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Magnetic Observatories in the 21st Century: an Endangered Species?

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Abstract

Magnetic observatories have a long history of producing data that has led to many scientific discoveries. However, a long history is no guarantee of a long future and it is important to keep under review the factors that influence the support given to magnetic observatory operations. The data that observatories produce must be seen to be relevant to current and future scientific research, and also to ‘real-world’ applications. By understanding local and international demands for data, in terms of quality, resolution and availability, observatories can tailor their operations, choosing appropriate instrumentation and methods for data acquisition processing and distribution. The INTERMAGNET programme has attempted to address several of these issues.

1. Introduction

Because of the utility of the magnetic compass for navigation and curiosity about the magnetic properties of the Earth, geomagnetic field measurements have been made and recorded for more than 400 years. The main spatial and temporal variations of the geomagnetic field, including correlations with auroral sightings and solar activity, were discovered by the middle of the 19th century. Systematic observations of the geomagnetic field at multiple locations, the start of the development of a global magnetic observatory network, began with the establishment, by Gauss, of the Göttingen Magnetic Union in 1834. Further impetus to the development of the network was given by the International Polar Years, and particularly by the International Geophysical Year, which ran from July 1957 to December 1958. More recently, the INTERMAGNET programme has helped to accelerate the modernisation of observatories and coordinate activities across the international network.

Although early observations established a good deal of the phenomenology of the geomagnetic field, scientific understanding remains incomplete, and there is strong interest in geomagnetism and solar-terrestrial interactions today. The broad scientific objective is to develop understanding of the sources and processes, internal and external to the Earth's surface, which generate the magnetic fields that combine to produce the overall field observable at any point in space and time. Data help to constrain theories, and magnetic observatories are a source of such data.

The role and importance of synoptic measurements to solar-terrestrial physics was the subject of a study commissioned by the Royal Society of London (1992), the findings of which were also reported by Willis *et al.* (1994). (The term 'synoptic data' was defined as data acquired in a consistent fashion over a long period of time, generally at several sites, providing a general survey of conditions.) The Royal Society study, which considered the role of magnetic observatories, cited the underpinning value of synoptic data to fundamental research, the relevance to studies of global change, the potential for new discoveries, and practical applications, as benefits of long-term monitoring. The general scientific requirements for a global geomagnetic observatory network were discussed in a report to the US Geodynamics Committee (Heirztler *et al.* 1994), and by Langel *et al.* (1995) who emphasized the requirements for geomagnetic main field modelling.

A decade on from these studies it is worth re-examining the role of magnetic observatories. Recent satellite missions have re-invigorated scientific research into geomagnetism and it is a reasonable expectation that there will be near-continuous observations made by satellites in the future. This raises the question of whether satellites can replace some observatory functions. Also, the funding environment for scientific research has changed. The relevance of research to societal concerns such as health, wealth and safety are factors currently influencing funding decisions in directed research programmes. Does observatory science contribute to the understanding of what are now commonly considered to be priority issues?

2. The Core Field

A strong motivation in running magnetic observatories is to monitor the evolution of the Earth's main magnetic field, originating in the fluid outer core. The importance of long-term observations in support of this endeavour is illustrated in Fig. 1 where (irregular) declination measurements at a number of locations in the vicinity of London, and regular measurements at the observatories in Greenwich (1842-1925), Abinger (1926-1956) and Hartland (1957-2005) are plotted together. (Simple site differences between the observatories have been applied to approximately reduce the data to Greenwich.) The plot shows that, over the last 425 years, magnetic declination has varied between extremes of around 11°E and 25°W in London.

Long data series, such as those in Fig. 1, are important in characterizing the scales of temporal variations in the core-generated field, which are termed secular changes. The typical time scale is years to centuries, and the typical magnitude is 10-100 nT y^{-1}. These parameters help to define the observational requirements for magnetic observatories: they should run for many years, achieve measurement accuracy in all components of the field vector of around 1 nT, and maintain the long-term stability needed to resolve the typical secular change signal.

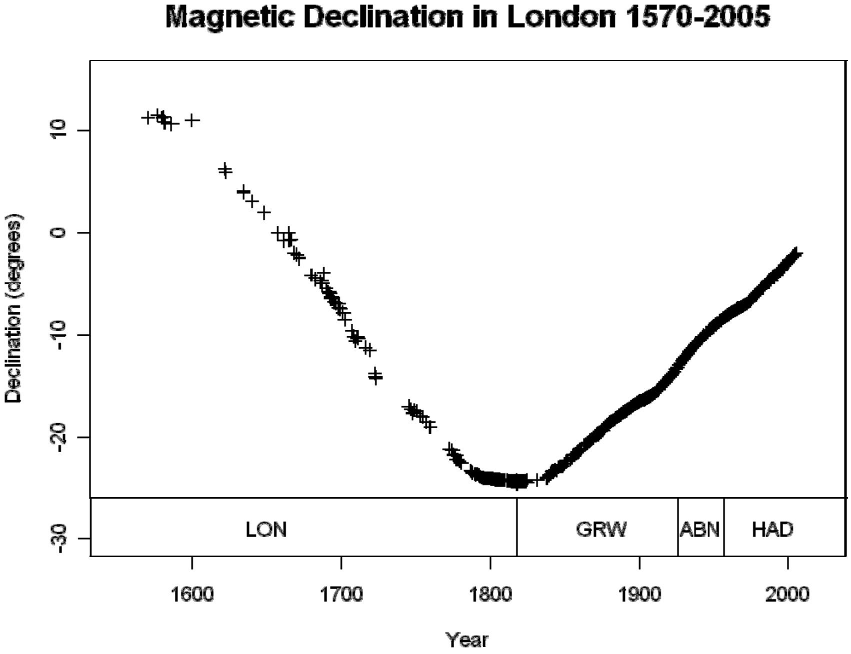

Fig. 1. A composite plot of magnetic declination measurements from sites around London (LON), and Greenwich (GRW), Abinger (ABN) and Hartland (HAD) magnetic observatories.

Put into a more mathematical form, the geomagnetic field $\boldsymbol{B}$ at position $\boldsymbol{r}$ and at time t may be expressed relative to its state at time t_o in the form of a Taylor series:

$$\boldsymbol{B}(\boldsymbol{r},t) = \boldsymbol{B}(\boldsymbol{r},t_o) + \frac{\partial \boldsymbol{B}(\boldsymbol{r},t_o)}{\partial t}(t-t_o) + \frac{\partial^2 \boldsymbol{B}(\boldsymbol{r},t_o)}{\partial t^2}\frac{(t-t_o)^2}{2} + ... \; . \qquad (1)$$

The first term on the right hand side of the equation is the ‘snapshot’ of the main field at time t_o, the time rate of change of the main field in the second term is the geomagnetic secular variation and the second time derivative of the field is the secular acceleration. The accuracy of this approximation depends on the time interval (t–t_o) and on the spectrum of the time variations of the field.

Considering Eq. (1), and the typical time scales of secular changes, it is reasonable to approximate the main field snapshot at an observatory location by an annual mean value and estimate the secular variation by differencing annual means. Most global geomagnetic field models have the form of Eq. (1), using spherical harmonic functions to describe the spatial variation of the main field and the secular variation. An example is the 10th generation International Geomagnetic Reference Field (IGRF), with a nominal lifetime of five years (Macmillan and Maus 2005).

In fact, there are features of secular change on rather shorter timescales that are not immediately apparent in plots such as Fig. 1. In Fig. 2 the first differences of the declination data shown in Fig. 1, for 1900 onwards are plotted. (No correction for the spatial gradient in secular variation between London and Hartland has been made.) There are several abrupt changes in the slope of the secular variation curve for declination, the majority in recent decades. The existence of such ‘geomagnetic jerks’ was first recognised by Courtillot *et al.* (1978) and Malin *et al.* (1983), who noted the step change in secular acceleration at 1969/70.

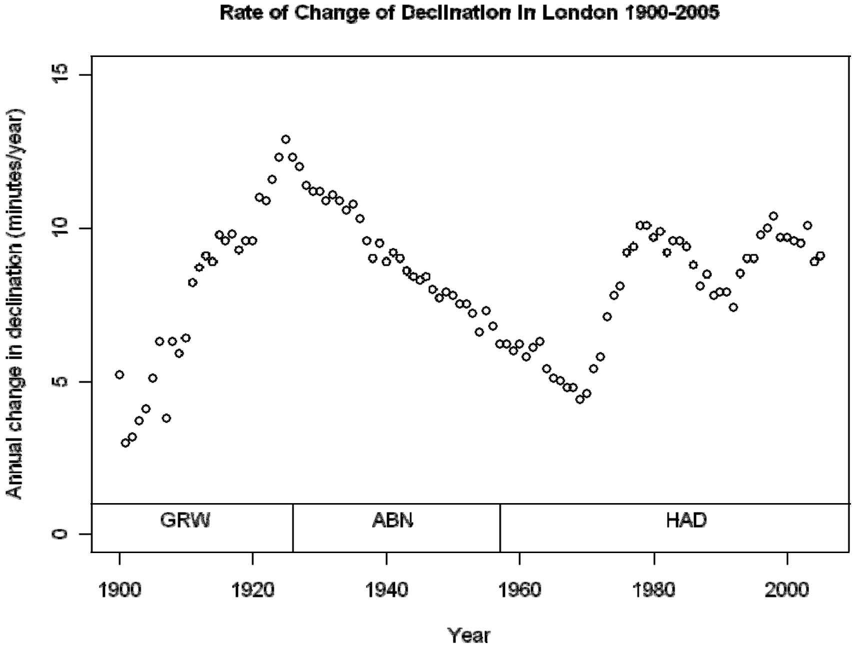

Fig. 2. Secular variation of declination in London estimated using data from Greenwich (GRW), Abinger (ABN) and Hartland (HAD) magnetic observatories.

The main field and secular variation provide a means of probing the pattern of fluid motions at the core surface, yielding an estimate of a typical velocity of about 10 km y^{-1} (e.g. Gubbins 1982, Whaler 1982). The observation of jerks has provoked questions concerning the nature of the core dynamo and the electrical conductivity of the mantle, and intriguing correlations have been found with decadal changes in the length of the day, linking geomagnetic observations to exchange of angular momentum between the mantle and the core (e.g. Holme and de Viron 2005).

3. External Fields

With the adoption of continuous recording instruments at magnetic observatories, studies of the patterns of short-term changes in the geomagnetic field and their geographical distribution became possible. Cycles in geomagnetic field behaviour such as the annual and solar cycle modulations of the solar quiet time variations, the 27-day recurrence pattern in magnetic disturbances, and the semi-annual variation in the frequency of magnetic storms, emerged. Our current understanding of the electric current systems in the ionosphere and magnetosphere, and the magnetic fields they create, has resulted from various types of measurement on the ground and, (crucially for mapping the magnetosphere) in space, and data from magnetic observatories have played a part.

In recent years, long-term changes in the nature of short-term effects of external origin have come to light. The source of these effects is solar forcing, whether by means of electromagnetic radiation or interactions of the main geomagnetic field with the solar wind. If the Earth as the ‘receiver’ is not changing in its response, the changes most likely reflect changes in the behaviour of the Sun. Figure 3 shows the annual number of magnetic storms per year since 1868, with the count based on the *aa* index, together with sunspot number. The upward trend in magnetic activity during the 20th century is evident, and Clilverd et al. (1998, 2002) ascribe this to changes in solar activity. Lockwood (1999) explained the effect in terms of changes in the solar coronal magnetic field, with a consequent effect on total solar irradiance. If this theory is correct, then there are implications for the natural component of climate change. Courtillot et al. (2007) have reviewed the evidence for a connection between geomagnetism and climate change provided by a number of recent analyses of long series of geomagnetic and solar data (see references therein).

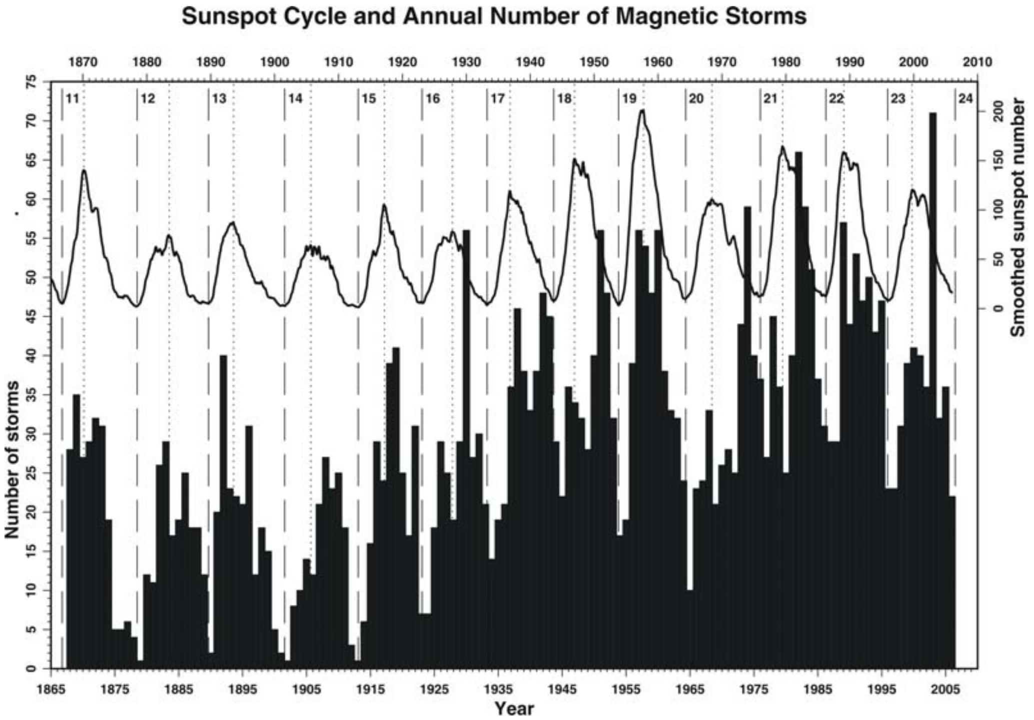

Fig. 3. Changes in magnetic storm activity (histogram) and sunspot numbers (line) 1868-2006.

4. Modern Applications of Magnetic Observatory Data

One of the early motivations for establishing magnetic observatories was to provide data for navigation. Modern developments, especially the availability of GPS to all sectors, including low-cost receivers for the general public, have relegated the magnetic compass to the status of a back-up device for many activities. An important application running counter to this general trend is the use of the geomagnetic field as a directional reference for production drilling in the hydrocarbons industry (Russell *et al*. 1995). The reference geomagnetic field data at a drilling site are usually computed using a global geomagnetic field model. In some instances, data from nearby observatories are used to monitor the state of disturbance of the field, especially where near-real-time access to the data is possible (Reay *et al*. 2005).

When the geomagnetic field is disturbed, the accuracy of magnetic navigation decreases and the level of hazard posed to a range of technologies increases. The reality of the risk posed to electrical distribution networks during magnetic storms was made clear by the well-known event of March 1989 when Quebec lost its electricity supply because of Geomagnetically Induced Currents (GIC) flowing into the power distribution system. It is a real possibility that the likelihood of similar events will increase in the future as grid systems become more interconnected. Magnetic observatories provide data on the inducing magnetic fields and, in combination with knowledge of the Earth’s conductivity structure, these data can be used to model the GIC flowing in an electrical grid system and provide data to support decision-making by grid operators (e.g. Thomson *et al.* 2005).

There are many more examples of applications that make use of magnetic observatory data. For instance, observatories act as national standards bodies in many countries, offer calibration facilities and act as reference stations for magnetic surveys. Other applications, such as launch planning and management of low Earth orbit (LEO) satellites, rely on solar and magnetic activity indices for atmospheric density modelling (e.g. Mugellesi and Kerridge 1991).

5. INTERMAGNET (www.intermagnet.org)

INTERMAGNET aims to create a global near-real-time geomagnetic monitoring system by co-ordinating the activities of the worldwide network of national observatories. By the end of 2006, 100 magnetic observatories, more than half of the total number of observatories in operation worldwide, were participating. INTERMAGNET has improved observatory operations and improved access to high-quality near-real-time globally-distributed magnetic observatory data for the international scientific research community. These achievements have resulted from a range of activities including: definition of target standards for observatory operations; provision of technical advice and assistance to raise standards; establishment of Geomagnetic Information Nodes (GINs) to collect data; web delivery of data; publication of an annual CD-ROM of definitive data from participating observatories with independent quality control; co-operation with other organisations including the World Data Centres and the International Association of Geomagnetism and Aeronomy (IAGA) on matters such as data formats; and, ‘horizon scanning’ to ensure that observatories are prepared to meet future scientific needs and that relevant technological developments are recognised. Examples of current challenges are automation of absolute measurements of the geomagnetic field vector, and meeting the demand for high time resolution data from the space physics community.

6. Conclusions

Magnetic observatories have contributed to many important scientific discoveries because they have produced long series of continuous, high quality measurements at low-noise sites, and significant new results based on observatory data continue to be published. Because of important discoveries in climate-related fields such as ozone depletion over Antarctica (Farman *et al.* 1985) and global dimming deduced from evaporation pan measurements (e.g. Stanhill and Cohen 2001), there is an increasing appreciation of the benefits of long-term monitoring to acquire data on the state of the planet. This increased appreciation is apparent in the establishment of GEO, dedicated to developing a Global Earth Observation System of Systems (GEOSS). GEO will coordinate the operations of various types of monitoring systems, improving interoperability and access to data and information. GEO began as an initiative of the space sector in Earth Observation, but now embraces ground-based observations. INTERMAGNET intends to provide the link from geomagnetism to GEOSS.

The Ørsted and CHAMP satellite missions, launched in February 1999 and July 2000, respectively, have produced excellent magnetic survey data and opened up new possibilities for geomagnetic field research. The success of these missions in generating new knowledge and understanding has been influential in making the case for the SWARM constellation of three satellites to be launched in 2010 by the European Space Agency. In some respects this success can be seen as a threat to observatory operations; for example, studies investigating whether secular variation can be determined from satellite data have been carried out (e.g. Mandea and Olsen 2006). Provision of secular variation data is the traditional role of magnetic observatories. In practice, for a variety of purposes – discrimination between different magnetic field sources is one example – there are advantages to be gained by combining observatory and satellite data; the two data types are complementary.

Magnetic observatories continue to meet the expectations of synoptic monitoring as described in the 1992 Royal Society report in all respects. The challenge to future operations is to respond effectively to the needs of interest groups in science, government and the private sector. There is good reason for optimism because of the strong relevance of observatory data to the needs of these groups.

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