

Instruments and Methodologies for Measurement of the Earth's Magnetic Field

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Abstract

In modern magnetic observatories the most widely used instrument for recording magnetic field variations is the triaxial fluxgate magnetometer. For absolute observations, the declination-inclination magnetometer, in conjunction with a proton precession or an Overhauser magnetometer, is the norm. To meet the needs of users, a triaxial fluxgate must have a resolution of 0.01 nT. It must also have good temperature and long-term stability. Several sources of error can lead to degradation of the data, temperature variations and tilting of the sensors being among the most important. The declination-inclination magnetometer consists of a single-axis fluxgate sensor mounted on a nonmagnetic theodolite. With care, most sources of error can be eliminated, and an absolute accuracy of better than 0.1 minutes of arc is achievable. Proton precession and Overhauser magnetometers make use of the quantum-mechanical properties of protons and electrons to determine the strength of the magnetic field. The Overhauser magnetometer is rapidly supplanting the proton magnetometer (0.1nT once per second sensitivity) because it can sample the field much more rapidly and precisely (0.01nT once per second). Potassium magnetometers, which belong to the family of optically pumped magnetometers, are an attractive alternative to Overhauser magnetometers, especially when used in a dIdD instrument.

4.1 Introduction

Instruments to measure the Earth's magnetic field at magnetic observatories fall into two categories: those that measure the temporal changes in the field on a continual basis without regard to the absolute accuracy of the observation, and those that measure the absolute value of the magnetic field at an instant in time. For almost a century and a half, the photographic variometer, or magnetograph, was the primary instrument for recording temporal fluctuations in the magnetic field. Today, the triaxial fluxgate is the instrument most widely used for this task, although some observatories use a suspended magnet system that produces an

electrical output. A wide variety of instruments have been used to measure the absolute value of the magnetic field: the induction magnetometer, the QHM (quartz horizontal magnetometer), the BMZ (balance magnétométrique zéro), the declinometer, the declination-inclination magnetometer (DIM), and scalar magnetometers such as the proton precession magnetometer and the Overhauser magnetometer. Although the QHM and declinometer are still in use, they have been replaced by the DIM and ppm or Overhauser magnetometer at most observatories.

Magnetometers, in particular the fluxgate and scalar, have a wide variety of uses outside the observatory environment. The ppm/Overhauser is used to calibrate other magnetometers. It is an essential tool for mineral and oil exploration, and has scientific applications in the fields of volcanology and archeology. Numerous arrays and chains of triaxial fluxgates have been deployed for studying the rapid variation magnetic field and solar terrestrial interactions. Arrays of fluxgates, often in conjunction with telluric sensors for measuring the electric field, have been used for studies of crustal conductivity. Fluxgates and scalar magnetometers have been installed aboard ships, aircraft, and satellites for mapping the magnetic field near and above the Earth's surface. Fluxgate and scalar magnetometers also have a wide range of non-scientific applications (Gordon and Brown, 1972). These include: submarine detection, weapons and vehicle detection, navigation, non-destructive testing of materials and many more.

In this chapter we will concentrate primarily, but not exclusively, on those instruments that are used in a modern observatory setting: the triaxial fluxgate, the DIM and various forms of scalar magnetometers. Fluxgate magnetometers suitable for observatory use are also suitable for magnetometer arrays. We will describe the basic theory behind each instrument, its mode of operation, and the development of ancillary equipment for storage and telemetry, its relative and/or absolute accuracy and the related sources of error. Short descriptions of other magnetometers, that were once popular or that may be popular in the future, are also given.

4.2 Fluxgate Magnetometer

Since the invention of the fluxgate magnetometer in the 1930s, more than 100 different variations of the instrument have been designed, using different core configurations and different core materials (Jankowski and Sucksdorff, 1996). In part, this is a reflection of the myriad of commercial and scientific uses to which fluxgates have been put, as detailed above. However, for observatory use, instruments are needed that have both high sensitivity and good long and short term stability, as discussed in the next section. Only two designs are currently capable of meeting these requirements: those using ring core sensors and those using double core sensors. (A third design, the so-called race-track sensor, is intermediate between these two). The fluxgate mechanism is discussed in Section 4.2.2.

4.2.1 Instrument Standards and Sources of Error

In 1986, the first IAGA Workshop on Magnetic Observatory Instruments was held in Ottawa. Of the 27 instruments tested or exhibited at the workshop, seven were triaxial fluxgates (Coles, 1988). Reading the results of the comparison between instruments (Coles and Trigg, 1988), leads us to make the following observations:

1. Do not always believe the manufacturer's specifications, especially the temperature coefficient.
2. The sensitivity and noise of most instruments were approximately, 5-10 $\mu\text{V/nT}$ and 0.1 nT respectively. These were almost identical to values given by Stuart (1972) in his review of magnetometry circa 1970. The one exception was the Narod ring core fluxgate whose low noise performance enabled a resolution of 0.01 nT (Narod, 1988).
3. Thermal and mechanical stability were major problems (Coles and Trigg, 1988). Again, there had been little apparent progress since Stuart (1972)

One result of the Workshop was the development of specifications for an ideal observatory variometer (Trigg, 1988). The consensus reached by those at the workshop is given in Table 4.1 Also shown in the table are current INTERMAGNET standards, denoted by * (St-Louis, 2008).

Note that no mention is made of the absolute accuracy of the system. The magnetometer is considered a variometer. INTERMAGNET requires an absolute accuracy of 5 nT in definitive data, that is, in data that are corrected by adding baseline values obtained from absolute observations. Stability is an important factor for both relative accuracy and absolute accuracy. (See Appendix A-1 for a discussion of baselines and absolute and relative accuracy.)

The geomagnetic time spectrum spans over twenty orders of magnitude, from millions of years to fractions of a second (Constable 2007). Traditionally, magnetic observatories have been concerned with the part of the spectrum that includes secular, solar cycle, diurnal and magnetic storm variations. These cover eight orders of magnitude, from centuries to minutes. The magnetic variations of the spectrum in this range are relatively large, from about 1 nT at 1-minute to about 1000 nT at about 1000 years. Relatively noisy magnetometers with low resolution (~ 0.1 nT) are adequate for recording this part of the spectrum.

Table 4.1 Specifications of an Ideal Magnetometer (after Trigg, 1988)
(* denotes INTERMAGNET standards)

Rugged	mean time before failure 24 months.	Passband	DC to 1Hz DC to 0.1 Hz*
Reliable	mean time to repair 1 day	Noise	0.03 nT in passband
Protected against	lightning, humidity, RF interference	Linearity	0.1% at full scale
Power	< 100 W, uninterruptible	Timebase	1s/month 5 s/month*
Resolution	0.1 nT 0.1 nT*	Sampling rate	10 Hz
Dynamic Range	>±3000 nT (8000 high latitude 6000 elsewhere)*	Measurement interval	5 s 1.0 s*
Stability	0.25 nT per month 5 nT per year*	Temperature coefficient	sensor <0.1 nT/°C console <0.1 nT/°C 0.25nT/°C*
3 component sensor construction	orthogonal within ±30' Stable to 0.3"/month 0.3"/°C	Tilt sensors	resolve 1" (every 10 min.) Stability 1"/month

There is currently a great deal of interest in the space science community in studying fluctuations in the one-second to one-minute range. Most of the major magnetometer chains and arrays (THEMIS, MACCS, CARISMA to name only a few) now record data at one-second intervals. However, the amplitude of the geomagnetic spectrum decreases by two orders of magnitude in the band between one-minute and one second, which means that magnetometers are required whose noise characteristics and resolution (sensitivity) exceed the current standards. In 2005, INTERMAGNET conducted a survey of users of magnetic observatory data to ascertain the required resolution and timing accuracy of one-second data (Love, 2005). Although the response to the survey was not large, there appears to be a consensus that a resolution of 0.01 nT and a timing accuracy of 10 ms meet the current needs of the scientific community. These requirements were adopted by INTERMAGNET with one important revision. The resolution requirement was revised to 1 pT. (Chulliat, 2008). INTERMAGNET is currently working towards

developing standards, based on these requirements, for the recording of one-second data at its observatories.

4.2.2 Fluxgate Mechanism

A fluxgate magnetometer is a device for measuring magnetic field by utilizing the non-linear characteristics of ferromagnetic materials in the sensing elements (Aschenbrenner and Goubau, 1936). All fluxgate sensors use cores with high magnetic permeability that serve to concentrate the magnetic field to be measured (Evans, 2006). We will describe the operation of the sensor with a linear twin core (Fig 4.1). A winding through which the excitation current is applied, is placed around each core. In a twin core sensor, the cores are wound so that they are excited in opposite directions. The excitation current must be large enough to drive the cores into saturation; typically, currents an order of magnitude larger than theoretically necessary are used. The output signal is obtained from a second winding, that encircles both cores.

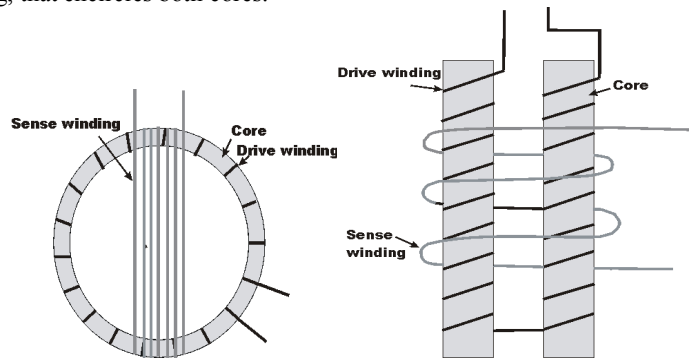


Fig. 4.1 Ring core sensor on the left, twin core sensor on the right

When the core is not saturated (the excitation current I is zero), the core's relative permeability, μ_r , is maximum; this concentrates the ambient field within the core, producing a magnetic flux, Φ , that is μ_r times larger than the field in a vacuum. When the current I is fed into the winding it creates a magnetic field, H_s , that is strong enough to saturate the core, the permeability becomes close to that of a vacuum and the flux collapses. It recovers during the next half cycle of the excitation signal, only to collapse again when the core saturates. The sense or pick-up coil, detects these flux changes, which occur at twice the frequency of the excitation signal since there are two flux collapses during each cycle. In the absence of an external field the saturations are symmetrical and the sensor coil will pick up only odd harmonics. The presence of an external magnetic field (to be measured) disturbs this symmetry creating even harmonics too, the second harmonic being dominant. Even harmonics are a measure of the applied magnetic field. In general,

the sense coil will pick up all harmonics. This can be problematic since the odd harmonics (generated by the excitation current) are much larger than the even ones. Using a two core sensor (Fig 4.1), in which the excitation phase is oppositely directed in each core, solves this problem since the induced voltage produced by the excitation winding is cancelled by the phase reversal. This also holds true for ring core and racetrack sensors.

The signal from the sense coil is fed to a phase sensitive detector referenced to the second harmonic. Because fluxgate sensors work best in a low field environment (Stuart, 1972), most fluxgate magnetometers use negative feedback so that the sensor essentially operates as a null detector. To raise the precision of the measurements, the sensor may be placed inside bias coils that cancel most of the Earth's magnetic field (Fig 4.2).

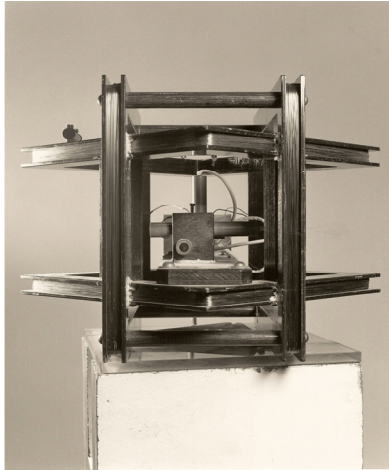


Fig. 4.2 Triaxial fluxgate sensor with bias coils which cancel out the Earth's magnetic field so that the sensors can operate in a low field environment.

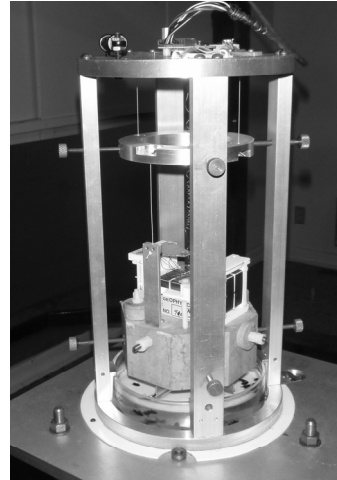


Fig. 4.3 Narrow ring core sensors mounted in a tilt-reducing suspension.

Primdahl (1979) derived an equation for the voltage output of the sense coil in terms of changes in the permeability of the core μ_r . The Earth's magnetic induction component, B , induced along the core axis, produces a magnetic flux,

$\Phi = BA$, in a core of cross-sectional area A . As described above, when the permeability, μ_r , changes, the flux changes, inducing a voltage in the sense coil.

$$V_s = nA \frac{dB}{dt} \quad (4.1)$$

where n is the number of turns in the sense coil. Inside the core, the field is given by

$$B = \frac{\mu_r B_e}{[1 + D(\mu_r - 1)]} \quad (4.2)$$

where B_e is the external magnetic induction. From these expressions, Prindahl (1979) derived the basic fluxgate equation

$$V_s = \frac{nAB_e(1-D)(d\mu_r/dt)}{[1 + D(\mu_r - 1)]^2} \quad (4.3)$$

D is called the demagnetizing factor. It can be seen from this equation that the output voltage is produced by the change in permeability and that the demagnetizing factor plays an important role in determining the signal size. The demagnetizing factor is highly dependent on the shape and size of the core.

Stuart (1972), in his exhaustive review of the state of magnetometry circa 1970, pointed out several engineering problems that had to be overcome to achieve a fluxgate magnetometer with the precision, accuracy, and stability necessary for observatory deployment. These include the need to eliminate other harmonics without causing phase distortion of the second harmonic, and the need to ensure that the fundamental excitation voltage should not contain a second harmonic component. Gordon and Brown (1972) state bluntly: "Properly designed optimized electronics are axiomatic for best low-level fluxgate response." Other difficulties that must be addressed by the manufacturer of an observatory-quality fluxgate include the following:

1. The requirements for a very low noise sensor.
2. The presence of zero offset, which means that the sensor does not give a zero output in a zero field.
3. The variability in the output due to changes in temperature. Temperature affects the instrument in several ways. The coil characteristics may be dependent on temperature; temperature differences may cause strain on the mechanical system; temperature may also affect electronic components.

Thermal stability is of major concern to those who use fluxgate magnetometers in an observatory setting. To achieve an absolute accuracy of better than 5 nT for each datum requires both frequent calibrations as discussed in Part 4.3, and a magnetometer that has good long-term stability. We should add that in addition to thermal stability, mechanical stability is also required — the sensor must not move (tilt). The manufacturers of magnetometers attempt to achieve thermal stability in a variety of ways. In the Narod magnetometer sensor, for example, all sensor materials are chosen to have similar thermal expansion coefficients; the sensor also has a temperature feedback loop (Narod and Bennest, 1990). Similarly, sensors produced by the LEMI company are fabricated from ceramic glass which has a near zero thermal expansion factor (Korepanov, 2006). In the sensor of the widely used UCLA magnetometer, the ring core is placed in a hermetically sealed container filled with paraffin oil (Russell et al, 2008), and on deployment in the field the sensor is buried. According to the authors, this reduces the effect of temperature to 2nT seasonally and 0.1 nT diurnally. Narod and Bennest (1990) claim a thermal stability of 0.1 nT per degree for the sensor and 0.2 nT per degree for the electronics. The LEMI sensors have a thermal stability of less than 0.2 nT per degree. The temperature dependency of the LEMI sensors is also linear, so that corrections for temperature may be possible, since the instruments have thermal sensors imbedded in the sensor and the electronics. The problem of temperature can be circumvented by keeping both sensor and electronics in a thermostatically controlled, constant temperature environment. The effect of temperature is reduced to an amount that is less than the error in the absolute observations. It has been found, however, that the on/off cycling of some temperature controllers produces noise in the data. Therefore, any thermostatically controlled system should be thoroughly tested before it is installed in an observatory.

Tilt is another problem that can seriously affect the output of a fluxgate magnetometer. If the sensor is mounted on a pillar that moves for some reason — the freeze-thaw cycle, the wet-dry cycle, changes in temperature — then the orientation of the fluxgate sensor assembly will change, and the sensors will no longer measure the three magnetic field components that they are supposed to measure. This is not a serious problem if the tilting progresses slowly and remains small. It is then manifested as a slow drift in one or more of the magnetic field components for which corrections can be applied by adding baseline values derived from absolute observations. Absolute observations are made once per week at most observatories. If tilting progresses rapidly and non-linearly, so that significant changes occur on a time scale shorter than one week, aliasing can occur, which means it is impossible to obtain the true value of the magnetic field components on a minute-to-minute basis. One way to eliminate the problem of tilt is to place the sensor assembly in a tilt-compensating suspension. Trigg and Olsen (1990) describe the suspension developed for use with the Narod magnetometer sensor (Fig 4.3). Rasmussen and Kring Lauridsen (1990) describe the suspension developed for the larger DMI (Danish Meteorological Institute) magnetometer sensor. Note that tilt-

compensating suspensions cannot compensate for a rotation of the sensor due to twisting of the pillar.

4.2.3 Data Collection and Telemetry

Early fluxgate magnetometers existed in an analogue world. They provided a voltage that produced an analog output on a chart recorder, so the processing and use of the information were virtually identical to those of a photographic magnetogram. When the computer age arrived, a few forward-thinkers saw the potential in a magnetometer-computer partnership, which meant recording data digitally, or alternatively digitizing analog records afterwards. Alldredge and Saldukas (1964) described one of the first magnetometer systems designed with a digital output that recorded on magnetic tape. The system, called ASMO, was also capable of transmitting data over a phone line to a remote receiving centre. In 1969, the first AMOS (Automatic Magnetic Observatory System) was deployed in Canada (Fig 4.4). It was designed to record digitally on 200 bpi tape. The system also featured an innovative telephone verification system that enabled an operator to communicate with the AMOS and to diagnose system operating problems remotely (Delaurier et al, 1974).

Digital recording was not for the faint of heart. Delaurier et al (1974) wrote: “Such problems as power failures, electronic device breakdowns, mechanical troubles and other unpredictable difficulties can cause data gaps, bad coding, parity errors and irregular physical record length.” Thus, it became necessary to develop a suite of editing programs to deal with a class of errors that had never existed in the analogue era. But there was no going back since scientists had already discovered that having digital data made it possible to use a wide range of analytical tools that enabled them to extract much more information than they were able to obtain from photographic records or hourly mean tables.

It soon became apparent that magnetic tape was not a suitable medium for recording geomagnetic data, especially at remote observatories where there was little control over the cleanliness of the environment in which the tape drive was located. Thus, observatory operators were quick to embrace alternative storage devices. Many different types of data collection platforms have been developed or tried: personal computers (PCs), personal digital assistants, or PDAs (Merenyi and Hegymegi, 2005), WORM (write once read many) drives, Zip drives, and many others. Important criteria for any data acquisition system are robustness and stability, low power consumption, and a user friendly interface.

At many observatories, the PC has become the centre of the magnetometer system. All magnetometers feed data into the PC, which controls the operation of each of them. Data can be stored on the PC's hard disk as well as on peripheral

storage devices. The PC also controls the telemetry of data via satellite or the internet (see fig. 4.5). To achieve the timing accuracy that users require (10 ms), most observatories use a timing system based on the GPS (global positioning system).

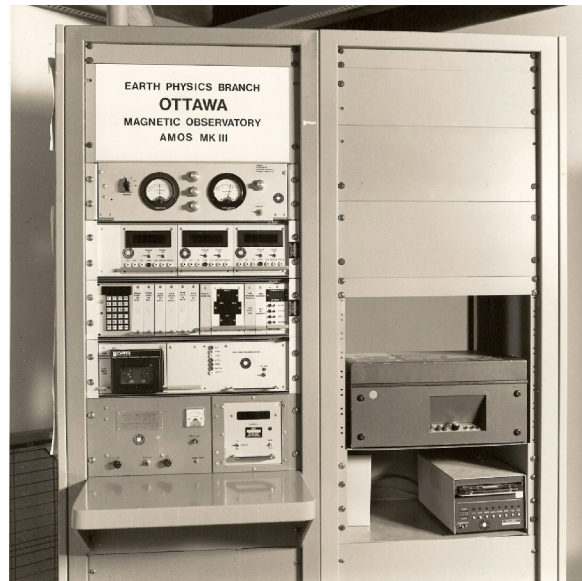


Fig. 4.4 The AMOS Mk 3 is a second-generation automated Observatory system deployed at Canadian observatories during the 1980s

4.3 Declination-Inclination Fluxgate Magnetometer

The declination-inclination fluxgate magnetometer (commonly called the DI-flux or DIM) is the instrument of choice for doing absolute observations of the magnetic field. Although INTERMAGNET does not forbid the use of other instruments, the technical manual does state that a DIM and a proton precession/Overhauser magnetometer are an increasingly popular combination (St-Louis, 2008). In fact, all INTERMAGNET observatories use the DIM/Overhauser combination as their primary absolute instruments. Although Jankowski and Sucksdorff (1996) do describe other instruments in the *Guide for Magnetic Measurements and Observatory Practice*, they state that the DIM combined with a ppm “is the recommended pair of absolute instruments”. At the XII IAGA Workshop on Geomagnetic Observatory Instruments, Data Acquisition and Processing held at Belsk in 2006, all 29 instruments that took part in the instrument comparison session were DIMs (Reda and Neska, 2007).



Fig. 4.5 Instruments typical of a modern magnetic observatory. Clockwise from lower right: computer for data storage and system control. Fluxgate sensor in a tilt reducing suspension; Overhauser magnetometer and sensor; fluxgate magnetometer electronics; satellite transmitter.

However, some observatories still use classical declinometers and QHMs, (quartz horizontal magnetometers) so we describe them briefly in a later section. Those who want more details can find them in Jankowski and Sucksdorff (1996) or Wienert (1970).

Although the use of the DIM may be almost universal today, its acceptance by the magnetic observatory community was slow in coming. An early version of the instrument was developed by Paul Serson who used it in 1947 and 1948 in a field survey to determine the position of the North Magnetic Pole (Serson and Hannaford, 1956). Its first use in a Canadian observatory dates from 1948, and by 1970 it was in use at all Canadian observatories. However, the instrument is not even mentioned in Wienert's (1970) *Notes on Geomagnetic Observatory and Survey Practice*. In 1978, the Institut de Physique du Globe in France developed a version of the instrument for use at its high southern latitude observatories (Bitterly et al, 1984). The motivation for this development was the same as that of Serson. The use of classical instruments, such as QHMs, becomes extremely difficult at high latitudes because of the weakness of the horizontal component of the magnetic field. After they had made 127 comparisons to the standard instruments at Chambon-la-Forêt Observatory, Bitterly et al (1984) concluded that the instrument was stable, with no apparent long-term drift and that its accuracy was better than 5" of arc for both D and I.

4.3.1 Observing Procedure

A DIM consists of a fluxgate sensor mounted on the telescope of a magnetically clean theodolite and the associated electronics (Fig. 4.6). The fluxgate sensor is mounted with its magnetic axis parallel to the axis of the theodolite's telescope. In practice, there will always be a misalignment which results in a collimation error. Fortunately, this, as well as most other errors, can be eliminated by proper observational procedure.

There are two methods of observation possible: the null method and the residual method. Both methods require that the sensor be placed in four positions that cancel the collimation and offset errors. Both methods also require that total intensity be recorded simultaneously with the observations of D and I. We shall describe the null method first. The telescope is set in the horizontal plane and the alidade is then rotated until the output of the magnetometer is zero. This indicates that the sensor is aligned perpendicular to the horizontal component of the magnetic field. The angle at which this occurs is noted. The alidade is then rotated roughly 180° and finely adjusted until zero output is achieved again. Next, the telescope is inverted and two more positions at which the output is zero are found. The average of these four values (call it A) gives the direction of the horizontal magnetic field in some arbitrary frame of reference. To get the declination (D) we must compare A to the direction of true north. At an observatory this is done by sighting a reference mark (B) whose true bearing is known (Az). Then

$$D = A - (B - Az) \quad (4.4)$$

To measure inclination, the telescope is first aligned in the magnetic meridian, the direction of which is usually obtained from the previous declination observation. (The inclination is actually quite insensitive to misalignment in the meridian, so an approximate value is often sufficient, as discussed in section 4.3.2) Then, two positions at which the output is zero are found, one with the sensor above the telescope, one with the sensor below. The alidade is rotated exactly 180 degrees, and the positions of two more nulls are recorded. The inclination is derived from these four values.

The residual method follows the same basic procedure except that the position of the telescope is not adjusted to give a zero output. Instead, it is set to some convenient value near the null position and the value of the magnetic field component is read off the magnetometer's meter.

Since the magnetic field will vary over the length of time required to observe in all four positions, it is important to null the meter or read the residual in sync with the observatory's triaxial fluxgate. This will allow changes in the field to be taken into account during post-observation processing. To compute baselines for com-

ponents of the magnetic field other than D and I, values of total intensity are obtained from the observatory's ppm or Overhauser magnetometer.

Detailed instructions for observing with a DIM in an observatory setting are given by Jankowski and Sucksdorff (1996). Newitt et al (1996) give instructions for the use of the instrument in a field setting. Both of these Guides may be obtained by contacting the Secretary-General of IAGA¹. The theory behind the operation of the instrument is given by Kring Lauridsen (1985) and Kerridge (1988). The former deals with the residual method; the latter deals with the null method.

4.3.2 Instrumental Accuracy and Sources of Error

One important function of the first International Workshop on Magnetic Observatory Instruments was a comparison of absolute instruments. Six of the nine instruments so compared were DIMs (Newitt et al, 1988). The most obvious, and the best, way to compare two instruments is to make simultaneous measurements on two pillars. Since an observation contains an error component that is dependent on the observer, two sets of observations should be made with the observers exchanging places after the first set. The differences in D and in I between the two pillars must be known precisely. If they are not known, then the instruments must be interchanged, and another two sets of observations carried out.

This method is obviously not practical when the number of instruments is large. As an alternative, each set of observations from each instrument can be used to calculate spot baseline values, (as discussed in Appendix A-1) for the observatory's triaxial fluxgate magnetometer. The baseline values are then compared to determine differences in the DIMs. This method of comparing instruments is dependent on one major assumption: the observatory fluxgate magnetometer must be stable or at worst must vary only very slowly with time. At the first IAGA Workshop, this assumption was found to be invalid. Newitt et al. (1988) wrote: "it is obvious that the Ottawa AMOS does not have sufficient temperature stability to allow comparisons with an accuracy of a fraction of a nanotesla." Nevertheless, "under adverse conditions baselines can be determined with an accuracy of 1 to 2 nT." The authors also felt that an accuracy of better than 1 nT would be achievable under more favourable observing conditions.

Comparisons of absolute instruments have been made at all subsequent Observatory Workshops. Since the fifth workshop, in 1992, the instruments have been exclusively DIMs. The results of these comparisons have been published in the proceedings of each workshop, but it is difficult to compare the results from one workshop with those of another since the statistics were seldom computed in the

¹ Secretary General of IAGA's email is iaga_sg@gfz-potsdam.de

same manner. However, the published results of the workshops indicate that a skilled observer using a magnetically clean instrument can obtain an absolute accuracy of a few arc-seconds, or roughly 1 nT.

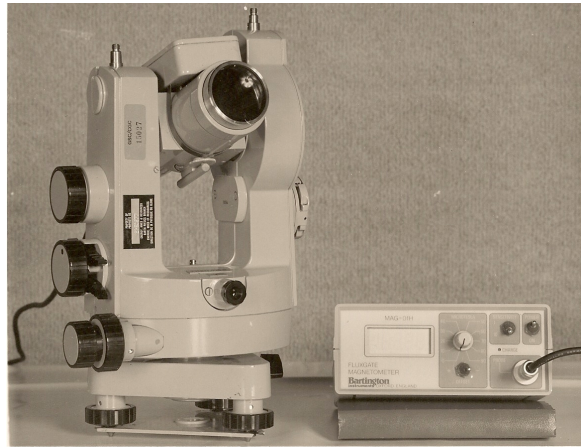


Fig. 4.6 A declination inclination magnetometer. The instrument shown here consists of a Zeiss-Jena 010 theodolite and a Bartington 01H single axis fluxgate.

Several factors can contribute to the error in an observation made with a DIM. Most of these can be reduced to zero by proper procedure and care. Potentially serious sources of error are discussed below:

1. Magnetization in the theodolite can lead to large errors, but it is well-known in the observatory community that theodolites said to be non-magnetic must nevertheless be checked. This is a source of error that can and should be totally eliminated.
2. Movement of the sensor with respect to the telescope will result in an error. This is a problem that can be detected by routinely calculating the collimation angles from the four D readings or the four I readings (see, for example, Jankowski and Sucksdorff, 1996), so the problem can be detected easily and fixed.
3. Large vertical magnetic gradients are a source of error, especially if the gradients are non-linear. The theories developed by Kring Lauridsen (1985) and Kerridge (1988) assume that the magnetic field is the same regardless of the position of the sensor. If there is a vertical gradient, the field will be different in the sensor up and down positions. Experiment has shown that if the gradient in

the vertical field is linear, the observational procedure will eliminate its effect. However, this will not be the case for non-linear gradients. It is normal practice to choose a site for a magnetic observatory with low magnetic gradients; Jankowski and Sucksdorff (1996) recommend gradients be less than 1 nT/m, both horizontally and vertically. For such observatories, gradient errors are a non-issue. However, perfect sites cannot always be found, and observatories have and must be built in areas where the gradient is higher than desirable. Observations made with a DIM at such observatories may contain an error of unknown size due to gradients. Some field or repeat station observations made with a DIM are also likely to contain gradient errors.

4. The measurement of declination with a DIM requires referencing the observed value to a known azimuth. An error in the azimuth will result in a systematic error in the declination. In the field, azimuth has traditionally been determined by sun observations, with an accuracy of roughly one minute of arc (Newitt et al, 1996). North-seeking gyros have also been used (see, for example, Kerridge, 1984), and the use of GPS is now becoming quite common. At a magnetic observatory, a professional surveyor can be brought in to determine the azimuth of the reference mark to a very high degree of accuracy, so this should not be a source of error.
5. There is a very real potential for error when sighting the reference mark. A large temperature contrast between the observatory building and the outside will cause an apparent erratic motion of the reference mark when viewed through an open window. Viewing through glass can lead to a systematic error due to the index of refraction of the glass, unless the sight line is at right angles to the window. The human factor also comes into play here. In a test carried out at Ottawa Magnetic Observatory, three observers made a series of sightings on the azimuth and noted the angle. Differences in the angles recorded by the observers were as large as 12 seconds of arc.
6. Failure to set the telescope in the magnetic meridian will introduce an error in inclination. However, both Kerridge (1988) and Kring Lauridsen (1985) state that the positioning is not very critical. Coles (1985a) worked out an analytical expression for computing the true inclination when the theodolite is not aligned with the magnetic meridian:

$$\cos^2 I = \frac{\cos^2 I'}{\cos^2(D - D') + \cos^2 I' \times \sin^2(D - D')} \quad (4.5)$$

where I is the true inclination I' is the observed inclination $D - D'$ is the angle between the true and assumed magnetic meridian.

Table 4.2 gives errors for a few values of I' and $D - D'$. For values of inclination typical of Europe, (55° to 70°) aligning the telescope to within $5'$ of the

true magnetic meridian will lead to errors in inclination of about 1 or 2 seconds of arc.

Table 4.2 Error in inclination when telescope is not set in the magnetic meridian.

Inclination (degrees)	Azimuth Error (degrees)	Inclination Error (minutes)
85	1	0.05
85	10	4.60
70	1	0.17
70	5	4.20
40	1	0.26
40	2	1.03
40	5	6.45
10	1	0.09
10	2	0.36
10	5	2.24

7. Improper leveling of the theodolite will lead to errors in declination. This is another error that is completely preventable if a theodolite with a gravity-oriented vertical scale is used. Even if the base of the theodolite is slightly off-level (by less than four minutes of arc) the vertical scale will indicate the true angle of the telescope relative to the horizontal. The telescope can then be placed in the horizontal by setting the vertical scale to exactly 90° or 270° before each reading. If a theodolite without this feature is used, this source of error becomes much more important. Coles (1985b) has developed analytical expressions for the leveling error. These lead to the following rule of thumb: The error in declination is approximately equal to four times the leveling error.
8. Magnetic disturbances are another potential source of error. In theory, both the null and the residual methods should be immune to the effects of disturbances because readings are synchronized with the sampling cadence of the variometer. In practice, the ability to null the instrument or to read the display with a timing error of less than one second depends on the frequency content of the magnetic field variations and the skill of the observer. It is always a good idea to avoid observing during disturbed periods. However, at high latitudes this is almost impossible. In such situations, the accuracy of the baselines determined from observations can be improved by taking several observations.

4.4 Scalar (Quantum) Magnetometers

Scalar magnetometry is an offspring of nuclear magnetic resonance (NMR) and electron paramagnetic resonance. Development in this field goes back to the early 20th century. Studies of the then newly discovered spin of electrons and some nuclei led to NMR spectroscopy, which allowed scientists to decipher structural formulae of complex chemicals, follow chemical/physical processes etc. NMR experiments are done in artificial, strong, and well known magnetic fields. Powerful, medical tools, based on NMR, such as magnetic resonance imaging (MRI) enable us to see the inner details of the human body. MRI has many applications a cancer detection is one of them.

Scalar magnetometers reverse the above experiments. Using a chemical or an elemental vapour of known composition for the sensor enables measurement of the applied magnetic field. Along with nuclear magnetic resonance, scalar magnetometers have been a phenomenal success. First of all, they allow measurements to be made while in motion since the measurements are only very weakly dependent on the sensor orientation. Their unsurpassed absolute accuracy is in the parts per million range. Sensitivities have reached the fT (femtotesla, 10^{-15} T) range with some claims that are orders or magnitude better.

4.4.1 Background Physics

Quantum magnetometry is based on the spin of subatomic particles: nuclei, usually protons, and unpaired valence electrons (Abragam 1962, Slichter 1963, Kudryavtsev and Linert 1996).

Magnetic dipoles are produced by the spin of charged particles precessing around the magnetic field direction. The precession has an angular frequency (Larmor frequency) ω_0 :

$$\omega_0 = \gamma_n \mathbf{B} \quad (4.7)$$

γ_n is a gyromagnetic constant (not always a constant) and \mathbf{B} is a magnetic induction or flux density.

Scalar magnetometers measure magnetic induction \mathbf{B} and not magnetic field \mathbf{H} . Units of measurement (nanotesla) are units of \mathbf{B} and not \mathbf{H} . However \mathbf{B} and \mathbf{H} are in vacuum or air tied by a constant μ_0 :

$$\mathbf{B} = \mu_0 \mathbf{H} \quad \mu_0 = 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}}$$

Gyromagnetic constant γ_n is well known only for protons in water (IAGA recommendation: http://www.iugg.org/IAGA/iaga_pages/pubs_prods/value.htm).

$$\gamma_p = 0.2675153362 \quad \gamma_p / 2\pi = 0.0425763881 \quad (4.8)$$

This precision opens the possibility of measuring \mathbf{B} with high sensitivity and accuracy depending on the spectral line width (or length of decay time T_2 , see below), the value of γ_n and the signal/noise ratio of the precession frequency signal.

Spinning dipoles orient themselves in the applied magnetic field creating a weak nuclear or electron paramagnetism.

The macroscopic magnetization due to the polarized particles is (Abragam 1961):

$$\mathbf{M} = \frac{N\gamma_n^2 \hbar^2 / 4\pi^2}{4kT\mu_0} \mathbf{B} \quad (4.9)$$

N is the number of particles; μ_0 is the magnetic permeability of vacuum; T is the absolute temperature, \hbar and k are constants. Magnetization is collinear with the magnetic field direction and proportional to the number of particles in the sensor, the square of the gyromagnetic constant, and the applied magnetic induction, and is inversely proportional to the absolute temperature. The dynamics of magnetization is described by two time constants: T_1 and T_2 . Placed in a magnetic induction, \mathbf{B} , the magnetization will reach equilibrium exponentially with time constant T_1 ; turned 90° away from the direction of \mathbf{B} , the magnetization \mathbf{M} will precess around it, its amplitude decaying with the time constant T_2 :

T_2 may be shortened by inhomogeneity in the magnetic field.

By irradiating the assembly of spins with a magnetic field of Larmor frequency, absorption of its energy by particles at the lower energy level can equalize the two populations. This is called saturation. Saturation will obviously eliminate the magnetization \mathbf{M} .

4.4.1.1 Polarization

Magnetization \mathbf{M} due to the spin of protons/electrons is just too small to produce detectable signals. To improve this, one needs to increase \mathbf{M} by polarizing the particles. From equation (4.9) one can do that four different ways:

- a) by reducing the absolute temperature to a few degrees Kelvin
- b) by placing the sensor in a strong “polarization” field for a time interval comparable with T_1
- c) by increasing the sensor volume so that there are more particles (N)
- d) selecting particles with higher gyromagnetic constant γ_n directly or indirectly

There is one additional way:

- e) by the optical pumping of valence electrons so as to manipulate the misbalance of populations of the two energy levels (Alexandrov, Bonch-Bruevich 1992, Happer 1972)

Of these five methods, a) is impractical and c) has an easily realized practical limit.

b) An auxiliary DC polarization magnetic field is used in proton precession magnetometers. Fields of a few hundred Gauss are created by sending a polarizing current of some fraction of an Ampere through the sensor coil. After polarization, the same coil serves as the pick-up coil for the precession signal. Polarization must be carried out at approximately right angles to the ambient field. Once the polarization field is removed, the newly formed magnetization will find itself in the plane of precession. It will precess and decay to thermal equilibrium (i.e. in noise) with the time constant T_2 . T_2 determines the time interval available for measuring of the precession frequency. In liquids and gases T_2 may reach several seconds, while in solids it is milliseconds. This is the reason nuclear (proton and Overhauser) magnetometers use liquid sensors while optically pumped use vapours.

d) Overhauser effect magnetometers deal with a mixture of protons and unpaired electrons in the so called free radicals (Kurreck, et al 1988)

Polarization of unpaired electrons in thermal equilibrium is about 660 times greater than that of protons. By placing electrons in local fields of Nitrogen nuclei in the molecules of nitroxide free radicals, this ratio is increased to over 30,000. Although only part of this polarization can be transferred to protons, gains in polarization of the protons in thermal equilibrium of over 1000 times are possible. Transfer of electron thermal equilibrium polarization to protons happens when we saturate the electron spectral line by irradiating the sample by an appropriate RF magnetic field of Larmor frequency of free electrons. Transfer dynamics is again determined by the time constant, T_1 . The transferred polarization is colinear with the magnetic field direction, and is static. To create a precession signal, one applies a strong, short magnetic pulse (90° or $\pi/2$ pulse) to rotate the magnetization into the plane of precession. A steady state precession signal can also be achieved by applying a weak rotating magnetic field of the proton precession frequency in the plane of precession.

e) Optical pumping deals with vapours of elements in the first column of the periodic table of chemical elements (alkali metals) namely Potassium, Rubidium and Cesium (Lithium and Sodium are chemically too active). These elements have one, unpaired electron in the valence shell and in a vapour form they are ready for electron paramagnetic resonance (EPR). Helium 4, which is in the second column of the periodic table, has two electrons in the valence shell. It can be “prepared” for EPR by applying a weak discharge that lifts one of the two electrons into a metastable state, but only for a very short time, (few microseconds). The return of the electron from the metastable state eliminates the atom from the process. As a result of this depolarization, the spectral line of Helium 4 is wide, some 70nT.

All alkali metals need to be heated in a vacuum to some 45-55⁰C to achieve the proper density of vapour.

4.4.2 Proton Precession Magnetometer

The proton magnetometer was the first of the scalar magnetometers. Packard and Varian (1954) patented the method and in the 1960s newly formed Geometrics brought out an instrument that read the Earth’s magnetic field to about 1nT sensitivity. Barringer and Scintrex followed, all with hard wired electronics. EDA ventured into geophysics and brought out the first computerized proton magnetometer. Geometrics, Scintrex and GEM Systems followed suit, each with some improvements. Sensitivities of 1nT or 0.5 nT were standard. Proton magnetometers were first used in magnetic observatories in the late 1960s.

The proton precession magnetometer was the standard scalar magnetometer up to about the mid 1980’s (pre-Overhauser times). In slow mode, with readings in three seconds or so, a sensitivity of 0.1 nT can be achieved. With faster readings (one second is now becoming a standard at Intermagnet observatories) perhaps 0.25nT is achievable with about 0.5 sec polarization and 0.5 sec reading time.

For the highest absolute accuracy and long term stability, the frequency reference of the Larmor frequency counter must be of adequate stability. A calibrated Temperature Compensated Crystal Oscillator (TCXO), or GPS timing is needed.

A relatively large polarization current (approximately 0.5A) will polarize protons but will also generate large stray magnetic fields that may interfere with a nearby fluxgate or similar vector magnetometers.

Standard sensor liquid (kerosene) is a mixture of chemicals and its chemical shift² is not well known. This will degrade the achievable absolute accuracy. Alternatively, a liquid with known chemical shift can be used, such as methanol with a chemical shift of 3.6 parts per million, benzene 7.4 ppm, acetone 2.2 ppm (Pouchert 1983). Water has a chemical shift of about 5.6 ppm in relation to a reference tetra methyl silane (TMS).

To maximize signal strength the proton magnetometer sensor coils are usually immersed in the liquid. Some use toroidal sensors that are omni-directional and contain the polarizing magnetic field completely, i.e. they will not interfere with the other nearby magnetic sensors (fluxgates or similar). Toroidal sensors are not as efficient as directional sensors with two immersed coils wound in opposition to eliminate far away sources of interference. When installing that kind of sensor one needs to make sure the polarizing magnetic field is at right angles to the magnetic field of Earth. It is best to point the coil axis East-West. The angles are not critical though. It is of utmost importance to install the sensor in a field that is as homogeneous as possible for two reasons:

- a) Any movement of the sensor will change the readings due to local gradients and add to the noise and/or long term drift.
- b) Inhomogeneity, if excessive (over few hundred nT/m), may shorten exponential decay of the precession signal and reduce the time of measurement and, as a consequence the sensitivity.

Proton magnetometers as well as pulsed Overhausers, do not have measurable 1/f or low frequency noise, an excellent feature for long term monitoring.

At present, with the requirement for one-second measurements with a sensitivity of 0.1nT or better, proton magnetometers are becoming marginal for observatory measurements. However they are still used extensively in mineral exploration and elsewhere.

4.4.3 Overhauser Magnetometers

The Overhauser method has become the standard for magnetic observatories around the world. In essence, an Overhauser magnetometer is a proton magnetometer with all its valuable features plus numerous extras: better signal strength with better sensitivity, less power consumption, no DC polarization and its stray

² Chemical shifts are due to configuration of the sensor liquid molecules, their nuclear properties, orbital influences of electrons and their span is about 10 parts per million or about 0.5nT in a field of 50,000 nT.

fields, and no significant interruption in measurement. Low power RF polarization allows for concurrent measurement so the measurement of the magnetic field is near-continuous (about 30 msec gap every second).

The use of a simple, chemically pure sensor liquid (methanol or similar) allows for fine tuning of the gyromagnetic constant by taking its chemical shift into account. This gives high absolute accuracy and long term stability.

The determination of the strength of the magnetic field (magnetic induction) using a proton or Overhauser magnetometer is carried out as follows: The precession frequency signal is sufficiently amplified and all zero-crossing times are measured precisely. From a set of zero-crossing times one determines the average period of the precession frequency. The reciprocal of the average period is the precession frequency which is then divided by the gyromagnetic constant for protons.

The major advantage of this method is the ease with which one can obtain readings of a desired resolution, and the ability to choose a sampling rate.

Sensitivities of commercially available Overhauser magnetometers are in the 10 – 20pT range for a one second reading interval. The maximum practical rate of readings is 5 per second.

For high absolute accuracy, the Overhauser magnetometer, like the proton magnetometer, needs a higher stability TCXO adjusted to proper nominal frequency. GPS time, accurate to 1μsec, can be used for calibration. Omnidirectional sensors are available. Directional sensors must point in a direction which is at right angle to the magnetic field direction.

4.4.4 Time of Reading

In scalar magnetometers, determination of the magnetic field is achieved by timing the zero-crossings of the precession signal over a period of time. For a reading rate of once per second the period of integration is about one second. The time of measurement could be shorter than one second if the sensor experiences an excessively large magnetic gradient that shortens the decay of the signal, reduces the sensitivity, and changes the timing of the reading

To determine the true time of reading, i.e. average time t_0 of the signal zero-crossings, one needs to know the times of the first and last zero-crossings.

The precision with which the first and last zero-crossing can be determined depends on the precession frequency or magnetic field strength. At 50,000 nT the precession frequency is about 2,019 Hz

The average period is then $1/2019$ sec or 0.469 msec and this is the precision of the determination of time of any zero-crossing. If zero-crossings can be taken every half a period, the uncertainty will be 0.2345 msec instead. With the uncertainty of the last zero-crossing added linearly, the overall worst-case uncertainty becomes 0.469 msec.

For low magnetic fields, say 25,000 nT, this will double to about 0.938 msec, while for strong fields it will be reduced. The delay between triggering and the start of taking zero-crossings is up to 30 msec in Overhauser magnetometers. If rounded time of reading t_0 (full second) is required, then the triggering should be at 15msec before 0.5 sec mark.

Optically pumped magnetometers (potassium) do not have this uncertainty in measuring as their precession frequency exceeds that of proton magnetometers by about 160 times.

4.4.5 Optically Pumped Magnetometers

Optically pumped magnetometers are presently quite rare in magnetic observatories. Cesium, Helium 4 and Potassium are available for airborne mineral and oil exploration surveys. Portable models of Cesium and Potassium magnetometers are available for ground mineral and diamond exploration. However, Potassium magnetometers offer good improvements in speed and sensitivity for observatory measurements (Alexandrov, Bonch-Bruevich, 1992). Potassium is the only Alkali metal magnetometer that operates on a single narrow EPR spectral line. This not only maximizes its sensitivity but it ensures a minimum heading error and very high absolute accuracy comparable with the absolute accuracy of Overhauser or ppm. Sub-pT sensitivities for once per second readings are routinely achievable.

4.5 Use of Scalar Magnetometers for Component Determination

The dIdD method of measuring the components of the magnetic field was first proposed by Alldredge (1960). The dIdD system consists of a proton or Overhauser or Potassium magnetometer centered within two orthogonal coil systems that are aligned to be perpendicular to the ambient magnetic field direction in horizontal and vertical planes. High degree of orthogonality of the two bias coils can easily be achieved. Positive and negative bias currents are applied to each coil

system in turn and biased total fields are measured; the ambient unbiased field is also measured. From these five readings one can calculate the total intensity and the angles between the magnetic field vector and the axis in which the system is aligned: dD and dI. If the orientations of the coils are known, D and I can be computed.

$$dD = \sin^{-1} \frac{D_p^2 - D_m^2}{4F \cos I \sqrt{\frac{D_p^2 + D_m^2}{2} - F^2}} \quad (4.15)$$

$$dI = \sin^{-1} \frac{I_p^2 - I_m^2}{4F \sqrt{\frac{I_p^2 + I_m^2}{2} - F^2}} \quad (4.16)$$

D_p and D_m , I_p and I_m are biased magnetic fields while F is the unbiased field. With known I , D , and F , all components can be computed.

Theoretically, a dIdD system is an absolute instrument; it is very weakly affected by temperature, has no zero offset and is linear over a complete range of measurement. However, it is subject to changes in orientation, which means that in practice it is at best a quasi-absolute instrument. Nevertheless, if installed on a good solid pillar, a dIdD can be used to improve the determination of baselines for an observatory's triaxial fluxgate under the assumption that its drift will be slower and more linear than the drift of the fluxgate. Thus baseline values are determined for the dIdD on a periodic basis (usually once per week) using a DIM. The corrected dIdD values are then used to compute baselines for the fluxgate magnetometer on a minute by minute basis.

A traditional problem with the dIdD has been the length of time required to take an observation – up to 25 seconds when using a Proton magnetometer. This is too long since an active magnetic field can change substantially in 25 seconds. The problem of excessive time of measurement can be overcome by replacing the proton magnetometer with an Overhauser or Potassium magnetometer. A dIdD equipped with an Overhauser magnetometer can complete a sequence of measurements in one second (0.2 sec each segment); a dIdD equipped with a Potassium magnetometer can measure five times per second (0.04 sec per segment). A Potassium dIdD can achieve a sensitivity of one arc second measuring once per second. Although switching from one bias to another requires a delay for transients to die out, the time required is so short that either instrument can be considered virtually continuous.

A variation of dIdD proposed by Alpár Körmendi (2008) of Hungary has four sensors installed in toroidal bias coils and working under constant bias (I_p , I_m , D_p , and D_m) and supplemented by unbiased measurements. All components of the measurement are now collected concurrently and the main weakness of the standard dIdD – sequential measurements – is eliminated. However, the proposed system has its own weaknesses. It is expensive since it requires five sensors instead of one. The sensors are not in exactly the same magnetic field. The bias fields are not exactly equal, and it is difficult to make them orthogonal.

4.6 Automated Absolute Observations

Newitt (2007) lists six elements of observatory operations that must be fully or partially automated before an observatory can truly be called automated: data collection, data telemetry, data processing, data dissemination, error detection and absolute observations. For institutes that run remote magnetic observatories and for those who desire to put observatories (as opposed to variometer installations) in remote locations, the automation of absolute observations is of particular importance, since it would remove the necessity of having a trained observer on site. At present, there have been only three serious attempts to automate absolute observations.

An automated vector ppm is described by Auster et al (2007, 2009). The instrument is equipped with a telephoto lens and a CCD camera, which, along with the accompanying imaging software, are used to determine the measurement direction with respect to a known azimuth. To determine H, Z, and D, the vector ppm is rotated around its vertical axis. The misalignment between the rotation axis and the true vertical axis is measured with tilt sensors. The rotation angle is monitored by a rotary encoder system. Measurements are made every 30 degrees. When the final measurement is made, the software automatically calculates the component values. Tests performed since 2006 indicate that it is possible to keep error to about 2 nT.

GAUSS (Geomagnetic Automated System) is an instrument in which a three component fluxgate sensor is rotated about a very stable, very well defined axis. All three components are recorded in three different positions, from which the magnetic field along the axis of rotation can be calculated. (Hemsborn et al, 2009, Auster et al, 2007). The instrument consists of a turntable on which are mounted a pair of support prisms for the three component fluxgate. All movements are carried out by piezoelectric motors. Angles are measured by encoders that have an error of 1 second of arc. A telescope focuses a laser beam which points along the measurement direction. The fluxgate must be linear over the entire range of the geomagnetic field (0 to ± 64000 nT), so an instrument originally designed for space applications is being used. The instrument determines the field intensity in

two horizontal directions. A ppm supplies the additional information required to determine the full vector field. The instrument, in its present form, was installed in the Niemegek magnetic observatory in April, 2008 for long term testing.

AUTODIF is an automated DIM that has been in development since the late 1990s. It was demonstrated at the Belsk Workshop in 2006 (Van Loo and Rasson, 2007) and rigorously tested at the Boulder/Golden Workshop in 2008 (Rasson, von Loo and Berrami, 2009). It is designed to reproduce the measurement sequence of a manually operated DIM. The telescope of the theodolite is replaced by a laser and split photo cells which are used to align the device in a known meridian by reflecting the laser beam off a corner cube reflector back onto the photo cell. Non-magnetic piezoelectric motors are used to move the sensor about the horizontal and vertical axes. The angles are measured by custom electronic optical encoders. An electronic bubble level mounted on the alidade provides reference to the horizontal. A lap top and a microcontroller control the instrument. In-house testing has shown that the instrument can achieve an angular accuracy of 0.1', which is comparable to that which can be obtained by a skilled observer. When tested at the Boulder Workshop the results were not as good; errors were about 0.2'. However, the system was being tested under environmentally challenging conditions (strong winds) which may have accounted for a large part of the difference. Since then, an instrument has been installed and is now running in operational mode at the Conrad Stufe II underground magnetic observatory in Austria.

Although all three of these instruments have given results that agree closely with those obtained by manual observations, long-term reliability under adverse conditions must yet be demonstrated. We may be in the enviable position of having a choice of auto-absolute instruments that work on three different principles.

4.7 Other Magnetometers

In the following sections we describe briefly other magnetometers still in use at some magnetic observatories.

4.7.1 Declinometer

The classical declinometer employs a magnet suspended from a long, torsionless fibre so that it is free to align itself in the direction of the horizontal magnetic field. A mirror is affixed to the magnet perpendicular to the magnetic axis of the magnet. This assemblage is mounted on a non-magnetic theodolite in such a way that the mirror can be sighted through the telescope of the theodolite. The observational procedure is in theory quite simple. The theodolite is turned until the

telescope is aligned perpendicular to the mirror. The direction of the magnetic meridian (A) is then read from the theodolite's base. Next, the reference mark is sighted and the angle (B) is read from the theodolite's base. Knowing the true bearing of the reference mark (Az), one can calculate the declination using equation 4.4.

In practice, this seemingly simple procedure becomes much more complicated for two reasons. First, it is impossible to attach a mirror exactly 90 degrees to the magnetic axis of the magnet. Second, a truly torsionless fibre does not exist. Thus, a real observation with the declinometer involves using two magnets with different magnetic moments, and taking observations with each magnet in upward and downward positions. Declination is now calculated using Equation 4.17:

$$D = A1 + c(A1 - A2) - (B - Az) \quad (4.17)$$

Where $A1$ is the average of the magnetic meridian values obtained using the first magnet in the up and down positions; $A2$ is the average value using the second magnet, and c is a coefficient related to the torsion in the fibre that must be determined experimentally (see Jankowski and Sucksdorff, 1996).

Declinometers can also be used to measure horizontal intensity using the classical method of oscillations and deflections developed by Gauss (Wienert, 1970).

4.7.2 Quartz Horizontal Magnetometer

The quartz horizontal magnetometer (QHM) is a simple instrument for measuring the horizontal intensity of the magnetic field. It consists of a tube from which a magnetic-mirror assembly is suspended by a fibre, and a telescope that fits onto an opening in the tube (Fig 4.7). The instrument may be mounted on a specially designed base or on some other theodolite base using an appropriate adapter. Measuring horizontal intensity with the QHM is straightforward. The theodolite is turned a complete number of half-turns, such that the magnet is moved from the meridian position (A_0) by an angle of at least 45° (A_+). The angle is recorded and then the theodolite is rotated in the opposite direction (A_-). H can then be calculated from the following formula (Jankowski and Sucksdorff 1996):

$$H = C / (1 - k_1 t) (1 - k_2 H \cos \Phi) \sin \Phi \quad (4.18)$$

$\Phi = (A_+ - A_-) / 2$ and $C = 2\pi \tau / M$, where τ is the torsion constant of the fibre and M is the magnetic moment of the magnet. C must be determined experimentally by comparison observations. The temperature dependence of C is given by the first term in the denominator; k_1 is the temperature coefficient and t is the temperature. The second term gives the effect of induction on the magnet. Here H refers to an approximate value of the horizontal magnetic field component such as

one would obtain from the IGRF. Great accuracy is not necessary since k_2 is typically in the range 0.0002 to 0.0008. Both k_1 and k_2 are determined experimentally. Because the three constants do change with time, the QHM cannot be considered a true absolute instrument. However, the constants are extremely stable; k_1 and k_2 are considered constant for about ten years; C must be redetermined after about two years (Wienert, 1970).

Observational errors should not exceed a couple of nanoteslas between periodic calibrations.



Fig. 4.7 Quartz Horizontal Magnetometer

4.7.3 Torsion Photoelectric Magnetometer

The torsion photoelectric magnetometer (TPM) is an example of turning a classical instrument into one that can satisfy the requirements of modern science. The TPM consists of a suspended magnet and mirror system enhanced to give voltage as an output. This is accomplished by reflecting the light beam onto a pair of phototransformers which transform the angle of deviation into a voltage. The output is amplified and fed to a negative feedback winding which acts to keep the mirror stationary. Thus, the current in the negative feedback circuit is a measure of the strength of the magnetic field component.

Although the TPM uses a classical suspended magnet system as its field detector, the use of negative feedback enables the system to record more rapid varia-

tions than a photographic variometer using the same suspended magnet. The sensitivity is also improved. The TPM has good long-term stability (a few nT per year) and a resolution of about 0.01 nT (Jankowski and Sucksdorff 1996),

4.7.4 Kakioka KASMMER System

Kakioka Observatory in Japan has an interesting set-up (KASMMER) for the measurement of components (Tsunomura et al, 1994). Besides standard three component fluxgate magnetometers, three biased scalar magnetometers measure three components of magnetic field concurrently.

Fansleau-Braunbek bias coils are positioned so as to cancel two components of the magnetic field that are not measured, leaving the third one for scalar measurement. Compensation of unwanted components is not overly critical as they are at right angles to the measured component and residual addition to the measured component is suppressed by vectorial addition of one large and two small residual fields.

The latest KASMMER uses custom designed continuous Overhauser magnetometers with one-second recordings.

Available space within bias coils with homogeneous magnetic field makes this set-up somewhat marginal for sensitivity. Proton and Overhauser magnetometers have reduced sensitivity in low magnetic fields. Proper replacement of continuous Overhauser magnetometers with Potassium magnetometers would more than eliminate this weakness.

4.8 Looking Forward

Magnetometry is a mature discipline, so it is unlikely that anything equivalent to the invention of the fluxgate, Proton precession, Overhauser and Potassium magnetometers will take place anytime soon. It is more likely that small incremental advances will be made towards the goal of a truly stable vector magnetometer. Advances will be made in power reduction, data storage and telemetry with the aims of increased automation and cutting costs.

The coming of age of the automated absolute instrument means that it is now possible to consider once again the possibility of a true underwater observatory. All that is needed is a means of determining the direction of true north, which can be accomplished using a north seeking gyroscope (Rasson et al, 2007).

The requirement for 1 pT resolution and sensitivity means constructing a sensor with noise less than or equal to $1 \text{ pT}/\sqrt{\text{Hz}}$ @ 1 Hz. Sensor noise is dependent on the quality of the material from which the core is made. The supply of material from which many of the low noise fluxgate sensors currently in use were made is almost exhausted, and the probability of obtaining more is small. The challenge, therefore, is to come up with new materials for making low noise sensors. Some manufacturers have made considerable progress in developing new materials and now claim that they can achieve a noise level of 5 to 7 pT at 1 Hz. Theoretical studies show that it should be possible to reduce noise by at least another order of magnitude, to under 100 fT (Koch et al, 1999). In addition, new methods of processing the output signal (e.g. time domain signal extraction) are also under development. In fact, fluxgate magnetometers with noise levels below 1 pT have already been built (Vetoshko et al, 2003), but their cost and complexity make the use impractical for geomagnetic purposes.

dIdDs equipped with Potassium magnetometers may prove to be an attractive alternative to fluxgates. With the recent developments in global positioning (GPS) there are now opportunities to precisely orient bias coils of dIdD in vertical (determination of I) and horizontal East-West direction (determination of D). With this orientation dI and dD become I and D.

Inexpensive GPS boards and antennas are now available to differentially determine position within 0.5cm. With two antennas separated by a distance of approximately 20m, the uncertainty in alignment will be 5×10^{-4} radians or 1.72'. For observatory use this set-up still needs initial calibration. However for some field use especially in directional drilling for oil and minerals this sensitivity and accuracy is more than adequate. Having both a fluxgate and a dIdD operating at the same time with the same sampling interval and hopefully the same filtering would provide an excellent check on data quality.

Experimental supersensitive Potassium gradiometer installations are now in operation at few selected observatories.

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A-1 Accuracy and Baselines

The different applications to which magnetometers may be put require either absolute accuracy or relative accuracy. Absolute accuracy is required for a wide variety of scientific investigations: studies of secular variation, main field morphology, fluid flow in the core; long-term external field variations, from Sq to solar cycle, to name a few. Only relative accuracy is required for most other types of investigations: studies of magnetic storms, sub-storms, pulsations. Spatial surveys over a small area carried out for mineral exploration may often need only relative accuracy.

To define absolute and relative accuracy let us consider an observation of the magnetic field (or one of its components), $F(t)$, where t refers to the time of observation. This observation will not normally equal the true value of the magnetic field which we will call $F_T(t)$. The difference between the true and the observed values, δ , is composed of a systematic error, ζ , and a random error, ε

$$\delta(t) = F_T(t) - F(t) = \zeta(t) \pm \varepsilon. \quad (4.19)$$

Note that the systematic error, ζ , and as a consequence, δ , is a function of time. When absolute accuracy is required, that is, when there is a requirement for δ to be close to zero, periodic calibration observations are made to determine the value of $\zeta(t)$. These calibration observations (normally called “absolute” observations) are carried out at least once per week. It is assumed that the change in $\zeta(t)$ between calibration observations is small and linear, so that values of $\zeta(t)$, referred to as baseline values, can be interpolated for all observations of F that fall between the times of the absolute observations. If this is not the case, then aliasing will occur, leading to spurious information for time scales shorter than two weeks. Under these assumptions, the absolute value at time t is

$$F_a(t) = F(t) + \zeta_a(t) \quad (4.20)$$

where $F_a(t)$ is the absolute value of the magnetic field and our best estimate of the true value. The absolute error, then, is

$$\delta_a(t) = F_T(t) - F_a(t) = \zeta(t) - \zeta_a(t) \pm \varepsilon \quad (4.21)$$

The most recent guide for magnetic observatories (Jankowski and Sucksdorff, 1996) claim that at the best observatories absolute accuracy of better than 1nT can be achieved. The INTERMAGNET Technical Manual (St-Louis, 2008) gives a more realistic figure of 5nT.

We now consider the case where observations are made at the same position at two different times t_1 and t_2 . The observed difference, $F(t_1) - F(t_2)$ will differ from the true difference $F_T(t_1) - F_T(t_2)$ by the amount $\delta_r = \zeta(t_1) - \zeta(t_2) \pm \sqrt{2}\varepsilon$. This is the relative error. The actual size of the systematic error ζ is unimportant. What is important is that it be constant over the time interval t_1 to t_2 .

A-2 Absolute Accuracy of Scalar Magnetometers

Most manufacturers of scalar magnetometers have ignored the question of their long term stability since it is of little importance for most usages. Temperature compensated crystal oscillators of stabilities of ± 1 ppm over -40 to $+40^\circ$ C temperature range and over one year aging are commercially available and recommended for observatory work. For long term stability and accuracy one needs to take into account several additional factors (Hrvoic 1996):

1. Gyromagnetic constant
2. Frequency reference
3. Details of taking zero crossings of the precession frequency
4. Phase stability of the precession frequency (Proton and Overhauser magnetometers)
5. Chemical shift of the Overhauser/ppm sensor liquid

While points 2-4 are engineering problems that can be resolved by proper design of the electronics, the gyromagnetic constant is “given” to us by National Standards Associations like NIST(USA), NPL (U.K.), VNIIM (Russia), NIM (China).

The value of the gyromagnetic constant and the tolerances are updated periodically. In the past we even had “western” and “eastern” γ_p determined by NIST, NPL and VNIIM and strong and weak fields γ_p . γ_p is traditionally computed for water as a solvent. For different solvents, the value must be corrected due to “chemical shifts” caused by molecules of the solvent.

Water has chemical shift relative to TMS (tetramethylsilane) of 5.6 parts per million i.e. under the same conditions the precession frequency of protons in water will be 5.6 ppm lower than that of TMS; Methanol has a shift of about 3.6 ppm i.e. in the same magnetic field it will give 2 ppm higher frequency. Since $B = \frac{\omega_0}{\gamma_p}$,

we need to increase γ_p for methanol by 2 ppm. The uncorrected error would be 0.1 nT at 50,000 nT magnetic field.

Any magnetic inclusions in the sensor will change the local field and influence the measurement. Paramagnetic and diamagnetic materials like housing, copper wire etc may also influence the measurement and reduce absolute accuracy. And so can the gradient over sensor volume.

Presently one can attain an absolute accuracy of a fraction of a part per million with properly designed scalar magnetometers (Overhauser or Potassium). This, at a minimum, requires a thermostated crystal oscillator or Rubidium/Cesium frequency standards and very careful design of sensors and electronics.

List of Abbreviations

AMOS	Automatic Magnetic Observatory System (Canada)
ASMO	Automatic Magnetic Observatory System (USA)
AUTODIF	Automated DIM
BMZ	Balance magnetometrique zero
CARISMA	Canadian Array for Realtime Investigations of Magnetic Activity
CCD	charge coupled device
dIdD	(delta Inclination / delta Declination)
DIM	Declination-inclination fluxgate magnetometer
DMI	Danish Meteorological Institute
EDA	Electronic Design Automation
EPR	Electron Paramagnetic Resonance
GAUSS	Geomagnetic Automated System
GPS	Global Positioning System
IAGA	International Association of Geomagnetism and Aeronomy
IGRF	International Geomagnetic Reference Field
KASMMER	Kakioka Automatic Standard Magnetometer
LEMI	The Laboratory of Electromagnetic Innovations
MACCS	Magnetometer Array for Cusp and Cleft Studies
MRI	Magnetic resonance imaging
NIM	The National Institute of Metrology (CHINA)

NIST	The National Institute of Standards and Technology (USA)
NMR	Nuclear magnetic resonance
NPL	National Physical Laboratory (U.K.)
PCs	Personal computers
PDA's	Personal Digital Assistants
QHM	Quartz horizontal magnetometer
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TCXO	Temperature Compensated Crystal Oscillator
TPM	Torsion photoelectric magnetometer
TMS	tetra methyl silane
UCLA	University of California at Los Angeles' fluxgate magnetometer
VNIIM	D.I. Mendeleyev Institute for Metrology (RUSSIA)