Chapter 3

Repeat Station Activities

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Abstract A repeat station is a site whose position is accurately known and where accurate measurements of the geomagnetic field vector are made at regular intervals in order to provide information about the secular variation of the geomagnetic field. In this chapter we begin by giving a brief history of the development of repeat station networks. We then describe the instruments used to make measurements at a repeat station. These include fixing the position of the station, finding the direction of true north and measuring the components of the geomagnetic field. Emphasis is given to techniques and instruments that are in current use. We next discuss the procedures that are used to reduce the measurements to a usable form and consider the uses to which the reduced data are put. Finally, we discuss the continued importance of such data in the present era of satellite geomagnetic surveys.

3.1 Introduction

We begin with a reminder: a repeat station is a site where accurate measurements of the geomagnetic field vector are made at regular intervals of, typically, two to five years. The position of a repeat station must be known very accurately and must be recorded in detail so that repeat measurements are always made at exactly the same location as earlier observations. As an aid to this, repeat stations are often marked in some way, for example by means of a non-magnetic pillar or a buried tile.

A possible physical explanation of the necessity for frequent repeat station occupations is that given for the need to update global geomagnetic field models such as the International Geomagnetic Reference Field (IGRF): from analyses of the secular variation derived from geomagnetic observatory time series, Barraclough and De Santis (1997) and De Santis et al. (2002) found evidence for chaotic behaviour of the geomagnetic field. This means that the field cannot be extrapolated for more than 5–6 years beyond the epoch of the latest reliable geomagnetic measurements.

This chapter gives a brief history of the development of repeat station networks; describes the instruments used to make measurements at a repeat station and the procedures that are used to reduce the data to a usable form; considers the uses to which repeat station data are put and discusses the continued importance of such data in the era of satellite geomagnetic surveys.

An earlier IAGA publication (Newitt et al. 1996) gives detailed guidance about setting up repeat stations, the instruments needed and the treatment of measurements made.

3.2 History of Repeat Stations

Observations of the geomagnetic field began with measurements of the declination. Because of their importance for navigation they were usually made at sea ports. Later, when magnetic phenomena aroused the interest of early savants, observations were also made

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in other cities. Before long it was realised that other elements of the geomagnetic field were of interest and these were also measured.

After the discovery of secular variation by Henry Gellibrand (1635) (or by Edmund Gunter, see Malin and Bullard 1981) it was realised that observations needed to be repeated at intervals to keep knowledge of the field up-to-date. Early accuracy requirements were not very severe and the interval between measurements tended to be quite long. Exact reoccupation of measurement sites was thus not too important, as exemplified in the data collections just cited. Examples of such collections include those made at London (Malin and Bullard 1981), Paris (Alexandrescu et al. 1996), Rome (Cafarella et al. 1993) and Edinburgh (Barraclough 1995). When demands on data accuracy increased, permanent geomagnetic observatories began to be established, once again often in or near to large towns or cities.

As interest in geomagnetic phenomena widened it became important to be able to describe how the field varied over extensive regions, for example over the territory of a particular country. The results were almost always expressed as contour charts of one or more of the geomagnetic elements and many early charts were based on rather heterogeneous collections of data derived from several sources rather than from a planned network of measurements. The earliest survey using a more or less regular network of points was that made in 1640 by Fathers Borri and Martini in Italy (e.g., Cafarella et al. 1992; De Santis and Dominici 2006). Measurements of declination were made at 21 sites and a simple declination map was drawn but was later lost (see also Malin 1987).

William Whiston (1721), between 1719 and 1720, measured the dip angle at 33 points in southern England and produced a (very idealised) contour map. Just over a century later James Dunlop (1830) made measurements of the horizontal intensity at 35 points in Scotland and northern England; unfortunately they were only relative values, expressed in terms of a value of 1.0 at Edinburgh (Gauss (1833) had yet to publish his method for measuring magnetic field in absolute units) so their usefulness is very limited.

Between 1834 and 1838 Edward Sabine and his co-workers Robert Were Fox, Humphrey Lloyd, John Phillips and James Clark Ross made an extensive magnetic survey of the British Isles (Sabine 1839, 1870). The project had been suggested at the third meeting of the British Association for the Advancement of Science in 1833 and was part of a growing interest in geomagnetic studies in the UK that Cawood (1979) has termed the "magnetic crusade". Measurements of declination, inclination, horizontal intensity and total intensity were made at 203 stations. The intensity results were all converted to total intensity values and were originally (Sabine 1839) presented as relative to a value of unity in London. They were later converted to absolute units (Sabine 1870). This survey, in the words of Sabine (1862), "deserves to be remembered as having been the first complete work of its kind planned and executed in any country as a national work, coextensive with the limits of the state or country, and embracing the three magnetic elements". In this same report Sabine also pointed out that such surveys are able "by their repetition at stated intervals to supply the best kind of data for the gradual elucidation of the laws and source of the *secular change* [Sabine's italics] in the distribution of the earth's magnetism". In furtherance of this, Sabine and his colleagues made observations of the same three magnetic elements as before at 105 stations in England, Wales and Scotland. Not all the later measurements were made at stations of the earlier network. In fact, data from only 29 locations were used to extract secular variation information and two of these were magnetic observatories, at Kew and Dublin.

To quote Sabine (1862) yet again, the example of the earlier of the two British surveys "was speedily followed by the execution of similar undertakings in several parts of the globe; more particularly in the Austrian and Bavarian dominions, and in detached portions of the British Colonial Possessions, viz. in North America and India" (Kreil 1845, Lamont 1854, Lefroy 1883, Schlagintweit et al. 1861). By the end of the nineteenth century magnetic surveys had been made, at least once, in most of Western Europe, the USA, the Dutch East Indies and Japan—an extension to other countries of the magnetic crusade.

These surveys all fall into the category that Newitt et al. (1996) describe as ground surveys rather than repeat station surveys. The accuracy of the measurements was relatively low, there was little or no attempt to remove the effects of external magnetic fields, the station positions were not described in sufficient detail to enable exact reoccupation and the stations themselves were not marked by pillars, tiles or similar means. In Italy the first modern three-component

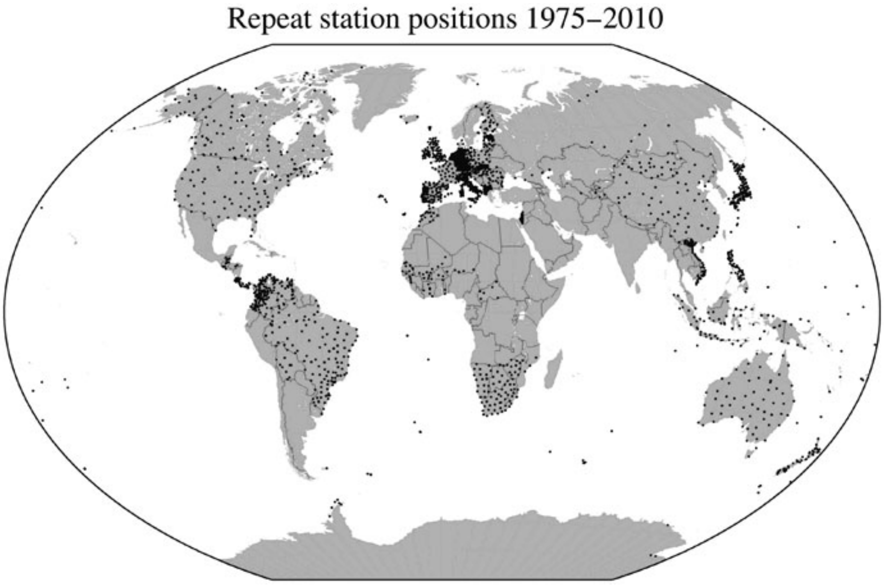

Fig. 3.1 Positions of all repeat stations that have been occupied at least twice since 1975 and have submitted their data to the World Data Centres

repeat station survey was undertaken by Chistoni and Palazzo in 1891–1892 (e.g., De Santis and Dominici 2006) and in the UK it was not until the work of Walker (1919) that a network of genuine repeat stations was established.

Meanwhile, a truly global network of repeat stations was being planned and established by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington (CIW) under its first Director L A Bauer. As well as networks established by land surveying parties, including stations in Australia, Canada, South Africa and South America, repeat stations were set up by the surveying ships *Galilee* and *Carnegie* at most of their ports of call and on many mid-oceanic islands (see Good 2007).

Since the beginning of the twentieth century many countries have established and have continued to reoccupy repeat station networks, in several cases building on the CIW work just mentioned. Figure 3.1 is a map, kindly provided by Dr Susan Macmillan of the British Geological Survey, showing the distribution of repeat stations that are currently used for modelling the main geomagnetic field and its secular variation. Most countries in Western Europe are covered, as are Canada, the USA, Australia and New Zealand. Northern South America, East and South Africa, China, Indo-China, Japan and Indonesia all have extensive networks.

3.3 Instruments and Procedures

3.3.1 Establishing the Position of a Station

A repeat station is usually located in a remote place, where man-made contamination is low or negligible. Where it is possible, to improve the global distribution of land-based data, a repeat station is placed on an island (e.g., the repeat station on Capri Island, Italy; Fig. 3.2).

The positions of early survey stations were determined by astronomical means: the position of the Sun or a star was measured using a sextant or similar instrument for latitude and a chronometer to measure the difference between local and standard time for longitude. More recently, in well-surveyed parts of the world, positions can be determined with sufficient accuracy from large-scale maps. Nowadays the Global Positioning System (GPS) provides an even simpler method of determining station positions.

In many cases, for reasons of security, there is no surface indication of the presence of a repeat station, its position being marked typically by a buried tile. To enable such a station to be found readily on subsequent reoccupations it is usual to select a

Fig. 3.2 View from Capri Island repeat station (Italy). Courtesy of G. Dominici

set of well-spaced and prominent features that will act as reference objects. The station description then includes bearings or alignments using these objects which enable the buried marker to be found.

3.3.2 Establishing the Direction of True North

To determine a value of declination it is necessary to know the direction of true north as well as that of the horizontal component of the geomagnetic field. The classical method for finding the former is an astronomical one involving observations of the positions of the Sun or a star at accurately known times. Rather laborious calculations and the use of an almanac or other astronomical tables or, nowadays, the use of appropriate computer software then give the desired bearing. The Sun or star must, of course, be visible and this can be a problem in many regions. One solution is to measure accurately and record the bearing of one or more prominent features, such as the reference objects described in the previous section. This is not a complete solution, however, as the object or objects selected may be destroyed or may move slightly between visits.

Newitt et al. (1996) give details of how to make the necessary astronomical observations and of the calculations involved. They also include listings of two Fortran programs for inputting sets of Sun observations and for performing the computations to determine the azimuth of a reference mark.

Nowadays the direction of true north is commonly found using a gyroscopic device that can be attached to the theodolite that is used to support the instruments that measure the direction of the geomagnetic field. This device is also known as a gyro-theodolite or a north-seeking gyroscope. The gyroscope rotates at very high speed, typically 22000 rpm, about a horizontal axis and is pulled out of its initial spin-plane by the Earth's rotation. The spin-axis oscillates about the meridian plane until it finally settles pointing true north. Newitt et al. (1996) give details of three methods for using a gyro-theodolite to find the direction of true north.

An observation with the gyro-theodolite takes about half an hour. The instrument must be protected from the weather and this is usually achieved by placing the equipment in a tent. Since the theodolite must not be moved between the gyro measurements and those that measure the geomagnetic field the tent must not contain any magnetic materials. This means using either a specially made tent or one that has been carefully modified by the removal of all ferrous material. The gyro is magnetic and it must therefore be removed from the theodolite before making the magnetic measurements, taking great care not to move the theodolite. Here it should be noted that the theodolite must be non-magnetic.

3.3.3 Measuring the Magnetic Field

In this section we give a brief survey of instruments that have been and are being used in repeat station surveys. Fuller treatments of the subject of geomagnetic instrumentation are given by Wienert (1970), Forbes (1987) and Korepanov (2006).

During the nineteenth and early twentieth centuries the instruments used to measure the geomagnetic field elements at observatories and survey stations, including repeat stations, used as sensors either suspended or pivoted magnets. Declination was initially measured using sophisticated versions of the magnetic compass, dip measurements used a dip needle and the intensity of the field was measured by Gauss's method or a development of it. Instruments used at observatories and in the field were very similar except that the latter were designed to be rather more portable.

Towards the end of the nineteenth century the unifilar magnetometer was developed. This enabled astronomical observations, determination of the declination and measurement of the horizontal intensity by Gauss's method, or Lamont's variation of it, to be made with the same instrument. One of the most widely used versions of this instrument was the Kew pattern magnetometer.

Dip circles are inherently inferior to compasses and instruments using suspended magnets because of the difficulty in designing pivots for the dip needle that allow free movement and that do not wear easily. They were replaced quite early by earth-inductors which use a coil of many turns of wire that can be rotated rapidly about an axis lying along a diameter of the coil. If the axis is not parallel to the direction of the geomagnetic field an alternating voltage is induced in the coil. To measure dip the direction of the rotation axis is adjusted until no signal is detected in a galvanometer connected across the coil.

By the 1920s instruments using electrical methods were coming into use. Examples of these, both of which used Helmholtz coils to produce a region of uniform field at their centre in which was suspended a small magnetic needle, were the Schuster-Smith coil (Smith 1923) and the Dye coil (1928). The former was used for measuring the horizontal intensity, the latter the vertical component. Observations could be made much more quickly and easily with these instruments than with the Kew pattern magnetometer or similar instruments.

Like their predecessors these electrical magnetometers were heavy and bulky. Two much more portable instruments that were much used in surveying work as well as at magnetic observatories were the quartz horizontal-force magnetometer (QHM) (La Cour 1936) and the magnetometric zero balance (balance magnétometrique zéro, BMZ) (La Cour 1942). The former was used for measuring both declination and horizontal intensity, the latter the vertical component. Neither was an absolute instrument and both needed regular calibration.

Fluxgate magnetometers were developed during World War II, initially for submarine detection. A fluxgate magnetometer measures the component of the geomagnetic field along the axis of the sensor, which is a rod or ring of high-permeability material with a non-linear relationship between the applied field and the magnetic induction. The core is surrounded by two coils of wire through one of which an alternating electrical current is passed. This drives the core through an alternating cycle of magnetic saturation, i.e., magnetised—unmagnetised—inversely magnetised—unmagnetised—magnetised. This constantly changing field induces an electrical current in the second coil, and this output current is measured by a detector. In the presence of an ambient magnetic field the core will be more easily saturated in alignment with that field and less easily saturated in opposition to it. The resulting biassed sinusoidal excitation creates a distorted AC signal in the second coil. Detection of the even harmonics in this signal provides a DC output that is proportional to the field being measured.

Three fluxgate elements arranged orthogonally constitute a vector magnetometer and such instruments are often used as variometers at magnetic observatories and in field surveys, including repeat station surveys where there are no nearby observatories that can be used for the reduction of the observations (see Section 3.3.4).

A draw-back to the use of fluxgate magnetometers to measure the field along the sensor axis with high accuracy is their sensitivity to ambient temperature. This is no longer a problem when a fluxgate sensor is used as a null detector and this is exploited in the fluxgate theodolite (also known as a DI fluxgate, declination-inclination magnetometer or DIM). In this instrument a single-axis fluxgate sensor is mounted parallel to the axis of the telescope of the non-magnetic theodolite. Rotating the assembly about a vertical axis and finding the position where the sensor gives zero output gives the direction—read off the horizontal circle of the theodolite—perpendicular to the horizontal component of the geomagnetic field. With the telescope and fluxgate positioned in the plane of the magnetic meridian (at right angles to the direction just determined) rotation about the horizontal axis enables a null position to be found which is in the direction perpendicular to the total geomagnetic field vector. From these two directions, and knowledge of the direction of true north, values of declination and inclination can be derived. In each of these determinations a total of four measurements of the null direction are made, inverting the telescope and rotating the telescope/fluxgate assembly, so as to eliminate errors due to misalignment of the fluxgate axis with respect to that of the telescope and to remanent magnetisation of the instrument. Details of these measurement procedures are given by Newitt et al. (1996). The fluxgate theodolite is used in many modern repeat station networks for the measurement of declination and inclination (see also Korepanov 2006).

For the measurement of the total field intensity, the instrument of choice is the proton precession magnetometer. This was developed in the 1950s and consists of a container full of a hydrogen-rich liquid such as water or paraffin surrounded by a coil of wire. A direct current is passed through the coil, producing a strong field in the liquid. The protons in the liquid are aligned with this field rather than with the ambient geomagnetic field. When the current is switched off they gradually realign themselves with the geomagnetic field and in so doing precess about it. The precession frequency *f* is given by the expression

$$f = \gamma_p' F/2\pi,$$

where γ_p' is the proton gyromagnetic ratio at low field strengths for a spherical sample of water at 25ºC; the value adopted by IAGA is 2.675153362×10^8 $\mathrm{T}^{-1}\mathrm{s}^{-1}$ (Mohr et al. 2008). An observation of total field intensity in absolute measure thus reduces to a measurement of frequency, which can be performed with high accuracy, and a knowledge of γ_p', which is known to high precision. Conventional proton precession magnetometers are based on this principle. Proton precession magnetometers, based on the Overhauser effect (Overhauser 1953) have several advantages over the conventional type and are becoming widely used. They can be cycled more rapidly than conventional types, they are more sensitive, they use less power and their polarising field is weaker, meaning that they can be sited closer to other sensors than traditional proton precession magnetometers.

Proton precession magnetometers are used to measure total intensity at the repeat station site, usually by recording the field continuously at a nearby position whilst the declination and inclination observations are being made. The site difference between the main site and the site of the recording proton precession magnetometer is determined by preliminary measurements made at both sites simultaneously. A proton precession magnetometer is also used to survey the area around the repeat station site, both when the site is being selected initially and at each successive reoccupation. Measurements are made on a regular grid usually oriented north-south and east-west with a spacing of a metre. The aim is to detect any significant departures from smooth field gradients. Any such departures in the initial survey would lead, if possible, to the selection of a site with smoother gradients. Such departures detected during a reoccupation would suggest man-made contamination. If the sources cannot be found and removed a new, nearby site has to be found.

3.3.4 Data Reduction

Measurements made at a repeat station include contributions from the main geomagnetic field that originates in the core, from sources in the Earth's crust and from sources above the Earth's surface. For secular variation modelling—the most important use to which repeat station data are put—only the first of these is required. The crustal contribution can be assumed to be constant over the time scales important for secular variation and is therefore removed when differences between measurements made at different times are computed. The effects of external fields, originating in the ionosphere and magnetosphere, and the effects of currents induced in the crust by these external fields, must be removed as completely as possible. This is the aim of the data reduction procedures.

In mid-latitude regions where there are nearby magnetic observatories the simplest and most economical method of data reduction is to use data from these observatories. It is important to make sure that measurements at the observatory are characteristic of the field and its variations over a wide enough region that includes the repeat station under consideration.

An advantage of the ready availability of internet access is that nowadays it is possible to follow in real time the behaviour of geomagnetic field components from the websites of many institutions that operate magnetic observatories. In this way, one can be made aware of the beginning of a period of disturbed magnetic activity and can then postpone repeat station measurements until the field returns to quiet conditions.

It is usual to reduce mid-latitude repeat station measurements to the value that would be measured during a quiet night-time interval since external magnetic fields have their smallest values during the night hours at these latitudes. Alternatively, the repeat station values are sometimes reduced to an annual mean value since the effects of most external sources are removed by taking means over a year. In either case the assumption is made that the effects of external sources are the same at the observatory and at the repeat station. It is also assumed that the secular variation is the same over the time interval between the epoch of observation at the repeat station and that to which the reduction is made. This implies that

$$\boldsymbol{E}_S(t) - E_S = \boldsymbol{E}_O(t) - E_O, \tag{3.1}$$

where $E_S(t)$ is the observed value of element E at the repeat station at epoch t; $\boldsymbol{E}_S$ is the corresponding value at the station reduced to either a quiet night-time value or to an annual mean; $E_O(t)$ is the value of the element E at the observatory at epoch t; and $\boldsymbol{E}_O$ is either the value of the element E at the observatory for a quiet night-time interval or an annual mean value of E at the observatory. (Note that the use of bold-face symbols does not imply that the corresponding variables are vectors; it is simply a useful device to differentiate measured and reduced or mean values.) Therefore

$$\boldsymbol{E}_S = E_S(t) + C \tag{3.2}$$

where

$$C = \boldsymbol{E}_O - E_O(t).$$

If the repeat station is bracketed in latitude by two nearby observatories and has a similar longitude to the observatories, data from the two observatories can be used with appropriate interpolation. This is often the case for a country such as the UK and Italy which are well endowed with observatories and are relatively long and thin in a north-south direction. The correction factor C in Eq. (3.2) then becomes

$$C = \frac{\Delta\varphi_2\,(\boldsymbol{E}_{01} - E_{01}(t)) + \Delta\varphi_1\,(\boldsymbol{E}_{02} - E_{02}(t))}{\varphi_2 - \varphi_1}$$

where φ_1 is the latitude of the observatory north of the repeat station; φ_2 is the latitude of the observatory to the south; $\Delta\phi_1 = \phi_1 - \phi_S$; $\Delta\,\phi_2 = \phi_S - \phi_2$; ϕ_S is the latitude of the repeat station and the subscripts 01 and 02 indicate that the values of the element E refer to the northern and southern observatory, respectively. Gaps in the observatory minute value data can lead to problems when using this method of data reduction. Several different strategies have been proposed for dealing with these difficulties (e.g., Mandea 2002; Schott and Linthe 2007; Herzog 2009; Marsal and Curto 2009; Newitt 2009; Love 2009). None of them appears to be completely effective when the missing data constitute more than about 10% of the total during more than moderately disturbed magnetic periods.

If there are no observatories sufficiently near to the repeat station survey area or if the morphology of the external field variations is complicated (as, for example, in the auroral zones), the recommended procedure is to use a variometer (nowadays usually using fluxgate sensors) to record the geomagnetic field variations continuously at a point near to the repeat stations. The aim is to make the repeat station plus variometer as similar to a standard magnetic observatory as possible. The variometer is therefore operated for several days during which absolute observations are made at frequent intervals at the repeat station so as to provide baseline values as at an observatory.

A quiet night-time interval is chosen from the variometer record and the repeat station measurements are reduced to this value. Newitt et al. (1996) and Korte and Fredow (2001) give further details of this procedure. They also discuss sources of error in this procedure and in that using nearby observatory data.

Another recently proposed method of data reduction uses a comprehensive field model such as CM4 (Sabaka et al. 2004) which takes into account lithospheric and external (ionospheric and magnetospheric) fields. These contributions can then, in principle, be removed from the repeat station measurements. Of course, this technique depends on the quality of the global model removed and in particular its accuracy over the area and time interval concerned (Matzka et al. 2009).

3.4 Uses of Repeat Station Data

Repeat stations provide an important source of vectorial data for main field and secular variation modelling. Their data contribute to global modelling of the geomagnetic field, and are essential for producing regional field models and charts, the former being important for scientific studies and the latter for navigational purposes. In the present satellite era, more and more global and regional models are based on satellite magnetic data with the addition of ground data, i.e., observatory and repeat station data, to stabilise the inversion (noise at satellite altitude is amplified when downward continued to the ground) and to take into account the true vertical gradient of the field. While spherical harmonic models are used for global representations (e.g., Sabaka et al. 2004), polynomial or spherical cap harmonic models are used for modelling restricted regions of the Earth. Spherical cap harmonic modelling is used either in its original version (Haines 1985) or in its more recent revision (Thébault et al. 2006). Although the repeat station data are imperfect and noisy, their inclusion in regional modelling greatly reduces the ambiguity in the vector components at different altitudes. They are also important for upward and downward continuation purposes (Korte and Thébault 2007).

When using repeat station data for secular variation modelling it is important to estimate the overall error budget due to all the steps in the measurement and reduction procedures. Ideally, accuracies should be comparable to those normally achieved at the best magnetic observatories. i.e., better than 1 nT for magnetic components and better than $0.1'$ for angular elements (Newitt et al. 1996). However, the various steps contribute errors that add together statistically producing a greater overall error: for instance, there will certainly be an error due to the measurement operations themselves and also to possible changes in environmental conditions (temperature changes being the most critical), together with errors coming from possible crustal and/or external contaminations, from imperfect reduction, and other known or unknown factors. Thus, more realistic errors are of about 5 nT in the components, and about 0.5–1 min of arc in inclination and declination (Newitt et al. 1996). This should be taken into account when modelling, usually by weighting repeat station data differently from observatory annual (or monthly) means.

Of special interest are repeat stations placed near or at airports, where magnetic declination is measured at special calibration pads for aircraft compass certification and checks (Loubser and Newitt 2009). These provide important information for aircraft navigation (Rasson and Delipetrov 2006). This kind of measurement is being requested more and more often by airport authorities, sometimes with a frequency of once per year and thus provides some of the most up to-date information for regional field modelling.

There are other indirect but still important uses of repeat station data: for instance, of particular interest is their possible use for estimating the Koenigsberger ratio of lithospheric rocks, i.e., for discriminating between remanent and induced lithospheric magnetisation (Hulot et al. 2009; Shanahan and Macmillan 2009). The former is practically constant on geological time scales while the latter tends to be proportional to the geomagnetic field. A comparison between repeat station intensity measurements made since 1900 and those made since 1960 shows a decrease that could be ascribed to the corresponding main field decay over the past century (Shanahan and Macmillan 2009).

Special mention should be made of a particular type of measurement that, although not actually repeat station measurements, show some similar aspects: finding how the North (or South) magnetic pole moves with time (e.g., Newitt et al., 2009). Here the same position is not reoccupied but the movement of a place with particular magnetic characteristics, i.e., where the magnetic inclination is ±90° is determined. These direct measurements should not be necessary at epochs with accurate geomagnetic field models. However, they provide independent verification of the model and enable the velocity at which the pole moves to be calculated.

This velocity may be related to jerks (Mandea and Dormy 2003), one of the fastest (and most intriguing) features of the recent secular variation.

3.5 State of the Art of Repeat Station Activities

Because of the increased need for ground measurements in connection with recent satellite missions (e.g., Matzka et al. 2010), the time between repeat station measurements has been getting smaller. In the past this interval was between 5 and 10 years but it is now between 2 and 5 years. IAGA Working Group V-MOD deals with several aspects of repeat station activities. According to its website these are: (a) to maintain a catalogue of regional and global magnetic surveys, models and charts; (b) to promote and set standards for magnetic repeat station surveys and reporting; (c) to define operating procedures and classification standards; (d) to encourage agencies to submit repeat data in appropriate formats to World Data Centres (WDCs); (e) to maintain a catalogue of national repeat station network descriptions; (f) to promote international interest in surveying, modelling and analysis of the international geomagnetic field, both globally and on a regional scale.

A regional magnetic survey questionnaire was circulated in 2000 to which 49 countries responded out of 82 contacted. The results confirmed the uneven distribution in space and time of repeat station data. From Fig. 3.1 it is evident that there are significant gaps over large parts of the Earth's surface: for example Mexico in North America, Chile and Argentina in South America, significant parts of Asia and Africa. Fortunately, regarding the last-named continent, some recent international efforts have improved the situation in Southern Africa (Korte et al. 2007). Even in Europe, where there appears to be a large number of data, some national repeat station networks are no longer active over their complete extent. For instance, Russia contributes only three stations in the most recent WDC data set.

To produce better regional and global models we need to have measurements in as many areas as possible, especially in remote regions, such as polar areas, the deep seafloor (e.g., Vitale et al. 2009) and on ocean islands (e.g., Matzka et al. 2009). Particular efforts have been made in this direction: a recent special issue of Annals of Geophysics collects some examples of measurements in remote regions (De Santis et al. 2009).

Another important aspect in repeat station activities is their close relationship with operating observatories. The absence of a nearby observatory together with the possibility of missing data can cause severe problems for repeat station surveys. IAGA encourage both the continuing operation of existing observatories and the establishment of new ones where this is possible.

At a European level, the European network of repeat stations (MagNetE) has had a central role in the last 10 years. It has organised four workshops so far (at Niemegk in 2003, Warsaw in 2005, Bucharest in 2007, Helsinki in 2009) and the next will be held in Rome in 2011. This recently established network among the European institutions dedicated to repeat station surveys has improved agreement between the institutions concerning intervals between reoccupations and measurement techniques. An up-to-date review of the situation of repeat station activities in Europe has been recently presented at the recent MagNetE workshop in Helsinki (Duma 2009). One of the next objectives of this network will be the preparation and realisation of a European magnetic declination map centred at some recent epoch: the latest discussions in the MagNetE community have proposed 2006.5. Any chosen map or model, although relating to a particular past epoch, should also provide predictive information, although the problem of extrapolation into the future is not a simple one and better solutions must be sought. One recently proposed alternative to the commonly used polynomial extrapolation reconstructs the temporal measurements in an ideal phase space where fitting and extrapolating techniques can be better performed (e.g., De Santis and Tozzi 2006). This technique is based on the nonlinear behaviour of the geomagnetic field in time (e.g., Barraclough and De Santis 1997).

Another aspect which is important is to look at the repeat station network in terms of efficiency: a large number of stations is not as important as the fact that they can be reoccupied more frequently, especially in those areas where secular variation is more rapid or significantly different from the rest of the country or of the continent (e.g., South Atlantic, South Africa, Australia). When resources are not available to reoccupy all the stations more frequently, a good compromise is to chose a subset of them, the so-called "super" or "class A" repeat stations (e.g., McEwin

1993) which are reoccupied more frequently, e.g., once every year or two years. Repeat stations of this type, which are rather similar to observatories, are better able to follow the secular change on time scales of a year or so.

3.6 Conclusions

The geomagnetic field is a fundamental property of our planet; it changes with space and time in a complex fashion. Most of it originates in turbulent motions in the outer metallic fluid core of the Earth at around 3000 km depth, with time scales from years to millennia. On the Earth's surface and above the potential from which it can be derived is usually represented by spherical harmonics as solutions of Laplace's equation in spherical coordinates. Very accurate observations of the field are made at geomagnetic observatories. However these are sparse and do not cover the Earth's surface as uniformly as needed. In order to follow the evolution of the field in time and space with sufficient accuracy it is necessary to complement the observatory measurements with other kinds of data, such as repeat station observations. The latter have high enough accuracy and can be made in less time than those at the observatories. Repeat station measurements lead to an increase in the spatial detail of secular variation studies, improving both regional and global geomagnetic field modelling in space and time. An optimum scheme for the reduction of repeat station measurements is to use a combination of the different techniques discussed above. In particular, a variometer installation, recording for one or more days whilst the repeat station observations are being made, and a nearby observatory are highly recommended. Use of a comprehensive model such as CM4 or another more recent global model that takes into account the external field contributions should also be considered. By studying the behaviour of magnetic indices such as K and Dst whilst measurements are being made we can also assess the quality of the final reduced repeat station component values.

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