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Historical evolution of the geomagnetic declination at the Royal Observatory of Madrid.

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Abstract.

The agonic line, representing geomagnetic declinations of 0º, recently crossed the Royal Observatory of Madrid (ROM) in December 2021, causing a shift in declination values from west to east. This event constitutes a notable milestone for this significant place, where the first geomagnetic observation series in Spain commenced around 1855. Consequently, a thorough investigation into the historical evolution of the declination has been undertaken to decipher prior occurrences of the agonic line crossing at the ROM. Despite the ROM hosted the first series of geomagnetic measurements in Spain, the present lack of geomagnetic measurements in this observatory makes necessary to extend the declination measurements to other observatories distributed throughout the Iberian Peninsula to better define the passage of the agonic line since 1855 up to the present. For periods prior to 1855, a bibliographic search for declination measurements conducted in the Iberian Peninsula has been carried out, complemented by historical data from the HISTMAG database. As a result, a time-continuous curve of geomagnetic declination is generated from 1590 to 2021 at the ROM coordinates. The declination curve reveals that the agonic line also crossed the ROM 400 years ago (around 1600) passing from west to east declination values.

1 Introduction

At the end of 2021, the agonic line crossed the Royal Observatory of Madrid (ROM) changing the declination on this place from west values to east values. According to the Geomagnetic Reference Model for the Iberian Peninsula and Balearic Islands (also named as Geomagnetic Iberian Model, Puente-Borque et al., 2023; more information in Supplementary Material) this event occurred on 12 September 2021 (see Fig. 1). The interest on this event, considering that this observatory does not have a great tradition on geomagnetism, comes from the fact that in this place were carried out the first regular observations of declination made in Spain.

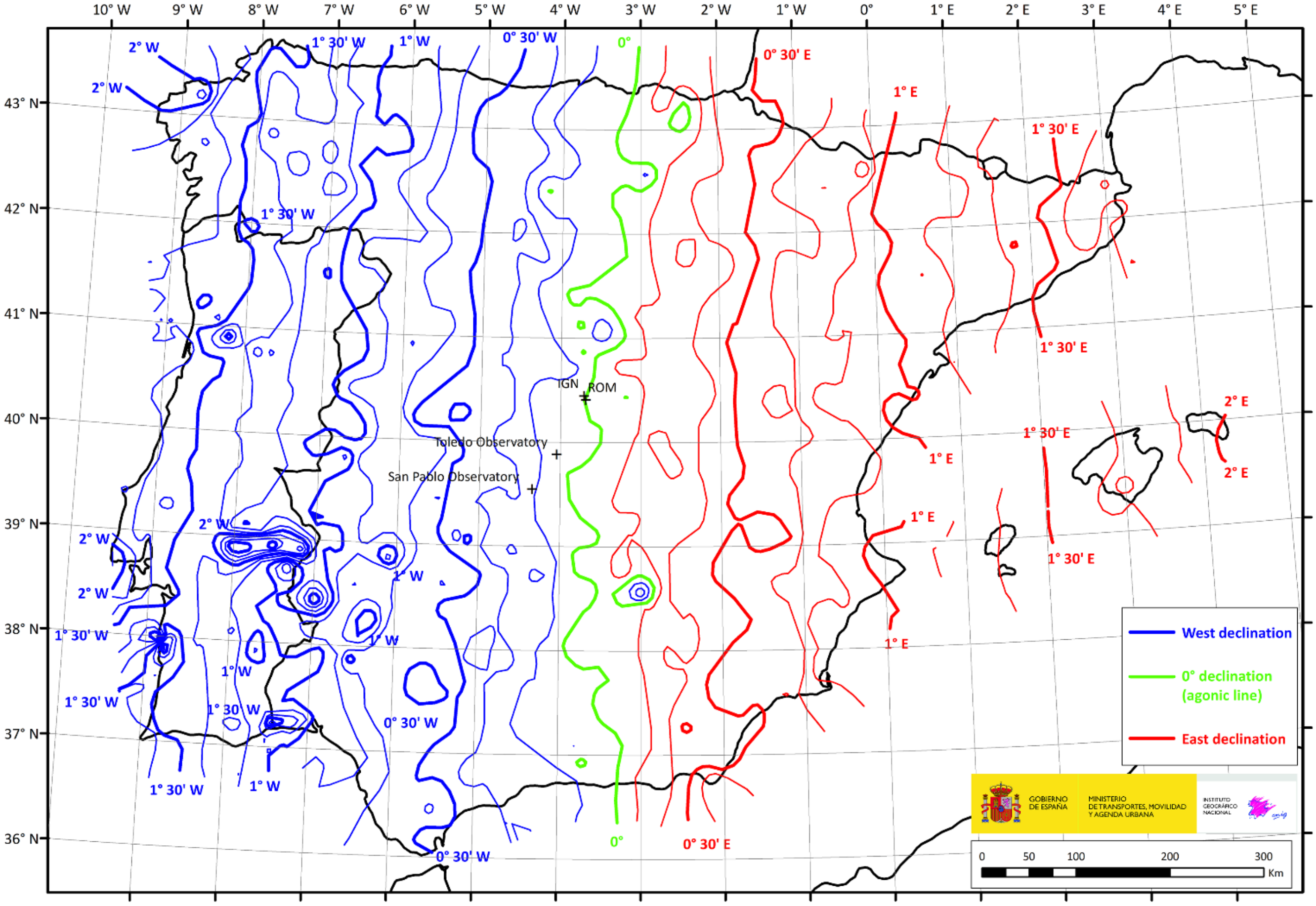

Figure 1: Declination map of the Iberian Peninsula for September 12, 2021 according to the Geomagnetic Reference Model for the Iberian Peninsula and Balearic Islands.

The event was monitored by IGN (see Supplementary Material) showing in near real time the declination deducted for the Royal Observatory of Madrid between 2021 and 2023. To get the real time declination at ROM, we translated the declination data observed at San Pablo de los Montes Observatory (SPT), the closest Spanish observatory (110 km far away from ROM). The spatial translation of the declination data from SPT site to ROM coordinates was carried out using the current spatial gradient provided by the Geomagnetic Iberian model (Puente-Borque et al., 2023). Original daily mean declination data from SPT and the translation data to ROM are plotted in Fig. 2a for the period 1 January 2021 to 1 January 2023. The translated data indicated that the agonic line crossed the ROM around December 06, 2021. Note that the difference between the date given in Fig. 1 (September 12, 2021) and its equivalent of Fig. 2a (December 06, 2021) is due to the magnetic anomalies beneath both ROM and STP observatories (the so-called anomaly biases) that slightly perturb the declination values given by the main geomagnetic field.

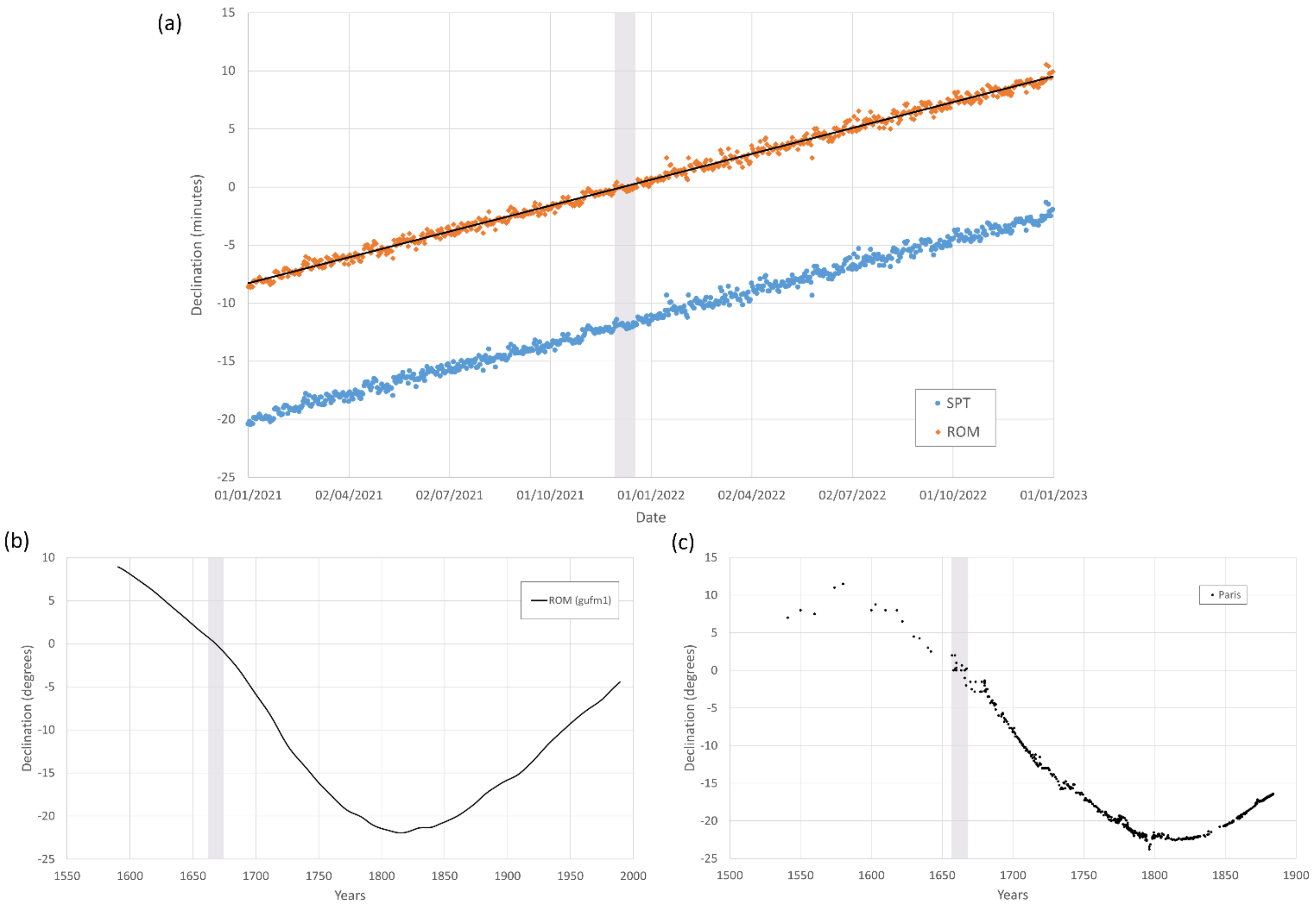

Figure 2: (a) Daily mean declination data recorded at SPT observatory and the translated declination data at ROM observatory. Declination data is translated from SPT to ROM by using the spatial declination gradient derived from the Geomagnetic Iberian Model. (b) Annual mean declination values at ROM estimated from the *gufm1* model. (c) Declination historical records in Paris.

In this work, in addition to detailed study of the crossing of the agonic line in recent times, we also focus our analysis in previous crossings that took place during the historical period covered by instrumental geomagnetic data, i.e. the last four centuries. According to the historical geomagnetic reconstruction *gufm1* based on a complete compilation of historical observations, mainly taken in naval shipping (Jackson et al., 2000), it seems that the last time that this event occurred was around 1668 (Fig. 2b). This epoch is in agreement with the declination data recorded in other French geomagnetic observatories (Alexandrescu el al., 1996; Mandea and Le Mouël, 2016) close to ROM (Fig. 2c). Note that an eastward drift of declination, i.e. the declination changed from east to west values, characterized the previous crossing.

The primary goal of this work is to highlight the historical significance of the Royal Observatory of Madrid, which served as the first site for geomagnetic measurements in Spain. Additionally, we have compiled a comprehensive dataset of Spanish geomagnetic declination values derived from a variety of sources, spanning the last four centuries. Then, we have translated this declination dataset to ROM coordinates, enabling us to construct a time-continuous declination curve. This curve serves as a valuable tool for more precisely determine the epochs at which the agonic line intersected the location of the ROM observatory.

2 History of the Royal Observatory of Madrid and the measurement of magnetic declination

The Spanish King Carlos III decided to project an Astronomical Observatory in Madrid in 1785 and it was commissioned to the famous architect Juan de Villanueva, who prepared the plans for the new Observatory (Tinoco, 1951). Its construction began around 1790 near to the Buen Retiro Palace. In parallel to the construction, some experts were recruited to further work in the Observatory and a collection of instruments was acquired. However, when the works were just completed the Napoleonic invasion of Spain in 1808 caused the destruction of documentation and instrumentation and, thus, the Observatory building was damaged and abandoned for years. The reconstruction of the building was undertaken in 1846 with a training period of new staff and acquisition of new instrumentation. Finally, the Royal Observatory of Madrid became constituted and operational in 1851. Figure 3 shows a picture of the Observatory taken in 1853.

Figure 3: The Royal Observatory of Madrid in 1853 (Source: Biblioteca Nacional de España, http://bdh.bne.es/bnesearch/detalle/bdh0000027343)

In addition to the astronomical section, the new Observatory incorporated a meteorological section. To fit up the meteorological section with a complete collection of instrumentation, in 1853 the following geomagnetic instrumentation was acquired (Real Observatorio de Madrid, 1867): a) two magnetometers, to measure the horizontal and vertical forces, with their corresponding telescopes. b) One *Barrow* theodolite, to determine the magnetic declination. c) One inclinometer needle. d) Two magnetized bars with their armours. These instruments were used by the responsible of the meteorological observations, Mr. Rico Sinobas, to perform the first series of geomagnetic declination and inclination measurements along the month of September of 1855. This constituted the first continuous time series of geomagnetic observations made in a location of the Iberian Peninsula (Rico Sinobas, 1856; see also Tables S1 and S2 and Fig. S1 and S2 of the Supplementary Material).

The declination series of observations were adjusted to the recommendations of relevant magnetic observatories of the epoch, referring the time to that given by the Observatory of Gottingen (Germany) and measuring during the hours of maximum and minimum variation. Two daily declination measurements were observed at 2h 30m and at 20h 00m (it seems that the time recorded here is the astronomical time and it is needed to add 12 hours to get the Universal Time). Meanwhile, inclination measurements (only 7 inclination measurements were observed along the month) are consigned to be made at 9h 00m (in the morning) or at 15h 00m (in the afternoon). We have digitized the magnetic declination data obtained by Rico Sinobas and obtained a daily mean value for each day of the series. Then we have compared these data with the daily declination value obtained by the historical geomagnetic model *gufm1* (Jackson et al, 2000) at the same coordinates (see Fig. 4).

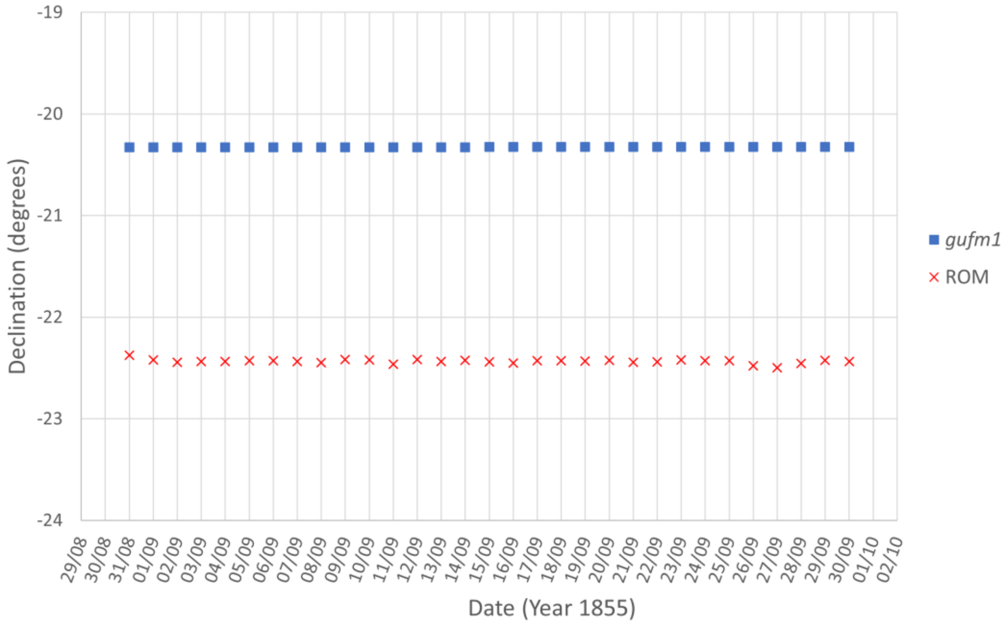

Figure 4: Observed declination data by Rico Sinobas at ROM and estimated declination values according to the *gufm1* model.

The comparison reveals a clear difference between both series of data of about 2º, this difference could be due to the anomaly bias that characterized the crustal field beneath ROM (this anomaly bias is not considered in the *gufm1* model, that only provides the main geomagnetic field). However, 2º is a large value to be considered of crustal origin. This problem related to the found difference was already pointed out in 1857 (De Prado, 1858) comparing with the declination values obtained by Dr. Lamont in his campaign in Spain to make a European magnetic chart (Lamont, 1858). The value calculated by him for Madrid on 1st July 1857 was 20º 12' west that pretty agrees with the *gumf1* model predictions. It was supposed that the measurements made by Rico Sinobas were influenced by the large masses of iron used in the construction of the building. Although this constant local influence seems not to affect to the recorded time variability in declinations (with a maximum difference of about 13.5' between maximum and minimum values), this set of data is not useful for the purpose of our analysis.

In 1878 a *Brunner* theodolite and a *Brunner* inclinometer were acquired (Fig. 5), which were installed as far as possible of all possible disturbance sources that could distort the measurements. One year later (1879) the observations of magnetic declination and inclination began to be carried out on a regular way at the ROM (Real Observatorio de Madrid, 1890).

Figure 5: Brunner inclinometer used in the Royal Observatory of Madrid (source: IGN archive)

These observations were carried out between 1879 and 1901 and published in the historical yearly books published by the Astronomical Observatory of Madrid from 1890 to 1904. Declination measurements were made every day at 08:00 and 13:30 (local time), close to the maximum and minimum daily value of this element. Unfortunately, only mean values for every decade of days and their average were published. These data have been digitized and compared with the *gufm1* model

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by Pro et al. (2018). Their analysis shows a good behaviour with better stability over the years and increasing differences since 1897.

As pointed out in the Yearbook of Astronomy for 1934 (Instituto Geográfico y Catastral, 1933), the observations were interrupted since 1902 due to the increase of electrical installations near the Observatory. In 1904 the Royal Observatory of Madrid was integrated in the Instituto Geográfico y Estadístico (today Instituto Geográfico Nacional, IGN). Figure 6a shows the declination values obtained at ROM between 1879 and 1901, published in its yearly books. The series measured by Rico Sinobas during September 1855, and other previous declination values for the city of Madrid that were noted by him (Rico Sinobas, 1856) are also shown in Fig. 6b (the full dataset recompiled by Rico Sinobas is given by Fig. S3 of the Supplementary Material). We have also estimated the declination values for these epochs using the *gufm1* model (see Fig. 6). Results show discrepancies between the Spanish declination measurements and the model predictions that increase for epochs before 1880. As it can be seen in Fig. 6, the amount of data available for the coordinates of the ROM is very scarce and it is impossible to define a declination curve using only these data covering the last centuries. In the following section we present other source of data that will help to solve this problem.

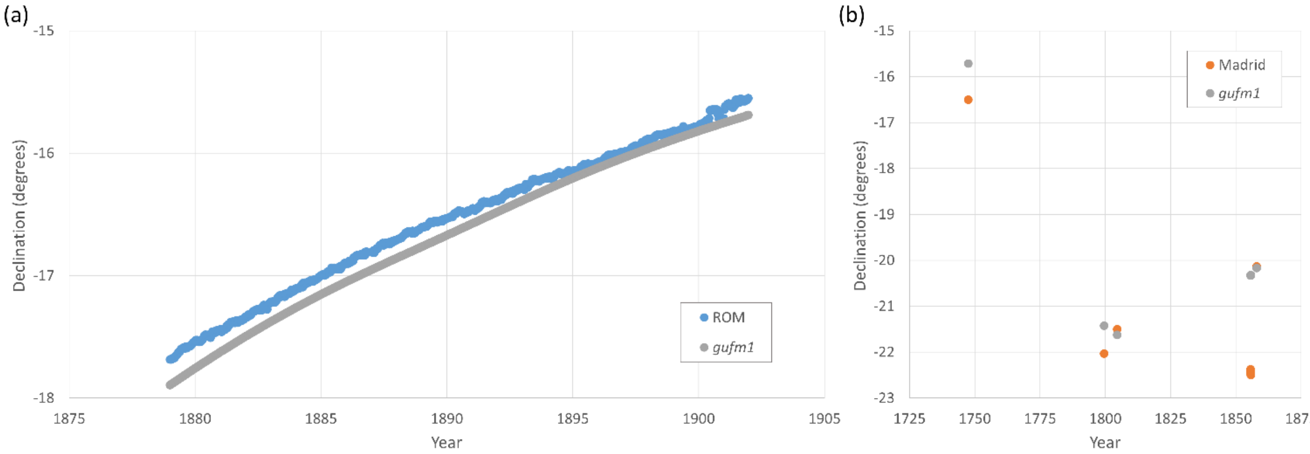

Figure 6: (a) Declination values measured at ROM and estimated from the *gufm1* model in the period 1879-1901. (b) Declination values in Madrid noted by Rico Sinobas (1856) and their corresponding estimations from the *gufm1* model.

3 Observatory data selection

3.1 Geomagnetic Observatories in Spain

The Royal Observatory of Madrid was the first observatory in Spain to take regular measurements of the magnetic field as part of the meteorological observations. Unfortunately, it was not a specific geomagnetic observatory with continuous recording of the magnetic field. In Spain, a network of geomagnetic observatories has been in operation since the late 19th century, with their numbers steadily growing throughout the 20th century. Many of these observatories continue to function to this day. Here we provide a brief summary of its history.

3.1.1 San Fernando Observatory (SFS)

The Spanish Navy installed the first geomagnetic observatory in Spain, being part of the Astronomical Observatory of San Fernando (SFS, Cádiz). Regular geomagnetic observations were started in 1879 (see Fig. 7a), as at the ROM, but with more facilities: one independent pavilion constructed without magnetic substances, isolated and buried, where the magnetometers were installed (Azpiazu and Gil, 1919).

It was equipped with a set of magnetographs *Adié* that continuously recorded the variations of the geomagnetic field. In addition, a magnetometer *Elliot* and an inclinometer *Dover* were available to make absolute measurements. The recorded data from SFS observatory have been published without interruption in the Observatory's yearbooks until now.

In the decade of the 1970's the railway electrification in the line Cádiz-Sevilla caused significant interferences over the geomagnetic records. For that reason, the geomagnetic observatory was moved to a new location, 8 km far at NE of the original location, in Puerto Real (Cádiz). It was operative from 1978 until 2004 (Real Instituto y Observatorio de la Armada en San Fernando, 2021). However, after detecting new interferences in the geomagnetic records, it was moved again to a new location with more stable geomagnetic conditions. The new SFS observatory is located in Cortijo Garrapilos, Jerez (Cádiz) and it is operative since 2005. This observatory is member of INTERMAGNET since 2005 under the IAGA code SFS. Yearly mean data obtained from the yearbooks published for San Fernando Observatory are shown in Fig. 7a.

3.1.2 Ebro Observatory (EBR)

Ebro Observatory (EBR) was founded in 1904 by de Society of Jesus, with the aim of study the Sun-Earth relations. It was located in the town of Roquetes (Tarragona) (Batlló, 2005). The EBR observatory began to record periodic measurements of the geomagnetic field in 1905, although the publication of regular results started in 1910 (Observatorio del Ebro, 1910). As noted by Azpiazu and Gil (1919), Ebro Observatory had an excellent location, away from possible disturbances originated by electric currents, iron masses and geological formations. This observatory had two pavilions specifically built to carry out geomagnetic measurements. The first one was dedicated to take absolute measurements with a *Dover* unifilar magnetometer, a *Schulze* dip inductor and a *Plath* galvanometer. The second pavilion was properly buried and isolated, and it was dedicated to the study of geomagnetic variations. It was equipped with *Mascart* variometers for the photographic record of magnetic elements.

EBR observatory published annual bulletins between 1910 and 1937, when the Spanish Civil war stopped its activity. After a break of 6 years, it started to work again in 1943, but annual bulletins were not published until 1995. Since 2002, Ebro Observatory is member of INTERMAGNET with the IAGA code EBR.

Due to electromagnetic interferences produced in the records because of the city growth, the variometric station was translated in 2001 to Horta de Sant Joan, 20 km away from the observatory. Since 2012, the measurements are referred to a new main pillar built at Horta de Sant Joan (Observatorio del Ebro, 2013). Figure 7a also shows the yearly mean data of Ebro Observatory obtained from its bulletins.

3.2 IGN Observatories

In 1912 the Instituto Geográfico y Estadístico (later Instituto Geográfico Nacional, IGN) started the works for the generation of the Spanish Geomagnetic Map, that was finally published for the epoch 1924.0 (Instituto Geográfico y Catastral, 1927). The measurements of the geomagnetic field carried out along the Iberian Peninsula were referred to Ebro geomagnetic observatory. This observatory was characterized by quite good quality data but a very eccentric location within the Iberian Peninsula, being located in the Northeast corner of Spain. That was a problem to be the reference observatory for the national geomagnetic cartography. Due to this fact, the Instituto Geográfico decided to install its own geomagnetic observatory in the centre of the Iberian Peninsula. This new geomagnetic observatory was initially projected in the city of Alcalá de Henares, but it was finally built in the city of Toledo (Azpiazu and Gil, 1919). This marked the beginning of expansion of geomagnetic observatories at IGN, a journey that persisted throughout the 20th century.

3.2.1 Toledo and San Pablo de los Montes Observatories

Taking advantage of the construction of the new Geophysical Observatory of Toledo in the Buenavista estate on the outskirts of the city, a magnetic section was stablished on it (Sancho de San Román, 1951; Payo and Gómez-Menor, 1998). In January 1935, the Instituto Geográfico proposed to carry out a new Magnetic Map of Spain, which was started in 1936. Thus, the works to have operative the Toledo Observatory were accelerated to give assistance to the field measurements (Payo and Gómez-Menor, 1998). The so-called Magnetic Section started to run in 1936 with a set of *Askania* variometers, but the Spanish Civil War produced a cessation of activity since 31th August 1936 up to 1941, when the activity in the geomagnetic observatory were resumed, but providing quite disturbed data due to conditioning works (Sancho de San Román, 1951). After 1947, the geomagnetic observatory was totally operative and yearbooks began to be published without interruption. Besides the *Askania* variometers, the observatory was equipped with a set of *Topfer* variometers and several instruments to take absolute measurements: one *Schimdt* magnetic theodolite, one *Askania* terrestrial inductor and one *Carnegie* magnetometer (Payo and Gómez-Menor, 1998). Toledo geomagnetic observatory was operative until 1981. In the decade of the 1970's, the growth of the city and particularly the railway electrification, produced significant disturbances over geomagnetic records, mainly in the hours of departure and arrival of trains to Toledo train station.

For this reason, the Instituto Geográfico projected different magnetic surveys in the Montes de Toledo mountain range to build a new observatory. Finally, a suitable location was found in the town of San Pablo de los Montes, where magnetic anomalies were minimal. In 1974, a plot of 10 Ha was acquired to build the new observatory (Payo and Gómez-Menor, 1998). The construction of this observatory finished in 1978, and a part of the geomagnetic instruments of Toledo Observatory were translated to San Pablo Observatory (SPT according to the IAGA codes). Since then, constant cross-checking work was carried out over a period of two years between both observatories. In 1982, SPT Observatory definitively replaced Toledo Observatory and started publishing their yearbooks. At present, San Pablo Observatory is still in operation and has become the reference observatory of IGN for geomagnetic works. Furthermore, it is member of INTERMAGNET network since 1992. As an example of the geomagnetic data recorded in both Toledo and SPT observatories, in Fig. 7b we plot the monthly mean values of declination.

3.2.2 The increase of the IGN network

After the celebration of the International Geophysical Year (IGY, 1st July 1957 to 31th December 1958), the Instituto Geográfico y Catastral (IGC, later IGN) reached an agreement with the International Union of Geodesy and Geophysics (IUGG) to increase the density of geomagnetic observatories in Spain. Then, new permanent observatories were stablished in the mainland of Spain, in the cities of Almería and Logroño. In addition, two more observatories (Miguel Lafuente, 1964) were stablished in Santa Cruz de Tenerife (Canary Islands) and Moca (Fernando Poo Island, Equatorial Guinea).

Almería Observatory

In 1949 the IGC decided to expand the Seismic Station of Almería, created in 1911, with a geomagnetic section. New geomagnetic pavilions were projected, whose works ended in 1954 (Morencos, 1964). This observatory was equipped with a set of *La Cour* variometers to record the variations of the geomagnetic field. The absolute instrumentation initially available was one declinometer with an oscillation box by *Sartorius* and one earth inductor by *Wind*. They were soon updated by a set of *Askania-Werke* instruments: a QHM, a BMZ and an earth inductor. With the new instrumentations, Almería Observatory could take continuous measurements since 1st January 1955. They were published continuously in the yearbooks of the observatory until 1989 when the observatory stopped its activity. The growth of the city of Almería that surrounded the observatory had made that the measurements were highly disturbed. Figure 7b shows the declination monthly mean values observed at Almería Observatory during the period 1955-1989.

Logroño Observatory

Logroño Geophysical Observatory was built by the IGC at 5 km west of this city. The observatory construction started with the geomagnetic pavilion, with the aim of being operative for the IGY. So, the geomagnetic observatory started to work on 8th July 1957, coinciding almost completely with the beginning of the IGY (Miguel Lafuente, 1964). The instrumentation initially installed at Logroño Observatory was a set of *La Cour* variometers for the record of continuous variations. Besides, there were the following instruments to take absolute measurements: a magnetic theodolite with its oscillation box, a *Sartorius* earth inductor, a torsion magnetometer QHM and a balance magnetometer BMZ. This observatory was continuously running and publishing their yearbooks until 1976, when it stopped its activity. The declination monthly mean values of this observatory are shown in Fig. 7b.

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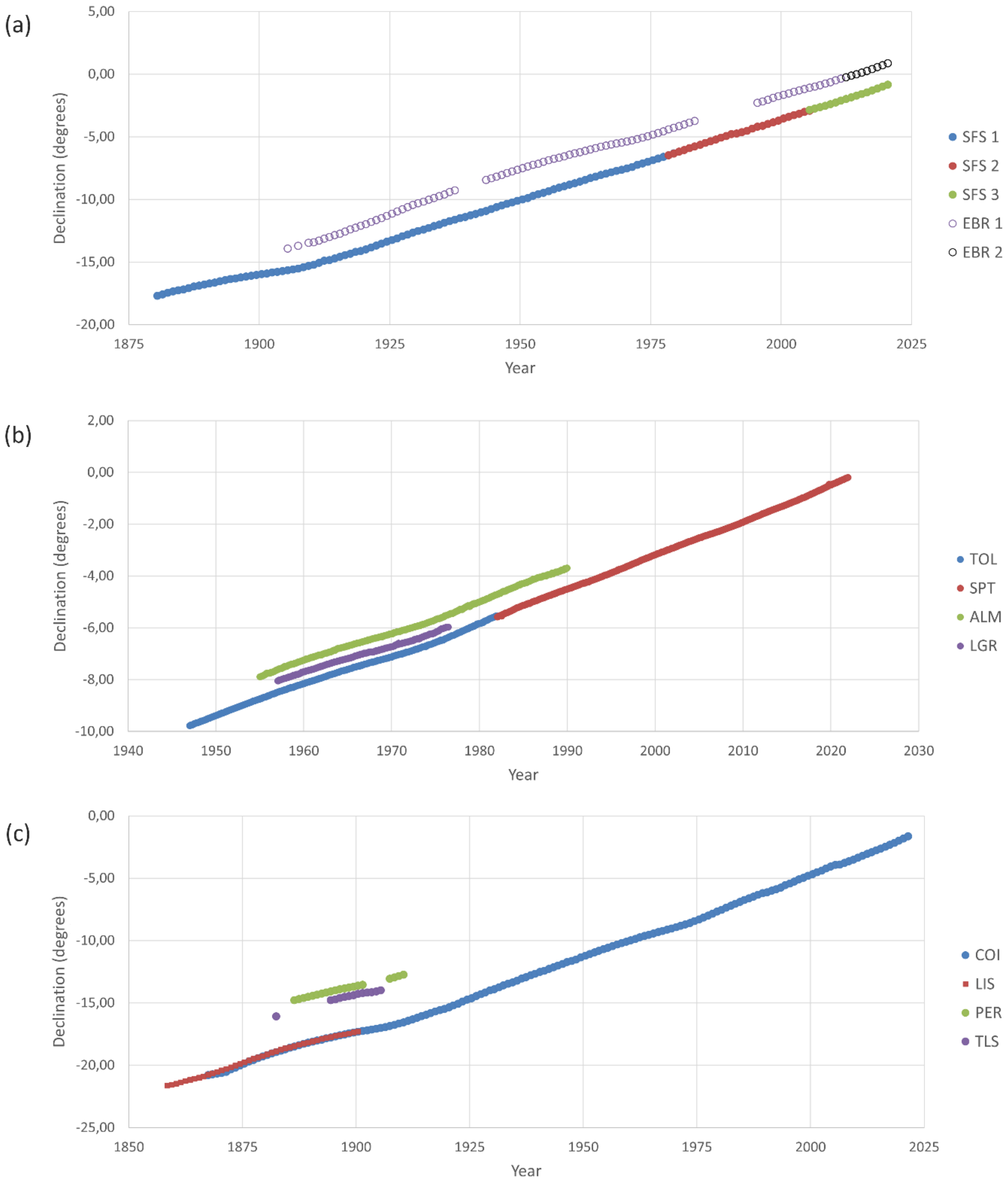

Figure 7: Evolution of magnetic declination: (a) San Fernando and Ebro observatories, (b) IGN observatories, (c) surrounding observatories.

3.3 Other Geomagnetic Observatories in the surroundings of Spain

In our study, we have also considered the geomagnetic measurements made in other geomagnetic observatories near Spain, situated in Portugal and southern France. In Portugal, the geomagnetic observatory with greatest tradition recording and measuring the Earth's magnetic field is the one of the *Instituto Geofísico da Universidade de Coimbra*. This observatory started to work in 1866, although in 1931 it had to be translated to a new location in Alto de Balaia Street to avoid the disturbances induced by the electric lines (Custodio de Morais, 1953). This observatory is still working today (as COI in the IAGA codes), so it has the longest geomagnetic measurements series of the Iberian Peninsula and one of the longest series in the world. The annual mean values of this series are published in the World Data Centre of Geomagnetism and are continuously updated. The declination values of this series are shown in Figure 7c. Besides, geomagnetic measurements were made in Portugal, in the city of Lisbon, since the year 1858, at *Observatorio do Infante D. Luiz* (Observatorio do Infante D. Luiz, 1863). This observatory published since this year the annual results of its measurements of the different components of the geomagnetic field, and it was operational until the year 1900. The installation of electric lines for the tram near the observatory disturbed the normal operation of the magnetic instruments and it was impossible to use their measurements since this date (Observatorio do Infante D. Luiz, 1904). The declination values of this series, extracted from the yearbooks published by this observatory, are shown in figure 7c.

In the south of France, there were also two geomagnetic observatories located in the cities of Toulouse and Perpignan. They started to record the geomagnetic field at the end of the 19th century, but they stopped at the beginning of the 20th century, so the measurement series of them are very short. The annual mean values of the geomagnetic components measured at these observatories are available at the World Data Centre of Geomagnetism. For Toulouse Observatory, the series begin in 1882, although it only has continuity between 1894 and 1905. For Perpignan Observatory, the series cover the period from 1886 to 1910, although it presents a gap of data between 1902 and 1906. Figure 7c also shows the declination values corresponding to these observatories.

4 Historical declination data selection

In the Iberian Peninsula, the first recorded geomagnetic observatory data date back to the latter half of the 19th century. These records have offered a good temporal coverage, spanning from that period to the present day. In order to add more information of declination data prior to the appearance of geomagnetic observatories, we have considered the information available at the HISTMAG database (Arneitz et al, 2017). This database has integrated a large amount of historic geomagnetic data from all around the world, including archaeomagnetic and volcanic data. The historical compilation is mainly based on the previous compilation of Jonkers et al. (2003) that bring together a huge amount of data obtained at naval trips with measurements made on land. In addition, HISTMAG completed the Jonkers' database with historical information from other sources that include measurements made for mining, sundials, cartography, etc. For the purpose of this work, we have made a query on HISTMAG database, considering a circular region with centre at ROM and radius of 1000 km. The historical declination data covers the period from 1500 to 1900. Figure 8 shows a map with the spatial distribution of the selected data.

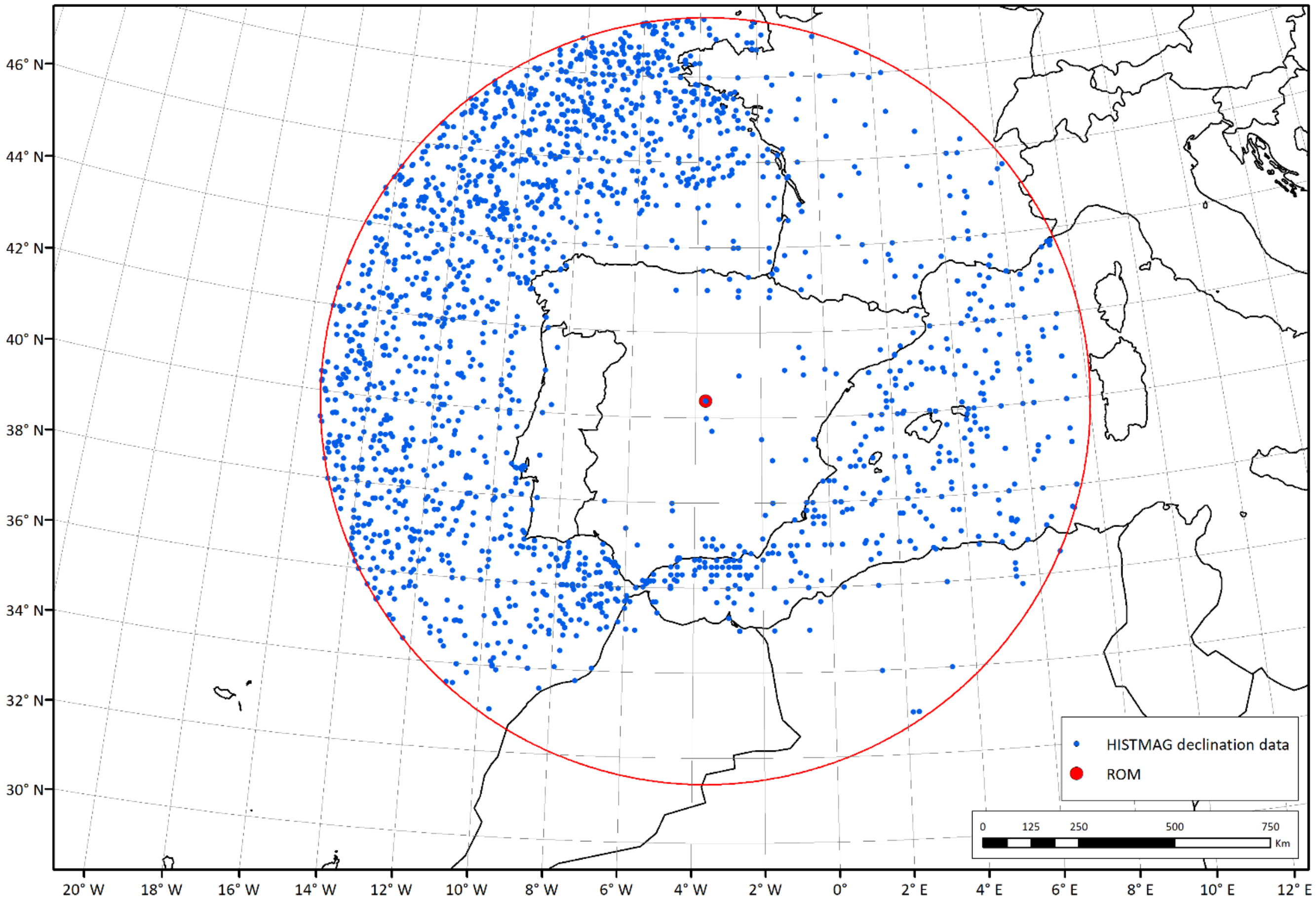

Figure 8: Declination points selected from HISTMAG database. Red point corresponds to the ROM coordinates (40.4000º N, 3.6879º W). The radius of the spherical cap is 1000 km.

The result of the query provided a total of 3512 declination records. To check the initial quality of these data, we have made a comparison of them with the data provided by the geomagnetic model *gufm1* (Jackson et al., 2000) using the coordinates of the points and the dates of their records, extracted from the database. The results, in terms of declination residuals, are shown in Fig. 9. The residuals follow a normal distribution, centre in 0.05º and standard deviation of 1.68º. This was expected since the major part of these data were used in the construction of the *gufm1* model. Therefore, we have considered that these data are suitable to be used in this study.

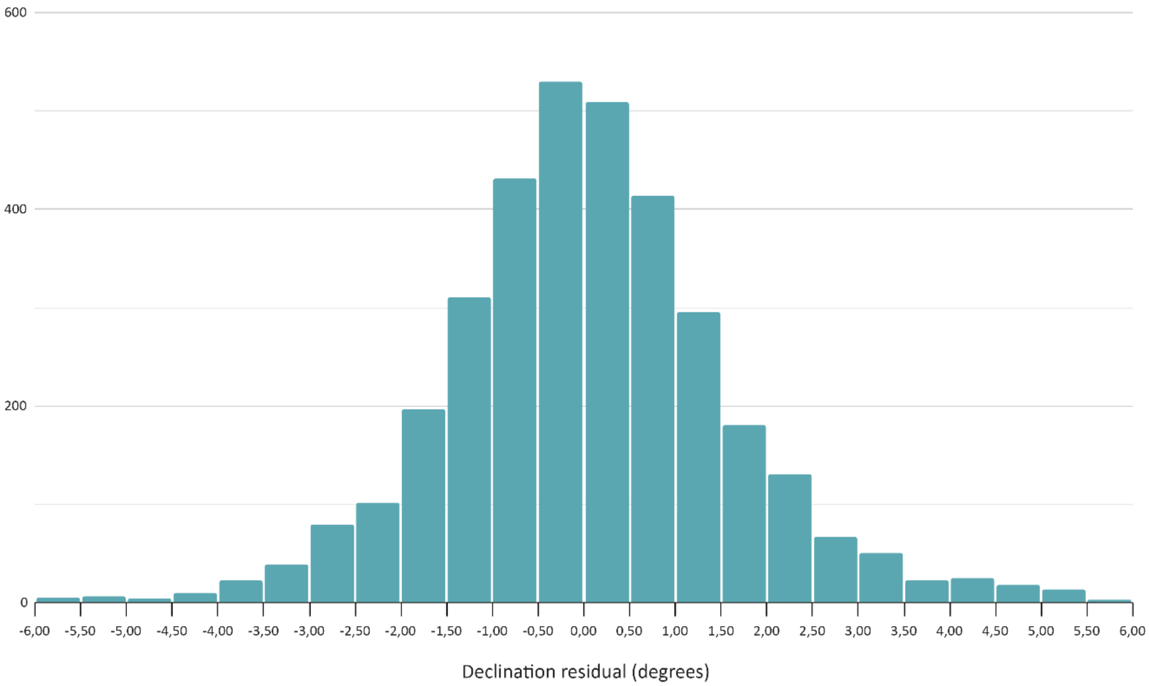

Figure 9: Residuals from the comparison between HISTMAG declination data with those given (at the same time and location) by the *gufm1* model.

5 Reducing declination data to the ROM coordinates

As indicated in the previous sections, the magnetic declination measurements recorded in the ROM are very scarce. They only cover some decades at the end of the 19th century. For this reason, if we want to analyse the time evolution of the declination element at the ROM coordinates, we need to translate the rest of the declination measurements (i.e., the observatory data from the Iberian Peninsula and the south of France, and all the historical data of the HISTMAG database) from the original locations to the ROM coordinates. This declination database will provide information about the declination at the ROM coordinates over the last 450 years. To reduce the declination data from the original locations to the ROM coordinates (40.4000º N, 3.6879º W) we use the declination spatial gradient estimated from the *gufm1* model from 1590 to 1840 and the most recent model Cov-Obs.x2 (Huder et al., 2020) from 1840 to the present days. To do that, we estimate for a certain time the difference in declination for the original location and the value given at the ROM coordinates. Then this difference, taken as a spatial gradient, is added to the original declination data, providing the translated value. In Fig. 10, we show the value of the declination gradient within the spherical cap of Fig. 8 for four different epochs (1600, 1750, 1900, and 2020).

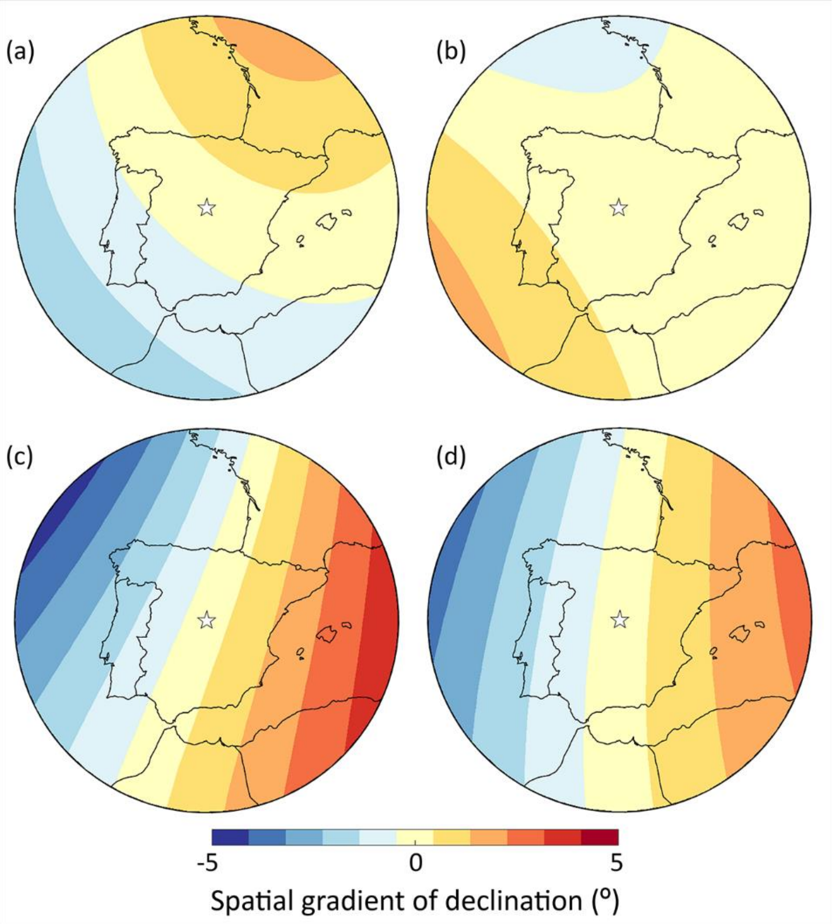

Figure 10: Spatial gradient map of the declination at four different epochs. Maps at (a) 1600 and (b) 1750 were estimated by *gufm1* model and (c) 1900 and (d) 2020 maps by the Cov-Obs.x2 model. The white star corresponds to the ROM coordinates (40.4000º N, 3.6879º W).

Figure 11a shows the result of applying the reduction method to the historical data obtained from the HISTMAG database. In addition, Fig. 11b shows the same result for data from observatories measured before the year 1900 at San Fernando, Coimbra, Lisbon, Perpignan and Toulouse. Besides, in Fig. 11c and Fig. 11d the reduced declination data from observatories for dates after 1900 are plotted. In Fig, 11c, the reduced declination data from the IGN observatories (Toledo, Almería, Logroño and San Pablo de los Montes) from which we have monthly mean declination values are shown. In Fig. 11d, we show the reduced data coming from other observatories of the Iberian Peninsula and south of France (San Fernando, Ebro, Coimbra, Perpignan y Toulouse) from which the annual mean declination values are available.

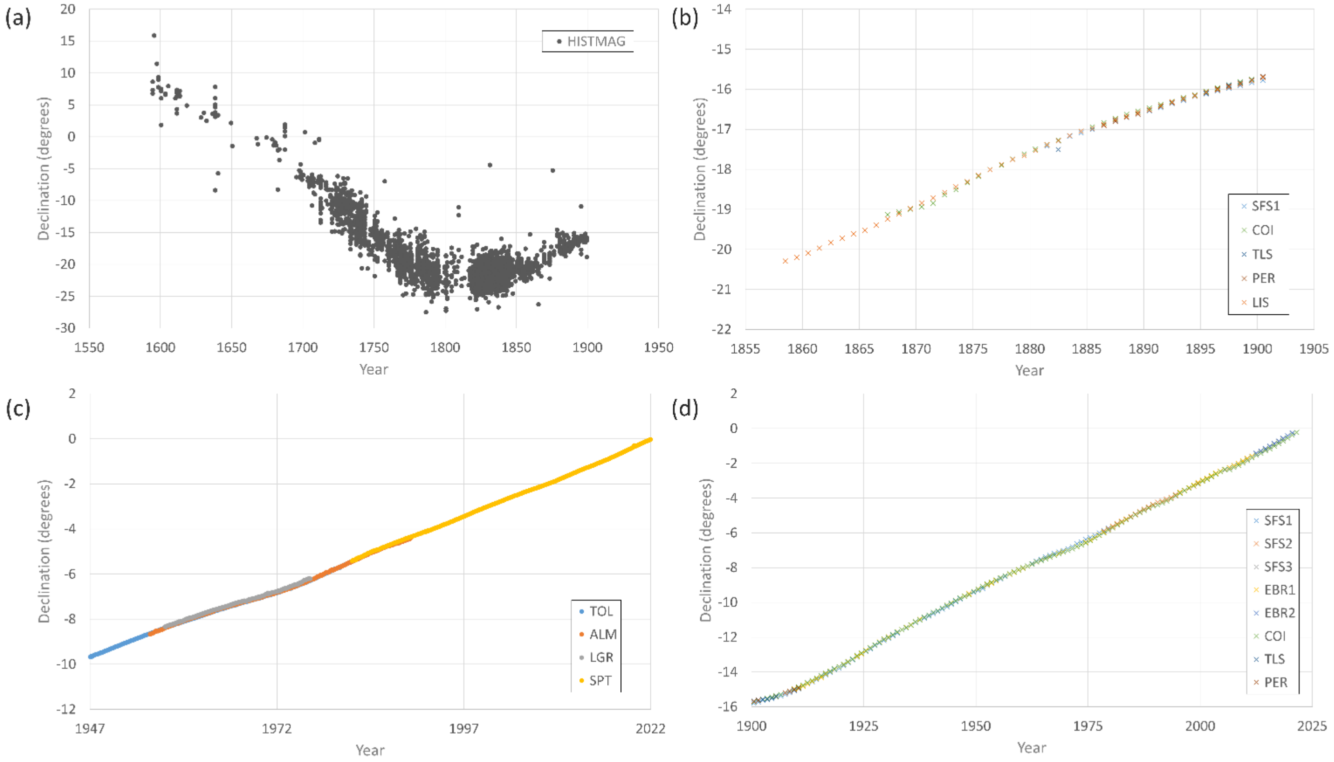

Figure 11: Declination data reduced to the ROM coordinates: (a) HISTMAG data, (b) Observatory data, before to 1900, (c) IGN Observatory data, after 1900, (d) Other Observatory data, after 1900.

6 Declination curve for the ROM

With the declination data reduced to the ROM coordinates shown in Fig. 11, we have generated a time-continuous curve for the declination from 1590 up to the present days. To obtain the curve, we have applied a bootstrapping method (Thébault and Gallet, 2010) taking into account the declination error of each individual data. In the curve construction, the temporal domain is expressed by means of penalised cubic B-splines in time. The set of data have been ranked into two categories: the historical data that covers from the earliest times up to 1900 and the instrumental series covering from 1900 to the most modern values.

It has been calculated the optimal value of the smoothing penalization parameter of the declination curve (λ) for each range of data in the fitting approach. The optimal value obtained for the historical data is $\lambda = 0.1$, and for the instrumental series is $\lambda = 0.001$. Furthermore, it has been considered a set of B-splines functions separated by knot points every 40 years for the whole time interval.

To get the error bars of the declination curve, the bootstrap approach considers 1000 set of data generated bootstrapping the data in both age and measurement uncertainties. In this sense, we have considered three different uncertainty values in the measurement of the declination for the different epochs at which the data were obtained. In the interval since 1900 to the present date we have considered an uncertainty of 1 minute of arc taking into consideration the accuracy of the declinometers used in the Spanish observatories during the 20th century (Batlló, 2005) and the analysis of the hourly mean values uncertainty carried out by Curto (2019). It is difficult to properly know an uncertainty value for the declination values before 1900. In relation with the data of historical values of declination collected at the HISTMAG database, we do not know the uncertainty of the compasses used in the measurement of the declination. According to Jackson et al. (2000), who include a noise error of 0.5° for these historical observations, we have used this value as uncertainty for the declination data before 1900. Although some of these data belong to the earliest observatories functioning in the Iberian Peninsula, no detailed information is available about the uncertainty of their measurements, so we have decided to be conservative and use the same value. Being even more conservative, we have decided to double this uncertainty value (i.e. 1°) for the historical declination data prior to 1750, so the accuracy of the measurement and the resolution of the compasses are supposed to be lower as we go back in time.

For each bootstrapped dataset, we generate a declination curve. The final curve is the mean of the 1000 obtained curves and the error bands (at 1σ of probability) are obtained using the standard deviation of the 1000 curves. As result, we get the declination curve for the ROM plotted in Fig. 12.

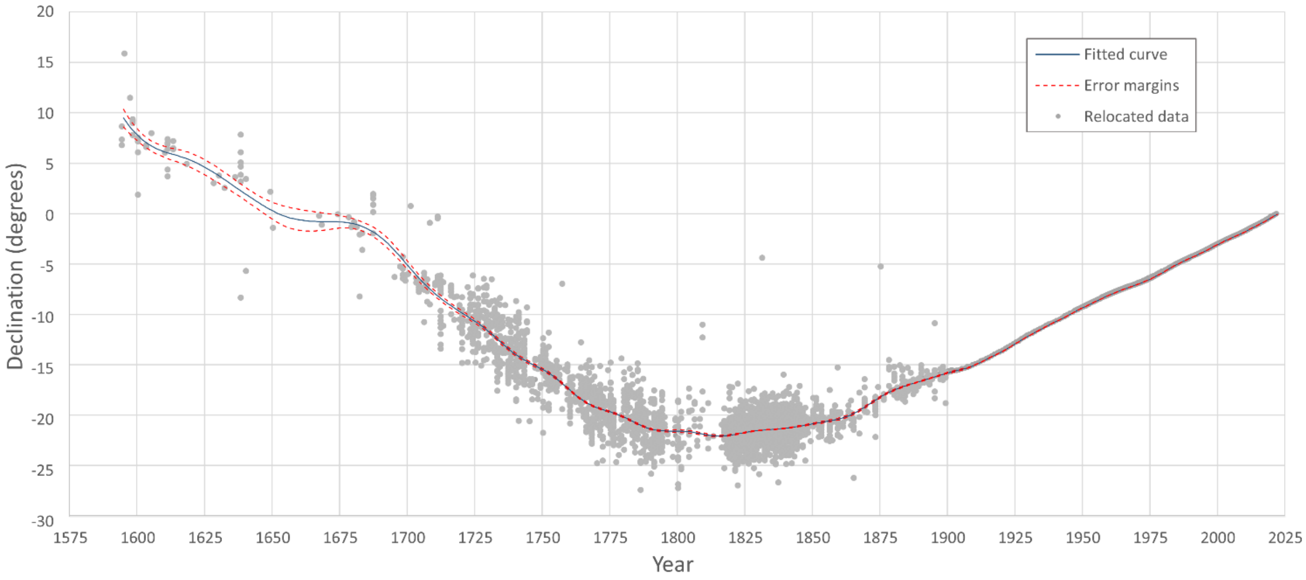

Figure 12. Fitted declination curve obtained for the Royal Observatory of Madrid and its error margins at 1σ. At the background, all reduced historical and instrumental data used for curve fitting are plotted by grey dots.

This fitted curve shows that at the Royal Observatory of Madrid the minimum declination value achieved in the period of study was -21.99° in the year 1816. Since then, the value of declination at that location has been continuously increasing until reach positive values at the end of the year 2021. Before the minimum, the declination value had been decreasing since the beginning of the selected period (year 1590) and the previous crossing of the agonic line would have taken place around 1652 changing declination from positive to negative values, being 1647-1671 the period of 95% probability (see Fig. 13).

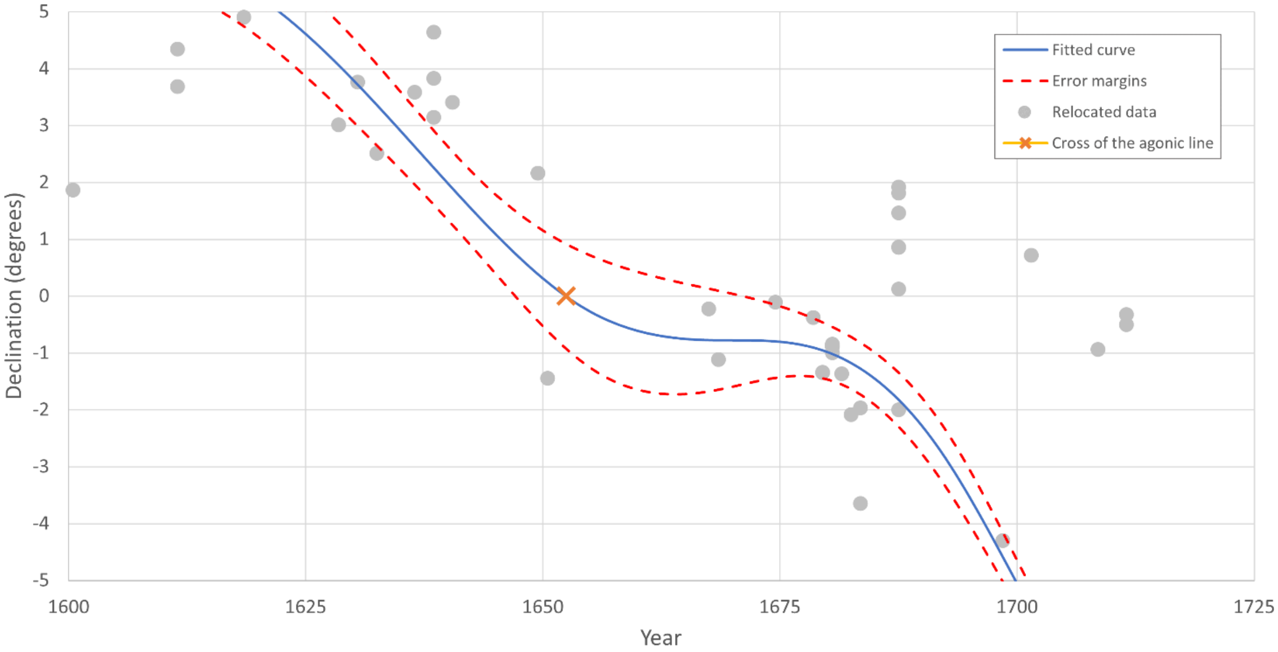

Figure 13: Detail of the declination curve obtained showing the crossing of the agonic line by the Royal Observatory of Madrid around the year 1652. Red dashes lines show the error margins of the declination curve. At the background, reduced data that have been used for curve fitting.

With the optimal declination curve obtained for the ROM, the residues of each type of data (i.e., historical and instrumental data) used in the calculation process with respect to the fitted curve have been estimated (Fig. 14). For the historical data, the histogram points out the contribution of two type of distributions: a Gaussian distribution plus a Laplacian distribution, both centred at 0° (Fig. 14a). For the instrumental data, the histogram follows a Gaussian distribution centred at 0° (Fig. 14b). These results indicate an appropriate fitting of both series of data to obtain the declination curve at the ROM coordinates.

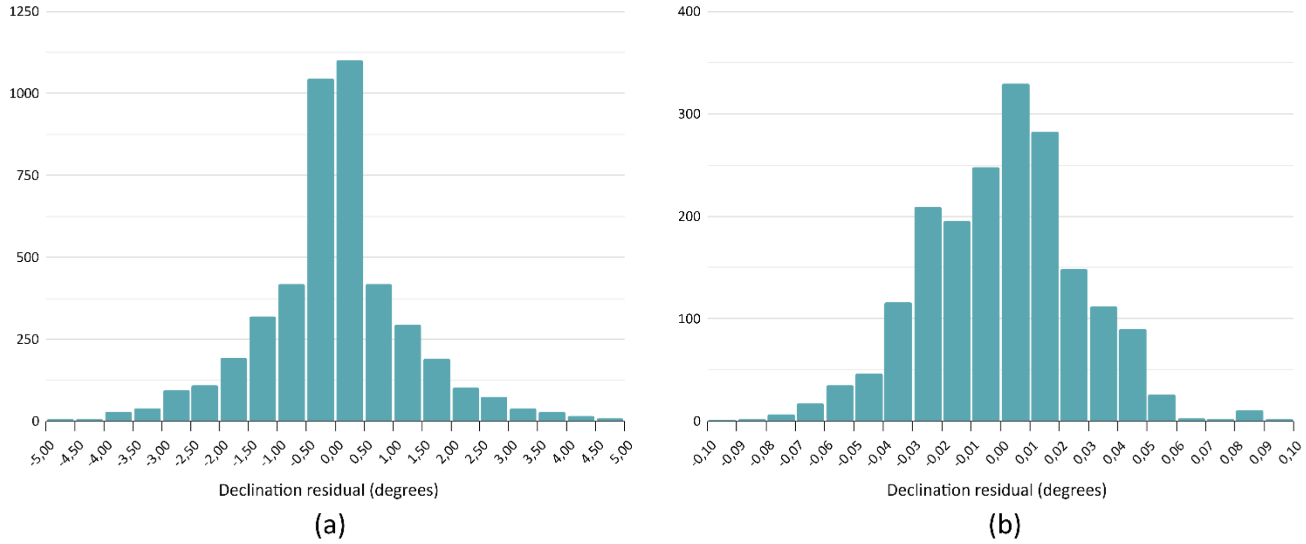

Figure 14: Distribution of residuals between original data and the fitted declination curve of the ROM: (a) Histogram of residuals for the historical data series; (b) Histogram of residuals for the instrumental data series.

The secular variation curve for declination has been calculated from the ROM declination curve previously obtained. This curve (Fig. 15a) shows how this secular variation of declination has not been constant along time, with strong changes in a short time, related with the processes in the deep Earth's interior. We compare the secular variation curve with those given by both *gufm1* and IGRF models, showing a clear agreement between them. Here, it is important to note that the obtained secular variation curve also reflects the impact of the external geomagnetic field on the declination measurements (that it has not been properly removed from the original data). As expected, the solar forcing recorded in the secular variation curve shows a 11-yr / 22-yr periods that correspond to the solar activity periods. To mitigate the effect of the solar activity, we have applied a filter removing periods shorter than 25 yr and the filtered curve is plotted in Fig. 15b along with the contribution of the solar activity (Fig. 15c). Note that the solar activity is not recorded before 1700 due to the scarce number of declination data (see Fig. 12). This result points out the necessity of filtered the geomagnetic observatory data to remove any possible contribution of the external field that has not been adequately mitigated.

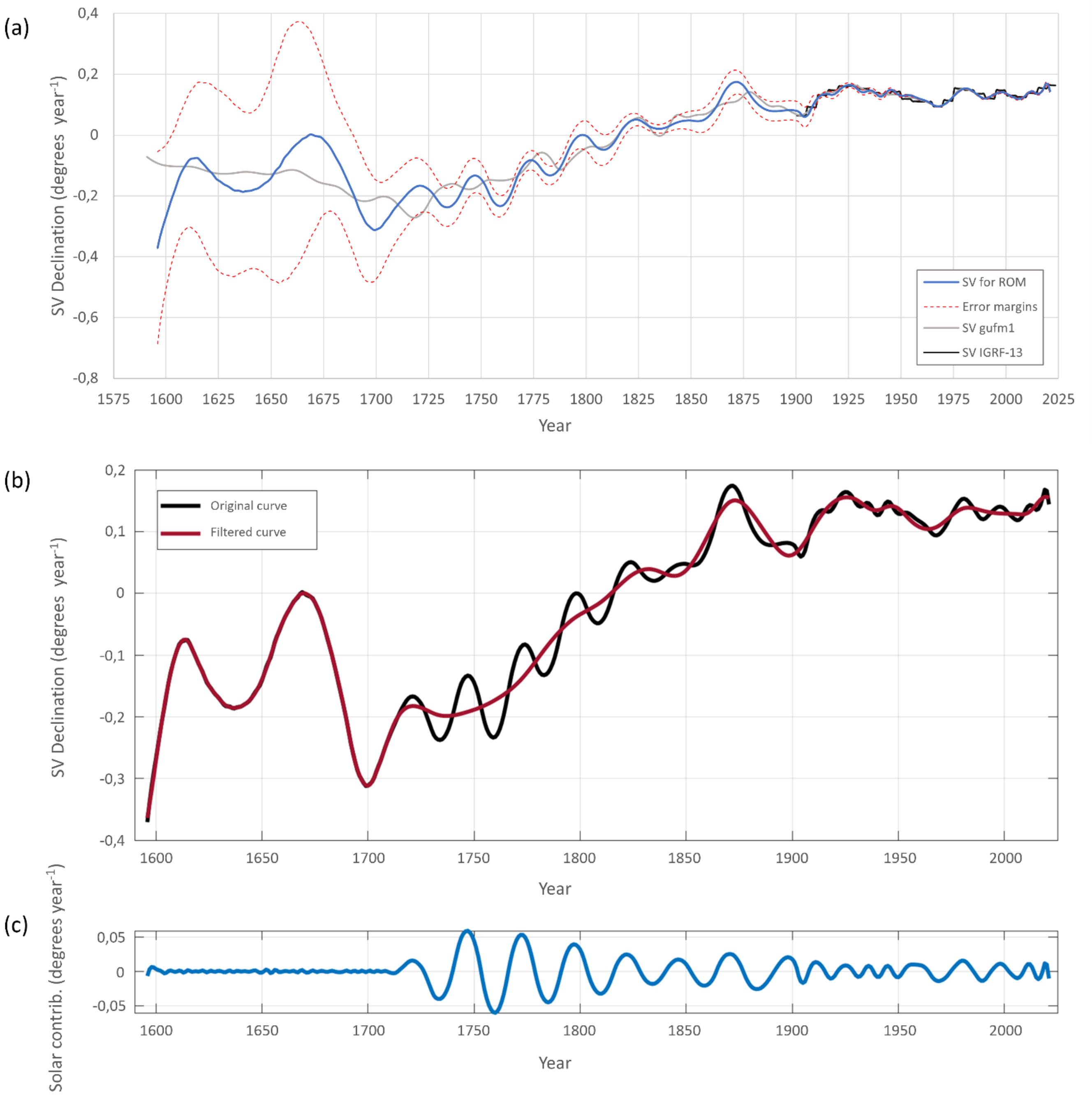

Figure 15. a) Secular variation curve obtained for the Royal Observatory of Madrid and its error margins at 1σ of probability. The secular variation determined by the model *gufm1* and the IGRF-13 are also represented. b) Filtered secular variation curve removing periods shorter than 25y (black line: original curve, red line: filtered curve). c) Solar contribution to the secular variation curve (residual between the black and red curves in b)).

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7 Discussion and Conclusion

We have processed declination data obtained in the Iberian Peninsula and its surroundings, measured at geomagnetic observatories since the second half of the 19th century, and data previously measured in land and sea that have been compiled in the HISTMAG database. With these data, we have obtained a declination curve for the Royal Observatory of Madrid that ranges between the last two crossings of the agonic line at the observatory.

Making use of this curve, we want to check the quality of the compilation of older declination values (not included in our previous declination curve) made by Rico Sinobas (1856). From this compilation (see supplementary material), we have selected the observations from 1600 onwards and discarded two observations whose location is badly defined. The coordinates of these selected points have been determined and the reduction of these observations to the ROM coordinates have been calculated in the same way described previously. They are listed in Table 1.

Table 1. Declination values compiled by Rico Sinobas and their value reduced to the ROM coordinates.

Location	**Date**	**Latitude**	**Longitude**	**Declination**	**Declination reduced to ROM**
Lisboa	1638.5	38.7080	-9.1390	7.65°	7.81°
Lisboa	1668.5	38.7080	-9.1390	-0.83°	-1.12°
Valencia	1675.0	39.4700	-0.3764	0.00°	0.35°
Lisboa	1683.5	38.7080	-9.1390	-30.00° *	-30.64°
Lisboa	1697.5	38.7080	-9.1390	-4.30°	-5.27°
Lisboa	1706.5	38.7080	-9.1390	-6.50°	-7.59°
Valencia	1707.5	39.4700	-0.3764	-5.00°	-4.42°
Cádiz	1724.5	36.5350	-6.2975	-5.42°	-6.16°
Gibraltar	1733.5	36.1400	-5.3500	-13.63°	-14.17°
Cabo de Gata	1733.5	36.7219	-2.1930	-13.93°	-13.93°
Cabo de San Vicente	1733.5	37.0250	-8.9944	-13.82°	-14.96°
Cabo de Santa María	1734.5	36.9602	-7.8871	-14.33°	-15.26°
Madrid	1747.5	40.4000	-3.6879	-16.50°	-16.50°
Gibraltar	1761.5	36.1400	-5.3500	-17.18°	-17.68°
Lisboa	1762.5	38.7080	-9.1390	-17.53°	-18.00°
Cádiz	1769.5	36.5350	-6.2975	-17.25°	-17.79°
Cádiz	1771.5	36.5350	-6.2975	-18.00°	-18.55°
Cádiz	1776.5	36.5350	-6.2975	-19.70°	-20.27°
Lisboa	1776.5	38.7080	-9.1390	-19.00°	-19.22°
Lisboa	1782.5	38.7080	-9.1390	-19.85°	-19.99°
Madrid	1785.5	40.4000	-3.6879	-20.00°	-20.00°
Cádiz	1791.5	36.5350	-6.2975	-21.93°	-22.51°
Madrid	1799.5	40.4000	-3.6879	-22.03°	-22.03°

Madrid	1804.5	40.4000	-3.6879	-21.50°	-21.50°
Cádiz	1807.5	36.5350	-6.2975	-22.50°	-23.00°
Lisboa	1811.5	38.7080	-9.1390	-22.75°	-22.30°
Lisboa	1820.5	38.7080	-9.1390	-22.70°	-22.18°
Lisboa	1829.5	38.7080	-9.1390	-22.38°	-21.81°
Lisboa	1853.5	38.7080	-9.1390	-22.38°	-21.18°
Cartagena	1853.5	37.6000	-0.9819	-18.88°	-20.37°
Málaga	1853.5	36.7167	-4.4167	-20.18°	-20.79°
Cádiz	1853.5	36.5350	-6.2975	-21.93°	-22.05°
Santander	1853.5	43.4667	-3.8000	-21.22°	-20.34°

* This value seems to be a misprint. For a most probable value of 30’ W de reduced declination would have a value of -1.14 degrees.

The result of these reduced observations is shown in Fig. 16, where it can be seen that they fit quite well with the declination curve obtained for ROM. Only one observation corresponding to Lisbon for the year 1683 shows a great discrepancy with the declination curve. It seems to be a mistake as the measurement of a declination value of 30º00’ W in the Iberian Peninsula has not been reached in the whole period studied. It appears that a value of 30’ W might have been more likely and would align with the declination curve, as illustrated in Fig. 16 by a red triangle. So, we can consider that this compilation made by Rico Sinobas has enough quality and it can be taken into account for future studies.

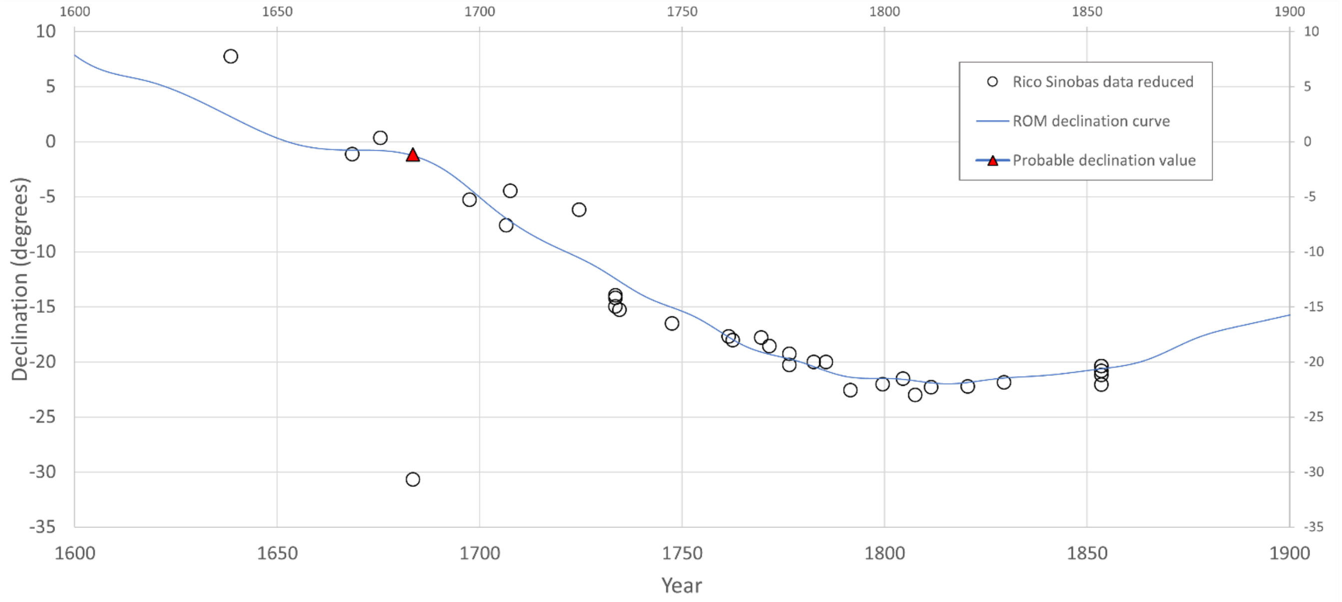

Figure 16. Declination curve obtained for the Royal Observatory of Madrid and declination values collected by Rico Sinobas and reduced to the ROM coordinates. The probable value for the wrong declination of Lisbon in 1683 is shown by a red triangle.

Author contribution

Conceptualization, J.M.T. and F.J.P.-C.; data curation, J.M.T. and F.J.P.-C; formal analysis, J.M.T. and F.J.P.-C.; investigation, J.M.T.; methodology, F.J.P.-C.; software, F.J.P.-C.; supervision, F.J.P.-C. and A.B.A; validation, J.M.T. and F.J.P.-C.; visualization, J.M.T, A.N. and F.J.P.-C; writing – original draft preparation, J.M.T.; writing – review and editing, F.J.P.-C., A.N. and A.B.A. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no conflict of interests.

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