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Geomagnetic Observations for Main Field Studies: From Ground to Space

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Abstract Direct measurements of the geomagnetic field have been made for more than 400 years, beginning with individual determinations of the angle between geographic and magnetic North. This was followed by the start of continuous time series of full vector measurements at geomagnetic observatories and the beginning of geomagnetic repeat stations surveys in the 19th century. In the second half of the 20th century, true global coverage with geomagnetic field measurements was accomplished by magnetometer payloads on low-Earth-orbiting satellites. This article describes the procedures and instruments for magnetic field measurements on ground and in space and covers geomagnetic observatories, repeat

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stations, automatic observatories, satellites and historic observations. Special emphasis is laid on the global network of geomagnetic observatories.

Keywords Geomagnetic field · Observations · Geomagnetic observatories · Magnetic satellite missions

1 Introduction

The largest part of the geomagnetic field is generated by the geodynamo in the Earth's liquid core (see, e.g., Kono 2007). Other sources to the geomagnetic field include electrical currents in the ionosphere and magnetosphere (the external field), magnetised rocks in the lithosphere (crustal field), and induced electrical currents in the mantle and oceans (induced field). The core, crustal and induced field combined is called the internal field. The core field, also referred to as the main field, varies slowly in time, typically on secular time scales. Knowledge of this secular variation is a key tool for exploring the spatial and temporal characteristics of the geodynamo. By exploiting potential theory, magnetic field measurements at the surface of the Earth or at the altitude of low-Earth-orbiting satellites can be used to separate magnetic field contributions from sources external and internal with respect to the measurements. Despite some problems related to e.g. the partial screening of the core field by the conductive mantle or partial overlapping of the core and the crustal field, it is possible to construct models that describe the main field down to the source region at the core-mantle boundary.

Producing the high-quality geomagnetic data that is required for geodynamo studies is a challenge for several reasons:

1. The geomagnetic field **B** is a vector and both its direction and strength have to be measured for a full description. At the Earth's surface, the absolute value of the main field is currently between 23000 nT and 62000 nT, and the typical change per year due to secular variation is a few tens of nT. To resolve these changes, the required accuracy is 1 nT, corresponding to about 20 ppm or an angular accuracy of 5 seconds of arc. It is a requirement from potential theory to use vector data, or certain vector components, for modelling to get unique solutions (see, e.g., Gubbins 2007). The measurement of the scalar field $F = |\mathbf{B}|$ is technically less demanding, but of more limited value for modelling (Backus 1970; Khokhlov et al. 1997).
2. Typical secular variation processes take time (e.g. Hulot et al. 2007; Jackson and Finlay 2007): from about a year for a geomagnetic jerk (Courtillot et al. 1978; Chulliat et al. 2010; Mandea et al. 2010a, this issue) or the so-called rapid secular variation fluctuations (Olsen and Mandea 2008; Mandea and Olsen 2009), to several decades for convective core flows, torsional oscillations, waves and magnetic diffusion (see, e.g., Finlay et al. 2010, this issue) and several centuries between archeomagnetic jerks (Gallet et al. 2003). Geomagnetic measurements have to be as homogeneous as possible over these time scales.
3. The secular variation processes usually act on a global scale, and the measurements on the ground have to be organised such as to give the best possible geographic coverage with observatories that follow consistent routines to give comparable data sets. A high spatial resolution is a prerequisite for downward-continuation of the data to the core-mantle boundary. Satellites have the advantage of global coverage with a single set of instruments.

4. Magnetic measurements are influenced by the spatially varying magnetic field from the Earth's crust (crustal field) and the distribution of electric conductivity in the ground. The local magnetic field gradient due to magnetic rocks can easily exceed several nT/cm and, therefore, sensor locations have to be stable over long time scales. The sensors also have to be protected against magnetic fields from man-made magnetic objects or electric currents.
5. Finally, superimposed on the internal main field and crustal field are time varying external fields of ionospheric and magnetospheric currents. They can vary quickly, and considerable currents are induced in the Earth's mantle and oceans, which again produce time varying magnetic fields. The external field variations have periods from a few seconds to hundreds of years, with peaks, for example, at the periodicity of the Earth's rotation (1 day), the solar rotation (27 days), the earth's orbit (1 yr) and the solar cycle (11 years), overlapping partly with the spectrum of the secular variation (Constable and Constable 2004). To properly separate the secular variation from these magnetic field changes is a challenge, and to avoid aliasing effects, the full spectrum of the variations has to be measured. The ionospheric and magnetospheric currents have a complicated geometry and the external field variations are spatially very variable, with the largest variations typically observed at high latitudes (see, e.g., Baumjohann and Nakamura 2007). Magnetic measurements from satellites have the disadvantage of containing a mixture of signals from spatial and temporal magnetic field changes. Furthermore, satellites are on orbits passing through ionospheric F region currents and the so-called field aligned currents, making magnetic field modelling more challenging (Hulot et al. 2007; Olsen et al. 2010a).

Also from a technical point of view, magnetic measurements on satellites and at the Earth's surface are quite different. Satellites have star cameras for attitude determination and exploit the rotation of the magnetic field vector with respect to the satellite during each orbit for the calibration of the magnetometer. This is not the case for ground based instruments, which have to measure the geomagnetic field in an almost constant direction. Currently, a full geomagnetic observatory setup, comprising several buildings and instruments as well as regular (e.g. weekly) manual calibration procedures (the absolute measurements), is needed to provide vector data with sufficient accuracy and temporal resolution. When this is achieved, an accurate long-term record of the temporal variation of external magnetic field sources is also obtained, which is an important contribution of geomagnetic observatories to monitoring space weather and its effects (e.g. Boteler 2001) as well as space climate reconstruction and research (Nevanlinna 2005; Le Mouël et al. 2005; Svalgaard 2009).

In this article we describe how magnetic measurements are conducted in observatories and aboard satellites in order to model the main magnetic field and its temporal variations with the highest accuracy and spatio-temporal resolution. We also describe the direct magnetic measurements available for epochs prior to the establishment of the global observatory network, which are also used in main field modelling.

Geomagnetic observatories have been the backbone of ground based geomagnetic measurements for almost 200 years and shall be described first (Sect. 2). We lay emphasise on the principles of operation, and show how these relate to the science objectives, the characteristics of the geomagnetic field, and the available instruments. The way how geomagnetic observatories are coordinated internationally and the ongoing efforts to higher sampling frequencies and faster dissemination of final data are subject of Sect. 3.

The geomagnetic observatory network has considerable geographical gaps, the largest being on the southern hemisphere and in oceanic regions. Recent advances with establishing geomagnetic observatories on oceanic islands are described in Sect. 4.1. Geographic coverage could be significantly improved by operating automatic instruments in remote regions, including the oceans. Automatic instruments that could be capable of producing observatory grade data are described in Sect. 4.2. Magnetic repeat stations measurements for regional and global secular variation studies are subject of Sect. 4.3.

Satellites play an outstanding role for geomagnetic measurements, as shown in Sect. 5. They produce high quality geomagnetic data with global coverage and high spatial resolution. Crustal field contributions are attenuated due to the distance to their source. Ionospheric contributions, however, can be both internal and external fields, and ionospheric currents, which are especially strong in the polar regions, complicate magnetic field modelling. Multi-satellite missions including the upcoming Swarm mission are subject of Olsen et al. (2010b), this issue.

Finally, historic geomagnetic data, dating back more than 400 years, are discussed in Sect. 6. Since the amplitude of the secular variation on these time scales can easily be in the order of tens of degrees or thousands of nT, even magnetic field determinations of low accuracy are valuable (Jackson and Finlay 2007).

2 Geomagnetic Observatories

At a geomagnetic observatory, the geomagnetic field vector is recorded continuously over a long period of time. The location must not be affected by artificial magnetic fields that could contaminate the records. To be representative for the geomagnetic field vector of a larger region, the location ideally is free of crustal magnetic anomalies and has no lateral changes in electric conductivity in its vicinity (Wienert 1970; Jankowski and Sucksdorff 1996). In the 1830s, Gauss and Weber introduced two different types of instruments: the absolute magnetometer and the variometer (see, e.g., Good 2007a). Despite a complete change in the underlying technology, it is still state-of-the-art to calibrate variation measurements, which are continuous and have a high resolution both in time and in the field component they measure, with sporadic absolute measurements, which are true vector measurements of sufficient accuracy, to obtain the geomagnetic field vector record. Modern observatory operations encompass:

1. Near-real-time dissemination of preliminary field vector records based on variometer data calibrated with recent absolute measurements.
2. Regular (e.g. weekly) determination of calibration parameters by absolute measurements
3. Yearly release of final observatory data based on the variation data and a large number of absolute measurements.

In preparation for the SWARM satellite mission (Friis-Christensen et al. 2006) there are currently international efforts to produce 'quasi-definitive' observatory data on a monthly basis (see Sect. 3).

This is generally considered the minimum outfit for a geomagnetic observatory:

1. Two buildings: the variometer hut and the absolute hut, which are set up in a fashion that the magnetometers are not subject to magnetic fields higher than their sensitivity level which could arise from neighbouring instruments or from the buildings, or any other contaminating magnetic field source from outside the geomagnetic observatory.

2. Additional equipment (data logger, computers, communication hardware, and possibly also power back up systems) is installed at a nearby building, often in a third hut. AC electric power is installed in all buildings, data transmission is installed between the variometer house and the electronics hut, and from there to a remote data collection centre.
3. A set of absolute instruments is kept on pillars in the absolute house. Any (time varying or constant) contaminating fields must be avoided during the time of absolute measurements, which usually are manual, take about an hour and are performed, under ideal circumstances, weekly. An azimuth mark in a minimum distance of 100 m is visible from the pillars.
4. A variometer is kept in the variometer house on a stable pillar at constant temperature and remote from any time-varying contaminating fields. The continuous variometer output is digitised and time stamped with UTC (see p. 133 of Jankowski and Sucksdorff 1996).

To ensure long-term stability and homogeneity of the observatory time series, the same locations and buildings are often used over many decades. Some geomagnetic observatories have residential and office buildings, workshops and magnetometer calibration facilities. Other geomagnetic observatories are only for geomagnetic field recordings and are visited by staff on a regular basis. Thanks to a smaller and more automated instrumentation, the size of recently established geomagnetic observatories is much smaller than that of older observatories.

The International Association of Geomagnetism and Aeronomy (IAGA), an association within the International Union of Geodesy and Geophysics (IUGG) which again is a member of the International Council for Science (ICSU), coordinates the operations of the national geomagnetic observatory programs through its Division V, Working Group V-OBS: Geomagnetic Observation. Among other things, this working group is assigning an universal three letter code, the IAGA code, for each observatory. Moreover, IAGA has been involved with long-term efforts supporting geomagnetic observatories via resolutions or, very recently, 'The electronic Geophysical Year' (Mandea and Papitashvili 2009).

In this review, we focus on the role of geomagnetic observatories to establish long-term records of the secular variation, originating in the Earth's core. However, the scientific value of observatory data is not limited to core field studies. Observatory data are also used for e.g. characterising the spatio-temporal properties of the external current systems in the ionosphere and the magnetosphere and are thus important for space physics (e.g. Baumjohann and Nakamura 2007) and global scale induction studies (see, e.g., Constable 2007; Kuvshinov 2007).

2.1 Geomagnetic Observatory Data

The geomagnetic field vector $\mathbf{B}(\mathbf{t})$ at a geomagnetic observatory is most commonly expressed in local Cartesian coordinates along geographic North X, geographic East Y, and vertical downwards Z. Alternatively, it is expressed in cylindrical coordinates as the horizontal component H, the magnetic declination D, which is the angle between geographic North and the horizontal component of the field, counted positively eastwards, and Z; or in spherical coordinates as D, the magnetic inclination I, which is the angle between the horizontal plane and the field vector, and the field modulus $F = |\mathbf{B}|$.

Annual means, monthly means, daily means and hourly means are generally centred on the centre of the respective time interval. Today, hourly means are calculated from the digital minute mean values record, but traditionally, geomagnetic field changes were recorded on photographic paper (by means of deflecting magnets with mirrors and light pointers) and hourly means were determined by visual judgement, aided by a transparent plate with rulings and graduations (McComb 1952; Wienert 1970). When analysing older data derived from photographic records, one should, however, make sure if tabulated values represent hourly means or hourly spot readings. Traditionally, the daily mean would be calculated from the hourly means, the monthly mean from the daily means, and the annual mean from the 12 monthly means with equal weighting. Annual and monthly means are also routinely calculated from a subset of days: the international 5 magnetically most quiet and 5 most disturbed days. These days are chosen on the basis of the Kp-index of geomagnetic activity, which is based on data from selected observatories (Bartels 1957). Today, some observatories prefer to calculate annual means directly from daily means. Minute means collected by INTERMAGNET (see Sect. 3) are centred on the top of the minute (St-Louis 2008). At some observatories, 1-second data are provided, either as spot-readings, or as means of higher frequency data. A 24-hour plot of geomagnetic field records (usually of all three components) is referred to as a magnetogram.

A few examples of 1-minute observatory records are shown in Figs. 1 and 2. Figure 1 is a montage of magnetograms to demonstrate the mid-latitude daily variation of the geomagnetic field during quiet days of the current period of low solar activity. Two 48 hour periods during which the Kp-index was low, close to the winter solstice 2008 (black lines) and close to the summer solstice 2009 (grey lines), were chosen. Shown is the geographic East component of the magnetic field for three geomagnetic observatories in the northern (Memanbetsu, IAGA code MMB, Japan; Fuerstenfeldbruck, FUR, Germany; Tucson, TUC, United States) and southern hemisphere (Alice Springs, ASP, Australia; Hermanus, HER, South Africa; Trelew, TRW, Argentina). The prominent variations in the East component are connected to the sunlight hours and follow the Earth's rotation with an antemeridian increase (decrease) in the northern (southern) hemisphere. Comparing December 2008 and June 2009 shows, that the amplitude of the variation is higher in the local summer season. These daily varia-

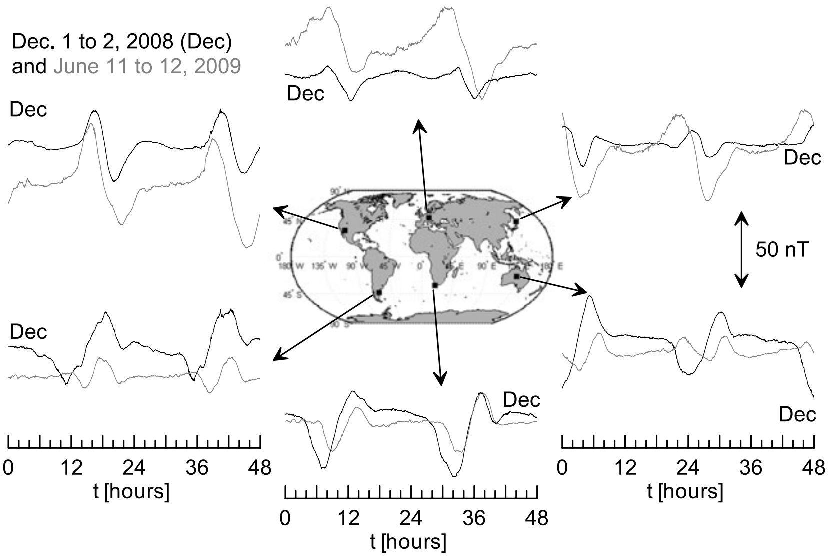

Fig. 1 Magnetogram montage for northern and southern hemisphere geomagnetic observatories at magnetically quiet periods (see text). *Black*: December 1st and 2nd; *grey*: June 11th and 12th. All plots depict the geographic East component. *The arrow* indicates the 50 nT scale, valid for all plots

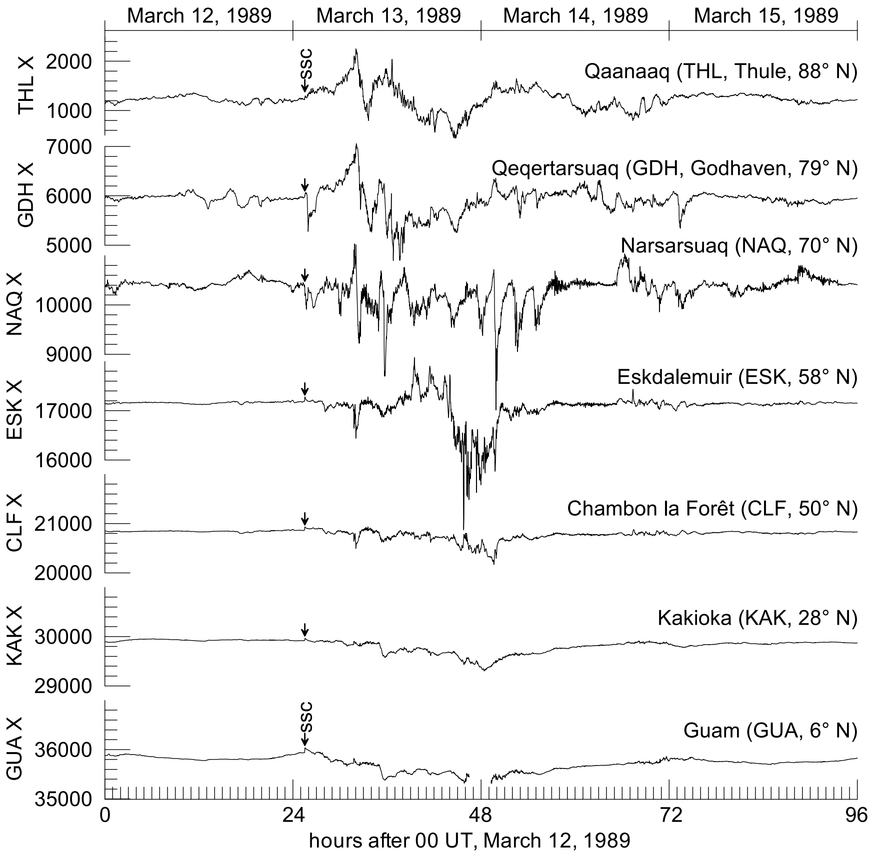

Fig. 2 Geographic North component *X* (in nT) of the geomagnetic field during the magnetic storm in March 1989 at seven geomagnetic observatories with various distance to the geomagnetic pole. The sudden storm commencement (ssc) is indicated by *arrows*. IAGA code, previous names (if applicable), and geomagnetic latitude are given in brackets. Note that the variations here are in the order of 1000 nT, whereas in Fig. 1 the variations were in the order of 50 nT

tions are caused by electric currents flowing in the E-layer of the dayside ionosphere, where a dynamo effect takes place due to interactions between electrically conducting tidal winds and the main geomagnetic field.

A geomagnetic storm commenced early on March 13, 1989, and Fig. 2 shows observatory records of the geographic North component *X* from March 12 to 15, 1989. The geomagnetic observatories were selected for their different geomagnetic latitude (i.e. angular distance to the geomagnetic pole), representing the polar cap (IAGA code THL), the cusp region (GDH), the auroral oval (NAQ), a sub-auroral (ESK), a mid-latitude (CLF) observatory and finally two low-latitude observatories (KAK and GUA). The storm disturbances at high latitudes are mostly caused by auroral electrojets flowing in the ionosphere, while at mid- and low-latitudes the effect of the magnetospheric ring current becomes dominant.

In order to use observatory data for core field studies, it is necessary to remove the contributions from the external fields such as the ones shown in Figs. 1 and 2. This can be done by modelling the external field (e.g. Sabaka et al. 2004). A simpler and more classical method to separate internal and external contributions consists in filtering out rapid variations by

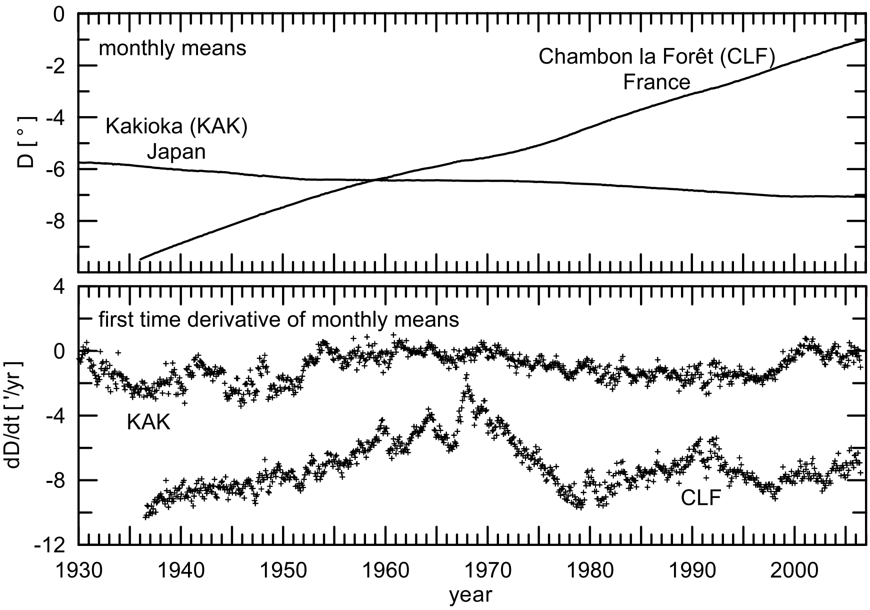

Fig. 3 Example for the long-term observation of secular variation of the geomagnetic field: Monthly means of the declination D at the French geomagnetic observatory Chambon la Fôret and the Japanese observatory Kakioka (IAGA codes CLF and KAK, *upper panel*) and first time derivative dD/dt of the declination (see text, *lower panel*). The sharp change in the secular variation (*lower panel*) for CLF just prior to 1970 indicates a geomagnetic jerk

averaging observatory data over one month or one year. An example for this is the time series of monthly means from Chambon la Fôret (IAGA code CLF) in France and Kakioka (KAK) in Japan. In Fig. 3, the declination and its first time derivative are shown. The first time derivative is obtained by calculating the difference between a monthly mean for a certain time and the monthly mean 12 months prior to it (to cancel out the seasonal modulation of the ionospheric magnetic field depicted in Fig. 1). The data displayed in Fig. 3 show the monthly means (upper panel) as a smooth curve, the first time derivative however indicates sharp changes in the secular variation, e.g the geomagnetic jerk prior to 1970 in CLF (Courtillot et al. 1978). Monthly means are now used for secular variation studies which aim at higher time resolution then annual means, and projects to compile monthly means are under way (Chulliat and Telali 2007), helping also to detect discrepancies between hourly means and annual means that are already available through the World Data Centres (WDCs). Although monthly means are used for secular variation studies, there is a certain influence of external field contributions (e.g. Olsen 2009). For a long time, observatory monthly and annual means were the only data available for calculating global geomagnetic field models. They are now complemented by high-precision satellite data (see Sect. 5) and various compilations of historical data (see Sect. 6). Modern core field models covering several decades to centuries rely on these three types of data. Thus maintaining and extending a global network of geomagnetic observatories providing high-quality data remains a high priority of the geomagnetism community.

In this section we have shown (with a few examples only) the range of spatio-temporal variability of the main field and the external field. For the main field to change by 1000 nT takes decades, during a magnetic storm there can be temporarily changes of this order within a few hours. Whereas magnetic storms of this magnitude occur seldom, there are daily magnetic variations from ionospheric currents with several tens of nT amplitude, modulated by the seasons and the solar cycle. But also induced fields have to be considered. For example, induction of ionospheric fields in the ocean has a significant influence on the daily magnetic variation at coastal geomagnetic observatories and on satellite measurements (e.g. Kuvshinov et al. 2007).

2.2 Principles of Geomagnetic Observatory Operations

Variometers with known scale value and properly oriented sensors, which are well placed and at constant temperature, are reliable instruments to measure field changes with periods from seconds to days or even longer. However, instrument drift and pillar instability cause problems for longer periods, which have to be corrected for by the means of absolute measurements. The classical variometers, where light pointers were used to amplify and record the deflection of suspended magnets on photographic paper, required both daily operator intervention and sufficiently large variometer houses. Today, much more compact, digitally recording 3-component fluxgate magnetometers are used. Figure 4 shows one of the most commonly used variometers, a Danish fluxgate variometer of type FGE (manufactured by DTU Space, Denmark). The compact design allows to suspend the whole apparatus, giving superior compensation for the effect of tilting pillars. Like the classical instruments, the fluxgate variometers are sensitive to temperature variations.

In contrast, absolute measurements are designed to be independent of instrument drift and environmental influences. Historically, a theodolite with a suspended magnet to determine the horizontal field strength H and the declination D was combined with an instrument to determine the inclination I. Today, a scalar magnetometer (proton magnetometer or Overhauser magnetometer, occasionally an optically pumped magnetometer) for field strength F and a fluxgate theodolite, also called a DI-flux, to measure the direction (declination and inclination) of the geomagnetic field are the standard. The DI-flux measurement involves an observer (Fig. 4). Important parts of the directional absolute measurements are to check the levelling of the DI-flux and to measure an azimuth mark together with the geomagnetic field directions in order to compensate for pillar tilt and rotation. The accuracy of absolute measurements is in the order of 0.5 nT.

More information on observatory variometers is found in Sect. 2.3 and absolute instruments are discussed in Sect. 2.4. More technical information on instruments is also found in Rasson (2007), and in Turner et al. (2007). The latter article discusses also observatory operations and other types of magnetic measurements in geosciences. Both give a short historical perspective.

Variometers and absolute instruments cannot be put on the same pillar and the absolute instrument for measuring the field direction, the DI-flux, has to be accessible to the operator. Consequently, in a geomagnetic observatory at least two pillars are needed: one for the variometer, which has to be kept permanently stable, and one for the DI-flux, which has to be stable for the duration of an individual absolute measurement. The scalar magnetometer can be put on an auxiliary pillar, since rotations are not critical. These pillars are often in separate buildings, as shown for the Qeqertarsuaq geomagnetic observatory in Fig. 4. The recently installed geomagnetic observatory on Tristan da Cunha is an example where the fluxgate variometer is placed in a temperature controlled shelter much smaller in size than variometer huts of older observatory buildings (Fig. 4).

To calculate the geomagnetic field vector record from the variometer output, the baselines for all three sensors of the variometer have to be known. Depending on the orientation

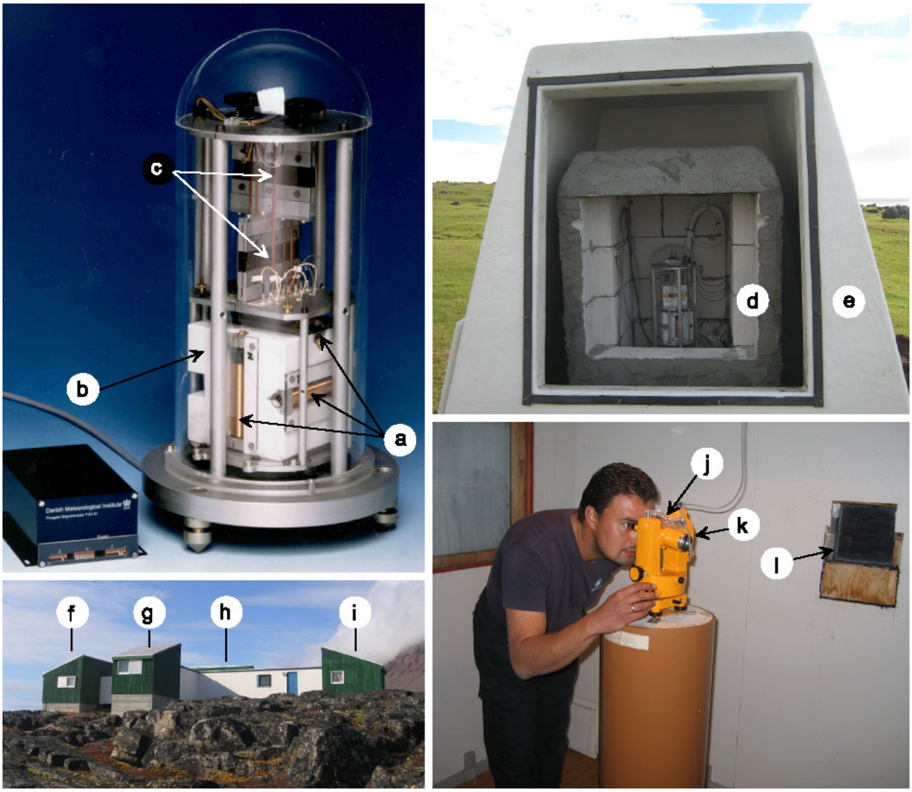

Fig. 4 *Upper left:* Fluxgate variometer (Danish variometer of type FGE): fluxgate sensors (*a*) are orthogonally mounted on a marble block (*b*) which is hanging on a bronze band suspension (*c*) for tilt compensation. *Upper right*: Simple variometer hut as part of a geomagnetic observatory on Tristan da Cunha, South Atlantic Ocean: aerated brick enclosure (*d*) for thermal insulation and fibreglass shell (*e*) against wind and rain; the FGE is sitting on a pillar with electrical heating (not visible). *Bottom left*: Geomagnetic observatory Qeqertarsuaq (IAGA code GDH) in Greenland with electronics building (*f*), proton magnetometer hut (*g*), variometer hut (*h*) and absolute hut (*i*). *Bottom right:* Observer making absolute measurements in Qeqertarsuaq with a DI-flux-instrument (fluxgate sensor (*j*) on non-magnetic theodolite (*k*)). The small window (*l*) allows sighting of an azimuth mark. All photographs by courtesy of DTU Space

of the sensors, some components of the geomagnetic field vector are calculated from one sensor, or from combinations of sensors. For example, the Z-component can be calculated from a vertical sensor alone, while the H-component can be calculated from two horizontal sensors. The baselines are found by comparing the results of the absolute measurements to the variometer output. Figure 5 shows the baselines for the year 2008 at the geomagnetic observatory Qaanaaq (IAGA code THL) in Greenland. Each point represents a baseline value determined from an absolute measurement, while the continuous lines represent the adopted baselines that were used to calculate definitive data. The set of baselines shown in Fig. 5 represents an ideal case: they vary not more than 1 nT throughout the year, indicating that there is almost no variometer drift. In Fig. 5 the adopted baselines are step functions. Alternatively, the adopted baselines could be continuous functions (e.g. splines automatically fitted to the measured baseline values) that are better suited to represent a continuous variometer drift. Step functions with steps larger than the resolution of the definitive data will introduce erroneous steps in the definitive data.

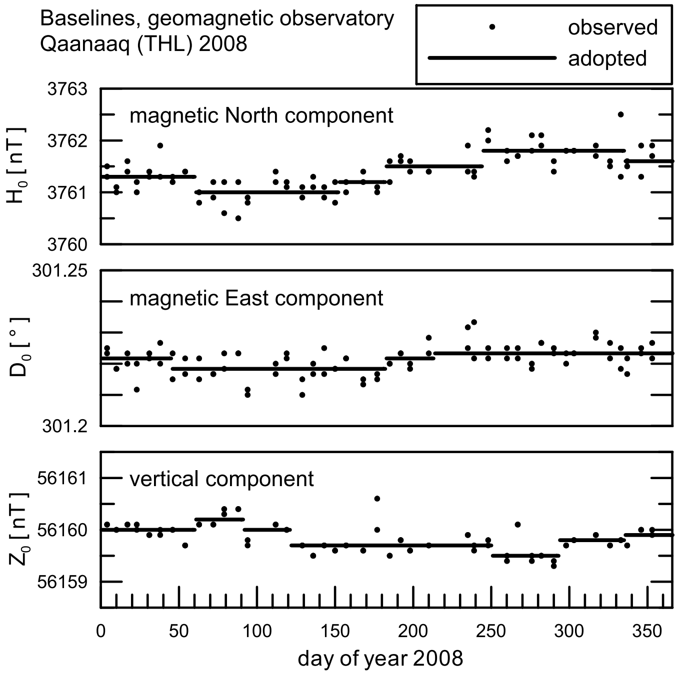

Fig. 5 Baselines for the year 2008 for the geomagnetic observatory Qaanaaq (THL) in Greenland. Both step functions (as in this example) or continuous functions are used for adopted baselines. Although step functions are rather common, they have the disadvantage of introducing steps in the definitive data

The measured and adopted baselines are an important indicator for the quality of observatory data and are part of the metadata that geomagnetic observatories have to deliver to get definitive data accepted by INTERMAGNET (St-Louis 2008). For example, continuously changing baselines suggest variometer drift, while steps in the baselines are often associated with certain events, like maintenance work or rotation of the variometer. Some observatories have several variometers running, and each needs its own set of baselines. This allows to merge the output of different variometers into the definitive observatory data and to fill in data gaps that otherwise arise from e.g. maintenance work at a variometer hut.

The crustal magnetic fields, including contributions from local magnetised rocks and soil, are difficult to separate from the other magnetic field contributions. When constant, they cannot be distinguished from the main field; if time varying (e.g. when their magnetisation changes with time, or rocks and soil are displaced), they can corrupt the information on secular variation or on the other time varying field contributions. These observatory biases can be derived through a comparison with magnetic models from satellite data (Langel and Estes 1985). The local bias field arising from rocks or soil close to the magnetometers can cause significant gradients in the geomagnetic field. For this reason, sensor positions have to be defined accurately in a geomagnetic observatory. Moreover, the magnetic field differences between the various pillars of a geomagnetic observatory have to be considered. At most observatories, magnetic field gradients are low (this actually is a site selection criteria), and only the difference in the field strength is taken into account between the DI-flux and the scalar magnetometer. When field differences are large, as could be the case e.g. on volcanic islands or in other igneous areas, then vector differences between the pillars should be taken into account (Jankowski and Sucksdorff 1996, p. 129). For example, at the Leirvogur geomagnetic observatory in Iceland, the magnetic field difference between the variation pillar and the DI-flux pillar is known and taken into account (Björnsson 2008, pp. 13 and 14).

2.3 Observatory Variometers

A variometer sensor has an output signal that follows magnetic field changes along a certain axis. It is characterised by its frequency response and sensor noise. To reach the desired resolution of 0.01 nT to 0.1 nT for a given dynamic range, often a large part of the static signal is compensated by a static bias field. A full variometer setup needs three such sensors, ideally in mutually orthogonal directions. A precise sensor orientation, usually better then 2 mrad, is important. The sensor output of classical instruments is the deflection of a light pointer which is digitised by a ruler from photographic paper. For modern instruments, the sensor output is commonly a voltage that is digitised by an analogue-to-digital converter. The sensor output has to be multiplied by a scale value (e.g. in nT/millimeter, nT/volt or nT/bit) to give the magnetic field changes in nT. The quality of an observatory variometer is determined by the long-term stability of its sensor orientation, offset and scale values. At many, but not all, observatories, a variometer can be kept at stable temperatures, relaxing the need for built-in temperature compensation mechanisms. Variometers have to be located on stable pillars to minimise any rotations of the instrument: in a field of 50,000 nT, a rotation by 1 second of arc can cause a field change of 0.24 nT.

Modern variometers have three orthogonal fluxgate sensors. A fluxgate sensor generates a DC voltage that is linear to the magnetic field along the sensor's axis. Usually, the fluxgate sensor is housed inside a coil, and a negative feed-back system controls the coil current to compensate the magnetic field along the sensor's axis. This feedback current is often used to compensate only for a part of the magnetic field component corresponding to the maximum expected variations. The remaining field is compensated by a constant bias current that produces the bias field. The strength of the feedback current is a measure for the field variation and usually measured as voltage drop at a resistor. The measuring range of the variometer specified by the worldwide INTERMAGNET network (see Sect. 3) is 6000 nT for low and mid latitudes, and 8000 nT for high latitudes (St-Louis 2008). The output voltage typically varies between 10 V and -10 V and is digitised with 16 to 24 bit. The currently targeted increase in the time resolution of geomagnetic observatory data from 1-minute means to 1-second means brings increasingly stricter requirements for the variometer's noise, frequency response and anti-aliasing filter, as well as the data logger's time stamping accuracy (Chulliat et al. 2009a; Shanahan and Turbitt 2009; Korepanov et al. 2007).

In a popular design, the three orthogonal sensors are suspended such that one sensor is aligned with the Z-component, and two sensors are horizontal. The instrument is set up on the pillar such that one horizontal sensor is either oriented along geographic North or along magnetic North. The latter is more easily accomplished, but needs correction for secular variation from time to time. A suspension compensates for tilting, but not for rotation, of the instrument or pillar (Rasmussen and Kring Lauridsen 1990; Trigg and Olson 1990). In many locations, e.g. on permafrost, uncompensated pillar tilt will significantly influence the data quality.

Mechanical, electrical and magnetic parts are ageing and this is affecting a fluxgate sensor's offset and scale value, as well as the bias field. Temperature variations can have a significant influence on these parameters, too, and should be avoided. Since natural temperature changes and the solar quiet (Sq) ionospheric fields have a similar 24-hour periodicity, a stable variometer temperature is a prerequisite for accurate Sq-studies. Ageing, temperature effects and the above mentioned pillar instability make it necessary to repeat the calibration of a variometer regularly. These calibrations are based on absolute instruments, which are described in Sect. 2.4.

A scalar magnetometers (see Sect. 2.4) can be used to measure every few seconds the total field strength absolutely. These measurements can be compared continuously to the total field strength calculated from a variometer. Any changes in the difference of the calculated and measured total field value indicate a problem at one of the instruments. This is a valuable method for checking the variometer (see, e.g., Reda et al. in press).

Besides the already mentioned FGE magnetometer by DTU Space (Denmark), variometers are also available from LEMI (Lviv Centre of Institute of Space Research, Ukraine) and Magson GmbH (Germany) and several geomagnetism programs have developed their own instruments based on fluxgate sensors.

2.4 Absolute Instruments

The traditional absolute instrument to determine declination and horizontal intensity is a theodolite with a magnet suspended on a glass fibre and a second magnet outside the theodolite (Gauss 1833). Observers had to be very experienced. For the method to be absolute, the restoring force of the suspension and the external magnet's magnetic moment had to stay constant during the measurement. These theodolites were in use until the 20th century, in combination with either dip circles or earth inductors for the inclination measurements (Good 2007a). The quartz horizontal magnetometer QHM (La Cour 1936) also contained a quartz glass fibre and a suspended magnet and became a popular instrument for determining H with an accuracy of 1 nT. The QHM was not an absolute instrument and had to be calibrated by comparison to absolute instruments every few years. Effects from ageing of the fibres could be approximated by linear inter- and extrapolation of the calibration constants (Kring Lauridsen 1977). QHMs were airfrighted for comparison between observatories.

The development of proton precession magnetometers (Packard and Varian 1954) and other scalar magnetometers, like Overhauser magnetometers and optically pumped magnetometers, have significantly simplified geomagnetic observations. All these instruments use quantum mechanical effects to produce an AC voltage with a frequency depending on the magnetic field strength F. Accurate frequency determinations are technically easy, and well calibrated through a radio transmitted time or frequency normal that is traceable to a national bureau of standards. Also instruments with internal clocks prove to be stable over extended periods and can be calibrated every two years at a IAGA Geomagnetic Observatory Workshop (Reda and Neska 2007; White 2009). Some sensors display a heading error: a bias depending on their orientation with respect to the geomagnetic field vector. For geomagnetic observatories, where sensors can be kept stable and the field vector changes slowly, this usually is not a problem.

Today, the most popular combination for absolute measurements is a scalar magnetometer for F, and a fluxgate theodolite for D and I, known as DI-flux. The DI-flux features a fluxgate sensor mounted parallely on to the telescope of a non-magnetic theodolite, like the non-magnetic version of the Zeiss Theo 020 or Theo 010. It is placed on a pillar or tripod to keep its position fixed for all measurements, and is levelled with foot screws such that the theodolite's alidade rotates around a vertical axis. These instruments have an automatic index, i.e. a pendulum that indicates the vertical with 0.3 second of arc (for the Theo 010), improving the levelling achieved with the foot screws. For convenient determination of geographic North with the DI-flux, a sighting mark with known azimuth in some 100 or 1000 m distance is established and regularly checked, e.g. by sun observations.

The direction of the field vector is determined by measuring the horizontal and vertical angles of the telescope as well as the (small) magnetic fields along the fluxgate sensor for a number of telescope directions roughly perpendicular to the field vector. From this, the direction of magnetic North, the inclination, the fluxgate's sensor offset and the misalignment between the fluxgate sensor and the telescope are calculated. The method is absolute, as long as the sensor offset and misalignment don't change during the measurement (e.g. sensor offset can be temperature dependent). A popular scheme for performing these measurements was developed by Kring Lauridsen (1985).

3 The Global Geomagnetic Observatory Network

The first global geomagnetic observatory network, the Göttingen Magnetic Union, was set up in the 1830s by Gauss, Weber and Humboldt, soon after the installation of the first geomagnetic observatory in Göttingen. It comprised up to 50 geomagnetic observatories, including 15 outside Europe. Participating observatories were measuring the field at simultaneous times. The obtained data were used by Gauss to calculate the first spherical harmonics model of the Earth's magnetic field (see, e.g., Stern 2002). After the Göttingen Magnetic Union ceased operations in 1841, the number of observatories remained low for several decades. It started to increase again after 1880, as more and more countries felt the need to monitor the secular variation on their territory for navigational purposes (Fig. 6). The International Geophysical Year (IGY, www.nas.edu/history/igy), in 1957–1958, prompted a rapid increase of the number of observatories, particularly in remote locations, and of the number of observatories producing hourly means. Today, about 170 observatories operate worldwide, including about 120 observatories producing 1-minute data (Love 2008).

Not seen in Fig. 6 is the very significant improvement to the data quality brought by the use of the proton precession magnetometer, from the 1950s onwards. In parallel, many observatories have been replacing their old instruments based upon pivoted or suspended magnet systems by electronic instruments such as the fluxgate magnetometer (Turner et al. 2007). As a result, more and more observatories have been able to produce 1-minute data in digital format. This improvement lead to the founding of INTERMAGNET, the global network of digital magnetic observatories (www.intermagnet.org), in 1987.

INTERMAGNET is an international organisation promoting high-quality standards for magnetic observatories and facilitating data distribution. As of January 2010, 110 observatories in 43 countries participate in INTERMAGNET. Several procedures help ensuring the highest quality for data produced by INTERMAGNET magnetic observatories (IMOs). Prior to its acceptance in the network, an observatory has to demonstrate the compliance of its data with the standards set by INTERMAGNET. Once in the network, its definitive data are carefully reviewed by a committee of experts before being published on a DVD and on the organisation's website. Also, the overall performance of each IMO is reviewed on a continuous basis and INTERMAGNET offers technical assistance to observatories experiencing difficulties. Another service provided by INTERMAGNET is distributing preliminary data in near-real time on a single website. Data from each IMO are first transmitted to a Geomagnetic Information Node (GIN), either via the Internet or via satellites, then to the central website. There are currently six such nodes, two in Europe (Edinburgh and Paris), two in North America (Golden and Ottawa) and two in Japan (Hiraiso and Kyoto).

Although the number of IMOs has been regularly increasing since the early 1990s, their geographical distribution is still far from optimum (Fig. 7). There are vast areas without any

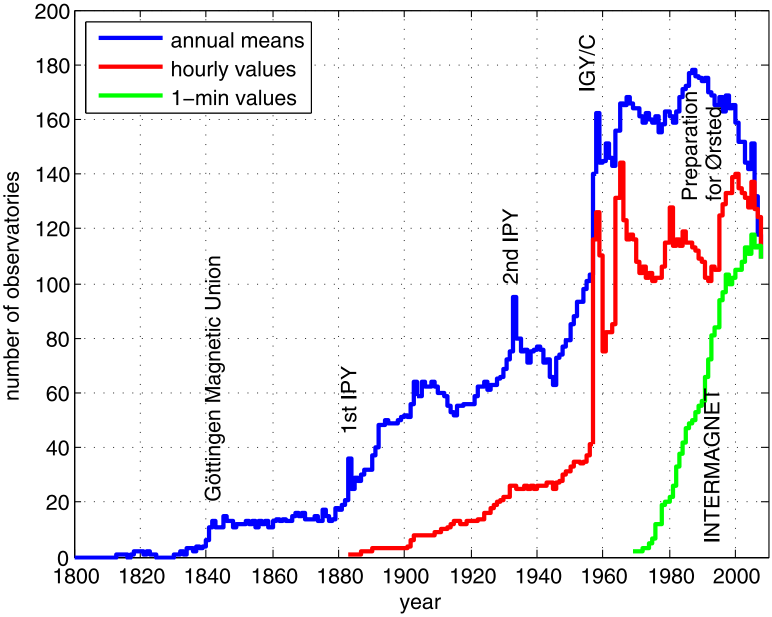

Fig. 6 The availability of certain geomagnetic observatory data types from 1800 to 2008. Important events were the foundation of the Göttingen Magnetic Union, the International Polar Years (IPY), the International Geophysical Year/International Geophysical Cooperation (IGY/C), the establishment of INTERMAGNET and the preparation for the Ørsted satellite. The small drop in data availability towards 2008 is in part due to the characteristic delay of definitive geomagnetic observatory data

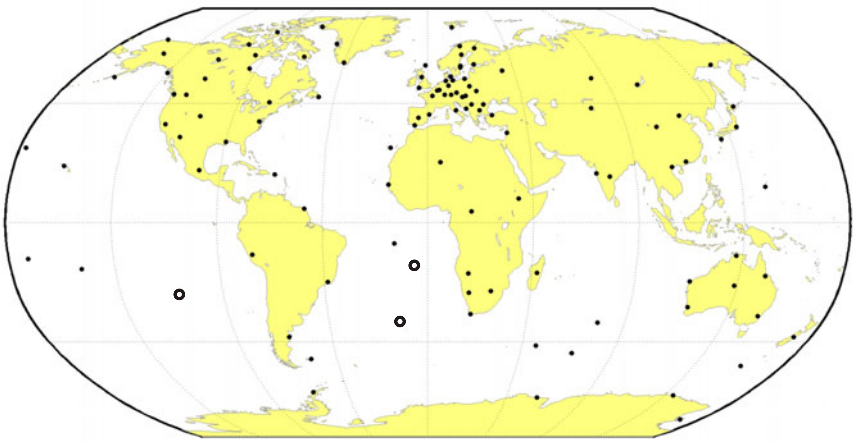

Fig. 7 Geographical distribution of INTERMAGNET magnetic observatories (IMOs) as of January 2010 (dots). The circles represent the recently established geomagnetic observatories in remote regions presented in 4.1 (not yet member of INTERMAGNET)

observatory in the Atlantic, Pacific and Indian Oceans, but also in the Middle East, Central Asia, Siberia, Africa and Antarctica. In order to fill out these gaps, some national institutions participating in INTERMAGNET have been providing assistance with the upgrade of existing facilities in other countries. These efforts enabled several old observatories, some of them operating since the end of the 19th century, to join the network. In addition, some institutions have been installing new observatories in remote locations, such as oceanic islands and Antarctica. Examples of such efforts are described in Sect. 4.1.

Recently, INTERMAGNET has embarked on the definition and distribution of two new data products: 1 Hz data (or 1-second data) and quasi-definitive data. The need for 1 Hz data emerged in the early 2000s from both the space physics community and the satellite geomagnetism community. Space physicists need 1 Hz data to study rapid external variations such as ULF waves, sudden impulses or storm sudden commencements (see, e.g., McPherron 2009). Several variometer networks currently produce 1 Hz data and the INTERMAGNET network would represent a very valuable addition to these networks. It is expected that 1 Hz data will also be useful for the purpose of modelling ionospheric and magnetospheric magnetic fields from a combination of ground and low-Earth orbiting satellite data. Requirements in terms of data resolution, time accuracy, frequency response and magnetometer noise spectrum were provided by a user survey (Love 2005). They will be published in the next version of INTERMAGNET's Technical Reference Manual (St-Louis 2008).

In order to be able to produce 1 Hz data satisfying users requirements, observatories have to make several modifications to their data acquisition systems as well as vector magnetometers. Perhaps most importantly, the time lag introduced by the whole measurement chain (including the analog part of the magnetometer) has to be carefully measured and corrected (Rasson 2009). This issue, often overlooked when producing 1-minute data, becomes critical for some applications such as travel-time magnetoseismology (Chi and Russell 2005; Chi et al. 2009). Another issue is the magnetometer's intrinsic noise, which for usual fluxgate magnetometers is larger than the typical ground geomagnetic signal around 1 Hz (Korepanov et al. 2007). This problem can be circumvented by choosing a cut-off frequency slightly below the Nyquist frequency of 0.5 Hz (Shanahan and Turbitt 2009), while other instruments such as search coils can be used to explore the geomagnetic signal at higher frequencies. Magnetometer manufacturers have started to address the new requirements and several observatory programs are currently deploying 1 Hz systems (Chulliat et al. 2009a; Worthington et al. 2009).

INTERMAGNET is currently working on another new data product, the so-called 'quasi-definitive' data, defined as data corrected using temporary baselines shortly after their acquisition and very near to being the final data of the observatory. Several individual users and groups of users have recently expressed their interest and need for such data. Main uses include the production and validation of global geomagnetic models, such as the International Geomagnetic Reference Field (IGRF) model and the Level 2 products of the upcoming ESA Swarm satellite mission, and the production of geomagnetic indices. As of January 2010, two methods have been proposed to calculate quasi-definitive data (Chulliat et al. 2009b; Baillie et al. 2009) and about 15 IMOs routinely produce quasi-definitive data within less than a few days using either of the two methods. According to these experimental implementations, the differences between quasi-definitive and definitive data can be made less than a few nT at most observatories, which should encourage more observatories to produce such data. Quasi-definitive data from nine IMOs were recently used to validate candidate IGRF secular variation models for the time interval 2010–2015, providing a useful independent data set for such tests (Chulliat and Thébault 2010).

4 Extending Ground Observations

4.1 Oceanic Islands

There are major gaps in the ground station network, especially in oceanic areas and on the southern hemisphere. Oceanic islands, though sometimes logistically difficult, can be used to improve the spatial coverage in these regions. The preparations for the Swarm mission (Friis-Christensen et al. 2006), to be launched in 2012, have initiated a number of geomagnetic observatory projects and here we briefly report about three of them under way in the southern hemisphere oceans: Easter Island in the Pacific Ocean, St. Helena in the South Atlantic Ocean and Tristan da Cunha some 20° south of St. Helena, each closing a significant gap in the global network (see Fig. 7).

Easter Island is an extremely isolated island in the southeastern Pacific Ocean, about 3500 km west of continental Chile. Yet it is inhabited by about 4000 people and is a popular touristic destination, making it easily accessible by commercial airlines. A first magnetic observatory (IAGA code EIC) was installed in Easter Island in the early 1960s, producing about one year of data (now available at the World Data Centres). Recently, a new observatory (Fig. 8, Isla de Pascua Mataveri, IAGA code IPM) was installed by Institut de Physique du Globe de Paris (France) and Dirección Meteorológica de Chile on the premises of the island airport (geographic lat. 27.17° S, long. 109.41° W, alt. 82 m; geomagnetic lat. 18.18° S, long. 36.11° W). The recordings of variation data started in August 2008 and full operations started in May 2009. The layout and instrumentation of the observatory are described by Chulliat et al. (2009c). The absolute hut and variometer hut are located near the southern end of the airport runway. Acquired data are transmitted via a radio link to the meteorological station office building located near the airport terminal, where they are forwarded to the Paris GIN via the Internet. Absolute measurements are made by the meteorological station staff on a weekly basis using standard equipment. The observatory is equipped with a magnetometer and a data acquisition system allowing the production of 1 Hz data with a cut-off frequency of 0.3 Hz and a timing accuracy of 10 ms (see Sect. 3 of the present paper and Chulliat et al. 2009a). The local magnetic gradient on the island is rather large (about 20 nT/m where the observatory was installed) due to volcanic rocks and the pillar difference is monitored by two scalar magnetometers. The Easter Island observatory is very isolated: the closest INTERMAGNET magnetic observatories are Huancayo in Peru (IAGA code HUA), located 3927 km northeast of Easter Island, and Pamataï in French Polynesia (IAGA code PPT), located 4249 km west of Easter Island. For this reason, data from the new observatory will be particularly useful for global geomagnetic modelling, both of the internal and external magnetic fields, as part of the model datasets or of independent datasets used for validation purposes. They will also help characterising the spatio-temporal distribution of rapid variations of external origin such as magnetic pulsations.

During the last years, the Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum has made a significant effort to establish remote observatories (see Korte et al. 2009a for details). One of them is situated on the island of *St. Helena* and has been a particular challenge, even if logistical support was obtained from the IDA seismological network of the University of California at San Diego (UCSD), which has one of its stations on St. Helena. Access to the island is only possible by a ship connecting Ascension island, St. Helena, Cape Town and Walvis Bay on a fixed, but somewhat irregular schedule. Also, such an installation is very costly, both in time and funding. The complete observatory installation was achieved during one 16-day visit, in 2007. St. Helena geomagnetic observatory (Fig. 8, geographic coordinates lat. 15.95° S, long. 5.73° W, alt. 586 m; geomagnetic lat.

Fig. 8 Geomagnetic observatories on remote islands: *Top*: Easter Island with absolute hut in the front and variometer hut in the back (by courtesy of IPGP); *Centre*: St. Helena where the variometer and electronics are buried (by courtesy of GFZ); *Bottom*: Tristan da Cunha, with absolute hut and pyramid-shaped variometer box (by courtesy of DTU Space)

11.59° S, long: 63.77° E) is located at the end of a cul-de-sac and has electricity and telephone connection, yet is far away from human and technical disturbances. However, the strongly magnetic volcanic rocks of the island cause very steep gradients of the order of 5 nT/m within the observatory premises, and a difference of 250 nT between absolute and variation pillar, which could not be avoided. In three containers the recording equipment is installed, consisting of a suspended FGE variometer, a GSM90, a GPS receiver and a MAGDALOG data logger developed at Niemegk observatory. The instruments are separated to avoid electrical interference. The containers with ground dimensions of 1.2 by 1.6 m and a height of 1 m are buried in the ground some 5 m apart. One contains the vector magnetometer sensor on a concrete pillar, one the Overhauser magnetometer electronics unit and the third one the vector magnetometer electronics including the data logger. The GSM90 sensor is mounted on a plastic pipe about 1.5 m above the ground. Cable trenches with pipe casing connect the instruments in the containers to a computer in the seismological station building 70 m away. A stable pillar for absolute measurements was constructed, with a roof and some canvas weather protection in one corner of the observatory premises. The absolute measurements are done with a DI-flux (Zeiss Theo 010B theodolite with Bartington fluxgate sensor) and a GSM19 to monitor the significant pillar difference on a regular basis. An azimuth mark made of concrete with a painted aluminium tip on top is installed on the hillside across a valley, about 470 m away. The absolute observations are carried out by a person living near-by, who is also contracted by UCSD to take care of the seismological station. The observer has been trained during the installation visit of the GFZ staff and also during his visit to Niemegk observatory. The recordings are transmitted regularly via Internet and the absolute measurements are sent by e-mail to Niemegk observatory, where data processing and distribution are carried out. The observatory is operational since November 2007.

Tristan da Cunha (Fig. 8, geographic lat. 37.07° S, long. 12.32° W, alt. 42 m; geomagnetic lat. 31.40° S, long. 53.62° E) is located within the South Atlantic Anomaly, the main field anomaly that is responsible for a large part of the global geomagnetic field weakening. The island is almost central in the South Atlantic Ocean, the next neighbouring observatories are Hermanus in South Africa (2850 km distance), Vassouras in South America (3400 km) and St. Helena (2450 km). Transport to the island is a challenge, there are only a few ships every year and landing on the island depends on weather conditions. Its geomagnetic latitude is similar to those of the observatories used for determining the equatorial ring current index D_{st} (Sugiura and Kamei 1991), making it an ideal location for identifying the ionospheric and the magnetospheric field contributions in geomagnetic observatory data. The geomagnetic observatory on Tristan da Cunha (preliminary code TDC) was established in October 2009 as part of a project to investigate the anomaly, the southern Sq-current system in the anomaly, the ring current strength in the Atlantic Sector, and induction processes in the region. Highly magnetic rocks give rise to a spatially very variable local bias field and efforts were made to carefully determine pillar differences. Since rock magnetisation varies with temperature, it was feared that the local bias field could change during the day or with the seasons, possibly degrading information on external field variations in the observatory recordings. Therefore, a soil and sediment covered flat area was chosen for the observatory and the magnetic field sensors were set up as high above the ground as possible. The lack of topography minimises uncompensated magnetic poles and volcanic sediments are expected to have smaller mean magnetisation than the volcanic source rock. Another problem is that the local bias field may change due to the transport of magnetic material (e.g. by volcanic, erosive, fluvial, or alluvial processes), or when the material's magnetisation pattern is changed, e.g. by a lightning strike. This will affect the long-term record of secular variation. Such problems can be identified by determining changes in observatory biases through careful comparison of ground station and satellite data (Mandea and Langlais 2002; Macmillan and Thomson 2003). The absolute hut is equipped with a DI-flux, a GSM-90 Overhauser magnetometer, and the loggers and other electronic equipment in 5 to 6 m distance from the sensors. There is a small, but measurable influence from the electronics on the absolute measurements (about 1 nT), which was accepted considering the unavoidable, strong influence from rock magnetisation. A separate variometer hut contains a temperature controlled Danish FGE variometer (Fig. 4). The pillar difference between the DI-flux and the scalar magnetometer was measured for H and Z and is smaller than anticipated, resulting in a difference of 8 nT for F. The pillar difference for the DI-flux and the variometer it is about 315 nT in H, 17 minutes of arc in D and 60 nT in Z. The buildings are small to preserve valuable grazing on the island. Two local operators were trained and perform the absolute measurements. The project is funded by the Danish Agency for Science, Technology and Innovation and run by DTU Space (The National Space Institute at the Technical University of Denmark). The Geomagnetism Program of the Unites States Geological Survey, the Tromsø Geophysical Observatory at the University of Tromsø, Norway, and the Hermanus

Magnetic Observatory in South Africa were involved and contributed to setting up the station, additional cooperation partners are at the Goddard Space Flight Centre (NASA) and the Institute of Geophysics at the ETH Zurich.

At the time of writing, several other initiatives are in planning or on the way to set up remote geomagnetic observatories. For example, the British Geological Survey is in the process of re-establishing a geomagnetic observatory on South Georgia (pers. comm Simon Flower).

4.2 Automatic Observatories

Automatic observatories that reach the standards for geomagnetic observatories, as demanded by INTERMAGNET (St-Louis 2008), would be a major breakthrough for geomagnetic measurements. True global coverage with an even distribution of geomagnetic observatories is only possible with automatic observatories. These could be set up in areas lacking infrastructure or the possibility of intervention from trained personnel, such as uninhabited remote areas or the ocean floor. Projects to develop a fully automated geomagnetic observatory have started decades ago, but the introduction of the DI-flux in the early 1980s simplified geomagnetic observatory operations and the interest for automatic systems temporarily decreased.

One of the pioneering concepts was the automatic standard magnetic observatory (ASMO) installed at the Fredericksburg geomagnetic observatory (IAGA code FRD) in the United States. It was built on the basis of a scalar absolute instrument (a rubidium vapour self-oscillating magnetometer) with two mutually perpendicular pairs of coils which controlled bias fields in a plane perpendicular to the mean magnetic field vector and allowed to determine the full geomagnetic vector (Alldredge 1960; Alldredge and Saldukas 1964). Similar systems were also developed at other geomagnetic observatories and were available commercially (e.g. from Elsec), but due to instrument drift and the resulting lack in absolute accuracy, they could never replace geomagnetic observatories. Several new efforts to design and realise automatic geomagnetic observatories have been started during the last decade. One of them is an automated DI-flux for making unattended measurements of the declination and inclination (van Loo and Rasson 2006; Rasson et al. 2009). Another approach is based on the method of rotating a three-axis fluxgate magnetometer about a defined axis, in order to determine the field component along that axis (Auster et al. 2007a). Another one is based on developing a new generation of ultra-high-resolution optically pumped ^{4}He magnetometers (Gravrand et al. 2001) or on optically pumped tandem magnetometers (Pulz et al. 2009). In the following paragraphs, we describe these development efforts as well as the special conditions for ocean bottom observations.

The AUTODIF instrument presented by Rasson et al. (2009) performs absolute measurements of the geomagnetic field direction (declination and inclination) without requiring a human operator. Combined with a scalar magnetometer, the full geomagnetic field vector can be determined. To produce 1-minute or 1 Hz data, this setup has to be combined with a conventional observatory variometer. The AUTODIF measures the direction to a reflecting azimuth mark with a laser/photocell-combination. The magnetic North direction and the inclination are determined in a similar fashion as the DI-flux procedures suggested by Kring Lauridsen (1985), with the axes of a theodolite being replaced by the axes of piezomotors. The challenge is to perform these tasks automatically with an aimed for accuracy of 6 seconds of arc, by using components that are non-magnetic (Van Loo and Rasson 2007) and to have an instrument that is easy to distribute and reliable in continuous operation (Rasson et al. 2009). The prototype in Fig. 9 was tested at the Dourbes geomagnetic observatory

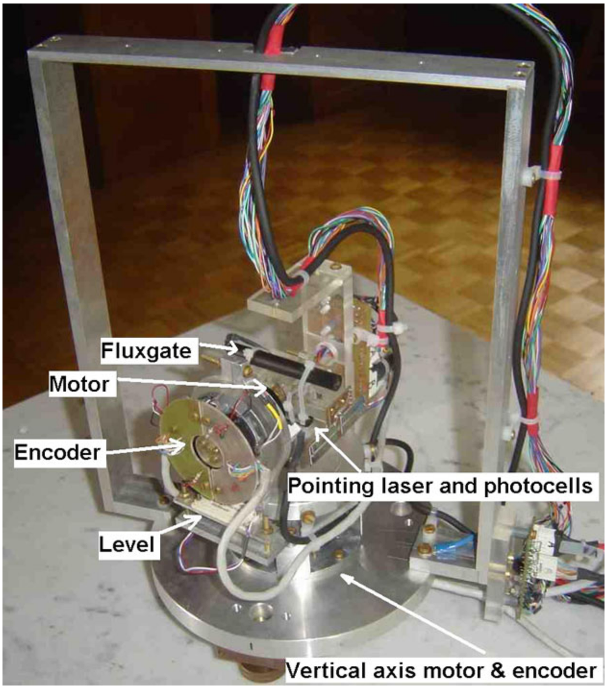

Fig. 9 Automatic Declination-Inclination Magnetometer AUTODIF at Dourbes geomagnetic observatory (by courtesy of J. Rasson)

(DOU) and at the instrument comparison of the XIIIth IAGA workshop at Boulder geomagnetic observatory (BOU) in 2008 and came close to the accuracy it was aimed for, see Rasson et al. (2009).

GAUSS, the Geomagnetic AUtomatic SyStem is based on the principle that the geomagnetic field along an axis can be measured absolutely by a 3-component fluxgate magnetometer that is rotating around this axis and by simultaneous absolute measurements of the scalar field F and a conventional variometer. The axis of rotation has to be stable and determined with great accuracy, other mechanical requirements are less stringent (Auster et al. 2007a, 2007b). From measurements in two horizontal directions, the horizontal field strength H can be determined. Knowing the geographic orientation of these two directions allows to determine D, and Z is calculated from H and F. The instrument was presented at the XIIth IAGA workshop 2006 in Belsk, Poland (Auster et al. 2007b). Several components were later exchanged with more reliable parts (e.g. more powerful piezomotors, ceramics parts to reduce friction at the motors, angular encoders) resulting in a largely new prototype (Hemshorn et al. 2009). The instrument (Fig. 10) consists of a central 'basket' that is mounted on a horizontal axis and contains the 3-component fluxgate. Rotation around the horizontal axis is measured with an accuracy of 1 minute of arc. The horizontal axis contains a laser source and is mounted on a table that can rotate around a vertical axis. The rotation around the vertical axis can be set by the piezomotors and encoders with an accuracy of 1 second of arc. The laser beam is detected with a remote photocell substituting the azimuth mark (Hemshorn et al. 2009). The prototype is located at the Niemegk geomagnetic observatory (IAGA code NGK) and an optically pumped potassium magnetometer is used as the accompanying scalar magnetometer. In order to substitute a geomagnetic observatory, it has to be combined with a variometer.

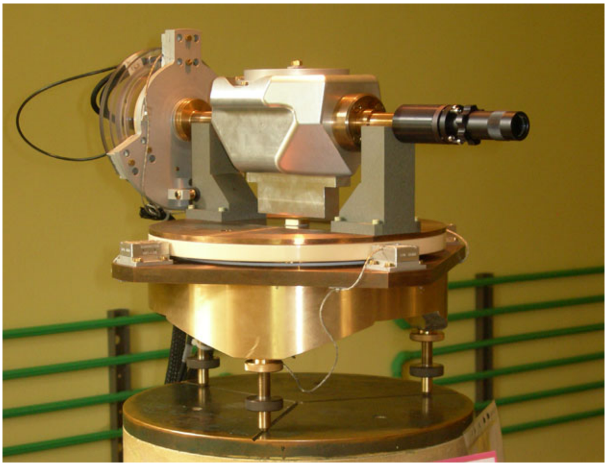

Fig. 10 GAUSS, the Geomagnetic AUtomatic SyStem, at Niemegk geomagnetic observatory (by courtesy of E. Pulz)

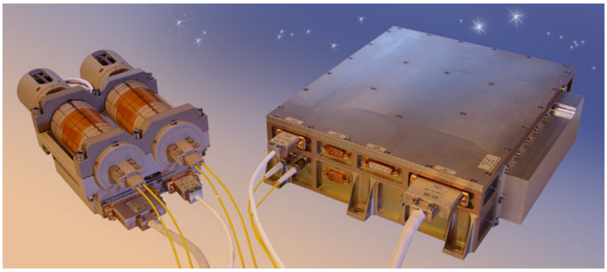

Fig. 11 ^{4}He magnetometer from LETI (by courtesy of J.-M. Leger)

An optically pumped ^{4}He magnetometer making vector measurements has recently been developed by CEA-LETI in Grenoble (Fig. 11). This instrument continuously delivers scalar and vector measurements at the same point: three low frequency AC magnetic fields are applied along mutually orthogonal directions to the helium cell (Gravrand et al. 2001; Leger et al. 2009). Under such conditions, the new instrument measures the scalar field corresponding to the superposition of the ambient Earth's magnetic field and these three artificial field modulations. This is made possible by the high resolution (1 $\mathrm{pT}/\sqrt{H}$) and high bandwidth (up to 400 Hz) of the scalar magnetometer. Simple deconvolution operation of the resulting scalar measurement provides a direct estimation of the magnetic field projections on the three modulation directions in addition to the scalar field measurement. In order to enhance the measuring range of the instrument and increase its accuracy, the local magnetic field is cancelled at the sensing head location thanks to a set of three mutually orthogonal coils driven by a feedback loop. Due to its way of operating and the very high mechanical stability of the ceramics on which the three modulation coils are mounted, this instrument provides vector measurements that are very stable in time. It is hoped that it can be used in the future to establish geomagnetic observatories where absolute measurements would be needed only once or twice a year. To this aim, its long-term stability is currently being tested at the Chambon la Forêt geomagnetic observatory (CLF) in collaboration with IPGP. This instrument will fly on the three satellites of the ESA Swarm mission (to be launched in 2012), where its vector mode will be used as a back-up for the fluxgate instruments of the mission. Another vector instrument is described by Pulz et al. (2009). It is a tandem magnetometer with a fast Cs sensor to track field changes with and without modulating fields, and a Cs-He sensor to calibrate the Cs signal when the modulating field is zero. Two mutually perpendicular coil systems with their axes in the horizontal plane gave promising results for Serson's method, where the modulating field is parallel or antiparallel to the vector component to be determined (see p. 122 in Wienert 1970). The final coil system for modulating fields of 5000 nT is planned to be suspended and can be rotated for accurate testing of the levelling. A laser beam is planned for azimuth mark detection. Four measurements with and one without bias field are performed every second, giving the full vector with 1 Hz. Optically pumped vector magnetometers were also flown on several planetary missions (see Balogh 2010), including the recent Cassini mission to Saturn (Dougherty et al. 2004).

Several attempts to observe the geomagnetic field vector at the ocean floor have been made. Toh et al. (2006) describe observational platforms with an Overhauser scalar magnetometer and a fluxgate vector magnetometer that were lowered on to the seafloor in the northwest Pacific in 2001 to 2003. These are submersible down to 6000 m, communicate through an acoustic modem and operate for about a year before they are recovered from the seafloor. Two tilt meters are directly monitoring tilting of the horizontal plane of the vector magnetometer. Tilting, determined with an accuracy of 5 seconds of arc, was strongest during the first 50 days and later continued with about 0.2 seconds of arc per day. A fibre optical gyro is mounted at some distance to the vector magnetometer. It monitors the platform's orientation with respect to geographic North with 10 seconds of arc accuracy, but only once every three months to save energy and avoid magnetic interference. The complete systems were calibrated at the Yatsugatake geomagnetic observatory (IAGA code YAT), Japan, prior to submersion. A special coil system was used to intermittently determine scale values for the fluxgate sensor during operation. Oceanic magnetic anomalies in the region cause a significant observatory bias, and platforms that are consecutively deployed in the same region are operating in parallel for some time to determine the difference in their bias.

To summarise: Very different but promising concepts are currently explored by continuous development and improvement of prototypes towards reliable automatic absolute instruments, which eventually will be built in a sufficient number for serious long-term testing at conventional geomagnetic observatories. If these prototypes prove stable enough on the long-term, in the near future some magnetic observatories could operate without the need of absolute measurements for extensive periods of time. Ocean bottom observatories still pose a significant technological challenge and ultimately need automatic absolute vector measurements in a geographic reference system.

4.3 Magnetic Repeat Stations

At magnetic repeat stations, the geomagnetic field vector is measured under comparable conditions every few years. Repeat stations are often organised as national networks and started as early as the 1830s, e.g. by Sabine in the UK, later many repeat station networks where established all over the world (see, e.g. Macmillan 2007). Motivated to get globally and evenly distributed data for modelling the main field and its secular variation, particular efforts were made by L.A. Bauer and colleagues from the Department of Terrestrial Magnetism at the Carnegie Institution of Washington in the first half of the 20th century (Good 2007b). Since 2003, particular efforts are made to coordinate the European repeat station networks (Korte and Mandea 2003). Although single networks can be sufficient for local mapping of the geomagnetic field vector, this coordination is of advantage for global and regional field modelling by introducing homogeneous standards, as well as even distribution and synchronised timing of repeat station measurements. Figure 12 shows the spatial distribution of the repeat station data available from the World Data Centre for Geomagnetism,

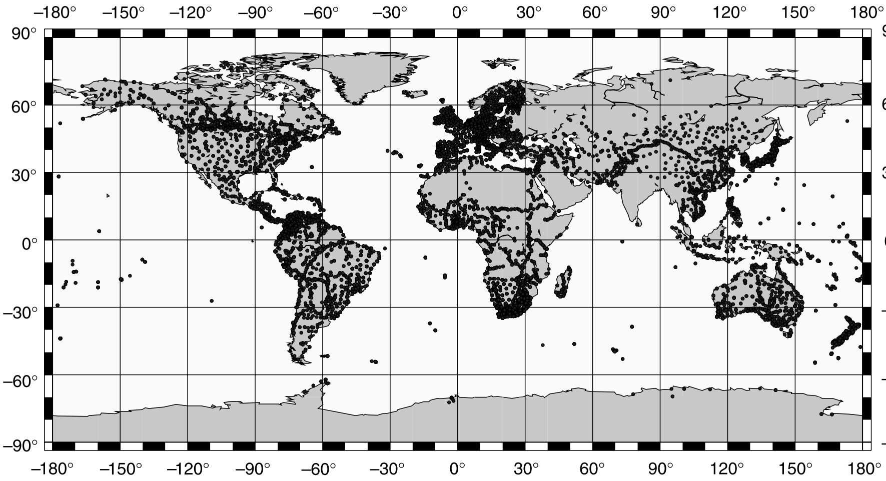

Fig. 12 Global distribution of magnetic repeat stations since 1900

Edinburgh, and the World Data Center for Solid Earth Geophysics, Boulder. Coverage is far from uniform because repeat station locations are often chosen on the basis of the local need for mapping and not for global coverage. Repeat stations should be occupied at least every 5 years and preferably more often, e.g. every 2 years (Vestine 1950; Newitt et al. 1996; Korte and Haak 2000).

The instruments used for repeat station measurements are the same as those used for geomagnetic observatories: a DI-flux and a scalar magnetometer (Newitt et al. 1996). When necessary, a gyroscopic theodolite or sun observations are used to determine geographic North, but usually the exact location of a repeat stations as well as an azimuth mark are documented and permanently marked in the field. A variometer that can be deployed in the field for a few days along with the absolute measurements is of advantage.

For continuous geomagnetic observatory data, the influence of external (ionospheric and magnetospheric) fields can be minimised by filtering, e.g. by making annual mean values, or data selection, e.g. with the help of indices that describe certain external field variations, or a combination of both methods (e.g. the annual means of the international quiet days). For repeat stations, the measurements cover a short time span, and the timing is often dictated by logistics rather than geomagnetic field conditions. Minimising the external field contributions in repeat station data is therefore a problem, and various strategies are being used. The chances for magnetically quiet periods are higher for certain months of the year, and the recurrence of geomagnetic activity with the 27 days solar rotation allows planning some weeks ahead. Ionospheric contributions are significantly decreased in the night, and a first step would be to determine the quiet night time level of the geomagnetic field at a repeat station. This can be done by absolute measurements in the night (or at least early in the morning and late in the evening). Alternatively, the geomagnetic variation from a nearby geomagnetic observatory or an on-site variometer operated as part of the repeat station measurements can be used to determine the quiet night time level. Absolute measurements can then be conducted during the day, and the comparison of variometer data and the absolute measurements is a valuable check of data quality. Ideally, the variometer data at the repeat station is compared with the closest geomagnetic observatory data to identify and correct for short period external field contributions (Korte et al. 2007). An attempt to reduce repeat station measurements to quiet night time levels by means of the CM4-modelled ionospheric and magnetospheric contribution has been described for the special case where no nearby variometer data is available (Matzka et al. 2009).

Finally, to be better comparable to geomagnetic observatory data, the equivalent to an annual mean value should be constructed for the repeat station. This is done by first comparing the geomagnetic observatory data from the time of the repeat station measurements with its annual mean, and then taking into account the expected difference in secular variation between the geomagnetic observatory and the repeat station (Newitt et al. 1996).

Repeat station data are used to calculate regional models of the magnetic field, using modelling techniques such as Spherical Cap Harmonic Analysis (SCHA) (Haines 1985; Korte and Haak 2000; Kotzé et al. 2007) or the Revised Spherical Cap Harmonic Analysis R-SCH (Thébault et al. 2004) used by Thébault et al. (2006) and Korte and Thébault (2007). Together with geomagnetic observatory and satellite data, repeat station data are sometimes used in global main field models, such as C^3FM which covers the years 1980 to 2000 (Wardinski and Holme 2006). The repeat station data are also used for investigating rapid secular variation fluctuations, as has been done over the southern African continent (Mandea et al. 2007). It can be summarised that repeat stations do increase the spatial coverage of ground vector data, but at a low temporal resolution and with the risk of being potentially biased by external field contributions.

5 Spaceborne Geomagnetic Observations

5.1 General Description

Since 1964, starting with NASA's OGO series of satellites, the Earth's magnetic field intensity has been measured intermittently by satellites at altitudes varying from about 350 km to 850 km. The main advantages to measure the magnetic field by satellites carrying magnetometers are the relatively constant altitude of these measurements, the possibility to get a globally homogeneous data distribution, and to obtain data with the same instrument characteristics.

The first satellite mission that provided vector data for geomagnetic field modelling was NASA's MAGSAT satellite (Langel et al. 1980), which operated over some six months in 1979 and 1980. The following 20 years lacked of high-quality spatial magnetic field missions, but the Danish Ørsted satellite, launched in 1999, soon followed by the German CHAMP mission (July 2000), and the less successful Argentinian SAC-C mission (November 2000), improved the situation. CHAMP satellite re-entered the Earth's atmosphere on September 19, 2010, after more than a decade of good and faithful service. This series of missions provides continuous monitoring of the geomagnetic field from space, which, it is hoped, will span more than the 10 years recommended by IUGG's International Decade of Geopotential Research. This could be achieved if ESA's multi-satellite mission Swarm is successfully launched on time (planned for 2012).

The Danish Ørsted magnetic satellite launched in 1999 is still operational (however, only intensity data are provided at time of writing). The satellite carries as its primary scientific payload a triaxial fluxgate magnetometer of a design called Compact-Spherical-Coil (CSC) and a star camera for measurements of the geomagnetic field (Neubert et al. 2001; Olsen 2007). Its position is acquired using Global Positioning System (GPS) receivers. The orbit is inclined 98° to the Earth's equator, resulting in a precession of the orbital plane relative to the direction to the Sun. This precession allows the mapping of almost the entire globe as Earth rotates. The initial local time of Ørsted was 02:26 on February 23, 1999. Its orbit

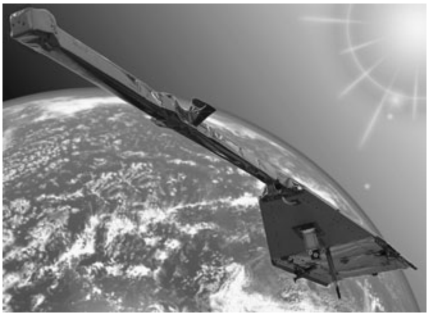

Fig. 13 The CHAMP satellite with a multitude of instruments, including two CSC fluxgate vector magnetometers, star cameras and a scalar magnetometer (by courtesy of GFZ)

plane drifts slowly and the local time of the equator crossing decreases by 0.91 min/day. The spacecraft main body carries the electronics while an 8-meter boom hosts the magnetic field instruments.

CHAMP (Challenging Minisatellite Payload, see Fig. 13) was launched in July 2000 (Reigber et al. 2002; Maus 2007). The CHAMP satellite was launched into an almost circular, near polar ($i = 87°$) orbit with an initial altitude of 454 km. After nearly 10 years in orbit the altitudes decreased to some 290 km in May 2010. With its highly precise, multifunctional and complementary payload elements (magnetometer, accelerometer, star sensor, GPS receiver, laser retroreflector, ion-drift meter) and its orbital characteristics (near polar, low altitude, long duration), CHAMP currently provides high-precision gravity and magnetic field measurements. The spacecraft has a length of 8.33 m (including the boom). Two CSC fluxgate sensors, which are separated by 60 cm, are mounted together with the star cameras on the same optical bench providing a mechanical stability between these systems of better than 20 seconds of arc. The optical bench is located about 2 meters away from the spacecraft main body, while the Overhauser magnetometer is at the end of the 4-meter boom (Fig. 13). This configuration results from a compromise between avoidance of magnetic interference from the spacecraft and cross-talk between the vector and scalar magnetometers.

SAC-C (Satélite Argentino de Observación de la Tierra) was launched in the same year as CHAMP, and is a joint Argentinian-US mission that hosts a Danish-US magnetometry package. SAC-C has a circular orbit in an altitude of 702 km and an inclination of 98.2°. It is Sun-synchronous and crosses the equator at local times of 10:24 and 22:24. The same package as for Ørsted is mounted on the SAC-C spacecraft, but the star camera has given no information during the course of the mission, possibly because of a cabling problem on the boom, and the vector data cannot be used. Magnetic-field measurements from SAC-C are restricted to the 1 Hz values from the scalar Helium magnetometer.

Swarm is an ESA satellite mission to be launched in 2012. It comprises three identical satellites on different polar orbits between 300 and 530 km altitude. Each of the three satellites is equipped with a fluxgate vector magnetometer, star camera, and the optically pumped ^{4}He magnetometer mentioned in Sect. 4.2. For details see Olsen et al. (2010b) in this issue, Friis-Christensen et al. (2006) and Friis-Christensen et al. (2009).

5.2 Instrumentation and Data Processing

As shown before, the magnetometry package of a satellite comprises a 3-component fluxgate sensor and star cameras mounted on a common optical bench, as well as a scalar magnetometer to measure the field intensity absolutely. Here we describe, as an example, the instrumentation and data processing of the CHAMP satellite.

An important issue in a multi-year mission is the verification of instrument performance at regular intervals. For the CHAMP vector magnetometers an in-flight calibration is performed every five days. In this procedure the readings of the scalar Overhauser magnetometer are used as a reference. By comparing field magnitude values with the measurements of the fluxgate magnetometer, the nine principle parameters of the vector instrument (three scale factors, three offset values, three angles between axes) can be determined in a non-linear inversion (Olsen et al. 2003). For the routine processing, the above nine fluxgate parameters are updated every 15 days. This allows for a certain amount of smoothing of the individual results, but does not produce large jumps in data at the interface of the intervals. This scalar calibration has proven its usefulness, but the uncertainty with which the nine parameters can be determined differs quite considerably. Small but systematic disturbances can alter some of the parameters significantly. This unpleasant effect still has to be investigated.

A very demanding task in the evaluation of spaceborne magnetic field measurements is the determination of the precise attitude related to each field vector data triple. To make full use of the fluxgate resolution an attitude precision of 1 second of arc is required, which is achieved with star trackers used on CHAMP. It is known that the angular resolution of star cameras is worst for the rotation about the bore sight. In order to eliminate this problem a dual-head star tracker system was installed on CHAMP. Readings of the two systems are appropriately combined, circumventing problems with anisotropy in attitude noise. This dual-head approach ensures that none of the CHAMP magnetic field components is biased by attitude noise. When analysing the available CHAMP magnetic field vector data, transformed into the geographic North-East-Centre (NEC) frame, some jumps appear. These have been traced back to problems linked to the attitude determination. Such jumps badly disturb the magnetic field modelling, in particularly, for the secular variation. A dedicated investigation of this effect is required to find how to correct these jumps; details are provided in Mandea et al. (2010b).

Data are available at different processing levels, as defined in the 'CHAMP project'. Level 0 are raw data as received by the telemetry. These are densely packed or even compressed in order to allow for an efficient transmission. Level 1 products are decoded and formatted but uncalibrated data, convenient to read by standard codes. They contain the full information of measurements performed in space. Level 2 products are properly scaled and calibrated data in physical units. Each of these products can be related to a certain instrument. It has to be noted that the definition of the processing levels in the 'CHAMP project' (Reigber et al. 2003) is somewhat different form the convention for ESA missions. Some details of the processing steps which are applied for generating the magnetic field Level 2 products are given in Mandea et al. (2010b). The description is ordered by instruments, starting with the raw data and presents the major steps to achieve the Level 2 products.

6 Historic Observations

Going back to the time before Gauss, the importance of Earth's magnetic field as a navigational tool, together with the intrigue it generated amongst prominent early scientists, result in large numbers of well documented direct field observations spanning the past four centuries. This period is commonly referred to as the 'historical era' in the geomagnetic literature. Detailed observations collected during this time allow workers to reconstruct the evolution of Earth's magnetic field on centennial time-scales (Bloxham et al. 1989; Jackson et al. 2000). Here only a brief summary of the most important historical sources are given; for further details readers should consult the review article of Jonkers et al. (2003) where a comprehensive database comprising 151,560 declination, 19,525 inclinations and 16,219 intensity observations made between 1510 and 1930 is described. Interesting accounts of the history of geomagnetism are given by Schröder (2000), Stern (2002) and Courtillot and Le Mouël (2007).

6.1 Sources of Historical Geomagnetic Observations

Historical observations of the geomagnetic field are dominated by directional measurements. By the second half of the 16th century compasses were widely employed to measure declination. Inclination, which required measuring the dip of the magnetic vector below the horizontal plane, was determined on a number of vessels in the late 16th and early 17th centuries. However since it never attained a place in standard navigational practise, inclination measurements are much more scarce consisting primarily of measurements by explorers, natural philosophers and some naval surveys. Useful relative intensity measurements were made only after 1790 while absolute intensity measurements were first carried out by Gauss in 1832.

The majority of the useful historical geomagnetic observations were made by mariners involved in merchant and naval shipping during their travels across the globe. Records from more than 2000 voyages have recently been collated (Jonkers et al. 2003). There are only a small number of observations available prior to AD 1590. Between AD 1590 and AD 1700 many more observations exist, thanks particularly to records made by mariners working for the Dutch and English East Indian companies. From AD 1700 to AD 1800 the number of observations again increased due to a dramatic expansion of naval traffic especially along Atlantic and Arctic trade routes. The 18th century declination observations from the database of Jonkers et al. (2003) are plotted geographically in Fig. 14. There are so many observations in the Atlantic and Indian oceans during this time that individual observations cannot be distinguished in the plot. Between 1800 and 1930, in addition to observations made on the oceans by mariners, extensive land surveys were also carried out in continental interiors.

The historical observations in the database of Jonkers et al. (2003) consist of both previously published observations and unpublished observations gleaned primarily from archived

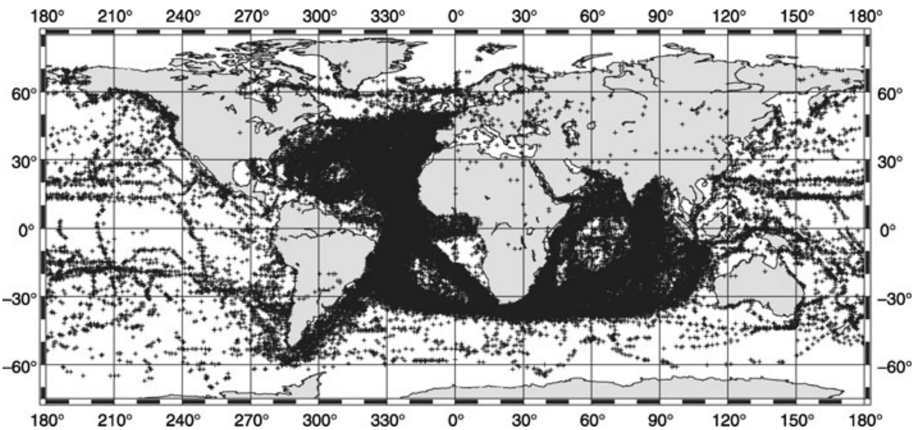

Fig. 14 Geographical data distribution of declination observations made from 1700–1799. In the database of Jonkers et al. (2003) are 68,076 points, some points may overlap; cylindrical equidistant projection

log books. The published sources (see Jonkers et al. 2003 for detailed references) include accounts of famous voyages and exploration for example in the early accounts by Hakluyt, Purchas, Churchill and Churchill, and Ramusio. There are also important records of magnetic observations in the periodicals of learned societies, especially in the Philosophical Transactions of the Royal Society of London and the Mémoires de l'Académie des Sciences de Paris, and periodicals associated with marine affairs including the Nautical Almanac in England and Connaissance des Temps and Annales Hydrographiques in France. Of paramount importance are past compilations of magnetic observations which were collected for various scientific and commercial reasons. These include works by Halley, Mountaine and Dodson, Hansteen, Becquerel, Sabine and van Bemmelen and Veinberg (again see Jonkers et al. 2003 for references).

It is difficult to concisely survey all the unpublished sources. These are predominantly navigational log books kept to systematically and chronologically record position, direction of travel, weather, ocean currents, landmarks, important events and also magnetic declination. The procedure eventually evolved into a formal record system whereby pre-printed sheets were submitted for official inspection on reaching the home port. Organisations that required systematic logbooks to be kept included the Dutch and English East Indian Companies, the Danish East and West Indian companies, the Royal Navy, the French Navy and Compagnie des Indes and the Hudson Bay company. Such unpublished records are now largely housed in major repositories, for example in England in the National Maritime Museum in Greenwich, the Public Record Office in Kew, and in the British library; in France in the Bibliothèque Nationale and the Archives Nationales, in the Netherlands in the Algemeen Rijksarchief in the Hague, and in Denmark in the Rigsarkivet in Copenhagen. Extensive efforts to locate useful observations from Spanish sources (including the enigmatic Manila Galleons) have sadly proved mostly fruitless.

Another important source consists of long time series of observations from specific locations (usually major cities) where permanent instruments were set up, for example at astronomical observatories. The most important records of this type are from London (Malin and Bullard 1981), Rome (Cafarella et al. 1992), Edinburgh (Barraclough 1995), Paris (Alexandrescu et al. 1996) and Munich, the latter being a compilation that includes time series from several permanently installed instruments (Korte et al. 2009b). Such series can be compared with the predictions of the *gufm1* model of Jackson et al. (2000). Other long and interesting local records include those made by Celsius and Hiörter in Sweden and those made in Sumatra in the eighteenth century by J. MacDonald. It is worth emphasising here that Earth is unique amongst the planets in there being long time series of direct magnetic observations.

The easiest manner for contemporary workers to access historical magnetic observations is undoubtedly to use the comprehensive compilation of Jonkers et al. (2003). It is available to interested parties from the World Data Centre for Geomagnetism, Edinburgh. This database consists of a fixed-format ASCII table of the data, an ASCII listing of prime meridians and a FORTRAN data extraction code. It is believed that the Jonkers et al. (2003) database now contains the vast majority of the available primary observations originating from north-western European countries.

Although it remains possible that major new archives of historical records could be unearthed, for example the records from the Manila Galleons or detailed and accurate records by Chinese mariners, the whereabouts of any such records are presently unknown. It seems more likely that future advances in the historical geomagnetic record will be rather minor, for example in newly discovered records made by explorers crossing continental interiors (Vaquero and Trigo 2006) or possibly by magnetic North directions indicated on old maps or sundials (e.g. Mandea and Korte 2007). Another possibility is that accurate indirect magnetic field measurements, for example obtained from archeomagnetic investigations (Korte et al. 2005), could be used to supplement the historical observations especially during the 16th and 17th centuries when direct observations are scarce.

6.2 Spatial and Temporal Variations in Historical Data Coverage

The heterogeneous origin of historical observations dictates that there are significant variations in the number of observations as a function of time. In Fig. 15 the number of historical data per 5 years is plotted together with a selection of modern data (from observatories, land and marine surveys and satellites during the twentieth century) used by Jackson et al. (2000) to construct the *gufm1* field model. Note that there are rather few data available prior to AD 1650. The situation gradually improved during the 18th century though there still usually are less than 5000 observations per 5 years. In the mid-19th century there is a clear increase in the number of available data, thanks in part to the magnetic endeavours of Gauss and Sabine. Clearly the number of observations available in the 20th century dwarfs the number of direct observations available at earlier times. Note that it is not just the number of available data but also the type of measurement (from declination and inclination to three component vector measurements) that changes with time.

As well as variations in availability of historical data as a function of time there are also major variations in the density of measurements with geographical location. A bias towards commercially and militarily important shipping routes is obvious, with trans-Atlantic paths very well covered. In contrast Pacific and Polar regions are sparsely covered. There are few observations in continental interiors, especially outside Europe, with Africa and South America particularly badly represented. In addition, the vast majority of the maritime observations are of declination with inclination and intensity measurements much rarer due to the greater difficulties involved in their measurement.

Variations in spatial coverage may seem to pose a major problem to modelling the time changes in Earth's field. Fortunately the nature of a potential field with its origin in Earth's core comes to the rescue. When modelling Earth's core-generated magnetic field it turns out that observations at Earth's surface are a weighted spatial average of the geomagnetic field at the core surface. The spatial averaging functions are different for each type of historical observation (declination, inclination or intensity) and come from the derivatives of the Greens function of the Laplacian of the magnetic potential (Gubbins and Roberts 1983; Bloxham et al. 1989; Johnson and Constable 1997). For example, the averaging function

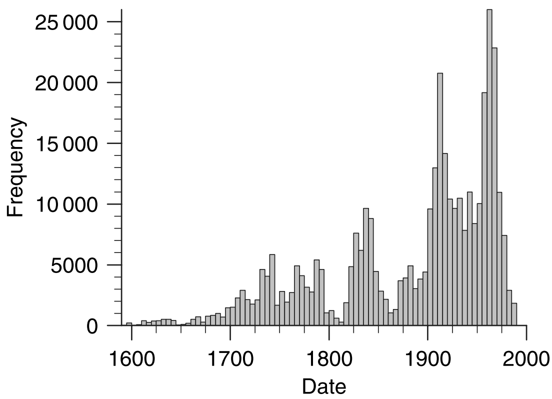

Fig. 15 The overall number of historical data (as described by Jonkers et al. 2003), together with observatory annual means, twentieth century survey data and repeat station data and satellite data used in the construction of *gufm1* (Jackson et al. 2000). *Each column* represents the number of data within a 5-year interval. Note that this depicts a subset of data available, as some data selection has taken place, based on criteria designed to avoid the effect of the correlation in errors due to the crust

for declination has two peaks offset from the observation position by about 23° and both inclination and declination have significant sensitivity to the core surface field within an angular distance of 50°. Since it is the core surface field we wish to estimate, this means it is possible to tolerate even rather large gaps in spatial coverage and still obtain good models of the core-generated field. In spite of this, the historical observations certainly do not provide a spatially or temporally uniform data constraint, especially with the changes in data type. Such issues must be borne in mind when carrying out historical field modelling; accurate error estimates and noise models together with both spatial and temporal model regularisation are required to produce stable models. For details, see Gillet et al. (2010) in this issue.

6.3 Errors in Historical Geomagnetic Observations

In order to extract the maximum amount of information from historical observations an understanding of their inherent errors is of great importance. Jackson et al. (2000) studied this issue in depth, developing error budgets accounting for observational errors, errors due to the influence of unknown crustal magnetic fields, and errors in positions due to positional uncertainty. Jackson et al. (2000) also show that historical declination measurements were surprisingly accurate, with a typical error of only 0.5°; the total error budget for such data is consequently dominated by the unknown crustal field in a manner similar to modern survey measurements. This surprising accuracy of the historical measurements, together with their worldwide extent, are the crucial factors allowing detailed reconstruction of the evolution of Earth's magnetic field over the past 400 years. To probe Earth's magnetic field further back in time indirect magnetic observations recorded in archaeological artifacts, volcanic lavas and lake sediments must be utilised (see Donadini et al. 2010 in this issue).

7 Conclusions

To be useful for main field modelling, geomagnetic field observations have to fulfil a number of requirements: they have to be vectorial, undisturbed, highly accurate, globally distributed as well as continuous and homogeneous over long time scales. The long time scales are necessary because of the slow nature of secular variation, and to be able to identify and remove ionospheric and magnetospheric contributions. Continuous observations are made by variometers, which measure the changes of individual geomagnetic field components. At a ground station, the variometer is calibrated by means of absolute measurements; on satellites this process is called in-flight-calibration.

The global network of geomagnetic observatories, its development, organisation and instrumentation were discussed. The strength of geomagnetic observatories is the long time scales they operate on and the fact that they operate in a source-free region; disadvantages are their close proximity to crustal field sources and their irregular global coverage. We also described the geomagnetic satellite missions that have provided a global coverage with geomagnetic observations, first intermittently with scalar data, and since 10 years continuously with vector data. Satellites give full global coverage, but their data have the ambiguity of temporal and spatial variations, and they fly through ionospheric currents. It is the complementarity of ground and satellite observations that makes each set of observations more valuable in combination with the other, and allows for the final aim of separating the magnetic field contributions from the various sources.

We discussed three strategies to improve global coverage with ground observations: setting up geomagnetic observatories on oceanic islands, developing automatic geomagnetic observatories (a prerequisite for installing such observatories on the ocean floor) and magnetic repeat stations. There is currently a clear interest in setting up geomagnetic observatories on islands in the Southern Hemisphere, very much motivated by the upcoming Swarm multi-satellite mission because of the aforementioned complementarity.

Finally, we discussed historic data, which are of much lower accuracy and often only consist of a declination measurement. But since they cover several hundreds of years, and as routine part of marine navigation cover significant areas of the Earth, they allow to follow the changes in the main field, which have considerable amplitude over such time scales, with a sufficient signal-to-noise ratio.

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