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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Historical Observations of the Geomagnetic Field

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Phil. Trans. R. Soc. Lond. A 1982 **306**, 71-78
doi: 10.1098/rsta.1982.0067

Phil. Trans. R. Soc. Lond. A **306**, 71–78 (1982) [71]
Printed in Great Britain

Historical observations of the geomagnetic field

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Reliable observations of the geomagnetic field date back to the sixteenth century. Several compilations of old data have been made, of which one of the most extensive is the catalogue of Veinberg & Shibaev. At some localities, notably London and Paris, long series of observations exist at the same or neighbouring sites. Such series are useful for the information they give on the behaviour of the secular variation of the geomagnetic field. Sources of historical observations suffer from several basic defects. For instance, until about 1850, the available data were restricted almost entirely to observations of the direction of the field. Ways of overcoming this lack of intensity information are discussed. A convenient way of using global collections of historical data is to produce from them models of the geomagnetic field at past epochs. These models, which usually take the form of expansions in terms of spherical harmonics, can then be used in attempts to study the evolution of certain core processes.

1. Introduction

The main geomagnetic field, originating as it does in the Earth's core, provides one of the very few means of investigating this remote region of the Earth's interior. It is a particularly valuable probe for studying the dynamics of the core and a knowledge of the long-term behaviour of the geomagnetic field is essential to studies of the evolution of the core.

For very long timescales it is necessary to use the results of palaeomagnetic and archaeomagnetic investigations. These can at present give only an approximate description of the geomagnetic field in the remote past but can be used to place broad constraints on some possible core processes.

On timescales of 100 years or so, there are available instrumental observations of higher accuracy and with better global distribution than present palaeomagnetic or archaeomagnetic data-sets. It is this body of information, extending back to the sixteenth century at some locations, that is taken here to be covered by the phrase 'historical observations'. This data-set is potentially very valuable for studies of the evolution of the core over the past three or four hundred years.

2. Long series of observations at specific sites

At some locations, series of observations have been made at frequent intervals and at almost the same site for hundreds of years. Examples of such locations are London, Paris, Rome, Boston and Cape Town. Bauer (1898) collected over 20 such series of observations of declination (D) and inclination (I). He displayed the secular variation by plotting D and I on a polar diagram to show the motion of the north-seeking end of a freely suspended magnetic needle. These are the famous Bauer plots, which have been repeated many times since.

Recent collections of observations at specific sites have extended and corrected Bauer's work. Abrahamsen (1973) has collected observations at Copenhagen extending back to 1649, and Malin & Bullard (1981) have carefully re-examined all observations of *D* and *I* in London back to 1570. Figure 1 shows their revised version of the Bauer plot for London.

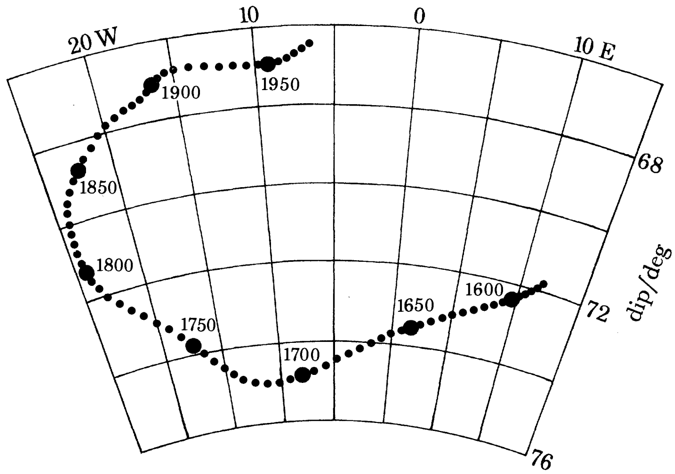

FIGURE 1. The direction of the geomagnetic field in London, 1575–1975. Zenithal equidistant projection; points plotted for every fifth year. (From Malin & Bullard (1981).)

The amount of information about core processes that can be derived from a series of observations at one site is limited. Malin & Bullard (1981) show, however, that the London data are consistent with a westward-drifting eddy current near the surface of the core that was vertically beneath London in 1634.

3. Sources of globally distributed data

For any studies involving the main geomagnetic field and its secular variation it is important to have data that cover the surface of the Earth as well as possible. The importance of good global coverage was realized at an early date, and the books by Stevin (1599), Kircher (1643) and Wright (1657) contain valuable collections of the earliest instrumental observations. An extensive collection of observations of declination was compiled by Mountaine & Dodson (1757).

The nineteenth century witnessed an upsurge of interest in geomagnetic problems, particularly on a global scale, and the scene was set by Hansteen's famous monograph (Hansteen 1819). This book contains an extensive collection of approximately 10000 observations of declination and inclination from the earliest instrumental observations to those made in the early years of the nineteenth century.

Other nineteenth-century collections of historical data are contained in Morlet (1832), Becquerel (1840) and Raulin (1867). Four of Sabine's *Contributions to terrestrial magnetism* (Sabine 1868, 1872, 1875, 1877) constitute a collection of over 10000 observations of declination, inclination and total intensity (*F*) made during the nineteenth century. Bemmelen (1899)

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extracted over 6000 declination observations, mainly from ships' logs, made between 1492 and 1741.

These collections and other less comprehensive sources of observations were used by B. P. Veinberg in an attempt to gather together all the instrumental observations of the geomagnetic field that had ever been made and of which records still existed. A summary of this work appeared in 1969 (Veinberg & Shibaev 1969) in the form of a catalogue giving values of declination, inclination and (from 1800 onwards) of horizontal intensity (H). The catalogue contains mean values derived from the original observations after these had been reduced to positions whose latitudes and longitudes are multiples of 10° and to a series of epochs: 50 years apart from 1550 to 1850; 1890; 10 years apart from 1910 to 1940.

4. Previous work on the evolution of the geomagnetic field

The earliest work (Carlheim-Gyllensköld 1896, 1906; Fritsche 1899, 1900) on the evolution of the geomagnetic field from the sixteenth century onwards was based on data extracted from magnetic charts, mainly from those of Hansteen (1819) and of Bemmelen (1899). Some of the more recent studies in this field (Braginskii 1969; Yukutake 1971) have used the same data-base, with the addition, in the latter instance, of archaeomagnetic data.

The studies of Braginskii & Kulanin (1971) and of Barraclough (1974) were based on the data in the catalogue of Veinberg & Shibaev (1969). Braginskii (1972*a*, *b*) has used data from this same catalogue, with the addition of data from charts and from archaeomagnetic studies.

In all the work cited, the first stage has been the production from the data of spherical harmonic models of the main geomagnetic field. This field is assumed to be derivable from a scalar potential (V) and to originate from sources within the Earth. Then V can be expanded in terms of spherical harmonics:

$$V = a \sum_{n=1}^{\infty} (a/r)^{n+1} \sum_{m=0}^{n} (g_n^m \cos m\lambda + h_n^m \sin m\lambda) P_n^m(\theta). \tag{1}$$

Here a denotes the radius of the reference sphere (usually taken to be the mean radius of the Earth: $a = 6371.2$ km); r the radial distance from the centre of the Earth; θ the colatitude; λ the longitude; $P_n^m(\theta)$ the associated Legendre function of degree m and order n, and (g_n^m, h_n^m) the set of spherical harmonic coefficients that constitute the model. Components of the geomagnetic field can be derived from V. Thus, the north (X), east (Y) and vertically downward (Z) components are given by

$$X = (1/r)\,(\partial V/\partial \theta),$$
$$Y\,(-1/r \sin\theta)\,(\partial V/\partial \lambda),$$

and

$$Z = \partial V/\partial r.$$

In practice, the expansion must be truncated at values of m and n well short of infinity and the series used to represent the early data have extended only to $m = n = 4$ or 5.

Braginskii (1972*b*, 1974) has used his models to investigate the spectrum of magnetic waves in the Earth's core. Barraclough (1974) discussed the movement of the eccentric dipole that best approximates the geomagnetic field and also investigated the non-dipole field in the region of the Pacific Ocean.

5. Some basic problems associated with historical observations

A fundamental difficulty encountered when attempting to analyse observations made before about 1800 is the total lack of reliable information about the intensity of the geomagnetic field. It has only been possible to measure magnetic intensity in absolute units since 1832 when Gauss (1833) devised his classical method. For some years before this, observations of the intensity relative to that at some base station had been made and it is often possible to convert these relative values to approximate absolute values. However, before 1800 even these relative observations become scarcer and, before long, non-existent. Two courses have been taken to overcome or circumvent this problem. One is to limit oneself to modelling only the pattern of the geomagnetic field. The other is to provide a scale factor, either by using archaeomagnetic data or by extrapolating values of the first spherical harmonic coefficient (g_1^0) backwards in time.

Before about 1700, a further problem arises: inclination observations now become very few and one is eventually left with declination data only. The chief effect of this on the spherical harmonic models produced is that the coefficients of the zonal harmonics ($m = 0$) are very poorly controlled by the data and are thus very uncertain. Archaeomagnetic values of inclination can be used to alleviate this problem to some extent.

To derive an accurate spherical harmonic model of the geomagnetic field, the distribution of the data must be as uniform and as nearly global as possible. The data distribution becomes progressively worse as we go further back in time until, in 1550, over half the Earth's surface is devoid of data, according to the catalogue of Veinberg & Shibaev (1969).

The accuracy of early observations is difficult to assess. It is certainly less than that of modern observations because the instruments used were much cruder, but there are some compensating factors. For instance, early observations at sea were made on wooden sailing vessels and are thus subject to far less artificial disturbance than those made on iron ships.

6. Some recent work with historical observations

Thompson & Barraclough (1982) have recently re-analysed the data in the catalogue of Veinberg & Shibaev (1969). The scale of the field was provided by the same linear extrapolation of g_1^0 as was used by Barraclough (1974), and the pre-1700 data were supplemented with archaeomagnetic inclination data to improve the accuracy of the zonal terms. The catalogue data were weighted proportionally to the number of original observations that contributed to the mean values in the catalogue. A series of spherical harmonic models extending to $m = n = 4$ were produced for epochs at intervals of 50 years from 1600 to 1850, inclusive, for 1890 and for 1910.

From these models, together with published models for 1942 and 1975, Bauer plots of D and I were produced at intervals of 10° in latitude and longitude. Figure 2 shows some examples of these Bauer plots. Although smooth curves can be drawn through the calculated points, it can be seen that some points deviate considerably from such curves. On the assumption that such deviations are caused by errors in the models, the set of 612 Bauer plots were smoothed by using cubic spline functions. The set of smoothed Bauer plots is shown in figure 3.

Values of D and I were derived from the smoothed Bauer plots at equally spaced time intervals and these were analysed as before. By using the same extrapolation for g_1^0 as before, a

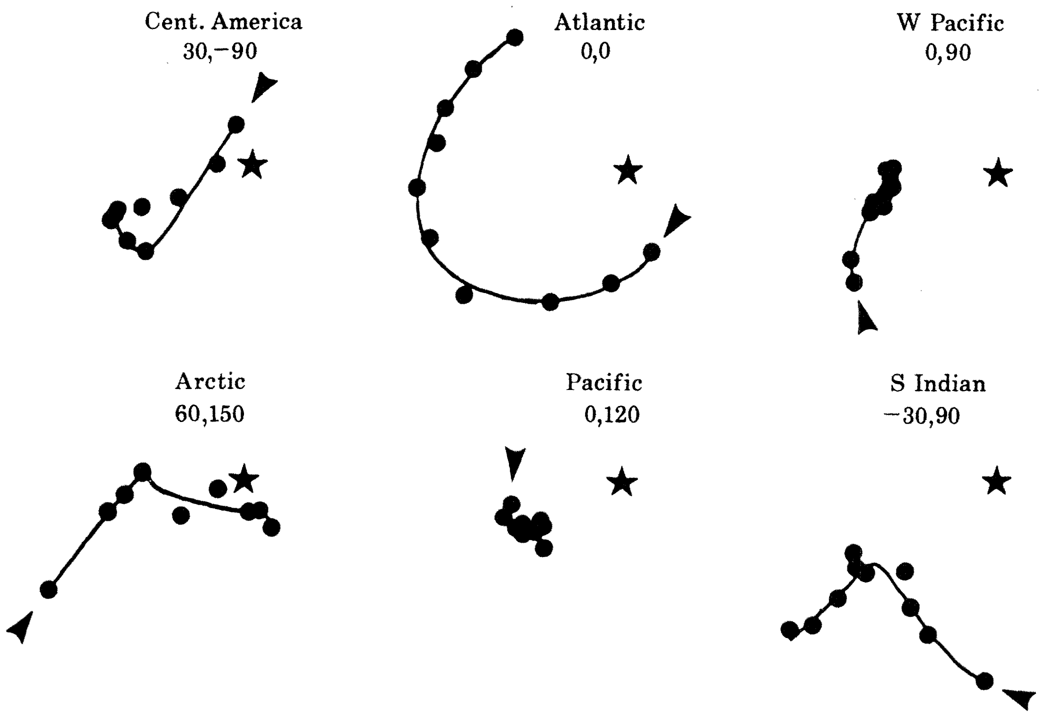

FIGURE 2. Bauer plots, 1600–1975, from degree and order 4 models (solid circles) together with smooth curves fitted by using cubic splines. The arrows indicate the values for 1600.

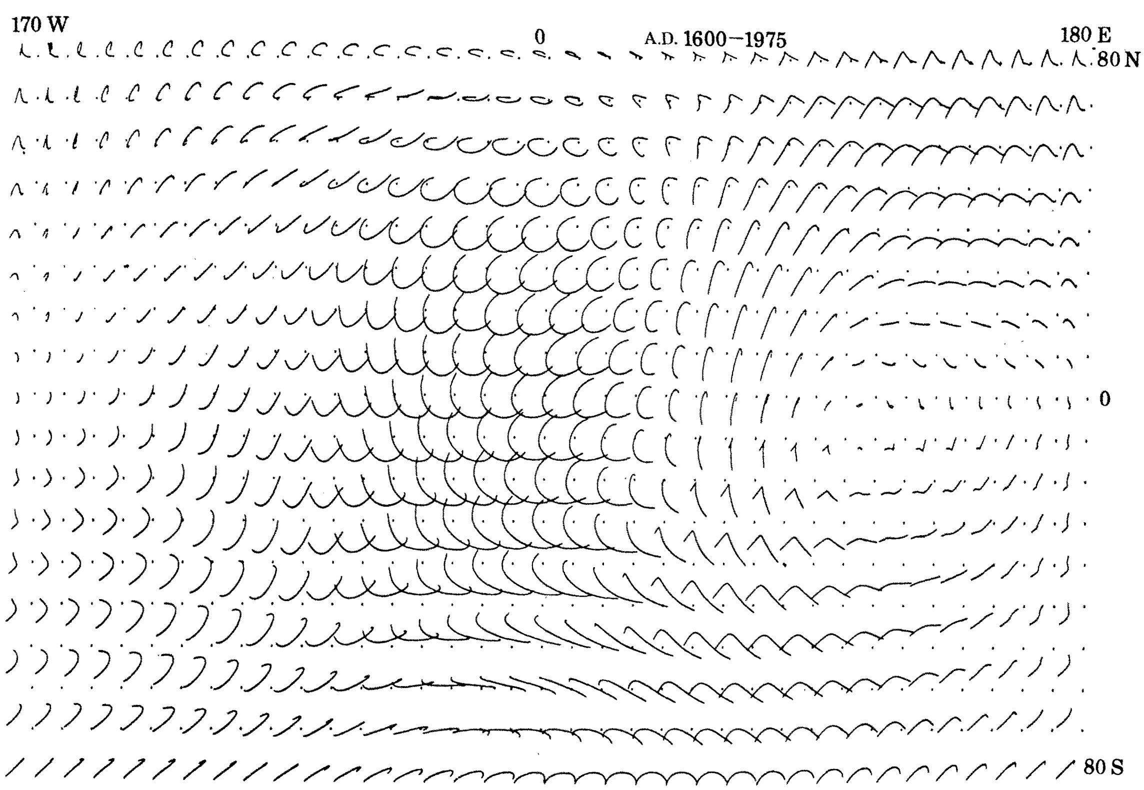

FIGURE 3. Smoothed Bauer plots, 1600–1975, derived by using cubic splines, at intervals of 10° in latitude and longitude.

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series of eight models (again extending to $m = n = 4$) were produced for epochs at intervals of 50 years from 1600 to 1950, inclusive.

Two preliminary results from this series of models may be mentioned. Firstly, the region of low non-dipole field, which at present extends over most of the Pacific Ocean, was very much smaller in 1600 and appears to have grown steadily over the past 350 years. Secondly, most of the Bauer plots show a generally clockwise motion of the north end of a freely suspended magnetic needle. There is an extensive region, however, in the southern Indian Ocean where the motion is anticlockwise and this region has also grown somewhat since 1600. The Pacific and Indian oceans are regions with sparse data coverage, particularly at the earlier epochs, so these results should be regarded as rather tentative.

Because some of the earlier studies based on the data in the catalogue of Veinberg & Shibaev (1969) (e.g. Barraclough 1974) do not appear to have paid much attention to the distribution of the residuals of the observations from the models, we have recently taken a fresh look at the catalogue data with this end in view. Starting with the data for 1850, a degree and order 4 model gave many unacceptably large residuals, of the order $\pm 10^3$ nT. Because the data distribution for 1850 is quite good, and to see if the reason for some of the large residuals was the low truncation level, the spherical harmonic expansion was extended to $m = n = 8$. The numbers of 'observations' (mean values from the catalogue) were 461, 448 and 391 for D, I and H, respectively. Of these, there were 13 observations of D, 22 of I and 25 of H with residuals greater than 2000 nT in absolute value. Attempts were made to investigate all these discrepant observations by searching for the original observations on which the mean values in the catalogue were based. Since the main source for this period appears to be Sabine's collection (Sabine 1868, 1872, 1875, 1877), the search concentrated on these references. In compiling the catalogue, corrections to epoch 1850 and to equidistant points were made. Because the values of these corrections are unknown and because not all the original observations could be found, it was only possible to make approximate corrections to the discrepant values. However, such corrections were made in all but eight cases, these latter 'observations' being deleted. The corrected data were re-analysed and, of the residuals from the resulting degree and order 8 model, 5 % of the D observations and 14 % each of the I and H observations were greater than 1000 nT in absolute value. Only one of these was greater than 2000 nT.

Re-analyses of the catalogue data have also been made for epochs 1700, 1750 and 1800, by using an improved expression for extrapolating the value of g_1^0. This expression, derived from all available spherical harmonic models of the geomagnetic field for 1829 and later, is

$$g_1^0(t) = -31357 + 16.2(t - 1900),$$

where t denotes the epoch in years A.D. The numbers of discrepant observations found in each of these three cases were similar to those for 1850. The task of correcting them was, however, much greater because the original observations are spread among several sources and these are, in general, arranged in a less systematic manner than Sabine's collection. The corrections made are thus even more uncertain than those for 1850.

The four spherical harmonic models, each extending to $m = n = 8$, for 1700, 1750, 1800 and 1850 that resulted from these re-analyses should be regarded as preliminary attempts at fitting the data for these epochs. They probably represent the best that can be done, however, with the data from the catalogue of Veinberg & Shibaev (1969).

7. Discussion and conclusions

The sources on which the catalogue of Veinberg & Shibaev (1969) is based contain most recorded historical instrumental observations. They thus represent all that we are ever likely to know about the behaviour of the geomagnetic field over the past 300 or 400 years and it is important to extract the maximum possible information from them. From the discussion in §6 it is clear that the summary of these data contained in the catalogue leaves much to be desired. Besides the inaccuracies that have been noted, the concept of reducing the original observations to relatively widely spaced points and epochs has inherent defects. Since the corrections employed in the reductions can only be known approximately, the procedure further degrades the already rather low quality of the data. It also introduces undue smoothing; for example the reduction to epochs 50 years apart prevents the search for short-term phenomena analogous to the recent jerk (Malin *et al.* 1982) whose internal origin has recently been confirmed (Malin & Hodder 1982). It is thus necessary to have the original observations in computer-readable form before any significant improvement can be made to our knowledge of the geomagnetic field over the past few centuries.

Problems of poor data distribution and low data accuracy still remain and alternative methods of analysing sparse data-sets need to be investigated. The problems of lack of intensity information and sparse inclination data also need to be considered. More extensive and more accurate recent archaeomagnetic data could help to alleviate these problems. Another line of attack may be to incorporate in the modelling procedure constraints, such as the constancy of the unsigned flux from the core.

Several of these suggestions are already being actively considered. The next few years should therefore see a significant improvement in the quality of the models of the geomagnetic field for the past few hundred years.

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