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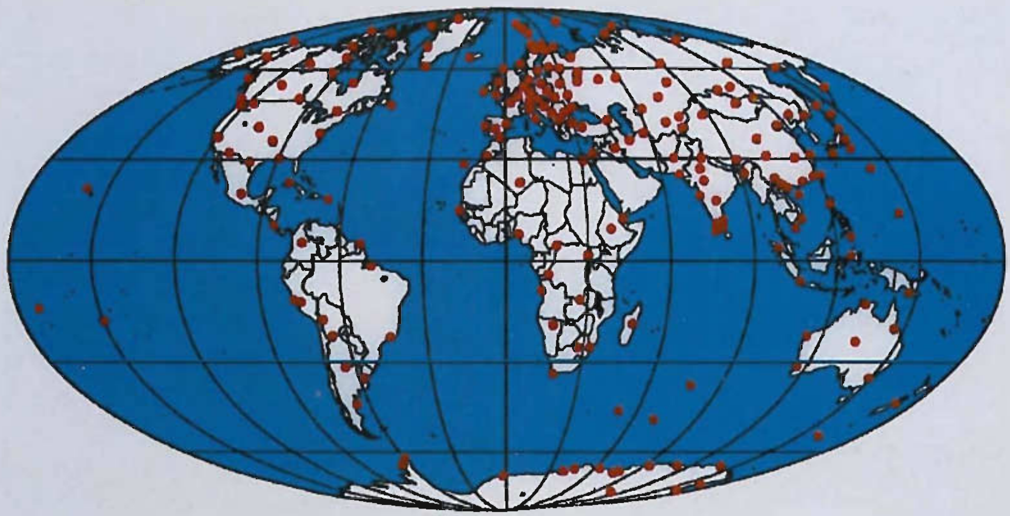
GUIDE FOR MAGNETIC MEASUREMENTS AND OBSERVATORY PRACTICE

by

JERZY JANKOWSKI and CHRISTIAN SUCKSDORFF



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GUIDE FOR MAGNETIC MEASUREMENTS AND OBSERVATORY PRACTICE

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1. INTRODUCTION

The objective of geomagnetic observatories is to record continuously, and over the long term, the time variations of the magnetic field vector and to maintain the accurate absolute standard of the measurements.

To fulfill the present requirements of accuracy means that over the whole recorded spectrum, the variations should be recorded with an accuracy of about 1% or better. To achieve this at the low frequency end of the spectrum, which means very slow variations like the annual change, current technology requires independent absolute measurements to be made periodically in order to calibrate the continuously recording instruments.

This Guide describes the present instrumentation in geomagnetism, concentrating mainly on the use of the instruments so that the required high accuracy is achieved. The main phenomena studied in geomagnetism are also briefly described, and so is the physics behind the measurement techniques, because we believe that understanding why and how the measurements are made increases the interest in the work and leads to higher quality results.

The history of magnetism and its practical use is thousands of years long, according to ancient literature and poems. No exact data exist on the discovery of the compass and its use; they are only mentioned in other contexts. The mystical power of magnetite or lodestone of attracting iron particles is mentioned by the Chinese hundreds of years B.C. So is the method for making needles magnetic and north or south orienting by rubbing the needles with lodestone. According to the book entitled *Dream Pool Essays* by the Chinese scientist Shen Kua, the Chinese used compasses in seafaring in the eleventh century A.D. On land, south pointing needles were in use in China perhaps thousands of years earlier. Iron technology was advanced in ancient China. The Chinese could produce steel, which was a good material for compass needles. The earliest definite mention of the use of a mariner's compass in Europe is by Alexander Neckam, about 1190, in his *De Utensilibus* and *De Naturis Rerum*, but probably the compass was already a routine instrument at that time (for the history of terrestrial magnetism see, e.g., Chapman and Bartels (1940), pp. 898–937, and for the Chinese inventions, e.g., Temple (1986), and, in greater detail, *Science and Civilisation in China* by Joseph Needham (Needham, 1962), where Vol. 4, Part 1, deals with the physical sciences including music and magnetism).

The magnetic variation or magnetic declination (the compass needle does not point exactly to geographic north) was probably known in China long before it became known in Europe. That the declination was known in Europe by about 1450 A.D. has been deduced from portable sun-dials, which often have a compass in which the deviation from geographical north is marked. Centuries older Chinese geomancer's compasses have two sets of points showing the magnetic declination at two different times in the past (Temple, 1986). Columbus on his voyage to America in 1492 supposedly reported the change of declination with longitude, but no reliable documents have been found.

That the magnetic needle also shows an inclination was probably first discovered by Georg Hartmann in Rome in about 1510, according to his letter of 1544 in which he pointed out that in addition to declination, the needle also tilted with respect to the horizontal plane.

Based on observations of inclination available from different latitudes, William Gilbert published in 1600 his famous book *De Magnete* in which he pointed out that the Earth itself acts as a great spherical magnet. This can be considered the beginning of the science of Earth magnetism.

Until the year 1634 it was believed that magnetic declination was only a function of position. In 1634 Henry Gellibrand measured declination in London to be 4.1°E. In 1580 Burrow and Norman had measured, at the same site, 11.3°W. The change in declination was too big to be an error in the observations. The conclusion was that declination changed with time: the so-called secular variation of the geomagnetic field was discovered.

The continuous daily variation of magnetic declination was published by Graham in 1722; he observed irregular variations of up to 30′ in his improved declinatorium. Celsius in Uppsala confirmed these observations in 1740, and his student Hiorter found that during auroral displays the compass needle could move by degrees. In a letter to Graham, Celsius asked him to make observations in London at the same times as Hiorter made observations in Uppsala. The simultaneity of magnetic disturbances was confirmed. Later observations showed that inclination also varied. After Coulomb's invention of a relative method to measure the intensity of the horizontal component of the magnetic field in 1785 (torque, oscillating magnet), the intensity was also found to vary with time. Finally, in 1832 Carl Friedrich Gauss' paper on absolute measurement of the intensity of the magnetic field was published.

Now tools were available for the measurement of all components of the vector representing the magnetic field of the Earth. The field was observed to vary with place and time.

Alexander von Humboldt showed that the intensity of the horizontal magnetic field was strongest at the equator and weakest at the poles. He made observations of oscillating magnets over several years in different parts of the world, including both Americas (1799–1803). On his initiative, magnetic observatories were created in many countries for synoptic observation of the variations of the field. In Göttingen, Gauss and Weber began in 1834 to participate in von Humboldt's program: during eight periods of 44 hours the needle was observed at least once every hour. In 1838 von Humboldt wrote to different authorities encouraging them to adopt Gauss' manner of observing. A number of observatories joined the *Magnetische Verein* (Göttingen Magnetic Union) which proposed that observations be made at 5-minute intervals. The total number of observatories participating in the years 1836–1841 was about fifty. The simultaneity of magnetic disturbances over large areas was confirmed. Gauss developed his general theory of geomagnetism and showed that almost all the magnetic field observed at the Earth's surface originated inside the Earth (Gauss, 1839).

Since the time of Gauss, the number of geomagnetic observatories has grown to about 150 (Figure 1.1), partly due to international campaigns like the International Polar Year 1882–1883, Second International Polar Year 1932–1933, International Geophysical Year 1957–1958 and several campaigns thereafter. The role of observatories has been and still is essential in monitoring the variations of the geomagnetic field, both for science and for commercial and governmental uses, as will be briefly discussed later. Today, in addition to the permanent geomagnetic observatories, there are many recording stations in operation during special campaigns in different parts of the world. These temporary stations have as a rule similar magnetometers to those used at modern magnetic observatories.

There are *global*, *regional* and *local* needs for geomagnetic observatories. An

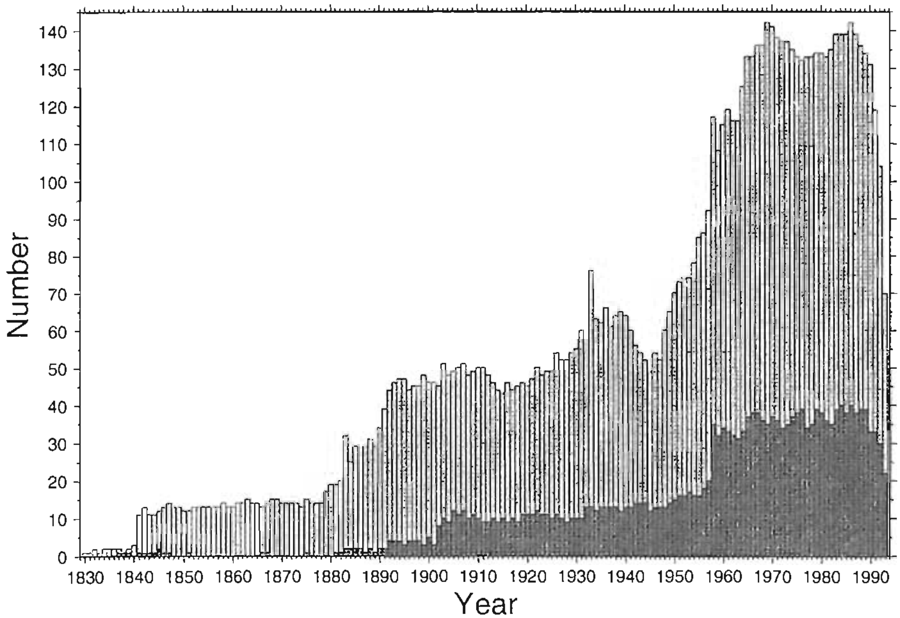


Figure 1.1. Number of magnetic observatories providing annual means to WDC C1 by the end of 1994, located in the northern (grey) and southern (black) hemispheres. Courtesy of the Geomagnetism Group, British Geological Survey.

Currently operating observatories on a Hammer equal-area projection

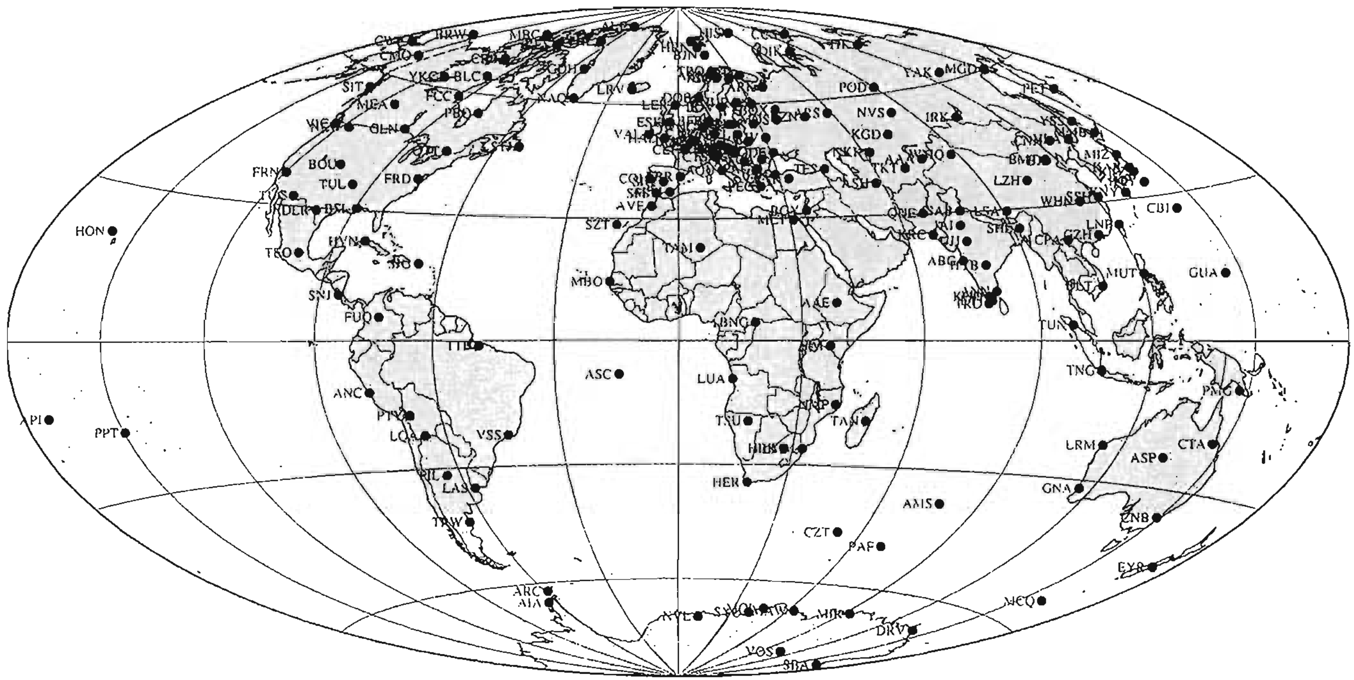


Figure 1.2a. Permanent geomagnetic observatories in operation in 1994. A list of the observatories with codes and coordinates is given in Appendix I. Courtesy of the Geomagnetism Group, British Geological Survey.

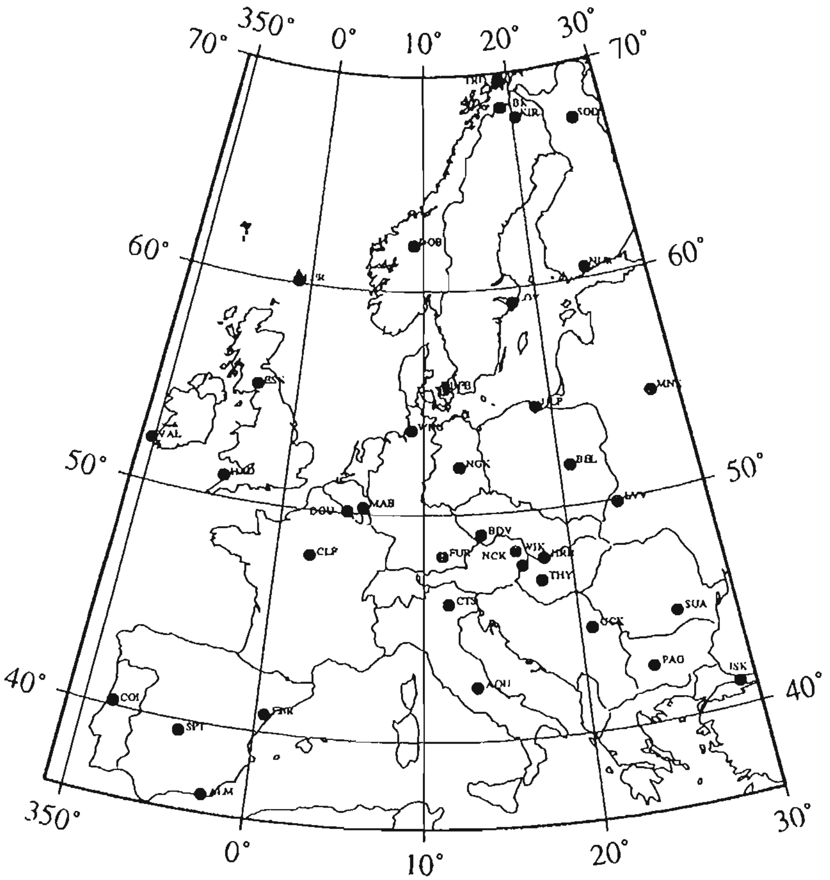


Figure 1.2b. European permanent geomagnetic observatories in operation in 1994. Courtesy of the WDC A.

important *global* task is to monitor the secular variation of the magnetic field all over the world, because the secular variation is the only known way to study the motions of the electrically conducting fluid in the Earth's outer core, in which the main geomagnetic field is generated. A sufficiently dense global network is also needed for the calibration and control of magnetic survey satellites used in detailed surveys of the magnetic field. A global network is essential in monitoring magnetic storms and other magnetic variations, because these phenomena affect large areas of the Earth and have different effects in different areas. A global network is needed for research into current systems in the ionosphere and magnetosphere and induced currents in the crust and mantle. A more dense network than the present one is needed in the polar cap areas due to their special role in a number of studies connected with magnetospheric phenomena, and also in the equatorial region, where the behavior of the equatorial electrojet needs detailed study. The variations of the magnetic field near the equator are also important for studies of the ring current in the near-Earth space.

A typical *regional* need for a magnetic observatory is to serve as a base station for magnetic surveys. The data from the observatory or preferably from several observatories in the region are used in reducing the measured survey data to the desired epoch (more on the reduction of data is to be found in the *Guide for Magnetic Repeat Station Surveys* by Newitt, Barton and Bitterly, 1996). The final product of a survey is usually a regional magnetic chart, which is later updated at regular intervals with the help of the secular variation recorded at the observatories, thus making a new detailed magnetic survey unnecessary. In many cases this means large savings of funds. Another regional use is working as a base station in magnetotelluric soundings.

From a *local* point of view, a magnetic observatory monitors the local magnetic variations, the knowledge of which is needed, for example, in connection with observed power failures or difficulties in telecommunications. An observatory provides facilities for calibration of magnetic instruments. Very often the observatory is the only place to obtain information on local geomagnetic declination and its change, and in the case of special phenomena like aurora, confirmation of the natural character of the phenomenon may be obtained from the observatory. Local recording of magnetic variations is often needed by prospecting companies for the reduction of their data.

The examples mentioned above show the need for magnetic observatories. To facilitate work at observatories, several guides for observatory practice have been written over the years. The last manual was K. Wienert's (1970) *Notes on Geomagnetic Observatory and Survey Practice*. It is an excellent book giving practical advice and solutions to probably all the problems at observatories and in magnetic field work faced at that time, more than twenty years ago.

Many of the problems in observatory work and their solutions are still the same. These we shall discuss only briefly in this Guide, referring to Wienert, whose *Notes...* we expect every observatory to have on its bookshelf. The older manuals, D.L. Hazard's (1947) *Directions for Magnetic Measurements*, H.E. McComb's (1952) *Magnetic Observatory Manual* and R. Bock's (1942) *Praxis der Magnetischen Messungen* deal with classical instruments which are practically no longer in use. Many chapters in these old manuals are devoted to the fields of permanent magnets.

The nature of the observatory work has changed much since Wienert's book was written. Today most observatories produce their data in digital form, which was so rare twenty-five years ago that Wienert did not discuss it at all. New techniques in instrumentation have made it possible to automate part of the observatory work. This, in principle, positive, fund-saving development has at the same time created some new problems. One is the fact that professional observers in charge are becoming more and more scarce. This has led, at some observatories, to a reduction in accuracy. We feel that this does not need to be the case. On the contrary, the modern instruments allow, if properly used, an increase of absolute accuracy. This is important, because the new era with global magnetic surveys using satellites will need even more accurate observatory data than before. For example, the annual secular variation in some areas is only of the order of one nT per year, which shows that the accuracy of the annual mean values has to be at least this high. Therefore, the highest possible absolute accuracy is a goal at all observatories. Efforts to achieve high accuracy used to be a tradition at the observatories where specially trained scientific staff with scientific ambitions worked. Today the observers are often technicians who are highly skilled in handling modern technology. One of the intentions of this Guide is to convince the observers of the importance of their work.

Methods of absolute magnetic measurement have changed during the last twenty years. The introduction of the proton magnetometer and non-magnetic theodolites with fluxgate sensors have dramatically improved the situation and made it possible for almost anyone, with proper training, to succeed in making good measurements. Twenty years ago the measurements were almost an art, requiring special skill and much training.

The importance of absolute measurements as a verification of the recording instruments is roughly the same as before. Some of the new recording instruments are stable enough to allow a reduction of the number of absolute measurements, especially at observatories with back-up recording. Some other methods to control the stability can in some cases also be applied. Although they do not replace real absolute measurements, they are helpful and will be discussed in this Guide.

The global network of magnetic observatories is in many areas too sparse to meet all the needs of magnetic surveying and for the study of physical phenomena inside and outside the Earth, as can be seen from Figure 1.2a, which shows large areas without observatories even outside the oceans. Some new observatories are under construction and planned, especially for developing countries, but more are needed. This Guide gives some advice for the construction of new observatories and recording stations. New observatories may also be needed for other reasons: railways, roads, buildings or other constructions may force the sensitive instruments at existing observatories to be moved to undisturbed areas.

Many magnetic observatories are traditionally places capable of answering special questions concerning magnetism and its measurement. Also measurement of the magnetism of some objects or limited magnetic surveys are sometimes requested. This Guide handles some of the most common questions and problems expected to appear.

In addition to advice on observatory practice, we try to give some physical background on the instruments and phenomena because we feel that this information is often requested from observatory staff and also that this may be helpful for repairing instruments or judging the relevance of the results of recordings or measurements.

As stated above, the measurements themselves require less skill from the observer than in older times. In many cases it is only a question of pushing a button or transmitting data collected in the memory of a computer. All this seems to favor automatic recording stations, visited rather infrequently by technicians. This is surely true for instrument arrays installed for special purposes, such as induction studies or studies of current systems in the ionosphere. But in the case of real magnetic observatories producing data for a variety of studies starting from secular variation where the absolute accuracy should be at least 1 nT, we favor manned observatories with skilled personnel, whose interest is to produce data of as high quality as possible. So, the difficulty today is not in the absolute measurements but in the skill to judge the correctness of the data produced and in taking action as soon as some doubt appears. This is not possible without continuous monitoring and use of the data. Using modern electronic networks, monitoring can be centralized for a number of observatories, but we still believe that having the observer on the spot is best to ensure the quality of the data.

Referring to the general needs for magnetic observatories mentioned above, one of the first matters in planning a new observatory is to consult the map and see if in the planned area there possibly already exists an observatory close enough for the planned needs (e.g., a base station for magnetic surveys, for the updating of magnetic charts, for tests of instruments or for scientific research). Advice and help from the Working Group for Magnetic Observatories (IAGA Div.V, WG 1; see Chapter 10) is always available and contact with the working group is recommended. In planning a new magnetic observatory, IAGA will provide advice, approve the official three-letter code for the observatory, recommend the scale for the activity indices *K* to be produced at the observatory, etc. INTERMAGNET (see Chapter 10) is also an excellent source of help and advice on observatory matters.

The authors of this Guide wish to thank IAGA Division V and its Working Group for Magnetic Observatories for the encouragement to write this Guide. We especially wish to thank the participants of the roundtable meeting arranged by the Polish Academy of Sciences to discuss the Guide during one week in February 1994. The participants were David Kerridge, Richard Coles, Emil Kring Lauridsen, and the authors. The roundtable workshop was of great importance in shaping the final form of the Guide.

Special thanks are due to David Kerridge and Richard Coles for their thorough revision of the final text and very beneficial language corrections.

2. THE MAGNETIC FIELD OF THE EARTH

The magnetic field of the Earth observed all over the globe is a vector field. Three components of the vector $\boldsymbol{F}$ are needed to describe the field. The usual components recorded or observed are plotted in Figure 2.1.

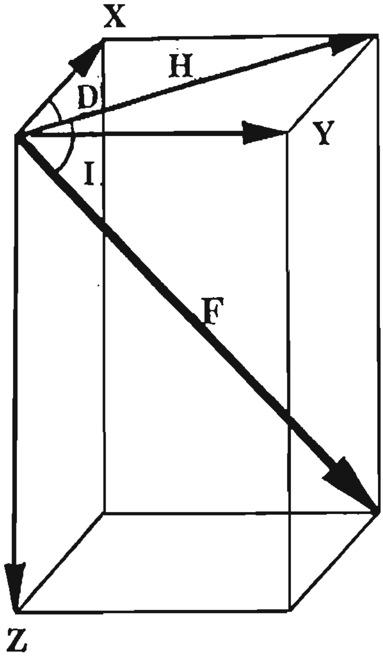


*Figure 2.1. The elements of the field vector describing the Earth's magnetic field. X = north component of the vector, Y = east component of the vector, Z = vertical component of the vector (positive down) called vertical intensity, H = horizontal intensity or the horizontal component of the vector along local magnetic meridian (positive direction towards the north), D = magnetic declination or the angle (positive east) between the geographic north direction and the magnetic meridian (angle between **X** and **H**), and I = magnetic inclination or the angle between the horizontal intensity vector (**H**) and the direction of the magnetic field vector of total intensity (F). I is positive downward.*

The formulas showing relations between the components (Figure 2.1) are

$F^2 = X^2 + Y^2 + Z^2 = H^2 + Z^2;$

$H^2 = X^2 + Y^2;$

$$X = H\cos D;$$

$$Y = H\sin D = X\tan D;$$

$$Z = F\sin I = H\tan I; \tag{2.1}$$

$$D = \arctan(Y/X);$$

$$I = \arctan(Z/H).$$

As mentioned in the historical notes of Chapter 1, William Gilbert (1600) deduced from observations made at different latitudes that the Earth's magnetic field is similar to that of a magnetized sphere. His conclusion was that the Earth is a spherical magnet. Later, more detailed observations showed that the field at the Earth's surface roughly resembles the field of a magnetic dipole placed close to the Earth's center and tilted 11.5° from the rotation axis of the Earth. More than 90% of the observed field can be approximated by this simple dipole model. Today we know that the field of a magnetized sphere is similar to the field of a magnetic dipole placed at the center of the sphere. We also know that the hypothesis of a magnetized sphere cannot be right because the iron in rocks cannot be magnetized at temperatures higher than the Curie point, which is exceeded at a depth of a few tens of kilometers. A static model cannot explain the long period variations of the field and even less the reversals of the field which are known to have occurred at irregular intervals of the order of hundreds of thousands of years.

According to the present explanation, the so-called hydromagnetic dynamo theory, the main part of the Earth's magnetic field arises from electrokinetic currents running at or close to the surface of the outer liquid core at a depth of about 2900 km. The field at the Earth's surface due to these currents is about 30 000 nT at the equator and 60 000 nT in polar areas. The current systems in the core do not seem to be stable and homogeneous. Therefore, the field measured at the Earth's surface shows large anomalies compared to a dipolar field. These *regional magnetic anomalies* have dimensions of thousands of kilometers and are caused mainly by the inhomogeneity of the electric currents inside the Earth. The non-uniform distribution of magnetic minerals in the Earth's crust is also seen as smaller scale anomalies in the otherwise rather smooth field. These local anomalies can be strong, several tens of thousands of nT.

2.1 Main field and secular variation

The *main field* of the Earth is that part of the field which has its origin in the core. The change of the main field is called *secular variation*, which well describes the slow character of the variation.

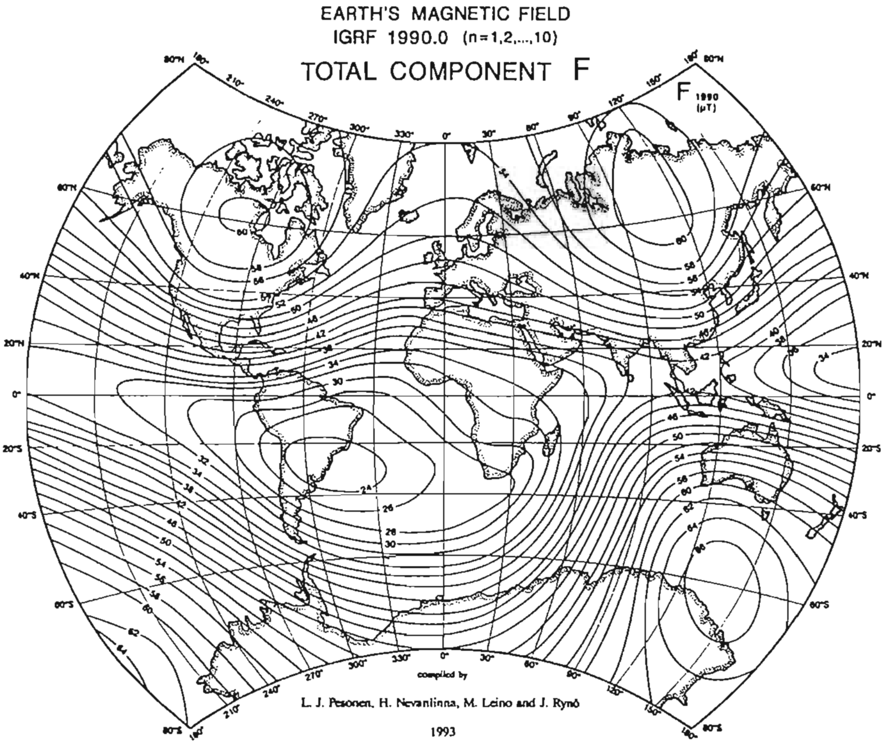


Figure 2.2. Chart of the total intensity F in 1990. The chart is based on a 10th degree spherical harmonic representation (n = 10) of the field (Pesonen et al., 1993).

The global magnetic field is usually represented by spherical harmonic coefficients (Chapman and Bartels, 1940).

The spherical harmonic expression of the magnetic field is based on the assumption that the Earth's field is a pure potential field ($\boldsymbol{F} = -\nabla V$, $\nabla \cdot \boldsymbol{F} = 0$). That seems to be true within the accuracy of the measurements. The expressions above yield the Laplace equation

$$\nabla^2 V = 0 \tag{2.2}$$

The potential at the Earth's surface is a sum of the potential from inside the Earth, V_i, and the potential from the sources outside the Earth, V_e. At the Earth's surface the field due to external sources is so much smaller than that from internal sources that it is often excluded. The potential from inside sources is:

$$V_i = a \sum_{n=1}^{\infty} \sum_{m=0}^{n} (a/r)^{n+1} P_n^m(\cos\theta) \left[g_n^m \cos m\lambda + h_n^m \sin m\lambda \right] \tag{2.3}$$

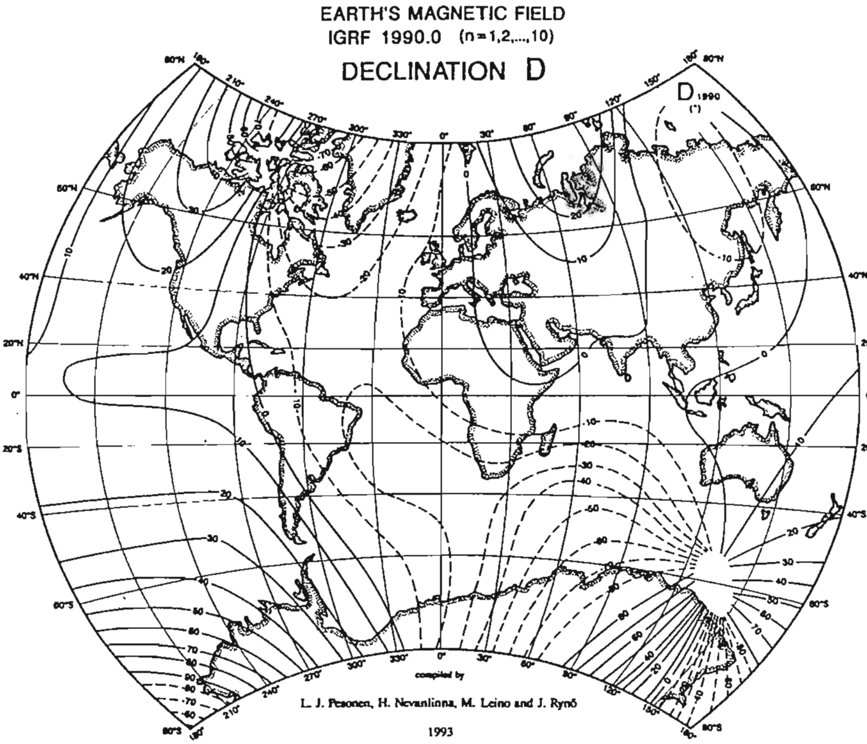


Figure 2.3. Chart of the declination D in 1990. The chart is based on a 10th degree spherical harmonic representation (n = 10) of the field (Pesonen et al., 1993).

The solution is given in polar coordinates r, θ, λ, where r is the radius (here from the Earth's center, θ is the colatitude measured from the north pole and λ is the longitude measured eastward from the Greenwich meridian. $P_n^m(\cos\theta)$ are the normalized associated Legendre functions, which can be found in several textbooks on geomagnetism (e.g., Chapman and Bartels, 1940; Parkinson, 1983). g_n^m and h_n^m are spherical harmonic coefficients or Gauss coefficients describing the field at the points r, θ, λ.

The components of the magnetic field vector are

$$X = r^{-1}\partial V/\partial\theta$$

$$Y = -(r\sin\theta)^{-1}\,\partial V/\partial\lambda \qquad (2.4)$$

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

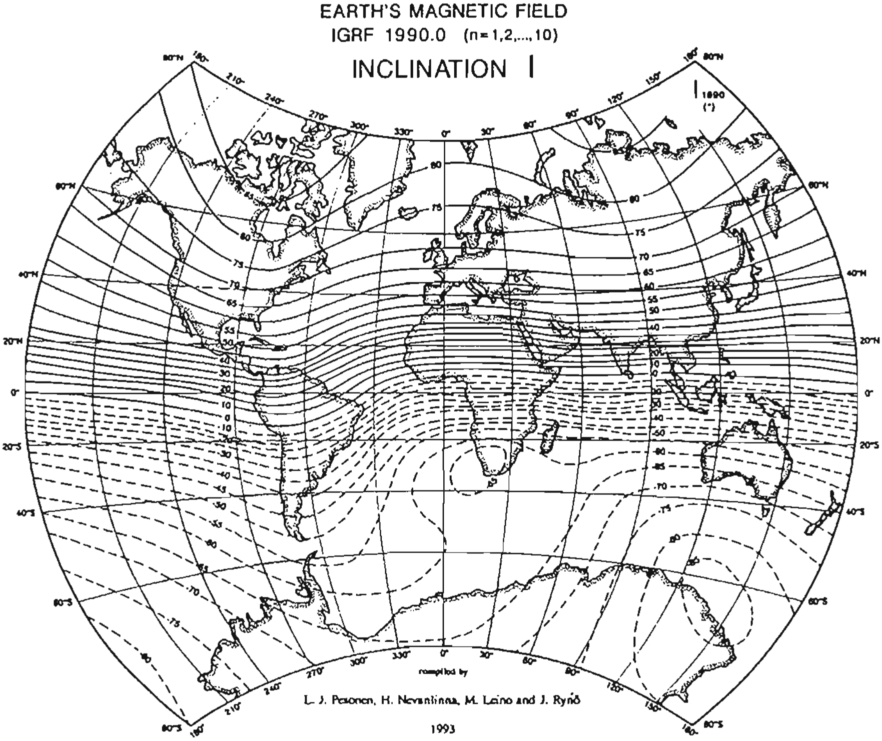


Figure 2.4. Chart of inclination I in 1990. The chart is based on a 10th degree spherical harmonic representation (n = 10) of the field (Pesonen et al., 1993).

where V is the potential V_i, if only the internal part of the magnetic field is considered, as usual, and $r = a$ at the Earth's surface.

Using the formulas given above it is possible to calculate the magnetic field at the Earth's surface ($r = a$), or in the near-Earth space. The first coefficient g_1^0 describes a dipole placed at the Earth's center and oriented along the rotational axis of the Earth. The next two coefficients, g_1^1 and h_1^1 (Table 2.1), describe two other dipoles at the center, perpendicular to the rotation axis. All three together describe an inclined dipole at the Earth's center. The magnitude of the resultant dipole moment is $(4\pi/\mu_0)\,B_0\,a^3$, where $B_0 = \left[(g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2\right]^{1/2}$. B_0 is the horizontal component at the *geomagnetic equator*. The polar angle or colatitude of the resultant dipole is $\theta_0 = \cos^{-1}(g_1^0/B_0)$, giving the latitude of the *dipole pole* or *geomagnetic pole*. The longitude of the geomagnetic pole is obtained from the equatorial dipoles: $\lambda_0 = \tan^{-1}(h_1^1/g_1^1)$. $(a_0, \theta_0, \lambda_0)$ is the geomagnetic south pole. The antipode, the geomagnetic north pole, is, in 1995, situated at 10.5° northern colatitude and 288.6° eastern longitude. The dipole moment $(4\pi/\mu_0)\,B_0\,a^3$ is approximately $8.1\cdot10^{22}$ A m^2.

The coefficients g_n^m and h_n^m are based on magnetic measurements made by satellites and at the surface. For many practical tasks and scientific work all over the world, a knowledge of the main field in different parts of the Earth is needed. Therefore, the International Association of Geomagnetism and Aeronomy (IAGA, see Chapter 10) has decided to publish at five year intervals the so-called International Geomagnetic Reference Field (IGRF), which is the field represented by harmonic coefficients up to 10th degree (n = 1, 2, ..., 10). The coefficients were first calculated for the year 1965.0. Later, IGRF's have been determined for the five-year epochs starting from 1945.0. The 1990 revision of the IGRF is described by Langel (1991). The IGRF's are formally accepted at the Assemblies of IAGA, which declares the IGRF as the Definitive International Geomagnetic Reference Field (DGRF) when changes or additions to the data used in the calculation of the coefficients are no longer probable. Figures 2.2–2.4 show the geomagnetic charts of the world based on the 1990.0 IGRF.

Table 2.1

The first three harmonic coefficients for the representation of the Earth's magnetic field for 1955.0–1990.0 (Langel, 1991). The first coefficient gives the intensity of the axial dipole, the second and third ones refer to the dipoles perpendicular to the first one. All three together represent the tilting dipole at the center of the Earth. The last column gives the annual change for 1990–1995

	n	m	1955	1960	1965	1970	1975	1980	1985	1990	1990 –95
g	1	0	−30500	−30421	−30334	−30220	−30100	−29992	−29873	−29775	18.0
g	1	1	−2215	−2169	−2119	−2068	−2013	−1956	−1905	−1851	10.6
h	1	1	5820	5791	5776	5737	5675	5604	5500	5411	−16.1

The geomagnetic zero-meridian is the meridian running from the geographical north pole through the geomagnetic north pole to the geographical south pole. In Figure 2.5 the geographical and dipole coordinates are superimposed on each other.

As mentioned earlier, the Earth's magnetic field experiences slow changes called secular variation. It is included in the harmonic representation of the field by adding time derivatives of coefficients to the representation of the International Geomagnetic Reference Field (IGRF). In Table 2.1 they are given for the year 1990 (1990.0–1995.0). The knowledge of the secular variation is essential in updating magnetic charts and in theoretical modeling of the geomagnetic dynamo responsible for the generation of the field. Monitoring the secular variation is the most difficult task of magnetic observatories because the annual changes are small. In the majority

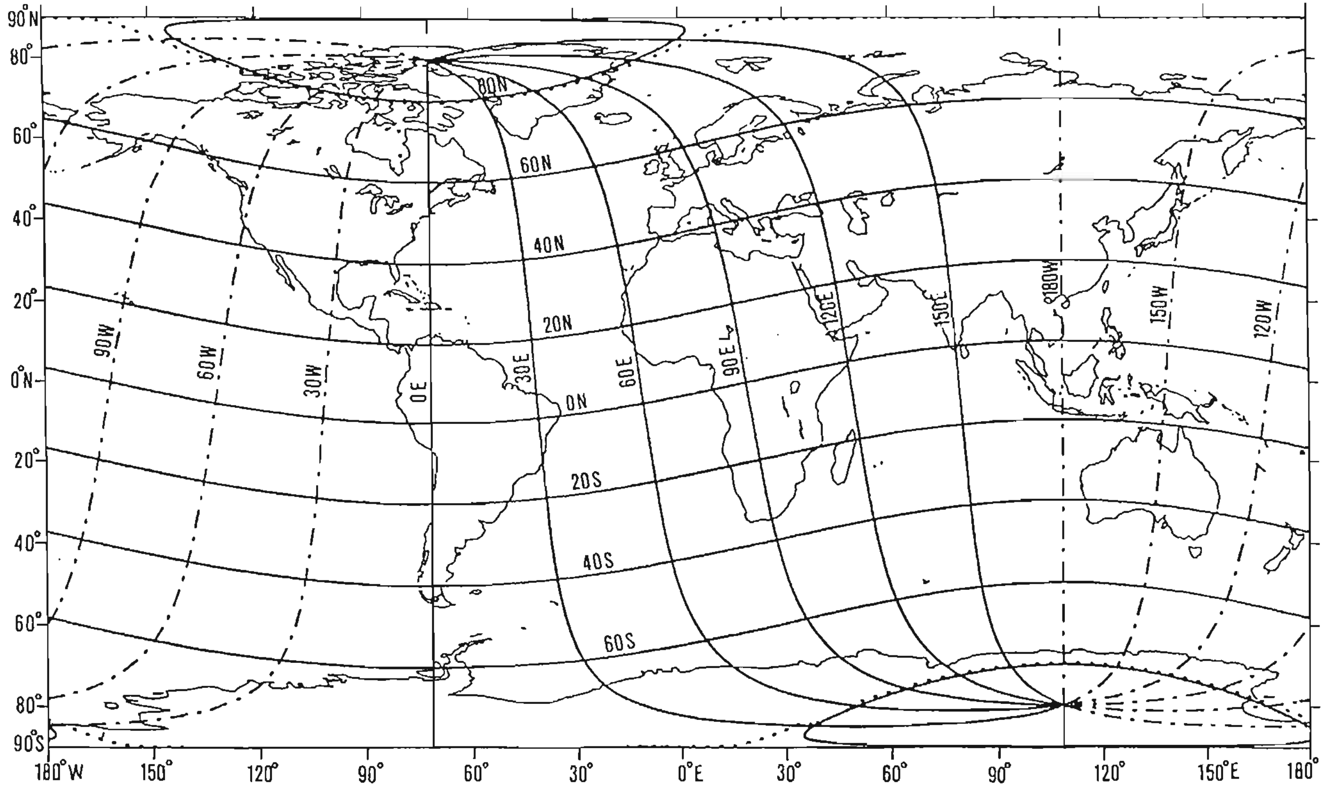


Figure 2.5. Geographical and geomagnetic (dipole) coordinates for 1990 superimposed on each other. Rectangular projection. Geomagnetic pole (IGRF 1990 and 1995): 79.5°N, 71.4°W. Note that the geomagnetic coordinates may change from year to year due to the secular variation of the geomagnetic field.

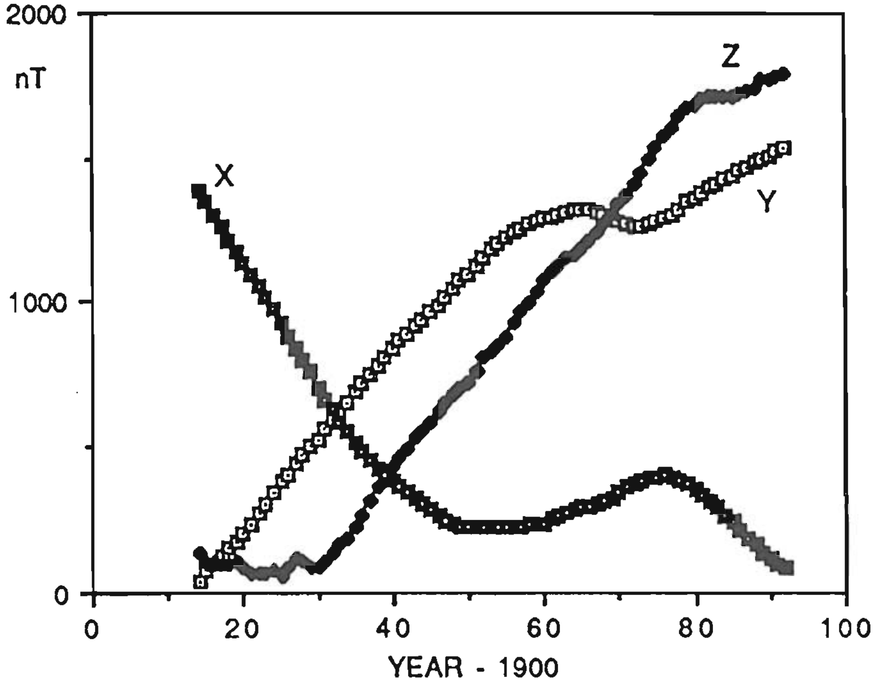


Figure 2.6. The X, Y and Z components as recorded at the Sodankylä geophysical observatory (67°22.2'N, 26°37.8'E) in 1914–1992. 49000 nT has to be added to the value of the vertical scale for the Z component, and 11000 nT for the X component. "0" of the horizontal scale corresponds to 1900.

of areas of the world the number of magnetic observatories is not adequate for sufficiently accurate determination of the secular variation. Therefore, so-called repeat stations have been created to help to fill the gaps. A special guide on these difficult measurements has been written by Newitt *et al.* (1996). An example of the secular variation at an observatory (Sodankylä) is given in Figure 2.6.

The secular variation is clearly seen also in the five-year values of Table 2.1 showing reduction of the strength of the central dipole. The coefficients of higher order (n = 2, ..., 10, not shown in Table 2.1) show regional changes of the field in different parts of the world. So, for example, the actual magnetic poles, where the field is vertical, do not coincide with the geomagnetic poles of the harmonic representation, and move from year to year. The actual magnetic equator is not a simple circle, as the geomagnetic one in Fig. 2.5. The actual north magnetic pole, the *dip-pole*, where the magnetic field is vertical in the northern hemisphere, was in 1994 at 78.3°N, 104.0°W (Newitt and Barton, 1995). The *dip-equator* or magnetic equator is situated where the lines of force are horizontal.

2.2 Crustal anomalies

The actual magnetic field departs from the model discussed above. The dipole field is a crude approximation, and a spherical harmonic representation of 10th degree is only an approximation of the field, which may differ by thousands of nT from the locally measured field. Harmonics of higher degree take more and more into account the local anomalies of the field, but the model is still limited in its ability to describe them. Separate harmonic representations can be used in limited areas to describe the field. The so-called spherical cap harmonics have been successfully used in Canada (Haines, 1985) and Finland (Nevanlinna *et al.*, 1988). Polynomial representation is simplest and has been widely used. All these smoothing methods are useful in making magnetic charts for rather large areas like countries. They are not intended to show local crustal anomalies but rather to show a reference field for the identification of the local anomalies. The local anomalies originate in the crust and provide information about the properties of the rock complexes. Thus, geomagnetic measurements are an important part of geophysical prospecting.

Originating at a depth of 2900 km, the current systems inside the Earth cannot be expected to produce anomalies of a scale less than the order of thousands of kilometers in diameter. The smaller ones, from hundreds of kilometers to a few meters, are of crustal origin. Part of the anomalous field is caused by remanent magnetization. For example, volcanic rocks may become magnetized in the Earth's field when cooling. Part of the field may be caused by induced magnetization in the Earth's present field. The ratio of these magnetizations is not known generally; it has been determined only for rocks close to the surface in connection with geophysical prospecting or in special geological research.

A very strong local anomaly has been found near Kursk, 400 km south of Moscow. It is 250 km long, and is composed of two parallel strips running from NE to SW. The horizontal intensity varies from 20 000 to 80 000 nT and the vertical intensity from 40 000 to 180 000 nT. The declination varies from 100°W to 60°E. Another strong anomaly is in Kiruna in Sweden, where the maximum value of the vertical intensity reaches 360 000 nT. The Kiruna ore is almost pure magnetite. An example of dangerous anomalies occurs at Jussaro in the Gulf of Finland, where the anomalous part of the field is over 60 000 nT and where the disturbances in declination have caused several shipwrecks. Very local anomalies of a similar strength can be found in many areas. Sometimes the dimensions can be just a few meters if there is a boulder containing much magnetite close to the surface.

In the hands of experienced geophysicists, maps of anomalies of the magnetic field tell about the geological structure of the crust. Combined with other geophysical and geological information, the magnetic data may lead to the finding of profitable ores. Therefore, aeromagnetic surveys are commonly carried out in most areas of the world. The whole area of many countries has been surveyed. An example of an aeromagnetic map is shown in Figure 2.7, depicting the magnetic field in the surroundings of the Sodankylä observatory.

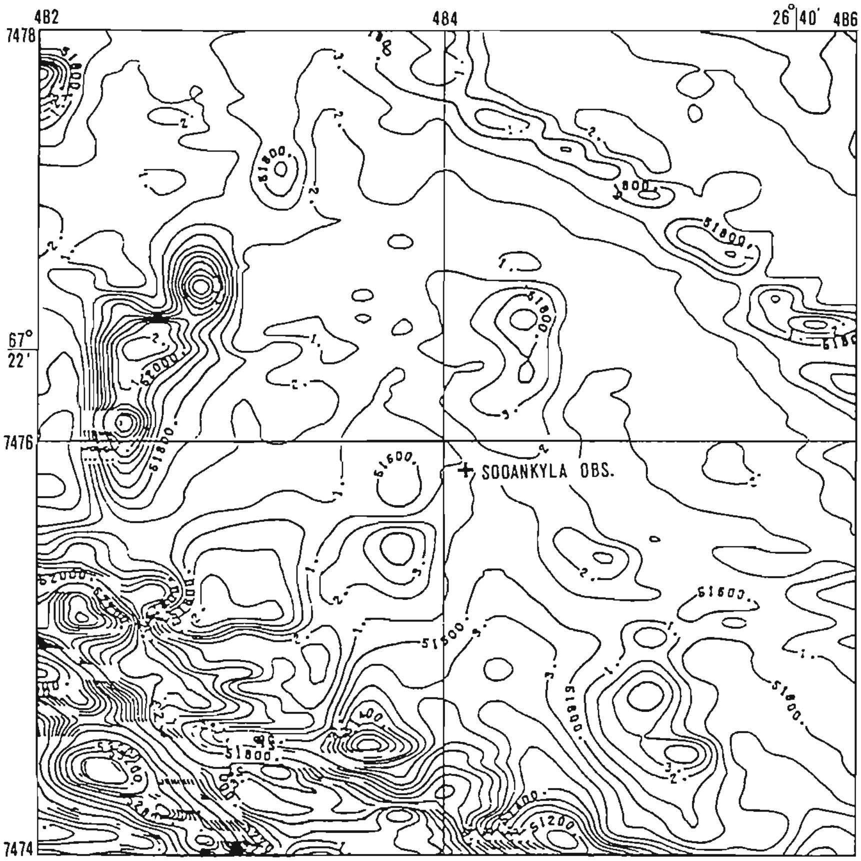


Figure 2.7. Aeromagnetic map of total intensity F of the area of Sodankylä observatory in North Finland. The separation of contour lines is 50 nT. The spacing of the numbered lines is 200 nT. The lines labeled 1, 2 and 3 mean 50 nT, 100 nT and 150 nT higher values counted from the line with the explicit field value. The flight altitude was 40 m and the spacing of flight lines 200 m. Finland's whole area has been aeromagnetically measured from an altitude of 150 m, line spacing 400 m. Courtesy of Geological Survey of Finland.

2.3 Regular variations of the magnetic field

The regular variations of the magnetic field are related to rotation and/or orbital movements of the Earth, Sun and Moon. The most prominent is the diurnal variation or solar daily variation, having an amplitude of the order of 10–100 nT. Solar radiation ionizes the higher atmosphere during the daylight hours, and the gravitational forces of the Sun and the Moon force the ionospheric layers in a tidal motion. So the ionized gas in the ionosphere moves in the magnetic field of the Earth, creating electric currents which are seen as daily variations in magnetic recordings. There are two well-known periodic variations, the solar daily variation and the lunar daily variation. The lunar tides are of course not fixed to the solar day, so the lunar

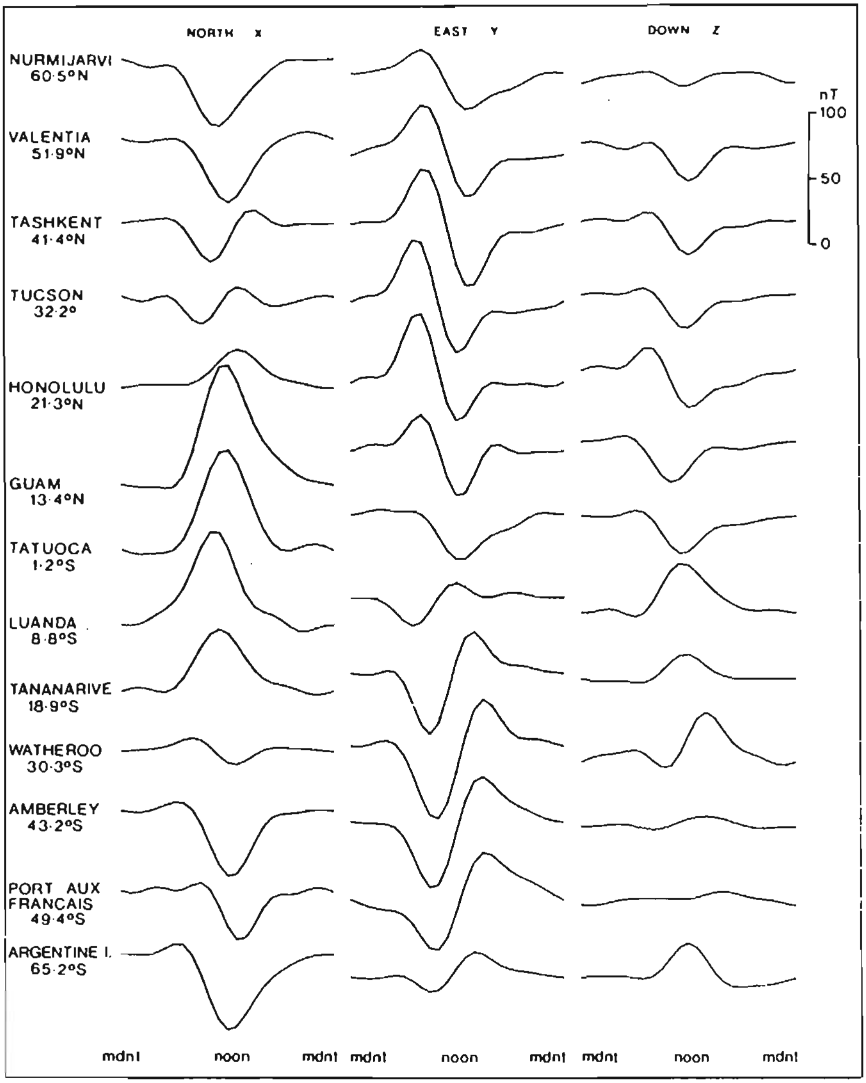


Figure 2.8. Diurnal variation of the magnetic field at different latitudes on solar quiet days (S_q variations), after Parkinson (1983).

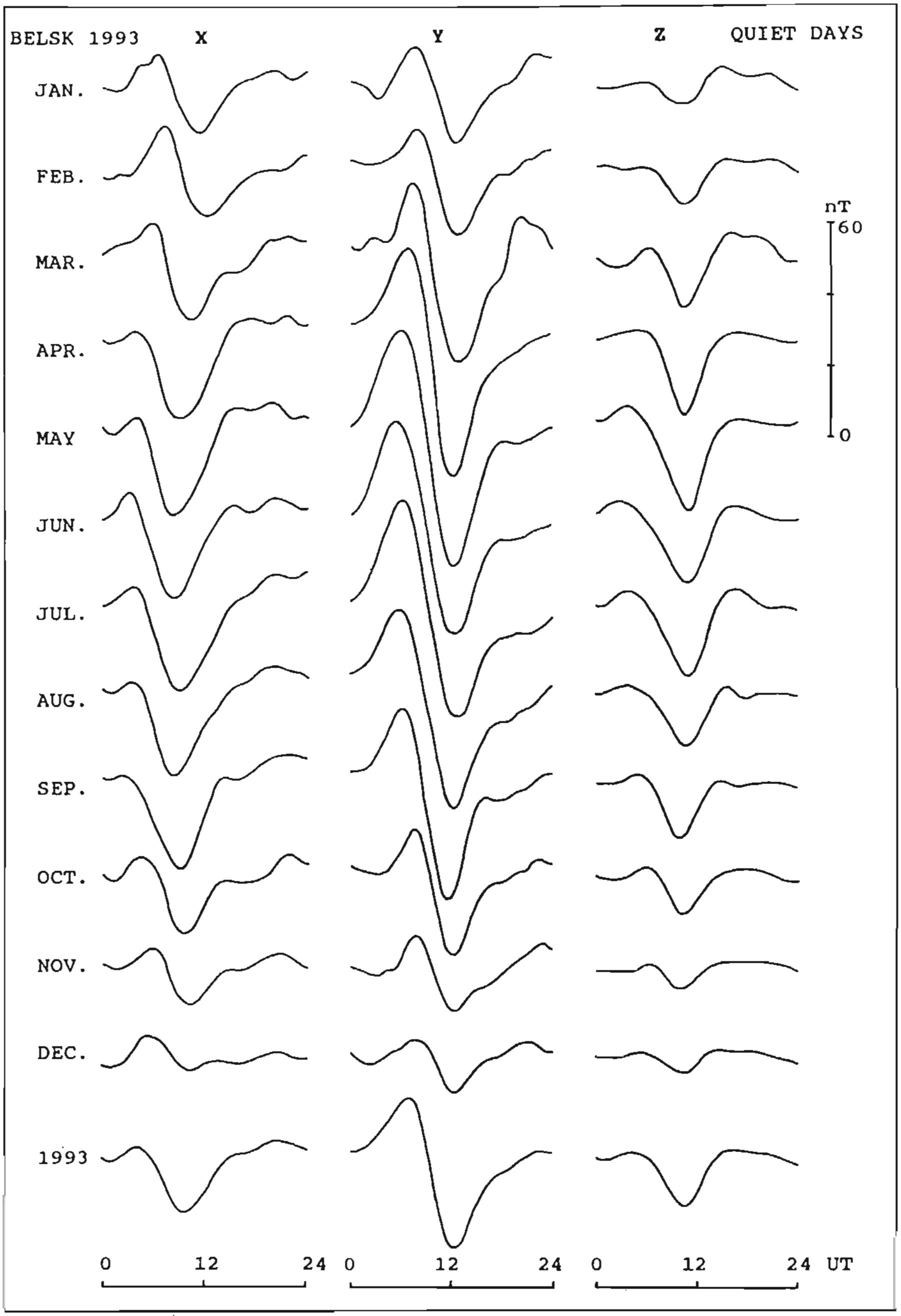


Figure 2.9. Diurnal variation of the magnetic field during solar quiet days (S_q variation) at Belsk observatory for different months of 1993.

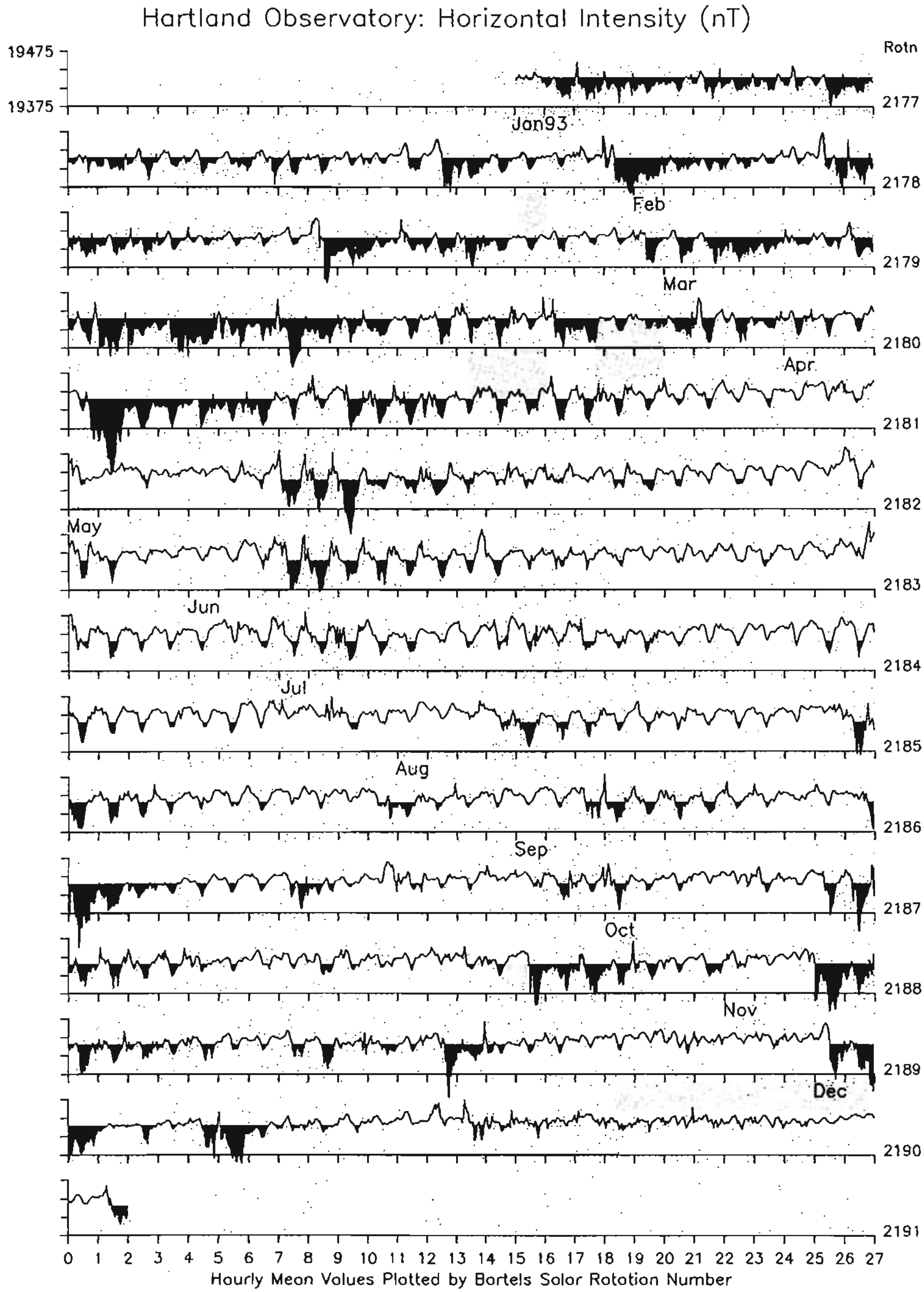


Figure 2.10. Variations of the horizontal intensity as a function of time for the year 1993 at Hartland observatory. The time axis is from 0 to 27 days which corresponds to the time of solar rotation. Courtesy of David Kerridge, British Geological Survey.

magnetic effect, which is small, a few nT, depending on time and latitude, can be separated only statistically from the solar effect having an amplitude up to 100 nT during summer times. The regular solar daily variation is also a function of the time of the year, solar activity, and the geomagnetic latitude (Figures 2.8 and 2.9).

Observatory yearbooks often give the average solar daily variation for different months of the year, and even separately for quiet, disturbed and all days. Based on the activity index K (see Chapter 7), the five quiet and disturbed days are selected very soon after the end of each month by the International Service of Geomagnetic Indices (now in Paris, see Chapter 10) and distributed quickly to all researchers interested in this information (see Chapter 7). The variation of the magnetic field on magnetically quiet days is called the *solar quiet day variation* or S_q *variation*. Correspondingly, for disturbed days, the variation that is fixed to the local time is called the S_D-variation, S for solar and D for disturbed. The variation fixed to the time of a magnetic storm is called the D_{St} *variation*, D for disturbance and St for storm time. In this way, the storm has the same time scale everywhere in the world.

Another periodic variation seen in magnetic data is the yearly variation, which has a small amplitude, of the order of a few nT. A possible explanation for this variation is the orbital movement of the Earth around the Sun and the tilting of the Earth's rotational axis compared to the Sun's equatorial plane so that the corpuscular radiation is more likely to hit the Earth during some times of the year than during others.

In magnetic activity, a period of 27 days can also be seen. The period corresponds to the rotation of the Sun's latitude zone where the most active areas and sunspots are situated (the equatorial zones of the Sun rotate faster than the areas close to the poles).

2.4 Magnetic disturbances

Big magnetic disturbances are mainly caused by particle radiation from the Sun. The flow of these particles is called the *solar wind*. The interaction of the solar wind with the Earth's magnetic field creates a system of magnetospheric and ionospheric currents. Also the solar X-rays and UV-radiation can enhance the ionospheric current systems so much that the magnetic field experiences strong disturbances.

At the Earth's surface, the effects of these currents are seen as *magnetic storms*, which are usually a sum of several *substorms*, if the currents are strong. In the very complicated magnetospheric current system, there are some general features. One is the ring current, which flows around the Earth mainly in the equatorial plane at a distance of a few Earth radii. It runs in the east-west direction, diminishing the horizontal magnetic field observed at the surface. The ring current receives more particles from the Sun during disturbed and active periods of the Sun. The time constant of the ring current is a few hours. How the particles, mainly electrons and protons, penetrate the boundary layer of the magnetosphere and are fed to the ring current is still under intensive research, as are also the changes in the other current systems in the magnetosphere. The mechanism of injecting particles to the ionosphere at auroral latitudes, creating auroras and currents along the auroral latitudes, is an object of intensive studies as well. Schematic pictures of the principal current systems in the magnetosphere are shown in Figures 2.11 and 2.12.

Depending on the strength of a magnetic storm, the most disturbed area may move from its normal position at auroral latitudes several degrees toward the equator. During strong magnetic storms, auroras may be seen at unusually low latitudes, radio propagation may be severely disturbed and radio connections over polar areas completely cut. As a result of some severe storms, electric power lines have suffered from induced currents. Breaks in power have sometimes lasted several hours and caused remarkable economic losses. As a consequence of magnetic storms, satellites suffer from enhanced density of particles from the Earth's expanding atmosphere and disturbances in radio connections. All these consequences, in addition to other ones, are reasons to enhance the observations of the magnetic field and to learn more about the mechanisms of magnetic disturbances and finally to learn to predict severe magnetic storms.

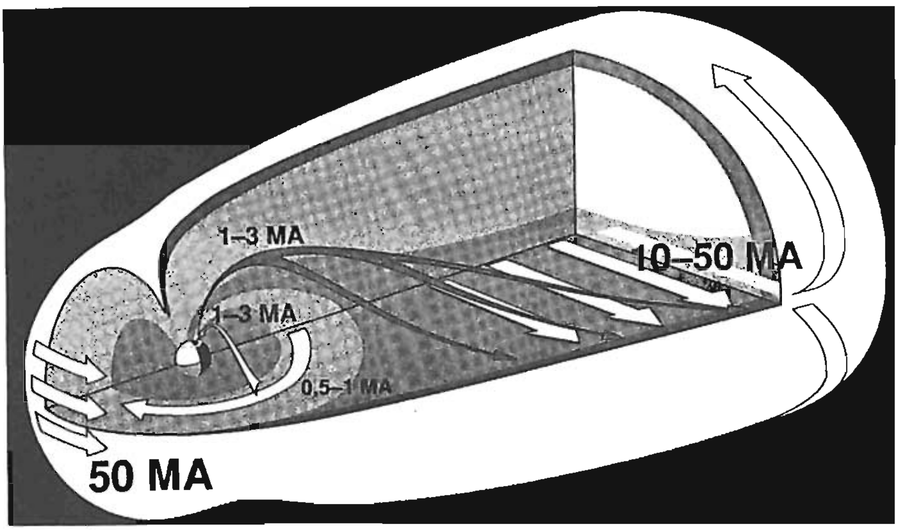


Figure 2.11. Schematic picture of the current systems around the Earth. The numbers attached to the currents give, in mega-amperes (MA), the normal value and a value during magnetic storms (courtesy of Hannu Koskinen, Finnish Meteorological Institute).

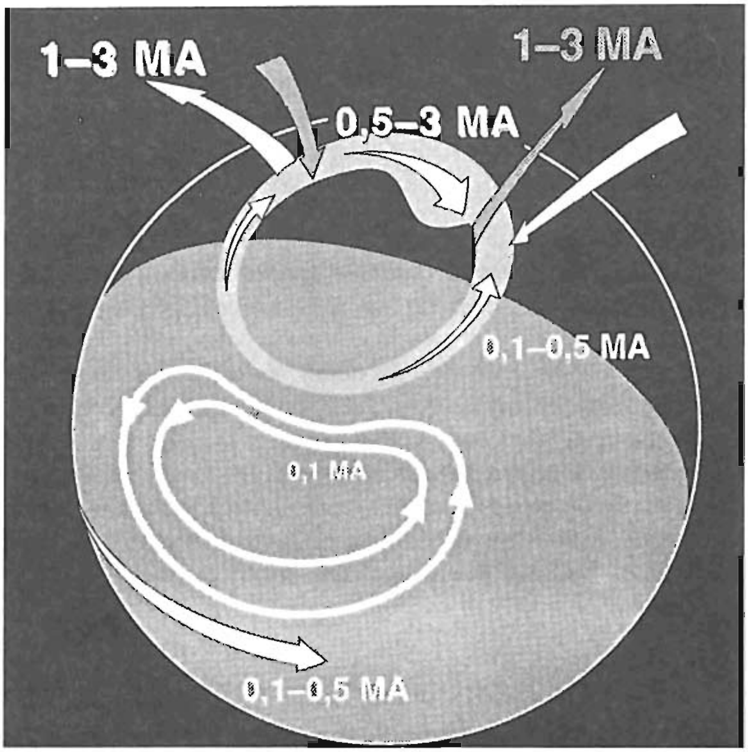


Figure 2.12. Current systems in the ionosphere. The numbers attached to the currents give, in mega-amperes (MA), the normal value and the value during magnetic storms. The grey color corresponds to the day-side, and the black area of the globe is in shadow. The current circling the polar cap area is in the auroral zone. The day-side currents are simplified dynamo currents in the atmosphere (courtesy of Hannu Koskinen, Finnish Meteorological Institute).

2.5 Special events and magnetic pulsations

Sudden impulses (SI) are often seen on magnetograms. Sometimes they are clearly seen before the start of a magnetic storm. In that case, the sudden impulse is identified as a *storm sudden commencement*, ssc, which is a rapid change of the magnetic field back and forth, a few nT or tens of nT (Figure 2.13). Ssc's (and SI's in general) are produced by a sudden change of the pressure of the solar wind against the sunward boundary of the magnetosphere (at a distance of about 10 Earth radii). In the case of the ssc, the magnetosphere is compressed and pushed in towards the Earth. *Solar flare effect*, sfe, is another group of rather sudden phenomena seen on magnetic recordings. It happens rather infrequently, and is difficult to distinguish on

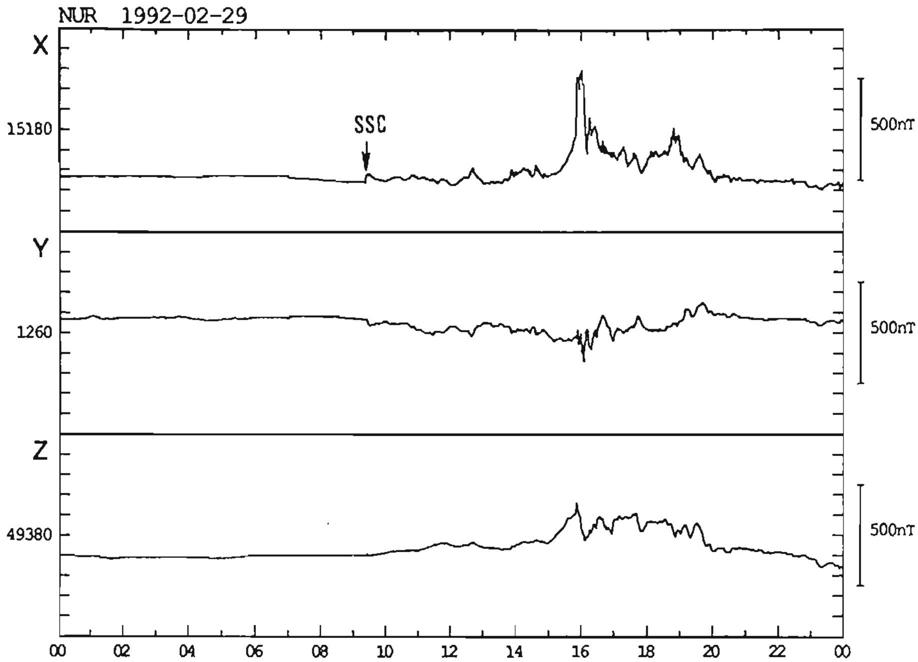


Figure 2.13. Magnetic recordings at Nurmijärvi magnetic observatory showing a magnetic storm with a storm sudden commencement (ssc).

magnetograms. Sfe is caused by a sudden increase in the solar UV- or X-ray radiation ionizing the upper atmosphere and enhancing the electric currents there. Magnetic *bays* are phenomena of rather regular shape, lasting about one hour or two. They are a consequence of enhancement of polar electrojets during night time. Depending on the closeness to the electrojet, the amplitude of the bay may be of the order of hundreds of nT.

General patterns of the bays, ssc's, sfe's and sudden impulses (SI) are represented in the *Provisional Atlas of Rapid Variations* printed in *Annals of the International Geophysical Year* (1959).

There is a group of variations of the magnetic field called *magnetic pulsations*. Many magnetic observatories also record these continuously, as recommended by IAGA. Magnetic pulsations are classified according to the frequency and the underlying physics. The main classification of continuous pulsations (Pc) follows the statistical distribution of the occurrence of the pulsations in frequency bands, although the statistical distribution is no longer as clear as it was thought in 1963, when IAGA made its recommendation on the classification (Samson, 1991).

Pc 1, period 0.2 to 5 seconds
Pc 2, period 5 to 10 s
Pc 3, period 10 to 45 s
Pc 4, period 45 to 150 s
Pc 5, period 150 to 600 s
Pc 6, period over 600 s.

The irregular or impulsive pulsations have also been grouped by IAGA according to their period:

Pi 1, period 1 to 40 seconds
Pi 2, period 40 to 150 s
Pi 3, period over 150 s.

The magnetic pulsations are intensively studied today because they are a profitable way to study phenomena and conditions in the ionosphere and magnetosphere. Samson (1991) divides the pulsations into two types of wavepackets, continuous and impulsive. In the frequency domain he divides both continuous and impulsive pulsations into three sub-classes: low-frequency (1–10 mHz), mid-frequency (10 mHz – 0.1 Hz) and high-frequency (0.1–10 Hz).

The low-frequency continuous pulsations are generated mainly by hydromagnetic instabilities, such as the Kelvin-Helmholtz, drift-mirror and bounce resonance instabilities. Many pulsations of the mid-frequency band are caused by proton cyclotron instabilities in the solar wind. High frequency continuous pulsations are mostly due to the ion cyclotron instabilities in the magnetosphere where the energy for this instability is provided by anisotropic distributions of energetic protons.

The Pi-pulsations are generated by transient phenomena, such as sudden impulses in the solar wind, flux transfer events and rapid changes in magnetospheric convection. In the mid- and high-frequency band of impulsive pulsations, much of the energy is due to field-aligned current-driven instabilities.

There has been good progress in the theory of pulsations during the last two to three decades, especially for continuous pulsations. These pulsations are useful in the diagnosis of the near-Earth plasmas, fields and their interactions. Long records of pulsations at observatories are important in investigating the long-term variability of the plasma regions.

Figure 2.14 shows a schematic amplitude spectrum of magnetic variations.

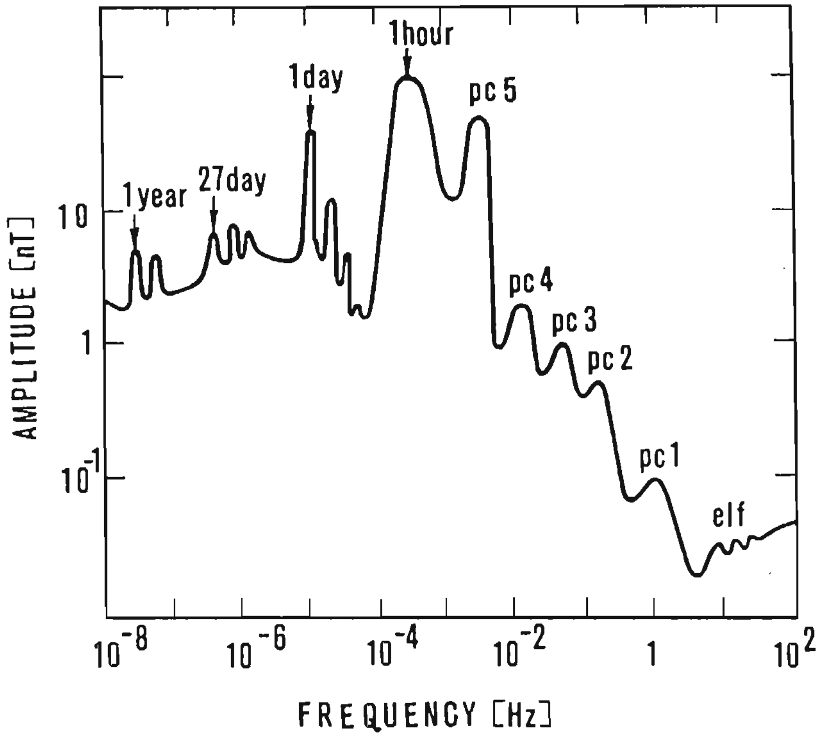


Figure 2.14. Amplitudes of natural variations of the horizontal component H (after Serson, 1973).

2.6 Geomagnetic coordinates and geomagnetic time

For the study of many phenomena connected with the Earth's magnetic field, the use of dipole or geomagnetic coordinates is more practical than the use of the geographical ones. For example, the conjugacy of auroras or magnetic pulsations or whistlers (radio signals from lightning propagating along magnetic field lines) in southern and northern hemisphere follows the geomagnetic coordinate system. The formulas for conversion are (Fraser-Smith, 1987)

$$\sin\Phi = \sin\varphi \sin\varphi_0 + \cos\varphi \cos\varphi_0 \cos(\lambda - \lambda_0)$$

$$\sin\Lambda = \cos\varphi \sin(\lambda - \lambda_0)/\cos\Phi \qquad (2.6)$$

or instead of the second of these equations:

$$\cos\Lambda = -(\sin\varphi - \sin\varphi_0 \sin\Phi)/\cos\varphi_0 \cos\Phi$$

where Λ and Φ are the geomagnetic coordinates and φ_0 and λ_0 are the geographic latitude and longitude of the northern geomagnetic pole. Λ is measured positive eastward from the dipole meridian, running from the geomagnetic northern pole through the geographical south pole to the geomagnetic pole in the southern hemisphere. While calculating Λ one can get two possible angles due to the ambiguity in inverting sine or cosine, and a proper one is to be chosen (see Fraser-Smith, 1987). Φ is the geomagnetic latitude.

Normally an accuracy of 0.1° is sufficient for the geomagnetic coordinates.

Geomagnetic time t_g is another unit used in connection with studies of magnetic storms, auroras and other ionospheric and magnetospheric phenomena. Geomagnetic time is defined by the angle between the geomagnetic meridian through the station and the one opposite to that through the Sun. It can therefore be found by computing the geomagnetic longitude of the station and the azimuth of the Sun. At stations in middle and low latitudes, the geomagnetic time differs only slightly from the geographical local time. The apparent geomagnetic local time T' differs from the geomagnetic hour angle t' by 12^h

$$T' = 12^h + t'$$

t' can be calculated from the formula (Simonov, 1963)

$$\cot(t' - \Lambda) = \pm \frac{\sin\varphi_0 \cos(t - \lambda + \lambda_0) - \cos\varphi \tan\delta}{\sin(t - \lambda + \lambda_0)} \tag{2.7}$$

where $t = T + t_e - 12^h$, t is the hour angle of the apparent Sun, T is the local mean time, δ is the declination of the Sun. Times are given in degrees (1° = 4 min). $t_e = t + 12^h - T$ is called the equation of time (apparent minus mean time); t_e can be obtained from astronomical almanacs (here represented in degrees). Also the declination of the Sun is available from astronomical almanacs. In this connection, the requirement of accuracy is rather low. Therefore, simple formulas are enough for the calculation of t_e and δ as presented by van Biel (1990). These formulas give an accuracy of $\pm 0.14^\circ$ for t_e and 0.2° for the declination.

$$t_e = 0.00429718 + 0.107029 \cos\beta - 1.83788 \sin\beta - 0.837378 \cos2\beta - 2.34048 \sin2\beta$$

$$\delta = 0.39637 - 22.913 \cos\beta - 4.0254 \sin\beta - 0.38720 \cos2\beta + 0.05197 \sin2\beta$$

$$\beta = 360(\text{day})/365 \quad (\text{day} = 0 \text{ is Jan 1}).$$

Here t_e and all the other units are expressed in degrees. Time t_e varies roughly between $+4^\circ$ and -4°. The declination of the Sun, δ, is the angle between the Earth's equatorial plane and the direction to the Sun, varying from $+23.5^\circ$ (summer solstice, northern "midsummer") to -23.5° (winter solstice).

In detailed studies of conjugacy, the dipole coordinates are not accurate enough. In many cases the eccentricity of the dipole has to be taken into account, which means at least the first eight harmonic coefficients to be known. We have to notice, however, that as more than 99 percent of the surface magnetic field is a potential field originating inside the Earth, only the magnetic field produced by the dipole decreases inversely proportional to r^3. The contributions of the higher order terms decrease more rapidly, so that every unit added to n increases the power of r with one unit. That means that the contribution of the higher order terms rapidly looses significance with growing distance from the Earth. For the study of conjugacy of, for example, auroras and magnetic pulsations and the footprints of satellites, more accurate magnetic coordinates have to be used (Gustafsson *et al.*, 1992). Going farther out, a few Earth radii, the contribution of the magnetospheric electric current systems begins to be the most important, and more sophisticated models of the magnetic field have to be used (Zyganenko, 1989).

3. SELECTION OF OBSERVATORY SITE AND LAYOUT OF THE OBSERVATORY

Twenty years ago, Wienert wrote in his *Notes on Geomagnetic Observatory and Survey Practice*: "The creation of a geomagnetic observatory is an ambitious enterprise which entails considerable financial commitments. Even more of a burden is the maintenance of the installation and the processing of data. A full-scale standard observatory can neither be run by one individual nor can the work be coped with by part-time scientists and technicians. With efficient and inventive staff, a full-time scientist and two technicians will be adequate to handle the data output of a standard observatory in the sense of the International Association of Geomagnetism and Aeronomy (IAGA), which includes the production of yearbooks and reporting to one of the world data centers. Research will hardly be possible. A staff of four, two scientists and two technicians, will permit a modest research programme. Practical experience has shown that there is very little point in trying with less, because the end will invariably be inadequate performance and hence frustration".

Over the last twenty years, the huge progress made in instrumentation, data collection, data processing and data transmission using electronic means has in principle made it possible to meet observatory standards without the full staff described by Wienert. However, a magnetic observatory still cannot be run totally unattended. Absolute measurements need a person and have to be made regularly, say once a week at least. Also someone has to be available to carry out repairs in case of malfunctions. So at the moment there are two solutions available for a real magnetic observatory: full-time or part-time manning.

Partly manned observatories are becoming more and more popular. Modern, less elaborate absolute measurements are in use, modern computer technology is applied with centralized remote control of data, and servicing of instruments is done by replacing whole units. The data may be transmitted in real time to a central office thousands of km away and checked there for proper functioning of the instruments.

However, the authors of this Guide support the idea of manned observatories at the present state of technology. An observer in charge with the ambition of producing good data is difficult to replace: the absolute measurements can be made more frequently, especially if doubt appears in the results, and calibrations and checking can be made without delay. A manned observatory can also serve as a place for calibration, training and information, as will be described in other chapters. If the country has only one or two observatories, they should preferably be manned. It is especially good if the magnetic data produced at the observatory are used by the observer in charge for scientific or other purposes. This guarantees the quality of the data produced.

It is often possible to carry out other scientific activities at a magnetic observatory. Observatories recording several geophysical parameters show considerable savings in operational costs. Having several geophysical programs at an observatory adds to the number of staff, which is also good, because a one-man observatory is too vulnerable. In addition to the economic benefits in having several geophysical programs concentrated at the same observatory, there come the benefits of cross-discipline communications. So we feel that Wienert's views of an observatory are still at least partly valid.

3.1 Requirements for the observatory site

Magnetic observatories are intended to operate over the long-term. One of their main tasks is to keep track of the geomagnetic secular variation. For that task, ten or even hundred years is a short time. Therefore, the choice of the site for the observatory is of the utmost importance: changes in the magnetic properties of the surroundings are not acceptable. It is important that the observatory site be magnetically representative of its region, both for the secular variation and for short-term variations.

The magnetic properties of the area for the planned observatory have to be studied carefully in advance. If magnetic maps are available (see Fig. 2.7), they will give a good general impression of the magnetic homogeneity of the planned area. In addition, a local survey at the surface must be carried out. This is easily accomplished using two proton magnetometers, one as a reference for temporal variations of the field, the other for the survey. The entire area of the planned observatory should be surveyed using a net of about 10 by 10 meters or less. If there are no aeromagnetic charts available, the neighborhood should be surveyed using a more coarse network to distances of several km from the observatory. Large magnetic anomalies (hundreds of nT) should not be accepted close to the observatory area, and the observatory area itself should preferably not have differences between the 10m points larger than a few nT. In particular, the place for absolute measurements should be free of horizontal and vertical gradients (less than 1 nT/m, if possible).

There is also another possible cause of non-representative data at a magnetic observatory, namely induced currents in the Earth. The effect of induced currents at the observatory is much more difficult to study: simultaneous recordings of magnetic disturbances at the observatory and at sites around the observatory should be made. In most of the magnetic observatories in the world such a study has not been made. That is understandable, because suitable portable recording instruments have been available only during recent years. It has been known for a long time, however, that due to the high conductivity of seawater, the variations of the magnetic field at coastal stations are different from the variations observed inland. Therefore, coastal observatories cannot be used as base stations, for example, for magnetic surveys. The influence of induced currents will be discussed in greater detail in Chapter 9.

In addition to the magnetic properties of the area of the observatory, many other factors also have to be taken into account: for example the manned or partly manned observatory should not be too far from civilization or else it may be unattractive to skilled personnel. On the other hand, the observatory should be and should remain far enough from man-made disturbances. It is difficult to predict building activities for future decades or hundreds of years, but one should try to do that. In any case, a large enough area should be reserved for the observatory, which means an area of 300 m radius measured from the absolute house and at least 1 km to the nearest railroad. If the railroad is electric, the distance has to be several kilometers, and in case of DC trains tens of kilometers, depending on the conductivity of the ground. Examples of the disturbing effects of some objects are listed in Table 3.1 at the end of this chapter (Section 3.4). The disturbing effects of magnetic material are described in greater detail in Appendix IV.

3.2 Buildings at a magnetic observatory

The buildings needed at a manned magnetic observatory with mainly classical instruments for recording and for absolute measurements are well-described in Wienert's *Notes on Geomagnetic Observatory and Survey Practice*. The old variation rooms are usually excellent shelters for modern instrumentation, although modern instruments do not need such large and expensive constructions.

There are three main requirements for the shelter of modern variometers: stable pillars for the sensors, stable temperature (typical temperature coefficients for fluxgate variometers are 1 nT/°C), and non-magnetic materials in the building. The variation rooms of classical observatories usually fulfill these requirements. Modern sensors are usually small and rarely require servicing, and the electronics usually does not need to be adjusted after installation. So, the classical variation room with several pillars may be reduced to a well insulated hut or even a box. This of course can be constructed inside an old variation room. If there are no other reasons for keeping the temperature constant in the whole building, then only the box for the variometers needs to be heated.

Using modern instruments, absolute measurements can be made closer to the recording instruments than before, depending on the instruments. Figures 3.1–3.3 show examples of a layout of buildings at a new magnetic observatory. The distance between the absolute house and the variation room can of course be less than that in Figure 3.1, if the absolute instruments produce a sufficiently small disturbing field. If a vector proton magnetometer is used, then the magnetic field of the compensating

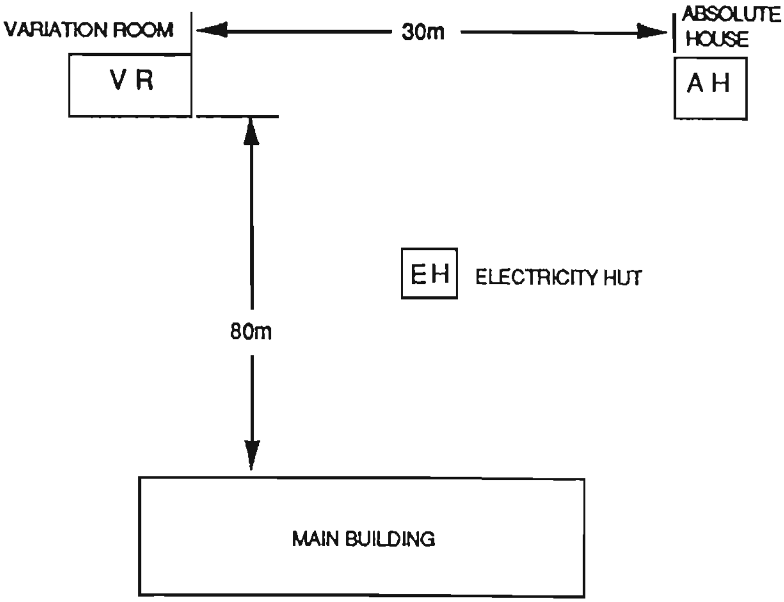


Figure 3.1. Layout of a magnetic observatory with rather small buildings. The distances between the houses are typical minimum ones, but can be varied, depending on the instruments in use.

coil may cause a disturbing effect quite far from the instrument, depending on the construction of the coil (see Chapter 8).

As shown in Figure 3.1, four separate buildings or huts are recommended at a complete observatory. We stress the importance of an uninterruptible battery-based power supply. Therefore, the small electricity hut is considered important, although its functions may be housed inside the main building. The electricity hut contains, in addition to the electronics connected to the variometers, batteries which are charged continuously from the mains or in special circumstances from solar cells. In many cases it is advisable to use the batteries as buffers for the power supply to the variometers. The electricity hut should preferably have a stabilized temperature, especially if large thermal coefficients in electronics are suspected. In many cases, however, the electronics for fluxgate magnetometers (preamplifiers) are non-magnetic enough to be kept quite close to the variometer (1 m or even less, although this has to be tested). In this case, the electronics may be in the same temperature stabilized box or room as the variometer. The Canadian solution is presented in Figure 3.5.

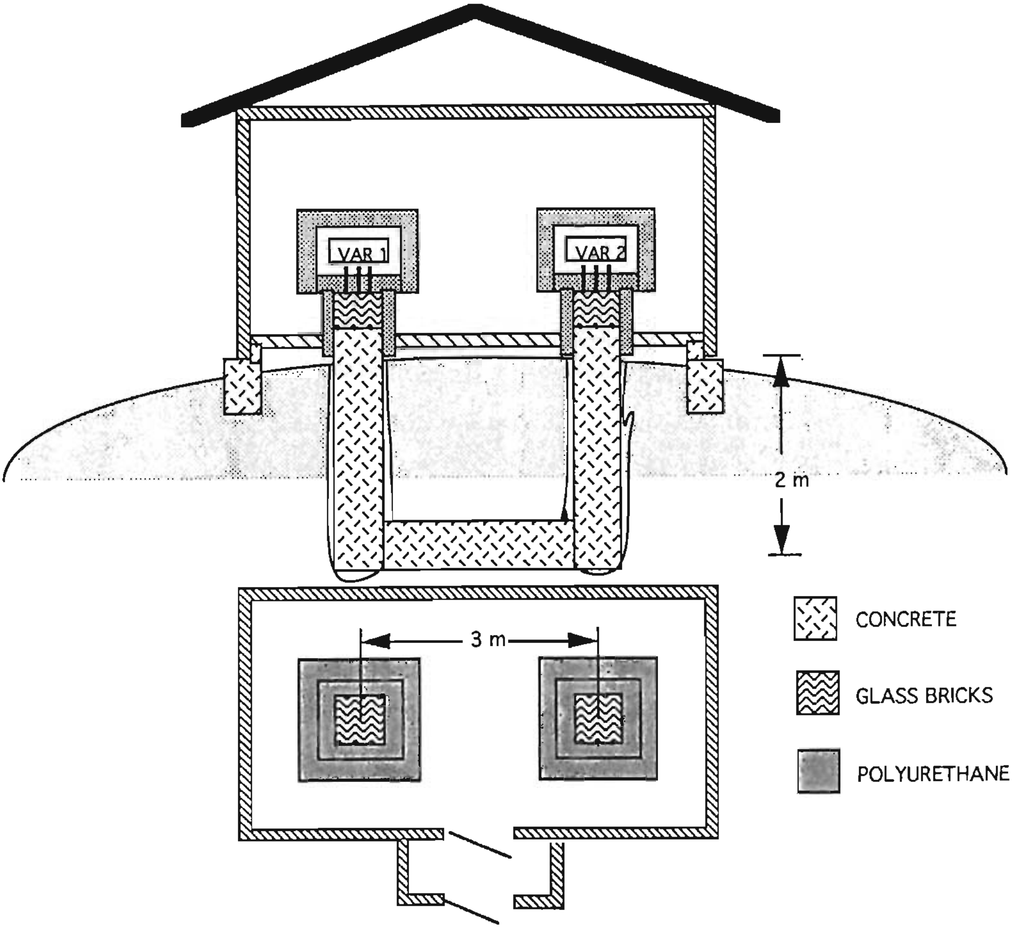


Figure 3.2. Layout of a variation room for two variometers. The walls have to be well insulated. Gravel around the pillars under the ground is recommended for efficient drainage. Drainpipes have to be installed following local regulations. The pillars should preferably be joined together under ground for additional stability. The boxes around the variometers are made of a very good insulator, such as polyurethane. An example of such a box with electric heating is shown in Figure 3.5.

The distance between the sensors and the electricity hut should be at least 15 m, and the separation of the absolute house and the electricity hut should be similar. The electricity hut should also be available for temporary storage of absolute instruments. It also serves as a center for distributing power and signals, as can be seen from the wiring diagram in Figure 3.4.

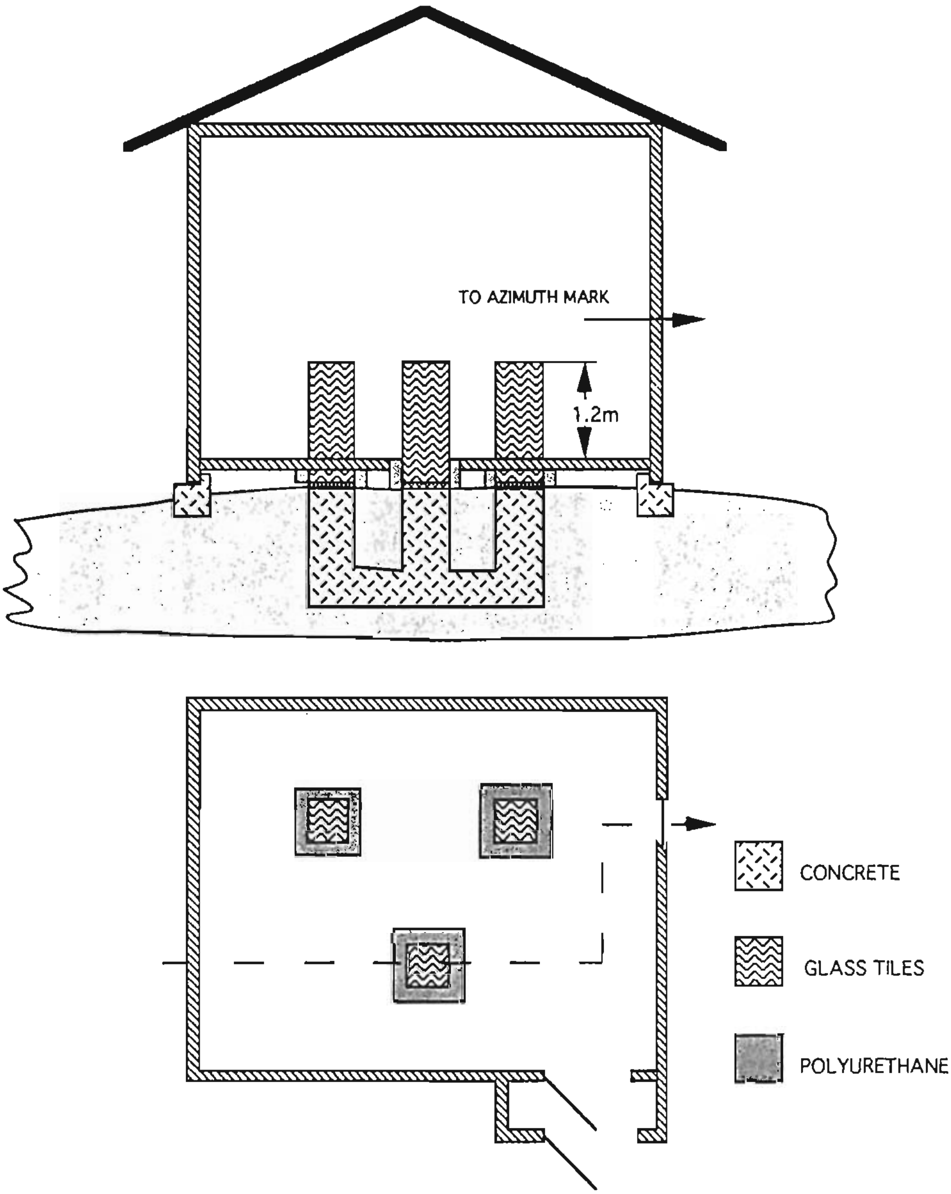


Figure 3.3. Possible layout of a house for absolute measurements. The walls should be well insulated. There must be enough room above the instruments to ensure that the lamps used for illumination do not produce appreciable disturbing fields.

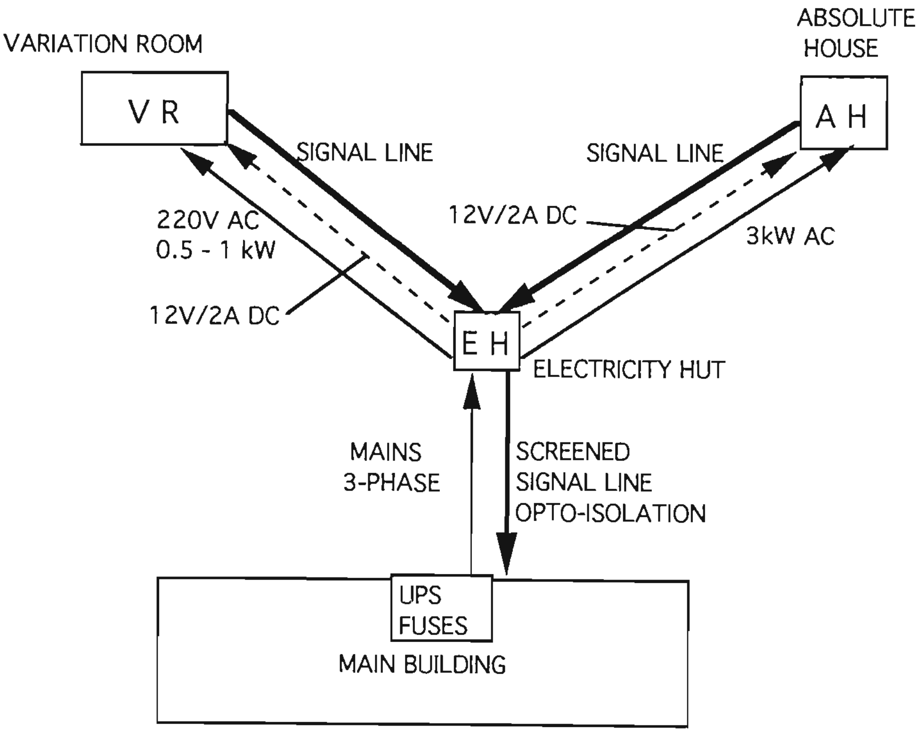


Figure 3.4. A possible wiring diagram for the magnetic observatory presented in Figure 3.1. All the cables should be buried in the ground to reduce the risk of damage caused by lightning. The cables should be well marked and shielded. The signal cable should have optical isolation at both ends. It is even better if an optical fiber cable is used.

In the construction of a modern variation room there is a remarkable difference in comparison with classical designs: the observer had to visit classical variation rooms every day, whereas the modern variometers hardly need any servicing after installation. Therefore, the variation room can be just a shelter for the variometer. We stress, however, that the pillars for modern sensors have to be very stable. Using electronic tiltmeters and good temperature sensors it is in principle possible to correct digitally for the effects of tilting and for the variations of temperature. The use of tiltmeters has, however, proved to be rather difficult in practice. The solution successfully used in geomagnetism has been tilt-correcting suspended sensors (Rasmussen and Kring Lauridsen, 1990, Trigg and Olson, 1990). We recommend stabilized temperature in the cover for the sensor assembly or in the whole variation room, and temperature should be recorded (see Figure 3.5).

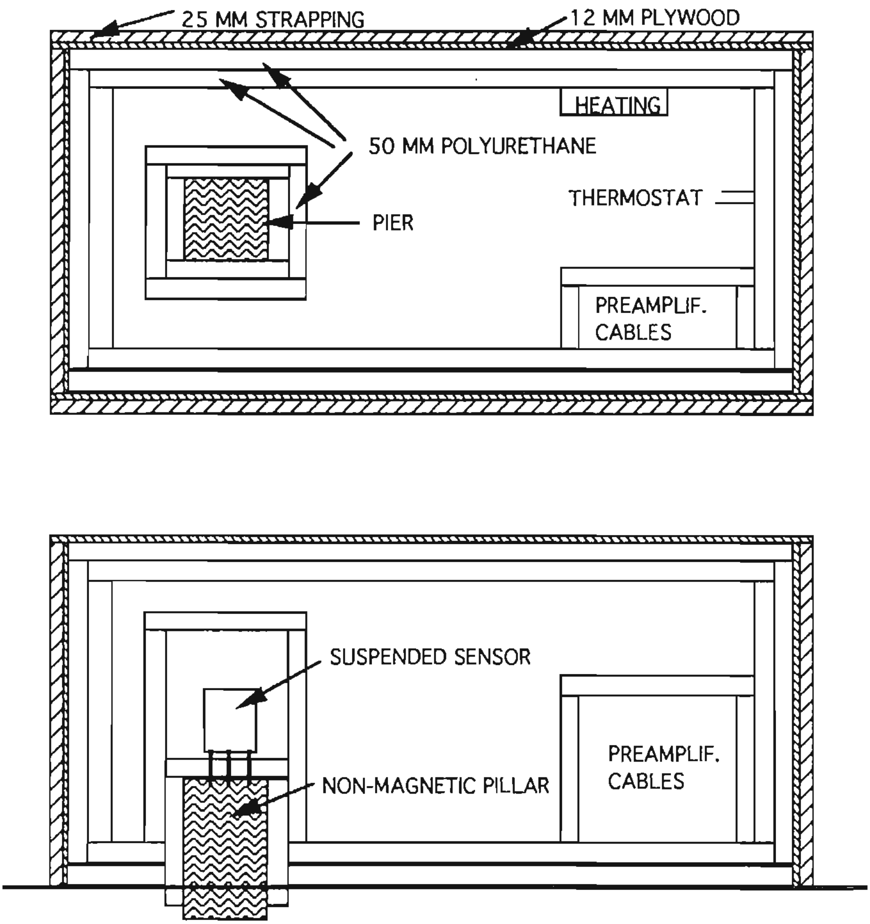


Figure 3.5. Example of an insulated box and a heating system for variometers. This type of box has been used successfully in Canadian magnetic observatories.

The requirements for the construction of the absolute house have not changed drastically since the use of classical instruments. In old absolute houses, several pillars were needed. Now the absolute house can be made smaller, depending, however, on instrumentation. In some cases one pillar is enough when no instrument calibrations or comparisons are planned. It is not necessary to have stabilized temperature in the absolute house, but it should be possible to heat the house to normal room temperature. The pillars for absolute measurements have to be absolutely non-magnetic, but their stability is not as critical as that for variometers.

The constructions shown in Figures 3.2 and 3.3 are naturally just examples. Often it is not reasonable or economically possible to have all needs fulfilled, and the absolute house can be made very small. Only a hut with one pillar may be required if the instruments normally used do not need separate pillars. If there are two pillars in the variation room, building them on the same foundation adds to stability (see Figure 3.2). Where a vector proton magnetometer is used, it should be mounted on a single isolated pillar. The final construction depends very much on local conditions. There are, however, some important points to be taken into account in planning:

1) The pillars for the sensors in the variation room have to be stable. It is good if bedrock is available for the foundation, but this is seldom the case. Therefore, the pillar has to be founded deep enough below the level which can be affected by freezing in cold climates or by rainwater. In practice this means some 2 m below the ground in the majority of areas. It is advisable to consult the local building authorities. Rainwater is a common problem. Therefore, water has to be free to run away from the surroundings of the pillars, which means that gravel should be placed under and around the pillars and tubes for drainage should be placed at the level below the pillars and also in the surroundings. The foundation of the hut has to be separated from the pillars. The floor has to be separated from the pillars using a soft material. In some areas (e.g. permafrost) the construction of stable pillars is impossible and other solutions, such as suspended sensors (see Chapter 6), or recording of tilt have to be found.

2) Thermostatically controlled temperature to better than 0.5°C is important in the variation room or in the box of the variometers, in addition to the systems compensating for the temperature effects of the variometers. The variation room or the boxes containing the sensors or both (Figure 3.2) have to be well insulated to ensure that the temperature variations are smooth, which makes the possible corrections of the temperature effects in the final treatment of the data more accurate. If there is enough electric power available, it is quite easy to keep the temperature of the boxes or the whole room constant. If the insulation is good, then power requirement is, in practice, low, just a few tens of watts, depending on the climate and the insulation of the boxes. A good way to stabilize the temperature is to have the sensors in a shelter under ground. For heating, standard electric heaters made of aluminum foil are non-magnetic and generally available. Usually, the heating foil is installed behind the ceiling panel or inside the floor. Commercially available thermostats are usually magnetic. They have to be checked and the magnetic parts removed. One possibility is to have the sensor of the thermostat close to the magnetometer and the regulator or switch far away, for example in the electricity hut. One solution for the heating system for a box for variometers is shown in Figure 3.5.

The electronics may also have a temperature coefficient, sometimes of the order of 1 nT/°C. Such electronics have to be kept in a temperature-stabilized environment. Naturally, the temperature coefficients of both the variometers and their electronics have to be tested before installing the instrument. The temperature of the variometers has to be monitored together with magnetic field data. It is advisable to change the temperature of the variation room (or box for the variometers) twice a year, following the mean temperature outside. This practice saves on the power used for heating and enables thermal coefficients to be checked.

In a very warm or hot climate, sunshine is a problem. Painting with white, heat-reflecting paint helps, as does a double roof. A variation room under ground is the best solution, if other conditions will allow.

3) All materials close to the sensors have to be non-magnetic. In practice this means that everything has to be tested: concrete (white cement to be used, the sand to be tested), bricks, metal parts like hinges, locks, thermostats, electric heaters, switches, plugs, even the asphalt for the roof. Testing the materials is easy using the fluxgate theodolite, normally used for absolute measurements. Naturally, a QHM (in the turned, field-measuring position, see Chapter 5) can also be used. The concrete can be tested by making a small test block which can be brought close to the fluxgate. In the sensor room it is sufficient if at a distance of 0.5 m from the sensor the materials give a field smaller than 1 nT. In the absolute house, the requirement is higher. This means that slightly magnetic materials, if unavoidable, have to be farther from the sensor. The cleanliness of the pillar is especially important. Usually the concrete part of the pillar in the absolute house is made only to the level of the floor, and the upper part is made of some tested non-magnetic material like wood, bricks of glass or limestone (the latter may be magnetic and has to be carefully tested, which is not easy because of the weight of the pillar).

There are some other general considerations which should be taken into account in building a new observatory. One very unfortunate tendency is the growing level of vandalism. This forces the construction of observatories in places which are under continuous supervision. This is contradictory to the requirement that the observatory should be in a remote place, far from disturbances from urban society. To make an observatory safe against vandalism adds to the construction costs considerably, and this is a factor supporting the case for manned observatories.

The absolute house should preferably have at least two pillars to make simultaneous measurements by two instruments possible; very often observatory staff are asked to test instruments and to make special measurements.

It is important, as recommended by IAGA, to install for reference at least one pillar outside of the building, and preferably two or more in different directions from the buildings. The distance from the absolute house should be at least 50 m. The differences of the field elements between these pillars and the main pillar in the absolute house have to be measured regularly, say once a year. Any change in the differences should be investigated.

From the pillars for absolute measurements there has to be a free view to an azimuth mark, preferably hundreds of meters or more away. The geographical direction to the azimuth mark is determined using observations of the Sun (see Chapter 5) or stars. If it is not possible to observe the Sun or stars directly from the absolute pillar, the direction to the azimuth mark can be determined by making the observation of the Sun exactly on the absolute pillar–azimuth mark line. Only one theodolite is needed for this. The Sun observation can also be made anywhere at a place with a clear view of the theodolite on the absolute pillar (through the door or through the window). In this case two theodolites are required: the geographic direction from the theodolite outside to the theodolite on the pillar is determined by observing the Sun, and the geographic direction from the theodolite inside to the theodolite outside is the reverse bearing. The readings from theodolite to theodolite are very accurate if it is possible to view through the other theodolite's objective to the vertical line in the optics. From the latter, the direction to the azimuth mark is easy to calculate. If it is not possible to view through the objectives, which is only possible when the theodolites are quite close to each other, the theodolites have to be several tens of meters from each other to achieve an accurate enough result. The whole procedure has to be repeated several times to reach the required accuracy (at least 6″).

If the azimuth mark is viewed through a closed window then, depending on the quality of the glass, there may be an error in the apparent direction to the mark because of refraction. The possible effect of the window should be determined by observing the mark with the window closed and open during quiet climatological conditions, when the temperature outside and inside is roughly the same. Other windows are not needed in the absolute house, and that used to observe the azimuth mark may be small. To provide illumination, a strong lamp must be placed above the pillar. Needless to say the lamp has to be non-magnetic and preferably high above the pillar, at least 1 m above the fluxgate theodolite. The lamp has to be exactly over the middle point of the theodolite to provide light to the theodolite through its side mirror. (The mirror will be in shadow of the body of the theodolite if the lamp is closer than about 1 m.) Opal glass with lamps above it is sometimes used above the pillar. Another solution is a roof window and outside, at a safe distance, a lamp. The heat of the lamp may in some cases be a source of error in the measurement by heating the sensor of the fluxgate theodolite more strongly when it is in the up-position (see Chapter 5) than in the down-position. This may change the alignment of the sensor with the telescope between the measurement positions, causing an error which is not compensated by the observing procedure. This is another reason for keeping the lamp as far as possible from the theodolite.

If the azimuth mark is not far enough away, say at least 100 m from the absolute pillar, one has to place the theodolite very carefully in the middle of the pillar. For a distance of 100 m, a displacement of 1 cm perpendicular to the direction to the azimuth mark means 0.3 minutes of arc (0.3′). Therefore, there have to be fixed slots on the top of the pillar for locating theodolite bases, which may have different sizes, exactly at the same spot (Figure 3.6). A poor azimuth mark may be a source of error in the measurement of declination *D*. Figure 3.6 (right) shows an azimuth mark which is found to give good results.

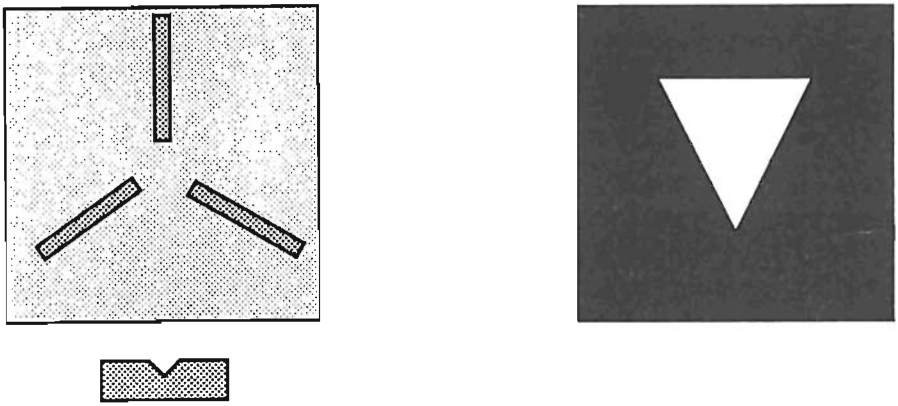


Figure 3.6. Left: Slots of copper or aluminum on the top of the pillar for absolute measurements; below is shown the cross-section of a slot. The angles between the slots have to be 120°. Right: An azimuth mark suitable for accurate sighting. The size of the mark has to be such that the vertical line of the telescope of the theodolite does not cover the white triangle.

3.3 Avoiding gaps in recordings

At magnetic observatories, continuous operation without interruptions is very important. Therefore, all measures have to be taken to avoid gaps in the recorded data. One source of gaps is interruptions in electric power. Therefore, all systems have to be supported by batteries (UPS, Uninterruptible Power Supplies). The duration of interruptions in the mains power depends on local conditions. Breaks of one day are possible almost everywhere, meaning that the station has to be able to run for at least 24 hours on its own batteries.

Equipment failure is another source of gaps. Usually professional technical help is not available immediately even when a fault is detected promptly. To ensure continuous recording, most observatories run secondary systems. This usually is not a very expensive solution, especially if there is older system which has been replaced by more modern equipment. It is often possible to keep the old system running and use the data when the primary system fails. However, both recordings should be compared at regular intervals to ensure functioning of both systems and to keeping track on the absolute level so that in case of failure of the primary system the secondary system data can be used to fill the gaps. In constructing the shelter for the sensors in a new observatory, it is good to allow space for another sensor. This requires another pillar in the sensor hut or room, 2–3 m from the first one. In the variation rooms of old observatories there is usually plenty of space for several sensors. It is recommended that the pillars be oriented according to geographic or geomagnetic north and that the directions on the top of the pillars be shown by clearly drawn lines.

In some areas of the world, humidity may create a problem, although new instruments are not as sensitive to humidity as classical ones. To reduce the effect, it is best to arrange good ventilation in the observatory buildings. In seriously humid areas the sensitive parts may be put in sealed containers, which is not difficult with modern small sensors. The electronics may be specially treated to withstand humidity effects. In some places, the parts and cables have to be protected against insects and small animals. Modern data collection equipment often uses floppy or hard discs or cassettes, which can be rather sensitive to dust.

Usually, electronics like preamplifiers which must be placed close to the sensors are non-magnetic enough so that they can be tolerated within 1 m or even less. The main electronics, as stated earlier, should be in the electricity hut not less than 15 m from the sensors, and the data collecting unit may be even hundreds of meters away. If there is a house for staff living nearby, it is best to keep the data collection there so that it is under good control.

The main building of an observatory may have different functions depending on the site and the level of automation. The main instruments for servicing may be kept there. At an observatory, a mechanical workshop with basic tools is useful. The main building may also be the residence of the observer in charge, and it may have guest rooms for visitors.

As stressed in the introduction, a magnetic observatory should preferably be made a part of a geophysical observatory. This means that the main building serves other activities and so the magnetic observatory can be run very economically.

3.4 Some practical advice

Very strict precautions are found to be necessary in building work at an observatory. No nails of iron should be allowed, even in scaffolding. All tools should be counted every day after work, because in building work it is common for screwdrivers, hammers or saws to be forgotten and lost during construction. Iron is naturally not allowed anywhere in the constructions. Aluminum can be used instead of iron in the concrete.

It is inadvisable to run long cables through the observatory area. During magnetic disturbances, strong currents may be induced in them, producing magnetic fields which distort the recordings. For example, in high-voltage AC power lines, DC currents of the order of 10 A (at high latitudes even 100 A is possible on rare occasions) have been recorded during magnetic storms. The magnetic effect of 10 A at a distance of 1000 m is 2 nT, as can be seen from the law of Biot-Savart which states that the magnetic induction of a very long straight line current, is

$$B = \mu_0 i / 2\pi r$$

where μ_0 is the permeability of free space ($= 4\pi \cdot 10^{-7}$ henry per meter), i is the current in amperes [A], r is the distance in meters [m], and B is the magnetic induction in teslas [T].

Many observations are spoiled by a magnetic object the observer is carrying while observing or which is kept too close to the site of observation or recording. Dangerous items are tools, electronic instruments, cars, bicycles, etc. Spectacles are especially dangerous for absolute observations, because they may be used very close to the magnetometer. Sometimes even a mended tooth is found to contain enough iron to cause a measurable disturbance. Modern methods of making absolute measurements do not require as high absolute cleanliness of the observer as the older methods for reasons described in Chapter 5.

Table 3.1

Distances r_i at which some common objects, if suitably placed and oriented, produce a magnetic field of 1 nT.

Object	r_i [m]
Safety pin	1
Buckle of belt	1
Watch	1
Metallic pen	1
Knife	2
Screwdriver	2
Revolver	3
Hammer	4
Spade	5
Rifle	7
Bicycle	7
Motor cycle	20
Car	40
Bus	80

It is not easy to answer the question how far away one has to keep a magnetic object to be at a "safe" distance (see Appendix IV); Table 3.1 gives rough estimates of the effect of some objects.

At a distance r the amplitude of the anomaly is $(r_i/r)^3$, where r_i is the distance listed in Table 3.1. In two cases, namely when the permanent magnetization is higher than the induced magnetization, or when the body is large compared to the distance to the measurement point, the value shown in Table 3.1 can be smaller than that actually observed. The best way to avoid problems caused by a magnetic body is to measure the magnetic effect at a much shorter range than the distance at which it is required to know the disturbing field and to use the $(r_i/r)^3$ formula to calculate the effect. However, the effect of very long objects may diminish only as r_i/r.

In testing the magnetic effect of a body by bringing it close to a magnetometer one has to move the object very slowly, especially if it is made of good conductor like aluminum or copper. Moving the object in the Earth's magnetic field induces currents in the object which are seen in the magnetometer as variations of the magnetic field, and a magnetically clean object may be mistaken to be magnetic.

From Table 3.1 it is easy to see that for the accuracy required at modern magnetic observatories (about 0.1 nT) the distances to the listed objects have to be more than twice those listed.

4. MAGNETOMETERS

The history of geomagnetism recognizes a large number of instruments, starting from ancient compasses and inclinatoriums through Gauss', Eschenhagen's, La Cour's and many others instruments, to the present ones. There are many ingenious inventions in these instruments. Detailed descriptions and theories of them are to be found in many textbooks on geomagnetism, and also in the earlier observatory manuals, listed at the beginning of this Guide.

The main objective of this chapter is to describe the physical principles of the most popular contemporary magnetometers. We start with the physics behind the classical ones; they are still in operation at many observatories, and several modern variometers use classical sensors combined with sophisticated feed-back systems. Classical magnetometers are still used also in some absolute measurements. The main emphasis is, however, in the operation of the most modern instruments, the fluxgate, proton precession, and optical pumping magnetometers.

Knowledge of the operation of magnetometers is not needed for the practical performance of measurements which will be presented in Chapter 5. In case of failure, however, it is often good to know how the instruments work. And knowing the general principles makes the measurement more interesting and may positively influence the work.

4.1 Definitions

Before describing the operation of magnetic instruments, let us define some terms commonly used in geomagnetic vocabulary.

- *Absolute instrument* means an instrument capable of giving the magnitude of the magnetic field or its component in absolute physical basic units (m, kg, s, A, or their derivatives or angle compared to geographical direction or horizontal plane) or universal physical constants (e.g., gyromagnetic ratio of proton or electron).

- *Relative instrument* is an instrument which measures the deviation from an undetermined field. To know the value of the undetermined field, it is necessary to make an absolute determination. In the case of a variometer this value is called a base-line.

- *Semi-absolute instrument* means a relative instrument which by frequent enough comparisons with absolute instruments gives acceptably high absolute accuracy for the measurement in question.

- *Absolute measurements* are made using an absolute or semi-absolute instrument to achieve the required absolute accuracy.

- *Sensitivity* tells how many units at the output of an instrument correspond to one physical unit (e.g., how many bits for one nT).

- *Scale value* is the inverse of sensitivity.

- *Base value* is the value (usually almost constant) to be added to the recorded one to obtain the final component-value in question.

- *Base-line value* is the same as the base value, usually used in connection with magnetograms where a straight line for scaling exists.

- *Temperature coefficient* indicates how much a measured or recorded value depends on temperature (e.g., nT/°C). It is based on a linear relation between magnetometer output and temperature.

- *Range* refers to the upper and lower limits of the values which can be recorded with the instrument in question (e.g., ±4000 nT).

- *Dynamic range* is the ratio between the maximum recordable amplitude and the resolution. Normally it is expressed in decibels (dB), and the formula for its calculation is $20 \cdot \log\,(A_{max}/A_{min})$ where A_{max} and A_{min} are the maximum and minimum amplitudes, respectively.

- *Resolution* describes what are the smallest changes recordable. The resolution is limited by the noise level.

- *Accuracy* describes the real absolute accuracy. Accuracy of 0.1 nT says that the difference between the true value and the measured one is not more than 0.1 nT.

- *Mean square error* (m) is calculated from the scatter of the measurements. $m = \left[\sum_{i=1}^{n} v_i^2/(n-1)\right]^{1/2}$, where v_i is the deviation from the mean and n is the number of measurements.

- *Systematic error* of a series of measurements is the deviation of the mean value from the true value.

- *Absolute accuracy* is determined by sum of the mean square error and the systematic error.

- *Relative accuracy* of a recorded event is the ratio between the accuracy of the recorded event and its amplitude, normally given in percents (%).

- *Precision* describes the scatter of values. Precision of 0.1 nT means that the values are within 0.1 nT from their mean value, but it says nothing of the accuracy.

- *Variometer* is a magnetometer which is used to record variations of the magnetic field.

4.2 Short notes about some historical instruments

Before describing the operation of magnetic instruments, we list below names of some classical instruments which are commonly found on the shelves of observatories but are not used anymore. We also mention some instruments which have been used in geomagnetism, but are so seldom in use that they are not described in detail in this Guide.

- *Magnetic theodolite.* This was an instrument for measuring the declination and the horizontal intensity. The declination was measured using the method described in this Guide. In the measurement of horizontal intensity, the Gauss method was mainly used. It was based on free oscillation of a magnet with magnetic moment M. This measurement gives the product $M{\cdot}H$. The ratio M/H was obtained from the deviation of another magnet from the direction of the magnetic meridian in the field of H and in the field of the magnet with moment M.

- *The Earth inductor* is an instrument which measures the inclination of the field. The method is based on the alignment of the axis of a rotating coil along the direction of the magnetic field.

- *BMZ (magnetometric zero balance).* This instrument was designed by La Cour and has been used as relative instrument for the measurement of the vertical component. It has a zero indicator (freely moving horizontal magnet), and two magnets which compensate the vertical component of the field. One of the magnets is vertical. The other can be rotated. The measure of the field is the angle of rotation of this magnet.

- *Field balance.* Many of these instruments were used for prospecting and mapping of the vertical intensity and, in some cases, the horizontal intensity. It was an instrument for relative measurements only. This instrument has a magnet supported by an agate edge. The zero reading corresponded to the horizontal position of the magnet (in Z-measurement) which means that the magnetic moment was in balance with the gravity force. Deviation from this position was a measure of the magnetic field component.

4.3 Torsion magnetometers

The classical magnetometers are based on the observation of a magnet in a changing magnetic field. The magnet is suspended by a thin fibre. The torque of the magnetic field on the suspended magnet is compensated by the torque of the suspension fibre. More generally, one should take into account also the moment of the gravity field, but if the center of mass is on the rotational axis of the magnet, which is the usual practice, this moment is zero. The basic equation for torque T, in the static case when the magnetic field is not changing, is

$$\boldsymbol{m} \times \boldsymbol{B} = \boldsymbol{T} \tag{4.1}$$

where $\boldsymbol{m}$ is the vector magnetic moment of the magnet, and $\boldsymbol{B}$ is the vector describing the magnetic field

For a horizontal field H the formula of equilibrium is

$$mH \sin \alpha = c\varphi \tag{4.2}$$

where m stands for the magnetic moment of the magnet, c is the torsion constant of the fibre, α is the angle between the magnetic meridian and the magnetic axis of the magnet, φ is the angle of twisting of the fibre, and H is the horizontal component of the magnetic field. The classic absolute measurements of declination D using declinometers (as an example, see Kring Lauridsen, 1981), and horizontal intensity H using QHM (Kring Lauridsen, 1977) are typical static cases. Sections 4.3.1 and 4.3.2 will handle those measurements.

4.3.1 Declinometer

In the classical measurement of magnetic declination D (see, for example, Kring Lauridsen, 1981), the magnet is hanging from a very thin (low torque) fiber. The system with the suspended magnet is placed on top of a non-magnetic theodolite so that it is possible to look at the magnet's mirror through the telescope of the theodolite. The theodolite is turned so that the mirror is perpendicular to the optical axis of the theodolite. Let the circle reading of the theodolite be A, which is the theodolite reading of the magnetic meridian, provided that the mirror is perpendicular to the magnetic axis of the magnet and there is no torque in the fiber. If we look with the same theodolite at an azimuth mark with known azimuth A_z (geographical direction), and take the reading B from the theodolite, we get for the magnetic declination

$$D = A - (B - A_Z) \tag{4.3}$$

In principle, the measurement of declination is this easy. In practice, there are some sources of error, which have to be eliminated in the measurement. It is almost impossible to fix the mirror to the magnet so that it is perpendicular to the magnet's magnetic axis. Therefore, another measurement has to be taken, turning the magnet by 180° round its own axis ($A = [A_{up} + A_{down}]/2$).

Another source of error is the possible torque of the suspending fibre. Usually the suspension fibre is very thin, 0.02–0.04 mm in diameter, or it is a ribbon, made of tungsten, phosphor-bronze or quartz, and rather long, 15–50 cm, so that it has a low torque. The effect of torsion can be measured by turning the torsion head. The head is on top of the tube inside which the wire is suspended. The head usually has a degree-scale. The turning of the magnet can be observed at the diaphragm scale of the theodolite. Usually turning the torsion head by 1° means about 0.1′ in the orientation of the magnet.

In practice, it is not possible to have zero torsion in the D-measureme Therefore, the measurement has to be made using two magnets with different magnetic moments. The stronger magnet naturally opposes the torsion better than the weaker magnet giving a possibility to calculate the true, torsionless direction of the magnets. It is not necessary to know the magnetic moments of the magnets, only their ratio, which is easily obtained by deflecting the magnets in the theodolite by turning the torsion head, say, ±90° and taking the mean α_{I} of the deflection angles of the stronger magnet (I) and the corresponding value α_{II} of the weaker magnet. The moments of the magnets are inversely proportional to the deflected angles.

The final formula for the declination using both magnets is

$$D = A_{\mathrm{I}} + \gamma(A_{\mathrm{I}} - A_{\mathrm{II}}) - (B - A_z) \tag{4.4}$$

where A_{I} is the circle reading (actually mean of a number of readings A_{up} and A_{down}) of the stronger magnet, A_{II} is the corresponding reading of the weaker magnet, and B is the circle reading of the azimuth mark whose azimuth is A_z. γ is called the torsion ratio. It is a constant for the same pair of magnets and can be determined as shown below.

From Figure 4.1 and applying formula (4.2) for both magnets we get

$$c\varphi = m_{\mathrm{I}} H \sin(A_{\mathrm{I}} - A_0) \tag{4.5}$$

$$c\varphi = m_{\mathrm{II}} H \sin(A_{\mathrm{II}} - A_0)$$

In both equations the terms $c\varphi$ can be considered to be the same, because the torsion angle φ is big compared to the angles under the sine. The sine terms can be replaced with the angles, because they are small. By division and replacing the magnetic moments with the inverses of the measured angles α_{I} and α_{II} we get

$$\alpha_{\mathrm{I}}(A_{\mathrm{II}} - A_0) = \alpha_{\mathrm{II}}(A_{\mathrm{I}} - A_0) \tag{4.6}$$

from which the correction $(A_0 - A_{\mathrm{I}})$ to the observed reading A_{I} is solved:

$$(A_0 - A_{\mathrm{I}}) = \alpha_{\mathrm{I}}(A_{\mathrm{I}} - A_{\mathrm{II}})/(\alpha_{\mathrm{II}} - \alpha_{\mathrm{I}}) = \gamma(A_{\mathrm{I}} - A_{\mathrm{II}}) \quad \text{and} \quad \gamma = \alpha_{\mathrm{I}}/(\alpha_{\mathrm{II}} - \alpha_{\mathrm{I}}) \tag{4.7}$$

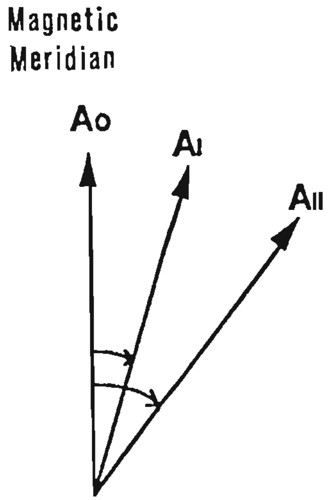


Figure 4.1. Influence of torque of the suspension fibre on the stronger (theodolite reading A_I) and weaker (theodolite reading A_{II}) magnet of the declinometer. A_0 would be the theodolite reading to the magnetic north.

4.3.2 Quartz horizontal magnetometer QHM

The QHM is a compact tubelike instrument containing a small magnet with a mirror suspended on a quartz fibre (Figure 4.2). There naturally is a clamping system for transport of the instrument; moving the QHM in the unclamped position almost certainly breaks the thin quartz fibre, which can be replaced only at the manufacturer's laboratory in Denmark. The QHM can be mounted on almost every non-magnetic theodolite using a self-made or factory-provided adaptor.

The principle of measurement of horizontal intensity H with a QHM is shown in Figure 4.3.

Denoting $(A_+ - A_0) = a_+$ and $(A_0 - A_-) = a_-$ we get the following equations of equilibrium, applying formula 4.2 (see also Figure 4.3),

$$mH\sin\alpha = c\varphi$$

$$mH\sin(\alpha + a_+) = c(\varphi + 2\pi) \tag{4.8}$$

$$mH\sin(\alpha - a_-) = c(\varphi - 2\pi)$$

From these we can obtain H:

$$H = 4\pi c/m\ [\sin(\alpha + a_+) - \sin(\alpha - a_-)] \tag{4.9}$$

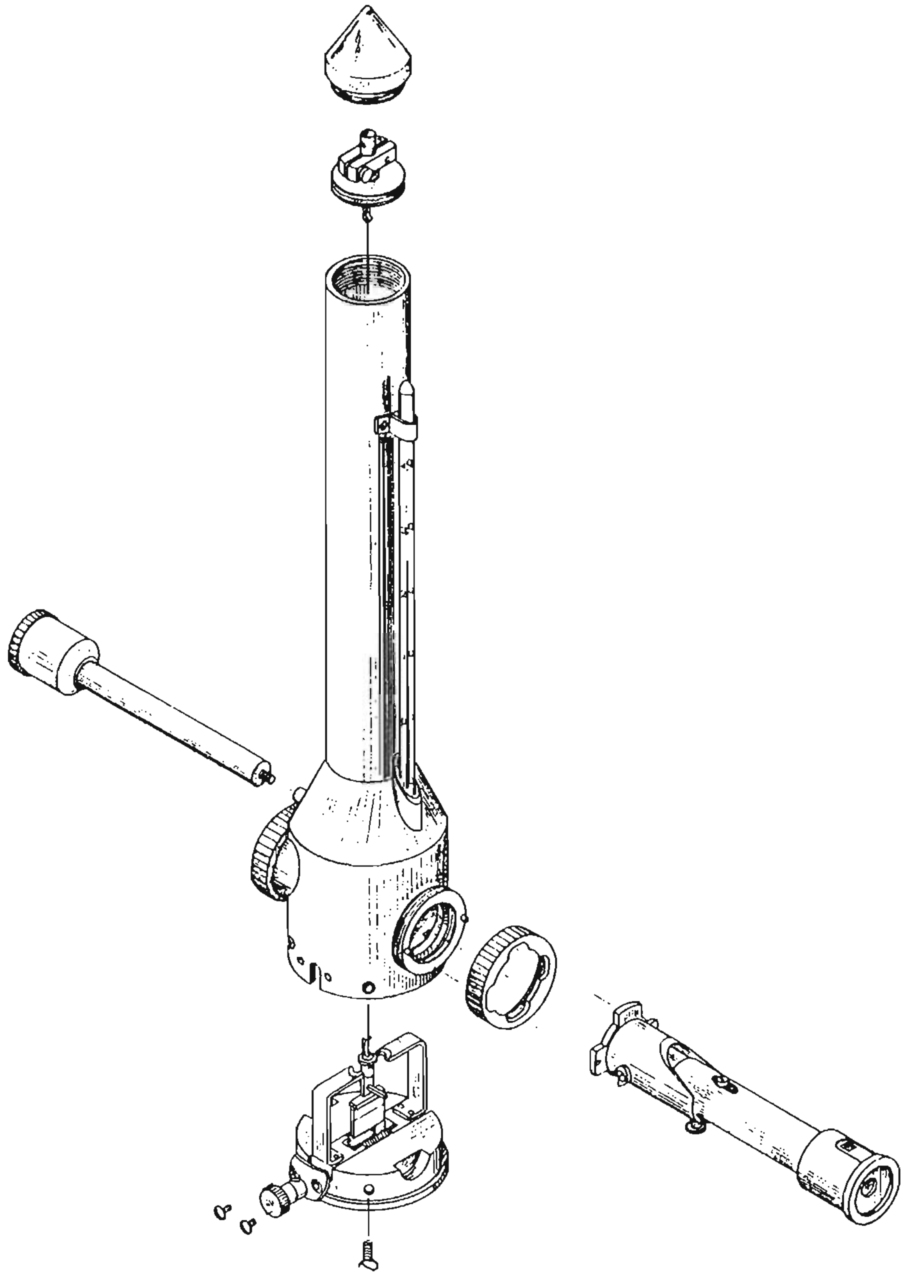


Figure 4.2. The quartz horizontal magnetometer QHM.

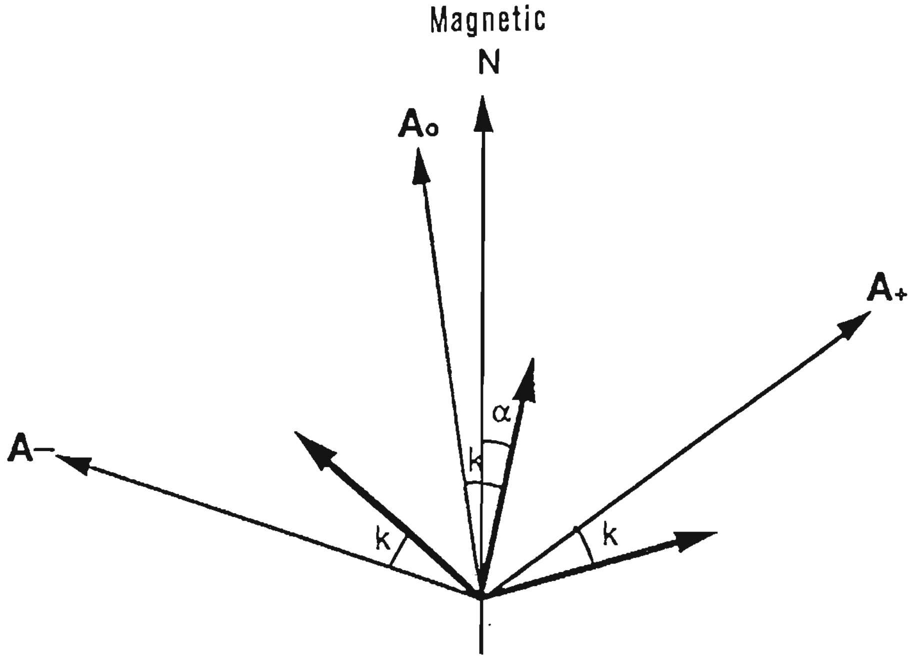


Figure 4.3. The principle of measurement of horizontal intensity H with QHM. The thick arrows show the positions of the magnet. The angles k between the directions of the magnet and the theodolite directions (A-readings) are caused by collimation. They are constant in one series of observations unless the telescope is touched, which would ruin the observation. α is a small angle caused by torsion φ of the suspending fibre. α is made small by the manufacturer of the instrument.

Using the well-known trigonometric formula (subtraction of two sine terms) we get

$$H = 2\pi c/m\ [\sin((a_+ + a_-)/2)\ \cos((a_+ - a_-)/2 + \alpha)] \tag{4.10}$$

The magnetic moment m of the specially treated QHM-magnet is very stable, and so is the torsion constant c of quartz. m and c keep their values for a long time and can be considered constant so that the term $2\pi c/m$ can be set equal to C. α usually is very small by adjustment of the instrument so that $\cos((a_+ - a_-)/2 + \alpha)$ can be replaced with 1, and we get:

$$H = C/\sin\varphi \tag{4.11}$$

where $\varphi = (a_+ + a_-)/2$.

If the absolute value of $(a_+ - a_-)$ exceeds 10′ for φ of about 45°, it is best to use the complete formula. For that a value for α is needed. That is given in the certificate of the instrument, or it can be determined by applying formula (4.14) below. Smaller φ-values are more sensitive and larger are less sensitive to the difference $(a_+ - a_-)$.

The constant C is determined in comparison measurements at a magnetic observatory having absolute standards. In addition to C one has to determine two other constants, namely the temperature constant and the induction constant. The magnetic moment and the torsion factor are functions of temperature. The magnetic moment of the magnet depends on the external magnetic field H along its magnetic axis. Introducing these corrections to the equation for H we get ($\tilde{H}$ is an approximate value of H)

$$H = C/(1 - k_1 t)\,(1 + k_2 \tilde{H} \quad \cos\varphi)\,\sin\varphi \tag{4.12}$$

where C, k_1 and k_2 are the main constants (always given for torsion angle 2π) and the temperature and induction constants are determined at a standard observatory. If $(a_+ - a_-)$ is too big, then the denominator gets one more factor:

$$H = C/(1 - k_1 t)\,(1 + k_2 \tilde{H} \quad \cos\varphi)\,\sin\varphi \cos\,[(a_+ - a_-)/2 + \alpha] \tag{4.13}$$

where α is determined from

$$\tan\alpha = (\sin a_+ - \sin a_-)/(2 - \cos a_+ - \cos a_-) \tag{4.14}$$

This formula is derived from equations (4.8).

4.4 Torsion variometers

For more than a hundred years, torsion magnetometers with suspended and balanced magnets were used at nearly all magnetic observatories in the world for continuous recording of the field variations. The variations were recorded in analog form on photopaper, and this is the main reason why this system is no longer used at most observatories. This also is the reason that we in this guide only briefly describe this type of instrument. For more details, the reader is advised to consult Wienert's *Notes...* or in greater detail the paper by Laursen and Olsen (1971). The main principle of this type of classical variometer is illustrated in Figure 4.4.

The theory of the dynamic case is somewhat more complicated than that of the static case. Let us assume that due to a change of the horizontal magnetic field $\delta \boldsymbol{H}$, $(\delta \boldsymbol{H} = (\delta X, \delta Y))$, the magnet rotates by an angle Φ. The classical formula for an oscillator gives in this case (for example, Yanovskiy, 1978).

$$I\,\mathrm{d}^2\Phi/\mathrm{d}t^2 + b\,\mathrm{d}\Phi/\mathrm{d}t = m\,\delta H_\perp - mH \sin(\alpha + \Phi) + c(\beta - \Phi) \tag{4.15}$$

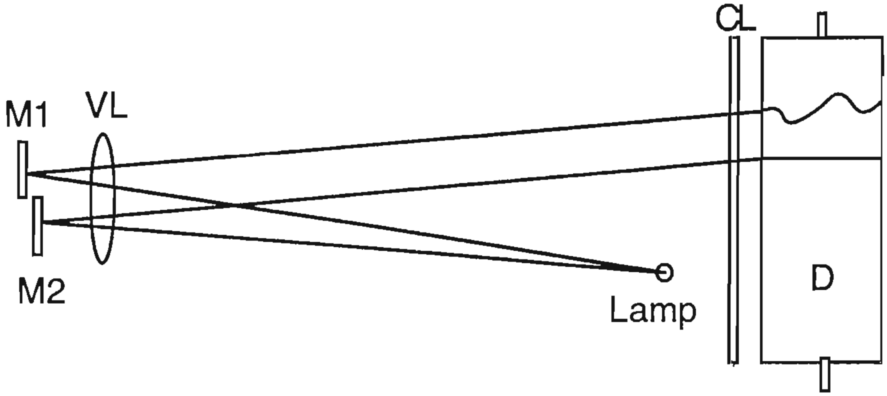


Figure 4.4. Main principles of a classical variometer system. The light source (lamp) is placed at the focal distance of the variometer lens VL. The light beam goes from the lamp through the lens VL to the variometer mirror M1, reflects from there back through the lens VL and a cylindrical lens CL and focuses at the rotating drum D where it forms a sharp spot. Photopaper is wrapped around the drum. The lightspot draws the magnetogram at the moving photopaper. Another lightbeam reflects from a fixed mirror M2 and draws a straight line on the photopaper, so producing the base-line of the magnetogram. The figure shows the principle of the recording of one component. All three components are usually recorded on the same magnetogram.

where I is the moment of inertia of the suspended magnet and mirror, b is the coefficient of damping, and $\delta H_\perp$ stands for the amplitude of variation of the horizontal component of the magnetic field perpendicular to the magnetic axis of the magnet.

For a small angle Φ the equation is simpler:

$$I\,\mathrm{d}^2\Phi/\mathrm{d}t^2 + b\,\mathrm{d}\Phi/\mathrm{d}t + \Phi\,(C + mH\cos\alpha) = m\,\delta H_\perp \tag{4.16}$$

Introducing new constants

$$\varepsilon = b/2I \quad \text{and} \quad \omega_0 = ((C + mH\cos\alpha)/I)^{1/2}$$

we get

$$\mathrm{d}^2\Phi/\mathrm{d}t^2 + 2\varepsilon\,\mathrm{d}\Phi/\mathrm{d}t + \omega_0^2\Phi = (m/I)\,\delta H_\perp \tag{4.17}$$

Using the Fourier transform we get the transfer function $K(i\omega)$ of the system (see, for example, Papoulis, 1962):

$$K(i\omega) = m\left[I\left((i\omega)^2 + 2\varepsilon(i\omega) + \omega_0^2\right)\right]^{-1} \quad (4.18)$$

The complex value $(K(i\omega))$ can be expressed in the form

$$K(i\omega) = (\text{Mod } K(i\omega))\, e^{i\text{Arg}K(i\omega)}$$

from which we get the dependence of the sensitivity on ω:

$$\text{Mod } K(i\omega) = U(\omega) = (m/I)\left[(\omega^2 - \omega_0^2)^2 + 4\varepsilon^2\omega^2\right]^{-1/2} \quad (4.19)$$

For the dependence of phase shift on ω we get

$$\text{Arg } (K(i\omega)) = \varphi(\omega) = \text{arc tan } (-2\varepsilon\omega/(\omega^2 - \omega_0^2)) \quad (4.20)$$

where ω_0 is the angular frequency of the free oscillation of the magnet (with mirror and suspension). In modern magnetometers it is about 1 Hz. As can be seen from (4.19), if the frequency of variation ω is much lower than the natural frequency of the magnet ω_0 , and the product of the damping factor ε and frequency ω is also smaller than ω_0 , then the sensitivity of the system does not depend on the frequency and is equal to $m/(C + mH\cos\alpha)$. In this case, the phase shift is zero (4.20). This can be considered to be the situation in classical magnetometers, which have been successfully used for a long time.

The formulas presented above are important for understanding the behavior of classical variometers and especially modern variometers using classical sensors combined with electronic feed-back. The latter will be described in Section 4.5.

4.5 Photoelectric feed-back magnetometer

The main shortcoming in classical variometers is the necessity of using analog photographic recorders. The introduction of phototransformers (optoelectronical devices which transform the angle of deviation to voltage) helps to overcome this difficulty.

The following presentation is mainly based on the paper by Marianiuk (1977). The principle of torsion photoelectric magnetometers (TPM) is shown in Figure 4.5.

The working principle of torsion photoelectric magnetometers is illustrated in Figure 4.6.

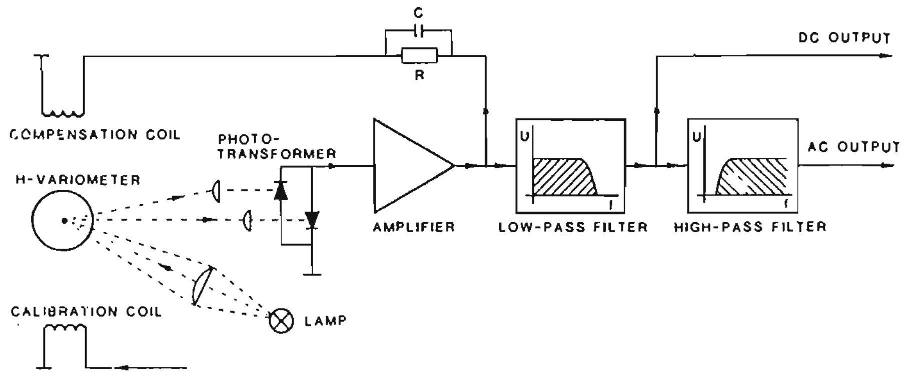


Figure 4.5. Principle of a torsion photoelectric magnetometer (TPM). The light beam from a lamp is reflected from the variometer mirror to a pair of photodiodes in a simple optical arrangement. Currents from the photodiodes are fed to an amplifier with high amplification. Part of the output is fed to a negative feed-back winding (compensation coil). The compensation coil around the variometer magnet is perpendicular to the magnet. The feed-back current compensates for the change of the magnetic field, so that the current is a measure of the change of the component of the magnetic field sensed by the magnet in question. The resistor R controls the strength of the feed-back, and the capacitor C protects the system from excitation.

The transfer function of a magnetometer with negative feed-back is:

$$K_S(i\omega) = K_1K_2/(1 + K_1K_2K_3) = A/[a_0(i\omega)^3 + a_1(i\omega)^3 + a_1(i\omega)^2 + a_2(i\omega) + a_3]$$

$$= U_S(\omega)\, e^{-i\varphi_S(\omega)} \tag{4.21}$$

where $A = mk/K$, $a_0 = \tau$, $a_1 = 2\varepsilon\tau + 1$, $a_2 = 2\varepsilon + \tau\omega_0^2 + AG_SC_S$, and $a_3 = AG_S/R_S + \omega_0^2$.

The transfer function for amplitude is

$$U_S(\omega) = A/[(a_3 - a_1\omega^2)^2 + (a_0\omega^3 - a_2\omega)^2]^{1/2} \tag{4.22}$$

When $\varepsilon\tau << 1$, then

$$U_S(\omega) = A/[(\omega_1^2 - \omega^2)^2 + 4\varepsilon_1^2\omega^2]^{1/2} \tag{4.23}$$

where $\omega_1 = (\omega_0^2 + AG_S/R_S)^{1/2}$ and $\varepsilon_1 = \varepsilon + AG_SC_S/2$ is the damping constant of the arrangement.

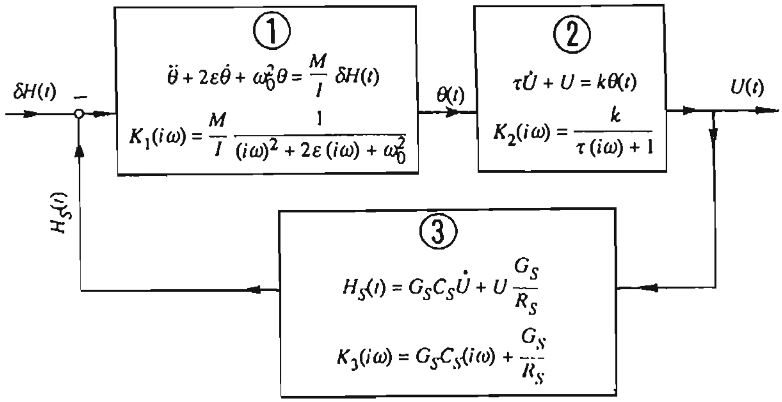


Figure 4.6. Working principle of torsion photoelectric magnetometers (TPM). (1) is the variometer, (2) is the photoelectric converter, and (3) contains the elements of the feed-back loop. $\delta H(t)$ is the variation of the component of the magnetic field to be recorded and $U(t)$ is the corresponding output voltage. $H_S(t)$ is the field produced by the feed-back coil to compensate for the effect of $\delta H(t)$. M is the magnetic moment of the magnet and I is the moment of inertia of the moving system. θ is the angle of deflection of the magnet, ε is the damping coefficient, ω_0 is the natural frequency of the magnet, τ is the time constant of the amplifier, k is the amplification (V/rad), G_S is the feed-back coil factor (nT/mA), R_S and C_S are the resistance and capacitance of the feed-back loop (denoted R and C in Figure 4.5), and ω is the frequency of the magnet.

The transfer function of phase is

$$\varphi_S(\omega) = \arctan\,[2\varepsilon_1\omega/(\omega_1^2 - \omega^2)] \tag{4.24}$$

For $\omega \ll \omega_1$ (at least three times smaller)

$$U_S = R_S/G_S \quad \text{and} \quad \varphi_S = 0 \tag{4.25}$$

Comparing (4.23) and (4.19) we can see some similarities. In both cases the transfer functions have one resonance frequency, but in the system of strong negative feed-back the resonance frequency is shifted to a higher value, in practice one order of magnitude. This means that using the same variometer one can record more rapid variations. Even more important is the difference in sensitivity. In the classical variometer without feed-back the sensitivity depends on the magnetic moment of the magnet and the torsion constant of the fibre. In the feed-back system with high amplification and strong feed-back, the sensitivity of the whole system does not depend on the sensitivity of the variometer itself but only on the ratio R_S/G_S, as shown by formula (4.25). The feed-back loop compensates for all changes of elements in the loop, for example variations of the intensity of the light. A change of several tens of percent in the light intensity cannot be seen as a change in sensitivity in practice. It has to be stressed, however, that the feed-back system does not correct for possible instabilities in the permanent compensation of the main part of the external field, nor does it correct for the possible change of recording due to tilting or thermal coefficient. But, as presented above, the use of phototransfer with feed-back not only allows us to express the variation of the magnetic field as electric voltage, but also improves some parameters of the variometer.

Widely used is the Polish torsion photoelectric magnetometer TPM, which has been installed at observatories in several countries and is also used in field work. Based on roughly the same principle, similar magnetometers have been constructed (e.g, Beblo, 1990). Below we describe the Polish TPM as a typical one (Marianiuk *et al.*, 1978).

The instrument is based on quartz variometers designed by Bobrov (1962). Bobrov quartz variometers are of a type in which the quartz fibres are attached to both sides of a magnet so that the magnet is suspended on the fibre. During recording, the

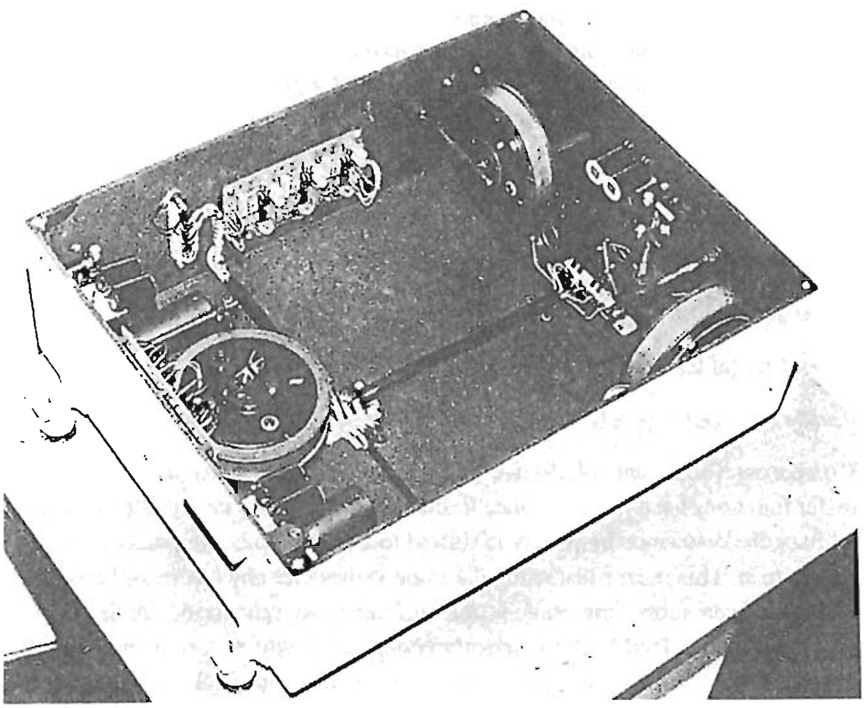


Figure 4.7. The box of torsion photoelectric variometer with sensors and sensor electronics.

magnetic field perpendicular to the magnet is kept almost zero. Most of the field is compensated using stable magnets with near-zero thermal coefficients. These magnets are fixed to the quartz frame of the variometer. Additional small magnets can be used outside the variometer to produce compensation in a field different from that for which the magnetometer was designed.

To the classical variometers, photoelectric converters are added. The electronics and the photoelectric converters are similar for all three components. The interior of a TPM is shown in Figure 4.7. In addition to the three quartz variometers and the three photoelectric converters, the casing contains the electronics for the compensation of temperature variations and for the recording of temperature. The instrument is shown to have quite good technical parameters. The long-term stability is usually a few nanoteslas per year, and the resolution is not less than 0.01 nT. After transportation one can expect some work to be needed in correcting the position of the light spot and possibly in changing the lamp (or LED which is sometimes used instead of a lamp to save power) or in some cases also the photodiodes. The normal life-time of the lamps is more than five years. The LEDs also last several years before losing too much of their light intensity.

4.6 Proton precession magnetometer

In contemporary physics, the measurement of frequency is the most accurate technique. The modern ways to measure frequencies are easy due to the progress in electronic technology. This is the reason why for any physical quantity to be measured an attempt has been made to transform its measurement to that of frequency.

In geomagnetism, proton and optical-pumping magnetometers are based on the transformation of intensity of the magnetic field to a frequency to be measured. The measurement in the spectral domain is the determination of the location of the center of the spectral line. When the spectral line is narrow, it is possible to determine its position with a very high relative accuracy, 10^{-12} is common in physics. In geomagnetic measurements the accuracy is not higher than 10^{-7} (often only 10^{-5}), due to the rather broad spectral line depending on the signal-to-noise ratio in the magnetometers.

The proton precession magnetometer or simply proton magnetometer is based on free precession of protons in a liquid. The angular precession ω of protons depends linearly on the magnetic field:

$$\omega = 2\pi f = \gamma_p F \tag{4.26}$$

where γ_p is the gyromagnetic ratio of the proton which is a natural constant known with high accuracy. The National Bureau of Standard value of γ_p is

$\gamma_p = 2.6751525 \cdot 10^8 \pm 40\ \mathrm{T}^{-1}\mathrm{s}^{-1}$.

IAGA has recommended that from the beginning of the year 1992 the best known value should be used in geomagnetic work. Prior to 1992, the value used in geomagnetic work was the value adopted by IAGA in 1960

$\gamma_p = 2.67513 \cdot 10^8\ \mathrm{T}^{-1}\mathrm{s}^{-1}$.

All magnetic data produced and published before 1992 are based on this value.

As mentioned above, the gyromagnetic ratio γ is a natural constant relating the spin of a subatomic particle to mechanical moment $\boldsymbol{p}$ and magnetic moment $\boldsymbol{m}$:

$$\boldsymbol{m} = \gamma \boldsymbol{p} \tag{4.27}$$

where $p = jh/2\pi$, with j being the quantum number of the particle; for the proton and electron it is 1/2, and h is Planck's constant ($6.62 \cdot 10^{-34}$ Js). The gyromagnetic ratio of a free electron, γ_e, is about 658 times higher than that of a proton.

The coupling energy E of magnetic moment $\boldsymbol{m}$ in magnetic field $\boldsymbol{F}$ is

$$E = -\boldsymbol{m} \cdot \boldsymbol{F} = -mF\cos\theta \tag{4.28}$$

Because, as a rule, there are $2j + 1$ allowed energy levels, protons and electrons with $j = 1/2$ have only two possible energy levels, corresponding to θ-values of plus and minus 45°. In a sensor, which is a large sample of, say, protons, the populations of the two energy levels are proportional to $\exp(-E/kT)$, where k is the Boltzmann constant ($1.38 \cdot 10^{-23}$ J/K) and T is the absolute temperature. This means that the ratio of populations at two energy levels is

$$N_1/N_2 = \exp\,[(E_1 - E_2)]/kT \tag{4.29}$$

where N_1 and N_2 are the numbers of particles at the two energy levels.

In thermal equilibrium, the lower energy level is slightly more populated than the upper one. In a magnetic field $\boldsymbol{F}$, and when there is a difference in the populations of the energy levels, there will be a net magnetization $\boldsymbol{M}$ of the sensor colinear with $\boldsymbol{F}$

$$\boldsymbol{M} = \kappa \boldsymbol{F} = (N\gamma^2 h^2 \boldsymbol{F})/16\pi^2 kT \tag{4.30}$$

where κ = nuclear susceptibility and N = number of particles in the sample. In a magnetic field, $\boldsymbol{M}$ is oriented along the field. In a proton magnetometer, $\boldsymbol{M}$ is deflected from this direction by applying a roughly perpendicular magnetic field, which means that $\boldsymbol{M}$ orientates along the new field direction acquiring a new value of $\boldsymbol{M}$ which depends on the strength of the perpendicular field and on its duration. The new value is achieved exponentially with time constant T_1. It is essential to realize the two effects of the deflecting field in a proton magnetometer:

1) the deflecting additional field increases the magnetization of the sensor according to formula (4.30), and

2) the additional field deflects $\boldsymbol{M}$ from the direction of the field to be measured, so that when the deflecting field is removed rapidly, the protons begin to precess around the remaining field spiralling towards the direction of the field, again exponentially with time constant T_2.

The gyrofrequency f of protons is measurable in magnetic fields which are of the same order of magnitude as the field of the Earth. F and f are connected by equation (4.26). From this equation it follows that 1 Hz corresponds to 23.48720 nT (the old IAGA value was 23.4874 nT/Hz).

The sensor of the proton magnetometer is usually a bottle containing some 200– 500 cc proton-rich liquid such as water (good but not practical in cold climate), alcohol or kerosene. Around the bottle there are about 1000 windings of copper or aluminum wire for applying a polarizing field to the liquid (fields up to 0.01 T are used) and for picking up the signal from the precessing protons after cutting off the polarizing field. In some proton magnetometers a double bottle with oppositely directed coils is used to compensate for possible disturbing electromagnetic fields (Jankowski *et al.*, 1965). In the measurement the bottle is oriented so that the polarizing field is roughly perpendicular to the measured field. When the polarizing field is cut off rapidly, the protons begin to precess around the magnetic field vector, whose magnitude is to be measured. The signal from the protons is small, only of the order of one microvolt in the coil, but its frequency is measurable for 1–5 seconds depending on the homogeneity of the measured field and the polarizing field used. As shown above, the frequency is linearly proportional to the magnitude of the field. The generation of the free precession signal of a proton magnetometer is shown in Figure 4.8.

The ratio of amplitude-to-noise of the decaying signal shown in Figure 4.8 depends on several factors: the volume of the sensor, strength and duration of the field used for the polarization, the band-pass of the filter and the homogeneity of the field to be measured. For practical purposes the sensor should be light, the power consumption low and the filter not too narrow. All these factors can influence the signal-to-noise ratio, which in commercially available magnetometers is usually some tens to one.

In any case, it is necessary to measure a frequency between 1 and 4 kHz of a weak, noisy signal which decays exponentially in a few seconds, with an accuracy not less than 10^{-5}.

There are several methods for the determination of the frequency f from the proton

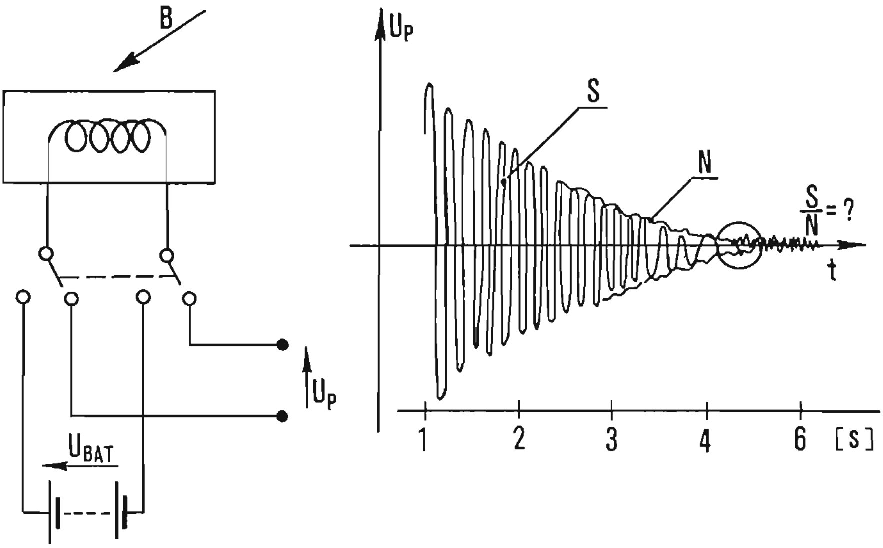


Figure 4.8. The generation of free precession signal in a proton precession magnetometer. B = magnetic induction, U_{BAT} = voltage of the battery, U_P = voltage of the precession signal, S/N = signal-to-noise ratio.

sensor. The oldest method, which is still in use in several proton magnetometers, is to measure the time for a preset number of proton oscillations. This can be called the simple period mode version of the instrument (Figure 4.9).

Utilizing formula (4.26) we get

$$F = 48101.8 \cdot 10^5 / N \quad [\mathrm{nT}] \tag{4.31}$$

assuming that N oscillations of the 100 kHz oscillator of the proton magnetometer were counted during $n = 2^{11} = 2048$ proton oscillations.

If the proton signal (or the signal of a test oscillator) is 2 kHz, the time of the 2^{10} oscillations is little more than half a second. The 100 kHz oscillator counts N = 1024/2000 × 100000 = 51200 oscillations, which is the figure an older type proton magnetometer should give. If we have five digits in the display, which is the normal case, one digit corresponds to 0.5 nT. For a good magnetometer having high signal-to -noise ratio, this is the real resolution of the instrument. The scatter of results is mainly caused by inaccurate closing of the gate at the end of the measuring period, where the signal-to-noise ratio is smaller than at the beginning. This is especially true when there is a gradient of the field at the position of the sensor.

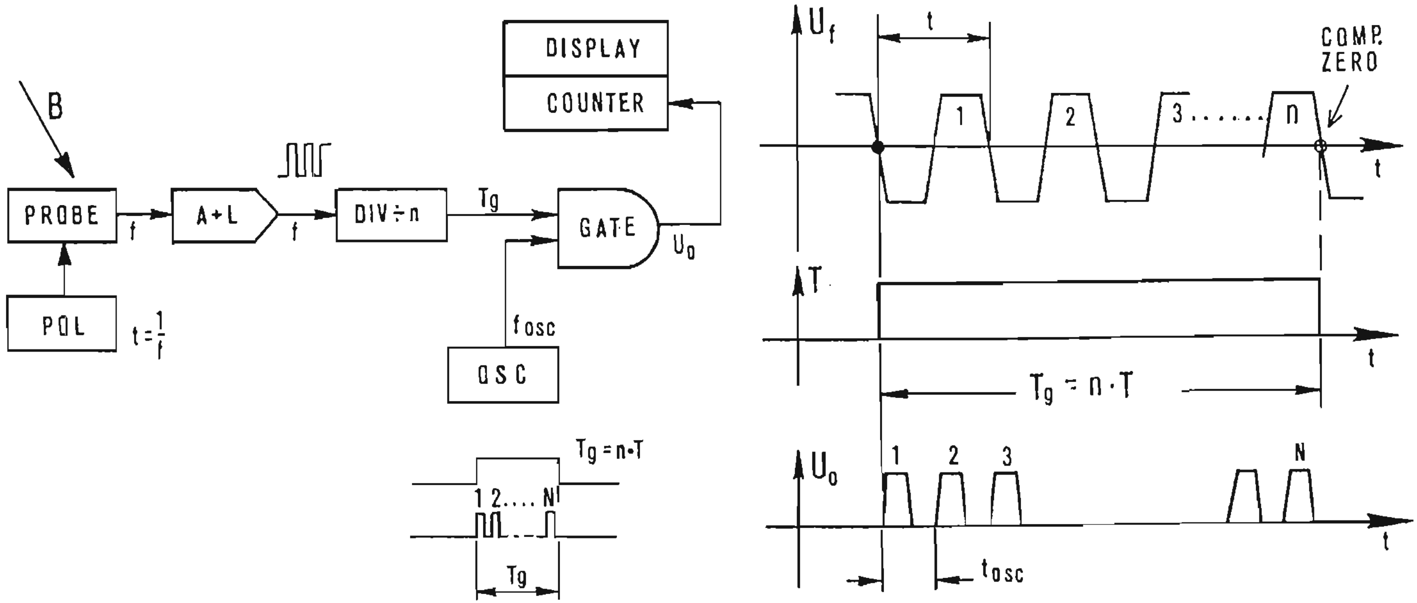


Figure 4.9. Schematic diagram of a period mode counting proton magnetometer. A = amplifier, L = limiter, OSC = oscillator. The precession signal is amplified to produce a series of square pulses. Usually $n=2^{10}$ or $n=2^{11}$ pulses are counted and the time T_g of n pulses is recorded using the crystal oscillator of the magnetometer.

Note that for a fixed signal-to-noise ratio, increasing the frequency of the quartz oscillator does not improve the accuracy. One can get a better resolution only by increasing the signal and counting a greater number of oscillations, but as it was stated before, this would need a big sensor and much power, which is impractical. This is the reason why this type of magnetometer has a resolution of 0.5 nT and seldom better. A shortcoming of this method is also that the display shows N instead of the field intensity in nanoteslas, which has to be calculated using formula (4.31).

Probably the most popular method used in proton magnetometers is the phase-locked system for measuring frequency. There the signal from an oscillator is

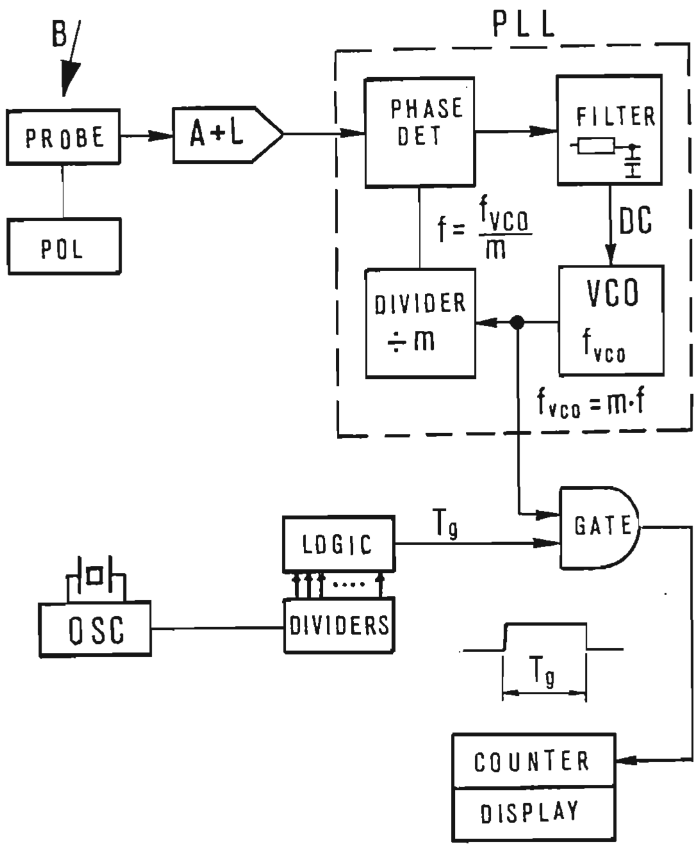


Figure 4.10. Phase-locking method of frequency measurement. The phase-locked loop (PLL) is used to multiply the frequency m times. The frequency output of a voltage-controlled oscillator (VCO) is automatically adjusted by the voltage appearing at the output of the phase detector (PHASE DET) until the divided frequency $f_{VCO} = f$. *The frequency* f_{VCO} *is measured directly by a frequency counter during the time period* T_g, *which is the time when the gate is open.*

phase-locked to the signal from the proton sensor. The principle of this method is illustrated in Figure 4.10.

On the display of the phase-locked proton magnetometer we have a number N which corresponds to cycles of the VCO counted in period T_g.

$$N = T_g f_{VCO} = T_g\, mf \tag{4.32}$$

and

$$F = 2\pi N/\gamma_p T_g m\ . \tag{4.33}$$

Putting the ratio $2\pi/\gamma_p T_g m = 1$, which is easy by selecting a suitable multiplication factor m and a proper time period T_g, we get

$$F = N.$$

One advantage of the phase-locked system compared to the previous one is first of all that the readings are directly in nanoteslas, which is convenient. There is some profit in the use of the frequency of the voltage-controlled oscillator. This means some averaging. Therefore, the phase of its signal has smaller fluctuations than the original signal of the free precession. In this magnetometer the sensitivity can be made higher than in the previous one, say to about 0.1 nT. On the other hand, the fact that the precession frequency is not measured directly but rather a frequency which is synchronized with the precession frequency is a shortcoming of this method: the indirect measurement may be worse than the direct one. In some cases, the voltage-controlled oscillator may generate a signal even when the precession signal no longer exists, for example when a high gradient causes the signal at the end of the measuring period to be smaller than the noise.

Based on a central microprocessor, new proton magnetometers have been designed during recent years. The use of new technology has made it possible to improve the technical parameters of the instrument. Using processors for the measurement of the precession frequency is rather simple. This is illustrated in Figure 4.11.

The use of computer technology allows sophisticated treatment of the measurement results stored in the memory of the processor. Figure 4.11 presents one example where the least squares fit can be used, or the so-called digital filter algorithm. In any case, as can be seen from Figure 4.12 where data from the first method and the microprocessor method are presented, the statistical possibilities clearly improve the precision. Naturally, using computer technology it is easy to obtain the results directly in nanoteslas.

Additionally, the use of computer technology can make the instrument "intelligent" in the sense that only signals higher than noise are utilized. Also, it is easy to produce,

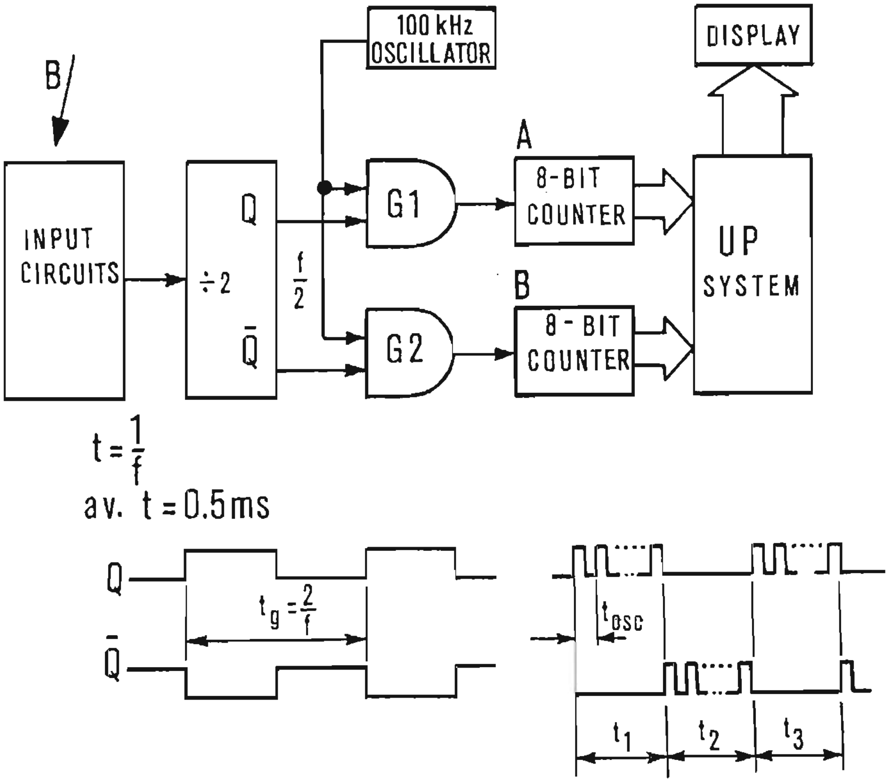


Figure 4. 11. Schematic block diagram of the frequency measuring system of a proton magnetometer utilizing a microprocessor for the on-line processing of the signal. The times produced by the 100 kHz oscillator, starting from zero when the gate is opened, are recorded separately for each positive and negative crossing of the zero-line of the amplified precession signal. The times are stored in the memory of the processor which calculates and displays the result after the measuring period by applying statistical methods to the stored data.

together with the result, an estimate of its accuracy. Computer technology also makes it possible to store the data, and to transmit the data through, for example, a standard serial interface (RS-232). Using the method described above an accuracy of 0.1 nT is easily achieved.

The polarization of the liquid in the sensor bottle takes, depending on the field used, usually 2–6 seconds. The longer times are used for getting more protons oriented into the direction of the field, which means a stronger and longer signal in the measurement, allowing higher sensitivity (0.1 nT) to be used.

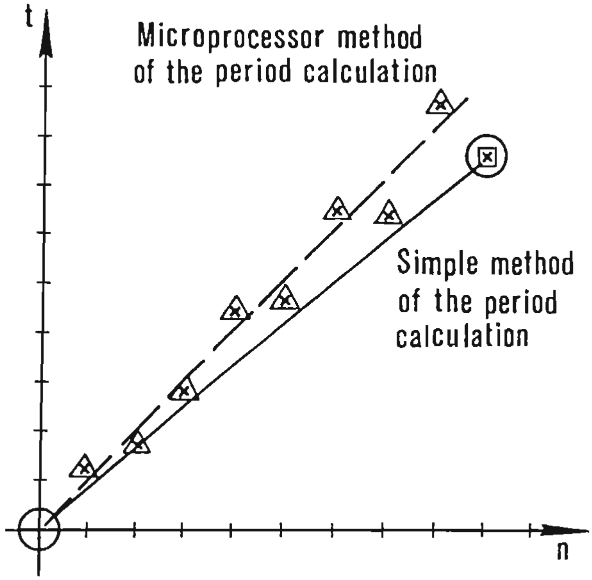


Figure 4.12. Illustration of the difference between the simple and microprocessor methods of the period calculation. n = consecutive number of zero crossing, t = time of the corresponding crossing. In the old simple method the line had to be determined from 2 points (crossings of the amplified precession signal through the zero line) only, one at the beginning and one at the end of the measuring period. The processor allows all the crossings to be taken into account and a statistical fit to be applied.

4.7 Overhauser magnetometer

Proton magnetometers described above are the normal instruments for absolute measurements at magnetic observatories, and also for taking samples of the field in other connections. As shown above, proton magnetometers cannot take samples very frequently. When faster sampling is needed, without reducing the accuracy, two methods using the proton precession have been applied. In the method of Skripov (1958) the liquid is polarized outside the pick-up coil and the liquid runs through the coil continuously. In this method, the time used for polarizing is saved and the samples can be taken once in a second or so. There are only very few such magnetometers in use.

The other method, applying the so-called Overhauser effect, has become widely used (Overhauser, 1953; Hrvoic, 1990). In this method:

a) The increase of magnetization of the sample is achieved by adding free electrons to the liquid and utilizing the coupling of these electrons to the protons. The magnetization is increased applying a suitable radio frequency, as will be presented in somewhat greater detail below. In normal proton magnetometers, this is done by applying a strong polarizing field to the sensor liquid.

b) The generation of the proton signal is done by short pulses, perpendicular to the measured field, or continuously by a perpendicular rotating field regulated by feedback from the proton signal.

c) The detection and measurement of the signal of the precessing protons is done in principle the same way as in normal proton magnetometers. In the Overhauser system the continuous signal allows, however, sampling rates up to several samples per second.

As stated in the beginning of this chapter, the quantum number of both proton and electron is 1/2, which means that there are only two possible energy levels for both, and their combination has the four possible energy levels presented in Fig. 4.13. All transitions are possible, some dealing with only electrons and some with only protons. The Overhauser effect deals with the combined mutual transitions 1–4 and

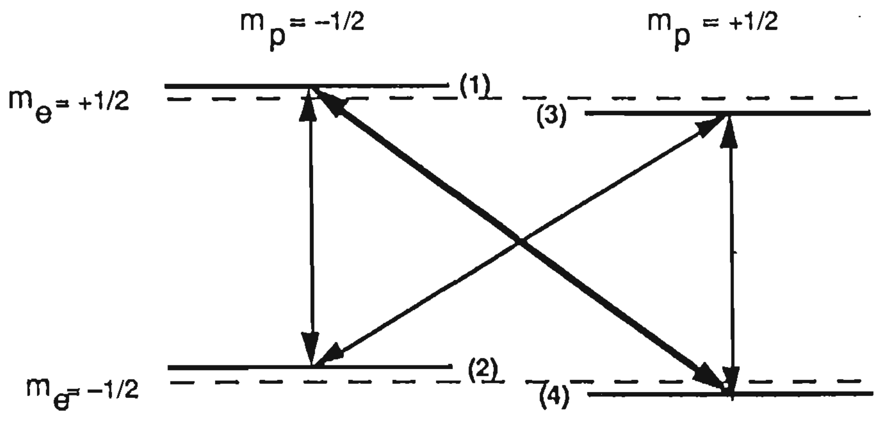


Figure 4.13. The four energy levels of a system with protons and free electrons in a proton-rich liquid. m_p and m_e are the possible quantum numbers of protons and electrons, allowing the four energy levels. The Overhauser magnetometers utilize the transitions between energy levels (1) and (4). Applying a suitable radio frequency, both energy levels are saturated which means that there will be a net polarization of protons according to the Boltzmann law.

2–3, from which 1–4 is the most probable in magnetometers utilizing the weak scalar coupling of protons of the liquid and electrons of the free radicals in the liquid.

That a net polarization will result can be explained (Hrvoic, 1990) as follows:

$$N_+ n_- W_{(1-4)} = N_- n W_{(4-1)} \qquad (4.34)$$

where N_+ and n_+ are numbers of protons and electrons at +1/2 energy level, and N_- and n_- are the corresponding numbers at –1/2 energy level. $W_{(1-4)}$ and $W_{(4-1)}$ are probabilities of transitions (1–4) and (4–1). In thermal equilibrium they follow the Boltzman law

$$W_{(1-4)}/W_{(4-1)} = \exp\,[(E_1 - E_4)/kT] = \exp\,[-\,h(\omega_e - \omega_p)/2\pi kT] \qquad (4.35)$$

where E_1 and E_4 are the energies corresponding to levels (1) and (4) in Figure 4.13, and ω_e and ω_p are the corresponding angular frequencies. By using a suitable radio frequency the electron spectral lines will be saturated. There will be a difference in the population of proton spin energy levels

$$N_+/N_- = \exp\,[h(\omega_e - \omega_p)/2\pi kT] = 1 + h(\omega_e - \omega_p)/2\pi kT \qquad (4.36)$$

which in the absence of electrons would have been $N_+/N_- = 1 - h\omega_p/2\pi kT$. As stated earlier, the electron resonant frequency ω_e exceeds the corresponding proton frequency ω_p 658 times. In other words, theoretically the proton polarization will be increased this much. In practice the increased polarization is not this high.

Further improvement of the method based on the Overhauser effect is achieved by using nitroxide free radicals where electrons exhibit strong scalar coupling with the nucleus. Experimentally, using free radicals, 5000 times increased proton polarization is obtained instead of the theoretical 658 presented above. The big advantage of high resonant frequency is that the saturating radio frequency can stay constant for the whole range of fields measured or recorded in Earth magnetism.

As presented above, a rather strong polarization of protons in the liquid is achieved by applying a suitable radio frequency. This consumes much less energy than the strong polarization needed in classical proton magnetometers.

To be able to measure the gyro frequency of protons, the direction of the polarization has to be deflected from the direction of the prevailing field to a direction nearly perpendicular to that. There are several methods in use for that in Overhauser magnetometers, all using much less energy than the classical magnetometers. One used successfully is the so-called 90° pulse, which lasts below a millisecond and deflects the increased proton magnetization into the perpendicular plane of the field to be measured. A new pulse is applied as soon as the frequency of the precessing protons has been measured. The magnetization is kept high by the Overhauser effect.

It is also possible to create continuous proton precession by applying a weak magnetic field which rotates in the plane of precession with a frequency very close to the frequency of the gyrating protons (within the width of the spectral line of the protons, which is about 2 nT). In this method the precession signal is detected and a voltage controlled oscillator (VCO) is locked to it. The VCO frequency is measured and a small correction applied leading to an accuracy of a small fraction of nT. Another method is to amplify the proton precession signal and feed it back to the coils to produce the excitation field. The major advantage over the much simpler VCO method is the possibility to follow the changes of the magnetic field with high speed.

The advantages of the Overhauser magnetometers compared to the classical proton magnetometers can be listed as follows:

- It is possible to create a steady proton precession signal, which makes possible the true average measurement of the magnetic field, instead of sampling.
- Small consumption of power. Pulsed Overhauser magnetometers use typically 1 Ws of energy per reading compared with several times higher consumption in classical proton magnetometers.
- Faster rate of readings, because no time is wasted for polarization.
- The sensor can be made rather small (pulsed Overhauser magnetometers have used sensors smaller than 0.2 l liquid with noise standard deviations 0.02 nT rms).

However, shortcomings have also been found in Overhauser magnetometers compared to the classical ones:

- The radio frequency used may disturb nearby instruments.
- Production of the polarizing signal is more difficult than in the classical proton magnetometers.
- The construction is more complicated leading to reduced reliability.
- The liquid used is not always stable and it is often a secret of the manufacturer.

4.8 Optically pumped magnetometers

In this Guide, the optically pumped magnetometers are described shortly, because they are rather seldom used in observatory practice. More detailed description can be found in geophysical literature (see Stuart, 1972; Forbes, 1987). The operation of optically pumped magnetometers is based on Zeeman splitting of the energy levels of atoms into sublevels, whose energy separation depends on the orientation of the magnetic moments relative to the ambient field. The energy separation corresponds to the frequency which is a measure of the ambient magnetic field. Similarly as for proton magnetometers, measurements of the field intensity are reduced to frequency measurements. In order to understand the principle of operation of this type of magnetometers, some knowledge on atomic physics is needed.

For field measurements, the low-frequency transition $\Delta F = 0$, $\Delta m_F = \pm 1$ of alkali atoms or the Zeeman transition $\Delta m = \pm 1$ of the metastable state 2^3S_1 of ^4He is used. Here F is the quantum number of the total angular momentum of the atom in a given state, and is a sum of the nuclear spin and the electronic orbital and spin momenta; m_F is the magnetic quantum number and it can assume values from $-F$ to $+F$. In the optical transition, m_F may only change by 0 or ± 1.

Energy differences between levels of hyperfine splitting are small. In order to measure them, a technique called optical pumping can be applied. For explanation of this method, let us assume a gas cell containing alkali vapor, e.g., rubidium 85, illuminated by the D_1 resonance line. Let us assume further that the light is σ^+–circularly polarized.

The energy diagram for ^{85}Rb atom is shown in Figure 4.14. The $^2S_{1/2}$ level is the ground state, $^2P_{1/2}$ is the excited state. Atoms absorbing σ^+ photons change their magnetic quantum number by +1. The atoms in the $m_F = +2$, $F = 2$ state cannot then absorb photons from the rubidium lamp, typically used as an excitation source. Due to spontaneous emission from the excited level to the ground level, atoms change

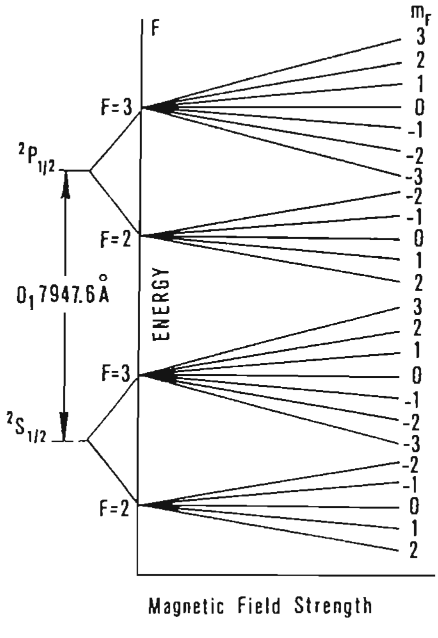


Figure 4.14. Energy diagram of ^{85}Rb.

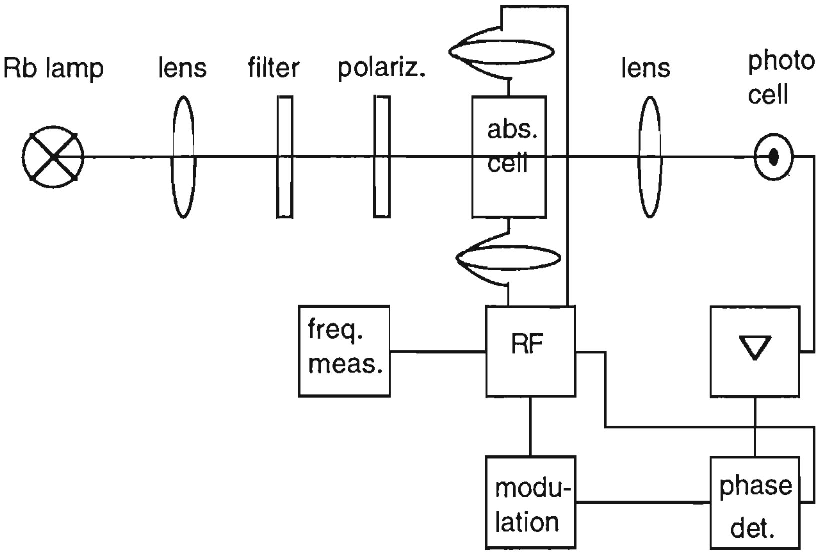


Figure 4.15. The working principle of rubidium magnetometer. The rubidium light passes through an interference filter, a circular polarizer and an absorbing cell, which is filled with rubidium vapor. The light is pumping atoms and the cell becomes transparent to the resonant light. The light intensity is measured by means of a photocell. The radio frequency from the oscillator follows the resonance frequency due to negative feedback from the photocell.

Table 4.1

Properties of the elements used in optically pumped magnetometers

Element	Quantum number F of relevant atomic state	Total no. of sublevels m_F	Gyromagnetic ratio γ_1 (Hz nT^{-1})
^{85}Rb	3	7	4.667
^{87}Rb	2	5	6.999
^{133}Cs	4	9	3.499
^{4}He	1	3	28.0

their magnetic number by 0 or ±1. This means that after certain time nearly all atoms will be pumped into sublevel $m_F = +2$ of the ground state. This phenomenon is called optical pumping. In this state, atoms in a gas cell cannot absorb photons of light. If we now apply a radio frequency electromagnetic field of frequency corresponding to the difference between $m_F = +2$ and $m_F = +1$ sublevels of the $F = 2$ hyperfine level, the $m_F = +1$ sublevel will be again populated and optical σ^+ photons will be absorbed. The resonant frequency is called a Larmor frequency, and is characterized by a gyromagnetic ratio (see Table 4.1). In Figure 4.15 we give an example of block diagram of rubidium magnetometer.

There is a variety of designs of optically pumped magnetometers. The one presented in Figure 4.15 is of a locked oscillator type. Another type is a self-oscillator magnetometer. There are several differences even between the instruments of the same type, related, e.g., to relaxation processes in the gas cell, direction of alternating field and so on. Comparing with proton magnetometers, the optically pumped magnetometers have some advantages:

- The gyromagnetic ratio is bigger and the measured frequency is higher.
- The resolution is very high, up to 0.001nT.
- The duration of measurements can be shorter.

The disadvantages are the following:

- The relation between the frequency and the magnetic field for alkali vapor is slightly nonlinear; for example, for ^{85}Rb we have $f = (4.667 \cdot B - 72 \cdot 10^{-10} B^2)$ $\mathrm{Hz} \cdot \mathrm{nT}^{-1}$.
- The construction of magnetometers is more sophisticated and the whole instrument is expensive. Some elements of the instrument can be subject to ageing.
- For absolute measurements, the instrument is not as suitable as a proton magnetometer.

4.9 Fluxgate magnetometer

The fluxgate magnetometers are based on the nonlinearity of the magnetization of "soft" magnetic materials. The sensitive element of a fluxgate magnetometer consists of an easily saturable core made of material with high permeability. Around the core there are two windings: an excitation coil and a pick-up coil. If an alternating excitation current with frequency f ($\omega = 2\pi f$) is fed into the excitation coil so that saturation occurs and if there is an external field along the fluxgate element, there exists in the pick-up coil a signal having not only the frequency f but also other harmonics. The second harmonic is particularly sensitive to the intensity of the field.

Fluxgate magnetometers have a long history. The first instrument was described before the second world war (Aschenbrenner and Gaubau, 1936), and it was further developed during the war for detecting mines. Up to now more than a hundred different types of instruments have been designed. Different types of cores are in use: single bar cores, cores of two parallel bars, ring cores. Several different alloys are also in use as cores: permalloy, mumetal, ferrite, amorphous magnetic materials, etc.

Different configurations for the excitation field are also in use: parallel or orthogonal to the axis of the sensor with many different waveforms of the excitation signals. An excellent review of fluxgate magnetometers has been written by Primdahl (1979); see also Coles, (1988). Because the fluxgate magnetometer is now at most observatories the basic instrument for the absolute measurement of D and I and widely used also for recording, we shall describe its principle of operation in greater detail.

Let us start from a simple mathematical model (Yanovskiy, 1978). We assume that the hysteresis curve can be approximated by a polynomial of third degree

$$B = aH^3 + cH \tag{4.37}$$

In the fluxgate sensor the magnetic field consists of the external field H_0 and the excitation field $H_1 \cos \omega t$, and we get for B

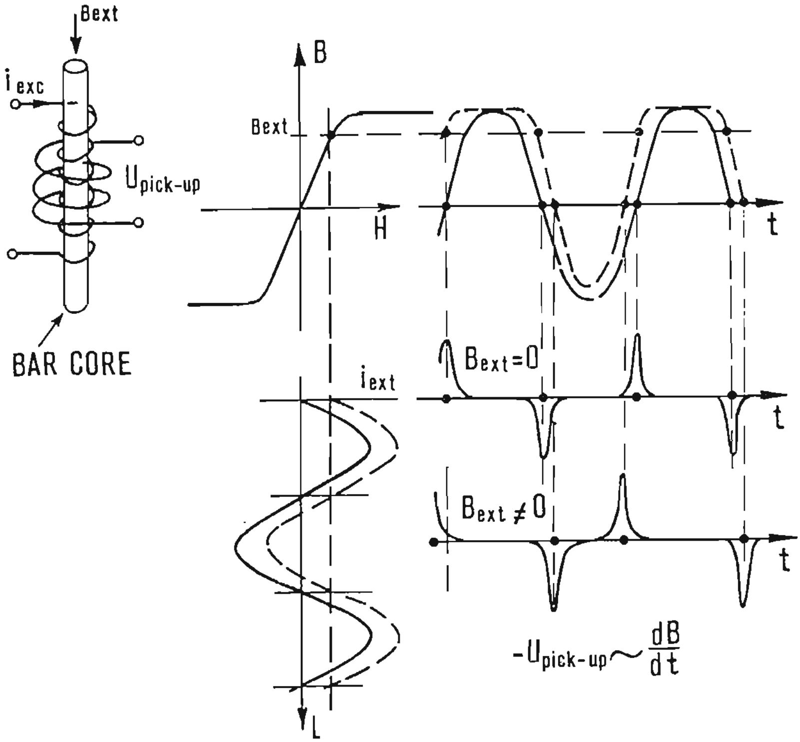


Figure 4.16. Waveforms of a fluxgate sensor with the core consisting of a single bar.

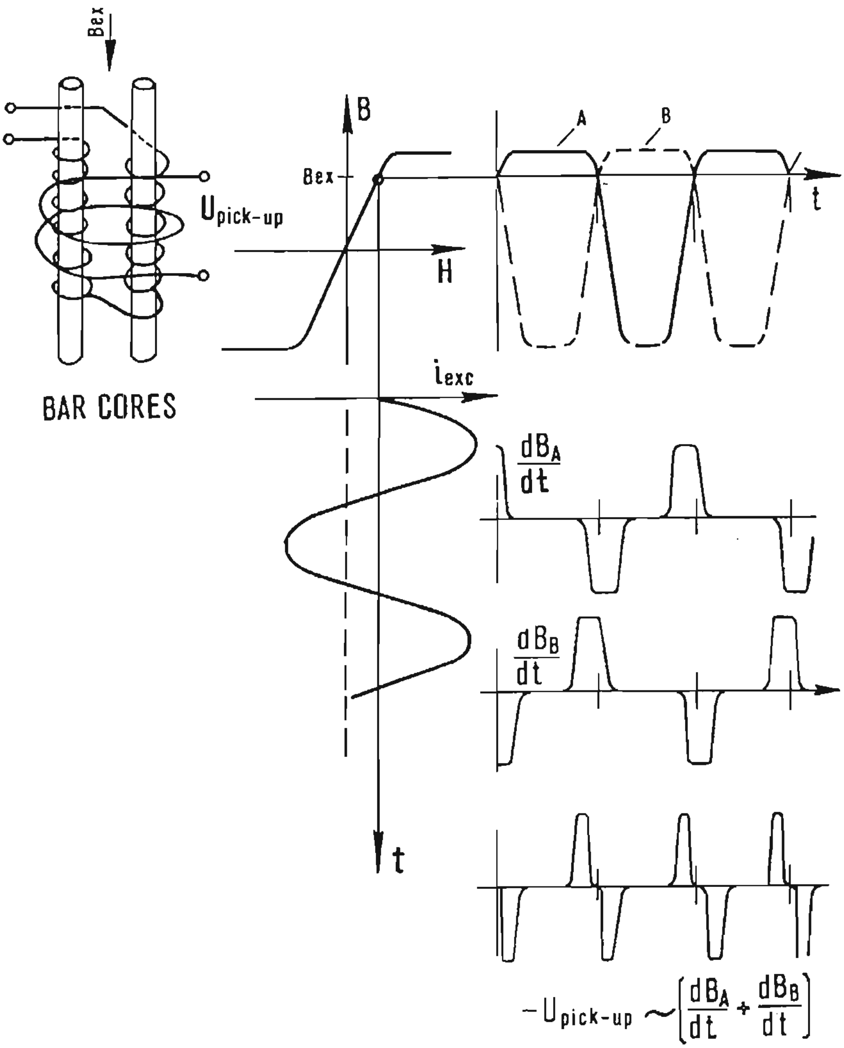


Figure 4.17. Waveform in a double-core fluxgate sensor.

$$B = a(H_0 + H_1 \cos \omega t)^3 + c(H_0 + H_1 \cos \omega t) \tag{4.38}$$

which, by applying standard expressions for trigonometric functions, gives

$$B = aH_0^3 + cH_0 + \frac{3}{2} aH_0H_1^2 + \left[\frac{3}{4} aH_1^3 + 3aH_0^2H_1 + cH_1 \right] \cos \omega t + \frac{3}{2} aH_0 H_1^2 \cos 2\omega t + \frac{1}{4} aH_1^3 \cos 3\omega t \tag{4.39}$$

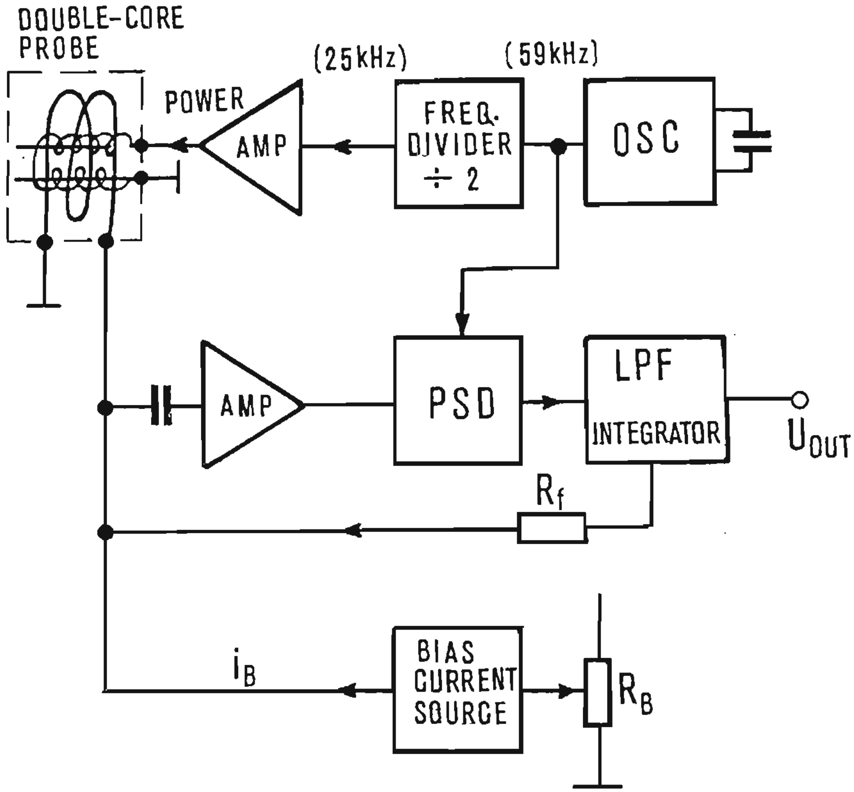


Figure 4.18. Block diagram of a fluxgate magnetometer with feed-back and with a separate unit for the production of bias current for the compensation of main part of the field. PSD = phase sensitive detector, LPF = low pass filter.

From (4.39) we see that there exists a second harmonic ($\cos 2\omega t$) in the output signal having an amplitude proportional to H_0. Notice, however, that the model above shows only the main principle and is oversimplified. The formal treatment of the real situation is more complex.

Figure 4.16 illustrates the waveform of a single-bar fluxgate sensor. In the case with no external field, the output signal is symmetrical around the points $\omega t = 0$, π, 2π, etc., and there are no even harmonics. In the case of an additional external field, the core saturates more easily during one half-cycle of the excitation, and later during the next corresponding half-cycle, etc., and we have even harmonics in the output signal with amplitudes proportional to the external field. In a double core sensor the excitation coils are connected in series and excited in opposite directions, in antiphase, as presented in Figure 4.17. This results in enhanced even harmonics in the voltage induced in the pick-up coil, and cancelling of the fundamental and odd harmonics. The ring core sensors can be treated as a generalization of double core sensors and the waveforms of the signals are similar.

Most magnetometers use a negative feed-back system in which the fluxgate sensor is a zero-field indicator. In this case there are two practices in use: the whole field component is compensated by the feed-back current, or the majority of the field is compensated by a bias current from an independent power supply and only the rest of the field is compensated by the feed-back current. A block diagram of a simple second harmonic fluxgate magnetometer having a unit for bias current and a feed-back loop is shown in Figure 4.18.

In a standard fluxgate magnetometer, the excitation of the sensor is produced by an oscillator. The signal from the pick-up coil is amplified with a tuned amplifier and fed to a phase-sensitive detector, referenced to the second harmonic of the excitation frequency. A current proportional to the output voltage is fed back to the feed-back winding of the sensor to oppose the field detected by the sensor. Due to high amplification and strong feed-back, the stability and linearity of the magnetometer are high and depend on changes of the parameters of the feed-back loop, especially on the resistance and the coil constant.

In observatory practice, long-term stability is the essential requirement. As presented above, it depends mainly on the stability of the compensation of the main part of the field. It is not easy to construct a good offset compensator, because all parameters should be stable to ten parts per million. A serious problem is the temperature stabilization of the dimensions of the bias coil. Therefore, the bias and feed-back coils are as a rule wound around quartz tubes or frames. Also some ceramics and plastics have very small temperature coefficients.

Fluxgate magnetometers exist also without separate field compensation, which means that the whole component of the magnetic field is compensated for by the feed-back current. These magnetometers are used to record not only variations of the field but also the full strength of the field itself. To have a resolution of 0.1nT requires 20 bits in the analog-to-digital converter. This kind of construction seems to be more difficult to make stable than the construction with a bias field.

Some parameters of the magnetometer can be corrected for by additional electronics or mechanical construction. Sometimes the compensation of temperature effects is done electronically. Today it is possible to make the corrections digitally, because most of the new magnetometers have microprocessors and the temperature is as a rule recorded together with the magnetic data. It is, however, important also to store the raw data before the calculated temperature correction. In places with unstable pillars, suspending the fluxgate sensor has proven to be a good solution (Rasmussen and Kring Lauridsen, 1990, Trigg and Olson, 1990). Also the corrections for tilting can be made digitally if the tilting of the instrument is recorded, which is possible with the commercially available sensitive recording levels. Stable enough recording levels are, however, rather expensive.

Fluxgate magnetometers have been built for so many different uses that it is difficult to list their technical parameters. The typical new fluxgate magnetometer has a resolution of 0.1 nT (for space research there are instruments with resolution of 0.01 nT) and a typical band-width is from dc to 5 Hz. The best fluxgate instruments made for observatory use have a base-line stability of better than 5 nT per year.

In fluxgate magnetometers constructed for observatory use or for other continuous monitoring of the magnetic field, there usually are three orthogonal sensors fixed to the same frame for the recording of the three components of the magnetic field. The sensor assembly is usually rather small and robust. Fluxgate magnetometers are becoming the most popular instruments at modern digital observatories due to their robust construction and reliable electronics.

The comparisons of data from recording observatory instruments have shown (see Chapter 8), however, that one should never trust the manufacturer specifications: before installing the instruments the orthogonality of the sensors, the temperature coefficients and sensitivities have to be checked. Some advice how to do this will be given in Chapter 8.

4.10 Superconducting magnetometers

SQUID (for superconducting quantum interference device) is the most sensitive instrument for the recording of variations of the magnetic field. A SQUID can reach 10^{-6} nT resolution, which is 10000 times more than is needed in the recording of

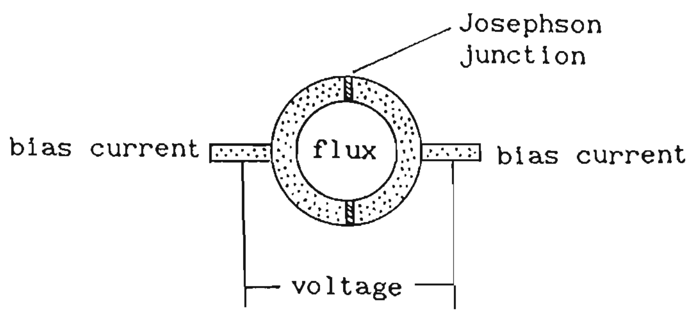


Figure 4.19. The working principle of SQUID. The voltage over Josephson junctions in the superconducting ring changes in cycles (flux quanta) when the magnetic field through the ring changes.

magnetic pulsations today. Until recent years liquid helium was needed for the use of SQUIDs, making them difficult and expensive to run continuously, such as at magnetic observatories. Today there are SQUIDs working at the temperature of liquid nitrogen (77K or –196°C). These SQUIDs are based on new superconducting materials which are ceramics, the most common at the moment being an oxide of yttrium, barium and copper, called YBCO.

SQUIDs are based on three discoveries in physics, all leading to the Nobel Prize: superconductivity at low temperature (H. K. Onnes), the physical explanation of superconductivity (J. Bardeen, L. N. Cooper and J. R. Schrieffer), and the effect of a thin insulating layer between two superconductors called a Josephson junction (B.D. Josephson). Superconductivity is explained by electrons forming pairs so that the two electrons in each pair have opposite spin and momentum (Cooper pairs). Each pair is weakly bound together and has zero net spin and momentum. At low enough temperature the lattice vibrations are so weak that they do not disrupt the Cooper pairs which are free to move without resistance. At higher temperature, these pairs are disrupted and the electrons scatter, experiencing resistance.

In a superconductor, there is a single wave function describing all the Cooper pairs. The Josephson junction separates two superconductors. The wave functions leak through the thin junction (tunneling effect) and, depending on the difference in phase, the voltage over the junction is higher or lower in a superconducting ring with two Josephson junctions, as shown in Figure 4.19. When the flux of the magnetic field through the ring changes, the voltage oscillates back and forth, each cycle meaning one flux quantum, a very small unit. So the SQUID is a quantum mechanical device, and the changes of the magnetic field are measured in flux quanta. A short, clear and illustrative description of SQUIDs has been published by John Clarke in *Scientific American* (Clarke, 1994). More details are to be found in Clarke (1993).

As shown above, the SQUID measures only changes of the magnetic field, but does so with always the same small and accurate steps (flux quanta, which depend on the construction of the SQUID). Therefore, it can be used also in observatories in all recordings from pulsations to secular variation, the data being in digital form. Until now the main use close to geomagnetism has been in the measurement of paleomagnetic and archeomagnetic samples. Where very sensitive gradiometers are needed, the SQUID is superior. The SQUID magnetometers are commercially available, and the prices are not much higher than the prices of conventional magnetometers.

5. ABSOLUTE MAGNETIC MEASUREMENTS

Observatories record variations of the geomagnetic field using different kinds of variometers, as will be described in Chapter 6. The absolute value of the recorded data is determined by separate absolute measurements. The variations of the components of the geomagnetic field are usually within ±3000 nT, although at high latitudes the variations may be as great as ±4000 nT. Therefore, there is no need to record larger values than these, and one has to add a value, usually called *base-line value*, to obtain the final absolute value of the component of the field. Most variometers nowadays are rather stable. Changes of the base-line values of the best modern instruments are about 5 nT per year or less. But there are changes, and therefore absolute measurements are unavoidable. There is no way to know when a change of the base-line may happen. Therefore, quite frequent absolute measurements are necessary. Once a week is normal practice if there are two independent recording systems which are compared to each other on a daily basis or continuously.

Over the last 150 years several authors of textbooks on geomagnetism have described in detail classical geomagnetic absolute measurements. Wienert's *Notes on geomagnetic observatory and survey practice* describes the methods which were in use in 1970. Here we shall discuss briefly the classical methods which are still commonly used today and concentrate on the new ones, which means the use of the proton precession magnetometer and the fluxgate theodolite. *Today the fluxgate theodolite* (often called *DI*-flux because *D* and *I* are determined using the instrument) *combined with the proton magnetometer is the recommended pair of absolute instruments.*

In principle, the accuracy of some classical instruments is the same as that attainable by modern instruments (with the exception of measurement of the total intensity *F*), but the use of classical instruments, especially for the intensities of the geomagnetic field components, is much more difficult, and almost impossible without long training, which makes the results less accurate in practice.

As pointed out in Chapter 3, observatories should have special pillars outside the absolute house for checking the absolute level from time to time, especially if there is doubt on artificial changes of the field in the absolute house. A good routine would be to measure the field components at the auxiliary pillars once a year and follow the year to year change, which should not differ from the recorded secular variation.

5.1 Use of fluxgate theodolite to measure declination D and inclination I

The fluxgate theodolite for the measurement of the magnetic declination D and inclination I is based on the so-called geodetic universal theodolite capable of measuring horizontal and vertical angles with an accuracy of roughly one second of arc (1″). A fluxgate sensor is mounted on top of the telescope of the theodolite. The most popular modern non-magnetic theodolites are Zeiss 010B (precision of 1″) and Zeiss 020A (precision of 0.1′). Both are available in degree-scale and grad-scale. In observatory work, the higher-precision model is preferable, which also makes the measurements easier. Such a theodolite is shown in Figure 5.1. A convenient feature of these theodolites is their gravity-oriented vertical scale, which means that the

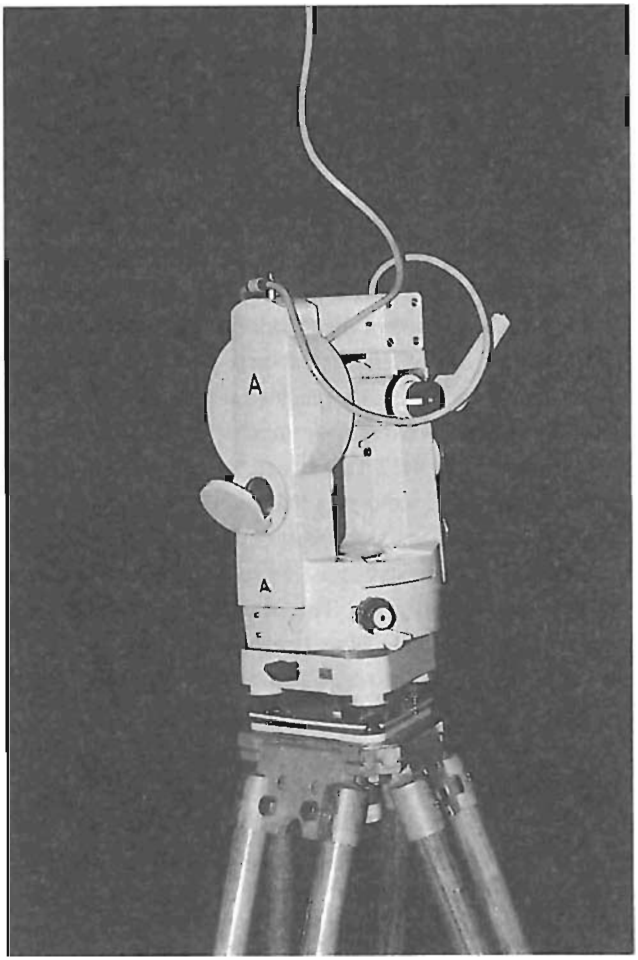


Figure 5.1. Theodolite Zeiss 010B with fluxgate sensor ("fluxgate theodolite") for the measurement of magnetic declination D and inclination I.

reading of the vertical scale is correct even when the levelling (see below) of the theodolite is not perfect. The gravity orienting system works if the levelling of the theodolite is better than ±4′.

All measurements begin with levelling of the theodolite. Levelling means adjusting the theodolite's vertical axis into the vertical with the help of levels, which are fixed to the alidade (the upper turning part of the theodolite). It is best to first adjust the theodolite roughly vertical. Usually there is a low-sensitivity circular level for this purpose. For the final adjustment the alidade is turned into the position where the high-sensitivity level is parallel with the line of two footscrews. The reading of the level is observed and the alidade is turned 180°. In this position, half of the difference between the new reading of the level and the previous reading is corrected by turning two footscrews in opposite directions so that the left hand turns the left screw clockwise and the right hand the right screw anticlockwise, or vice versa. The levelling in the perpendicular direction will not change if both screws are turned equally. The new reading of the level is the level's zero position. Thereafter the alidade is turned 90° and the bubble of the level is adjusted to its zero position by turning the third footscrew. Now the vertical axis is supposed to be vertical, which has to be checked by repeating the procedure.

The measurement of magnetic declination is simple. The fluxgate sensor (see Chapter 4) is fixed to the telescope of the theodolite so that it measures the magnetic field roughly in the direction of the optical axis of the theodolite. By setting the telescope horizontal (the vertical scale reads exactly 90° or 270°) and turning the theodolite until the sensor measures no magnetic field, the sensor is brought perpendicular to the magnetic field. Let us call the horizontal circle reading of the theodolite in this position $A_{W\uparrow}$, indicating that the theodolite has been turned into a position where the telescope looks to the west and the fluxgate sensor is on the upper side of the telescope. The telescope must be exactly horizontal, which has to be checked by reading the vertical scale. The next reading is taken after turning the telescope around its vertical axis by approximately 180° into the opposite horizontal position where the sensor measures zero again, which shows that the sensor is again perpendicular to the field. The horizontal circle reading is then $A_{E\uparrow}$; the telescope looks to the east and the sensor is on top of the telescope. The next horizontal circle reading is $A_{W\downarrow}$, taken after turning the telescope around its horizontal axis 180° and finding the position giving a zero reading on the magnetometer (a null position) by adjusting the horizontal direction. Finally, $A_{E\downarrow}$ is found by turning the theodolite around its vertical axis to the opposite null position. The circle reading A to magnetic north is the mean of the four readings:

$$A = (A_{W\uparrow} + A_{E\uparrow} + A_{W\downarrow} + A_{E\downarrow})/4$$

The magnetic declination D is then (see Chapter 4, formula 4.3)

$$D = A - (B - A_Z) \qquad (5.1)$$

where B is the circle reading to the azimuth mark, whose geographical azimuth is A_Z. D is naturally the mean declination of the times of the four observations $A_{W}\uparrow$, $A_{E}\uparrow$, $A_{W}\downarrow$, and $A_{E}\downarrow$.

The four observations compensate for the misalignment between the magnetic axis of the fluxgate sensor and the optical axis of the telescope and for the possible zero-field offset of the fluxgate magnetometer. Naturally, the observations can be taken in any order, but it is advisable to always use the same order. To increase the accuracy, at least two readings should be taken in each position. It is important to ensure that the telescope is horizontal before each reading. As described above, this is easy for modern theodolites with gravity-oriented vertical scales; one only needs to adjust the telescope so that the vertical scale shows exactly 90° or 270°. The levelling has to be better than 2″ for an accuracy of 0.1′ in declination.

The fluxgate magnetometer which is used for the search of zero position usually has an output in nanoteslas. Instead of searching for the position of exactly zero by turning the alidade of the theodolite, it is often more practical to turn the theodolite to a close-to-zero value and to record the reading in nanoteslas from the magnetometer. This is especially advisable if several readings are taken from the same theodolite position. It also makes possible an accurate measurement even when the observer is slightly magnetic, because one does not need to be close to the theodolite when taking the readings from the magnetometer. Naturally, the electronics box has to be far enough from the sensor. The batteries are often rather magnetic (this has to be tested using the same magnetometer and bringing the electronics with its batteries close to the sensor and turning it in different positions). The close-to-zero technique can be used only if the output of the magnetometer close to the zero position is linear. Usually this is the case with sufficient accuracy.

Using the close-to-zero technique, the correction to be added to each A-reading is

$$\Delta A = \arc \sin(S/H). \qquad (5.2)$$

which in degrees of arc [°] is

$$\Delta A[^{\circ}] = (180/\pi)(S/H) = 57.296(S/H)$$

and which in arc seconds [″] is

$$\Delta A[''] = 206265\ (S/H)$$

where S is the reading of the magnetometer in nanoteslas and H is an approximate value of the horizontal component. The sign of the correction ΔA depends on what is the positive direction of the fluxgate sensor, so that if the magnetometer shows

Table 5.1

An example of a complete measurement of declination.
Place: Nurmijärvi observatory, main pillar. Date: 1991-11-27.
Fluxgate theodolite: Zeiss 010B + GEO fluxgate. Observer: P. Posio.

Position	(UT) [h m s]	A'' [° ′ ″]	S [nT]	ΔA [″]	$A=A''+\Delta A$ [° ′ ″]	X_{rec} [nT]	Y_{rec} [nT]	D_c [° ′ ″]	A' [° ′ ″]
$B_\downarrow$	07 56 00	150 25 18							
$B_\uparrow$	58 00	330 25 08							
$W_\uparrow$	08 01 00	247 52 43	– 0.3	+ 4.1		14960.3	1314.1		
	02 00		– 0.1	+ 1.4		14959.6	1314.0		
	03 00		– 0.4	+ 5.5		14958.7	1314.4		
	04 00		– 0.1	+ 1.4		14958.4	1314.3		
Mean				+ 3.1	247 52 46	14959.2	1314.2	5 01 14	**247 52 32**
$E_\uparrow$	08 05 00	67 49 45	+ 0.2	+ 2.8		14958.4	1315.0		
	06 00		– 0.2	– 2.8		14958.2	1314.9		
	07 00		– 0.4	– 5.5		14957.7	1314.4		
	08 00		– 1.0	– 13.7		14956.8	1313.6		
Mean				– 4.8	67 49 40	14957.8	1314.5	5 01 20	**67 49 20**

Table 5.1

(continued)

Position	(UT) [h m s]	A'' [° ′ ″]	S [nT]	ΔA [″]	$A=A''+\Delta A$ [° ′ ″]	X_{rec} [nT]	Y_{rec} [nT]	D_c [° ′ ″]	A' [° ′ ″]
$W_\downarrow$	08 10 00	67 47 52	− 0.1	+ 1.4		14956.3	1315.9		
	11 00		+ 0.2	− 2.8		14955.7	1315.5		
	12 00		+ 1.2	− 16.5		14955.0	1314.7		
	13 00		+ 2.4	− 33.0		14955.8	1313.8		
	Mean			− 12.7	67 47 39	14955.7	1315.0	5 01 30	**67 47 09**
$E_\downarrow$	08 14 00	247 57 04	− 0.1	− 1.4		14954.4	1313.7		
	15 00		− 0.4	− 5.5		14954.6	1313.8		
	16 00		+ 0.3	+ 4.1		14953.3	1313.9		
	17 00		+ 1.0	+ 13.7		14953.4	1315.1		
	Mean			+ 2.7	247 57 07	14953.9	1314.1	5 01 20	**247 56 47**
All mean					**157 51 48**	**14956.66**	**1314.44**	**5 01 21**	157 51 27
$B_\downarrow$	19 00	150 25 16							
$B_\uparrow$	20 00	330 25 09							
B	**Mean**	240 25 13							

Table 5.2

An example of a complete measurement of inclination.
Place: Nurmijärvi observatory.
Continuation of D-measurement of Table 5.1.

Position	(UT) [h m s]	V' [° ′ ″]	S [nT]	ΔV [″]	$V=V'+\Delta V$ [° ′ ″]	X_{rec} [nT]	Y_{rec} [nT]	Z_{rec} [nT]	H_c [nT]	F_c [nT]	I_c [° ′ ″]
$N\uparrow$	08 21 00	73 02 48	– 1.1	4.4		14953.0	1314.6	49267.9			
	22 00		– 1.4	5.6		14953.1	1314.4	49267.7			
(1)	23 00		– 1.5	5.9		14954.0	1316.1	49267.5			
	24 00		– 1.4	5.6		14953.5	1315.9	49268.4			
Mean				5.4	73 02 53	14953.40	1315.25	49267.88	15011.13	51503.96	73 03 18
$S\downarrow$	08 25 00	253 01 57	– 0.5	– 2.0		14955.0	1316.1	49268.1			
	26 00		– 1.9	– 7.5		14954.9	1314.7	49268.2			
(2)	27 00		– 1.6	– 6.3		14953.6	1314.6	49267.4			
	28 00		– 2.3	– 9.1		14953.5	1313.8	49267.5			
Mean				– 6.2	253 01 51	14954.25	1314.80	49267.80	15011.94	51504.12	73 03 14

Table 5.2
(continued)

Position	(UT) [h m s]	V' [° ′ ″]	S [nT]	ΔV [″]	$V=V'+\Delta V$ [° ′ ″]	X_{rec} [nT]	Y_{rec} [nT]	Z_{rec} [nT]	H_c [nT]	F_c [nT]	I_c [° ′ ″]
$N\downarrow$	08 30 00	286 55 11	+ 0.5	+ 2.0		14951.7	1313.4	49267.1			
	31 00		– 1.1	– 4.4		14950.2	1312.8	49267.0			
(3)	32 00		– 1.8	– 7.1		14949.9	1312.2	49267.2			
	33 00		– 2.3	– 9.1		14949.6	1314.3	49267.1			
Mean				– 4.6	286 55 06	14950.35	1313.18	49267.10	15007.91	51502.28	73 03 29
$S\uparrow$	08 34 00	106 56 10	+ 0.9	– 3.6		14948.2	1316.2	49267.4			
	35 00		+ 0.9	– 3.6		14947.4	1315.9	49267.5			
(4)	36 00		+ 0.8	– 3.2		14947.4	1315.5	49267.4			
	37 00		0.0	0.0		14948.5	1314.8	49268.1			
Mean				– 2.6	106 56 07	14947.88	1315.60	49267.60	15005.66	51502.10	73 03 38
All mean						**14951.47**	**1314.71**	**49267.59**	**15009.16**	**51503.11**	

positive field when the telescope is turned towards the north, then the corrections for the observations with the telescope looking west have the opposite sign to S, and the corrections to observations where the telescope looks towards the east have the same sign as S. If, however, the fluxgate sensor has been installed in the opposite position, giving positive readings when the telescope is directed towards the south, then the signs of the corrections are opposite to those given above.

For example, in a field $H = 15{,}000$ nT and where the magnetometer shows positive values when directed northwards, the corrections to the circle readings A in seconds of arc [″] are

$\Delta A = -13.75 \cdot S$, when the telescope is looking towards the west (the observer in the east and the observation marked A_W),

and

$\Delta A = +13.75 \cdot S$, when the telescope is looking towards the east (the observer in the west and the observation marked A_E).

An example of a complete measurement of declination D is shown in Table 5.1. In this table, $B\uparrow$ and $B\downarrow$ are the circle readings of the azimuth mark when the fluxgate sensor is above or under the telescope, X_{rec} and Y_{rec} are the X and Y values from the digital recording for the times of the observations, and D_c is the declination calculated from the X_{rec} and Y_{rec} values. The "All mean" value of A is the only one needed for the calculation of declination. The "All mean" value of calculated declination D_c is needed for the final calculation of the base-line values. A' is the mean value of A reduced to $D_c = 5^{\circ}01'00''$, used for calculation of the misalignment of the sensor (see section 5.2).

If the direction to the mark (the azimuth of the mark) is $A_z = -2^{\circ}25'06''$, which is the case at the Nurmijärvi observatory, we obtain, applying formula (5.1)

$$D = A - (B - A_z) = 157^{\circ}51'48'' - (150^{\circ}25'13'' + 2^{\circ}25'06'') = 5^{\circ}01'29'' \qquad (5.3)$$

In our example, D calculated from the recorded X and Y is $5^{\circ}01'21''$. This shows that there is a small error in the base-line value of X or Y or both, so that the recorded D is 8″ too small.

An ambiguity of 180° may appear in the result if the zero of the horizontal circle has been crossed in the observations. It is possible to avoid this by adjusting the horizontal circle of the theodolite suitably, but an error of 180° is usually easy to detect and correct for.

If one of the components recorded is declination D, then the D-value obtained in the absolute measurement minus the recorded D (mean of the D-values from the times of observations) is the correction to be added to the base-line of the recording.

If, however, the components X and Y are recorded, then for the determination of the base-lines of X and Y we also need the absolute value of H for the time of the observation of D. It is obtained from the results of the absolute measurement of the total intensity F and the inclination I.

The inclination angle I is measured immediately after the measurement of D, because A, determined in the D-measurement, is used to orientate the theodolite so that the telescope is in the magnetic meridian. The A-value without correction is good enough for this, because in the observation of I the horizontal direction of the theodolite is not critical; an accuracy of $10'$ is good enough. The circle reading is simply fixed to the mean of the A-readings (or $A - 180^\circ$ after turning the theodolite) which means that the telescope and the fluxgate sensor are in the plane of the magnetic meridian.

In the I-observation, the zero readings on the magnetometer are found by turning the telescope around its horizontal axis and the vertical circle readings are noted. Again, it is not necessary to adjust the inclination of the telescope so that the value is exactly zero, meaning that the fluxgate sensor is exactly perpendicular to the magnetic field. It is more convenient to observe small readings in the same way as in the D-measurement.

Assuming again that the magnetometer shows positive values when the telescope looks northwards, we get analogously to the D-case a correction ΔI:

$$\Delta I = \arcsin(S/F) \qquad (5.4)$$

which in degrees of arc is

$$\Delta I = (180/\pi)(S/F) = 57.296(S/F)$$

and in seconds of arc is

$$\Delta I = 206265(S/F)$$

For example, in a field $F = 52000$ nT this means, in seconds of arc, the following corrections ΔV to the readings of the vertical circle:

$\Delta V'' = -4.0 \cdot S$ when the telescope looks towards the north and the sensor is on top of the telescope (↑)

$\Delta V'' = +4.0 \cdot S$ when the telescope looks towards the south and the sensor is under the telescope (↓)

$\Delta V'' = +4.0 \cdot S$ when the telescope looks towards the north and the sensor is under the telescope (↓)

$\Delta V'' = -4.0 \cdot S$ when the telescope looks towards the south and the sensor is on top of the telescope (↑)

If the theodolite is a modern one with a gravity-controlled vertical circle, the circle readings are correct automatically. If an older theodolite is in use, levelling has to be carried out carefully and has to be checked after each turning of the theodolite or its telescope, so that an accuracy of at least 2″ is achieved.

An example of a series of observations of inclination *I*, which is a continuation of the *D*-observation, is shown in Table 5.2.

The *A*-value calculated from the uncorrected *A*-values for the *D*-measurement is $A_1 = 157°51'51''$. This is the fixed position of the theodolite during two observations, and the opposite, $A_2 = 337°51'51''$, is the position for the other two observations. As in the *D*-observation, four observations are taken for each of the four readings of the vertical scale *V*. Here *N*↑ is an observation with the telescope looking towards the north and the fluxgate sensor on top of the telescope; this observation is marked V_1, etc.

From these observations the mean value of the inclination is

$$I = (V_1 + V_2 - V_3 - V_4)/4 + 90° = \mathbf{73°03'23''}.$$

For the calculation of *I*, it can be shown that two observations are sufficient: $I = (V_1 - V_4)/2 + 90°$ or $I = (V_2 - V_3)/2 + 90°$. By calculating both separately we get information on the precision of the measurement.

For the final absolute values we would ideally measure the total intensity *F* at the same time and at the same place as the *D*- and *I*-measurements. This is naturally not possible. Therefore, *F* should be measured simultaneously with the measurement of *I* but at another place, which is far enough from the absolute pillar not to disturb the measurement of *I*, or it should be measured totally separately. The difference in *F* between the main pillar and the remote side for the proton sensor is easy to determine by measuring *F* alternately at both places many times so that the difference is known to 0.1 nT. The difference can be considered constant except during a big magnetic disturbance, which is not a suitable time for absolute measurements anyway. The difference has to be checked, however, say once a year. Naturally, *F* can be measured before or after the *I*-measurement at the absolute pillar, or at the remote site. Then the result of the *F*-measurement has to be reduced to the time of the *I*-observation by using values from the observatory recording system.

Let us assume that *F* at the *F*-pillar is 5.1 nT lower than at the main pillar where *D* and *I* were measured, which is the case at Nurmijärvi. A typical observation of *F* is shown in Table 5.3.

Table 5.3
An example of a measurement of F.
Place: Nurmijärvi F-pillar. Date: 1991-11-27.
Instrument: PPM 1. Observer: P. Posio

Time (UT) [h m s]	F [nT]	X_{rec} [nT]	Y_{rec} [nT]	Z_{rec} [nT]
08 39 00	51497.8	14947.8	1315.8	49267.9
40 00	51497.6	14947.5	1315.3	49267.6
41 00	51497.1	14947.7	1314.3	49267.5
42 00	51497.8	14947.8	1312.8	49268.0
43 00	51497.6	14947.7	1313.0	49267.9
Mean values	**51497.58**	**14947.70**	**1314.24**	**49267.78**
Pillar difference	+ 5.10			
Absolute *F* =	**51502.68**			

Note that if F is measured at a different place than that where the components are recorded, the F-difference between the two sites may vary depending on the field at the time of measurement if there is a difference in one or more components of the field between the sites. The error may be more than 1 nT in extreme field conditions (see Chapter 6). Therefore, it is good practice to measure the site differences of the field components and to avoid absolute measurements in unusual field conditions.

The field values in Table 5.3 are in nT. From the recorded X, Y and Z values we may compute the value F_c

$$F_c = (X_{rec}^2 + Y_{rec}^2 + Z_{rec}^2)^{1/2} = 51502.18 \text{ nT}$$

which is 0.5 nT lower than the true absolute value. Accordingly, to obtain the true value F, 0.5 nT has to be added to the F-values calculated from the recorded X, Y and Z. Thus, for the time of I-observations

$$F_I = (X_{Irec}^2 + Y_{Irec}^2 + Z_{Irec}^2)^{1/2} + 0.5 = 51503.11 + 0.5 = 51503.61 \text{ nT}$$

where X_{Irec}, Y_{Irec} and Z_{Irec} are the mean values of the recorded X, Y and Z values at the times of the observations in the I-series, and 0.5 nT is the correction to the calculated F value as explained above.

From F_I and I we calculate the absolute H and Z values

$$H_I = F_I \cdot \cos I = 51503.61 \cos(73^\circ 03' 23'') = 15009.72 \text{ nT}$$

$Z_I = F_I \cdot \sin I = 49267.94$ nT

The correction to be added to the base-line of Z is thus

$\Delta Z = Z_I - Z_{Irec} = 49267.94 - 49267.59 = +0.3$ nT.

where Z_{Irec} is the mean value of the recorded Z values during the I-measurement.

The corrections for the base-lines of X and Y have to be calculated from H_I and the absolute D. The recorded H value during the I-measurement was

$H_{Ic} = 15009.16$ nT

which shows that the H-values recorded have to be corrected by an amount

$\Delta H = H_I - H_{Ic} = 15009.72 - 15009.16 = +0.56$ nT.

The H-value during the D observation is

$H_{Drec} = (X_{Drec}^2 + Y_{Drec}^2)^{1/2} = (14956.66^2 + 1314.44^2)^{1/2} = 15014.31$ nT,

and the absolute H-value during the D-measurement, H_D, is

$H_D = 15014.31 + 0.56 = 15014.87$ nT,

and

$X_D = H_D \cdot \cos D = 15014.87 \cos(5^o01'29'') = 14957.17$ nT

$Y_D = H_D \cdot \sin D = 15014.87 \sin(5^o01'29'') = 1315.09$ nT

The corrections to be added to the X and Y base-lines are then

$\Delta X = X_D - X_{Drec} = 14957.17 - 14956.66 = +0.5$ nT

$\Delta Y = Y_D - Y_{Drec} = 1315.09 - 1314.44 = +0.6$ nT

where X_{Drec} and Y_{Drec} are the means of the recorded X and Y values during the D-observation.

5.2 Calculation of misalignment of the fluxgate sensor

Instead of computing only the absolute D- and I-values from the observations described above, we recommend that one should also calculate the angles between the direction of the fluxgate sensor and the optical axis of the theodolite, and the offset of the fluxgate electronics.

To determine of the misalignment, the observations of A in the four different positions of the D-observation are needed, corrected for the change of declination. Therefore, the mean recorded D-values for each position are listed in Table 5.1 on the right side of the series of D-observations. The A-values can be corrected relative to an arbitrary D-value, as recommended and used in the Danish practice by Kring Lauridsen. It is convenient to select a numerically simple value; in the example, we have chosen 5°01′00″, which means that the corrections to be added to the observed A-values are 5°01′00″ minus the corresponding recorded value. The so corrected A-values are marked A' in the table of D-observations.

From the D-observation, using the A'-values we can calculate D':

$$D' = (A'_1 + A'_2 + A'_3 + A'_4)/4 - (B - A_z)$$

$$= 157^\circ 51'27'' - (150^\circ 25'13'' + 2^\circ 25'06'') = 5^\circ 01'08'' \qquad (5.5)$$

instead of 5°01′00″, which shows that the recorded values of D are by 8″ too small (we obtained the same result in formula (5.3)).

The formulas for δ (the angle between the direction of the fluxgate sensor and the optical axis of the theodolite in the horizontal plane when the telescope is horizontal), ε (the corresponding vertical angle), and S_0 (the offset of fluxgate electronics) are presented below (Kring Lauridsen, 1985). The results using data from our examples are also given.

$$\delta = (A'_3 + A'_4 - A'_1 - A'_2)/4$$

$$= (67^\circ 47'09'' + 247^\circ 56'47'' - 247^\circ 52'32'' - 67^\circ 49'20'')/4 = 31'' \qquad (5.6)$$

$$\varepsilon = (A'_1 - A'_2 - A'_3 + A'_4 \pm 360^\circ)/4 \tan I$$

$$= (247^\circ 52'32'' - 67^\circ 49'20'' - 67^\circ 47'09'' + 247^\circ 56'47'' - 360^\circ)/4 \tan 73^\circ = 59'' \qquad (5.7)$$

$$S_0 = (A'_1 - A'_2 + A'_3 - A'_4) \cdot H/4 \cdot 57.296 = -7.1 \text{ nT} \qquad (5.8)$$

ε and S_0 can also be found from the I-observations. The values used below are the observations of the vertical scale (V) corrected using the values of S. I_c and H_c are calculated means from the recorded X_{rec}, Y_{rec} and Z_{rec}. Let the corrected $V_{N\uparrow}$ be V_1 and the corresponding I_c-value be I_{c1}, etc. Then

$$\varepsilon = 180^\circ - (V_1 + V_2 + V_3 + V_4)/4 + (I_{c1} + I_{c2} - I_{c3} - I_{c4})/4$$

$$= 180^\circ - (73^\circ 02'53'' + 253^\circ 01'51'' + 286^\circ 55'06'' + 106^\circ 56'07'')/4$$

$$+ (73^\circ 03'18'' + 73^\circ 03'14'' - 73^\circ 03'29'' - 73^\circ 03'38'')/4 = 52'',$$

or

$$\varepsilon = 180^\circ - (V_1 + V_2 + V_3 + V_4)/4 - [(H_{c1} + H_{c2} - H_{c3} - H_{c4}) \sin I$$
$$- (Z_{rec1} + Z_{rec2} - Z_{rec3} - Z_{rec4}) \cos I]/(4F/57.296)$$
$$= 180^\circ - (73^\circ 02'53'' + 253^\circ 01'51'' + 286^\circ 55'06'' + 106^\circ 56'07'')/4$$
$$- [(15011.1 + 15011.9 - 15007.9 - 15005.7) \sin 73^\circ$$
$$- (49267.9 + 49267.8 - 49267.1 - 49267.6) \cos 73^\circ]/(4 \cdot 51500/57.296) = 52'' \quad (5.9)$$

$$S_0 = -[(V_1 - V_2 - V_3 + V_4)/4 + 90^\circ] \cdot F/57.296$$
$$+ [(I_{c1} - I_{c2} + I_{c3} - I_{c4})/4] \cdot F/57.296,$$

or

$$S_0 = -[(V_1 - V_2 - V_3 + V_4)/4 + 90^\circ] \cdot F/57.296 - [(H_{c1} - H_{c2} + H_{c3} - H_{c4}) \sin I$$
$$- (Z_{rec1} - Z_{rec2} + Z_{rec3} - Z_{rec4}) \cos I]/4 = -8.0 \text{ nT} \quad (5.10)$$

The values are close to the values obtained from the *D*-measurement.

For rapid measurements, when high accuracy is not needed, δ, ε and S_0 can be used to correct a single reading of the horizontal or vertical circle:

$$D = A_1 - 90^\circ - (B - A_z) + \delta - 57.296 \cdot S_0/H - \varepsilon \tan I \quad (5.11)$$

$$I = V_1 + \varepsilon + 57.296 \cdot S_0/F \quad (5.12)$$

In (5.11) and (5.12) δ and ε are expressed in degrees.

Some remarks regarding the examples given above: the results show that the fluxgate sensor is well aligned with the optical axis of the theodolite; the offset is rather large and should be adjusted, but it does not cause an error in the results because of the measuring method. In our example the offset seems to have slightly changed from the *D*-series to the *I*-series. The change during the measurement series is a source of error. Therefore, the calculation of S_0 is recommended for all series.

There may be ambiguities of ±180° or its multiples, but such errors are easy to detect. If the theodolite reads a value between 90° and 270° when the telescope points to magnetic north, no correction of ±180° will be needed. The times given for the observations of the azimuth marks are not needed for the calculations, but they may be useful in some cases when the observation has taken a long time or there is a doubt concerning the stability of the theodolite during the measurement.

It is instructive to go through the different steps of the calculations presented above, but for routine observatory use it is best to make a one-page form for the measurement and a program for a PC or for a pocket calculator. Two calculations of

D are presented above; the first one is for explaining the procedure step by step, the second one is for routine calculations. We recommend the use of the second method, in which the measured A-values are reduced using observatory data to an arbitrary, convenient D-value. Using these values the misalignment and the offset can be calculated. These quantities should be calculated in connection with every absolute measurement, because they provide a good check of the fluxgate theodolite. Kring Lauridsen (1985) transforms the A-values to minutes of arc (seconds could also be used), but we have used degrees in the calculations, which is convenient when using pocket calculators. In formula (5.8) for S_0 one radian has to be expressed in the same unit which has been used in the calculations (57.296°, 3438′ or 206265″).

Four observations in each position, as in our example, may not be necessary, depending on the stability of the readings of the magnetometer. At high latitudes, where the field is seldom really quiet, the number of observations clearly adds to accuracy. If the field is quiet, two observations in each position are enough.

If the absolute measurements are analysed using a computer having direct access to the recorded data, one only needs to feed in the results of the absolute observations and their times. But to let the computer correct the base-lines automatically is not a good idea, because an error in the absolute measurement may damage the recording badly. The observer has to decide whether the base-line corrections are sensible, or whether a new absolute measurement may be needed.

It is recommended that a form is made for recording the observations. The form has to have places for at least the following information, in addition to the results of the measurement itself: location (which pillar etc.), date and time are compulsory; the instrument used (the theodolite and fluxgate unit); and the name of the observer, which may be important to know at a later date. It is good to have some room for notes: all information on unusual incidents or disturbances during the measurement may be valuable afterwards. One easy way to keep the observations in good order is to draw the forms on pages of a booklet or notebook.

The absolute observation described above is a normal, typical one. It is, however, possible to measure both D and I simultaneously in the same series of observations (Kerridge, 1985, or Forbes, 1987). In this case the telescope is tilted from its horizontal position by an angle β, which is about half of $90° - I$. The observations are then taken in exact tilted positions $90° + \beta$, $270° + \beta$, $90° - \beta$, and $270° - \beta$, each with the sensor up and down.

If the magnetic azimuth of the sensor (and telescope) is α, the reading of the vertical circle is β, and the position is found where the output S is zero, we have

$$S = F(\cos I \cos\alpha \cos\beta - \sin I \sin\beta) = 0 \qquad (5.13)$$

$$I = \arctan(\cos\alpha / \tan\beta)$$

If both of the two possible null positions have been found, then the mean of the two respective readings of the horizontal circle will give the reading corresponding to magnetic north.

This type of measurement may be handy in rapid field work, where two observations are usually enough for the accuracy needed. For observatory use we recommend the normal series described above.

5.3 Use of the proton precession magnetometer to measure total intensity *F*

The proton magnetometer is a push-button device, usually robust and weatherproof. As described in Chapter 4, older instruments may give the results in counts; modern instruments produce the results in nanoteslas. The most modern proton magnetometers are microprocessor controlled and use statistical methods to improve the accuracy of the measurement. They also may present an estimate of the accuracy of the result.

In observatory absolute measurements, one should not trust an instrument without verification. The correct functioning of the proton magnetometer should be checked by measuring a known artificial frequency close to the frequency at which the protons would precess in a typical field (2 kHz), as described in Chapter 8. In some older type magnetometers, checks have to be carried out before and after the absolute measurement and the possible corrections have to be interpolated to the measured data. Usually the crystals and the electronics of the most modern proton magnetometers are so stable that it is sufficient to carry out checks once a year.

The measurement itself is easy, and a series like that presented in the previous section is a typical one. It is important to know *F* exactly at the same place where *D* and *I* are measured, which means at the level of the horizontal axis of the theodolite over the middle point of the theodolite. The normal routine is to measure *F* at another pillar. The difference between the main pillar and the *F*-pillar has to be measured a sufficient number of times so that it is known with an accuracy of 0.1 nT. The constancy of the difference has to be checked from time to time, say once a year, because it may change.

5.4 Use of the proton precession magnetometer for measurement of the magnetic field components

By installing the proton magnetometer sensor inside a coil, it is possible to measure the magnitude of the vertical and horizontal components *Z* and *H* of the magnetic field vector. The coil must produce a sufficiently homogeneous field in the volume of the sensor bottle, otherwise the proton precession signal decays too rapidly for an accurate measurement. There are many types of coils which produce a large enough homogeneous field (see Section 8.7). The best known and simplest is the Helmholtz coil, which has two circular windings on the same axis, separated r cm from each other, where r is the radius of the winding. A Helmholtz coil with $r = 40$ cm produces a large enough homogeneous field for proton vector measurements. Much smaller, but more complicated, coils producing large enough homogeneous fields have been described in the literature, e.g. Shtamberger (1972). However, leading the current into the coil, so that it does not cause a field inside, is often difficult in small coils. The Helmholtz coil can also be made square. In this case, the separation of the windings is 0.554 times the length of the side.

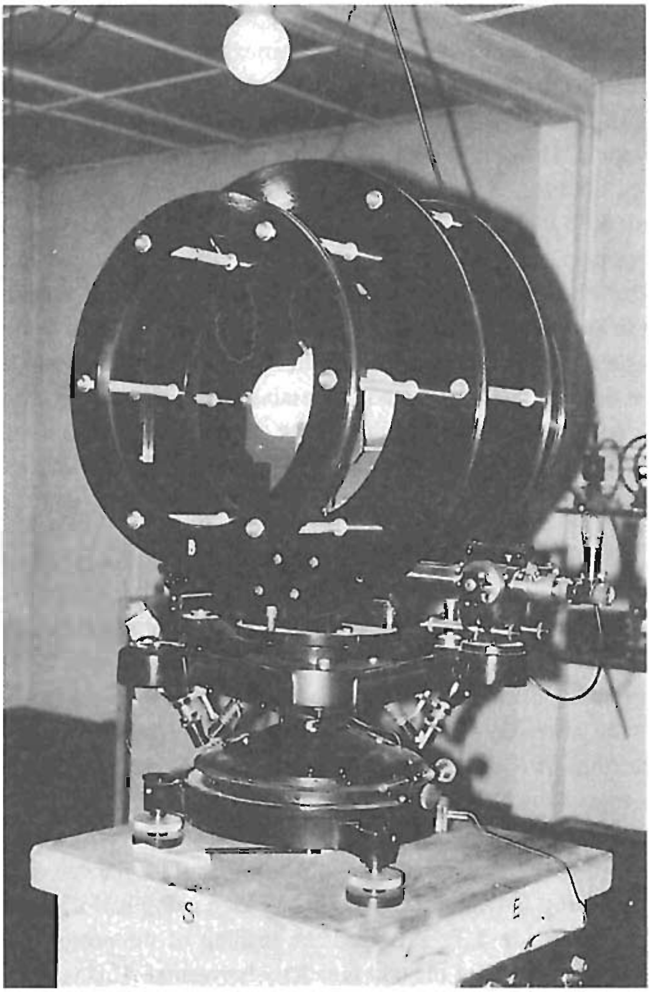


Figure 5.2. Proton vector magnetometer at Belsk observatory. The coil is of the Braunbeck-type (see Section 8.7).

It is possible to use fixed coils for the measurement of H and Z, as will be shown later, but usually the proton vector magnetometer has a coil which can be turned around the vertical axis. An old non-magnetic theodolite can be used as the turntable (see Fig. 5.2), but also other constructions are in use, allowing the coil to be turned 180° back and forth. A level has to be attached to the coil. It has to be sensitive enough to measure tilts of two seconds or smaller. (The sensitivity, or the scale value of the level, is easy to determine by putting the level on top of the telescope of a theodolite and reading the vertical scale together with the readings of the level). A stable current source is needed for the coil.

There are two methods widely used to measure the components of the magnetic field using proton vector magnetometers. In *Nelson's method*, one of the field components is compensated by applying an equal and opposite coil field and the remaining component is then measured with the proton magnetometer. Nelson's method is good for middle latitudes for both H and Z but cannot be used for H at high latitudes and for Z at low latitudes because after compensating one of the components the remaining field is too small to be measured with a proton magnetometer (the practical limit is 15,000–20,000 nT). In *Serson's method*, a bias field is added to the weaker component, which makes it usable everywhere. Both methods have the advantage that the current in the coil does not need to be known. The only requirement in Serson's method is that the current remains the same for the short time needed for a pair of observations with the coil in opposite positions and the current in opposite directions. In Nelson's method the stability of the current is not very critical. One part in 1,000 is enough which is easy to obtain with common laboratory instruments. In Serson's method the current has to be stable with an accuracy of one part in 100,000 during the short time of two measurements with opposite currents.

The principle of Nelson's method is depicted in Figure 5.3. It is important to level the coil system so that the vertical axis around which the coil is turned is vertical with an accuracy of at least 2″. The north–south position is determined by turning the coil approximately to the east–west direction and by producing a bias field in the coil. The value F_+ (current in positive direction in the bias coil) has to be the same as the value F_-, which is the observed F after reversing the current (same bias field but in the opposite direction). If F_+ is not the same as F_-, the coil direction has to be adjusted until this is true. After that, the coil is turned 90°. The magnetic axis is now in north–south direction with high accuracy (actually this is not very critical, 10′ is good enough). After this, by applying a field opposite to H, so that the values of F with and without the opposing H-field are the same, and then using half of the current, H is compensated (see Figure 5.3). Z is then the reading of the proton magnetometer, provided the magnetic axis of the coil is exactly horizontal. This is practically never the case. Therefore, another similar measurement has to be made after turning the coil 180° and reversing the current. The final Z is the mean of the two observations, which can be called Z_N and Z_S. The possible change of levelling can be corrected for in

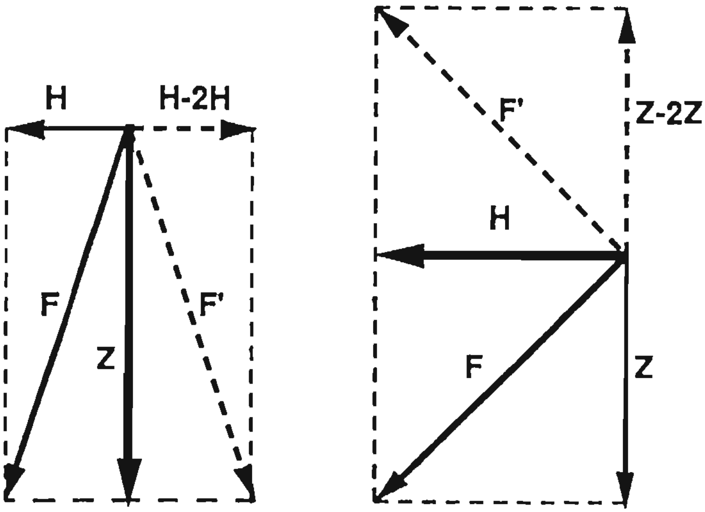


Figure 5.3. The principle of measuring the vertical intensity Z (left) and the horizontal intensity H (right) with a proton magnetometer, applying Nelson's method where one of the components is cancelled by the coil field. The current to the compensation coil is found by first making $F = F'$ and then using half of the current for compensation.

calculations afterwards, or the levelling can be adjusted after turning the coil so that the level shows the same as before the coil was turned.

The correction to be added (including the sign) to the base-line value of Z of the digital recording is then

$$\Delta Z = [(Z_N - Z_{reg1}) + (Z_S - Z_{reg2})]/2 \tag{5.14}$$

where the Z_{reg}-values are data from the digital recording for the times of Z_N and Z_S.

The magnetic axis of the coil may have some inclination, which makes the Z_N and Z_S values different. It is best to adjust the coil so that these values are close to each other, say within 10 nT or closer.

The measurement of H by Nelson's method is made by nulling the Z-component with a vertical bias coil. Again the vertical axis has to be vertical with an accuracy of better than 2″. The suitable current for the coil is determined the same way as in the Z-measurement. Now four readings of H have to be taken, turning the coil 90° between the readings. Let us call them H_N, H_E, H_S and H_W. The final H is the mean value of the four readings, and the correction to be added (including the sign) to the base-line value of H is

$$\Delta H = [(H_N - H_{r1}) + (H_E - H_{r2}) + (H_S - H_{r3}) + (H_W - H_{r4})]/4 \qquad (5.15)$$

where the H_r-values are the H data from the digital recording for the times of the measurements of H_N, H_E, H_S and H_W.

With Serson's proton vector method, any component of the magnetic field can be measured even when the component is too small (< 15,000–20,000 nT) to be measured accurately with the proton magnetometer utilizing Nelson's method. The principle of the method is shown in Figure 5.4.

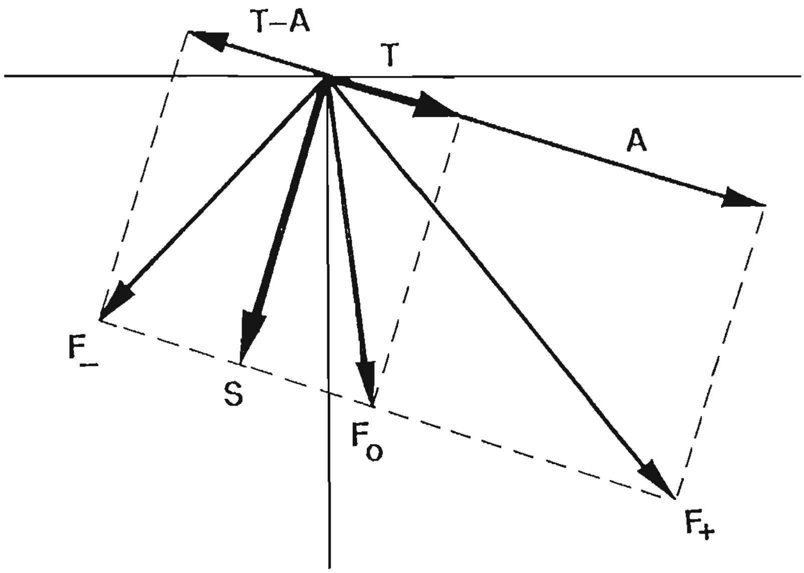


Figure 5.4. Serson's method for the measurement of components T and S of the magnetic field using a proton vector magnetometer. The coil field A is chosen to be roughly 2×T.

In Serson's method, an additional field A is added to the component to be measured. The coil axis is aligned with the component. Three measurements are necessary: a reading F_0 with no current in the coil; a reading F_+ ,i.e., the magnitude of the sum of vectors $\boldsymbol{F_0}$ and $\boldsymbol{A}$ *(A* is an additional field), and a reading F_- , i.e., the magnitude of the sum of vectors $\boldsymbol{F}$ and $\boldsymbol{-A}$. In practice, two additional measurements are needed with the coil turned 180°, as will be shown later.

Referring to Figure 5.4 we get

$$F_+^2 = S^2 + (T + A)^2$$

$$F_-^2 = S^2 + (T - A)^2$$

$$F_0^2 = S^2 + T^2$$

from which:

$$T = (F_+^2 - F_-^2) / 4A$$

$$A = [(F_+^2 + F_-^2) /2 - F_0^2]^{1/2} \tag{5.16}$$

where T is the projection of vector $\boldsymbol{F}_0$ on the direction of vector $\boldsymbol{A}$, and S is the projection of $\boldsymbol{F}$ on the direction perpendicular to $\boldsymbol{A}$. If, for example, $\boldsymbol{A}$ is horizontal and lies in the magnetic meridian, then $T = H$ and $S = Z$, and using formula (5.16) we can calculate H and Z.

The proton vector measurement is in principle a simple one, but achieving high accuracy is difficult because of stringent requirements on levelling, stability of current and coil, and accuracy of the proton magnetometer readings. By differentiation we get for the error in the measurement of H

$$\Delta H = (A - H)F_+\Delta F_+/2A^2 - (A + H)F_-\Delta F_-/2A^2 + HF_0\Delta F_0/A^2 \tag{5.16a}$$

From formula (5.16a) it can be deduced that the error in H is smallest when the bias field A is between $2H$ and $3H$.

The effects of tilting of the vertical axis of the bias coil, γ (radians), and the azimuth angle between the A-field and the magnetic meridian, α (radians), are

$$\Delta H = -H\alpha^2/2 + Z\gamma \tag{5.16b}$$

This formula shows that in a Z-field of 50000 nT, tilting of 1″ gives an error of 0.24 nT. Angle $\alpha = 10'$ gives an error of –0.06 nT in a H-field of 15000 nT and $\alpha = 20'$ correspondingly an error of –0.26 nT (see, e.g., Marianiuk and Oberc, 1976; Wienert, 1970).

At high latitudes, the H-component is small and therefore only a horizontal bias coil is needed. The coil system is the same as in Nelson's method for Z described above. The north–south direction for the coil is found as described above, and now a bias field is used, which is about 2 times H. The observation consists of 5 readings of the proton magnetometer, as presented in the practical example below.

Naturally, all the observations have to be corrected for changes of the field during the observation. If we take the time of the F_0-observation as the time to which the other observations have to be reduced (which also becomes the time of the absolute values of H and Z), the corrections to the measured F-values will be (from Figure 5.4)

$$\Delta F_+ = [(H+A)/F_+](H_0 - H_+) + (Z/F_+)(Z_0 - Z_+)$$
$$\Delta F_- = [(H-A)/F_-](H_0 - H_-) + (Z/F_-)(Z_0 - Z_-) \qquad (5.17)$$

where H_0 and Z_0 are the recorded values of H and Z at the time of the F_0 observation, etc. If the current i used in the production of the bias field A has changed from the F_+ observations to the F_- observations, this correction has also to be taken into account, so that both F_+ and F_- are corrected for the effect of the deviation of the i-value from its mean value (i_m). If the coil constant is β [nT/mA], we get instead of (5.17)

$$\Delta F_+ = [(H+A)/F_+][(H_0 - H_+) + \beta\,(i_m - i_+)] + (Z/F_+)(Z_0 - Z_+)$$
$$\Delta F_- = [(H-A)/F_-][(H_0 - H_-) - \beta\,(i_m - i_-)] + (Z/F_-)(Z_0 - Z_-) \qquad (5.18)$$

where $i_m = (i_+ + i_-)/2$.

The formulas above are given for the measurement of H (the numerical example below is for H). The other components, Z and D, are measured in the same way, applying the general formula (5.16), but the measurement of D is not strictly absolute.

At both high and low latitudes it is recommended to measure the stronger component using Nelson's method and to determine the weaker component by Serson's method.

The vector proton magnetometer methods for determining the absolute components H and Z are not as easy as the use of the fluxgate theodolite, but they give, if correctly performed, high absolute accuracy (in long series of observations the error is less than 0.5 nT), and are an independent method, and so are highly recommended.

An example of a real measurement with a proton vector magnetometer at high latitude is given in Table 5.4. The corrections due to changes of the field and changes of current during the measurement have been included in the calculations.

Here N_0 is the observation without current in the bias coil, N_+ the observation with the coil pointing towards magnetic north and with current in the bias coil in such a direction that the measured F is larger, N_- is the observation with opposite current in the bias coil, S_+ and S_- are the corresponding observations after turning the coil 180°, and i is the current in the coil in mA. The level readings are in seconds of arc (″). Taking the zero-current observation as a reference and correcting the other observations to that time, we obtain, applying (5.18) and knowing that for the Nurmijärvi coil $\beta = 175.587$ nT/mA and approximate values are $H = 15100$ nT, $Z = 49100$ nT, and $A = 26500$ nT

Table 5.4

An example of a measurement with a proton vector magnetometer at high latitude.
Place: Nurmijärvi observatory, Z-pillar, Date: Dec. 29, 1983
Magnetometer: PMP 5, Observer: M. Kivinen
Control (2 kHz) before: 46974.4, after: 46974.4

Posi-tion	Level	UT [h m s]	i [mA]	F_{obs} [nT]	X_{rec} [nT]	Y_{rec} [nT]	Z_{rec} [nT]	H_{calc} [nT]
N_0		08 06 00		51383.0	15086.4	1174.2	49103.5	15132.0
N_+	+2.4	08 07 00	151.38	64429.4	15086.4	1174.0	49103.5	15132.0
N_-	+2.4	08 08 00	151.36	50418.4	15086.8	1173.9	49102.8	15132.4
S_+	+1.9	08 10 00	151.32	64431.6	15088.4	1173.6	49102.5	15134.0
S_-	+1.9	08 11 00	151.30	50417.3	15088.4	1173.6	49102.8	15134.0

$$\Delta F_{N_+} = [(H+A)/F_+][(H_0 - H_+) + \beta\,(i_m - i_+)] + (Z/F_+)(Z_0 - Z_+)$$

$$= 0.646\ (0 - 1.8) + 0.762\ (+0.0) = -1.16 \text{ nT},$$

$$\Delta F_{N_-} = [(H-A)/F_-][(H_0 - H_-) - \beta\,(i_m - i_-)] + (Z/F_-)(Z_0 - Z_-)$$

$$= -0.226\ (-0.4 - 1.8) + 0.974\ (+0.7) = +1.18 \text{ nT}.$$

Applying formulas (5.16) we get

$$A_N = [(F_{N_+}^2 + F_{N_-}^2)/2 - F_0^2]^{1/2}$$

$$= [((64429.4 - 1.16)^2 + (50418.4 + 1.18)^2)/2 - 51383.0^2]^{1/2} = \mathbf{26577.31} \text{ nT},$$

$$H_N = [(F_{N_+})^2 - (F_{N_-})^2]/4A$$

$$= [(64429.4 - 1.16)^2 - (50418.4 + 1.18)^2]/(4 \cdot 26577.31) = \mathbf{15133.81} \text{ nT}.$$

Correspondingly

$$\Delta F_{S_+} = 0.646 \cdot [-2.0 - 1.8] + 0.762 \cdot (1.0) = -1.69 \text{ nT}$$

$$\Delta F_{S_-} = -0.226 \cdot [-2.0 - 1.8] + 0.974 \cdot (+0.7) = +1.54 \text{ nT}$$

and applying formulas (5.16) we get

$$A_S = [(F_{S_+}^2 + F_{S_-}^2)/2 - F_0^2]^{1/2}$$

$$= [((64431.6 - 1.69)^2 + (50417.3 + 1.54)^2)/2 - 51383.0^2]^{1/2} = \mathbf{26578.63} \text{ nT}$$

$H_S = [(F_{S_+})^2 - (F_{S_-})^2]/4A$

$= [(64431.6 - 1.69)^2 - (50417.3 + 1.54)^2]/(4 \cdot 26578.63) = \mathbf{15135.79}$ nT .

The final value of H is

$H = (H_N + H_S)/2 = \mathbf{15134.8}$ nT

Z can be calculated from F_0 and H:

$Z = (F_0^2 - H^2)^{1/2} = \mathbf{49103.5}$ nT

Here the change of level has not been taken into account in the calculation. The level has only been checked in each position to make sure that it has not changed during the turning of the coil by more than one second (from the mean value), which is good-enough for an accuracy of 0.2 nT. The effect of tilting can be taken into account by subtracting $(N-S)Z/2$ from the final H value. Here N and S are the readings of the level in N and S positions expressed in radians. It is convenient, however, to keep the level the same in both N and S positions by adjusting after turning, when necessary.

Five series of observations like the series described above are usually enough for adequate final accuracy of the base-line values. The new Z base-line can be obtained directly. In the series described above, the recorded Z was 49103.5 nT, which was also the result of the absolute measurement. The difference of 2.8 nT in H shows that X or Y, or both, need to be corrected, but for that a knowledge of the absolute D-value is also needed, as described in connection with the observations using the fluxgate theodolite.

Kring Lauridsen (1980) has successfully used rather large fixed square Helmholtz coils for the determination of H and Z at Rude Skov and Brorfelde magnetic observatories in Denmark. As he points out, and as described above, the elimination of a possible misalignment of the coil axis is usually achieved by turning the coil and making measurements in two opposite directions of the coil. This demands an installation which occupies the pillar, making it unavailable for other purposes. For instance, the important check of pillar differences becomes troublesome.

The use of a stationary coil has some advantages. There is no need for a turntable, the coil can be large, whereby a homogeneous field can be achieved with less perfection of the coil geometry, the proton sensor can easily be removed from the pillar so that other measurements (for instance of D and I) can be performed at the same pillar which then becomes the main pillar of the observatory. In addition, a spacious coil affords a good working place for all sorts of calibrations. For descriptions of coils and their fields, see Chapter 8.

In order to solve problems with possible misalignments of the coil, classical or fluxgate instruments can be used to detect the influence of the coil field on the component to be measured. For instance, if Z is annulled in Nelson's method for measurement of H, a variometer is put up at the place of the sensor and the influence of the field in the coil on H is measured by means of the variometer. This value can then be used as a correction to the H-value measured by the proton magnetometer, or the levelling of the coil can be adjusted until no measurable misalignment remains.

If a classical variometer is used it should be well damped and it is recommended to submerge the magnet and mirror system in silicone oil. The variometer housing can simply be an acrylic tube with a window arrangement. The reading facility can be a lamp and scale, or a telescope and scale. In old observatories there probably are old variometers available for the purpose described here.

If H is too small to be measured by the proton magnetometer, it is possible to use a similar procedure for Z. In this case, an old Z-variometer or BMZ-instrument must be used in determining the effect of misalignment.

5.5 Use of the declinometer to measure declination D

All older magnetic observatories have classical declinometers, which usually consist of a non-magnetic theodolite and on top of it a box in which a suspended magnet is free to move.

The classical determination of D has roughly the same accuracy as the measurement with a fluxgate theodolite, but requires more skill and care. Because the classical D-measurement is an independent method to the fluxgate method, it is highly recommended to perform a measurement from time to time as a check.

Let the circle reading of the theodolite be A when observing the magnet (see Fig. 5.5). This is the theodolite reading of the magnetic meridian. The corresponding reading to the azimuth mark with known azimuth A_z (geographical direction) is B, and the magnetic declination is given by

$$D = A - (B - A_z) \tag{5.19}$$

Taking into account the effect of torsion of the suspending fibre, the final formula for declination is:

$$D = A_I + \gamma(A_I - A_{II}) - (B - A_z) \tag{5.20}$$

$$\gamma = \alpha_I/(\alpha_{II} - \alpha_I) \tag{5.21}$$

where A_I is the circle reading (actually mean of a number of readings A_{up} and A_{down}) for the stronger magnet, A_{II} is the corresponding reading for the weaker magnet, and

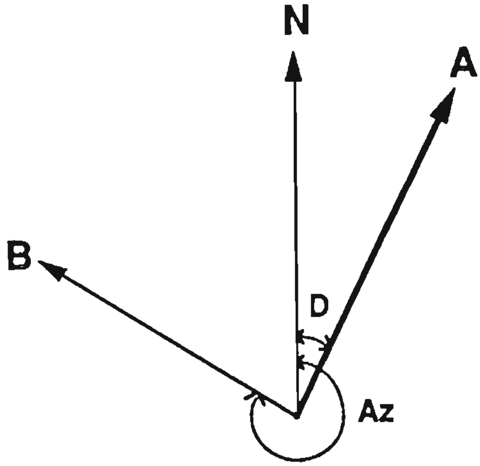


Figure 5.5. The principle of the measurement of magnetic declination D. A is the circle reading in the direction of the magnet, N is the direction to geographic north, and B is the circle reading to the azimuth mark, whose azimuth A_z is known.

B is the circle reading of the azimuth mark whose azimuth is A_z, γ is the torsion ratio. The torsion ratio γ and its determination for a pair of magnets is explained in Chapter 4.

The magnetic field almost always changes during the measurement. The changes have to be taken into account as corrections. Therefore, it is best to take all the readings A at full minutes (or half-minutes) so that it is easy to find the corresponding values from the recorded digital data. In practice, this means that the value of A_{II} has to be corrected by the change of declination from the time of observation of A_I to the time of observation of A_{II} so that if the declination has increased, the change of D has to be subtracted from A_{II}. The formula above then gives the absolute declination D for the time of the observation of A_I (actually for the mean time of all observations A_I). If D calculated from the recorded digital data is not the same as the measured absolute D, then the base-line value of the digital recording has to be corrected.

The D-measurement is very sensitive to possible small amounts of magnetic material in the theodolite. Therefore, it is good to make the observations in all possible positions of the theodolite by turning the base by 120° and, if the magnets have mirrors at both ends, as is usual, to make the observations from both north and south. The final value is then the mean of all observations. Even the mean value may be erroneous if the results from different positions differ much, say by more than 1′.

Table 5.5
An example of a D-measurement.
D-observation at Nurmijärvi, Main pillar. December 20, 1985,
Observer: M. Kivinen.
Declinometer: Askania 5114058. Theodolite: Askania 580144.
Azimuth to the A_z mark = –2°25.1′.

Position	UT [h m s]	Circle read. [° ′]	X_{rec} [nT]	Y_{rec} [nT]	D_{calc} [° ′ ″]
B		257 15.8			
B		257 15.9			
A_{ISdown}	08 27 00	263 55.1	15101.9	1183.6	
"	28 00	263 55.3	15101.9	1183.6	
A_{ISup}	29 00	264 27.2	15101.9	1183.6	
"	30 00	264 27.2	15101.9	1182.8	
A_{INdown}	08 32 00	263 55.9	15103.5	1182.5	
"	33 00	263 55.9	15103.5	1182.9	
A_{INup}	34 00	264 23.9	15103.1	1183.2	
"	35 00	264 24.2	15102.3	1184.0	
Mean		**264 10.59**	**15102.50**	**1183.28**	**4 28 48**
$A_{IISdown}$	08 39 00	264 22.6	15105.1	1184.4	
"	40 00	264 22.6	15104.3	1183.3	
A_{IISup}	42 00	264 01.8	15103.5	1184.0	
"	43 00	264 01.8	15104.3	1182.9	
$A_{IINdown}$	08 45 00	264 21.6	15103.5	1184.4	
"	46 00	264 21.6	15103.5	1183.3	
A_{IINup}	48 00	263 59.2	15105.1	1184.0	
"	49 00	263 59.0	15105.1	1182.9	
Mean		**264 11.28**	15104.30	**1183.92**	**4 28 55**
B		257 15.9			
B		257 15.8			

Usually the magnet is in a box which has a clamping mechanism and copper plates to damp the oscillations of the magnet. That the damping plates are non-magnetic has to be checked using measurements without them. In some magnetometer boxes, the material or the surface painting has been such that in a dry climate electrostatic charges may be accumulated at the surfaces deflecting the magnets or the torsion weight. In this case, cleaning the surfaces with antistatic liquid is recommended. Such a liquid is used in making gramophone records antistatic.

One common source of error is the window of the box through which one looks at the mirror. The window is very often slightly prismatic. Therefore, the observation of the azimuth mark has to be made through the same window. The other window on the other side of the box has to be open when observing the azimuth mark. Alternatively, the window has to be checked by observing the azimuth mark with and without the window until one is convinced that it really is plane-parallel.

Taking into account all the precautions discussed above it is possible to make a very good absolute determination of D using classical instruments. The final accuracy is usually 0.2′ or better.

In Table 5.5 we give an example of a D-measurement. The symbols used are the same as above.

The left side of the table contains the readings of the observation, and the right side presents the simultaneous observatory readings. Here the recorded components were X and Y. If H and D had been recorded, the calculation would have been even more straightforward.

Here the circle readings for the azimuth mark are marked B, and the readings for the stronger magnet are A_I. S means the observation from the south, and N that from the north (there are mirrors at both ends of the magnet). The notations "up" or "down" show which position the magnet is in when turning 180° around its magnetic axis (there is a mark on the magnet pointing up or down). The values of X_{rec} and Y_{rec} recorded simultaneously with the observations are also shown, as well as the declination D calculated from the recorded values during the series made with the stronger and the weaker magnet. We see that the declination has increased 7″ from the series made with the stronger magnet to the series made with the weaker magnet, which means that 7″ has to be subtracted from A_{II}. From experiments made with the magnets the torsion ratio γ is known to be 0.70 (see formula 5.21), and the direction to the azimuth mark, A_z, is, at Nurmijärvi, –2°25.1′, so we can calculate the declination by applying formula (5.20):

$$D = A_I + \gamma(A_I - A_{II}) - (B - A_z)$$

$$= 264^\circ 10.59' + 0.70(264^\circ 10.59 - (264^\circ 11.28' - 7'')) - (257^\circ 15.85' + 2^\circ 25.1')$$

$$= 4^\circ 29.2'$$

This is the measured absolute D. The recorded value, D_{rec}, for the same time (the time of the series with the stronger magnet) was 4°28′48″ = 4°28.8′, which is 0.4′ lower than the true value. This means that the base-lines of X and/or Y have to be corrected. To be able to make the corrections to the X and Y base- lines we need to know the absolute value of the horizontal intensity H for the time of the D-observation. Naturally, if D is one of the components recorded, the correction is applied directly to the D base-line.

5.6 Use of the QHM to measure horizontal intensity H

The quartz horizontal magnetometer (QHM) is an excellent instrument for the measurement of horizontal intensity H. It is still in wide use at many observatories. It is not an absolute instrument, but keeps its constants so well, with an accuracy better than 1 nT/year, that it can be used to check the H base-lines of recording instruments if the constants are determined regularly (say every 1 to 3 years). The QHM has also been used for declination measurements, but it is not good enough for observatory practice. Like many other geomagnetic instruments of the first half of this century, the QHM is an invention of D. La Cour (Kring Lauridsen, 1977).

The principle of a QHM-measurement is very simple (see also Chapter 4): the first step is to unclamp the instrument in roughly the north-position (the telescope looking northward) and to turn it until the reflection of the scale or cross of the telescope coincides with itself. Let us call the reading of the theodolite circle in this position A_0. The next step is to turn the theodolite clockwise (+ direction) $360° = +2\pi$, or any multiple of π, and some more until the reflection of the scale or cross of the telescope coincides with itself again. The number of half-turns has to be chosen so that the magnet turns at least 45° from its zero-position. Let us call the reading of the theodolite circle in the plus-position A_+. We now know that the quartz fibre has been twisted exactly 2π in the plus-direction (or some other multiple of π, but 2π is the normal value and we shall use that in this example). The next step is to turn the theodolite in the corresponding minus-position where the circle reading is A_-. We obtain the value of the horizontal intensity H from the formula (see Chapter 4)

$$H = C/(1 - k_1 t)(1 + k_2 \tilde{H} \cos\varphi) \sin\varphi \tag{5.22}$$

where C, k_1 and k_2 are the main constant (always given for torsion angle 2π), the temperature and induction constants, respectively, determined at a standard observatory, and $\tilde{H}$ is an approximate value of H. φ is $(a_+ + a_-)/2$, where $a_+ = (A_+ - A_0)$ and $a_- = (A_0 - A_-)$. If $(a_+ - a_-)$ is large (>10′), then the denominator has an additional term:

$$H = C/(1 - k_1 t)(1 + k_2 \tilde{H} \cos\varphi) \sin\varphi \cos[(a_+ - a_-)/2 + \alpha] \tag{5.23}$$

where α is determined from

$$\tan\alpha = (\sin a_+ - \sin a_-)/(2 - \cos a_+ - \cos a_-) \tag{5.24}$$

If the torsion angle 2π does not give a suitable φ, then π or 3π or 4π has to be used in some cases. For calculating in these cases, the main constant C has to be changed correspondingly, so that in the case of π the constant will be $C/2$, in the case of 3π it will be $3C/2$, etc.

To obtain good results from QHM-observations, the observer should have some practice, because in turning the instrument the magnet begins to swing and it has to be damped. This is done using a small weak magnet, for example part of a needle fastened in a cork or some other piece which is comfortable to keep in the hand. An experienced observer can damp the swinging of the magnet in ten seconds by rhythmically moving and turning the damping magnet first close and later farther away from the magnet. The damping is very important, because the whole measurement has to be performed to a fixed schedule to avoid the effect of elastic creep of the suspending fibre. The recommended series of observation is

0, +, –, –, +, 0

performed so that there is a fixed time, usually one to two minutes, between the observations. It is important that the same schedule is also used when comparing the instrument at a standard observatory. The following series of observation is also frequently used:

0, +, –, –, +, +, –, 0

It is recommended that each pair of observations be calculated separately to get an idea of the precision of the measurement. Naturally, the observations have to be corrected for the possible changes of declination: if the declination D has increased from the time of the plus-observation to the time of the minus-observation, the circle reading of the minus-observation is too high and a_- is to small. In other words $(D_+ - D_-)$ has to be added to A_- before calculating φ. D_+ and D_- are the values of declination at the times of the plus- and minus-observations.

Examples of calculations can be found in Wienert's *Notes...* . If a different kind of series is used, e.g. many readings are taken with the instrument first in the plus-position, and then in the minus-position, to avoid the difficult turnings of the instrument, the effect of elastic creep has to be taken into account, or the constants have to be determined using similar observations. The theory of the QHM has been handled in detail in several publications by Kring Lauridsen of the Danish Meteorological Institute. An example of a QHM-measurement made at Nurmijärvi observatory is given in Table 5.6.

The observations of the A_z mark are not needed. They are, however, a good verification of the stability of the theodolite during the observation.

The series above is an example in which the position of the QHM has been kept the same during both half-series, which makes the observation easier. In this kind of series it is very important to always use the same schedule. An exactly similar series has to be used when determining the main constant C at a standard observatory. Also, the temperature should be roughly the same, because the elastic after-effect of the quartz fibre, the elastic creep, depends on temperature.

Table 5.6
An example of a QHM measurement.
Place: Nurmijärvi, Main pillar, Date: November 14, 1983
QHM: 219, Theodolite: Askania 580144, Observer: M. Kivinen
C: 9026.5 nT, $k_1 = 0.000408\,/\,^\circ C$, $k_2 = 115\cdot 10^{-10}\,/nT$

Position	UT [h m s]	t [°C]	A [° ′ ″]	X_{rec} [nT]	Y_{rec} [nT]	D_{calc} [° ′ ″]
A_z mark	257°16′54″					
0	09 41 00		85 45 42	15116.8 nT	1195.7 nT	4 31 21
$+2\pi$	09 43 00	17.2	122 35 42	15118.4	1192.6	
$+2\pi$	44 00	17.3	35 30	15119.2	1194.1	
$+2\pi$	45 00	17.4	35 30	15119.2	1194.9	
$+2\pi$	46 00	17.4	35 12	15120.0	1195.3	
$+2\pi$	47 00	17.4	35 00	15120.8	1195.3	
Mean			**122 35 23**	**15119.52**	**1194.44**	**4 31 52**
-2π	09 49 00	17.5	48 56 12	15120.8	1193.3	
-2π	50 00	17.5	56 12	15120.8	1192.2	
-2π	51 00	17.6	56 18	15121.9	1192.2	
-2π	52 00	17.6	56 06	15121.9	1194.9	
-2π	53 00	17.7	56 06	15121.6	1194.9	
Mean		**17.46**	**48 56 11**	**15121.40**	**1193.50**	**4 31 37**
A_z mark	257°16′54″					

The standard QHM-series where the QHM is turned more often is not critically dependent on the schedule of the observation.

If the QHM is well adjusted, which is normally the case, formula (5.22) gives a sufficiently accurate result for H. Below we calculate H first applying (5.22), and later using the complete formula (5.23).

From the recorded data we see that the declination D has decreased 15″ = 0.25′

from the $+2\pi$ series to the -2π series. Therefore, the angle A obtained in the -2π series is by 0.25′ too small. Applying this correction we get for φ

$$\varphi = (122^\circ 35'23'' - (48^\circ 56'11'' + 15''))/2 = 36^\circ 49'28'' = 36.8246^\circ$$

Putting φ and the constants of the QHM and an approximate value of H into formula (5.22) we get

$$H = C/(1 - k_1 t)(1 + k_2 \tilde{H} \cos\varphi) \sin\varphi = 9026.5/(0.99959 \cdot 1.00014 \cdot 0.59948)$$
$$= 15166.0 \text{ nT}$$

The H-value corresponds to the mean value of the ten recorded X and Y values. Calculating $H_{recorded}$ from these values we get

$$H_{recorded} = 15167.5 \text{ nT}$$

which shows that the recorded H is 1.5 nT too high. In this case, having X close to H and Y rather small, the probability that the error is in the X component is very high, but in principle we do not know in which component the error is. For that we need the absolute D-value for the time of the H observation.

To take into account the possible effect of the asymmetry of the positive and negative deflection angles we calculate α applying formula (5.24), using $a_+ = A_{+2\pi} - A_0$ and $a_- = A_0 - A_{-2\pi}$, naturally corrected with the changes of the declination. The corrected values are $a_+ = 36.8336^\circ$ and $a_- = 36.8155^\circ$. Placing these values into the formula for tan α gives $\alpha = 0.03631^\circ$. The complete formula for H (formula (5.23)) now gives

$$H = C/(1 - k_1 t)(1 + k_2 \tilde{H} \cos\varphi) \sin\varphi \cos[(a_+ - a_-)/2 + \alpha] = 15166.0 \text{ nT}$$

which is the same result as that obtained using the shorter formula. In fact, the formulas differ only by $\cos[(a_+ - a_-)/2 + \alpha]$ in the denominator. In this case

$$\cos[(a_+ - a_-)/2 + \alpha] = 0.9999999 .$$

5.7 Determination of azimuth from Sun-observations

The geographical direction to a mark is called its azimuth. The azimuth is reckoned positive clockwise starting from the north. In astronomical literature, however, the azimuth of the Sun is reckoned from the south.

In geomagnetic work at observatories and in field measurements the direction of the azimuth mark is mainly determined by observing the Sun. The azimuth A_z of the Sun is determined from the spherical triangle depicted in Figure 5.6.

From the triangle in Figure 5.6 we obtain:

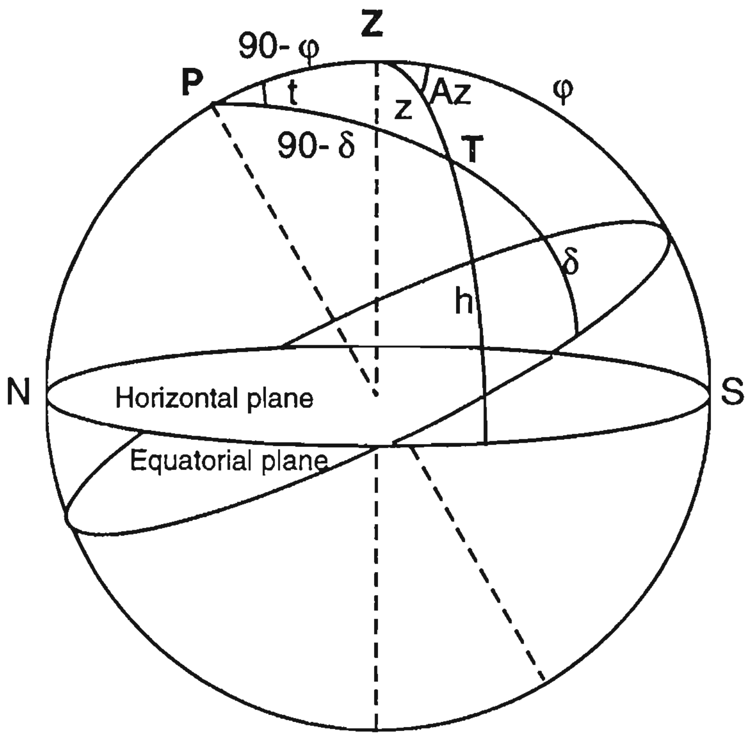


Figure 5.6. Celestial spherical triangle from which the azimuth A_z of the Sun is determined. Z is the Zenith, z = zenith distance of the Sun, δ = the declination of the Sun, t = meridian angle or hour angle of the Sun, $90° - \delta$ = distance (angle) of the Sun from the pole P, $90° - \varphi$ = colatitude of the place of observation, N shows the north and S the south in the local horizontal plane. T is the location of the Sun.

$$\sin z \cos A_z = -\cos\varphi \sin\delta + \sin\varphi \cos\delta \cos t, \tag{5.25}$$

$$\sin z \sin A_z = \cos\delta \sin t,$$

and by dividing the lower by the upper expression:

$$A_z = \arctan\left[\sin t / (\sin\varphi \cos t - \cos\varphi \tan\delta)\right] \tag{5.26}$$

which is the formula for the calculation of the azimuth A_z of the Sun. The Greenwich hour angle GHA and the declination of the Sun, δ, can be found in nautical or astronomical almanacs. Simple computer programs are available for their calculation as well. t is simply GHA + longitude (positive to the east).

For the calculation we need the Julian day (JD) of the observation. The Julian period starts on the first of January year 4713 BC at noon Universal Time (UT or Greenwich Mean Time), and can be obtained from the formula

$$\mathrm{JD} = \mathrm{int}(365.25F) + \mathrm{int}(30.6001(G+1)) + D - \mathrm{int}(F/100)$$

$$+ \mathrm{int}(F/400) + 1720996.5 \qquad (5.27)$$

where F = year – 1 and G = month + 12 if month < 3, otherwise F = year and G = month, and D = day in both cases. (To know how to calculate the Julian day may be useful also in some other connections, as the Julian day is commonly used in astronomical calculations.) In astronomical calculations a time unit (T) is introduced, giving the time in fractions of centuries starting from some even number of hundreds of years. In the formulas below the reference time for T is 00 UT on January 1, year 1900 (corresponding to Julian day 2415020), giving for T:

$$T = (\mathrm{JD} + \mathrm{UT} - 2415020)/36525 \qquad (5.28)$$

where UT has to be given in fraction of day (three digits are enough).

The calculations below are based on an algorithm by G. G. Bennett (1980). Note that when programming the formulas below for a computer, double precision has to be used. Pocket calculators often use a sufficient number of decimals. Nine will be enough.

The orbital elements needed in the calculation of the right ascension (α) and the declination δ of the Sun are

$$M = 358.475 + 35999.050\,T - 360\,\mathrm{int}[(358.475 + 35999.05\,T)/360]$$

$$V = 63 + 22518\,T - 360\,\mathrm{int}[(63 + 22518\,T)/360]$$

$$Q = 332 + 33718\,T - 360\,\mathrm{int}[(332 + 33718T)/360] \qquad (5.29)$$

$$J = 222 + 32964\,T - 360\,\mathrm{int}[(222 + 32964\,T)/360]$$

$$\Omega = 101 + 1934\,T - 360\,\mathrm{int}[(101 + 1934\,T)/360]$$

Most pocket calculators can deal with angles over 360° and then the latter parts in the above equations beginning with –360 etc. are not needed. The constituents in the Apparent Longitude of the Sun are then:

The Mean Longitude:

$$L_1 = 279.69019 + 36000.76892\,T$$

$$- 360\,\mathrm{int}[(279.69019 + 36000.76892\,T)/360] \qquad (5.30)$$

The Equation of Center:

$$L_2 = (1.91945 - 0.00479\,T)\sin M + 0.02\sin 2M + 0.00029\sin 3M \tag{5.31}$$

The Lunar Perturbation:

$$L_3 = 0.00179\cos(261 + 445267\,T) \tag{5.32}$$

The Perturbation Due to Venus:

$$L_4 = 0.00134\cos(90 + V) + 0.00154\cos(90 + 2V) + 0.00069\cos(258 + 2V - M) + 0.00043\cos(78 + 3V - M) + 0.00028\cos(51 + 3V - 2M) \tag{5.33}$$

The Perturbation Due to Mars:

$$L_5 = 0.00057\cos(90 + Q) + 0.00049\cos(306 + Q - M) \tag{5.34}$$

The Perturbation Due to Jupiter:

$$L_6 = 0.00200\cos(91 + J) + 0.00076\cos(270 + 2J) + 0.00072\cos(175 + J - M) + 0.00045\cos(293 + 2J - M) \tag{5.35}$$

The Effect of Nutation in Longitude:

$$L_7 = 0.00479\cos(90 - \Omega) + 0.00035\cos(295 + 2M) \tag{5.36}$$

The apparent longitude of the Sun, L, is

$$L = L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7 \tag{5.37}$$

$$L = L - 360\,\mathrm{int}(L/360)$$

The obliquity of the ecliptic, ε, is

$$\varepsilon = 23.45229 - 0.01301\,T + 0.00256\cos\Omega \tag{5.38}$$

The right ascension α and the declination δ are

$$\alpha = \arctan(\sin L\cos\varepsilon/\cos L) \tag{5.39}$$

$$\delta = \arcsin(\sin L\sin\varepsilon) \tag{5.40}$$

The Greenwich Hour Angle (GHA) is then

$$\mathrm{GHA} = \mathrm{UT} + 99.6913 + 36000.76892\,T + 0.917\,L_7 - \alpha$$

$$\mathrm{GHA} = \mathrm{GHA} - 360\,\mathrm{int}(\mathrm{GHA}/360) \tag{5.41}$$

The GHA obtained may differ by 180° from the correct value, which should be 00° for north and 180° for south.

The local (east longitude = λ) hour angle (LHA) is

$$t = \text{GHA} + \lambda \tag{5.42}$$

and the azimuth of the Sun (A_z) is finally calculated using formula (5.26).

As an example of calculation of the direction to azimuth mark we show, in Table 5.7, a real measurement. For the GHA the formulas given above are used.

Table 5.7
An example of calculation of the direction to an azimuth mark.
Place: Kumlinge, lat. (φ) 60°15′12″N, long. (λ) 20°46′48″E.
Date: September 21, 1961.
Theodolite: Askania.
A_z-mark 1: Middle of the second floor window in the house close to N.
A_z-mark 2: Right-hand corner of the chimney of the house in E.

	UT [h m s]	Theodolite reading [° ′ ″]
A_z-mark 1		151 10 33
A_z-mark 2		242 56 39
Sun right	12 58 27.0	187 20 15
Sun left	12 58 46.1	186 50 24
Sun left	12 59 44.0	187 05 09
Sun right	13 00 27.9	187 51 54
Sun right	13 00 59.4	187 59 48
Sun left	13 01 22.9	187 30 36
Sun left	13 01 49.6	187 37 24
Sun right	13 02 20.5	188 20 33
Sun right	13 02 48.9	188 28 00
Sun left	13 03 15.1	187 59 57
Mean value	**13 01 00.1**	187 42 24
A_z-mark 1		151 10 33
A_z-mark 2		242 56 39

The calculation of GHA by applying the procedure presented above is

$\text{GHA} = 16°58'25''$, and $t = \text{GHA} + \lambda = 37°45'13''$

$\delta = 0°40'34''$

Applying (5.26) we finally get for the azimuth of the Sun

$A_z = \text{arc tan } [\sin t/(\sin\varphi \cos t - \cos\varphi \tan\delta)] = 41^\circ 58'27''$

The azimuths A_{zm} of the marks are then

$A_{zm} = A + (A_z - A_{Sun})$

where A and A_{Sun} are theodolite readings to the mark and Sun, respectively.

A_z-mark 1: $151^\circ 10'33'' + (41^\circ 58'27'' - 187^\circ 42'24'') = 5^\circ 26'36''$

A_z-mark 2: $242^\circ 56'39'' + (41^\circ 58'27'' - 187^\circ 42'24'') = 97^\circ 12'42''$

In the example above, a theodolite having only a normal ocular was used. There are special oculars available for the Zeiss theodolites which point at the middle of the Sun, making the measurement easier and more accurate.

Sometimes it is interesting to know also the elevation h of the Sun. From the stellar triangle (Figure 5.6) we get

$$h = \text{arc sin } [\sin\delta \sin\varphi + \cos\delta \cos\varphi \cos t] \tag{5.43}$$

which gives the elevation angle without taking into account refraction; the latter lifts objects at the horizon by 0.5° (about the diameter of the Sun). An object seen at the horizon, e.g., the upper limb of the Sun, is in reality 37′ below the horizon. The effect of refraction, r, is calculated by applying the recursive formula

$$r = [(60.305 \sin z')/3600]/[0.68 \cos z' + 0.32((\cos z')^2 + 0.00726)^{1/2}] \tag{5.44}$$

$$z' = z - r$$

so many times that the absolute difference between two subsequent r-values is smaller than say 0.00001°. The first value for $z' = z = 90 - h$, which is the zenith distance without taking into account refraction.

Some remarks about observations of the Sun are to be made: the telescope must have a dark glass eyepiece made for Sun observations. Looking at the Sun without a special eyepiece may cause permanent damage to the eye. There is a special prism available for Wild theodolites, called a Wild-Roelofs solar prism. It allows direct pointing to the center of the Sun, improving accuracy and simplifying the calculations. The theodolite has to be carefully levelled. At least one, and preferably several azimuth marks in different directions have to be observed before and after the Sun observation. Several observations of the Sun have to be made reading the time and the circle when, alternately, the left and the right side of the limb, or, if the Wild-Roelofs prism is available, the middle point of the limb passes the vertical line of the diaphragm of the telescope. The correction required to the time of the clock used has to be known with an accuracy of 0.2 s. The time signals from most of the normal radio stations are much more accurate than needed for this purpose. Special radio stations giving continuous time signals transmit in most parts of the world. Accurate time is available everywhere today from the GPS satellites (GPS = Global Positioning System) (see Section 6.4). The geographic coordinates needed in the calculations of the azimuth of the Sun or stars may be obtained from the position given by GPS (an accuracy of 50 m is enough in practice).

The time given in radio time signals is the so-called UTC-time (Universal Time Coordinated). This is not exactly the same as the time which is fixed to the rotation of the Earth, which is the time needed in the calculation of the azimuth. The UTC or UT, as it is called in the text above, is kept to be close to the rotational time by adding one second at the beginning of the year, if needed. This means that the UT time and the rotational time may differ from each other by up to one second which is too much for the required accuracy. Therefore, a correction has to be obtained and applied. In most countries the place receiving the lists of corrections from the Bureau International de L'Heure in Paris is the local Geodetic Institute. (One second in time may mean 15″ in azimuth angle.)

The elevation of the Sun has to be lower than 45° above the horizon to obtain accurate observations of the azimuth. Most systematic errors can be eliminated by taking sunshots in the morning and the afternoon with the Sun at equal elevations.

A Fortran program written by Andrew Lewis, and advice concerning Sun observations, is to be found in the *Guide for Magnetic Repeat Station Surveys* (Newitt *et al.*, 1996).

For accurate determination of the direction to the azimuth mark at an observatory, observation of North Star (in the northern hemisphere) is the best method. The star measurement is more accurate than the observation of the Sun partly because the star has no angular diameter, the ephemerides are exact, and the requirement on the accuracy of time is less when the star is not too far from the pole. Many stars can be used. Their ephemerides (right ascensions and declinations) are given in astronomical almanacs.

6. RECORDING OF MAGNETIC VARIATIONS

Magnetic variometers are magnetometers which continuously measure and record the magnetic field variations. Three components of the field are usually recorded. For special purposes, like functioning as a base station for prospecting, one component, usually F in this case, might be enough. In observatory use three components are recorded, and often F with proton magnetometer as an additional, absolute verification. The most commonly used variometers at modern magnetic observatories are three-component fluxgate magnetometers combined with microprocessor-based digital data collection.

The data are samples of the magnitude of the field components variations. The primary samples are usually taken at very short intervals, several times per second. Applying digital filtering techniques, one-minute or more dense values are produced and stored. If magnetic pulsations have to be recorded using the same original data, much more dense component values have to be stored and a higher resolution has to be used. As a rule, the samples represent only the varying part of the field, having a range of ±4000 nT or so, and a base value has to be added to the recorded one for getting the final value of the component. The base values are determined by making absolute measurements as presented in Chapter 5.

For a more complete description of recording instruments, including SQUID magnetometers and recording systems using optical pumping and three-component proton magnetometers, see for example Forbes (1987) or Stuart (1972). Here we concentrate on instruments which we consider the best at a modern magnetic observatory. For the physics of the magnetometers used as variometers, see Chapter 4.

6.1 Installation of the station

Before installing the instruments at a magnetic observatory one should be sure of the following:

- The place is suitable for the observatory (see Chapter 3).
- The shelter is suitable for the sensor of the variometer (Chapter 3).
- The pillar is stable. If one cannot be sure of that, a suspended sensor should be selected (see Section 6.3 below).
- The geographic direction (north–south or east–west line) is drawn on the pillar to facilitate the installation of the sensor. The geographic direction can be determined as explained in Chapter 3.

- The differences (for all components) between the field at the variometer pillar and at the absolute pillar are measured before installation, because this is not possible later.

- The whole instrument, including the magnetometer system and recorder, is thoroughly tested at a magnetic observatory before installing it at a new place. This includes the measurement of the orthogonality of the sensor elements, sensitivity (see Chapter 8), temperature effects (see Section 6.2 below) and magnetic effects of the different parts of the system.

The tests of the variometer system which should be done before bringing the variometer to the recording site will be described in Chapter 8. They should be made in a standard magnetic observatory having a coil system or other equipment for the tests. At the standard observatory, the orthogonality of sensors of the three different components is tested. It is not necessary to have the sensors orthogonally oriented, but it is necessary to know the angles between the sensors. It is also best to check at the observatory the sensitivities of the components. That they keep the original values, measured at the observatory, has to be checked regularly after installation, using the built-in sensitivity-calibrating system of the instrument, if available. The true value of the calibrating system has to be determined at the standard observatory. Do not trust the values given by the manufacturer in the data sheet of the instrument; request a test certificate from a magnetic observatory. If possible, it is also good to determine the temperature coefficients at the standard observatory, although they can be determined also after the installation by changing the temperature of the room or box in which the magnetometer has been installed and making absolute measurements when the variometer is in different temperatures. Observe that the electronics may also have temperature coefficients affecting the magnetometer readings, so the temperature coefficients of the electronics should also be determined.

The methods for measuring the orientations relative to the geographic axis are described in Chapter 8.

Before the final installation of the magnetometer it is recommended that all the wiring be final, and all magnetic parts removed. The power consumption of the variometer has to be measured and sufficiently large batteries installed in a separate place (see Chapter 3) for running during power failures. We recommend large enough batteries for running at least 24 hours, but in areas with known longer power interruptions correspondingly larger batteries are required. The batteries have to supply the magnetometer and the data collection unit. The power consumption of modern magnetometers and modern electronics for data collection is usually rather small, of the order of 10–20 W altogether, so purchasing sophisticated, service free batteries will not be a big investment. Usually it is advisable to use the batteries as a buffer all the time. This reduces the likelihood of damage from voltage pulses, often present in the mains. Damage caused by lightning is to be expected if protection against it has not been incorpoprated. Opto-isolation is a good protection for the signal cable, which, however, should preferably be of optical fiber itself. The proposal for wiring at a magnetic observatory described in Chapter 3 is an example of how to shield the system against lightning pulses propagating along the main power line and pulses caused by induction in the wiring at the observatory. As suggested in Chapter 3, the batteries should preferably be in an isolated and ventilated place within the electronics hut if they are of the type producing hydrogen or corroding gases when charged.

Before installing the variometer, the magnetism of the preamplifier or the electronics box of the magnetometer has to be measured. This can be done simply by bringing it close to the absolute instrument in the absolute house or by using the variometer itself. Preferably the preamplifier (or the whole electronics) should be installed in the variometer room far enough from the sensors to give an effect of less than 2 nT, and the unit should be fixed so that it cannot be moved. The unit should not produce any varying fields at the sensor due to any varying DC-currents in the electronics. This also has to be checked before installation. The magnetism of the sensor has to be measured, if there is a likely effect on another variometer in the same variometer room. As stated in Chapter 3, we recommend two variometers for magnetic observatories, for backup.

The sensor of the variometer usually has two perpendicular levels. If not, separate levels have to be used. Their readings corresponding to the correct vertical position of the Z-sensor should be kept in mind from the calibration at the magnetic standard observatory, or they should be adjusted there to show the middle position. This makes it easy to install the sensor at its final place, so that the vertical intensity is measured correctly. If the sensor head can be turned around its vertical axis, the verticality can be checked by adjusting the sensor until the Z-sensor shows the same value in all positions. If the components H and D will be recorded, then the installation is easy: just turn the sensor until the D-component shows zero value (in undisturbed field). But after a few years, due to the secular variation, the orientation will no longer be in the H–D direction, and the sensor will have to be turned or one will have to introduce small corrections to the components, as described in Chapter 7.

Very often the sensor is oriented geographically, as recommended also by IAGA, especially for observatories at high latitudes. This has the advantage that no turning of the sensor is needed because of the secular variation and also no corrections are needed in the calculations during big magnetic disturbances, common especially at high latitudes. It is also important to notice that if the declination at the site is not representative for the area (not close to the declination shown in magnetic charts), then the recorded variations of H and D are not representative for a larger area (Eleman, 1966). For example, the observed secular variation of H and D can differ from the secular variation of the surroundings and not represent the source inside the Earth. Similarly, all variations of D and H, e.g., the daily variation, will be nonrepresentative. For these reasons, recording of X and Y is highly recommended, because variations in them will be correct. Of course, from the recorded H and D it is possible to calculate X and Y if one preferes to install the magnetometer in the HD position.

The installation to measure the north and east components, X and Y, can be done simply by turning the sensor until the Y-component shows the value of the known Y at the pillar. Another method is to use the north–south or east–west lines marked on the sensor at the standard observatory in the calibration process, and to install the sensor at the pillar utilizing the N-S or E-W lines drawn on the pillar.

Making use of modern microprocessor technology it is possible to install the sensors in arbitrary positions and calculate the desired components. The orientations can be calculated from absolute measurements, provided full components are recorded. Naturally it is convenient to have the orientations roughly geographical. For details of determining the orthogonality of the sensors and the sensitivities, see Chapter 8.

An interesting suggestion for the orientation of the fluxgate sensors is to have one of them horizontal, recording deviations from the magnetic meridian, and the other perpendicular to total intensity F in the plane of the magnetic meridian, measuring deviations from a mean inclination value. In this installation, both sensors are in almost zero field, which adds in accuracy. The third component in this case should be F, measured with proton magnetometer.

The sensor (containing three components) *has to be fixed to the pillar* so that its orientation does not change by mistake. Glue or modeling can be used to fix the base plates of the three feet of the sensor.

Many observatories use a proton magnetometer to record F at the same time as the three-component magnetometer records the components. Recording F with a proton magnetometer is a good check of the other components, because the proton magnetometer is an absolute instrument. The different components affect F with different weights, however, so that a failure in the smallest component may hardly be seen in F.

In recording F with proton magnetometer one source of a small error is obvious, if the magnetic field in the observatory is not homogeneous. The proton sensor cannot be placed close to the place where the other components are measured or recorded, so there may be a pillar difference between the place of the proton sensor and the three-component variometer. If there is a pillar difference in F or, more precisely, some of the components of F, then the pillar difference does not remain the same if there is a big change of the magnetic field. The size of the change depends on the changing component and on the component(s) in which the pillar difference exists. The following very arbitrary example shows how important it is to know the difference between the F-pillar, where F is recorded with the proton magnetometer, and the variometer pillar. Large differences are presented in the example below, and are not likely at magnetic observatories where the homogeneity of the field has been checked carefully, but even much smaller differences may be seen in modern measurements with 0.1 nT resolution.

Let us assume that in normal field the F-difference between the pillars is zero, and the different components at the pillars are

Variometer pillar	F-pillar
F = 50 000.0 nT	F = 50 000.0 nT
X = 20 100.0	X = 20 000.0
Y = 2 000.0	Y = 2 000.0
Z = 45 738.3	Z = 45 782.1

If X grows by 1000 nT, we get

at the variometer pillar	at the F-pillar
F = 50 410.3 nT	F = 50 408.3 nT

showing that there now is a difference of 2 nT between the pillars. In observatory areas the difference of 100 nT in one component is not likely; and the field rarely changes by 1000 nT, but as our aim is an accuracy of a fraction of nT, even moderate changes of field components may be seen as changes in pillar differences.

Our example shows that a) it is important to know the differences of the components between the pillars and not only the difference of the total intensity F, b) the difference of F between the pillars may change with time, and c) F is not necessarily a good verification of the other components if there is a difference in some of the components between the pillars, as in our example where both X and Z had rather large differences. Ten times smaller differences would affect modern accurate measurements where 0.1 nT is in use.

6.2 Temperature effects

The elements of the variometer have temperature coefficients. The manufacturers of the magnetometers have tried to make them as temperature stable as possible and have often also equipped them with electronic temperature compensation. In fluxgate elements the most sensitive part is the compensating coil, which usually is wound on a frame made of quartz or some other material having a very small temperature coefficient. The usual temperature coefficients are about 1 nT/°C, which shows that the temperature has to be measured at least close to the sensor and preferably also close to the electronics. The temperatures have to be recorded together with the magnetic data. The final correction for the temperature effects should be done in the processing of the data.

It is good to determine the temperature coefficients of the variometer when testing the instrument at a reliable magnetic observatory. In addition, they should be checked at the new place of installation by recording and making absolute measurements when the variometer system is at different temperatures. To save energy, a good practice is to keep the temperature of the variometer shelter higher during the warm season and colder during the colder season and to calculate the temperature effect caused by the change of the temperature. The temperature should preferably be maintained at all times so high that the thermostat (see Chapter 3) can keep the temperature of the shelter of the magnetometer stable.

6.3 Tilt: compensation and correction

As mentioned several times, the stability of the pillar of the magnetometer sensor is very important. Not every soil is suitable for erecting stable pillars. In permafrost areas, for example, it is not possible to build stable pillars. There are several methods of correcting the recorded values for changing tilt. The first method is to make base-line determinations frequently, e.g., every day. The second is to determine the tilting coefficients for E-W and N-S directions (the tilting coefficient says how many nT correspond to a change of the level by 1 minute of arc), and to record tilting variations using a digital tiltmeter. The knowledge of these parameters enables us to correct magnetic variations numerically. The last method uses suspended sensors and is shown to be good in practice. Some of the classical suspended magnet sensors (e.g., Bobrov, 1962) also compensate for the effect of the tilt.

There are two types of suspended sensors in rather wide use, the Danish one (Figure 6.1) (Rasmussen and Kring Lauridsen, 1990), and the Canadian one (Figure 6.2) (Trigg and Olson, 1990).

The Danish suspended fluxgate has been used several years at the Greenland observatories; before the suspended sensors had been installed, the base-line values were a serious problem. After installation, the base-lines have shown normal changes, which means some 2–4 nT/year compared to the previous ones which were more than ten times larger and irregular. Experiences from Canada are similar.

A recording tiltmeter—such as the one made by Applied Geomechanics in California—is another solution. Tiltmeters are available for different requirements of resolution: 1 microradian, 0.1 microradian and 10 nanoradians. The tiltmeter has to be placed at a safe distance from the magnetic sensors. Naturally, if a tiltmeter is used, one has to calculate the correction to the components. Using suspended sensors, no additional calculations are needed.

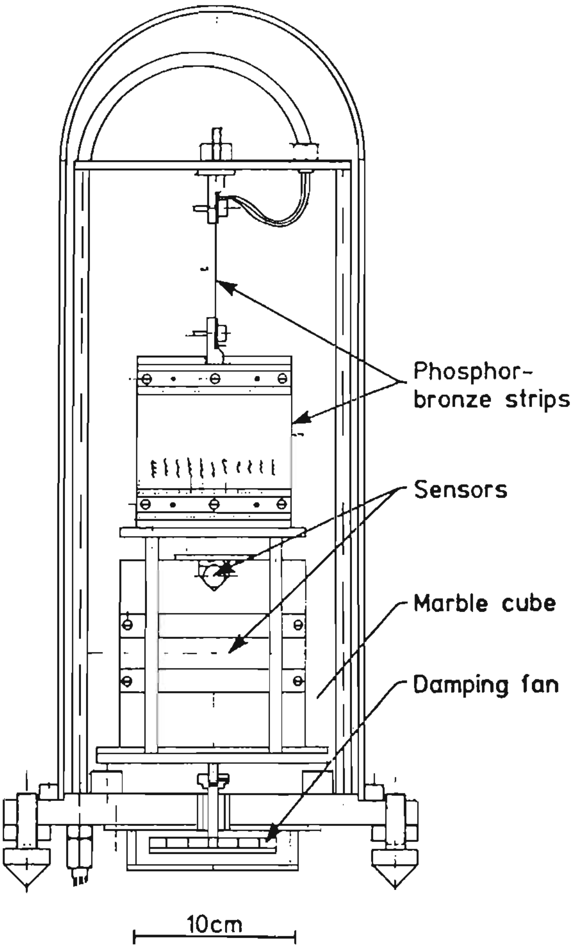


Figure 6.1. Suspended three-component fluxgate sensor of the Danish Meteorological Institute.

The suspended sensor or correction of the tilt using the tiltmeter does not correct for any possible turning of the pillar. This naturally can also be recorded using, for example, a light beam reflected from a mirror fixed to the pillar, but no commercially available systems exist as far as we know. The easiest check of the turning is to make frequent absolute measurements. In Section 3.2 we recommended that if there are two or more pillars in the variation room, they should be connected to each other under ground. This reduces the turning. If the whole block turns and there are two independent variometers, the turning will be seen as similar effects in both recordings.

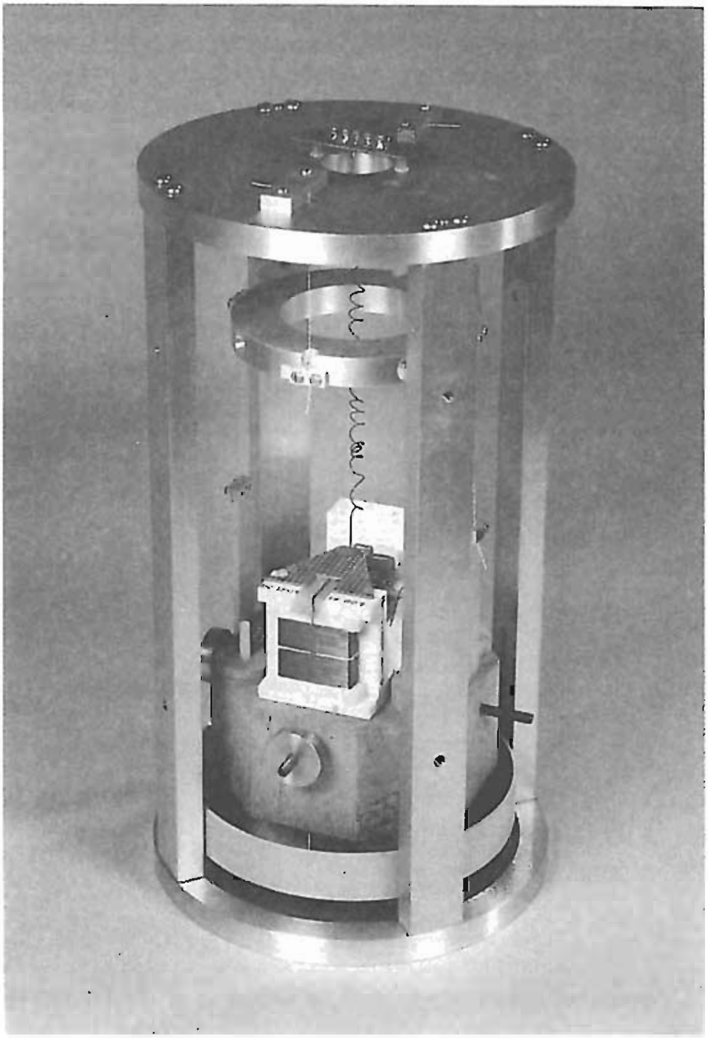


Figure 6.2. Suspended three-component fluxgate sensor of the Geomagnetic Laboratory of the Geological Survey of Canada.

6.4 Time keeping at a magnetic observatory

Correct time is essential in all recordings. The accuracy needed depends on the use of the data, but for example in one-minute values the accuracy should be at least 1 s, and for faster sampling, better still. Many comparisons of magnetic recordings have been spoiled by poor timing.

Often normal personal computers (PC), lap-top computers or corresponding microprocessors are used as recorders of magnetic data. As a rule, the clocks of the PC's are not accurate enough for this purpose. A drift of 1 s per day or more seems to be common. Therefore, the time of the PC has to be corrected several times per day if the PC commands the data sampling and if the time of the PC is recorded. The programming of the correction of the PC-time is not trivial, because it has to be done at the same time as the PC collects the data. Using a data logger which has a satisfactory clock is therefore a more simple solution, but not as flexible as a PC, for example in changing data collection rate.

In magnetic recording it is advisable to use universal time (UTC, see Chapter 5). Time is available several times per day in most radio programs with sufficient accuracy but in impractical form for use in modern automatic recording systems.

Nowadays there are exact time signals available in coded form from different sources. After decoding, the time is in normal digital form. We would like to mention GPS (Global Positioning System) which transmits the time continually with very high accuracy and which is easily available all over the globe. Commercial clocks based on GPS are available. All over Europe there is the DCF-system (transmitter in Germany). There are also clocks utilizing the Omega navigation system. The time of Omega is precise, but has a systematic error of several seconds due to leap seconds which have not been taken into account (see Chapter 5). Sophisticated clocks based on the systems mentioned above have standard RS 232 or NMEA outputs. Unfortunately, most of them are rather expensive.

There are many manufacturers of GPS receivers. They are made primarily for navigation. Most of them have a standard NMEA or RS 232 output which allows for easy construction of a clock. In Figure 6.3 we give an example of the use of a standard GPS receiver as a self-made observatory clock. In our example the time signal from the GPS receiver is fed to a microprocessor. It is programmed to produce the time using a stable frequency from an auxiliary oscillator. The processor is programmed to compare the processor time with the exact time of the GPS, when available, and to correct the processor time. The PC used for data collection receives the correct time from the processor. It also receives the exact minute pulses which are used to make the correction of the PC-clock more accurate, because the time through the RS 232 may not be accurate enough. Programming the PC to correct its internal clock to the exact time when collecting data simultaneously from the channels of the magnetometer may not always be easy, depending on the computer.

The clock presented in Figure 6.3 is actually a rather simple and accurate central clock which can be used for several purposes at the observatory. If its oscillators are accurate enough, the output frequency may be used for controlling and adjusting the proton magnetometer, for example.

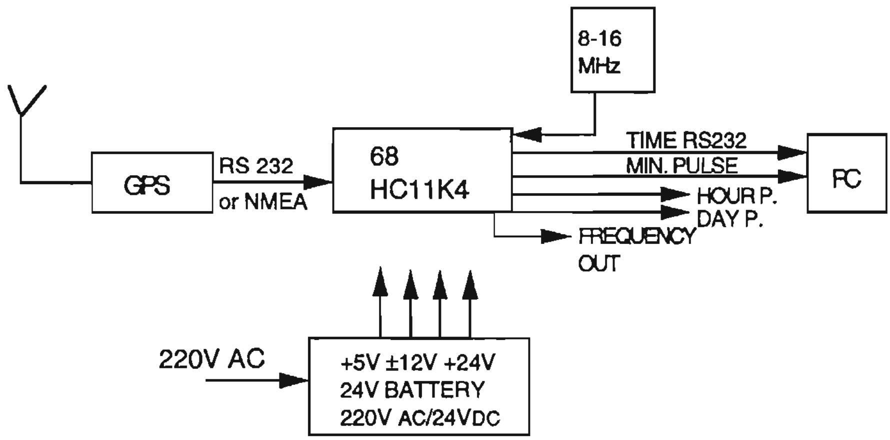


Figure 6.3. Central clock system for an observatory. The accurate time is received from Global Positioning System (GPS) satellites using a standard GPS receiver.

6.5 Digital recording

For recording data in digital form some general requirements can be given:

- ° The capacity of the storing unit should be at least one megabyte, which means that the capacity is sufficient for about 10 days if 10 s data are stored with a resolution of 0.1 nT.
- ° The accuracy of time has to be at least 1 s for one-minute values, and better for faster sampling.
- ° The dynamic range has to be large enough for the recording of the biggest magnetic storms to be expected in the observatory area. In most areas ±4000 nT is enough.
- ° Changes of the constants like base-line values, sensitivities and temperature coefficients have to be easy to make.
- ° Acquisition and transmission of data have to be possible using standard computer ports (RS 232).
- ° Reading the stored data from the storage medium has to be easy and must not disturb the data collection.

During recent years, several institutes have made their own digital loggers for the collection of geomagnetic data in digital form. Some of these have even been made commercial. The rapid development in processors, personal computers (PC's), lap-top computers and hard discs and even optical discs have opened an enormous variety of possibilities to use commercially available, not too expensive equipment for the data collection. Suitable hardware is easy to obtain in most places, and the main problem lies in programming the processor or the computer. For programming it is best to use professional help, but so that the observer in charge works together with the programmer presenting the requirements for the program and becoming sufficiently familiar with the program that he or she can make changes to the program if needed later. What tasks the program has to perform will be discussed also in Chapter 7.

When applied to geomagnetic work, the commercial PC's have two problems. One is that most of them need power from normal mains, 110 or 240 V ac. As stressed several times, the magnetic recording should not have gaps, and the mains sometimes have interruptions. So for every type of recording we recommend the use of UPS (Uninterruptible Power Supply) or batteries. The laptop computers run on batteries and usually do not use as much power as the other PC's. Therefore, they are more suitable for recordings at observatories in many cases. But the development in this field is rapid; for example, the CMOS solid state memories are getting bigger and cheaper every year, so the power consumption probably will be a minor problem in the near future.

The other common problem in commercial personal computers is their poor clock, which means that they do not keep time with the accuracy requested from observatory recordings, as stated in Section 6.4. Therefore, it is very important to introduce an automatic correction to the time of the logger (PC or laptop computer) using time from an accurate clock.

The original signals from variometers are usually in volts, which means that analog to digital (A/D) conversion has to be made before the data can be treated and stored. To be able to record variations of the order of ±4000 nT with a resolution of 0.1 nT, which are realistic figures, that means the sign and 16 bits. Fast (many conversions per second), stable and reliable A/D converters for even more bits are available, and the prices of these are going down all the time, although the best ones are still rather expensive. But because the converters are fast enough, it is possible to use the same converter for all three components and also for the temperature, but we do not recommend it.

The data handling and related problems will be discussed in Chapter 7, complementing this chapter.

6.6 Analog recording

The classical, traditional method of recording the variations of three components of the Earth's magnetic field is photographic. The light from one or more lamps is reflected from the mirrors of magnetometers (one fixed mirror for the base-line and one mirror fixed to the moving magnet) to photopaper which is wrapped on a drum. The drum rotates so that the light spot focussed on its surface moves 20 mm per hour in the direction of the time axis of the magnetogram. The classical photographic recording systems have been described in detail in Wienert's *Notes...* .

The analog photographic recordings have been in use for more than hundred years and are still in wide use. They are reliable and practically no service is needed besides the change of the lamp once a year or so. If a flashing lamp is used, the lamps seem to last many years. Once in, say, five years some service is needed to the clock which drives the photopaper drum. The analog curve on the photopaper is produced by a light beam without any friction in the system, which is an advantage compared to the ink recorders. One shortcoming in the photographic recording is the disappearance of the curve during rapid changes of the field, or, if the rapid changes are made visible, the curve during quiet times is too thick. This shortcoming can be avoided by letting the lamp flash every ten seconds and not letting it be on all the time. Selecting a suitable current for the lamp will not make too thick a trace during quiet time and the points will still be visible during storm. By making the lamp stay on for a longer time every ten minutes and even longer at a full hour, the trace will have the time marks. For the ten-second flashes, the lamp may be on for one second.

Two separate recording systems are recommended for magnetic observatories. The old photographic system may be kept as a supplementary one if funds and space permit. Monitoring the magnetic field in real time is highly recommended, because the observatories should be prepared to answer questions on the behavior of the magnetic field in almost real time. Visualizing digital data at the computer screen as graphs of the components of the magnetic field is naturally one good way to monitor the field. To keep a chart recorder running for the monitoring is also a simple and economic way.

6.7 Comparison of analog and digital recording systems

The shortcomings of photographic recording systems are obvious compared to the digital systems, which have many possibilities for providing a supplementary analog monitoring of the field as well, as can be seen from the following table in which characteristics of photorecorders are compared with digital recorders.

Photographic recording system	**Digital recording system**
o delay in visualizing the data	o data may be monitored in real time
o geometry makes the trace nonlinear	o linear data
o expensive and laborious photopaper	o cheap memory media
o limited dynamic range, two systems needed	o large dynamic range
o crosstalk between sensors in storms	o no crosstalk
o traces overlapping and may be mixed	o no mixing of data possible
o traces may disappear in rapid changes	o no losses because of rapid changes
o difficult to put in machine readable form	o in machine readable form
o necessary to visit the variometer room	o no need to visit the sensor room
o laborious routines	o easy and flexible routines
o reliable, simple construction	o failures rare but may be difficult to repair

7. DATA PROCESSING

The processing of analog data is handled in detail in Wienert's *Notes...* and we shall not discuss it here.

Most recording stations today produce raw data in digital form. That makes the processing of the data easy in principle, only a programming problem. But the whole system of data processing depends on the equipment in use. The formats of data are different, although INTERMAGNET (see Chapter 10) is setting some standards, and so are the World Data Centers. Program languages are quite different and change with time. In practice, the programs needed for data processing at a magnetic observatory are rather large and not easy to produce. In addition to the data collection, the programs have to be able to display the recorded data on the monitor of the computer and treat the data in many different ways, as will be described in detail below.

Here we shall not discuss programming. We only stress the importance of obtaining with new instrumentation the programs needed, including the necessary training in their use. If the programs are not available, it is advisable to contact experienced people from some other observatory having similar instrumentation.

There are two types of programs. There are programs in the data collecting unit controlling the sensors and data capture. Other programs do the data processing and reduction, which may be performed at the observatory or at the headquarters, which may be thousands of kilometers away.

The main tasks of the data processing programs are listed below. The division between tasks performed at the data collection platform and somewhere else depends on local circumstances.

° Filtering the raw data

° Storing the filtered data

° Displaying the data

° Correcting the time (automatic or keyboard operation or both)

° Adjusting the base-line values (keyboard operation)

° Adjusting the sensitivities (keyboard operation)

° Adjusting temperature coefficients (keyboard operation)

° Corrections for orientations of the sensors (keyboard operation)

- Removal of artificial disturbances such as
  – calibration signals
  – spikes
  – clearly seen artificial disturbances

- Filling gaps using data from a second variometer

- Plotting the data

- Preparing tables for the yearbook

- Reformatting the data

- Calculation of *K*-indices

As is obvious from the simple list given above, the requirements for the programming are rather heavy. In addition to the list above, there are some special requirements like alarm functions in case of failures of some parts of the system or discrepant data.

7.1 Sampling rate

There are different sampling rates to be discussed: the sampling of the raw data from the sensors and the time resolution of the final products which will be stored. The distribution of products to the World Data Centers (WDC) and to possible customers is another important consideration. The format should be suitable for the distribution to the WDC's, and, as a rule, to users of the observatory data.

The sampling rate of magnetic data to be stored in data archives is normally one-minute. Many users request, and several observatories store, ten-second or more rapidly sampled data. Technically, it is easy to sample much faster. When a signal is sampled, frequencies above the Nyqvist frequency ($1/2\Delta t$, where Δt is the sampling interval) contaminate those below this frequency; this phenomenon is called aliasing. By sampling rapidly enough, the effect of aliasing can be made small because the power in the geomagnetic field spectrum decreases with increasing frequency. To derive longer-period averages, one-minute values, for example, from more rapidly sampled raw data, a digital filter is used. Probably the most commonly used is the Gaussian filter which is also recommended by INTERMAGNET. Below we describe the Gaussian filter as presented by A. W. Green, Jr. in the INTERMAGNET context.

The Gaussian filter can be described by the Fourier transform pair $f(t)$ and $F(\omega)$, where

$$f(t) = \exp[-(t/\tau)^2/2] \qquad (7.1)$$

$$F(\omega) = \tau \exp[-(\omega\tau)^2/2] \tag{7.2}$$

Both functions have the shape of the Gaussian distribution. At zero frequency ($\omega = 0$),

$$F(0) = \tau$$

and at the –3 dB cut-off point

$$F(0)/\sqrt{2} = \tau \exp[-(\omega\tau)^2/2]$$

or

$$\sqrt{2}/2 = \exp[-(\omega\tau)^2/2]$$

from which $\omega\tau = 0.83255461$.

As an example we form a filter operating on 5-second values to generate 1-minute values. The filter is designed as a low-pass filter with its –3 dB point at a period of 120 seconds:

$$\omega_{120} = 2\pi f_{120} = 2\pi/120$$

$$\tau = 0.83255461 \cdot 120/2\pi = 15.90062182$$

from which

$$f(t) = \exp[-(t/15.90062182)^2/2]$$

Assuming the $t = 0$ coefficient to be 1.0, and requiring the smallest coefficient to be 1% of that

$$f(t) = 0.01 = \exp(-4.605170)$$

which, applying formula (7.1), gives

$$t = 3.03485420 \cdot 15.90062182 = 48.2561\text{s}$$

and

$$F(48.2561) = 0.01 \cdot f(0)$$

For $t = 45$ s we get

$$f(45) = 0.01823029 \cdot f(0)$$

which we consider to be small enough at the end points of our filter. We assumed that $\Delta t = 5$ s in our filter. This means that the filter will have 19 coefficients:

$f(0) = 1.0$	$i = 0$
$f(5) = 0.95176190$	$i = 1$
$f(10) = 0.82056552$	$i = 2$
$f(15) = 0.64084772$	$i = 3$
$f(20) = 0.45337029$	$i = 4$
$f(25) = 0.29054132$	$i = 5$
$f(30) = 0.16866283$	$i = 6$
$f(35) = 0.08869262$	$i = 7$
$f(40) = 0.04224859$	$i = 8$
$f(45) = 0.01823029$	$i = 9$

The coefficients have to be normalized, so that when convolved with the data time series, there will be unity scaling. In other words,

$$\sum_{i=-9}^{i=9} C_i = 1.0$$

$$C_i = k^{-1} f(i) \qquad f(i) = f(-i) \qquad k = \sum_{i=-9}^{9} f(i)$$

$k = 7.949842162$ leading to the final coefficients shown in Table 7.1.

Table 7.1

The Gaussian coefficients of a 19-point filter used by INTERMAGNET for the production of 1-minute values from 5-second values ($C_i = C_{-i}$)

$C_0 = 0.12578865$	$C_5 = 0.03654680$
$C_1 = 0.11972085$	$C_6 = 0.02121585$
$C_2 = 0.10321785$	$C_7 = 0.01115655$
$C_3 = 0.08061140$	$C_8 = 0.00531440$
$C_4 = 0.05702885$	$C_9 = 0.00229315$

The output value has to be centered on the minute which means that the first coefficient C_9 is applied to the 5-second values 45 seconds before and after the minute, and the coefficient C_8 to the values 40 seconds before and after the minute, etc.

To have a concrete example of the processing of digital data at a magnetic observatory we present an outline of the procedure used in Canada (courtesy of the National Geomagnetism Program, Geological Survey of Canada) in Section 7.3.

The most rapid data rate currently recommended by IAGA to be stored is one minute. This is also the greatest sampling rate in data collected by the WDC's at the moment, although the new data storage devices with ever-growing capacity may change this situation. Many observatories are already storing more dense values. They are used for studies of magnetic disturbances and even pulsations.

The hourly mean values in digital systems are calculated from the more dense values during the hour in question, and the annual mean values are the mean values of the hourly mean values. The annual and hourly mean values are, therefore, centered on the middle of the year or of the hour. This is not the case with one-minute values, which, according to the IAGA resolutions, are centered on full minutes. This has led to confusion in timing. Therefore, it is very important to use the same timing system everywhere. The IAGA resolution from Canberra (1979) states:

The first value within an hour is labeled $00^h\ 01^m$ *and is the mean calculated from* $00^h\ 00^m\ 30^s$ *to* $00^h\ 01^m\ 30^s$.

It follows from this that the first hour of a day is labeled 00.

The hourly mean value is the mean of the values taken at 01^m–60^m, or the correspondingly filtered value. The daily mean value is then the mean of the values of the hours 0–23, the monthly mean value is the mean of the daily mean values starting from day 1, and the annual mean value is the mean of the daily mean values of the calendar year. Thus, as a consequence of the different logic, some values start from 00 and others from 01. The disparity is a consequence of the traditional thinking of time as a more step-like function instead of a continuous function, which it naturally is.

The same labeling as that presented for one-minute values is valid for the more dense ones. The one-minute mean value for the minute XX calculated for example from ten-second values is the mean of the values of the times $(XX-1)^m 30^s$–$XX^m 30^s$. The values centered at full ten seconds may be spot values, filtered values or mean values; preferably, however, filtered ones as explained before. Also the one-minute value produced from the more dense values should preferably be a filtered one.

Note: In the INTERMAGNET system the first minute of an hour is labeled 00, and so is the first hour of a day, but the first day of a year is still 01. We prefer the INTERMAGNET practice.

7.2 Base-line values

The base-line value is the value which has to be added to the data produced by the variometer to obtain the final absolute value of the magnetic field component. Usually, the variometer only measures variations within ±4000 nT, which is the range of possible magnetic variations in most areas of the world. Modern magnetometers are so stable that the base-line values change very slowly. The same value with an accuracy of better than 0.25 nT is often valid for weeks. The base-line values are determined in absolute measurements, as described in Chapter 5. In the calculation of final magnetic data, final base-line values have to be used. These are usually obtained by smoothing the results of the absolute measurements over a time of several weeks. It is good practice to plot the result of each absolute measurement on graph-paper. The scale should be sensitive enough, say one or half mm per 0.1 nT. The smoothing can be done by hand. The points should be added to the graph immediately after each absolute measurement to see whether the result fits the general trend. If not, a new measurement should be made, and if that also shows a jump from the normal trend, there may be a real change of the base-line, which should be confirmed with new measurements.

The smooth line through the points represents the final base-line values which should be fed into the computer for the calculation of the final magnetic data. The final data are then stored in the data archives. Spikes and other artificial effects have to be removed from the data before the final storage. Figure 7.1 shows a plot of base-line determinations over a year and the adopted base-lines.

7.3 Removing artificial disturbances

In magnetic recordings there may be artificial disturbances. Spikes may be caused by lightning or other sudden changes of voltage in electronic circuits. They have to be removed from the final data. Calibration signals are necessary but should not be present in the final data. Gaps have to be filled, if possible. Someone may have been close to the variation room on a bicycle, causing a strange looking signal, which has to be removed, for example.

Some of the artificial signals may be removed automatically in the data processing. For example, too rapid changes of the field can be removed by a program. But there is always a risk that a record of an unusual and interesting natural phenomenon will be lost. Therefore, we recommend that the recording is displayed on the screen of a computer in large enough form and the editing of the curve is carried out by an experienced geomagnetician. If possible, there should be the same curve from the secondary variometer visible at the same time very close to the other curve so that it is possible to compare the curves accurately. Programming the computer to do this and to make it possible to remove part of the curve and replace the gap, and other possible gaps, with pieces of the other curve (recorded digital data) is not a trivial task. Such programs exist at some observatories or organizations running magnetic observatories, and we recommend consulting these, especially if they have a similar equipment.

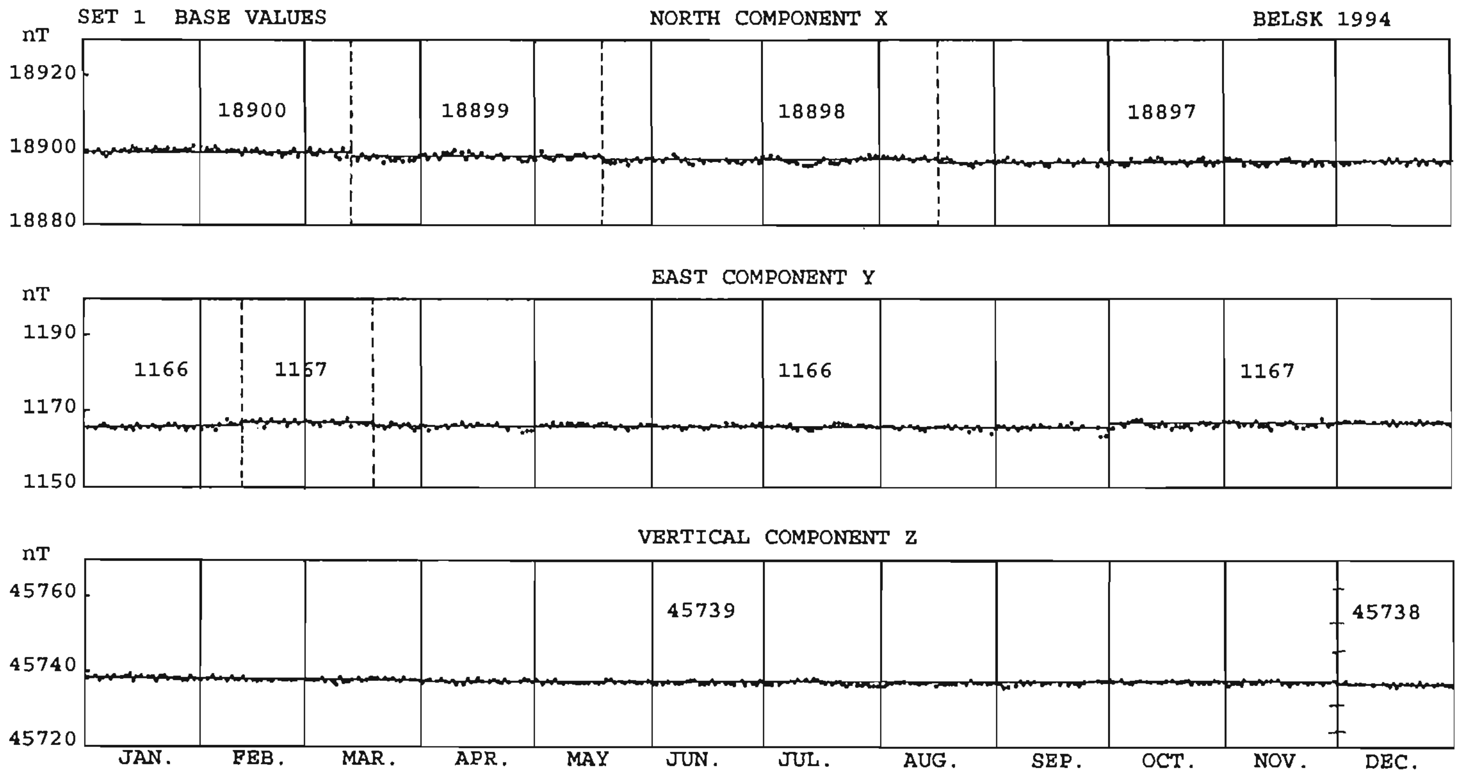


Figure 7.1. Yearly plot of the results of base-line measurements for the year 1994 at Belsk observatory. The full lines show the adopted final base-line values.

As an example of a data sampling system which removes at least the main part of artificial disturbances, we describe the system used at the Canadian observatories.

The CANMOS observatory magnetometer system has a basic sampling rate of 8 Hz. The data are first checked to eliminate spikes:

° If the difference between two consecutive values is greater than 100 nT, the later value is invalidated and the preceding value becomes the reference for the next value.

° For this next value, one uses a consecutive difference of 200 nT relative to the reference.

° If there is no success, the fifth value is taken as good and the sequential verification is restarted.

The 1-Hz data are produced from the 8-Hz data by simple averaging. In case of errors, a single invalid value is permitted; it is replaced by the mean of the two neighboring values. For t, $t+1$, $t+2$, ... etc. seconds

$$H(t) = \frac{1}{9} \sum_{n=-4}^{4} H\left(t + \frac{n}{8}\right) \qquad (7.3)$$

where H denotes one of the recorded geomagnetic field elements.

The following corrections are made to the 1-Hz data for each component:

° multiplication by the scale values

° subtraction of the zero-offset value

° correction for temperature at the electronics (not in use, temperature is maintained constant)

° correction for temperature at the sensor (not in use, temperature is maintained constant)

° correction for errors in orthogonality

° correction for pillar differences

° correction for residual base-lines to reduce the variometer values to those at the absolute pillar at the time of installation.

The 5-second data are produced from the 1-Hz data by applying a 9-point Gaussian filter. In the case of errors, a single invalid value is replaced by the mean of the two neighboring values. For t, t+5, t+10, ... etc. seconds

$$H(t) = \frac{1}{9} \sum_{n=-4}^{4} C_n H(t+n) \tag{7.4}$$

$$C_{-n} = C_n$$

where

$$C_0 = 0.30123004$$
$$C_1 = 0.22657992$$
$$C_2 = 0.09642526$$
$$C_3 = 0.02321702$$
$$C_4 = 0.02321702$$

The 1-minute data are produced from the 5-second data by applying the 19-point Gaussian filter presented above. Again one invalid value is permissible, replaced by a mean from the two neighbors. For t, t+1, t+2, ... etc. minutes

$$H(t) = \frac{1}{19} \sum_{n=-9}^{9} C_n H(t+5n) \tag{7.5}$$

where the coefficients C_n are the same as presented in Table 7.1.

In CANMOS observatories, readings of the total intensity F are taken every 5 seconds and smoothed by applying the same Gaussian filter.

7.4 Dissemination of data

Due to the worldwide scientific interest in magnetic data, IAGA has issued several resolutions concerning forms and formats in which magnetic data should be made available to the international scientific community. Referring to the list of IAGA resolutions on observatory matters copied in Appendix III, we here highlight and comment on the most relevant ones for observatory practice today.

The data which are recommended to be produced and made available for the scientific community in digital form are:

- One-minute values of three components of the magnetic field vector (X, Y, Z preferably, or D, H, Z), calibrated by absolute measurements. F should also be given if recorded with a proton magnetometer.

- Hourly mean values of three components, calibrated by absolute measurements.

In addition, it has been recommended that annual mean values of all days of the year, of international quiet days (five each month selected monthly by the International Service of Geomagnetic Indices, see Chapter 10), and international disturbed days (five each month) be supplied as early as possible, because they form the basis for calculation of the secular variation. This information is needed for updating of magnetic charts, for example.

Many observatories have stopped producing values of international quiet and disturbed days because there are better ways of finding, for example, quiet periods from recorded data using computer methods.

The data are sent to one of the World Data Centers (WDC), which distributes the data or the information on the availability of the data to the other WDC's. The addresses of the WDC's are given in Chapter 10. Usually it is enough to send the data once a year, as soon after the end of the year as possible when the data are in final form. For more dense data than one-minute values and in many cases also for one-minute values it is enough to inform the WDC that data are available and from where. During special international research campaigns, the data may be requested to be more dense and to be sent more often.

Some recommendations exist as to the formats of the data. The WDC's use standard formats in their data exchange. Unfortunately, the precision they use is only 1 nT. INTERMAGNET has clear formats for data transmitted via satellites, via electronic mail, etc. (Trigg and Coles, 1994), which could be used also for other data. Computer specialists claim, however, that changing format is not a problem, and because of the rapid progress in computers and data media the most convenient formats may change. Naturally, a common format facilitates data exchange. Here we give some general features which should be taken into account.

The *resolution* of the digital data in the data exchange has been under discussion without general agreement. Our feeling is that because the accuracy of absolute measurements using modern instruments is clearly better than 1 nT, and the recording instruments easily produce data with higher resolution than 1 nT, the dense values, like one-minute and more rapidly sampled data, should be stored with a resolution of 0.1 nT. There are scientific requirements for this. This means that six digits are the minimum for each component. For the storage of the hourly mean values, a resolution of 1 nT has been used by the WDC's, but also here 0.1 nT could be realistic for the best observatories, where the absolute accuracy already exceeds 1 nT. *So we advise a resolution of 0.1 nT to be used in the data formats in storing the data.*

Depending on the use of data, some people prefer to have the data organized so that all values of one component are stored first for some period which may be one hour, one day, one month or even one year, then the next component for the same time period, and finally the third one for the same period. Other users prefer having all three components following each other for each of the shortest times to be stored. The conversions are not a problem anymore.

The next question discussed in planning formats has been: should whole component values (meaning 6 digits per component) be stored or should a constant part be subtracted first, which saves some room in the data storage media. The high density of modern data media, and the data compression programs available, have made the number of digits used less critical at least in hourly mean values. In one-minute and more dense values the subtraction of a constant part is often done in spite of the fact that these constants are shown to be a source of mistakes in data archives. Even the signs are found to be wrong sometimes. So one has to be very careful in programming the subtraction of a constant. Exceptionally large variations of the magnetic field have to be taken into account. Another method to save space has been to store the whole field value only infrequently, say once each hour, and to store the changes of the field from minute to minute (or from sample to sample in case of more dense sampling). With the capacity of modern mass storage media the space should not be a problem anymore. *Therefore, we recommend the storing of full field values.*

The date and the time have to be stored preferably rather often, say once per hour or at least every day, to avoid problems if some values are missing or there is some confusing error in the data. Having the time stored often enough may save time and trouble in using the data. Universal time (UT or UTC) should be always used (UTC= Universal Time Coordinated, which corresponds to the time at the zero-meridian or Greenwich meridian, very often given in the form UT or GMT).

And finally: in data exchange it is simplest and safest to use the ASCII format.

7.5 Observatory yearbooks

IAGA recommends the publication of recorded hourly mean values and of some combinations of these in the form of yearbooks, in addition to the hourly values sent to the WDC's in digital form. The yearbooks have a long tradition and it is good practice to produce them, because in preparing the yearbook the work from the previous year gets its final touch, including final base-lines, filling of possible gaps using supplementary recording, etc. The yearbooks contain information which is usually not available from the data files.

According to the convention, the yearbook should contain monthly tabulations of the hourly mean values of the three recorded elements of the magnetic field. Daily mean values should be given, and also monthly mean values for each hour. The magnetic element, the possible constant to be added to the hourly values, the unit used, the time used (which should be UT) and also the name of the observatory should appear in each tabulation.

Today, with the data in digital form available from several archives, even more important information in the yearbook is a description of the observatory and of possible changes there during the year. The legend should include at least the geographical coordinates, altitude above sea level, and a short history of the observatory. A description of the measurements of the base-line values, the instruments used, and the results of the absolute measurements are important parts of the description. The instruments used for the production of the data are also described there, also the calibrations, sensitivities, temperature coefficients and the procedure of calculating the data including the filters used. The names of the persons in charge of different parts of the work should be mentioned as well.

In addition to the monthly tabulations of the hourly values, the yearbooks usually contain some useful additional tabulations: the daily variation for each month and for each Lloyd season: Winter (Nov., Dec., Jan., Feb.), Equinox (Mar., Apr., Sep., Oct.), and Summer.

It is useful to include tabulations of annual mean values recorded at the observatory since its beginning. Also, the values for all-day means, means based on the international quiet days, as well as those for the international disturbed days should be given. For the convenience of the users, the observatories usually print the annual mean values of all components, X, Y, Z, D, H, I and F, and not only the recorded ones.

Many observatories scale or calculate the three-hourly activity indices K, which need only a couple of pages of the yearbook and it is convenient to find them in the same place with all the other current information.

Some observatories have started to produce the information discussed above on a monthly basis, in addition to the yearbooks or instead of the yearbooks. In these monthly bulletins copies of magnetograms (nowadays mostly plots made using the digital data) are published. The monthly bulletins are as a rule made for prompt use. Therefore, the base-line values may not be final, nor the quiet and disturbed days. With the modern stable recording instruments and excellent instruments for base-line control, the base-line values usually do not need adjustment afterwards by more than 1 nT.

It is recommended to make copies of the magnetograms available. Many observatories send microfiches or microfilms of the recordings to the WDC's on a yearly or monthly basis, if they do not publish them as described above. Some observatories do both. Users of digital magnetic data often like to see a copy of an analog recording for the same time, produced by a different system, because sometimes the digital data show mysterious errors, which are not easy to detect and correct without an independent source.

Many observatories have dropped the publication of yearbooks, because the quantities routinely published in yearbooks are nowadays easy to calculate from computer files of the original observatory data. These data are usually available at the World Data Centers. For reasons given above, IAGA recommends the publication of the yearbooks as a not too expensive way to preserve the very important information on the instrumentation, absolute measurements, treatment of the data, and persons working at the observatory. All information on quality control of the data is of uppermost importance. Also, having the hourly mean values, etc., in a standard form from year to year in similar yearbooks is useful, but not as important as before, because all combinations of data are easy to produce using the data archives and computers. Instead, the yearbooks could present, in addition to the important legend information mentioned above, combinations of the data and deductions from the data, e.g., in the form of plots and figures.

7.6 Activity indices and special events

A measure of magnetic activity is needed for the studies of different phenomena observed in the ionosphere or in the near-Earth space. Therefore, most magnetic recording stations scale from their recordings indices which describe the state of the magnetic field. For different purposes, several indices of magnetic activity have been introduced (see, e.g., Mayaud, 1980). The most commonly produced and used is the *K*-index, which for each three-hour period gives a one-digit number to describe the magnetic activity. The index is quasi-logarithmic, as shown in Table 7.2, and it is based on the amplitudes of the magnetic field variation during the three-hour period. The *K*-index is scaled from the two horizontal components *H* and *D* or *X* and *Y*, and the larger of the scaled amplitudes determines the index. The amplitude is measured by subtracting the minimum value from the maximum value measured from a smooth curve, which represents undisturbed conditions for that time (Figure 7.2).

Table 7.2

The standard scale of K-indices. The ranges are different for different observatories, so that statistically the K-values from all observatories are the same. The scale for an individual observatory is obtained from the standard one by multiplying the values of the standard scale by a factor α, which can be received from the International Service of Geomagnetic Indices (see Chapter 10).

K-value	0	1	2	3	4	5	6	7	8	9
Range	0	5	10	20	40	70	120	200	300	500<

Until recent years observatories have scaled *K*-indices from analog magnetograms by hand, which is the original recommendation by IAGA. Today most of the observatories record digital one-minute or more dense values and have started to

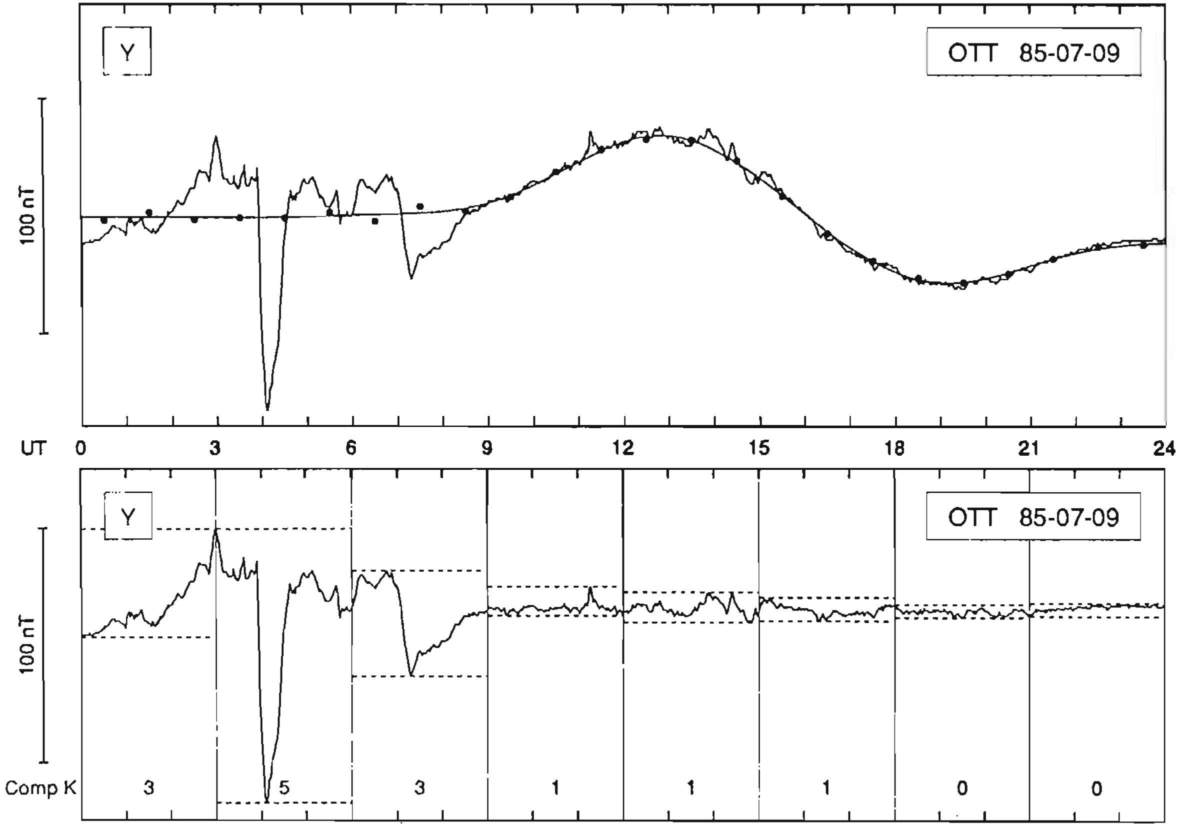


Figure 7.2. Example of scaling the amplitudes of a magnetogram for K-indices. Upper part: fitting S_R to the recorded variations; lower part: scaling of K-indices, after subtracting S_R.

produce the K-indices using computers. Therefore, IAGA, after elaborate testing of different computer methods for the K-production, at its assembly in Vienna 1991 could only confirm that the hand-scaling by experienced observers still is the best method, but that the best computer methods are better than the hand-scaling at most observatories today. We describe here two of the methods shown to give good results.

The only difficulty in computer production of K-indices is the estimation of the so-called S_R-curve (S_R for Solar Regular), which is the imagined curve for the day in question in quiet magnetic conditions. In the method called Adaptive Smoothing (Nowożyński *et al.*, 1991), the S_R-curve is deduced from a least squares fit of one-minute values, with limitations on the second derivatives and with weight factors to make the influence of quiet periods larger than that of the disturbed ones during the 24 or 48 hours long data set (the day in question and 12 hours from the previous and the following day). There are three free parameters to be adjusted (in reality, two of them are the same) for each observatory to achieve the best agreement with the hand-scaled K's.

Another method giving good results is the so-called FMI-method (FMI for Finnish Meteorological Institute) (Menvielle *et al.*,1995). The 24 values (one for each hour) used in producing the S_R-curve are the means of all data points inside each UT hour and $n + m$ minutes on both sides of the hour. The mean is thus the same as the middle point of a line fitted to the values in question. m depends on the local time, and n depends on the magnetic activity ($n = K^{3.3}$ minutes, where K is a preliminary value obtained from the difference: maximum minus minimum). During disturbed times $n + m$ can be so high that the values from the whole previous day or the next day or both are needed for the calculation.

There are other computer programs giving satisfactory results for the production of K-indices. They are available at the International Service of Geomagnetic Indices (for the address see Chapter 10).

The K-indices produced at observatories SIT, MEA, FRD, OTT, HAD, ESK, LER, WNG, LOV, BFE, CAN, EYR (A list of observatories is reproduced in Appendix I) are used to produce the so-called planetary K-indices K_P, which are widely used in many studies of geophysical phenomena. The computation of the K_P-indices and their linear equivalent, the A_P-indices, is carried out monthly at the Institut für Geophysik, Göttingen, for the International Service of Geomagnetic Indices. The K_P-indices have a more dense scale than the K-indices using also values in between and marking them with + or –, e.g., 5+, 6o or 6–. Also, other than the K_P observatories usually send their K-values to the Service of Geomagnetic Indices, which is now in Paris, and also to the WDC's.

There are several other indices describing the behavior of the magnetic field or magnetic activity (Parkinson, 1983). Individual observatories do not produce these indices; they are produced by using *K*-indices from several observatories or by processing other synoptic magnetic data from several observatories. Widely used is the AE-index, which is calculated using data from observatories under the auroral oval and describes the strength of the auroral electrojet, and the D_{st} index, which describes the strength of the ring current around the Earth (see Chapter 2).

According to the IAGA resolutions, magnetic observatories are recommended to select from their magnetograms some special events and report them to the IAGA Service collecting such data. Storm sudden commencements (ssc) should be reported as well as their type, and also solar flare effects (sfe) and other sudden impulses (si).

Classification of the special events can be found in the *Provisional Atlas of Rapid Variations* (1959).

7.7 INTERMAGNET

For many scientific campaigns and also for practical purposes like protecting satellites and protecting electric and electronic systems against induced electric currents during magnetic storms, real-time or nearly real-time global knowledge of the behavior of the magnetic field is needed. For real-time collection of magnetic data from observatories all over the world, a system called INTERMAGNET has been created. Observatories collect their digital data on floppy or hard discs. There are two ways to transmit data to INTERMAGNET: through electronic mail or through satellites (Fig. 7.3). In data collection via satellites, the data are transmitted in a specified format to the nearest geostationary meteorological satellite, which transmits the data to GIN's (Geomagnetic Information Node). The radio frequency used is of the order of 400 MHz. METEOSAT receives the magnetic data once per hour, and the other satellites every 12 minutes. More and more observatories are sending their data to the GIN's via electronic mail.

The INTERMAGNET one-minute data are in 0.1 nT units. The data are collected via satellite in near real-time, and via electronic mail within 72 hours. All details about formats, data, organization, etc., are in the INTERMAGNET Technical Reference Manual obtainable from

INTERMAGNET	or from	INTERMAGNET
c/o U.S. Geological Survey		c/o National Geomagnetism Program
Box 25046 MS 968		Geological Survey of Canada
Denver Federal Center		1 Observatory Crescent
Denver, CO 80225–0046		Ottawa, CANADA
USA		KIA 0Y3

Complete addresses of INTERMAGNET and its GIN's can be found in Chapter 10.

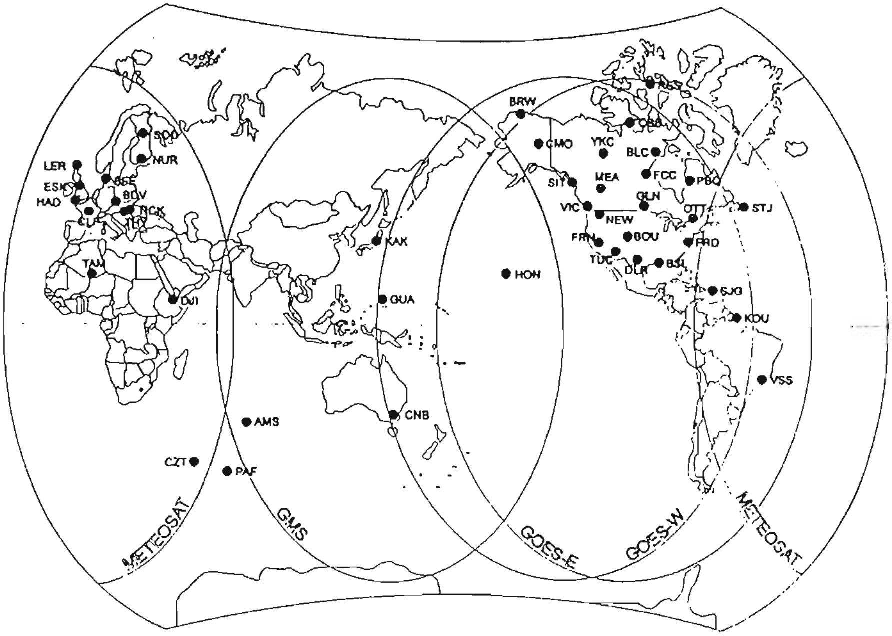


Figure 7.3. The footprints of geostationary meteorological satellites in 1993. Most of the satellites are receiving and transmitting magnetic data in the INTERMAGNET system. The observatories in the INTERMAGNET system in 1993 are also shown.

As an example of formats we give below the INTERMAGNET GIN dissemination format for one-minute values:

Block header (64 characters):

IDC_DDDDDDD_DOY_HH_COMP_T_GIN_COLALONG_DECBAS_RRRRR RRRRRRRRRRRCrLf

where

IDC	IAGA three-letter code for the observatory (see Appendix I).
DDDDDDD	Date, e.g. FEB1591, for February 15, 1991
DOY	Day of the year (1–366).
HH	Hour (0–23). The first line following the header will contain the values corresponding to minute 0 and 1 of this hour. The first value of the day file is hour 0 minute 0.

COMP	Order of components, e.g. *HDZF* or *XYZF*.
T	Data type: *R* = reported (raw data), *A* = adjusted, *D* = definitive.
GIN	Three-letter code for the GIN responsible for the processing of the data.
COLALONG	Colatitude and east longitude of the observatory in tenths of degrees.
DECBAS	Base-line declination value in tenths of minutes East (0–216000). If components are *X*, *Y*, *Z* then *DECBAS* = 000000.
RR ... RRR	Reserved 16 bytes.
_	Space character.
CrLf	Carriage return, Line feed.

Data space (64 characters per line):

AAAAAAA_BBBBBBB_CCCCCCC_FFFFFF_AAAAAAA_BBBBBBB_CCC
CCCC_FFFFFFCrLf

.

.

.

AAAAAAA_BBBBBBB_CCCCCCC_FFFFFF_AAAAAAA_BBBBBBB_CCC
CCCC_FFFFFFCrLf

where

AAAAAAA	Component 1 data field, ('+' sign for positive values optional)
BBBBBBB	Component 2 data field, ('+' sign for positive values optional) In case of *D*, in hundredths of minutes
CCCCCCC	Component 3 data field, ('+' sign for positive values optional)
FFFFFF	Total field data field, (unsigned)

INTERMAGNET has corresponding data formats for hourly and annual mean values and also formats for transmitting data to different satellites, all published in the *INTERMAGNET Technical Reference Manual*.

If an observatory wishes to join the INTERMAGNET system and so to make its data available on a timely basis, and at the same time to get the corresponding data from all the INTERMAGNET observatories on a timely basis, an Application Form is available from the INTERMAGNET addresses above.

The INTERMAGNET organization has strict rules on the quality of data. For the final data, the final base-lines are used, the spikes removed from the recordings, and gaps filled, if possible. All the data collected are copied on CD-ROM's on a yearly basis. The INTERMAGNET CD-ROM's are available from the INTERMAGNET Office, free of charge to all contributing observatories.

7.8 Observatory routine

The routine at a manned observatory differs somewhat from the routine at a partly manned one, although the same checks have to be done at both. In the case of a partly manned observatory, the checks are often done using remote control.

Utilizing computer technology, some important checks are possible on a continuous basis. If there are two independent variometers, the difference of the recorded data can be calculated all the time and an alarm can be given if the recordings differ from each other. The same can be done by comparing readings from a proton magnetometer with the value calculated from the components. An alarm may also be given if one of the temperature sensors shows an unusual value.

Daily at a manned observatory, the routine includes overall checking. This means a check of the normal running of the system, checking of the temperature of the sensor, checking of the data to confirm that they are meaningful. The latter can be done by comparing the recorded data with the reading of a proton magnetometer, if it is not done automatically. It is also good to check the voltage of the batteries. Preferably the data recorded should be shown on the screen of a monitor or displayed in some other way for checking that there are no unusual spikes or gaps in the recording. To put the daily mean values on a graph-paper manually is also a good practice, one new point for each component every day. It is important to check the clock every day. Observatory time (recorder time) is expected to be correct with an accuracy of better than one second.

All adjustments and everything done to the recording system has to be carefully noted in a diary.

Weekly, or more often if needed, the absolute level of the recorded data has to be checked by making absolute measurements. It is important to calculate the results of the absolute measurements immediately after making them. If the result does not fit the recorded data, a new absolute measurement should be done to check that there was no mistake in the measurement. After this, the base-line values of the variometer(s) can be changed. The time of the change of the base-line value has to be carefully recorded. It is convenient to keep the base-lines as close to their final absolute values as possible, so reducing the work in the final adjustment, which is usually done after the end of each year before publishing the annual yearbook and before the final data are archived and sent to the WDC's. The modern instruments are often so stable that the preliminary data may be the final version.

Also the sensitivities (scale values) should be checked once a week unless experience shows that once a month is enough.

Monthly one should check the sensitivities. Usual monthly routine is to print monthly tabulations of hourly mean values, draw daily magnetograms for the month, and calculate monthly means for each hour. The international quiet and disturbed days have usually not been selected at the beginning of the next month for the previous month, but many observatories select their own five quiet and five disturbed days and also include these preliminarily selected days in their tabulations. The K-values for the month are also tabulated. Several observatories publish the monthly tabulations and send them to the World Data Centers. Other observatories send to the WDC's the tabulations and copies of magnetograms as microfilm or microfiche.

For a classical observatory with analog recordings, a very detailed description of the observatory routine can be found in Wienert's *Notes on Geomagnetic Observatory and Survey Practice.*

8. TESTING AND CALIBRATING INSTRUMENTS

The testing and calibrating of instruments is an essential part of all measurements, especially important in observatory practice where the user of data has to be able to trust in the given absolute accuracy. As mentioned in previous chapters, modern instruments are capable of measuring the field components with an absolute accuracy of 0.1 nT. To meet this high requirement, careful testing and calibrations are needed. Therefore, rather regular international comparisons and tests have been arranged for both absolute and recording instruments (see, for example, Kauristie *et al.*, 1990b).

8.1 General connection between field-component variations and the output of variometers

Normally, a magnetic variometer recording three orthogonal elements of the magnetic field has three sensors. As a rule, one sensor is vertical and one of the horizontal sensors is pointing towards the geographic or geomagnetic north and the third is perpendicular to the plane containing the other two. In field work and, for example, in sea bottom magnetometers, any orientation is acceptable. It is only necessary to know the azimuth of the variometer. In all recording practice it is necessary to know the corrections to the data if the sensors are not orthogonal.

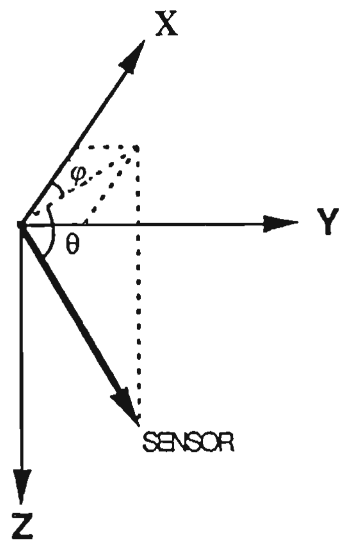


Figure 8.1. The direction of one magnetometer sensor with respect to the geographical coordinate system used in geomagnetism.

Let the angle between the horizontal plane and the direction of the sensor be θ and the angle in the horizontal plane between the projection of the sensor and the x-axis be φ (Figure 8.1). In a magnetic field $\boldsymbol{B} = [X, Y, Z]$ the sensor will measure the field

$$F = X\cos\varphi\cos\theta + Y\sin\varphi\cos\theta + Z\sin\theta \tag{8.1}$$

For field variations we can simplify formula (8.1) by taking into account that the angles φ and θ are small in practice (not more than 1°–2°). Let us call ΔF_x the amplitude of the variation in a direction deviating from the X-component by small angles φ_x and θ_x , and similarly ΔF_y and ΔF_z (φ_z may not be small)

$$\Delta F_x = \Delta X + \varphi_x \Delta Y + \theta_x \Delta Z \tag{8.2a}$$

$$\Delta F_y = \varphi_y \Delta X + \Delta Y + \theta_y \Delta Z \tag{8.2b}$$

$$\Delta F_z = \theta_z \cos\varphi_z\, \Delta X + \theta_z \sin\varphi_z\, \Delta Y + \Delta Z \tag{8.2c}$$

or in matrix form

$$\begin{Bmatrix} \Delta F_x \\ \Delta F_y \\ \Delta F_z \end{Bmatrix} = \begin{Bmatrix} 1 & \varphi_x & \theta_x \\ \varphi_y & 1 & \theta_y \\ \theta_z\cos\varphi_z & \theta_z\sin\varphi_z & 1 \end{Bmatrix} \begin{Bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{Bmatrix} \tag{8.3}$$

The output of a variometer is as a rule in volts which are changed to bits by an A/D converter. To get the data in nT, it is necessary to multiply the numbers of bits Δn_x, Δn_y and Δn_z, by scale values ε_x, ε_y, ε_z:

$$\Delta F_x = \varepsilon_x \Delta n_x \qquad \Delta F_y = \varepsilon_y \Delta n_y \qquad \Delta F_z = \varepsilon_z \Delta n_z \tag{8.4}$$

Multiplying equations (8.3) by the inverse of the matrix of these equations (the inverse matrix is computed under the assumption that the second-order terms are neglected) we get

$$\begin{Bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{Bmatrix} = \begin{Bmatrix} 1 & -\varphi_x & -\theta_x \\ -\varphi_y & 1 & -\theta_y \\ -\theta_z\cos\varphi_z & -\theta_z\sin\varphi_z & 1 \end{Bmatrix} \begin{Bmatrix} \Delta F_x \\ \Delta F_y \\ \Delta F_z \end{Bmatrix} \tag{8.5}$$

Taking into account equation (8.4) and changing notation, we have

$$\begin{Bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{Bmatrix} = \begin{Bmatrix} \varepsilon_x & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_y & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_z \end{Bmatrix} \begin{Bmatrix} \Delta n_x \\ \Delta n_y \\ \Delta n_z \end{Bmatrix} \tag{8.6}$$

where $\varepsilon_{xy} = -\varphi_x\varepsilon_x$, $\varepsilon_{xz} = -\theta_x\varepsilon_x$ and so on.

The matrix (8.6) is called the scale values matrix. It has nine elements. For accurate recording one has to know all of them, or to adjust the orientations so that the nondiagonal elements are small enough. In the next sections we shall discuss how to measure all the elements of the scale values matrix (8.6).

8.2 Testing orthogonalities by comparison

The method described below can be used to determine all components of the matrix (8.6), which means that we can compute the diagonal scale values, the orthogonality of the sensors and the orientation of the sensor assembly after the installation of the station. The method is easily used if there is a standard recording station with well known characteristics nearby. It will be more elaborate to collect the needed data from absolute measurements made during a magnetically active day. The method is based on a comparison of recorded natural variations of the magnetic field with simultaneously measured or recorded data which have no systematic errors. Because the natural variations generally have small amplitudes, the data series should be long and a least squares method of data treatment will be necessary.

Let us assume that there is no difference between the sites where the tested recorder is located and where the normal data come from. If not, the true values (x) have to be adjusted to the recording site (f-values). We start from the first of equations (8.6):

$$\Delta X = \varepsilon_x \Delta f_x + \varepsilon_{xy} \Delta f_y + \varepsilon_{xz} \Delta f_z$$

Assuming that we have n measurements with errors denoted by v, we can write in matrix form

$$\boldsymbol{x} + \boldsymbol{v} = \boldsymbol{f\varepsilon} \tag{8.7}$$

where $\boldsymbol{x}^{\mathrm{T}} = \{\Delta x_1, \ldots, \Delta x_n\}$, $\boldsymbol{v}^{\mathrm{T}} = \{v_1, \ldots, v_n\}$, $\boldsymbol{\varepsilon}^{\mathrm{T}} = \{\varepsilon_x, \varepsilon_{xy}, \varepsilon_{xz}\}$,

$$\boldsymbol{f} = \left\{\begin{matrix} \Delta f_{x1} & \Delta f_{y1} & \Delta f_{z1} \\ \cdot & \cdot & \cdot \\ \Delta f_{xn} & \Delta f_{yn} & \Delta f_{zn} \end{matrix}\right\}$$

The unknown quantities ε_x, ε_{xy}, ε_{xz} can be found from the so-called normal equations

$$\boldsymbol{f}^{\mathrm{T}}\boldsymbol{f\varepsilon} = \boldsymbol{f}^{\mathrm{T}}\boldsymbol{x} \tag{8.8}$$

The formula for the mean square error μ is then

$$\mu^2 = \boldsymbol{v}^{\mathrm{T}}\boldsymbol{v}/(n-3) = (\boldsymbol{x}^{\mathrm{T}}\boldsymbol{x} - \boldsymbol{\varepsilon}^{\mathrm{T}}\boldsymbol{f}^{\mathrm{T}}\boldsymbol{x})/(n-3) \tag{8.9}$$

The squares of the mean square errors of the unknowns are equal to the diagonal elements of the matrix

$$\mu^2(f^{\mathrm{T}}f)^{-1} \tag{8.10}$$

Exactly the same procedure should be repeated to find the unknown elements of the second and third row of equation (8.6).

The necessary data for the computation of quantities $\Delta x_1, ..., \Delta x_n$ can be obtained from absolute measurements made during a disturbed day or disturbed days. It is a rather laborious and time consuming way, but has the advantage that it can be accomplished after the installation of the variometer. And every observatory has the facilities for these measurements. The other possibility is to use simultaneous data from another very carefully calibrated and oriented recording station, if available.

The majority of observatories measure only diagonal elements of the matrix (8.6). That procedure is based on the assumption that the nondiagonal elements are negligible. If the variations have to be recorded with high accuracy, say higher than 1%, we cannot assume without checking that the nondiagonal elements of the matrix are small enough to be neglected. An assumption of 1% accuracy means that $\varepsilon_{xy}/\varepsilon_x$, $\varepsilon_{xz}/\varepsilon_x$, $\varepsilon_{yx}/\varepsilon_y$, $\varepsilon_{yz}/\varepsilon_y$, $\varepsilon_{zx}/\varepsilon_z$ and $\varepsilon_{zy}/\varepsilon_z$ are smaller than 0.01. That is fulfilled if the accuracy of the orthogonality is about 0.25°. Such an accuracy is quite difficult to achieve in constructing magnetometers. In any case, the true orientation of the sensors should be checked. The only two ways to achieve an accurate recording are either to use all nine elements of the matrix or to correct the orientation of the sensors so that the nondiagonal elements have no importance. We rather recommend the first solution.

If the variometer has not been installed so that the sensors are close to the correct directions (within 2°), then more complete formulas have to be used for the corrections. Such formulas will be presented in connection with the tests in three-component coils.

In the descriptions of the above procedures we made the assumption that the unknown angles are small. Theoretically this is not necessary, and both procedures can be based on the more exact equation (8.1) instead of equations (8.2). In this case the calculations are more complicated, but it does not matter when using computers which have matrix programs.

The testing of the variometer as described above is highly recommended at all observatories. Especially at low latitudes, however, it may take years before a suitable magnetic disturbance happens to occur at the same time that the observer has an opportunity to make the long series of observations needed. Therefore, it is good to have the instrument tested before installation at an observatory having the necessary facilities. Several observatories today have a sufficiently large and accurate three component coil system suitable for testing the sensor assemblies.

We point out that the testing of the instruments is very important in spite of the fact that the manufacturers of the instruments give values for the sensitivities and the orientations of the sensors. These quantities may have changed in time and during the transportation of the instrument. The test at a standard observatory gives the angles between the sensors and the sensitivities as described above, either by comparing to a standard recording or by testing in a coil system. The test naturally does not give the orientation of the sensor assembly at the place of installation, which may be very far from the test observatory. But if the instruments are carefully transported, the angles between the sensors, and in many cases also the sensitivities, probably remain the same. Note that there is no need to have the sensors really orthogonal and properly oriented. It is enough to know the angles between the sensors and the right directions. Modern data handling systems always have computer capacity available for the calculation of the corrections, in real time if needed. Naturally, it is more convenient to have the true components recorded, thus possibly avoiding mistakes in the long chain of data processing. In practice, it is usually possible to install the sensor assembly so that the vertical sensor is really vertical by leveling the assembly to the same level-readings as at the test observatory where the verticality was adjusted, or by turning the assembly around its vertical axis and adjusting the sensor assembly so that the reading of the vertical sensor does not depend on the orientation. The azimuth orientation can be made very close to correct by turning the assembly to an orientation giving zero for the Y-component (orientation to the magnetic north) or by turning until the Y-component shows the absolute value calculated or measured for the site.

The tests should be made just before the installation of the instrument. The observer in charge and possibly also other persons from the observatory where the instrument will be installed should be present during the tests. The instruments to be installed at temporary recording stations should also be tested the same way as the observatory instruments, at least once before the survey, and always after a possibly rough transportation of the instrument.

8.3 Testing orthogonalities and sensitivities using coil systems

A three-component coil system (see Section 8.7) is very useful in testing instruments, because both sensitivities and angles between the components are obtained in a rather simple measurement. In the coil system it is possible to determine all the unknown quantities without statistical evaluation of the data, as was necessary for the method described in the previous section. The reason for that is that the additional field can be made large enough for the required accuracy. For the sake of completeness, however, we also present a more general approach.

We assume that the three-component coil system is exactly oriented in X, Y, Z, which means that the additional fields created by the coils are directed along the normal coordinate axes, and the angles φ and θ refer to them.

We start again from Figure 8.1 and formula (8.1) but now we will not assume that the angles φ and θ are small. Therefore, the matrix (8.3) will contain the sine and cosine terms from equation (8.1):

$$\begin{Bmatrix} \Delta F_x \\ \Delta F_y \\ \Delta F_z \end{Bmatrix} = \begin{Bmatrix} \cos\varphi_x \cos\theta_x & \sin\varphi_x \cos\theta_x & \sin\theta_x \\ \cos\varphi_y \cos\theta_y & \sin\varphi_y \cos\theta_y & \sin\theta_y \\ \cos\varphi_z \cos\theta_z & \sin\varphi_z \cos\theta_z & \sin\theta_z \end{Bmatrix} \begin{Bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{Bmatrix} \tag{8.11}$$

where ΔX, ΔY and ΔZ are additional fields created by current in the X, Y or Z coil. They also include the changes of the magnetic field during the test. In comparisons without coils the natural changes are the only ones which can be used in the calculations. If the sensors are oriented along the coordinate axes, then

$$\varphi_x = 0 \quad \varphi_y = 90^0 \quad \varphi_z = 0$$

$$\theta_x = 0 \quad \theta_y = 0 \quad \theta_z = 90^0$$

and the matrix takes the form

$$\begin{Bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{Bmatrix} \tag{8.12}$$

In the following we use the procedure described by Häkkinen *et al.* (1990b). It includes the statistics, but in practice, using large coil fields, the statistical treatment is not needed. The test takes only about a quarter of an hour, so it is advisable to repeat the procedure two or three times to check that the scatter of the results is not too high.

Considering the component X we get for ΔF_x

$$\Delta F_x = \varepsilon_x \Delta n_x = \Delta X \cos\varphi \cos\theta + \Delta Y \sin\varphi \cos\theta + \Delta Z \sin\theta \tag{8.13}$$

By making N measurements and recording the readings of the sensor Δn_{xi} and the simultaneous real field values (ΔX_i, ΔY_i, ΔZ_i which are known from the recorded data and the known additional fields produced by the coils), we get the matrix

$$\begin{Bmatrix} \Delta n_{x1} \\ \\ \Delta n_{xN} \end{Bmatrix} = \begin{Bmatrix} \Delta X_1 & \Delta Y_1 & \Delta Z_1 \\ \\ \Delta X_N & \Delta Y_N & \Delta Z_N \end{Bmatrix} \begin{Bmatrix} s_x \cos\varphi \cos\theta \\ s_x \sin\varphi \cos\theta \\ s_x \sin\theta \end{Bmatrix} \tag{8.14}$$

$$\underset{\boldsymbol{d}}{\equiv} \qquad \underset{\boldsymbol{G}}{\equiv} \qquad \underset{\boldsymbol{m}}{\equiv}$$

where $s_x = \varepsilon_x^{-1}$ is the sensitivity of the x-component.

We get the vector $\boldsymbol{d}$ and the matrix $\boldsymbol{G}$ from the measurements. The vector $\boldsymbol{m}$ will be determined using the method of least squares

$$\boldsymbol{m} = \begin{Bmatrix} m_1 \\ m_2 \\ m_3 \end{Bmatrix} \tag{8.15}$$

$$\boldsymbol{m} = [\boldsymbol{G}^{\mathrm{T}} \boldsymbol{G}]^{-1} \boldsymbol{G}^{\mathrm{T}} \boldsymbol{d} \tag{8.16}$$

After the numerical solution of this formula (see, e.g., Menke, 1992) we get

$$\begin{aligned} \varepsilon &= (m_1^2 + m_2^2 + m_3^2)^{-1/2} \\ \varphi &= \mathrm{arc\ tan}\,(m_2/m_1) \\ \theta &= \mathrm{arc\ tan}\left[m_3/(m_1^2 + m_2^2)^{1/2}\right] \end{aligned} \tag{8.17}$$

or

$$\sin\varphi = m_2/(m_1^2 + m_2^2)^{1/2}$$

$$\cos\varphi = m_1/(m_1^2 + m_2^2)^{1/2}$$

This way ε, φ and θ are calculated separately for each sensor. The matrix $\boldsymbol{G}$ remains, however, the same, only $\boldsymbol{d}$ changes when the measurement is made by adding current (and opposite current, etc.) to all three coils in succession.

The angles between the sensors are obtained from the formula of the multiplication of two vectors ($\boldsymbol{a} \cdot \boldsymbol{b} = a\, b \cos\gamma$)

$$\cos\gamma_{12} = \cos\theta_1 \cos\theta_2 - \sin\theta_1 \sin\theta_2 \cos(\varphi_2 - \varphi_1) \tag{8.18}$$

where the sub-indices 1 and 2 stand for two arbitrary sensors.

It is easy to use the same coil system for the orientation of the three-component sensor by the following simple measurement procedure:

The sensor head is first installed in the middle of the coil system so that the Z-sensor is roughly vertical. Then the *Z*-sensor is adjusted into the vertical by changing the leveling so that introduction of current in the *X*- and *Y*-coil does not change the Z-reading. After this has been accomplished, the levels should be adjusted so that the bubbles are in the middle.

The next step is turning the sensor head, keeping the leveling, around its vertical axis until a current in the *X*-coil does not change the *Y*-reading. We now know that the vertical sensor is really vertical (which should be checked again by adding current to the *X*- and *Y*-coil) and the east-sensor is pointing eastward. The east- or *Y*-sensor may still be tilted relative to the horizontal plane. This angle can be determined by adding a known Z-field, ΔZ, in the Z-coil. Then

$$\theta_y = \arc \sin (\Delta Y / \Delta Z) \tag{8.19}$$

where ΔY is the change of the Y-reading. It is good to use both positive and negative additional Z-fields, which may be rather large, thousands of nT. The same method can be used to determine the angle θ_x between the horizontal plane and the X-sensor and the angle φ_x between the X-sensor and the north direction, which is accomplished by adding a known additional field ΔY in the Y-coil:

$$\theta_x = \arc \sin (\Delta X / \Delta Z) \tag{8.20}$$

$$\varphi_y = \arc \sin (\Delta X / \Delta Y) \tag{8.21}$$

The correct east–west direction or north–south direction should be carefully marked on the sensor head to be able to install the sensor correctly at the pillar at the future recording site. If the sensor is small, as often is the case, then it may be difficult to have the direction marked accurately enough. Fixing a mirror to the sensor head is then a possible solution. The mirror should be installed in a known astronomical direction, say east-west, so that a reflection of a laser beam or a view through a theodolite can be used to align it in the final installation.

Naturally the directions of the sensors in the sensor head can also be adjusted in the test procedure described above, if the manufacturer has made it possible.

After orienting the sensor head in the coil system, the sensitivities of the three sensors are determined simply by adding currents alternately in opposite directions to the three coils. Observe that the sensitivities so obtained are the true ones taking into account the small misalignments of the Y- and X-sensors.

The effects of the two components on the third one have to be taken into account using the angles obtained as presented above. Because the angles are as a rule small, less than 1°, it is sufficient to make a linear correction:

$$\begin{aligned} X &= X_0 + \varepsilon_x n_x + b_x(Y - Y_0) + c_x(Z - Z_0) \\ Y &= Y_0 + \varepsilon_y n_y + a_y(X - X_0) + c_y(Z - Z_0) \\ Z &= Z_0 + \varepsilon_z n_z + a_z(X - X_0) + b_z(Y - Y_0) \end{aligned} \tag{8.22}$$

where ε are the scale values, n the raw readings of the magnetometer (measures of the current in the sensor's compensation coil), a, b and c the small factors taking care of the misalignments, and X_0, Y_0 and Z_0 are constant or base-line parts of the field applied in most systems, because the variometers usually only record changes of the field within the limits of the expected largest variations, say ±4000 nT. The formulas (8.22) are the same as those presented in (8.6). There the recorded bit-values were used instead of the changes of the field values as presented here in the corrections. In other words, the factor b_x in (8.22) corresponds to $\varepsilon_{xy}/\varepsilon_y$, etc.

8.4 Testing using a turntable

It is possible to make all the determinations also in the following simple way: A turntable is needed for the sensor assembly. This can be an old theodolite. First, level the turntable carefully so that its axis is vertical. Then place the sensor assembly on the turntable (controlling the leveling of the turntable) so that the vertical sensor is vertical with high accuracy. The sensor assembly has to be adjusted until turning the table does not change the Z-reading. We now know that the Z-sensor is vertical and measures only the Z-component. The levels of the sensor now have to be adjusted so that when installing the sensor at a new place it takes up the same vertical position.

We then turn the turntable until the X-sensor shows zero. The contributions of small deviations of the X-sensor from the north direction and horizontal plane compensate and we get:

$$H \sin\varphi_x - Z \sin\theta_x = 0 \tag{8.23}$$

When turning the turntable carrying the sensor assembly by exactly 180° we get:

$$-H \sin\varphi_x - Z \sin\theta_x = \Delta N \tag{8.24}$$

where ΔN is the reading of magnetometer in nT.

From (8.23) and (8.24) we get the formula for angle θ_x which gives the tilting of X-sensor compared to the horizontal plane.

$$\theta_x = -\arcsin\,(\Delta N/2Z) \tag{8.25}$$

The tilting of Y-sensor, θ_y, will be determined in the same way. For this procedure the offset of the magnetometer should be small.

The angle in horizontal plane between X- and Y-sensors can be measured in the following way: First turn the turntable until the Y-sensor reads zero. In that position the contribution of the Z-field in the Y-sensor is compensated by the contribution of the H-field:

$$Z \sin\theta_y = H \sin\varphi_y \tag{8.26}$$

from which φ_y is solved. Let the reading of the turntable be A_y in this position. The turntable is then turned until the X-sensor shows zero-reading and the reading of the turntable is denoted A_x. Then

$$Z \sin\theta_x = H \sin\varphi_x \tag{8.27}$$

from which φ_x is solved. The deviation of value $(A_y + \varphi_y) - (A_x + \varphi_x)$ from 90^o is the measure of non-perpendicularity.

The measured angle φ_y or φ_x has to be utilized in orienting the sensor assembly at the pillar, which, as presented earlier, has to have the astronomical or magnetic directions marked on top of it. The transfer of the astronomical or magnetic direction to the variation room has been discussed in Chapter 5.

In some magnetometers the sensors are oriented so that there are angles of 45^o between the sensors and the magnetic field, and the readings of the proton magnetometer are used to adjust the base-line values so that the sum of the components is the same as the reading of the proton magnetometer. This is not recommended for two obvious reasons: it is not known in which of the components there may be a change of the base-line, and the proton magnetometer records spikes more often than the other sensors, thus producing erroneous values in the components, if used automatically for checking each reading. On the other hand, this method allows a missing component to be recorded using F and the two remaining components. We recommend the recording of X, Y and Z and independently F with a proton magnetometer. X, Y and Z are preferred over H, D and Z for the reasons discussed in Chapter 3.

Worth mentioning is also the method of recording D and I (actually deviations of the direction to mean magnetic meridian and deviations of the mean inclination angle) with fluxgate sensors combined with a proton magnetometer. This method naturally requires the installation of the sensors so that they show almost zero field, and the D-sensor has to be in the horizontal plane with high accuracy, so as not to record variations of Z; the I sensor correspondingly has to be in the magnetic meridian plane, although here the requirement of accuracy is not as high as in the case of D.

8.5 Testing and adjusting absolute instruments

The checking and testing of the absolute instruments is at least as important as the testing of the variometers. No instruments can be trusted without tests and comparisons.

The proton magnetometer is a typical push-button device, also usually robust and weatherproof, although the new microprocessor-controlled ones are not as simple to use as the previous ones. In observatory use, checking of proton magnetometers is also necessary. In observatory practice one should suspect and check everything.

The first item to test is the sensor which has to be free of magnetic material. If the result is exactly the same regardless of the orientation of the sensor, then the sensor is clean. In addition to magnetic material there might be a small magnetic field from

DC-current running into the coil through the switch of the polarizing voltage source: the switch may not have a sufficiently high resistance. In practice, the field does not cause an error to *F* if the bottle axis is perpendicular to the field vector.

The magnetometer has a crystal oscillator, which is used to measure the Larmor frequency of protons. The frequency of the oscillator may change with time. Therefore, it has to be checked at regular intervals. Also the frequency may be a function of temperature, so that tests have to be made in different temperatures unless the electronics of the proton magnetometer are always kept in the same temperature at the observatory. The test is easy if there is a suitable frequency (about 2 kHz) available from a good crystal clock or some other source with an accuracy of 10^{-6} or better. The frequency can be fed to the bottle by one turn of wire around the bottle. The magnetometer should give the field which corresponds to the frequency. The frequency of 2000 Hz should give the value of 46,974.4 nT. If not, a small correcting factor has to be adopted to be used for the readings of the magnetometer, or the crystal of the oscillator has to be adjusted. This may be a function of temperature. In some cases it may also be a function of the voltage of the magnetometer batteries, which should be checked.

If the magnetometer has a clock, then the checking of the frequency of the crystal is simple by observing the time given by the clock. If the time correction in seconds remains the same after ten days it means that the stability is not less than 10^{-6}. Some magnetometers have different crystals for the clock and for counting the proton frequency, in which case the checking of the clock is not equivalent to the checking of accuracy of the magnetometer. Measuring the frequency of the crystal oscillator with a frequency meter (which are usually accurate to 10^{-7}) is a simple and safe method and is recommended.

Some magnetometers have given slightly different values depending on the sensitivity used or depending on the tuning adjustments for the field (many of the new magnetometers adjust automatically to the field). The manufacturer of the instrument is probably the only one able to correct this. Tests described above reveal the best sensitivities and adjustments to be used.

Almost every malfunctioning of proton magnetometers is connected with the analog part where signals of microvolt amplitude are generated and amplified. Typical reasons for erroneous signals are

- bad contact in the socket
- too high gradient of the magnetic field
- pick-up of external noise.

For all these reasons, the signal-to-noise ratio can be reduced. If there is something wrong in the measurement, clean and dry the socket, move the sensor to another location, and try again. If this does not help, it is necessary to check the signal-to-noise ratio. Some magnetometers have a meter or earphones for that purpose. In any case, an oscilloscope can be used. If the signal-to-noise ratio is too small, the magnetometer needs professional service.

Fluxgate theodolites have sometimes been found to give wrong results. The main reason has been small amounts of iron somewhere, usually in a screw. It is easy to replace the screw with a magnetically clean one. To detect the error is often difficult. In a comparison of instruments, the error may be detected. Measurements with the lower part of the theodolite in different positions may give different results which shows that something is wrong. The parts of the theodolite may also be tested using a fluxgate sensor or a classical instrument and bringing the suspected part of the theodolite close to the sensor. An astatic magnetometer is excellent for testing a weakly magnetic material. Such instruments are available at many classical observatories. An astatic magnetometer consists of two similar magnets which are fixed to a vertical rod in opposite positions. The system is suspended from one end of the rod with a low-torsion fibre. The Earth's magnetic field does not affect the system because the magnets are in opposite positions and have the same magnetic moments. If the piece to be tested is brought close to one of the magnets, the system turns if there is magnetism in the material.

Fluxgate theodolites often have small errors in the adjustments. If the absolute measurements are made properly, as described in Chapter 5, these small maladjustments usually do not cause any errors in the final results. The errors are due to the following reasons:

- The optical axis and the direction of the fluxgate sensor do not coincide.

- There is an offset in the electronics.

- The readings are not linear, which would be necessary in one of the measuring techniques described in Chapter 5.

- The vertical line of the optics is not vertical.

- The optical axis of the theodolite is not perpendicular to the horizontal axis of the theodolite.

In Chapter 5 we described how to calculate the two angles of misalignment between the magnetic axis of the sensor and the optical axis. It is convenient to have the misalignment rather small. The corrections can be made according to the results of the calculations presented in Chapter 5, or the adjustments can be made, for example, in the following way if there is a possibility for making them. Not all commercially available fluxgate theodolites have this possibility.

To begin with, be sure that the magnetic field is quiet, and make the normal determination of the magnetic declination D as described above. Then we know the true magnetic meridian, and we turn the theodolite perpendicular to that (in the east–west position) and with the telescope carefully horizontal at the same time. If the sensor makes an angle α with the direction perpendicular to the magnetic meridian and β with the horizontal plane, and if there is in addition a bias field B along the sensor, then we get in the monitor the reading R instead of zero:

$$R = H \sin\alpha + Z \sin\beta + B. \qquad (8.28)$$

When the theodolite is turned 180° around its vertical axis, we get

$$R = -H \sin\alpha + Z \sin\beta + B. \qquad (8.29)$$

This shows that we have to turn the fluxgate sensor in the horizontal plane (compared to the optical axis) so that the part containing H disappears, which means reducing half of the difference between the two readings of R. That the adjustment has been made successfully has to be checked by repeating the turnings between the east and west positions. Now the term containing H is absent from the formulas above, and we can make the adjustment in the vertical direction. For that we turn the theodolite around its horizontal axis, again by exactly 180°. Now the term containing Z changes its sign, and we adjust the sensor by turning it in the vertical direction so that half of the difference is again compensated. Naturally this operation has to be repeated until one is sure that the Z-term has disappeared.

If the electronics produces an offset and if there is a possibility to adjust it, the adjustment is easily done by making the reading of the monitor zero. The offset is one of the values obtained in the routine calculations of the results from the fluxgate theodolite, as described in Chapter 5.

In practice, the adjustment is not as straightforward as described above, because adjusting the sensor in one direction often changes the other direction, and leads to many rounds of checking and adjustments. A perfect alignment of the sensor with the optical axis is very difficult to achieve, and better than $10'$ is a good result.

More important than a good alignment or a small bias field is that they do not change during the measurement. The sensor may be slightly loose in its holder so that it changes position when turning the telescope. Therefore, it is important to ensure that the fluxgate sensor is properly attached to the telescope and that the sensor inside its holder is properly fixed. Also the possible effect of temperature change to the sensor should be tested, because in some cases the heat from the lamp above the theodolite may cause the sensor to move. When turning the telescope to the down position where the sensor is in shadow it cools and may change its position again. Heating from one side naturally tilts the whole theodolite, but by making the observations as described above the effect is compensated. Direct sunshine is not permitted on the theodolite.

Temperature may have some effect also on the electronics. Therefore, it is best to keep the electronics at the observation temperature long enough before the measurement, and also to turn the power on at least a few minutes before the observations begin.

One also has to test the linearity and make sure that the readings of the fluxgate magnetometer are in known units. This is easily done by turning the theodolite to plus and minus directions from the null position and taking the readings, say, for each minute of arc close to the null position and less frequently farther away. If the angle is α and the field H, then the reading X corresponding to the angle α should be

$$X = H \sin\alpha . \tag{8.30}$$

Sometimes the vertical line of the eyepiece of the telescope is not exactly vertical. This can be checked by moving the telescope in the vertical direction. If this is the case, then one has to align at exactly the middle point of the line where the horizontal line crosses the vertical one. This is a good practice in any case.

It is common to have a small collimation in the telescope which means that the optical axis is not exactly perpendicular to the horizontal axis of the theodolite and not exactly perpendicular to the vertical direction in positions 90° or 270° of the vertical circle. The effect of collimation is compensated totally by taking the readings in up and down positions (see above). Most telescopes have a small collimation error. Therefore, the measurements have always to be made in both positions.

8.6 Comparisons of absolute instruments

Comparisons of absolute instruments were of uppermost importance during the era of quasi-absolute instruments like the QHM. Also the measurement of the magnetic declination at observatories arranging comparisons was found useful because the measurement of declination, in spite of its absoluteness, was difficult as discussed above in connection with the possible sources of error in classical magnetometers.

Today, when making the absolute measurements with the proton magnetometer and the fluxgate theodolite, the comparisons are no longer needed as frequently as before. But they are still useful, as shown by the experiences from the Nordic countries who make comparisons every two years. The enhanced requirements of accuracy (tenth of a nanotesla instead of one nanotesla which used to be the requirement a few years ago) support the continuation of the comparisons. To reach this high accuracy, perfectly working instruments are necessary. Defects have been found during comparisons. The importance of the observers-in-charge to meet each other and to learn from each other's experiences also supports the organizing of comparisons.

The proton magnetometer is often thought to be a fool-proof absolute instrument. Do not trust it without testing. It is best to compare it with a tested proton magnetometer.

The comparison of two proton magnetometers is made simply by putting the sensors on two non-magnetic supports (e.g. wooden chairs or poles of wood) some 20 m apart and making exactly simultaneous measurements with both of them. One series of ten observations is normally enough. After that, the locations of sensors are interchanged and a new series of observations taken. If magnetometer A is known to be right and the mean of its readings at Place 1 is $A1$ and the mean of its readings at Place 2 is $A2$, and the corresponding data of magnetometer B are $B2$ and $B1$, we get for the correction to be added to the F-reading of magnetometer B

$$\Delta F_B = [(A1 + A2) - (B1 + B2)]/2 \qquad (8.31)$$

and the difference of F between the places (Place 1 minus Place 2) is

$$\Delta F_{1-2} = (A1 - A2 + B1 - B2)/2 \qquad (8.32)$$

The comparison of other instruments is carried out by making normal absolute measurements and determining the base-line values for the recording system. If the base-lines of the variometer are correct, then the possible difference is caused by change of the constant of the QHM or, in the case of a fluxgate theodolite, some error in the measurement, impurities in the theodolite (sometimes a screw has been found containing iron), loose sensor which moves when turning the theodolite, etc. Measuring declination with a declinometer has several possible sources of error, as described in the section dealing with classical measurements. The comparisons may show that something is wrong and one has to find the source. In any case, the measurement has to be repeated several times and preferably during at least two or three days before making any final conclusions.

In comparison measurements at magnetic observatories, the final base-line values with the final accuracy which nowadays is about 0.2 nT are not known as a rule during the comparisons. The differences between the different instruments can be calculated immediately during and after the comparisons, and the final adjustments can be made afterwards, as soon as the final base-lines are available.

Naturally, if two or more pillars for the absolute measurements are available and are located far enough from each other, the instruments can be compared directly by making the measurements simultaneously, provided the pillar difference is known. If it is not known, both the pillar difference and the difference in instruments are obtained by applying the same method as in the comparison of proton magnetometers.

8.7 Coil systems for testing magnetometers

Serson (1974) describes several types of coils which could be used in geomagnetic work. His paper presents suitable coil systems for most purposes. Here we only describe some of them. Note that the more sophisticated the coil system, the more sensitive it is for imperfections.

We have already mentioned (Section 5.4) about the circular and square Helmholtz coil systems, which are probably the most popular due to their simplicity. The circular Helmholtz coil system consists of a pair of coils with radius and separation equal to r. It is best to wind the wire on a frame so that there is only one layer. The wire leading the current to the coil system and from one coil to the other and back has to be carefully made so that the wires have exactly the same length and are twisted. This way, their magnetic effect inside the coil system is nullified. There will be a short piece of uncompensated wire at both coils unless the winding has been done as described later in connection with the Alldred and Scollar coil system. Also, having two layers of windings, back and forth, reduces the uncompensated wire to be insignificant. In this case, the mean radius of the windings has to be used as the distance between the coils.

The frame should preferably be made of a material having a small temperature coefficient. Wood and special plastics are good, quartz is excellent but difficult to get and expensive in larger coils. In practice, most frames are made of aluminum or wood, and the temperature is kept stable during the measurement. Wood is sensitive to humidity.

The square Helmholtz coil system is in principle similar to the circular one. The coils are square and the distance between them is now $0.5445L$, where L is the length of the side of the square.

The magnetic field in the middle of the normal Helmholtz coil system (along the axis of the coils) is

$$B = 8\mu_0 In/5 \cdot \sqrt{5}\, r = 899.18\, In/r \text{ [nT/A]} \qquad (8.33)$$

where I = current in amperes, n = number of turns in one winding, r = radius in meters. To achieve a spherical volume (r = 5 cm) inside the coil, in which the homogeneity of the field is 10^{-4} or better, the radius r has to be 52 cm.

The magnetic field of a square Helmholtz coil close to the middle point is

$$B = 4\mu_0 IL^2/\pi(L^2 + 4a^2)(L^2/2 + a^2)^{1/2} \quad (8.34)$$

which at the middle point gives

$$B = 1628.7\, In/L \text{ [nT/A]} \quad (8.35)$$

where I is in amperes, n is the number of turns of the wire in one square, L is the length of one side of the square, and a is the distance (0.5445 $L/2$) to the middle point. The homogeneity corresponds to the homogeneity of the normal Helmholtz coil.

Widely used coil systems giving better homogeneity are Braunbeck and Fanselau coils. Both have 4 circular (square have also been made) coils on the same axis. In the Fanselau system the outer coils are smaller having radius a_1. The two inner ones have radius a_2. The distance from the middle point to the outer coils is d_1 and the corresponding distance to the inner coils is d_2. The ratios are

$d_1/a_1 = 1.107$ $\quad a_2/a_1 = 1.309$ $\quad d_2/a_1 = 0.364$ $\quad d_2/a_2 = 0.278$

The same homogeneous space as with a Helmholtz coil can be obtained with a Fanselau coil having only 1/3 of the radius of the Helmholtz coil. All four coils of the Fanselau coil system have the same number of turns, and the current is the same in all coils. A current of $0.80852a_1$ amperes produces a field of 10^5 nT. A good alternative is a more compact system by Robinson (1983) in which all windings are wound on a tube.

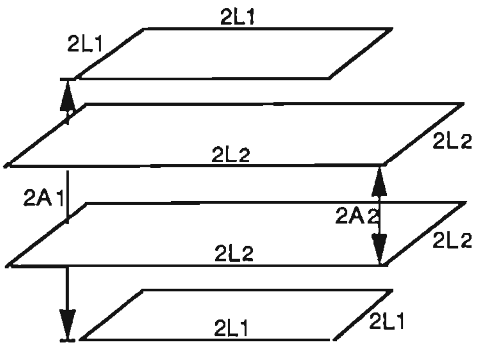
As an example of a three-component coil system which is not too difficult to build we describe a coil system published by Alldred and Scollar (1967) and built at the Nurmijärvi observatory, with dimensions given in Figure 8.2. Figure 8.3 shows the coil system in the test house of the observatory. A detailed description of such a coil at the Nurmijärvi observatory has been published by Häkkinen *et al.* (1990a).

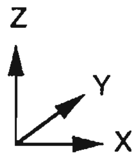
The frame of the Nurmijärvi coil was made of *u*-shaped aluminum. Special care was taken in winding. To avoid uncompensated pieces of wire the coils were wound first in one direction, leaving space for winding back to the point where the winding started. The space was left using extra wire. Only one layer of wire was used.

The sensitivities of the Nurmijärvi coil system having the dimensions given in Figure 8.2 are, according to careful determination using a proton magnetometer at a temperature of 20°C (computed values in brackets)

X:	42.409	(42.404)	nT/mA
Y:	48.252	(48.258)	
Z:	36.965	(36.987)	

In the middle of the coil system, the homogeneous area, having a homogeneity of





	X	Y	Z
2L1	1.8150m	1.5960m	2.0830m
2L2	1.9000	1.6700	2.1800
2A1	1.9960	1.7550	2.2905
2A2	0.5480	0.4810	0.6280

Figure 8.2. The principle of the Alldred and Scollar coil system and its dimensions at the Nurmijärvi observatory. The figures give the dimensions of the X-, Y- and Z-coil. In the outer squares there are 42 turns of 1 mm diameter copper wire. To make the width of the winding at the inner squares and the outer ones the same, 2 mm wire was used in the 22 turns of the inner ones.

10^{-6}, is about 50x50 cm in the plane perpendicular to the axis; in the planes 5 cm away from the middle plane, a homogeneity of 10^{-5} is found in 60x60 cm areas.

A big advantage with the Alldred and Scollar coil (and also with the Fanselau coil) is that there is enough room inside the coil for working with instruments.

It is good to know how strong a field a coil system creates outside the coil. At a distance which is several times the dimension of the coils system, the effect of the system is roughly the same as the field of a magnetic dipole. The magnetic moment m of the pair of coils is

$$m = 2\,nIS\ [\mathrm{Am}^2] \tag{8.36}$$

where n is the number of turns in one coil, I is the current in amperes, and S is the area of the coil. Far from the coil system the field is

$$B_r = 2\mu_0 m \cos\theta / 4\pi r^3 \tag{8.37}$$

$$B_\theta = \mu_0 m \sin\theta / 4\pi r^3 \tag{8.38}$$

where θ is the angle between the axis and the direction to the point P where the field is given, B_r and B_θ are radial and tangential components of the field, and r is the distance between the coil system and point P. In the case when P is on the axis, we

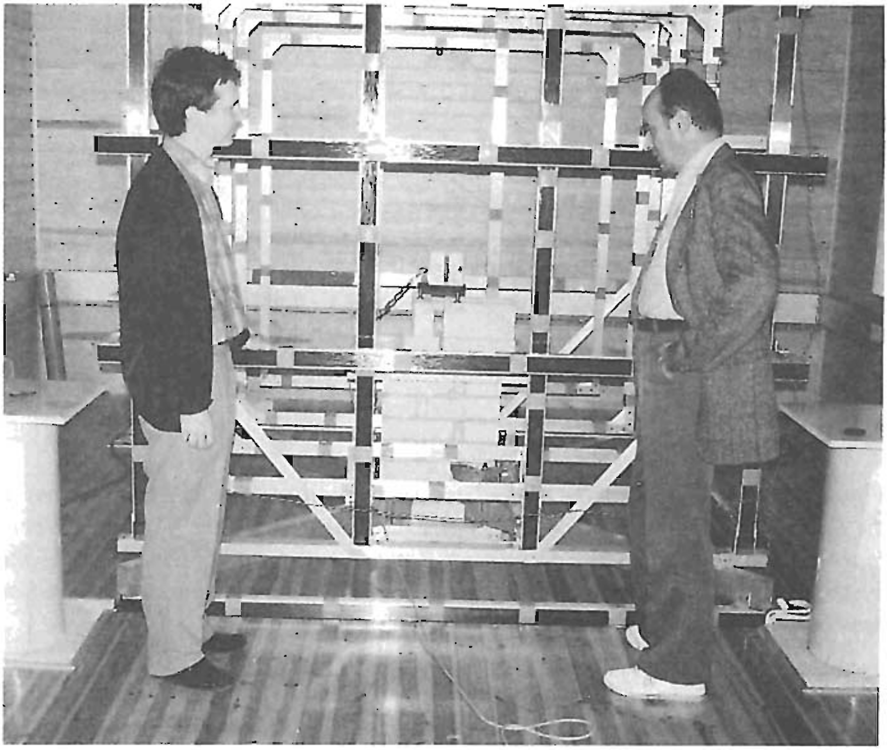


Figure 8.3. Coil system of Alldred and Scolar type at the Nurmijärvi observatory.

get $B_r = 400nIS/r^3$ [nT]. In a perpendicular direction, the effect is half of the above-mentioned one.

For the cases in between, the sine and cosine terms are not equal to 1 and both radial and tangential components have to be taken into account.

The field of the square Helmholtz coil on the axis, far from the coil, is roughly

$$B \approx 400\ InL^2/\ r^3\ [\text{nT}] \qquad (8.39)$$

and half of that in the perpendicular direction. Putting realistic values in the formulas above it is easy to see that one has to be careful in placing the coil systems, especially if they are big ones, used for adjusting instruments. Even Helmholtz coils used in proton vector magnetometers have to be placed at least 30 m from the variometers if an effect of 0.1 nT has to be avoided. An advantage of more compact coils is their smaller external effect.

9. INFLUENCE OF INDUCTION IN MAGNETIC RECORDINGS

In Wienert's *Notes on Geomagnetic Observatory and Survey Practice* the author writes: "The function of a magnetic observatory is to record the short and long term variations of the geomagnetic field in such a way that the information obtained is representative for a large area. This necessitates that at the observatory site (a) the geomagnetic elements are "normal", which means that the geomagnetic field at the observatory is not distorted by anomalies caused by abnormally magnetized geological bodies, (b) the subsoil of the surrounding area is fairly homogeneous in electrical conductivity".

Even for old observatories the first condition is usually fulfilled, but as a rule the second is not. There are two reasons for that situation. The first is technical: it is much easier to map the permanent magnetic field than its short-term variations. The other is associated with the nature of the phenomena: it is not so difficult to find an area without a distinct magnetic anomaly, but as we shall see it is nearly impossible to find a place for an observatory with an homogenous distribution of conductivity in the neighborhood. Even now most observatories do not know what is the effect of local inhomogeneities of electrical conductivity on the recorded variations. Generally, the effect of a magnetic anomaly at the observatory site on magnetic variations is much smaller than the influence of induced currents. It is, however, important to note that if a magnetic observatory is on an anomaly, the time variations of D and H are not as representative for larger areas as are the time variations of X and Y (Eleman, 1966).

The magnetic variations recorded at the Earth's surface are caused by two current systems. The first one, called external, is due to currents flowing in the ionosphere and magnetosphere. The other is induced by the variations of the external currents and is due to currents flowing in the conducting Earth.

The amplitudes of the variations caused by these two current systems have the same order of magnitude. Generally, the effect of the external current system is a little bigger, but in some cases the variations due to induced internal currents, especially in the vertical component, may be larger. The external current system is far away from the point of observation because the current is flowing at a height not less than 100 km. The internal currents may flow much closer, which is the reason why the internal part may be more inhomogeneous. Figure 9.1 is an example of such an inhomogeneity. It shows the recording of H, D and Z from nine stations placed 20 km from each other on a line crossing the Carpathian Arc. The shapes of the recordings of the horizontal components are rather similar. The amplitude of the H-component is higher at stations in the middle of the line. But the Z-component shows large differences from station to station and even a reversal in sign in the middle of the line.

Very often a correlation between the H and Z variations can be seen, which means

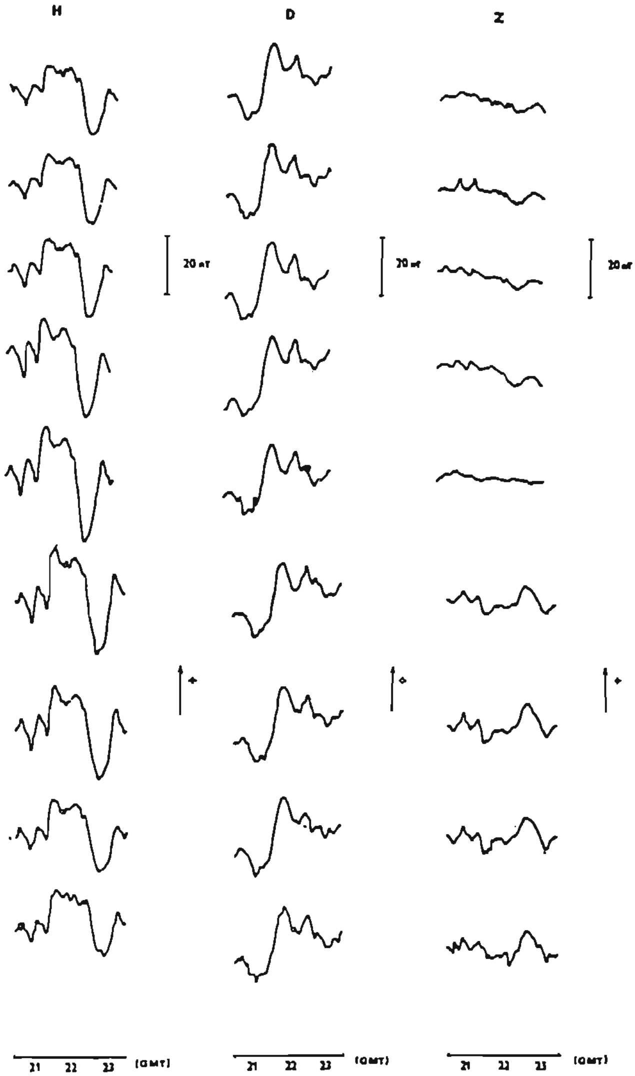


Figure 9.1. Simultaneous recordings at nine stations on a line crossing the Carpathian Arc. The distance between the stations is about 20 km.

that there exists some linear relation between the horizontal and vertical component variations. An approximate formula for the relation is

$$\Delta Z(t) = a\Delta H(t) + b\Delta D(t) = [a,b]\ [\Delta H(t),\ \Delta D(t)] \tag{9.1}$$

and a more exact formula, valid in the frequency domain, reads

$$\Delta Z(\omega) = [a(\omega),\ b(\omega)]\ [\Delta H(\omega),\ \Delta D(\omega)] \tag{9.2}$$

The vector $[a, b]$ is called the Wiese vector or arrow (Wiese, 1962). A very similar definition is given by Parkinson: it is called Parkinson arrow (Parkinson, 1962). The generalized vector $[a(\omega), b(\omega)]$ is known as the induction vector. Its components have complex values.

Figure 9.2. The Wiese vectors for the major part of Europe.

Figure 9.2 shows the Wiese vectors for the major part of Europe. We can see that practically for every measurement point it is possible to calculate a Wiese vector. This means that the influence of regional or local induction is visible on the recording of every observatory.

In the case of Europe, as shown in Figure 9.2, the Wiese vectors are of continental type. If there is a deep ocean nearby, then the effect of the high conductivity of the ocean water dominates the Wiese vectors in the shore areas, the vectors being long, and tending to be perpendicular to the shore line.

The induction effects are mainly studied by making models of the conductive bodies and trying to fit the observations of magnetic variations to the models. Contemporary numerical techniques using fast computers allow calculation of the induction for a two and three dimensional distribution of conductivity inside the Earth. The three-dimensional modeling is usually complicated. A thin-sheet approximation can be used in some cases quite successfully. Figure 9.3 presents the results of the use of a two dimensional model to a large sedimentary basin of known conductivity in homogeneous surroundings having another, known conductivity. This kind of syncline can be responsible for an inland anomaly. The spatial dimension of the anomaly is supposed to be much larger than the width of the basin.

Even a rather small thickness of sediments with high conductivity in surroundings with lower conductivity produces pronounced induction effects. Also in areas without sediments, such as an old crystalline platform, inhomogeneities inside this crystalline rock create induction anomalies.

Model computations show that the elongation of an induction anomaly is, as a rule, much bigger than the characteristic dimension of the geological structure causing the anomaly. It is also generally true that the amplitude of a local induction anomaly decreases with the period, as in the case presented in Figure 9.3.

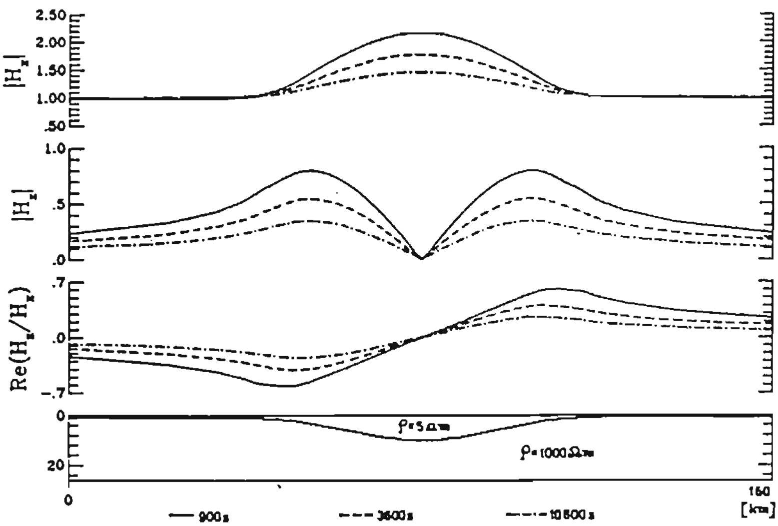


Figure 9.3. Induction effect of a large sedimentary basin. The ratio Z/H is calculated for periods of 900, 3600 and 10 800 seconds.

9.1 Practical consequences

As stated above, the records of every observatory are influenced by induction effects and it is practically impossible to find a location having a "normal" induction effect representative for a large area. Observatory data are used for many kinds of studies. For some of them the induction part embedded in the data is not disturbing, for some it may be, and for some the induction part is what one wants to study. Below we discuss the influence of induction on some specific studies.

1. *Geomagnetic secular variation.* Observatory annual mean values are used for the study of the secular variation. Therefore, local induction effects are smoothed out and the annual mean values are free from the local induction effects.

2. *Magnetic disturbances.* The majority of these studies are based on correlations between solar activity, upper atmosphere dynamics, radio wave propagation, etc., and for all these research areas local induction effects seem unimportant. In the study of the current systems causing the magnetic disturbances, however, the knowledge of the induced part in the recordings is essential.

3. *Magnetic activity indices.* The distortion of the horizontal intensity by induction can influence the index describing magnetic activity. However, the most commonly used index K is supposed to be calculated after adopting a proper range for the index. The range is established so that it statistically agrees with the general pattern of the activity based on global network. Therefore, the induction effect is at least partly taken into account in the choice of the range and is not substantially spoiling the activity index.

4. *Long-period variations (S_q and L).* The effect of local induction decreases with growing period. Due to this, the quiet solar (S_q) and lunar (L) variations are not seriously distorted by local induction. We have to realize, however, that they also have an induction part which is rather large, about one third of the variation, due to the highly conducting layers deep inside the Earth, but this effect is regular and regional. According to model calculations, strong local induction anomalies may have some effect on the higher harmonics of the S_q, but it is not very pronounced.

5. *Reduction of magnetic survey data.* For the accuracy of the field measurements, the induction effect both at the observatory and at the measuring point in the field measurement is harmful. The observatory data are used for the reduction of the survey data to epoch. During periods of disturbed magnetic field, the error in reduction due to local induction effects may be large, especially in the vertical component. As presented in this chapter (e.g., Figure 9.1), it is not possible to tell generally how far away the measuring area can be from the observatory to ensure a proper reduction. The only way to get good results in field measurements is to avoid magnetically disturbed times and to make long series of observations, thus smoothing out the induction effects. For magnetic surveys, a temporary recording station close

to the measuring area is recommended. Detailed information on reduction is to be found in the *Guide for Magnetic Repeat Station Surveys* by Newitt *et al.* (1996).

From all that has been described in this chapter we can conclude that

- The recordings of practically every observatory are influenced by induction in the locally inhomogeneous Earth.
- The vertical component is especially distorted. For some periods its phase can even be reversed.
- The elongation of an induction anomaly is usually large, often amounting to hundreds of kilometers, much larger than the geological structure causing it.
- The local induction effect decreases with increasing period of external field variations.
- Among users of observatory data, those who use the data for reduction of field measurements should be most careful. Periods of high magnetic activity should be avoided in the measurements. A temporary magnetic recording station at the area of measurements is recommended.
- Each magnetic observatory should have knowledge of the homogeneity of the field in its surroundings. One can perform such studies even with one transportable magnetic recording station, by comparing recordings made some tens of kilometers from the observatory in different directions (see Jankowski *et al.*, 1984; Kauristie *et al.*, 1990a).

10. USEFUL CONTACTS AND ADDRESSES

The International Council of Scientific Unions (ICSU) is an international non-governmental body which includes international Scientific Unions in its membership. The International Union of Geodesy and Geophysics (IUGG) is one such member. The International Association of Geomagnetism and Aeronomy, (IAGA) is one of the seven geophysical associations under the IUGG. The other associations are for geodesy (IAG), for seismology (IASPEI), for volcanology (IAVCEI), for meteorology (IAMAS), for hydrology (IAHS) and for oceanography (IAPSO). IAGA is the main coordinator of the collection of geomagnetic data. It has made many recommendations (resolutions) concerning magnetic observatories, the handling of the data, and making the data available. A collection of IAGA resolutions on magnetic observatories is to be found in Appendix III. In this chapter we list some addresses which may be useful in observatory practice.

10.1 IAGA, the International Association of Geomagnetism and Aeronomy

The International Association of Geomagnetism and Aeronomy is the best contact for questions concerning geomagnetic work. IAGA is the largest of the seven associations of the International Union of Geodesy and Geophysics (IUGG), which organizes a general assembly every four years. IAGA also meets in the middle of the period between the general assemblies of the union.

IAGA has five divisions, namely

° I Internal Magnetic Fields

° II Aeronomic Phenomena

° III Magnetospheric Phenomena

° IV Solar Wind and Interplanetary Magnetic Field

° V Observatories, Instruments, Surveys and Analyses

and two InterDivisional Commissions

° History

° Developing Countries

Almost all matters discussed in this Guide are handled by the IAGA Division V, which is further subdivided in special Working Groups (WG). The number of WG's is not fixed and may vary from IAGA meeting to meeting. Also the Chairman of

Division V is usually changed every four years during the General Assemblies. The best contact for all IAGA matters is its Secretary General, who in fact is not permanent either, but usually serves several four-year periods. The names and addresses of the Secretary General and of the Division Chairmen are to be found in IAGA News, which is published before and after each IAGA assembly and sent to most observatories and organizations responsible for observatories.

In each member country of IUGG (78 member countries in 1994) there is a National Committee of IUGG, usually under the Academy of Sciences or its equivalent. This is a good local contact in IAGA matters and has the latest knowledge of IAGA officers, its Divisions and Working Groups and their leaders.

Other good contacts are the World Data Centers (WDC) for geomagnetism, which have permanent addresses. They are helpful and have specialists in different fields of IAGA. They can also help in finding proper IAGA contacts in special matters. The addresses of WDCs are listed below.

10.2 World Data Centers

The following World Data Centers collect geomagnetic data. Their duty is to protect the incoming data, to copy and reproduce data maintaining adequate standards of clarity and durability, to supply copies of data to other WDC's, to prepare catalogs of data, and to make data available to the scientific community. The biggest data centers, WDC A and WDC B2, collect geomagnetic data in all forms: magnetograms on microfilm or microfiche, yearbooks, tabulations, and data in digital form. The others are more specific in their data collection, as presented below.

For all data:

World Data Center A.
NGDC, NOAA, Code E/GCI
325 Broadway, Boulder, Colorado 80303, USA
Tel: (1–303) 497–6513, (1–303) 497–6826
Telex: 592811 NOAA MASC BDR
Fax: (1–303) 497–6513
Email: info@ngdc.noaa.gov

World Data Center B2
Russian Geophysical Committee, Academy of Sciences of Russia
Molodezhnaya 3, Moscow 117 296, Russia
Tel: (7–095) 930–0546
Telex: 411 478 SGC SU
Fax: (7–095) 930–5509
Email: sgc@adonis.iasnet.com

World Data Center D for Geophysics
Institute of Geophysics, Academia Sinica
Beijing, China
Tel: (86–1) 2012497
Telex: 22040 BAOAS CN

For digital data:

World Data Center C1
Division of Geophysics, Danish Meteorological Institute
Lyngbyvej 100
DK-2100 Copenhagen, Denmark
Tel: (3) 4531291100
Telex: 15835 GEOMI DK
Fax: (3) 4531293400
Email: or@dmi.min.dk

For data needed for magnetic charts:

World Data Center C1 for Geomagnetism
Geomagnetism Group, British Geological Survey
Murchison House, West Mains Road
Edinburgh EH9 3LA, Scotland, U.K.
Tel: (031) 667–1000
Telex: 727343 WDDC C1
Fax: (031) 688–4368
Email: d.kerridge@bgs.ac.uk

For digital and space data:

World Data Center C2 for Geomagnetism
Data Analysis Center for Geomagnetism & Space Magnetism
Kyoto University
Kyoto 606, Japan
Tel: 075–751–753–3929
Telex: 5422302 SCIK TUJ
Fax: 075–722–7884
Email: iyemori@kugi.kyoto-u.ac.jp

10.3 International Service of Geomagnetic Indices

The International Service of Geomagnetic Indices (ISGI) is a permanent service of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS). ISGI is responsible for the production and dissemination of the official IAGA indices. At the time of writing of this book ISGI is led by Dr. M. Menvielle and situated at

Laboratoire de Physique de la Terre et des Planetes
Bat. 504, Université Paris Sud
F-91405 Orsay Cedex, France

10.4 INTERMAGNET

The address of the INTERMAGNET organization, collecting digital magnetic data in near real time from many observatories situated in different parts of the world (see also Chapter 7) is

INTERMAGNET
c/o U.S. Geological Survey
Box 25046 MS 968
Denver Federal Center
Denver, CO 80225-0046, USA

Richard Coles
Geological Survey of Canada
National Geomagnetism Program
1 Observatory Crescent
Ottawa
Canada K1A 0Y3

The INTERMAGNET organization has, as presented in Chapter 7, Geomagnetic Information Nodes (GIN), which collect one-minute magnetic data from observatories and distribute the data to customers (free of charge to observatories which are members of INTERMAGNET). The addresses of the GINs are

USGS – USA:
Donald C. Herzog
U.S. Geological Survey
Box 25046 MS 968
Denver Federal Center, USA
Fax: 1–303–273–8450
Email: gol_manager@gldfs.er.usgs.gov

IPG – France:
François-Xavier Lalanne
Institut de Physique du Globe de Paris, Departement des Observatoires
75252 Paris Cedex 05, FRANCE
Telephone: 33–1–44–27–49–27
Fax: 33–1–44–27–24–01
Email: par_manager@ipgp.jussieu.fr

GSC – Canada:
Gerrit Jansen van Beek
Geological Survey of Canada
National Geomagnetism Program
1 Observatory Crescent
Ottawa, Ontario, CANADA
K1A 0Y3
Telephone: 1–613–837–1067
Fax: 1–613–824–9803
Email: ott_manager@qnx4a.geolab.emr.ca

Japan:
Toyohisa Kamei
WDC-C2 for Geomagnetism
Faculty of Science
Kyoto University
Kyoto 606, JAPAN
Telephone: 81–75–753–3937
Fax: 81–75–722–7884
Email: toyo@kugi.kyoto-u.ac.jp

BGS – Scotland:
Simon M. Flower
Geomagnetism Group, British Geological Survey
Murchison House, West Mains Road
Edinburgh EH9 3LA, UK
Telephone: 44–131–667–1000
Fax: 44–131–668–4368
Email: e_gin_manager@unixb.nerc-murchison.ac.uk

Complete information on INTERMAGNET is to be found in the *INTERMAGNET Technical Reference Manual*, which is available from the INTERMAGNET address above. The *Technical Reference Manual* also includes forms for INTERMAGNET membership application.

11. MISCELLANEOUS

Magnetic observatories are places where people expect to get information and advice on a variety of matters, more or less closely connected to geomagnetism. We therefore discuss below some of the most common items.

11.1 Micromagnetics

Officers at a magnetic observatory are quite often approached by individuals or by institutions and asked to find buried objects. The proton magnetometer is a good and rather sensitive instrument for that purpose and can detect an anomalous body even at depths of several meters or deeper, depending on the body and its size. Its capabilities should not be overestimated, however. The formulas discussed in Appendix IV can be of some help in answering questions on whether or not the object is detectable applying the magnetic method. The information about a hidden body is very often scarce, so that before measurements at the site one usually cannot be sure whether the anomaly can be revealed.

In planning the measurements it is necessary to keep in mind that the depth of the anomalous body is always proportional to the width of the anomaly. In the case, for example, when the body is buried only a few meters under the ground, as is typical at archeological sites, the distance between the measurement points should not be more than one meter. Because you can expect the anomaly to be small, only a few nT, data reduction is needed. If there is a magnetic observatory in the surroundings, its data may be used for the reduction. Another proton magnetometer, preferably a recording one, is best for the reduction. Another solution is to use a magnetic gradiometer, which consists of two sensors for the measurement of the vertical gradient.

After concluding measurements in an area, it is necessary to draw a map. In the literature on geophysical prospecting, one can find descriptions on the interpretation of magnetic anomaly maps (e.g., Grant and West, 1965). In this connection, we can only determine the location of the anomaly. We wish to stress that the maximum of the anomaly does not correspond exactly to the underground position of the body and this is due to the fact that the magnetic field is normally not vertical.

11.2 Geomagnetism and biology

The present knowledge about the influence of the geomagnetic field and its variations on animals and human beings is very limited. People living in big cities experience variations of the magnetic field with amplitudes comparable to magnetic storms all the time. No correlation has been found between human behavior and the magnetic field. But there are so many modes of electromagnetic radiation with different frequencies that the question is still open.

That some animals like pigeons use the geomagnetic field for navigation has been reported in the literature and some influence of the magnetic field on their navigation has been proved. Magnetic activity is reported to affect the navigation, and observatories have been asked for information on magnetic activity, because pigeons are claimed to be lost during high magnetic activity. Because modern technology allows continuous monitoring of the magnetic field and its activity, we recommend the observatories to be prepared to answer questions concerning magnetic activity. Some information on this matter will be presented in a later section.

Turtles have also been shown to utilize the magnetic field in finding the way from their place of birth in the Caribbean area to the Sargasso Sea. They are shown to use both declination and inclination in their navigation. Some bacteria living close to the bottom of seas seem to use the geomagnetic field to find their way to the bottom.

11.3 Influence of magnetic activity on radio communications, satellites and power lines

The influence of big magnetic storms on radio communication has been well known for many decades. Short wave radio communication is in many cases impossible during magnetic storms, and the strong inhomogenous ionization of the low ionosphere in the polar cap area may totally prohibit radio communication through that area. During magnetic storms, auroras are seen in unusually low latitudes.

Professional organizations have access to continuous ionospheric data, but radio amateurs often ask magnetic observatories about magnetic activity when they experience difficulties in their radio communications. Visual recording of the magnetic field is therefore important at the observatories, for the real time service if needed.

The real-time knowledge of the behavior of the magnetic field has been needed sometimes in critical situations, when there has been power failure in large areas. Induced currents during an unusually strong magnetic storm have sometimes been the reason. To find the reason for a power failure the power companies often contact magnetic observatories. The automatic safety systems of railways are also shown to suffer from induced currents during severe magnetic storms. Some railway companies have even installed their own monitors which give an alarm if the field shows unusual activity. Observatories could perhaps offer this service more cheaply and more professionally.

Satellites are very important for modern society, and failures in their operation may cause trouble in many activities. During magnetic storms, radio communications between satellites and ground stations may suffer. Control of the orientation of the satellites has in some occasions been lost due to missing instructions from the ground, and the satellites have started uncontrolled movement. During magnetic storms also the upper layers of the atmosphere are heated by particle precipitation and expand. The expanded atmosphere increases friction on low-level satellites, thus shortening their lives and changing their orbits. Because of the known effects of the magnetic storms on satellite operations, observatories are the places where the satellite people expect to get an answer to the question whether the magnetic activity might be the cause of the observed trouble.

Naturally, other conductors like telephone cables and gas pipelines also experience induced voltages during variations of the magnetic field, and observatory staff may be asked how much voltage can be expected between two earthing points. A very rough answer is several volts per kilometer in severe storms, more at high latitudes and less at low latitudes. Lines in the E-W direction are more affected than the N-S lines, because the inducing currents in the ionosphere are mainly running E-W or vice versa, especially at high latitudes. In buried pipelines the induced voltage between the ground and the pipe accelerates corrosion. Therefore, gas pipe-lines are usually kept at a lower potential than the surrounding ground.

11.4 Prediction of magnetic activity

Observatory staff are sometimes asked to predict magnetic activity, which is quite natural due to the many negative consequences of magnetic storms discussed above. Sometimes predictions are asked for positive purposes also: tourists may ask for a suitable time to visit high latitudes to observe auroras.

Unfortunately, the prediction of magnetic activity is very difficult. There are some statistical results: magnetic storms are more probable during high solar activity, which means sunspot maximum time and especially the time a couple of years after the sunspot maximum. But a big magnetic storm may happen also during the lowest sunspot period. The equinoxes are more favorable for high magnetic activity than other parts of the year. Big magnetic storms also have some tendency to be repeated in some form after 27 days, which is the time for the Sun to rotate so that the same active area of the Sun points towards the Earth again. Also the day following a storm is very often rather active.

Table 11.1
The solar activity report of 14 February 1994.

```
15.02.1994 09:11:26                 14FEB94_FORECAST.TEXT

JOINT USAF/NOAA REPORT OF SOLAR AND GEOPHYSICAL ACTIVITY
SDF NUMBER 045 ISSUED AT 2200Z ON 14 FEB 1994
IA.  ANALYSIS OF SOLAR ACTIVE REGIONS AND ACTIVITY FROM 13/2100Z
TO 14/2100Z:  SOLAR ACTIVITY WAS VERY LOW. REGION 7671 (N10E65)
FEATURES A LARGE, DARK, SPOT EXTENDING OVER THREE DEGREES.
IB.  SOLAR ACTIVITY FORECAST:  SOLAR ACTIVITY IS EXPECTED TO BE
VERY LOW.
IIA.  GEOPHYSICAL ACTIVITY SUMMARY FROM 13/2100Z TO 14/2100Z:
THE GEOMAGNETIC FIELD HAS BEEN AT UNSETTLED TO MINOR STORM
LEVELS AT MID-LATITUDES AND MAJOR STORM LEVELS AT HIGH
LATITUDES. THE STORM WHICH BEGAN 05 FEBRUARY CONTINUES AT HIGH
LATITUDES, BUT APPEARS TO HAVE RECEDED AT MID-LATITUDES. THE
ENERGETIC ELECTRON FLUX IS ELEVATED FOR THE SEVENTH DAY
IN A ROW.
IIB.  GEOPHYSICAL ACTIVITY FORECAST:  THE GEOMAGNETIC FIELD IS
EXPECTED TO RANGE FROM UNSETTLED TO MINOR STORM FOR DAY ONE.
THE FIELD IS EXPECTED TO RELAX TO MOSTLY UNSETTLED LEVELS
FOR DAY TWO. A NEW CORONAL HOLE MAY DISTURB THE MAGNETIC FIELD
ON DAY THREE.
III.  EVENT PROBABILITIES 15 FEB-17 FEB
CLASS M     05/05/05
CLASS X     01/01/01
PROTON      01/01/01
PCAF        GREEN
IV.  PENTICTON 10.7 CM FLUX
OBSERVED            14 FEB  101
PREDICTED   15 FEB-17 FEB  100/105/105
90 DAY MEAN         14 FEB  106
V.  GEOMAGNETIC A INDICES
OBSERVED  AFR/AP 13 FEB  030/028
ESTIMATED AFR/AP 14 FEB  025/028
PREDICTED AFR/AP 15 FEB-17 FEB  020/020-010/012-015/018
VI.  GEOMAGNETIC ACTIVITY PROBABILITIES 15 FEB-17 FEB
A.  MIDDLE LATITUDES
ACTIVE                 35/25/30
MINOR STORM            20/15/20
MAJOR-SEVERE STORM     05/05/05
B.  HIGH LATITUDES
ACTIVE                 35/25/30
MINOR STORM            25/15/20
MAJOR-SEVERE STORM     05/05/05
```

Much work is going on for developing predictions of magnetic activity. For this purpose the Sun is monitored continuously by radio methods and by observing its spot areas and areas of eruptions. Using this information a prediction of effects on radio communication and magnetic activity for the coming days is made every day in several countries, including USA, Canada, France, Australia, etc. The forecast from USA (USAF/NOAA) looks as shown in Table 11.1. The forecast can be received from the Space Environment Center (SEC) in Boulder, Colorado, via electronic mail.

Observatories are advised to get access to this information, which may help in answering some normal requests in observatory routine. For observatory work itself this information may be helpful, e.g., in planning absolute measurements in quiet field conditions or measurements in disturbed conditions for special purposes, like checking base-lines or orientations of the sensors, as presented in Chapter 8.

12. A FORWARD LOOK

Looking back in time, and realizing the rapid development of instruments and methods in geomagnetic work during the last two or three decades, it is unrealistic to believe that a prediction of the future would be correct. But based on the instruments of today and on the knowledge of requirements and possibilities to fulfil them, it is possible to imagine an ideal situation. We shall try to give such an idealistic view.

12.1 Uses of geomagnetic data

The demand for magnetic data during the next twenty to thirty years looks similar to that at the time of the writing of this Guide. We see no clear change in the uses in science; the principal problems connected to core motions and dynamo theory still await solutions, as presented in the Introduction, and the demand for data in connection with space physics and ionospheric studies will be similar or greater than it is today.

Many scientific studies of ionospheric phenomena will need an up-to-date geomagnetic coordinate system, based essentially on a knowledge of the changes of the field obtained from observatory data.

Future international geomagnetic reference fields (IGRF) and magnetic charts will need a knowledge of the secular variation, and the magnetic observatories will continue to provide that information.

In the near future, the main part of large-scale magnetic surveys will be probably made using low-altitude magnetic satellites. This requires a properly distributed network of magnetic observatories, for checking, calibration, and reduction. In the future, more local magnetic charts will also use the knowledge of secular variation based on observatory data for updating the charts.

Global indices of magnetic activity and other parameters describing the magnetic field will continue to be needed in the future for many applications. Increasingly, more timely production and dissemination of these indices and parameters are being demanded. Applications include satellite operations and experiments, where magnetically active periods contribute to enhanced drag, electrostatic charging, and problems with radio telemetry. Knowledge of the state of the magnetic field is important for studies of induction effects on power systems and pipelines, and for understanding problems in conventional radio communications.

For navigational purposes, an up-to-date knowledge of the magnetic declination will be also needed in the future, as a safe and simple method complementing the more sophisticated systems.

Observatory data may be used in seismically active areas to help in predicting earthquakes.

Disturbances of the magnetic field seem to have biological effects. As mentioned in the previous chapter, pigeons seem to be sensitive to magnetic disturbances, and current knowledge of the magnetic activity and predictions of the magnetic activity are shown to be valuable for the pigeon racers. Other biological specimens seem to utilize the Earth's magnetic field for orientation. Probably in the future the study of biological effects of magnetic fields and their variations will be intensified.

12.2 Future instrumentation

It is still an open question when a magnetometer for absolute measurements will be designed, which can measure and record automatically the variations of the field with a desired sampling rate. We believe that at least the main part if not all of the technical solution already exists. Some instruments already in use nearly fulfill the requirements. For the total field it is the proton magnetometer. For the components of the field, a vector proton magnetometer equipped with tilt recording may be the solution. Sufficiently fast sampling is possible using Overhauser proton magnetometers. Another solution might be the recording of D and I using the fluxgate orientations as in the absolute measurement of D and I by the fluxgate theodolite. Here the tilting should also be recorded.

New magnetometers for observatory use will probably also become available, based on totally new techniques or techniques already available like cryogenic magnetometry (squid-magnetometers) or optical fibre.

After the construction of instruments described above, the whole ideology of operation of magnetic observatories will change. More and more of them will probably be unmanned. The absolute measurements will be needed less frequently. The future variometer system is probably a box, not very heavy, which contains the magnetometers, their electronics, and a compensation for a possible tilting of the pillar. It has stable, thermostat-controlled temperature, in addition to good temperature compensation. The stations will be connected to a global telecommunication network and the data from all stations will be available in real time or in almost real time; the INTERMAGNET system is a good start in this direction. The global magnetometer system will have a common control and quality check. It will also have a common time system, so that all data are taken at the same times with an accuracy of 0.1 s.

The trend of designing unmanned observatories is natural, but the authors of this Guide do not support this solution at present time, before the new stations are shown to fulfill the requirements of the scientific and other user communities. Up to now, the data from properly manned observatories are of superior quality compared to the data from the partly manned ones. Additionally, the observatories with staff can be used for other duties, like calibration of magnetic instruments and training, etc.

Actually we can see that technical solutions already exist for taking care of the problems of today's magnetometers. Most of the problems have been described in this Guide, namely

- temperature effects
- tilting of the pillars
- turning of the pillars
- changes of sensitivities
- timing
- quality control
- stability of the base-lines
- greater sampling rates
- greater dynamic ranges
- greater resolutions
- data processing
- transmission of data,

but no single instruments exist in which all modern solutions have been utilized. Because of the relatively small number of recording variometer systems needed, maybe 1000 at most, and the continuous progress in technology, commercially-made complete systems will probably never be available, even in the future. Therefore, recommendations by the IAGA will be of uppermost importance, steering the development of instruments, networks, data and the treatment and transmission of the data.

In this Guide, we have described the instrumentation in use today. Referring to the list of problems given above, we will comment some of the items.

The temperature effects should not be a problem anymore, because the electronics can be made insensitive to temperature variations, the coils in the sensors can be wound on frames having no temperature effect, and the whole system can stay in a stabilized temperature. Naturally, the temperature has to be recorded in spite of all automatic temperature compensations.

The tilt of pillars can be compensated using suspended sensors, or it can be recorded and taken into account in data processing. Suitable tiltmeters are already available.

The turning of the pillar can be reduced by the construction presented in this Guide. The turning is also easy to measure, for example, by observing a light beam reflected from a mirror fixed to the pillar. Gyroscopes can also be used; the modern ones are accurate enough. They are, however, magnetic, and have to be kept at a safe distance from the variometers. Absolute measurements naturally reveal the turning of the pillar.

The sensitivities can be made very stable using high-quality parts in the electronics. This can also be checked automatically, say once a day, by applying an artificial field to the sensor.

Timing is easy using automatic reception of time signals which are available from different sources almost all the time, as presented in this Guide.

Quality control of data is possible at the observatory or from a remote place using logical tests in data processing, or by comparing to the nearby stations.

The stability of the base-lines can only be checked using absolute measurements, if a really high accuracy is required. The instruments can be made very stable by using the best components available, leading to a drift of only one or two nT per year. A measurement with a proton magnetometer, in addition to the three recorded components, is a good verification, and with the view to the fact that the continuously recording proton magnetometers are becoming more and more reliable, they will be excellent instruments for this purpose.

Higher sampling rates are already possible, even for digital recording of pulsations. The capacities of new data storage devices allow for the storing of very dense data, say tens of samples per second. Probably, the observatories should be prepared for this.

The dynamic range should be great enough to record even the largest possible variations of the field. This is not a problem today.

Achieving greater resolution, such as the value of 0.01 nT required to record magnetic pulsations, is no longer a problem. Although most fluxgates currently in use cannot achieve such a level, sufficiently sensitive fluxgates do exist. Magnetometers that use other principles often have sufficient sensitivity. These include Overhauser proton magnetometers, optically pumped instruments (rubidium, cesium, helium), and some variometers that use classical sensors with electronic feedback. One important feature that some of these magnetometers possess is the ability to measure at high sensitivity over the whole range of frequencies recorded at an observatory.

Data processing is not a problem, in situ or at a remote location, because all modern systems utilize microprocessors. Ready made programs may be difficult to find. Naturally, it would be an advantage if standard data formats were available.

The dissemination of data is already rather easy using electronic data links, and it is becoming easier and faster all the time, so that centralized real-time data collection is in principle already possible, and it will probably be normal routine in the near future.

12.3 Network of observatories

The global network of magnetic observatories is based on observatories which individual countries often set up long ago, to fulfill the local needs. Altogether, there are about 180 permanent observatories. The distribution of the observatories is not optimal from the point of view of field variations. Europe, for example, has a dense network, but very few observatories represent the large oceanic areas. The number of observatories in polar cap areas and in the equatorial belt is too scarce to monitor the variations in those areas where the spatial changes of the field are rapid.

Permanent magnetic observatories have decreased in number during recent years. Increasing numbers of recording stations not supported by regular absolute measurements are in operation. The number of such stations is about four times higher than the number of permanent observatories (see, for example, Green, 1990). These variation stations are used in magnetospheric and ionospheric studies, in studies of conductivity, and in monitoring field variations in seismically active areas. At present, the accuracy of the data from these stations is lower than the accuracy from the observatories, but in the future the difference will decrease. Among those field stations there are also sea bottom magnetometers. Long term operation of these stations is difficult, but technically possible. Installation of sea bottom magnetometers as observatories is probably the most difficult problem to overcome, but the problems are of an economic rather than a technical nature.

We hope that in the future data from variation stations will be transmitted to the same nodes as observatory data, to be accessible to the whole scientific community. This would be major progress given that the number of variation stations is so high compared to the number of observatories, and knowing that for many studies the absolute long term stability of the observatories is not needed. Telecommunications should no longer be a problem, and will improve still further if today's progress continues.

We also believe that, in the future, by applying the new techniques which make the observatories less expensive to build and run, the number of high quality stations in the critical areas can be increased. Technically it is already possible to have an ideal network of magnetic recording stations all over the world, equipped with ideal instruments. In practice, however, such a network may take time to develop, depending on the needs of, for example, satellite operations, and on the willingness of the international scientific community to contribute in the funding of the network.

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APPENDIX I

MAGNETIC OBSERVATORIES

Listed below are magnetic observatories in operation at the beginning of 1993, according to the information available at the World Data Center A. The WDC has also complete lists of addresses of the observatories and of organizations running the observatories. The names of the responsible persons are in most cases available at the WDC (for the address of the WDC see Chapter 10). For the addresses of the observatories, please contact World Data Center A. The last two columns give the first and the last years for which values are available from the WDC's. The data from most observatories are available via Internet.

MNEMONIC	NAME	φ	λ	YEAR	
				FIRST	LAST
ALE	ALERT	82° 30′	297° 39′	1962.5	1992
HIS	HEISS ISLAND (DRUZHNAYA)	80 37	58 3	1960.5	1992
NAL	NEW ALESUND	78 55	11 56	1966.5	1991
CCS	CAPE CHELYUSKIN	77 43	104 17	1935.5	1992
THL	THULE (QANAQ)	77 28	290 46	1956.5	1993
HRN	HORNSUND	77 0	15 33	1979.5	1989
MBC	MOULD BAY	76 12	240 36	1963.5	1993
RES	RESOLUTE BAY	74 42	265 6	1952.5	1993
BJN2	BEAR ISLAND 2 (BJORNOYA)	74 30	19 0	1951.5	1993
DIK	DIKSON ISLAND	73 33	80 34	1933.5	1992
TIK	TIKSI	71 35	129 0	1944.5	1992
BRW	POINT BARROW	71 18	203 15	1933.2	1992
TRO	TROMSO	69 40	18 56	1930.5	1993
GDH2	GODHAVN 2	69 15	306 28	1976.5	1993
CBB	CAMBRIDGE BAY	69 6	255 0	1972.5	1993
ABK	ABISKO	68 22	18 49	1921.5	1991
MMK	LOPARSKAYA	68 15	33 5	1961.5	1988
KIR	KIRUNA	67 48	20 24	1965.5	1993
SOD	SODANKYLA	67 22	26 38	1914.5	1993

MNEMONIC	NAME	φ	λ	YEAR	
				FIRST	LAST
CWE	UELEN (CAPE WELLEN)	66° 10′	190° 10′	1933.5	1992
CMO2	COLLEGE 2	64 52	212 10	1948.5	1992
ARK	ARKHANGEL'SK	64 35	40 30	1985.5	1992
BLC	BAKER LAKE	64 20	263 58	1952.5	1993
LRV	LEIRVOGUR	64 11	338 18	1958.5	1993
YKC2	YELLOWKNIFE 2	62 28	245 32	1975.5	1993
DOB2	DOMBAS 2	62 4	9 7	1952.5	1993
YAK	YAKUTSK	62 1	129 43	1931.5	1991
POD	PODKAMENNAYA TUNGUSKA	61 36	90 0	1969.5	1992
NAQ	NARSSARSSUAQ	61 10	314 34	1968.0	1993
NUR	NURMIJARVI	60 31	24 39	1953.5	1993
LER	LERWICK	60 8	358 49	1923.5	1993
MGD	STEKOLNYY (MAGADAN)	60 7	151 1	1966.5	1992
LNN	VOEIKOVO (LENINGRAD)	59 57	30 42	1948.5	1990
LOV	LOVO	59 21	17 50	1930.5	1991
FCC	FORT CHURCHILL	58 46	265 55	1964.5	1993
BOX	BOROK	58 2	38 58	1977.5	1990
SIT2	SITKA 2	57 4	224 41	1940.5	1992
ARS	ARTI	56 26	58 34	1973.5	1992
KZN	ZAYMISHCHE (RAIFA)	55 50	48 51	1915.5	1992
BFE	BRORFELDE	55 38	11 40	1980.5	1993
MOS	KRASNAYA PAKHRA (MOSCOW)	55 28	37 19	1930.5	1991
ESK	ESKDALEMUIR	55 19	356 48	1908.5	1993
PBQ	POSTE-DE-LA-BALEINE	55 18	282 15	1985.5	1992
NVS	KLYUCHI (NOVOSIBIRSK)	55 2	82 54	1967.5	1992

MNEMONIC	NAME	φ	λ	YEAR	
				FIRST	LAST
KLD	KALININGRAD	54° 42′	20° 37′	1989.5	1992
MEA	MEANOOK	54 37	246 40	1918.5	1993
HLP	HEL	54 36	18 49	1957.5	1991
MNK	PLESHCHENITSY (MINSK)	54 30	27 53	1962.5	1989
WNG	WINGST	53 45	9 4	1939.5	1993
PET2	PARATUNKA	53 6	158 38	1973.5	1989
IRK	PATRONY (IRKUTSK)	52 10	104 27	1959.5	1992
NGK	NIEMEGK	52 4	12 41	1932.5	1993
VAL	VALENTIA	51 56	349 45	1899.5	1993
BEL	BELSK	51 50	20 48	1960.5	1993
HAD	HARTLAND	51 0	355 31	1957.5	1993
KIV2	DYMER	50 43	30 18	1964.5	1992
MAB	MANHAY	50 18	5 41	1933.5	1993
DOU	DOURBES	50 6	4 36	1952.5	1993
LVV	L'VOV	49 54	23 45	1952.5	1992
KGD	BEREZNYAKI (KARAGANDA)	49 49	73 5	1965.5	1988
GLN	GLENLEA	49 36	262 54	1982.5	1993
BDV	BUDKOV	49 4	14 1	1967.5	1992
VIC	VICTORIA	48 31	236 35	1958.5	1993
WIK	WIEN KOBENZL	48 16	16 19	1955.5	1993
NEW	NEWPORT	48 16	242 53	1967.5	1992
FUR	FURSTENFELD-BRUCK	48 10	11 17	1939.5	1993
CLF	CHAMBON-LA-FORET	48 1	2 16	1936.5	1993
HRB	HURBANOVO (O GYALLA, STARA DALA)	47 52	18 11	1890.5	1990
NCK	NAGYCENK	47 38	16 43	1961.5	1993
STJ	ST. JOHNS	47 36	307 19	1969.5	1993

MNEMONIC	NAME	φ	λ	YEAR	
				FIRST	LAST
YSS	YUZHNO-SAKHALINSK	46° 57′	142° 43′	1941.5	1990
THY	TIHANY	46 54	17 54	1955.5	1990
ODE	STEPANOVKA	46 47	30 53	1936.5	1992
CTS	CASTELLO TESINO	46 3	11 39	1965.5	1992
NKK	NOVOKAZALINSK	45 46	62 7	1974.5	1992
OTT	OTTAWA	45 24	284 27	1969.5	1993
SUA	SURLARI	44 68	26 25	1949.5	1993
GCK	GROCKA	44 38	20 46	1958.5	1993
CNH2	CHANGCHUN 2 (HELONG)	44 3	125 12	1979.5	1990
MMB	MEMAMBETSU	43 55	144 12	1950.5	1993
WMQ	URUMQI (WULUMUCHI)	43 49	87 42	1978.5	1990
VLA	GORNOTAYOZH-NAYA (VLADIVOSTOK)	43 41	132 10	1958.5	1992
AAA	ALMA-ATA	43 15	76 55	1965.5	1992
PAG	PANAGYURISHTE	42 31	24 11	1948.5	1991
AQU	L'AQUILA	42 23	13 19	1960.5	1993
TFS	DUSHETI (TBILISI)	42 5	44 42	1938.5	1992
TKT	YANGI-BAZAR	41 20	69 37	1964.5	1992
ISK	KANDILLI (ISTANBUL)	41 4	29 4	1946.5	1992
EBR	EBRO (TORTOSA)	40 49	0 30	1905.5	1983
BMT	BEIJING MING TOMBS	40 18	116 12	1991.5	1992
COI	COIMBRA (ALTO DA BALEIA)	40 13	351 35	1876.5	1993
BOU	BOULDER	40 8	254 46	1964.5	1992
BJI	PEKING 2 (BEIJING)	40 2	116 11	1957.5	1990
ANK	ANKARA	39 53	32 46	1986.5	1992

MNEMONIC	NAME	φ	λ	YEAR	
				FIRST	LAST
SPT	SAN PABLO DE LOS MONTES	39° 33′	355° 39′	1981.5	1993
MIZ	MIZUSAWA	39 7	141 12	1969.5	1993
FRD	FREDERICKSBURG	38 12	282 38	1956.5	1992
PEG2	PENTELI 2	38 5	23 56	1988.4	1993
ASH	ASHKHABAD (VANNOVSKAYA)	37 57	58 6	1959.5	1990
FRN	FRESNO	37 5	240 17	1983.5	1992
ALM	ALMERIA	36 51	357 32	1955.5	1991
SFS2	SAN FERNANDO 2	36 30	353 53	1991.5	1993
KAK	KAKIOKA	36 14	140 11	1913.5	1993
LZH	LANZHOU	36 5	103 51	1959.5	1990
TUL	TULSA	35 55	264 13	1968.9	1989
KNZ	KANOZAN	35 15	139 58	1961.5	1993
AVE	AVERROES	33 18	352 35	1967.5	1993
HTY	HATIZYO (HACHIJOJIMA)	33 4	139 50	1967.7	1993
TUC	TUCSON	32 15	249 10	1910.5	1992
BGY	BAR GYORA	31 43	35 5	1989.5	1992
KNY	KANOYA	31 25	130 53	1958.5	1993
SSH	ZO-SE (SHESHAN)	31 6	121 11	1933.5	1990
WHN	WUHAN	30 32	114 34	1959.5	1990
BSL	BAY ST LOUIS	30 24	270 36	1986.7	1992
SAB	SABHAWALA	30 22	77 48	1964.5	1989
QUE	QUETTA	30 11	66 57	1955.5	1993
LSA	LHASA	29 38	91 2	1957.5	1990
MLT	MISALLAT	29 31	30 54	1960.5	1987
DLR	DEL RIO	29 29	259 5	1982.8	1992
SZT	CANARIAS (SANTA CRUZ DE TENERIFE)	28 29	343 44	1960.5	1992
CBI	CHICHIJIMA	27 6	142 11	1973.5	1993

MNEMONIC	NAME	φ	λ	YEAR	
				FIRST	LAST
JAI	JAIPUR	26° 55′	75° 48′	1976.5	1987
SHL	SHILLONG	25 34	91 53	1976.5	1991
LNP	LUNPING	25 0	121 10	1966.5	1993
KRC	KARACHI	24 57	67 8	1985.5	1993
UJJ	UJJAIN	23 11	75 47	1976.5	1990
GZH	GUANGZHOU	23 6	113 21	1958.5	1990
HVN3	HAVANA 2	22 59	277 41	1984.5	1984
TAM	TAMANRASSET	22 48	5 32	1933.5	1991
CPA	CHA PA	22 21	103 50	1955.5	1991
HON3	HONOLULU 3	21 19	202 0	1961.5	1992
TEO	TEOLOYUCAN	19 45	260 49	1919.5	1993
ABG	ALIBAG	18 38	72 52	1904.5	1992
SJG2	SAN JUAN 2 (PUERTO RICO)	18 7	293 51	1965.5	1992
HYB	HYDERABAD	17 25	78 33	1966.5	1991
MBO	M'BOUR	14 24	343 3	1953.5	1991
MUT	MUNTINLUPA	14 23	121 1	1951.5	1987
GUA	GUAM	13 35	144 52	1957.5	1992
DLT	DALAT	11 55	108 25	1978.5	1992
ANN	ANNAMALAINA-GAR	11 22	79 41	1958.5	1991
SNJ	CHIRIPA (TILARAN, COSTA RICA)	10 26	275 5	1985.5	1986
KOD	KODAIKANAL	10 14	77 28	1902.5	1993
ETT	ETAIYAPURAM	9 10	78 1	1980.5	1987
AAE	ADDIS ABABA	9 2	38 46	1958.5	1989
TRD2	TRIVANDRUM 2	8 29	76 57	1958.5	1992
FUQ	FUQUENE	5 28	286 16	1955.5	1993
BNG	BANGUI	4 26	18 34	1955.5	1991
TUN	TUNTUNGAN	3 31	98 34	1982.5	1987
TTB2	TATUOCA 2	-1 12	311 29	1958.5	1992

MNEMONIC	NAME	φ	λ	YEAR	
				FIRST	LAST
NAI	NAIROBI	-1° 20′	36° 49′	1965.5	1980
TNG	TANGERANG	-6 10	106 38	1964.5	1992
ASC	ASCENSION ISLAND	-7 57	345 37	1993.5	1993
LUA3	LUANDA BELAS	-8 55	13 10	1958.5	1993
PMG	PORT MORESBY	-9 24	147 9	1959.5	1992
ANC	ANCON	-11 46	282 51	1991.5	1992
API	APIA	-13 48	188 14	1905.5	1992
NMP	NAMPULA	-15 5	39 15	1983.5	1984
PTY	PATACAMAYA	-17 15	292 3	1983.5	1991
PPT	PAMATAI (PAPEETE)	-17 34	210 25	1968.5	1992
TAN	TANANARIVE (ANTANANARIVO)	-18 55	47 33	1890.5	1993
TSU	TSUMEB	-19 12	17 35	1965.5	1992
CTA	CHARTERS TOWERS	-20 5	146 15	1985.5	1993
LQA	LA QUIACA	-22 6	294 24	1920.5	1992
LRM	LEARMONTH	-22 13	114 6	1987.5	1993
VSS	VASSOURAS	-22 24	316 21	1915.5	1993
ASP	ALICE SPRINGS	-23 46	133 53	1993.5	1993
HBK	HARTEBEESTHOEK	-25 53	27 42	1973.5	1993
LMM	MAPUTO (LOURENCO MARQUES)	-25 55	32 35	1960.5	1986
PIL	PILAR	-31 40	296 7	1905.5	1989
GNA	GNANGARA	-31 47	115 57	1959.5	1993
HER	HERMANUS	-34 25	19 14	1941.5	1993
LAS	LAS ACACIAS	-35 0	302 19	1962.5	1992
CNB	CANBERRA	-35 19	149 22	1979.5	1993
AMS	AMSTERDAM ISLAND (MARTIN DE VIVIES)	-37 50	77 34	1982.5	1993

MNEMONIC	NAME	φ	λ	YEAR	
				FIRST	LAST
TRW2	TRELEW 2	-43° 16′	294° 37′	1971.5	1991
EYR	EYREWELL	-43 25	172 21	1979.5	1993
CZT	PORT ALFRED (CROZET)	-46 26	51 52	1974.5	1993
PAF	PORT-AUX-FRANCAIS	-49 21	70 16	1988.5	1993
MCQ	MACQUARIE ISLAND	-54 30	158 57	1950.7	1993
ARC	ARCTOWSKI	-62 10	301 31	1979.5	1989
AIA	ARGENTINE ISLANDS (FARADAY)	-65 15	295 44	1958.5	1991
MIR	MIRNYY	-66 33	93 1	1956.5	1992
DRV	DUMONT D'URVILLE	-66 40	140 1	1958.5	1993
MAW	MAWSON	-67 36	62 53	1956.5	1993
MOL	MOLODYOZHNAYA	-67 40	45 51	1965.5	1992
SYO	SYOWA STATION	-69 0	39 35	1958.5	1994
NVL	NOVOLAZAREV-SKAYA	-70 46	11 49	1962.5	1987
SBA	SCOTT BASE	-77 51	166 47	1958.5	1993
VOS	VOSTOK	-78 27	106 52	1958.5	1991

APPENDIX II

SI AND GAUSSIAN UNITS IN GEOMAGNETIC PRACTICE

Today the recommended system of units in all physics is the so-called SI-system (SI for International System of Units), adopted by IAGA at the Kyoto General Assembly in 1973 for use in geomagnetism. The previous CGS-system (CGS for centimeter, gram and second) is still used by some authors. In the CGS-system the unit of magnetic induction B is gauss (G) and the unit for magnetic field strength H is oersted (Oe). In free space the numerical values of these units are the same. For practical purposes, a smaller unit for the magnetic field strength, gamma (gamma = $\gamma = 10^{-5}$ Oe), was used and is still in some use.

The SI-system is based on meters (m), kilograms (kg), seconds (s) and amperes (A). In the SI-system the unit of magnetic induction is tesla (T), and that of magnetic field strength is A/m (1 A/m = $4\pi\ 10^{-3}$ Oe $\approx 1257\ \gamma$). In vacuum, 1 nanotesla (nT) corresponds to 1 gamma (γ).

At present there seems to be no acceptable agreement on whether $\boldsymbol{B}$ or $\boldsymbol{H}$ is the fundamental magnetic field. The relation between $\boldsymbol{B}$ and $\boldsymbol{H}$ can be expressed in the SI-system as

$$\boldsymbol{B} = \mu_0 (\boldsymbol{H} + \boldsymbol{M}) \tag{II.1}$$

or

$$\boldsymbol{B} = \mu_0 \boldsymbol{H} + \boldsymbol{J} \tag{II.2}$$

where $\boldsymbol{M}$ is magnetization, and $\boldsymbol{J}$ is called magnetic polarization. In the CGS system there is no difference between $\boldsymbol{M}$ and $\boldsymbol{J}$ ($\boldsymbol{B} = \boldsymbol{H} + 4\pi\boldsymbol{M}$, or $\boldsymbol{B} = \boldsymbol{H} + 4\pi\boldsymbol{J}$); IAGA recommends the use of formula (II.1). As a matter of fact, in the majority of modern physics textbooks only this formula is given, and the term magnetic polarization is not used. More detailed comparisons including the fundamental equations in electromagnetism in the two systems of units have been given by Payne (1981). The tables below are mainly based on this paper.

Table II.1

Fundamental magnetic terms

Term	Symbol	SI unit	Gaussian CGS unit	Description
Magnetic induction	$\boldsymbol{B}$	tesla (T) = kg A^{-1} s^{-2}	gauss (G)	The field which causes a force to act on a moving charged particle
Magnetic field strength	$\boldsymbol{H}$	A m^{-1}	oersted (Oe)	The field which occurs as a result of the vector subtraction of the magnetization ($\boldsymbol{M}$) from the magnetic induction divided by the permeability of free space ($\boldsymbol{B}/\mu_0$)
Magnetization	$\boldsymbol{M}$	A m^{-1}	emu cm^{-3} = J G	Magnetic dipole moment per unit volume
Magnetic polarization	$\boldsymbol{J}$	tesla (T)	emu cm^{-3} = J G	Permeability of free space multiplied by the magnetization ($\boldsymbol{J} = \mu_0\boldsymbol{M}$)
Magnetic dipole moment	m	A m^2	emu = J G cm^3	The structure resulting from putting two oppositely charged (fictitious) poles infinitesimally close together
Magnetic flux	Φ	weber (Wb) = kg m^2 A^{-1} s^{-2}	maxwell (Mx)	A measure of the field lines which pass through a surface
Permeability of free space	μ_0	H m^{-1} = kg m A^2 s^{-2}	1	Constant defined to be $4\pi \times 10^{-7}$ in SI units

Table II.1
(continued)

Term	Symbol	SI unit	Gaussian CGS unit	Description
Permeability	μ	$H\ m^{-1}$	emu = G/Oe (dimensionless)	A measure of the ability of a material to let a magnetic field ***B*** to pass through in the presence of a magnetic field ***H***
Relative permeability	μ_r	dimensionless	dimensionless	Ratio of the permeability of a medium to the permeability of free space
Volume magnetic susceptibility	κ	dimensionless	dimensionless	A measure of the ease with which a material can become magnetized while in the presence of a magnetic field; the relation between the two systems is $\kappa\,(SI) = 4\pi\kappa\,(CGS)$
Demagnetizing factor	*D*, *N*	dimensionless	dimensionless	A quality which depends only on the geometry of a magnetized material

Table II.2
Conversion factors

Term and symbol	SI unit	Gaussian CGS unit
Magnetic induction $\boldsymbol{B}$	1 T	10^4 gauss
Magnetic field strength $\boldsymbol{H}$	1 A m^{-1}	$4\pi \cdot 10^{-3}$ Oe
Volume magnetization $\boldsymbol{M}$	1 A m^{-1}	10^{-3} emu cm^{-3}
Magnetic polarization $\boldsymbol{J}$	1 T	$10^4 (4\pi)^{-1}$ emu cm^{-3}
Magnetic dipole moment m	1 A m^2	10^3 emu
Mass magnetization	1 A m^2 kg^{-1}	1 emu g^{-1}
Current I	1 A	$3 \cdot 10^9$ emu cm s^{-1}
Magnetic flux Φ	1 Wb	10^8 maxwell
Permeability of free space μ_0	$4\pi \cdot 10^{-7}$ H m^{-1}	1
Relative permeability μ_r	1	1
Volume magnetic susceptibility κ	4π	1
Demagnetizing factor D, N	1	4π

APPENDIX III

IAGA RESOLUTIONS RELEVANT TO OBSERVATORIES

The main contents of IAGA resolutions relevant to magnetic observatory work and magnetic recording are presented here.

1922 Rome:

- Methods of scale value determinations are to be given in all observatory publications.

- National Committees should designate one observatory in each country for international intercomparisons of magnetic instruments.

1927 Prague:

- Greenwich Mean Time is to be used for all ordinary magnetic data.

- The annual secular variation is from January 1 to January 1. The value of a magnetic element on January 1 is the mean of 24 months comprising the 12 months which precede and the 12 months which follow January 1.

- Adequate provision should be made for securing a complete magnetograph record on highly disturbed days.

1936 Edinburgh:

- The magnetic instruments should be checked at least every two years, including the checking of the direction of magnetic axes of the magnets in the variometers.

- The directions of the electric currents in the Earth are positive when flowing toward the north or toward the east.

- Every observatory should provide means to record extreme values during magnetic storms.

- The Central Bureau of IAGA (Comment: now the World Data Center system) requests copies of magnetograms on film, or original registrations for copying at the cost of the Bureau. The copies should be supplied with information on base-line values, scale values, time corrections and other information necessary for the use of the curves.

1939 Washington:

° Every institution conducting geomagnetic work should have an efficient quantitative apparatus for testing non-magnetic material.

1948 Oslo:

° When planning new observatories, care should be taken to choose sites likely to remain undisturbed electromagnetically by artificial causes for many years: The distance from electrified railways should be not less than 30 km.

1951 Brussels:

° *K*-index was adopted as a local measure for the intensity of magnetic disturbance during three-hour intervals. K_p was adopted to describe the corresponding level of magnetic activity for the Earth as a whole.

° The 27-day numeration was adopted: The sequence 1601 began 1950 May 20.

1954 Rome:

° For magnetic charts the epoch .0 is to be used. The value to be assigned to the epoch .0 will be the mean of the values for the six months preceding and the six months following the adopted date of January 1.

° New stations in regions where $H < 10{,}000\ \gamma$(nT) should record X and Y.

° Inhomogeneities of conductivity in the Earth's crust in observatory areas should be examined in order to study the magnetic character of the district.

° Magnetic observatories are encouraged to publish in the form of yearbooks or other publications the following data, listed in the order of importance:

1) Hourly values of three elements, with notations regarding interpolated values. Mean values should be centered upon half-hour.

2) Yearly and monthly means, at earliest availability.

3) *K*-indices.

4) Account of normal equipment, and of records available, and information bearing on the reliability of the values; this information refers, for example, to absolute observations or consequent base-line determinations, scale-value determinations, performance of absolute and variation instruments, orientation and interaction of magnets, temperature coefficients, and calibration of the instruments used for absolute observations.

5) Reproduction of magnetograms of all days or, failing this, reproduction of selected magnetograms.

6) Daily sums and means, and sums and means by hours for each whole month, and the corresponding means for the selected five quiet and five disturbed days thereof.

7) The times of sudden commencements of magnetic disturbance, and as far as practicable, of crochets, pulsations, giant pulsations, and of similar changes and other remarkable phenomena, together with magnitude and sense in each magnetic element.

Desirable additional data are the following:

a) Composite daily variation or hour-by-hour departures of the general and selected-day means by months, Lloyd's seasons, and years.

b) Account of special equipment and statement on, for example, intervals for which rapid run magnetograms exist.

c) Recording of pulsations recommended.

1960 Helsinki:

° Gyromagnetic ratio of protons to be used in all observatories is: 2.67513×10^4 rad/(Gs · s). (Comment: from the beginning of 1992 the best known value is to be used, being in 1992: $2.6751525 \times 10^8 \pm 40$ rad/(T s). Until 1992 the previous value had to be used).

1963 Berkeley:

° Copies of magnetograms with full information on base-line values, etc., are to be sent to the World Data Centers as soon as possible after observation.

° Artificial magnetic disturbances should be marked on magnetograms.

° From 1964 January 1 on, the *Z*-component will not be used for the measure of the *K*-index. Observatories already measuring the *K*-index separately for three magnetic elements should send tables of these data to the Permanent Service.

° For new observatories, the lower limit for $K = 9$ should be chosen in consultation with the Working Group on Magnetic Activity Indices.

° The use of nuclear magnetometers is recommended for the measurement of absolute total intensity and components where possible.

° Observatories finding corrections in their standard of intensity should publish full information on these corrections.

° Complete calibration data for the records and instruments should be published.

° The classification for continuous pulsations is:

Pc 1	0.2	to	5	seconds
Pc 2	5	to	10	
Pc 3	10	to	45	
Pc 4	45	to	150	
Pc 5	150	to	600	

and for irregular pulsations

Pi 1	1	to	40	seconds
Pi 2	40	to	150	

1967 Zurich (St. Gallen for IAGA):

° Magnetic observatories are encouraged to become modernized to record in digital form.

° Mean hourly value data should be made available in machine readable form through World Data Centers.

° Recording of pulsations is recommended as one of the important tasks of magnetic observatories.

1969 Madrid:

° Continued publication of magnetic yearbooks is recommended in addition to the availability of the hourly values on microfilm through World Data Centers.

° Centralized publication of individual *K*-indices will be discontinued but the observatories are encouraged to publish the indices in their yearbooks or bulletins.

1971 Moscow:

° Numerical magnetic observatory data, past and current, should, whenever practicable, be put into machine readable form and transmitted to World Digital Data Centers.

1973 Kyoto:

° All countries are encouraged to set aside observations in which man-made sources of electromagnetic energy in the frequency range of interest to IAGA are excluded.

° The SI-units adopted to be used in geomagnetism are as stated below:

1. a) Values of geomagnetic *field* are to be expressed in terms of the *magnetic induction B* (SI-unit tesla = weber/metre^2).

   b) If it is desired to express values in gammas, a note should be added stating that "one gamma is equal to one nanotesla".

2. a) Values of *intensity of magnetization* are to be expressed in terms of *magnetization M* (SI-unit = ampere/metre).

   b) If it is desired to express values in emu., a note should be added stating that "one e.m.u. is equal to 10^3 ampere/metre".

3. a) Values of susceptibility are to be expressed as the ratio between *magnetization M* and the *magnetic field H*.

   b) If, during the transitional period, it is desired to use values of susceptibility in e.m.u., a note should be added stating that "χ_{SI} is equal to $4\pi\chi_{emu.}$".

° The recommended normal recording speed: 20 mm/h.

° Historically important data should be preserved and their existence made known to the scientific community.

° Records and data from temporary magnetic variation stations should be offered to the World Data Centers when the records are considered to be of possible value to other scientists.

° The term *magnetic pulsation* or *pulsation* are to be used instead of *micropulsation*.

° To the classification of pulsations one should add:
Pc 6 for continuous pulsations with periods longer than 600 seconds, and
Pi 3 for irregular pulsations with periods longer than 150 seconds.

1975 Grenoble:

° Any proposal to change the number and distribution of magnetic observatories should be discussed with IAGA.

1977 Seattle:

- For monitoring accurately the secular change, observatories are encouraged to continue the production of analog records using the traditional system at least until the digital system has been proven to be equal in performance.

- Noting the utility of analog records, in particular for submission to the World Data Centers, IAGA recommends continued production of analog records, whether by traditional instruments or from digital data.

- Repeat stations should be set up near each observatory to preserve the secular change record in the event of change of the observatory base reference. When it becomes obvious that an observatory should be moved, the instruments should be operated simultaneously at the old and at the new sites at least one year.

1979 Canberra:

- IAGA, *recognizing* the importance of rapid run magnetograms for global studies of ULF pulsations, *recommends* that observatories operating rapid-run magnetometers continue to do so, where possible increasing the sensitivity, and that other observatories initiate rapid-run recording.

- IAGA *draws attention* to the desirability of digital magnetic observatories using sampling rate no slower than once every ten seconds and *asks* these observatories to send these data to World Data Centers as one-minute means (with clear identification of the method of averaging). These means should be centered on the minute (e.g., the first value within an hour is labeled 00^h01^m and is the mean calculated from $00^h00^m30^s$ to $00^h01^m30^s$).

- Observatories basing their standard of horizontal intensity on QHM-measurements are urged to loan for comparison standard QHM's from the Danish Meteorological Institute.

- IAGA, *recognizing* the ever-increasing pressure upon geophysicists to provide fast returns in the form of practical applications of their research, *draws attention* to the fact that basic research motivated by intellectual curiosity is the most effective breeding ground for the long-term development of applications in resource exploration and exploitation, environmental protection, and new technologies; *urges* its member countries to provide continued strong support to basic research in the geosciences, and *encourages* them to embark in a concerted effort towards establishing an appropriate balance between the current opportunities offered in basic research and the long-term needs in applied fields and technology.

1983 Hamburg:

- ° Hand scaling of *K*-indices recommended. It is recommended that machine derived indices be given distinctly different names (Comment: the later development of machine production of *K*-indices has shown that the best machine methods give results which are very close to the results of hand scalings made by experts).

1985 Prague:

- ° Funding agencies are encouraged to safeguard the monitoring programme of magnetic observatories and the archiving and dissemination of their results.

- ° Geomagnetic observatories are urged to report activity indices and to return check lists without delay, because delays caused by a small number of observatories have a serious adverse effect on the usefulness of the whole network by delaying the publication of summary data on rapid geomagnetic activity.

1987 Vancouver:

- ° All member countries are urged to maintain uninterrupted observations.

1989 Exeter:

- ° IAGA, *recognizing* that key developments in the understanding of the coupled ionosphere magnetosphere and solar wind system will come from the integration of in situ satellite observations and measurements from spatially related networks of ground observatories and *recognizing* that Antarctica provides a unique platform upon which to deploy an optimum network of ground observatories from which to make such measurements and *noting* that several nations plan to deploy unmanned experimental facilities in Antarctica, *urges* national administrations through the ICSU Scientific Committee for Antarctic Research to support the development of an optimum international network of observatories. At each site, at least measurements of the geomagnetic field and absorption of cosmic noise should be made.

- ° Magnetic observatories providing data to the World Data Center C2 for Geomagnetism for the calculation of D_{st} and AE indices are encouraged to use real-time data transmission systems such as INTERMAGNET.

- ° The responsible institutes are strongly urged to work with IAGA to develop alternative solutions prior to taking a final decision to close an observatory.

1991 Vienna:

- Relevant organizations, agencies and member countries should review the services under their control, as well as the deployment of global networks supporting them, and should co-locate as many of these instruments as is practical, provided that the performance of all instruments is not compromised.

- Organizations in the developed countries that run magnetic observatory programs are recommended to adopt one or more observatories facing problems and provide the necessary assistance and training to ensure continuing operation at a satisfactory standard. Government funding agencies should consider this as a routine part of their international obligation to developing countries.

- IAGA, *recognizing* the importance of continued long-term monitoring of the geomagnetic field for scientific, industrial and other purposes, *noting* that many key observatories throughout the world have inadequate support and are under threat of closure, *encourages* the creation of a federation of those institutes operating magnetic observatories, working closely with IAGA, that will strengthen and coordinate their efforts, *by* maintaining standards set by IAGA, *by* working towards an improved distribution of observatories, *by* establishing and coordinating bilateral or multilateral assistance programs among participating institutes, *by* actively pursuing all sources of funding.

1993 Buenos Aires:

- The IAGA, *noting* the contribution made by magnetic observatories to long-term environmental monitoring, to fundamental research and to ground-based and satellite surveys and experiments, and *noting* also the extensive commercial and governmental use of geomagnetic models and indices derived from magnetic observatory data, *urges* relevant organizations, agencies, and member countries, to provide the resources to maintain continuity of synoptic magnetic observations and to adopt modern digital instruments.

- The IAGA, *noting* that a proper understanding of many aspects of the geomagnetic field requires continuous, high accuracy, high resolution long-term data of the type provided by the MAGSAT satellite of 1979/1980, supported by a well-distributed and modern geomagnetic observatory network, *recommends* that the relevant organizations, agencies and member countries provide all possible support to ensure that (1) a continuous sequence of MAGSAT-quality vector-magnetic satellites, such as the proposed UNIMAG, OERSTED, GAMES and DMSP/POGS satellite series, is operated for at least the next solar cycle [22 years], and (2) the current geomagnetic observatory network be maintained, and upgraded where necessary, and its coverage be extended into ocean areas.

APPENDIX IV

DISTURBING EFFECT OF MAGNETIC MATERIAL ON MEASUREMENTS

Many observations are spoiled by a magnetic object the observer is carrying while observing or which is kept too close to the site of observation. Dangerous items may be tools, electronic instruments, cars, bicycles, etc. It is not easy to answer the question how far away one has to keep a magnetic object, but here we shall give some general background for the estimation of the magnetic effects and finally some practical advice based on measurement and experience.

In textbooks on magnetism, one cannot find ready answers. Exact calculation of the magnetic field of bodies with complicated shapes is difficult, but it is possible to give guidelines for some simple cases. It is important to know the magnetic effect of different objects at a magnetic observatory, partly because the objects may affect the absolute measurements, and partly because a task at a magnetic observatory may sometimes be to estimate the magnetic field outside a more or less weakly magnetized body.

The effect of a magnetic object depends on many parameters:

- the distance
- the magnetic parameters and volume of the object
- the geometric shape of the object
- the angle between the component to be measured and the direction of magnetization of the object
- the past history of the magnetic body

The last point needs some explanation: every magnetic material may have two kinds of magnetism: induced magnetism M_I and remanent magnetization M_R. The latter depends on the past history of the magnetic object. For an iron body, the M_R is usually the result of a strong magnetic field. For rocks, M_R is accumulated during their formation or during subsequent metamorphic or chemical processes.

IV.1 Magnetic field of a sphere in an external magnetic field

The classical problem of calculating the magnetic field in space in the presence of a spherical body with susceptibility κ can be solved analytically. Let us assume that at the origin of a spherical coordinate system we have a spherical body. The total field is

$$H_i = H_0 - (1/3)M_I \qquad (H \,||\, M_I \text{ inside the sphere}) \qquad \text{(IV.1)}$$

$$H_r = (H_0 + (2/3)M_I\, a^3/r^3)\cos\theta$$

$$\text{outside the sphere} \qquad \text{(IV.2)}$$

$$H_\theta = (-H_0 + (1/3)M_I\, a^3/r^3)\sin\theta$$

where a = the radius of the sphere, H_0 = the external magnetic field along the vertical axis and M_I = the induced magnetization. θ is the polar angle. The formulas are given in the standard international system (SI) units.

$$M_I = H_0\, \kappa/(\kappa/3 + 1) \qquad \text{(IV.3)}$$

From formulas (IV.2) we see that the additional field is the field of a magnetic dipole with a magnetic moment $m = (4\pi/3)M_I a^3$. Strictly speaking, the magnetization is homogeneous and the magnetic field parallel to the external field only in the case of a sphere, but in many cases we can assume homogeneous magnetization also in bodies having other shapes.

IV.2 Demagnetization factor

Formula (IV.3) derived for a sphere can be generalized and rewritten in the form

$$M_I = \kappa(H_0 - NM_I) \qquad \text{(IV.4)}$$

where N is the demagnetization factor (for a sphere $N = 1/3$). In the case of a more complicated shape, N is a tensor.

For an ellipsoid, the magnetization along the main axes is

$$M_{I,Z} = \kappa(H_{0,Z} + N_{Z,Z}\, M_{I,Z}) \qquad \text{(IV.5)}$$

In this case, the magnetization is homogeneous but does not have the same direction as the inducing field. For an ellipsoid of revolution, with axes $a = b < c$ in the coordinate system x, y, z, the demagnetization factor can be expressed by elementary functions (Landau and Lifshits, 1957):

$$N_{Z,Z} = [(1 - e^2)/2e^3]\, \ln[(1 + e)/(1 - e) - 2e] \qquad \text{(IV.6)}$$

$$e = (1 - b^2/c^2)^{1/2}$$

Table IV.1.
The demagnetization factor N as a function of the ratio λ (length of the principal axis c, parallel to the external field, divided by the length of the other axes of the ellipsoid of rotation (a = b)).

λ	N	λ	N	λ	N
1	0.333	8	0.029	15	0.011
2	0.173	9	0.024	16	0.010
3	0.109	10	0.020	17	0.009
4	0.076	11	0.018	18	0.008
5	0.056	12	0.015	19	0.007
6	0.043	13	0.014	20	0.006
7	0.034	14	0.012	21	0.006

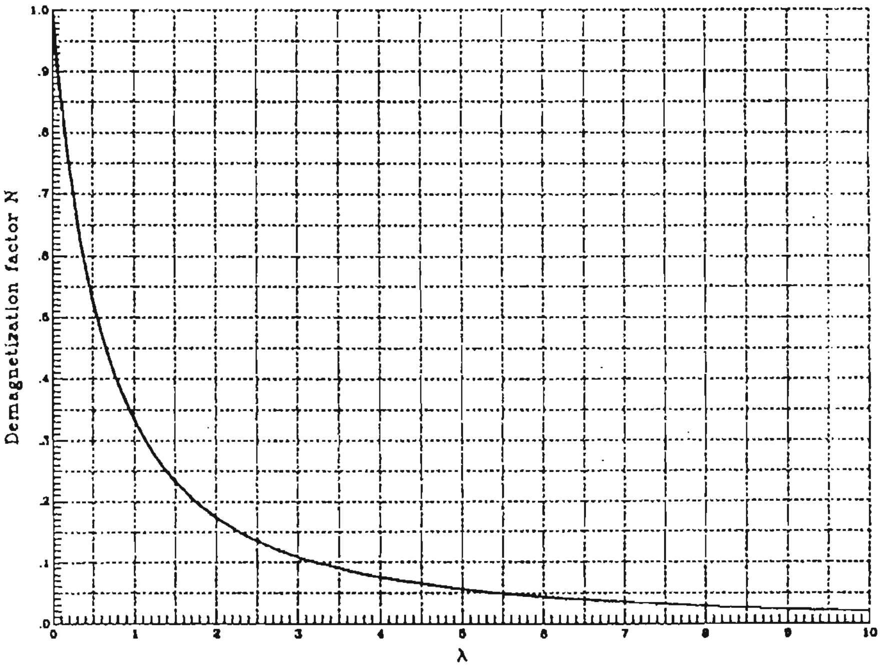

Figure IV.1. The demagnetization factor N as a function of the ratio λ (length of the principal axis, parallel to the external field, divided by the length of the other axes of the ellipsoid of rotation).

Correspondingly, for an ellipsoid with $a = b > c$ we have

$$N_{Z,Z} = [(1 + e^2)/e^3]\,(e - \arctan e) \qquad \text{(IV.7)}$$

$$e = (a^2/c^2 - 1)^{1/2}$$

The dependence of N on the elongation of the ellipsoid is presented in Figure IV.1, where the external field $\boldsymbol{H}_0$ is assumed to act in the direction of the z-axis.

IV.3 Induced and remanent magnetization of a magnetic body

From equation (IV.4) we get for the induced magnetization M_I:

$$M_I = \kappa H_0/(1 + \kappa N) \qquad \text{(IV.8)}$$

where $\kappa/(1 + \kappa N)$ is called the apparent or shape susceptibility.

For $\kappa N \gg 1$ we have

$$M_I = H_0/N \qquad \text{(IV.9)}$$

In this case, the magnetization does not depend on the susceptibility, only on the demagnetization factor N and the external field. Formula (IV.9) can be used for any iron body, provided that it is not very elongated.

When $\kappa N \ll 1$, then

$$M_I = \kappa H_0 \qquad \text{(IV.10)}$$

This formula is valid for the majority of rocks. Using the formulas above it is possible to estimate the induced magnetism if κ is known. Approximate values of κ can be found in many textbooks on geomagnetism. Some typical values are collected in Table IV.2.

Table IV.2.
Typical susceptibility values κ for various materials.

	κ
Different types of rocks	10^{-1}–10^{-5}
Bricks	10^{-2}
Magnetite	1–10
Typical iron	10^{+2}
Special iron alloys	10^{+6}

The remanent magnetization M_R of a body (in the case of iron the term permanent is also used) depends on its past history. For iron, the most important factor is magnetization in a strong magnetic field. The ratio of remanent to induced magnetization is called the "Koenigsberger ratio". For specially made alloys the remanent magnetization may be three orders of magnitude higher than the induced one. This is the case in "hard" magnetic materials, especially developed for permanent magnets.

The total magnetization is the vector sum of the induced and remanent magnetizations

$$\boldsymbol{M} = \boldsymbol{M}_I + \boldsymbol{M}_R \,. \qquad \text{(IV.11)}$$

Generally, $\boldsymbol{M}_I$ and $\boldsymbol{M}_R$ are not parallel. When a non-spherical magnetic body is rotated in an external field, the $\boldsymbol{M}_I$ is changing and $\boldsymbol{M}_R$ has a constant value. A rough estimate of M is $M = 2M_I$, when the direction associated with the minimum value of the demagnetization factor is parallel to the external field.

IV.4 Simplified formulae for the calculation of the effect of a magnetic body

We are interested in the effect of a magnetized body on a magnetic measurement at a distance r from the body. We make the following simplifying assumptions for the estimation of the disturbing field:

1. We assume that the disturbing field can be represented by a magnetic dipole. This assumption is valid if the dimension of the source is much smaller than the distance between source and observer. This is not fulfilled in the case of very long sources like a fence or pipeline and instead of the dependence of distance r^{-3}, valid for a dipole, one should rather use r^{-2} or even r^{-1}. The use of the formulae for a dipole field generally underestimates the anomalous field.

2. We assume that the external field, magnetic moment and the direction of magnetization are all parallel and that we measure in the direction of the assumed dipole axis. This assumption generally overestimates the amplitude of the disturbing field.

3. We assume that the total magnetization is twice the induced value ($M = 2M_I$).

After these simplifications, the final formula in SI-units is

$$\Delta B = w\kappa B_0 / \pi d r^3 (1 + \kappa N) \qquad \text{(IV.12a)}$$

where w stands for mass, d stands for density, and B is the magnetic induction. (B and B_0 in teslas or nanoteslas).

The disturbing effect ΔH can be expressed in CGS-units, which may be more common in the literature in this connection

$$\Delta H = 2m/r^3 = 2vM/r^3 = 4v\kappa H_0/r^3(1 + \kappa N) = 4w\kappa H_0/dr^3(1 + \kappa N) \qquad \text{(IV.12b)}$$

where v = volume, w = mass, d = density of the magnetic source, and m = magnetic moment. One should remember that when using tables or formulas for demagnetization factors the values should, in this case, be multiplied by 4π, and κ should be divided by 4π.

What we measure in practice is the vector sum of $\Delta\boldsymbol{B}$ and $\boldsymbol{B}_0$ (see Fig. IV.2)

$$\boldsymbol{B} = \boldsymbol{B}_0 + \Delta\boldsymbol{B}. \qquad \text{(IV.13)}$$

Assuming that $\Delta B \ll B_0$

$$B = (B_0^2 + 2\boldsymbol{B}_0 \cdot \Delta\boldsymbol{B} + \Delta B^2)^{1/2} \cong B_0 + \boldsymbol{B}_0 \cdot \Delta\boldsymbol{B}/B_0\,. \qquad \text{(IV.14)}$$

When $\boldsymbol{B}_0$ is parallel to $\Delta\boldsymbol{B}$, $B = B_0 + \Delta B$, and when $\boldsymbol{B}$ is perpendicular to $\Delta\boldsymbol{B}$, then $B = B_0$.

The nomograms presented in Figures IV.3 and IV.4, and also the list of disturbing magnetic effects of different objects presented in Chapter 3 (Table 3.1), have been calculated using formula (IV.14).

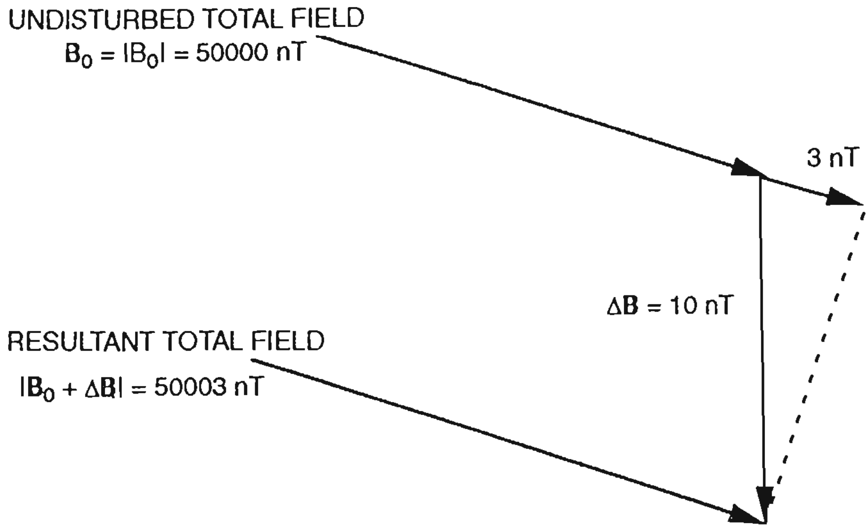

Figure IV.2. Sum of the two vectors: external field $\boldsymbol{B}_0$ and anomalous field $\Delta\boldsymbol{B}$.

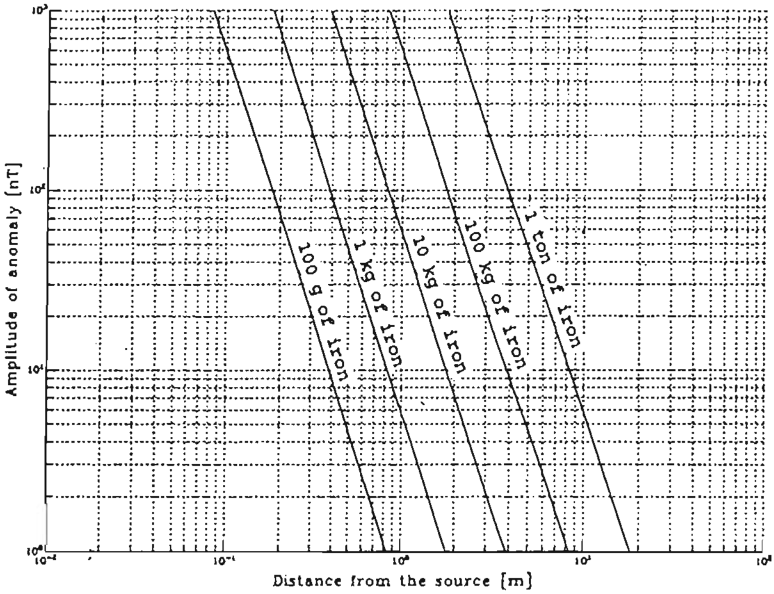

Figure IV.3. A nomogram for estimating the magnetic effect of a spherical body ($\lambda = 1$) at different distances from the body. A susceptibility $\kappa = 8$ is assumed.

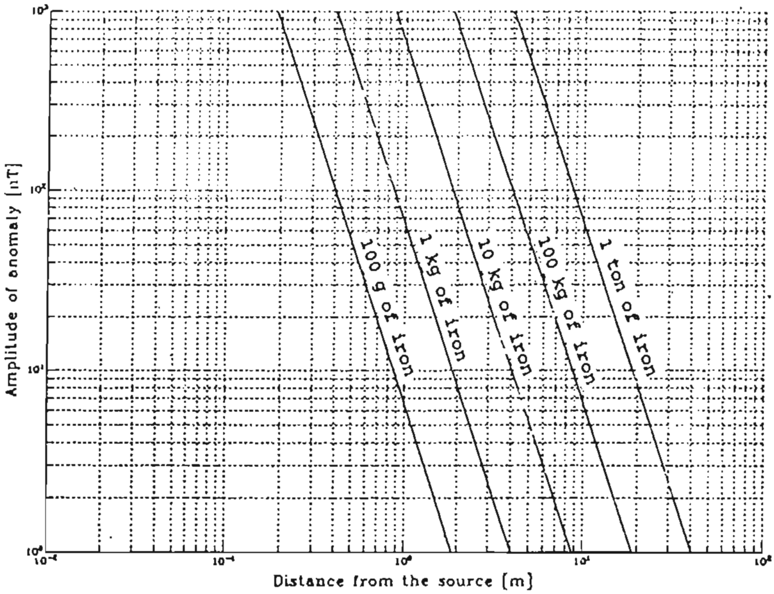

Figure IV.4. A nomogram for estimating the magnetic effect of an oblong body ($\lambda = 10$) at different distances from the body. A susceptibility $\kappa = 8$ is assumed.

Making the simplifications mentioned above we have tried to rather overestimate the value of the disturbing field. In two cases, namely when the permanent magnetization is much bigger than the induced magnetization, or when the body is large compared to the distance to the measuring point, the computed value can be smaller than the real value, however. The best way to determine the disturbance due to magnetic bodies is to check the surroundings of the measurement point with a proton magnetometer.

SUBJECT INDEX

This Guide provides comprehensive information how to organize and run a magnetic observatory and make magnetic measurements. The main topics are the following:

- Brief description of the magnetic field of the Earth
- Selection of observatory site and layout of the observatory
- Magnetometers
- Absolute magnetic measurements
- Recording of magnetic variations
- Data processing
- Testing and calibrating instruments

Copies available from the Secretary-General of IAGA.