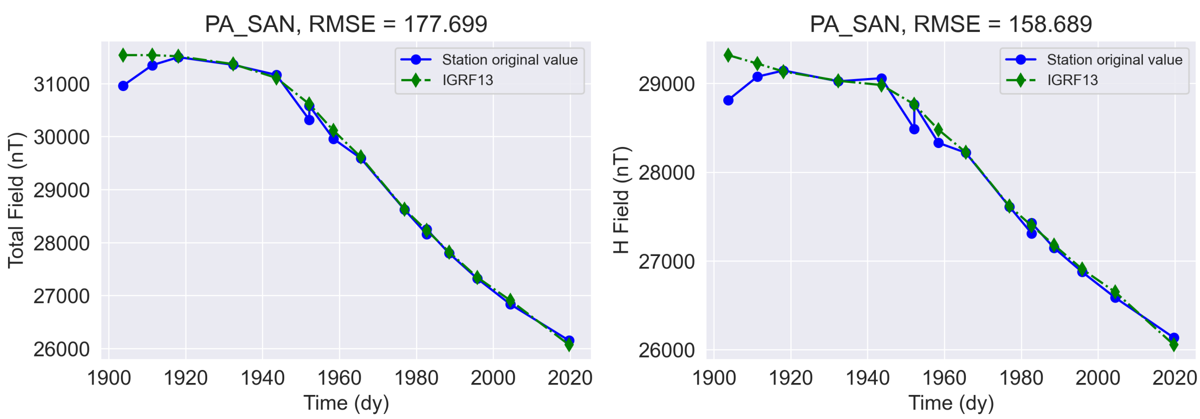

Figure 3.10: Temporal series of Total Field and Horizontal components at the `PA_SAN` repeat station (Santarém, Pará). Source: the author.

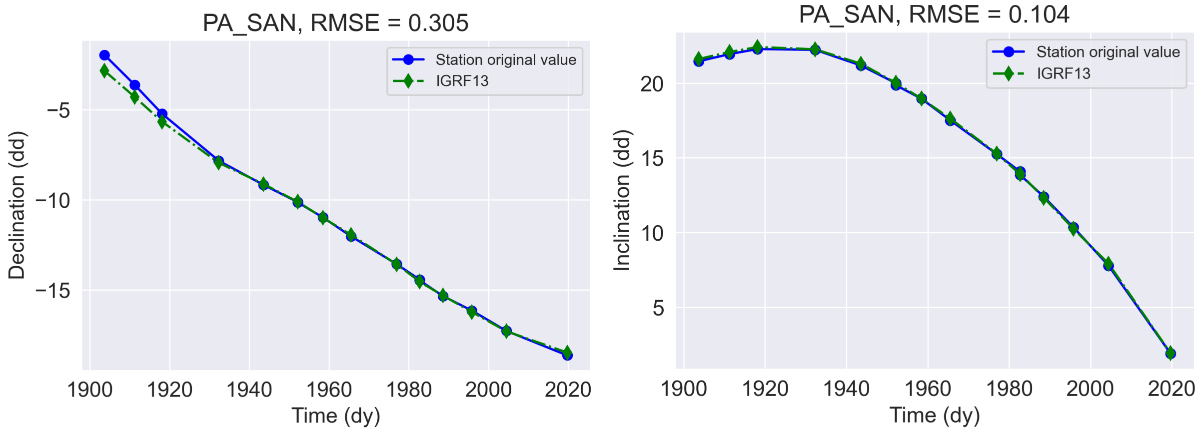

Figure 3.11: Temporal series of Declination and Inclination components at the `PA_SAN` repeat station (Santarém, Pará). Source: the author.

The other documentation set is the field reports for the surveys from 2017 to 2020. They describe the occupation of 10 stations per year, and each year was devoted to a specific region. In 2017 the stations localized in the Southeast region, in 2018 the survey covered the South region, and in 2019 and 2020 it was the Central West and North regions.

The reports also gave an information sheet for each station, describing their status, localization, and images. From these sheets, it was discovered that three repeat stations were contaminated magnetically (Santana do Livramento, Moraes de Almeida, and Jataí). Because of this, they were removed from the selection process for the new network.

Also, according to the reports, the survey instruments are not in good condition. The survey team requested a change of field instruments, as the ones in use are old. Also, they noticed a need for basic support equipment like tents and portable computers.

There is no mention of the reduction process in any report, therefore there is a possibility that repeat station data from 1980 to the present have not been processed to decrease the influence of external field effects and be reduced to annual mean values. In the end, in their current state, the data is not adequate for secular variation studies. This is why the network needed to be appraised in order to plan its future operations.

3.3 NEW BRAZILIAN NETWORK

Through the combination of the three established criteria (spatial distribution, number of occupations, and RMSE (Ω) values), 50 repeat stations were selected to be part of the new Brazilian repeat station network (3.12). The tables with information about all the selected repeat stations are available in the appendix. See A–1 and A–2 for a complete list of the selected repeat stations. At GitHub, there is also a file with the distance in km between each selected repeat station.

The selection process Folium map (2.3) allowed a visual analysis prioritizing the first two criteria (spatial distribution and occupation number). While these are the most crucial criteria for the selection process, the RMSE (Ω) value was used mainly in cases where the first two criteria did not provide a clear solution.

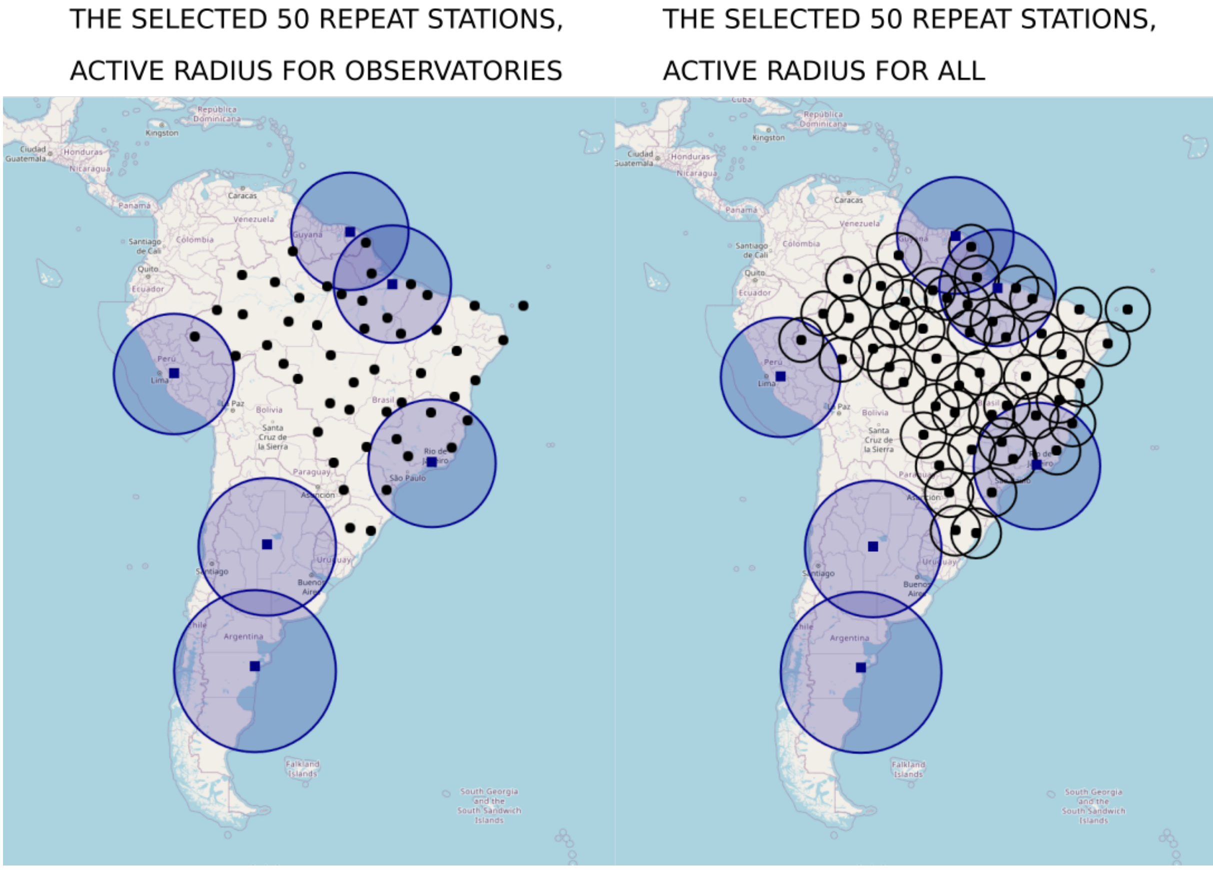

Figure 3.12: Screenshot of the Folium map with the 50 selected repeat stations (black circles) for the new network and the INTERMAGNET observatories in South America (darkblue squares). The left panel show the observatories coverage radius active and right panel has the radius active for both observatories and repeat stations. Source: the author.

The RMSE (Ω) criteria had a less weight in the selection process due to two reasons. The first is the priority of the first two criteria and the second is that a few repeat stations showed were very high Ω values as seen in the temporal series at `PA_SAN` (3.9, 3.10, and 3.11). 3.13, 3.14, and 3.15 show the Ω values for all components in the group with 12 or more occupations. A table with all the Ω values for the selected repeat stations is presented in A–3 and A–4.

The RMSE analysis showed worse results for the X component. For a few stations, independent of the occupation group, the RMSE values were extremely high. This could be attributed to several reasons like errors in the calculation of the component, the influence of external field effects, and the use of IGRF as a global field model.

Usually, during a station occupation, the measured components are the Total Field, Declination, and Inclination. The other magnetic components are derived later. As the majority of the component values present in the data are correct, it is not impossible to consider that a calculation error could have happened.

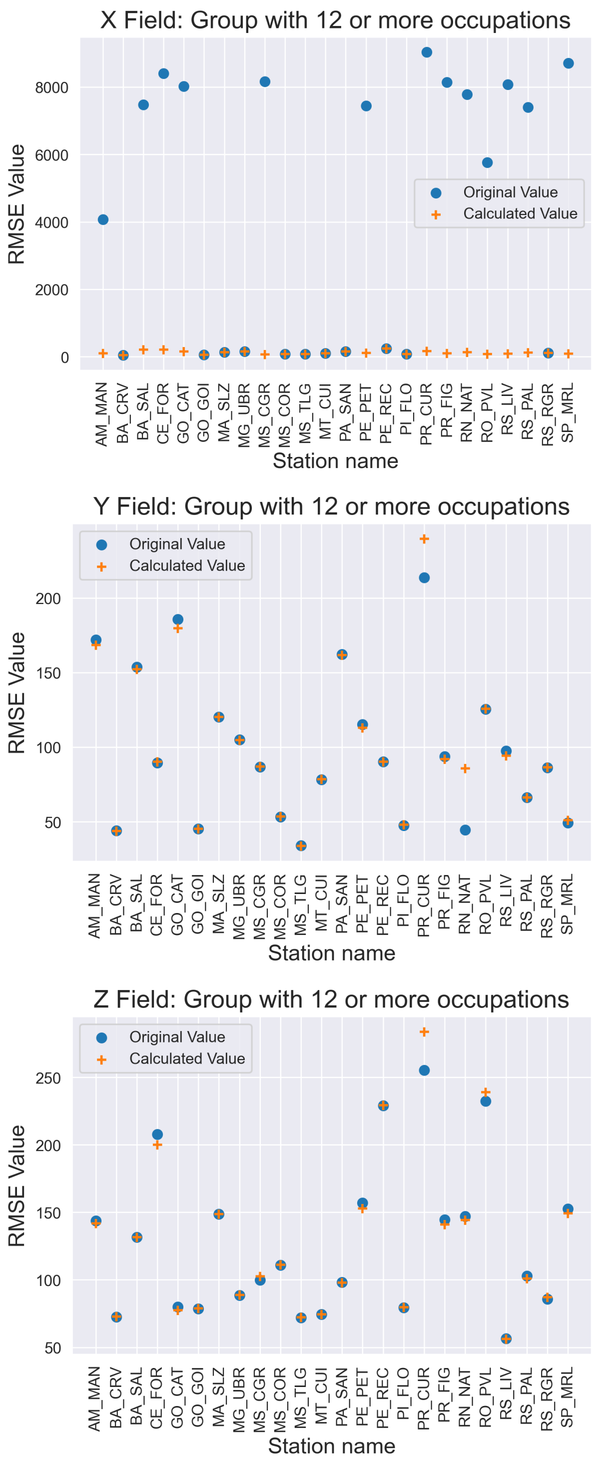

Figure 3.13: RMSE (Ω) for Temporal series of X, Y, Z, components in the group with 12 or more occupations. Blue circles are the RMSE values between the original repeat station and IGRF data sets while the orange plus symbol represent the RMSE between the calculated X, Y and Z components and the IGRF. Source: the author.

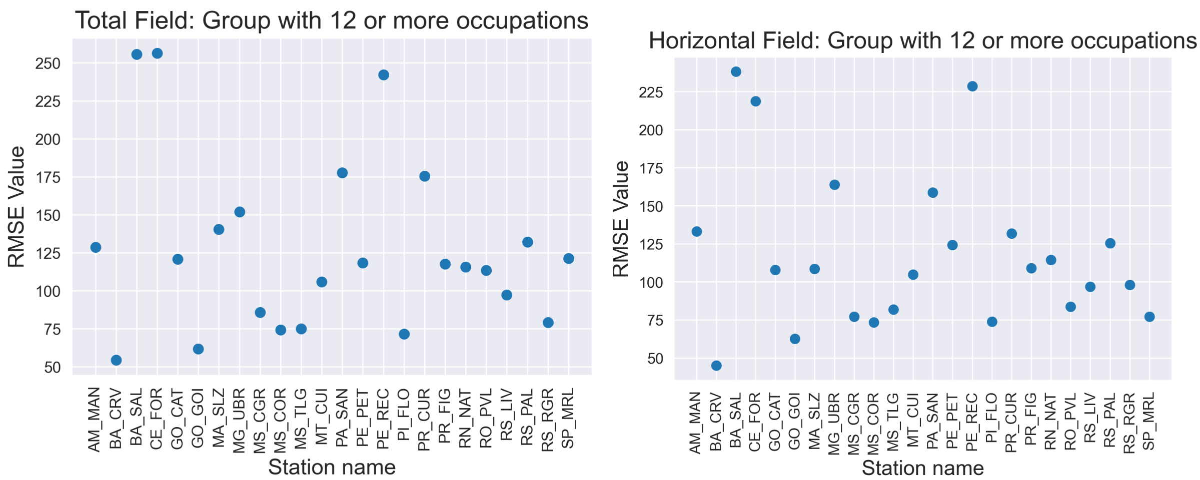

Figure 3.14: RMSE (Ω) for Temporal series of Total Field and Horizontal components in the group with 12 or more occupations. Source: the author.

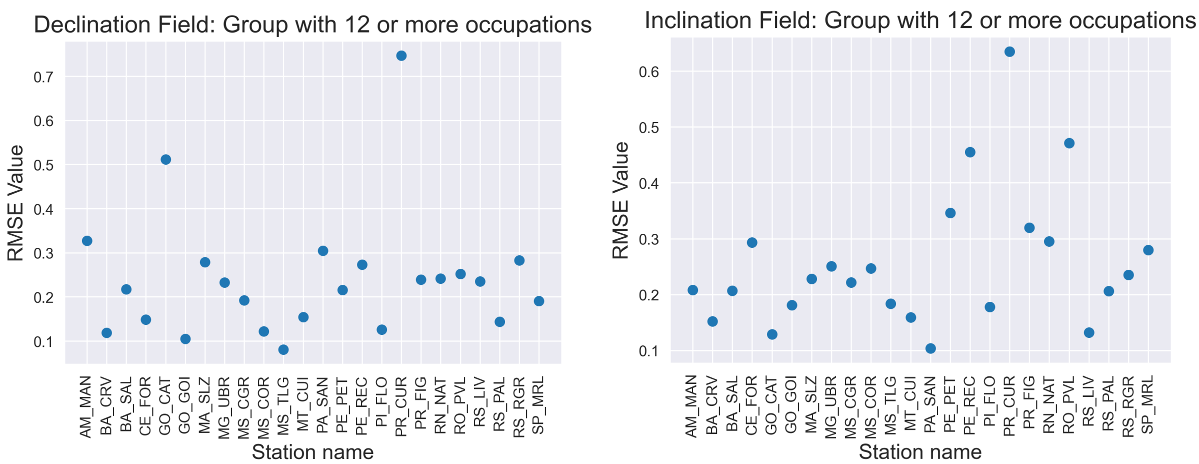

Figure 3.15: RMSE (Ω) for Temporal series of Declination and Inclination components in the group with 12 or more occupations. Source: the author.

Tozzi et al. (2012) describe how the solar cycle influences the measurements through the amplification of the ring current system, especially the X component. They compare two survey campaigns from the Italian network made at different periods in the solar cycle to show that the solar maximum period does have influence over the observations. Korte (2016) also elaborates further on the contributions of the external field in surveys made in Germany and South Africa. Finally, Vujić and Brkić (2016) explore the effects that induced fields (from oceans, ionosphere, and magnetosphere) produce in the observations at repeat stations close to coastal areas. Considering that Brazil has a large coastal boundary and various repeat stations located close to it, this effect could have influenced the Brazilian data set.

The IGRF is a model that expresses the internal field. Therefore, contributions from the external field are not taken into consideration. Since it is almost certain that the Brazilian data set have not been processed recently to minimize the influence of the external field, this could be another motive for the high differences between repeat station data and IGRF. For future studies, the use of other models that provide the effects for the external field like the CHAOS series (Finlay et al., 2020) ou the CM series (Sabaka et al., 2020) should be considered.

From the knowledge gathered after researching the network of other countries and the 50 repeat stations selection for the new network, the idea of creating distinct network models was born. The network models are based on the reduction method configurations presented earlier. The objective is to show options on how to conduct data reduction in a large country with distinct magnetic phenomena present.

3.3.1 Model 01

Model 01 assumes that the data reduction process for the new network is dependent on information from magnetic observatories only. This is the configuration observed in France, Vietnam, and Slovakia. The concept of coverage radius is also applied here, this time for the observatories. This parameter has a value of 800 km. It was deemed sufficient when the networks of France and Italy showed a similar radius size.

Considering that Brazil, at the moment, has two observatories in its territory, the utilization of nearby observatories from other countries is necessary to expand the geographical coverage. 3.16 (left panel) shows the actual network (repeat stations in black circles) configuration using all the available INTERMAGNET observatories in South America (dark blue squares), the blue circle represents the coverage radius of each observatory. It is clear that a large area of Brazil remains outside the observatories' influence. Therefore, two solutions are proposed:

- Utilization of local variometer for all the stations outside the coverage radius
- Creation of the new observatories in Brazil

The first idea seems plausible and less expensive than the second. However, the reduction process needs to correlate with a long time series for a variometer or a close magnetic observatory to transform the stations' measurements into annual means values appropriate for secular variation studies. Using the short time series of local variometer (a few days of operation per station) might not be enough to achieve high accuracy data, which directly undermines the network purpose.

The second idea offers a better solution. Large countries usually need a high number of magnetic observatories in their territory to achieve a satisfactory geographical distribution. Gu et al. (2006) reports that China performs magnetic repeat surveys using magnetic observatories for reduction, which is possible since the country has 35 observatories distributed over it.

This work proposes the construction of 3 new observatories in Brazil (3.16, right panel, dark red squares). The positions expressed in the figure are not defined locations. Their purpose is to show the general localization of observatories that culminates into a better geographical distribution.

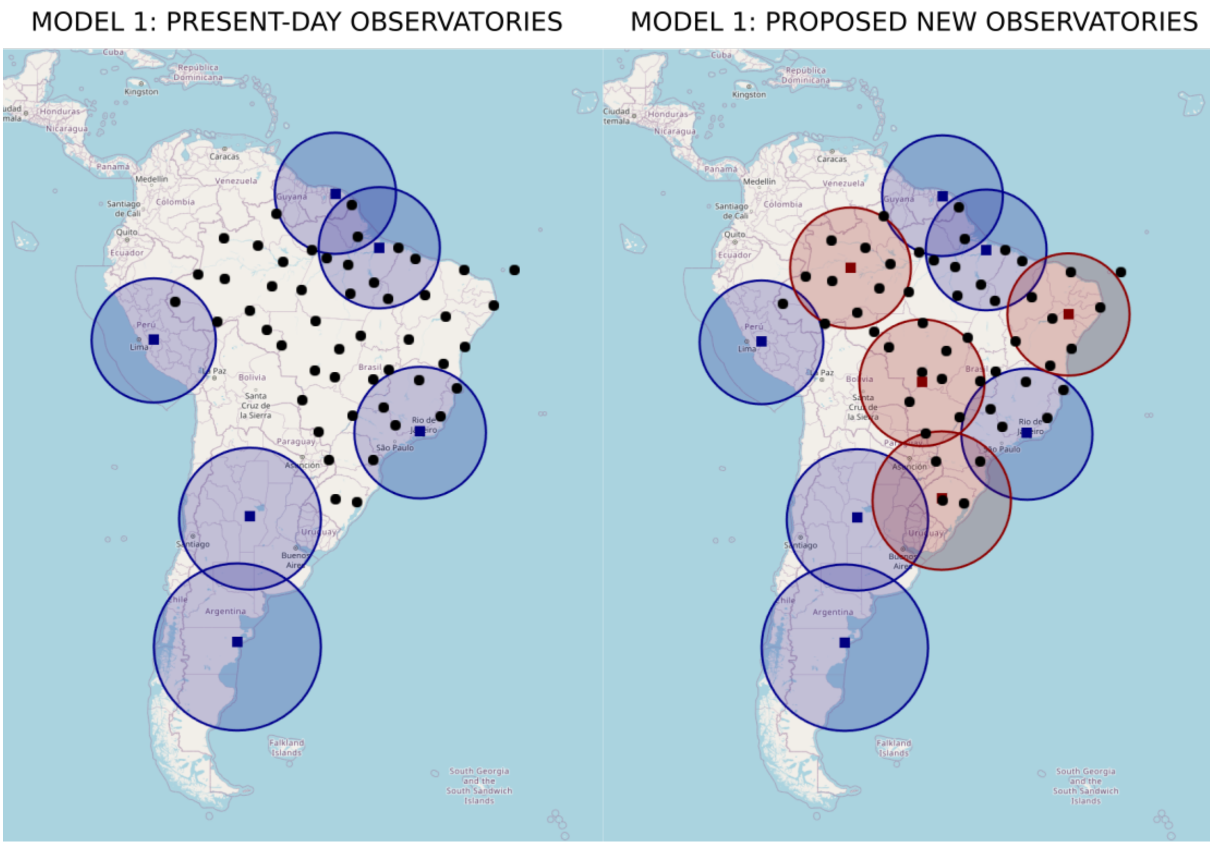

Figure 3.16: Model 01 for the new Brazilian network. In this configuration, black circles are the selected 50 repeat stations for the new network, the dark blue squares are the INTERMAGNET observatories in South America and the dark red squares are proposed new observatories to increase the geographical distribution. Source: the author.

3.3.2 Model 02

The *Model 02* assumes that the data reduction process for the new network is dependent on information from magnetic observatories and central variometer stations. This is the configuration observed in Germany and Italy. As was the case for the observatories, the concept of coverage radius is also applied here, but this time for the central variometer stations. This parameter has a value of 500 km. It was deemed sufficient as the Italian network has a similar radius size.

The present-day configuration for this scenario includes the available INTERMAGNET observatories in South America and a Magnetic Station recently installed in Macapá (Amapá, Brazil). This magnetic station is automated and continuously registers the local magnetic field, which means that it is capable of producing a long time series from the variometer. 3.17 (left panel) shows the present-day configuration for this Model, where the black circles are the selected 50 repeat stations for the new network, the dark blue squares are the INTERMAGNET observatories in South America and the pink triangle is the active magnetic station.

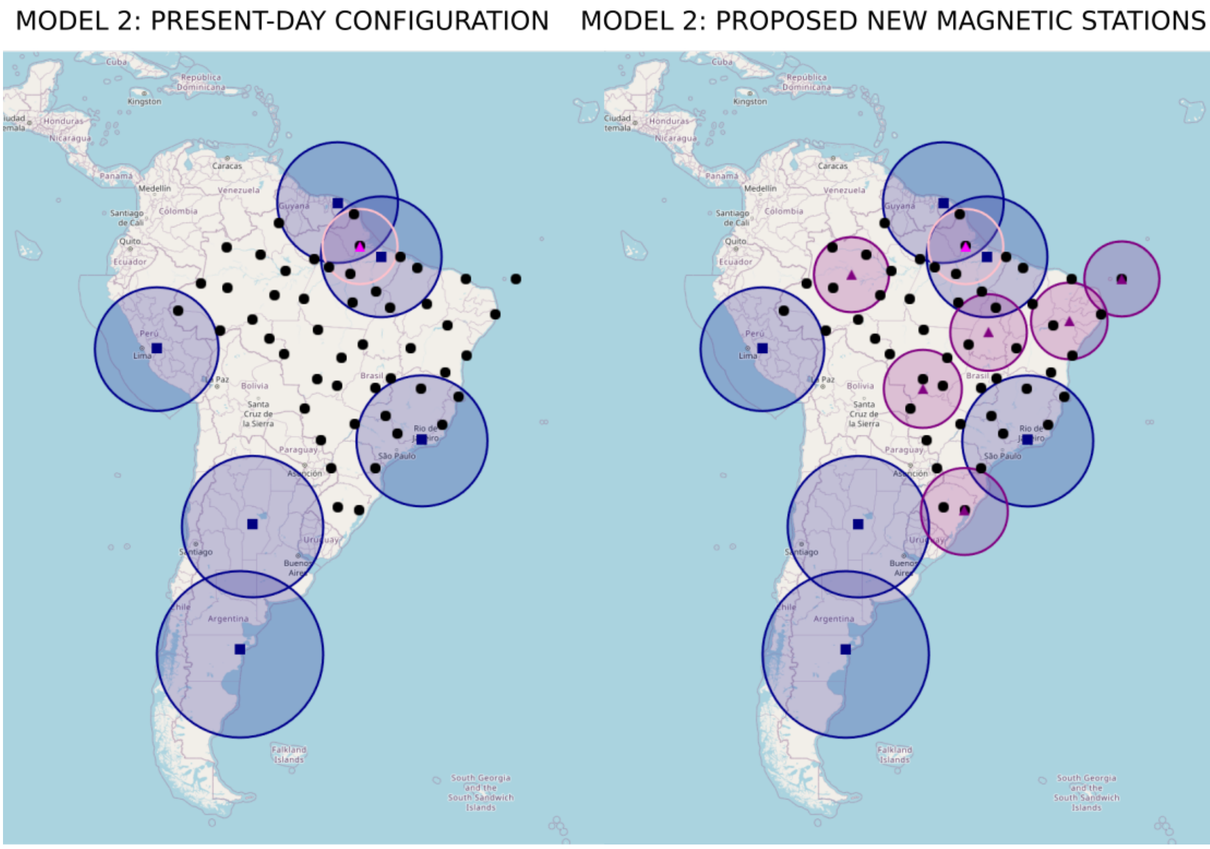

Figure 3.17: Present day configuration for Model 02 and the proposed new magnetic stations. In this configuration, black circles are the selected 50 repeat stations for the new network, the dark blue squares are the INTERMAGNET observatories in South America, the pink triangle is the active magnetic station, and the purple triangles are the proposed new magnetic stations. Source: the author.

Even though the presence of a variometer for survey in the Equatorial region is an advance for the network, only one magnetic station is not enough to provide the necessary geographical coverage. Therefore, in terms of central variometers, two solutions are proposed:

- Construction of new central variometer stations
- Partnership with the EMBRACER program to utilize their magnetometer stations

The construction of a magnetic station is less expensive than a full magnetic observatory. Besides, the station serves as a stepping stone for the creation of magnetic observatories with time. This option foresees the construction of five new magnetic stations in the Brazilian territory to increase the network spatial coverage. The main advantage of this option is the possibility of planning surveys around a specific magnetic station which translates into quicker and less costly surveys. 3.17 (right panel) shows the possible locations of these six new stations (purple triangles). Of course, these locations are not definitive since a rigorous study of the area is needed before the construction.

These six new stations are not enough to fully cover the repeat stations. In this context, the second solution is presented. Denardini et al. (2018) defines the EMBRACER program as a network to investigate the magnetic phenomena associated with aeronomy, space weather, and the study of the SAA and its influence in the deviation of the magnetic indices used to monitor the solar-terrestrial relationship associated with space weather. They have a series of active and inactive stations over South America (3.18). The status of each station is available in their website [2].

Through the combination of proposed new magnetic stations and the magnetometer from the EMBRACER program, a better geographical coverage is achieved. 3.19 shows the result of this combination where the black circles are the repeat stations, the blue squares are the available INTERMAGNET observatories, the pink triangle is the current operational magnetic station, the purple triangles are the proposed new magnetic stations, the green triangles are the online EMBRACER stations and the gray triangles are the offline EMBRACER stations.

[2] http://www2.inpe.br/climaespacial/portal/h-variation/

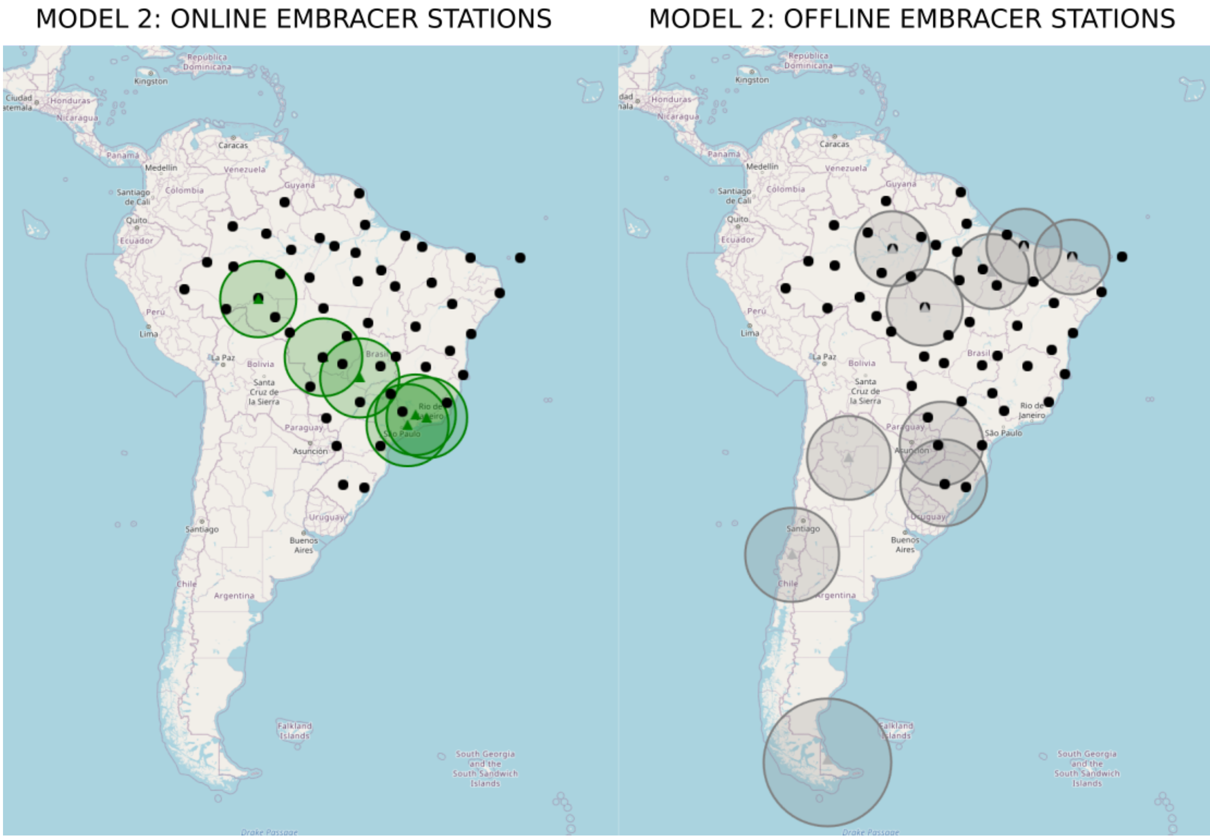

Figure 3.18: Green triangles mark the online EMBRACER stations(left panel) and gray triangles mark the offline EMBRACER magnetometer stations (right panel). Source: the author.

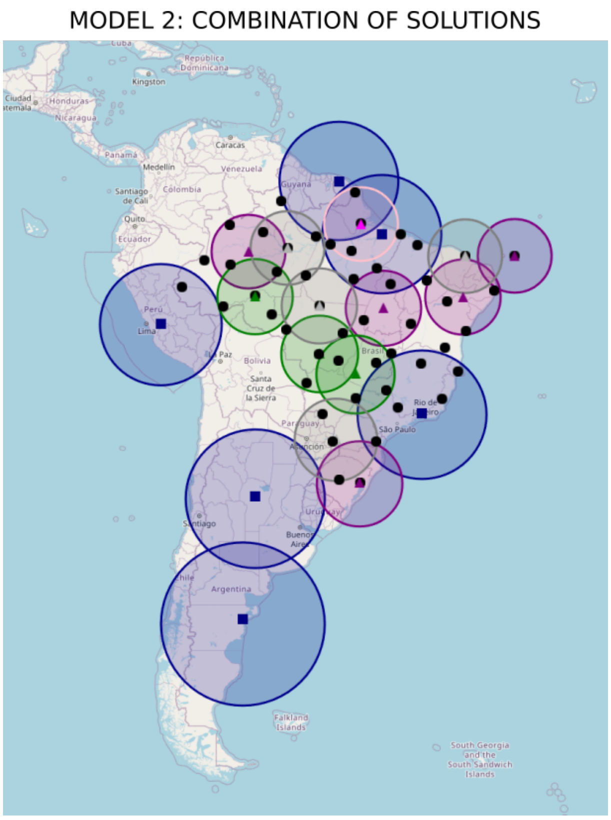

Figure 3.19: Model 02: combination of all presented solutions. Source: the author.

3.3.3 Model 03

Model 03 combines the best concepts from Model 01 and Model 02. It has two versions: Model 03a and Model 03b. Model 03a merges the ideas of proposed new magnetic observatories and central variometer stations to ensure the best geographical coverage possible. This approach allows a configuration where the central variometer and magnetic observatories coverage areas intercept each other. This means that the repeat stations inside these intercessions benefit from both the high accuracy data from magnetic observatories and the long time series of the central variometer. The reduction data process in this configuration permits a more effective minimization of external field effects and determination of annual mean values.

3.20 shows the configuration for Model 03a, where the black circles are the repeat stations, the blue squares are the available INTERMAGNET observatories, the dark red squares are the proposed new magnetic observatories, the pink triangle is the current operational magnetic station, the purple triangles are the proposed new magnetic stations, the green triangles are the online EMBRACER stations and the gray triangles are the offline EMBRACER stations.

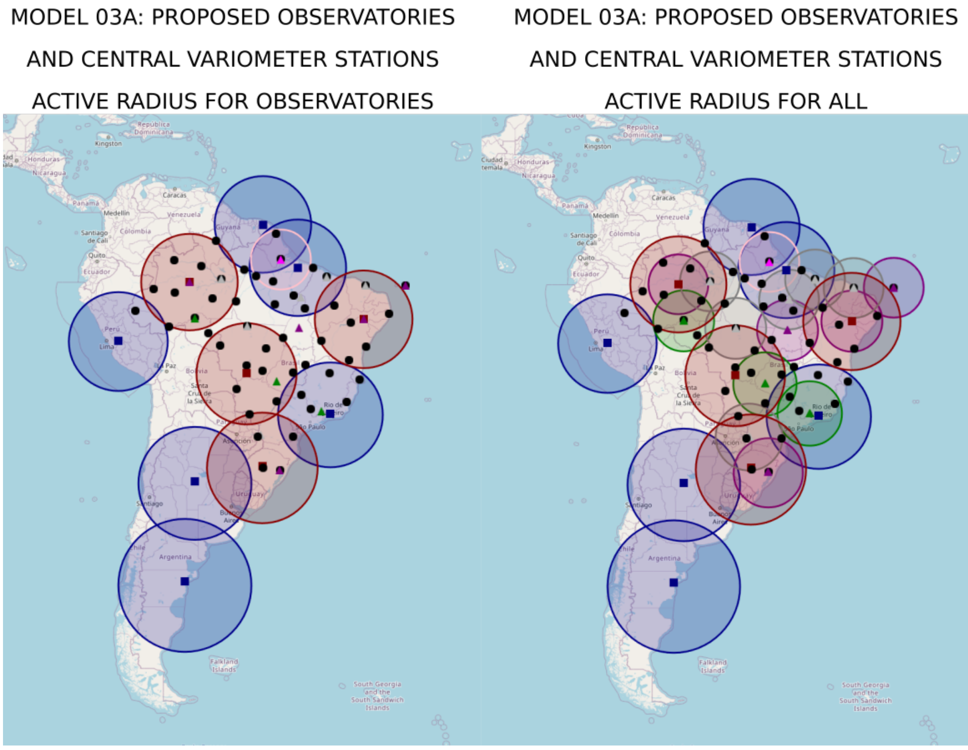

Figure 3.20: Model 03a: combination proposed magnetic observatories and central variometer stations. Left panel shows the coverage radius active for both present-day observatories as well as the proposed ones. Right panel shows the coverage radius active for all features in the model. Source: the author.

Model 03b strives to follow the guidelines established by Newitt et al. (1996). It assumes that each repeat station will have a local variometer close, active for a few days to acquire quiet time magnetic field behavior. Also, the construction of the new proposed observatories is crucial to combine magnetic observatories and local variometers for the data reduction process.

3.21 shows the configuration for Model 03b, where the black circles are the repeat stations, the blue squares are the available INTERMAGNET observatories, and the dark red squares are the proposed new magnetic observatories.

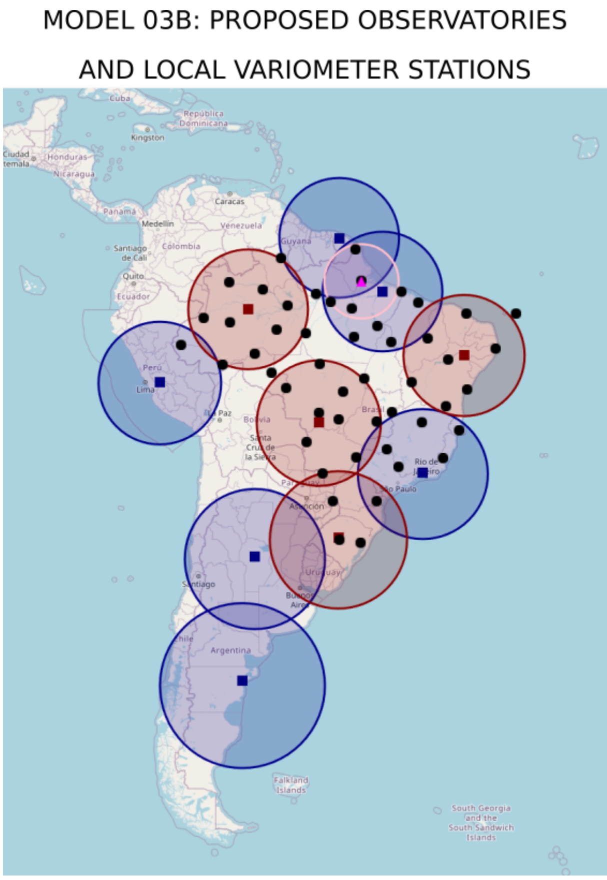

Figure 3.21: Model 03b: combination proposed magnetic observatories and central variometer stations. Source: the author.

Both versions of Model 03 offer great scientific value when considering the high-quality data a network would produce in the future. But of all the displayed Models, this one has the highest level of commitment to achieve. Necessary funding for the instruction of the proposed features and an agreement on a partnership with the EMBRACER program are just a few of the challenges. Independent of the model the Brazilian network will follow, it needs more than any other requirement, to have a dedicated management team to guarantee that the network operation stays stable and produces high-quality data for the scientific community.

4 CONCLUSION

This work aimed to assist the planning of the new Brazilian repeat station network. Although its effectiveness was diminished due to the lack of access to documentation about magnetic activities in Brazil. The work presented here is still a valuable foundation for the planning of the new network.

The knowledge about the repeat stations network of other countries is fundamental to understanding the better practices associated with the management and operation of a network. The analysis of the available documentation showed that a large part of the present-day data set needs to be further investigated and possibly processed in order to be adequate for secular variation studies. The production of the database showed how is important to have standards for data organization and archiving to facilitate the visualization and access of data. And finally, the models based on methods of data reduction offer options on how to plan the network taking into account how they affect its configuration.

APPENDIX

A– APPENDIX A: THE 50 SELECTED REPEAT STATIONS

This appendix contains the information about the 50 selected repeat stations for the new Brazilian network.

Repeat Station Code	Latitute (dd)	Longitude (dd)	Altitude (m)	Last Occupation (dy)	Number of occupations	Nearest OBS (TTB and VSS)	Name
AC_CZS	-7.599	-72.77	196.508	1995.869	6	TTB	CRUZEIRO DO SUL
AC_RBC	-9.996	-67.802	136.304	2002.927	10	TTB	RIO BRANCO
AM_BAR	-0.98	-62.922	31.832	2005.861	6	TTB	BARCELOS (AM)
AM_BJC	-4.367	-70.05	73.16	1984.706	8	TTB	BENJAMIM CONSTANT
AM_CRA	-4.878	-66.895	75.256	1995.906	4	TTB	CARAUARI
AM_MAN	-2.93	-59.975	90.7	2005.76	25	TTB	MANAUS
AM_MNC_A	-5.795	-61.278	41.728	2005.908	1	TTB	MANICORE A
AM_SGC	-0.115	-66.992	94.148	2005.878	5	TTB	SAO GABRIEL CACHOEIRA
AP_MCP	0.052	-51.068	12.899	2009.536	6	TTB	MACAPA
AP_OPQ	3.861	-51.796	32.563	2009.527	4	TTB	OIAPOQUE
BA_BAR_C	-12.079	-45.002	709.739	2008.651	3	VSS	BARREIRAS (BA) C
BA_CRV	-17.652	-39.249	7.88	2014.94	13	VSS	CARAVELAS
BA_SAL	-12.902	-38.327	13.998	2006.582	18	VSS	SALVADOR
BA_VCQ	-14.866	-40.859	906.908	2006.574	8	VSS	VITORIA DA CONQUISTA (BA)
CE_FOR	-3.878	-38.426	24.395	2014.686	13	TTB	FORTALEZA
ES_CIP	-20.836	-41.188	106.349	2014.954	10	VSS	CACHOEIRO ITAPEMIRIM (ES)
GO_FOR	-15.54	-47.355	946.42	1985.114	5	VSS	FORMOSA
GO_GOI	-16.631	-49.228	736.682	2001.411	12	VSS	GOIANIA
MA_CAR	-7.317	-47.442	175.444	1993.727	10	TTB	CAROLINA
MA_SLZ	-2.581	-44.239	41.712	2003.734	14	TTB	SAO LUIZ
MG_MTC	-16.722	-43.803	657.57	1989.38	8	VSS	MONTES CLAROS
MG_PCA	-21.787	-46.59	1253.964	2017.911	10	VSS	POCOS DE CALDAS
MG_UBR	-19.767	-47.963	797.527	1996.223	13	VSS	UBERABA
MS_COR	-19.012	-57.662	147.915	2001.762	16	VSS	CORUMBA

Table A–1: Table with the 50 selected repeat stations for the new Brazilian network (Part I). Source: the author.

Repeat Station Code	Latitute (dd)	Longitude (dd)	Altitude (m)	Last Occupation (dy)	Number of occupations	Nearest OBS (TTB and VSS)	Name
MS_PPO	-22.552	-55.705	651.116	2006.847	10	VSS	PONTA PORA
MS_TLG	-20.756	-51.688	327.278	2002.738	12	VSS	TRES LAGOAS
MT_AFT	-9.871	-56.106	275.495	2019.757	4	TTB	ALTA FLORESTA (MT)
MT_CUI	-15.657	-56.123	184.181	1975.515	12	VSS	CUIABA
MT_GNT	-13.154	-53.253	380.906	2007.562	1	TTB	GAUCHA DO NORTE (MT) A
MT_GUI	-16.352	-53.755	482.92	1974.697	2	VSS	GUIRATINGA
MT_SFA	-11.629	-50.696	197.822	2007.559	3	TTB	SAO FELIX ARAGUAIA
PA_ALT_C	-3.255	-52.247	113.534	2019.727	4	TTB	ALTAMIRA C
PA_JAC	-6.234	-57.775	97.46	2004.446	3	TTB	JACAREACANGA
PA_MRB	-5.368	-49.138	102.667	2003.709	5	TTB	MARABA
PA_PTR	-1.487	-56.491	54.854	2005.785	2	TTB	PORTO TROMBETAS
PA_SAN	-2.422	-54.785	28.66	2019.737	16	TTB	SANTAREM
PA_SFX	-6.664	-51.963	201.572	2007.548	1	TTB	SAO FELIX DO XINGU A
PA_VSU	-1.198	-46.199	28.512	2019.702	1	TTB	VISEU (PA)
PE_FNH	-3.85	-32.417	56.58	1988.17	5	TTB	FERNANDO DE NORONHA
PE_PET	-9.365	-40.565	384.49	2014.91	17	TTB	PETROLINA
PE_REC	-8.08	-34.895	1.12	2001.326	16	TTB	RECIFE
PI_FLO	-6.846	-43.077	193.33	2003.912	12	TTB	FLORIANO
PR_CUR	-25.525	-49.182	898.58	2007.754	12	VSS	CURITIBA
PR_FIG	-25.595	-54.492	222.528	2008.894	14	VSS	FOZ DO IGUACU
RO_JIP	-10.877	-61.85	169.14	2006.874	5	TTB	JIPARANA
RO_PVL	-8.709	-63.895	88.21	2006.872	16	TTB	PORTO VELHO
RO_VLN	-12.686	-60.094	611.352	2006.883	8	TTB	VILHENA (RO)
RR_BOV	2.839	-60.689	80.64	2005.755	11	TTB	BOA VISTA (RR)
RS_PAL	-29.992	-51.163	8.212	2007.789	18	VSS	PORTO ALEGRE
RS_SMA	-29.717	-53.7	85.2	1991.926	9	VSS	SANTA MARIA

Table A–2: Table with the 50 selected repeat stations for the new Brazilian network (Part II). Source: the author.

Repeat Station Code	RMSE D Original values	RMSE I Original values	RMSE F Original values	RMSE H Original values	RMSE X Original values	RMSE X Calculated values	RMSE Y Original values	RMSE Y Calculated values	RMSE Z Original values	RMSE Z Calculated values
AC_CZS	0.178	0.204	50.308	36.257	37.605	37.680	83.892	84.130	105.801	106.271
AC_RBC	0.560	0.291	86.356	86.354	94.392	94.667	259.678	259.546	141.101	141.442
AM_BAR	0.163	0.222	130.192	72.745	7435.109	72.709	91.531	83.793	184.312	168.085
AM_BJC	0.245	0.263	62.099	42.024	43.905	43.974	119.560	119.754	149.236	149.702
AM_CRA	0.222	0.236	31.757	44.168	41.469	41.376	106.824	107.543	110.291	109.858
AM_MAN	0.327	0.208	128.662	133.015	4074.033	97.073	171.983	168.497	143.647	141.949
AM_MNC_A	0.506	0.148	191.700	182.200	22128.100	126.184	NaN	264.399	NaN	89.371
AM_SGC	0.592	0.677	412.539	384.585	7568.770	393.817	281.119	281.445	277.701	371.984
AP_MCP	0.255	0.272	86.898	98.288	9125.755	84.635	133.252	131.661	136.266	130.428
AP_OPQ	0.104	0.240	50.522	28.261	9762.055	33.715	48.235	47.904	127.523	128.145
BA_BAR_C	0.267	0.110	52.255	59.628	17229.949	58.483	27.642	106.645	43.305	38.480
BA_CRV	0.119	0.152	54.539	45.058	50.529	50.676	44.040	43.858	72.464	72.712
BA_SAL	0.217	0.207	255.664	238.185	7470.992	205.180	153.745	152.278	131.621	131.736
BA_VCQ	0.091	0.147	60.531	74.781	11023.646	79.215	29.297	28.760	41.318	44.338
CE_FOR	0.149	0.293	256.376	218.821	8405.460	210.853	89.590	90.133	207.923	200.064
ES_CIP	0.095	0.076	47.918	46.367	48.542	48.334	32.528	32.951	34.182	34.192
GO_FOR	0.067	0.255	45.636	54.395	54.910	54.479	27.365	27.726	105.511	105.989
GO_GOI	0.105	0.181	61.833	62.583	62.222	62.018	45.352	45.207	78.663	78.976
MA_CAR	0.132	0.126	56.300	58.012	49.264	49.562	69.645	69.950	58.890	58.525
MA_SLZ	0.279	0.228	140.384	108.482	129.210	129.419	120.217	120.172	148.660	148.801
MG_MTC	0.050	0.138	64.418	74.008	71.733	71.065	28.001	27.506	46.177	46.441
MG_PCA	0.128	0.264	82.403	90.569	75.698	75.892	70.044	70.342	102.036	101.799
MG_UBR	0.233	0.251	152.076	163.954	160.095	159.925	104.993	104.836	88.462	88.822
MS_COR	0.122	0.247	74.252	73.321	73.968	73.911	53.195	53.569	110.829	111.251

Table A–3: Table with the RMSE values for the selected repeat stations (Part I). Source: the author.

Repeat Station Code	RMSE D Original values	RMSE I Original values	RMSE F Original values	RMSE H Original values	RMSE X Original values	RMSE X Calculated values	RMSE Y Original values	RMSE Y Calculated values	RMSE Z Original values	RMSE Z Calculated values
MS_PPO	0.064	0.276	58.744	56.249	9414.663	56.220	25.873	24.690	118.176	115.778
MS_TLG	0.081	0.184	75.006	81.767	81.018	80.763	34.090	33.882	71.991	72.335
MT_AFT	0.152	0.169	25.431	19.090	6.233	6.101	65.490	66.123	76.460	76.915
MT_CUI	0.154	0.159	105.813	104.857	98.110	98.502	78.311	78.590	74.459	74.443
MT_GNT	9.900	0.250	61.000	34.300	27564.700	861.641	NaN	3906.206	NaN	118.132
MT_GUI	0.109	0.152	23.993	31.023	37.187	36.505	44.354	45.223	63.177	63.553
MT_SFA	0.087	0.181	65.901	71.945	16051.774	78.120	26.922	21.914	58.584	71.387
PA_ALT_C	0.156	0.426	60.391	51.011	55.079	55.204	71.786	71.469	225.208	204.595
PA_JAC	0.038	0.154	32.121	38.176	37.152	36.640	18.752	18.314	67.871	68.397
PA_MRB	0.200	0.044	63.089	62.652	70.279	70.466	95.073	94.945	22.080	22.120
PA_PTR	0.163	0.421	99.617	140.222	14737.005	113.415	84.100	115.012	152.100	181.505
PA_SAN	0.305	0.104	177.699	158.689	151.594	151.369	162.109	161.763	98.130	97.864
PA_SFX	0.074	0.124	26.500	28.200	25578.200	39.268	NaN	22.451	NaN	49.668
PA_VSU	0.038	0.086	4.100	2991.000	2.900	2.192	17.300	17.606	39.000	39.230
PE_FNH	0.452	1.850	360.092	431.915	436.326	436.222	207.599	207.545	835.244	835.346
PE_PET	0.216	0.346	118.414	124.165	7446.796	111.813	115.292	113.094	157.034	152.981
PE_REC	0.273	0.455	242.159	228.651	247.253	247.749	90.339	90.363	229.012	229.354
PI_FLO	0.126	0.178	71.700	73.719	82.331	82.304	47.641	47.983	79.506	79.578
PR_CUR	0.747	0.635	175.553	131.757	9036.790	165.080	213.737	239.630	255.235	283.809
PR_FIG	0.239	0.320	117.606	109.025	8139.482	105.577	93.829	92.087	144.670	140.925
RO_JIP	0.506	1.321	425.610	427.419	11394.632	451.554	189.229	171.575	577.208	575.791
RO_PVL	0.252	0.471	113.491	83.600	5765.877	75.883	125.530	125.751	232.403	238.988
RO_VLN	0.086	0.126	41.308	41.893	9218.669	38.723	36.241	39.838	56.192	54.680
RR_BOV	0.500	0.452	309.836	229.880	4752.690	204.150	265.957	271.670	359.013	342.780
RS_PAL	0.144	0.206	132.193	125.419	7398.539	119.215	66.193	66.305	102.888	100.978
RS_SMA	0.241	0.197	51.595	68.178	69.163	69.214	89.968	90.235	76.267	75.942

Table A–4: Table with the RMSE values for the selected repeat stations (Part II). Source: the author.

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