IAGA

Guide for Magnetic Repeat Station Surveys

L.R. Newitt, C.E. Barton and J. Bitterly

International Association of Geomagnetism and Aeronomy
Working Group V-8: Analysis of the Global and Regional Geomagnetic
Field and its Secular Variation

GUIDE FOR
MAGNETIC REPEAT
STATION SURVEYS

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ISBN: 0-9650686-1-7

Published by:
International Association of Geomagnetism and Aeronomy
J.A. Joselyn, Secretary-General
NOAA Space Environment Center, 325 Broadway, Boulder, CO 80303-3328, USA

Camera ready copy prepared by:
Geomagnetic Laboratory
Geological Survey of Canada
1 Observatory Crescent, Ottawa, Canada K1A 0Y3

Printed and bound by:
Zespół Wydawniczy Centrum Badań Kosmicznych PAN
ul.Bartycka 18a, 00-716 Warszawa, Poland

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Foreword

This guide for magnetic repeat station surveys has been produced in response to an initiative from IAGA Division V: *Observatories, Surveys, Instruments, and Analyses* to produce practical guides for observational geomagnetism. A companion volume, "Guide for Magnetic Measurements and Observatory Practice" by Jankowski and Sucksdorff (1996) also contains information of relevance to anyone interested in repeat station measurements. The approach taken by Jankowski and Sucksdorff is more theoretical than the one we have taken. Our starting point in writing this guide was Gilbert and Bitterly's (1989) reference manual for French repeat station operations.

The guide should be of interest to everybody doing repeat station surveys, and should be particularly useful for groups embarking on repeat station work for the first time. The guide should also give those who model the geomagnetic field a better insight into the strengths and limitations of repeat data.

The procedures described and the recommendations given are not expected to be the "final word" in repeat station survey practice, but they do represent the best practices currently in use. We welcome comments and suggestions for future revisions of the guide.

LN, CB, JB
August, 1996

Acknowledgements

We thank Richard Coles for suggesting the production of this guide; Diane Regimbald for her word-processing expertise; the many national agencies from around the world who provided information about their repeat station survey operations; WDC-A for cooperation and support for the IAGA reporting scheme. Valuable comments were received from many individuals, including F. Boteler, N. Fukushima, G.V. Haines, D.J. Kerridge, A. Körmendi, L. Loubser, A.J. McEwin, L. Muniz Barreto, D. Parkinson, J. Rasson, A. de Santis, G. Schulz, and A.E. Taylor. We thank especially Daniel Gilbert, who contributed greatly to this guide prior to his retirement. Production of this guide was supported by IAGA, the Geological Survey of Canada, the Australian Geological Survey Organisation, and the École et Observatoire de Physique du Globe de Strasbourg. CEB publishes with permission from the Executive Director, Australian Geological Survey Organisation.

Explanation of Terms

Alidade: the rotational assembly, containing the horizontal and vertical graduated circles, of a theodolite.

Auxiliary station: a proton precession magnetometer station set up adjacent to either a repeat station or a variometer station. This is distinct from a secondary repeat station.

DI fluxgate: fluxgate theodolite magnetometer for measuring declination and inclination (same as DIM).

D,I,H,F,X,Y,Z: elements of the magnetic field — declination (positive east of north), inclination (positive downwards), horizontal intensity, total intensity, north component, east component, vertical component (positive downwards), respectively.

DIM: declination-inclination magnetometer (same as a DI fluxgate).

Diurnal (daily) variation: the variation of the geomagnetic field throughout the day regardless of the activity.

External field: geomagnetic field contribution originating from outside (the surface of) the Earth.

Geomagnetic Latitude: the latitude of a point on the Earth's surface with respect to the Earth's magnetic dipole axis, which is inclined approximately 11° to the rotational axis. Geomagnetic latitude is 90° at the geomagnetic poles.

GPS: Global Positioning System.

HC: horizontal circle of a theodolite.

IAGA: the International Association of Geomagnetism and Aeronomy.

IMF: interplanetary magnetic field.

IUGG: the International Union of Geodesy and Geophysics.

LT: Local Time.

Magnetic equator: also known as dip equator. A line circling the Earth where the inclination is at 0°. Geomagnetic latitude is generally not 0° at the magnetic equator.

Main field: the geomagnetic field originating in the Earth's core.

Mean night-time field: same as the "night-time" field defined below.

Night-time field: the field during the least disturbed time of day (it cannot be assumed that the night-time field is undisturbed and equal to the normal field).

Normal field: the geomagnetic field after removal of external contributions and associated internal induction effects. The term "normal field" is convenient for describing the combination of the main field and the static crustal field (remanent and induced) that we try to determine during regional field surveys. Our definition follows Chapman and Bartels' (1940) usage, but differs from that of Wienert (1970).

PC: personal computer.

PPM: proton precession magnetometer.

Primary station: the main repeat station.

Quiet night-time field: same as normal field.

Repeat data: same as repeat station data.

Repeat station: a fixed mark on the ground where absolute observations of the magnetic field are made; observations are always made at a fixed height above the marker.

Scalar field: total field intensity (F).

Secondary station: a second repeat station set up in the general vicinity (usually within a few hundred metres) of the primary station, used for back-up. This is distinct from an auxiliary station.

Secular variation: the first derivative of the normal field, usually expressed as the annual change of a particular field element. This is what we determine from first differences of observatory mean values when the effects of time-varying external signals have been removed. It includes the effects of changing magnetization induced in the lithosphere by the main field.

Sq: Solar daily variation on quiet days.

Standard height: the fixed height above the repeat station marker at which absolute observations are made.

SV: secular variation.

Telescope inverted (down) position: the DIM sensor is below the theodolite telescope (vertical circle right for a Zeiss-Jena theodolite).

Telescope normal (up) position: the DIM sensor is above the theodolite telescope (vertical circle left for a Zeiss-Jena theodolite).

Transient field (variation): the time variations of the magnetic field components, and their associated internal induction effects, arising from sources outside the Earth.

True secular variation: the first derivative of the main field (note that this is not what we usually determine from first differences of observatory annual mean values).

Undisturbed night-time field: the night-time field when there are no external field contributions. This will be equal to the normal field.

UT: Universal Time.

UTC: Coordinated Universal Time.

Variometer: a continuous-recording magnetometer.

Variometer station: an installation where one or more elements of the geomagnetic field are measured continuously; measurements are usually relative to some arbitrary baseline.

VC: vertical circle of a theodolite.

Vector field: three-component field.

WDC-A: World Data Center A for Solid Earth Geophysics, Boulder, Colorado, USA.

CHAPTER 1 Introduction

This guide presents specifications and procedures recommended for carrying out magnetic repeat station measurements. Some of the information presented is relevant to vector field (i.e., three-component) ground-surveys, but accuracy requirements for repeat station measurements are much more stringent than those for vector ground-surveys. Repeat station measurements are designed specifically to determine the secular variation, whereas vector survey measurements are used for spatial mapping of the geomagnetic field.

Permanent magnetic observatories provide the most accurate source of secular variation information, but the present network of magnetic observatories does not give adequate spatial coverage of the globe. Repeat stations provide an important and cost-effective means of supplementing observatory data with the most valuable stations being those remote from observatories. Repeat data have long been used for producing regional field models and charts. If repeat data are to be used widely for global field modelling, then accurate observational techniques and efficient reporting methods must be adopted. A scheme to encourage such practices is administered by IAGA Working Group V-8 (Chapter 8).

The recommendations in this guide are based on the experience of several groups around the world that have conducted magnetic repeat station surveys for many years. In practice, there may be many reasons why an observer cannot, or may prefer not, to follow the recommendations in their entirety. We try to offer a range of options that may be applied to differing situations, pointing out their relative advantages and disadvantages.

The key to obtaining useful repeat data is the ability to make an accurate correction for transient field variations so that the secular variation can be determined from the differences between results from successive station occupations. These corrections can be obtained either by using one or more permanent observatories as a reference standard, or by installing a variometer on-site and running the repeat station as a temporary observatory.

Each method has its advantages and limitations, as discussed in Chapter 6. The reference observatory method, being quicker, easier, and cheaper, is the natural choice when it can be demonstrated that the transient-field corrections obtained at the reference observatory are applicable at the repeat station. It is important to investigate and demonstrate this result, and not simply assume it for convenience, before adopting the reference observatory method. Data from a local variometer help to determine the quiet level of the magnetic field when the repeat station is far from an observatory, or when it lies in a region where the field variations are complex, such as the auroral zone.

We have structured the guide around the use of a declination-inclination magnetometer (DIM, also known as a DI fluxgate or a fluxgate-theodolite), a proton precession magnetometer (PPM), and a three-axis fluxgate variometer. This combination of instruments has rapidly gained acceptance world-wide, both for observatory and field survey operations, and is convenient for interfacing with digital recording systems.

Although well-calibrated classical instruments may be almost as accurate as modern instruments, the latter are easier to use and are less demanding on the skill of the observer.

The term "magnetic repeat station" refers strictly to a marked point on the Earth's surface, either at, or near, ground level, or a specially constructed pillar. Absolute observations of the vector field are made at a fixed height vertically above the centre of the station marker. The term is sometimes used in a general sense to refer to the general locality containing the actual repeat station.

The abbreviations and common terms we use are defined at the beginning of the guide. We draw particular attention to the distinction between the night-time field and the undisturbed night-time field. The former is the field during the least-disturbed time of any particular night, but may be displaced from the undisturbed value by, for example, the after-effects of a magnetic storm. The latter is the field when there are no external fields, (or after transient-field contributions have been removed), i.e., the normal field. The normal field includes contributions only from the main (core) field, crustal magnetic remanence and the magnetization of the crust induced by the main field.

Readers of this guide should refer to the companion IAGA guide, entitled "Guide for Magnetic Measurements and Observatory Practice" (Jankowski and Sucksdorff, 1996), where additional background information and details on the theory behind the operation of the instruments are given. Several earlier guides have been published previously on the subject of magnetic survey practice, going back to Hazard (1957). Vestine (1961) produced a detailed operating guide for the 1965 World Magnetic Survey, which was followed by Wienert's "Notes on Geomagnetic Observatory and Survey Practice" (Wienert, 1970). For the ground survey performed in conjunction with the MAGSAT satellite program, IAGA issued a circular (Voppel, 1979) updating Vestine's instructions and those of Wienert.

1.1 Repeat Stations and Ground Survey Stations

Confusion often arises concerning the difference between a repeat station and a ground survey station. The stations themselves may be exactly the same, but the observations required are quite different. The distinguishing features of repeat station measurements are:

(i) the point of measurement is precisely located so that when repeated at a later time there is no error caused by spatial variations of the field;

(ii) transient (non-secular) contributions to the observed field are eliminated with sufficient accuracy that a meaningful determination of the secular variation can be obtained by taking the differences between results from successive station occupations.

For a ground survey, the aim is to obtain a scalar or vector value of the field that is representative of the normal field in the region of the station. The exact location of the station is relatively unimportant, and the accuracy of the measurements required need only match the typical spatial variability of the field over the region represented by the station. A correction for the diurnal variation of the field is likely to be necessary, but a correction for night-time displacement of the field is not usually justified unless measurements are made during disturbed conditions.

Vector ground survey measurements may take only a few tens of minutes, whereas a reliable repeat station occupation usually takes two or more days. Mapping of the geomagnetic field on a regional scale requires hundreds-to-thousands of observation points in order to obtain information down to wavelengths of 100 km. Alldredge (1987) stresses the value of including such short wavelength information in regional maps in order to make them more accurate for direction-finding applications (the purpose for which most regional maps are produced). It is clearly wasteful to make repeat station observations when a simple ground vector measurement is adequate.

1.2 Categories of Repeat Station Surveys

Repeat station surveys generally fall into two categories.

First-order surveys. (i) Reference observatory method: multiple sets of absolute observations are made in the early morning and late afternoon spanning two days. Results should be consistent to within a few nT when using data from a reference observatory; agreement with results reduced using an alternative reference observatory is desirable.
(ii) Variometer method: variations of the vector magnetic field in the vicinity of the repeat station are determined continuously for 3 or more days of low magnetic activity and calibrated to an accuracy of 5 nT, or better, using sets of absolute observations made at the repeat station. The aim is to obtain records for at least two nights under conditions of low magnetic activity, with reliable daytime absolute observations before and after each night. At high latitude stations it may not be practicable to meet these objectives.

Second-order surveys. Frequent absolute measurements of the field are made at the repeat station throughout the day, typically for 6-8 hours centred on local noon, and possibly into the night. An accuracy of 5 nT or better is aimed for. The object is to obtain sufficient data to be able to correct approximately for the diurnal variation when no suitable reference observatory or variometer is available.

The techniques described in this guide are written primarily for first-order repeat station survey work, but are also relevant to second-order and ground survey operations. Second-order observations are usually made only when first-order measurements are not possible, e.g., in the event of failure of the on-site variometer, or when observational opportunities are limited, such as during polar traverses. Estimates of secular variation based on second-order survey data must be treated with caution, and are best obtained from a long time-series of observations that enables outliers to be identified. Ground survey measurements are not suitable for determining the secular variation.

1.3 The Importance of Accuracy

The most important consideration when conducting repeat-station surveys is to achieve a high level of accuracy. Repeat data must be at least good enough to improve the accuracy of SV models produced from observatory data alone. If they are not accurate enough to do this, then the effort expended on repeat measurements is wasted, and would be better spent on making a large number of ground station observations.

The annual change of the geomagnetic field exceeds 100 nT/yr in a few locations, but over much of the Earth's surface it is no greater than the typical errors that occur in repeat-station results (Table 1.1). To make repeat-station observations that are accurate to a few nanotesla is difficult, and, in some situations, may be impossible. Lower levels of accuracy are still acceptable, especially at repeat stations remote from magnetic observatories, but repeat data can then only be used to determine the secular variation over intervals of time for which the secular change of the field is large compared to the errors. Indeed, the greatest single limitation on the value of repeat data for geomagnetic field modelling is lack of accuracy, not the number or distribution of the stations. It is more valuable to obtain accurate data at a few, well-distributed stations, than to sacrifice accuracy in order to occupy more stations. Accuracy is discussed further in § 2.4 and § 6.3.

Table 1.1 Distribution of secular variation in F over the Earth's surface given by IGRF 1990 (after Barton, 1992).

Cumulative Area of Earth (%)	Bounds for SV (nT/yr)
5	± 1.0
10	± 2.5
15	± 4.5
20	± 7.0
25	± 9.0
30	±12.0
40	±17.0
50	±26.0
60	±33.0
70	±42.0
80	±55.0
90	±76.0
99	±100.0

CHAPTER 2 Specifications for Magnetic Repeat Station Surveys

This chapter describes the factors to consider when deciding how often to reoccupy repeat stations, how many stations to use, and how much time to spend observing at each station. Most survey groups have only limited resources and must therefore opt for some compromise determined by their particular scientific goals and logistical situations.

2.1 Frequency of Station Reoccupations

IAGA has recommended that repeat stations be reoccupied at 2-year intervals (Vestine, 1950). This should only be treated as a guide, and the actual interval adopted should be based on the scientific objectives of the survey.

If the primary purpose of the survey is to update old survey data so that a new series of magnetic charts can be issued, a survey carried out immediately before the epoch of the chart is adequate. Since charts are commonly published every 5 years, this means a 5-year reoccupation interval. On the other hand, to produce a secular variation model that can be used for forward extrapolation, a reoccupation interval of 2 years is desirable. The final occupation should be as late as possible in order to provide the best constraint on the extrapolation.

Annual reoccupations are recommended if detailed features of the secular variation, such as the 1969/1970 geomagnetic jerk, are to be tracked. Experience in Australia and Canada, where many repeat stations are remote from reference observatories, has shown that a better estimate of secular variation is achieved by increasing the frequency of station occupations rather than by extending the duration of each occupation (§ 6.3.7).

Practical considerations often necessitate modification of the ideal survey schedule. For example, it may be impossible to occupy all stations in the year prior to the production of a magnetic chart. In such a case, the survey work might have to be spread over more than one year prior to each epoch, and a few stations rechecked shortly before chart production to ensure that there has not been a significant change in the secular variation.

In order to satisfy multiple objectives cost-effectively, a different reoccupation interval may be used for different subsets of repeat stations. For example, stations can be grouped as: "Class-A", occupied every 2 years; "Class-B", occupied every 5 years; and "Class-C", occupied every 10 years. This is done in Canada (Newitt et al., 1985) and has been adopted in Australia. In choosing the subsets of stations, consider the purpose of the survey work, the distance of each station from a suitable reference observatory, and the magnitude and regional characteristics of the secular variation. For example, in north-eastern Brazil, the secular variation in I is greater than 25 minutes per year. To track these changes in detail, a 1-year occupation interval has been established (Barreto, 1987).

Descriptions of repeat station networks from many different countries, on file with IAGA Working Group V-8 (Barton and Newitt, 1995), reveal that occupation intervals vary from 1 to 10 years, with 5 years being the most common.

2.2 Distance Between Stations

The International Union of Geodesy and Geophysics, IUGG, has recommended that, for the purposes of main-field mapping, surface measurements of the magnetic elements be made at a spacing of about 200 km (Vestine, 1961). This means that, in theory, features with wavelengths greater than 400 km can be discerned. A comparable spacing is certainly adequate for repeat station observations since the true secular variation is a core phenomenon originating at least 2900 km beneath the Earth's surface. Piezomagnetic effects in tectonically active areas and seasonally-varying induction effects, particularly in the oceans, can distort secular variation observations. To investigate these phenomena properly, a denser network of stations would be required. Even on small islands it is useful to operate more than one station to verify that the secular variation being determined is not anomalous.

A balance must be reached between the number of stations occupied and the time interval between occupations. As a general rule, the accuracy of data obtained from each station should not be sacrificed in order to occupy more stations. Repeat station observations made hurriedly and with poor corrections are of little value for determining secular variation and are a very inefficient way of making ground survey measurements.

An examination of the repeat station network descriptions from 16 countries shows that average station spacings vary from 53 km to 415 km, with the mean being 230 km.

2.3 Duration and Timing of Observations

In principle, only a single set of absolute observations at the repeat station is needed, provided perfect corrections can be made to obtain an estimate of the normal field. In practice, it is usually necessary to take many sets of absolute observations, mostly outside the main period of diurnal activity. Early morning and late evening, when the diurnal variation of the field is relatively small, are good times to make observations, and night-time is even better. Further consideration of the timing of absolute observations is given in § 5.5.

The duration of a first-order repeat station occupation will rarely be less than 24 hours. If an on-site variometer is used, then the station occupation must usually span 2 or more days in order to get enough absolute observations to obtain an accurate baseline determination. Shorter station occupations are feasible if a reference observatory can be used to correct for transient field effects. Observations should not be made under magnetically disturbed conditions, so it may be necessary to delay the observations until quieter conditions prevail. Bear in mind that the magnetic field components, especially **H**, can be affected for up to 4 or 5 days after a magnetic storm.

Consider making absolute observations during the night. With modern instruments and a suitable reference mark (e.g., the secondary station) it is not difficult to arrange an illumination system. The inconvenience of working at night is offset by the fewer absolute observations required and the improved accuracy that may be obtained. If a variometer is being used, then some daytime observations, spanning a wide range of field and temperature variations, should be made to enable the scale values and temperature coefficients of the variometer to be determined.

The national repeat station network descriptions show that the length of stay at a station is highly variable. It is the practice in some countries to stay only a fraction of a day; in others, when variometers are set up, visits of up to 5 days have been reported.

2.4 Accuracy of Observations

To measure the secular variation of the magnetic field, it is desirable to aim for accuracies comparable to those achieved at the best magnetic observatories:

< 1 nT for intensity elements,
and 0.1′ for directional elements.

Modern instruments, such as the DIM and PPM, have sufficient precision to make this possible in principle. In practice, observational errors and data reduction errors are usually much greater at a repeat station than at an observatory. Hence, the error in the normal field value (annual mean) obtained at a repeat station is certainly greater than at an observatory. It is realistic to strive for errors of about 5 nT in components. This corresponds to mid-latitude errors of about 1 minute of arc in **D** and 0.5 minute of arc in **I**.

It is difficult to estimate errors in final results, especially the portion of the error that arises from inaccurate corrections for external field effects. Some estimates of accuracy for mid-latitude stations that appear in the literature are given in Table 2.1. A detailed discussion of errors is given in § 6.3.

2.5 Secondary Stations

<u>It is strongly recommended that a secondary station be installed some distance from the primary station</u>, and located so as to minimize the risk of both stations being destroyed together by future development. Parallel observations should be carried out at both stations during each occupation, in order to check the station differences, and also to test that no magnetic contamination has occurred at either station. If the primary station is later destroyed or contaminated, observations can be carried on at the secondary station with no break in the secular variation record (refer to § 5.2). The stations should be at least 200 metres apart. It is an advantage if the secondary station can be sighted from the primary station since each can then be used as an azimuth reference mark for the other. This is particularly useful for night-time observations when a light can be set up on a tripod as a reference mark.

Table 2.1 **Accuracy of Repeat Station Results**

	D(′)	I(′)	H(nT)	Z(nT)	F(nT)	
Australia	1-2		4-10	5-10	5	McEwin,pers.comm.
Brazil	2-4	5			10	Barreto, pers.comm.
France	1		4	3.5	4	Gilbert and Bitterly, 1989
Germany	1		3-4	3-4		Mundt, 1980
Italy	2		8	8	8	Molina et al., 1985
S. Africa	2-4			12-24		Scheepers, 1969
Switzerland	1-2				10	Fischer, et al., 1979
UK	1.5		6	6	5	Barraclough, pers. comm.

CHAPTER 3 Survey Preparations

3.1 Documentation

Maintain a detailed description of each repeat station, giving the station location, bearings of reference marks, field gradient data and other descriptive information (refer to § 4.5). If a new repeat station is being installed, check the literature to see if a station was previously located in the region of interest. The Carnegie Institution of Washington established stations in many parts of the world during the early part of this century (Bauer, 1912; Bauer and Fleming, 1915; Bauer et al., 1921; Fisk and Sverdrup, 1927; Wallis and Green, 1947). When successive stations are installed at the same locality, they should be named in sequence, e.g., Station-A, Station-B, etc. <u>It is essential to distinguish between different stations at the same locality, no matter how close together they may be.</u>

Obtain large-scale topographic maps covering each repeat-station site. They are useful for determining latitude and longitude if a GPS determination is not possible (§ 4.3.5), for preparing site diagrams showing reference marks, absolute and variometer station locations, and for selecting possible sites for new stations.

Refer to any available aeromagnetic anomaly maps of the region to check that the station is in an area of low magnetic field gradients (to reduce sensitivity to positioning errors) and low magnetic anomaly values (less risk of crustal induction effects).

Finally, if any of the repeat stations are on land to which access is restricted (airports, military bases, etc.), write in advance to the authorities concerned to inform them of the purpose of the survey, and to request access permission and cooperation.

3.2 Time of Year

Avoid carrying out magnetic surveys during times when the probability of magnetic activity is high. Maxima in magnetic activity generally occur during the sunlit summer months in the polar regions, and during the equinoxes over the rest of the Earth (Fig. 3.1). The effects near the equator of the equatorial electrojet are also greatest at the equinoxes.

Logistical and weather considerations also influence the times when surveys can be carried out. Avoid very hot conditions because atmospheric refraction affects the sighting of reference marks, and large daily temperature fluctuations will increase problems associated with temperature-drifts in fluxgate sensors and electronic instruments. Avoid rainy seasons. It is difficult to operate most instruments in the rain, astronomical observations are often impossible (but see § 5.4.3), and it is difficult to make a stable variometer installation in wet ground.

In the polar regions, it is generally impractical to undertake field work during the winter when magnetic activity is at a minimum. The observer must usually try to do the survey in the late summer or autumn, climate and snow conditions permitting, and stay as long as possible at each station. Even so, reduction to a quiet level is likely to be difficult.

If repeat data are to be reduced to equi-

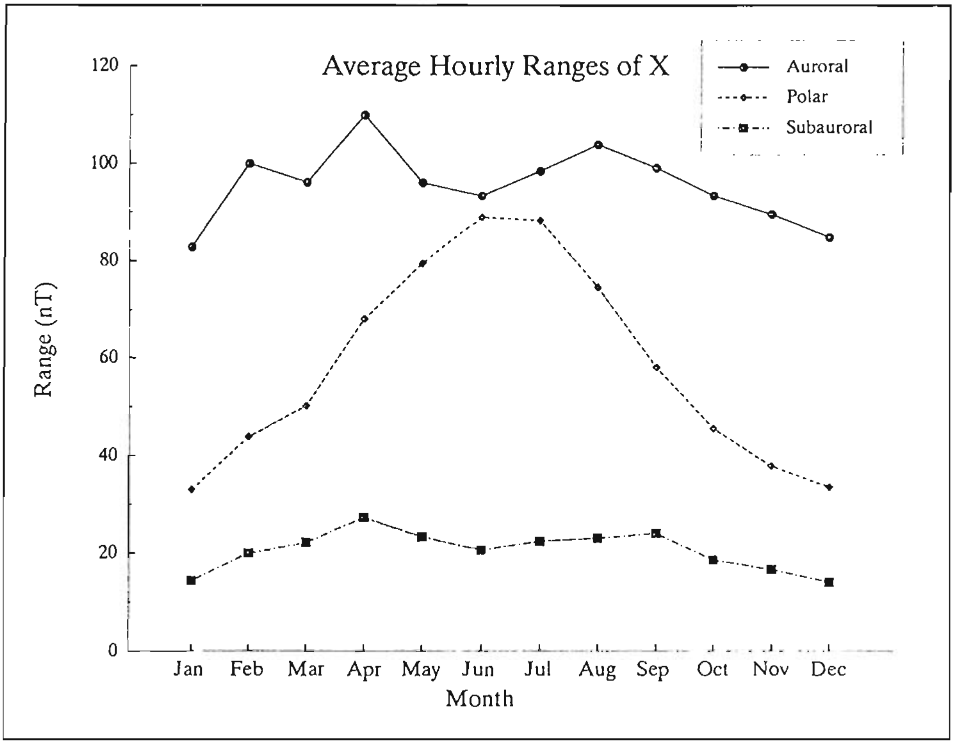

Figure 3.1
Seasonal variation of magnetic activity at a northern hemisphere mid-latitude observatory (Ottawa), an auroral observatory (Fort Churchill), and at a polar cap observatory (Resolute Bay). The hourly ranges have been averaged for every hour of each month over a complete solar cycle.

valent annual means using data from a reference observatory (§ 6.1), it is best to carry out the survey near the middle of the year in question. This reduces the error arising from the non-uniformity of secular variation between the survey site and the observatory (§ 6.3.4). Fortunately, the middle of a calendar year (epoch yyyy.5) corresponds to a time of reduced magnetic activity everywhere except in the polar regions. If the observations are not reduced to a mid-year value, it is desirable to reoccupy the station at the same time of year as the previous occupation. This helps to remove any seasonal effects from the determination of secular variation.

3.3 Logistics

3.3.1 Transportation

Most surveys are carried out using a truck or van over the existing road network. For remote locations requiring sea or air transport, the equipment required for a survey should be packaged into cases that can each be lifted by one person. The total weight of equipment, including a variometer and chart recorder, may be as much as 200 kg (see Appendix 1). For air travel, consider taking the equipment as excess baggage — there is less chance of delays, customs formalities are often easier, and the cost may not be unreasonable. Locate stations so as to simplify transportation requirements (e.g., on airfields).

3.3.2 Field crew

The field crew usually consists of one skilled observer plus one assistant. The assistant records observations and times, helps to determine station differences, carries boxes, constructs pillars or slabs when new stations are installed, and shares the driving. If possible, the assistant should be able to substitute for the observer. This is useful for simultaneous observations. It is also useful if the observer, or the assistant, has sufficient knowledge of electronics to be able to make simple repairs to the equipment. Surveys can be done by a single observer, but it is better to have an assistant. It may be possible to engage someone locally to assist.

3.4 Instruments

This section describes commonly-used modern instruments employing fluxgate sensors and the proton precession magnetometer. Absolute measurements at the repeat station are made with a DIM and a PPM. Details about measurement procedures are given in § 5.3, § 5.4, and § 5.5.

3.4.1 Classical instruments

Observations of the required accuracy for repeat station measurements can be made using "classical" equipment, provided the instruments are fully calibrated before and after each survey. Hazard (1957), Wienert (1970), and Jankowski and Sucksdorff (1996) give descriptions of the theory and operation of many types of classical instruments. A mixture of classical and modern instruments that is still popular for absolute measurements consists of an Askania declinometer for measuring **D**, a quartz horizontal magnetometer for **H** (and **D**, if desired), and a PPM for **F**. Some groups carry classical instruments as a backup for the electronic DIM.

3.4.2 DI magnetometer (DIM)

The portable magnetometer-theodolite, fitted with a fluxgate sensor, is becoming the standard instrument for absolute measurements of declination and inclination (Jankowski and Sucksdorff, 1996). This instrument is commonly called a declination-inclination magnetometer (DIM, the term used throughout this guide), or a DI fluxgate. A single-axis fluxgate sensor is mounted parallel to the axis of the telescope of a non-magnetic theodolite, and connected by a long, flexible cable to a battery-powered electronics unit. The instrument is usually used in the null mode; that is, it is aligned perpendicular to the direction of the magnetic field so that the output is zero. Some versions of the instrument can be used to measure field components directly (Bitterly et al., 1984).

Both the Zeiss-Jena 020B and the more precise 010B non-magnetic theodolites are commonly used for repeat station work. The former instrument has a precision of 12 seconds of arc (compared to 1 second of arc for the 010B), although accuracies of better than 5 seconds of arc can be achieved by taking several observations (Newitt and Jansen van Beek, 1990). The 020B is adequate for repeat station work and is easier to use than the 010B.

Many institutions using DIMs have constructed their own electronics but use

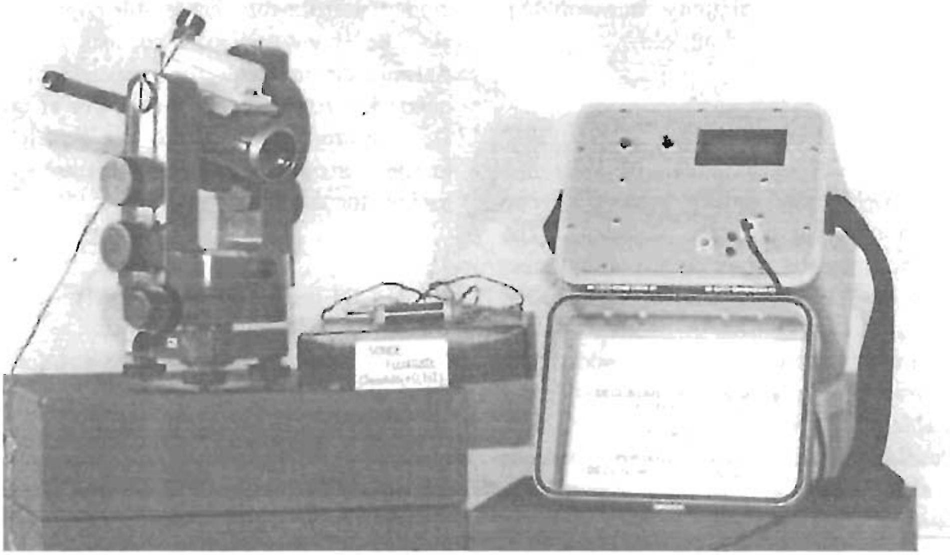

Figure 3.2
DI magnetometer (DIM) used for measuring declination and inclination. The instrument comprises a fluxgate sensor mounted on a non-magnetic theodolite, and associated electronics.

commercially manufactured fluxgate sensors. A few companies manufacture and sell the complete unit. Fig. 3.2 shows the apparatus currently used for magnetic repeat station surveys in France (Cantin et al., 1991).

The theodolite of the DIM is also used for the determination of azimuth by sighting the Sun, or stars, and for measuring the angles between reference marks (§ 5.4). Accessories used with the DIM are listed in Appendix 1.

The DIM is most accurate when used at mid-latitudes. The null adjustment to measure **D** at very high latitudes, or **I** at very low latitudes, is less sensitive. The instrument can withstand temperature extremes, although the cable attached to the fluxgate sensor may become brittle and prone to damage at very low temperatures. It can be replaced with a polyurethane jacketed cable, which has superior properties for use in cold conditions. Standard precautions must be taken when using the theodolite, such as to avoid temperature gradients across the instrument arising from direct sunlight. When the instrument is used in tropical regions, or in other regions of high humidity, ensure that the instrument is protected against moisture.

In principle, the DIM is an absolute instrument since only null observations are made. In practice, this must be checked using standard instrument comparison methods, as it is possible for permanent or induced magnetism of parts of the instrument to affect the final result. Intercomparisons between DIMs at mid-latitudes often show differences of a few tenths of a minute of arc in both D and I. Thus some care must be taken to achieve the levels of accuracy discussed in § 2.4.

Observational procedures for the DIM (§ 5.5.1) are designed to eliminate potential errors due to misalignment of the fluxgate and remanent magnetization of the instrument. Non-linear vertical gradients of the geomagnetic field cause errors in D- and I-observations since the mean of the field in the coil-up (fluxgate sensor above the telescope) and coil-down positions will not equal the field at the mean position, but it requires a strong non-linear gradient to produce a significant error. For example, if the distance between the coil-up and coil-down positions is 10 cm, a change in vertical gradient of 1 nT/m per cm will produce an error of only 0.5 nT.

Information about the DIM can be found in published proceedings of several recent international workshops on magnetic observatory instrumentation (Coles, 1988; Kauristie et al., 1990; Geophysical Transactions, 1991), and elsewhere (Trigg, 1970; Kerridge 1985a; Kring Lauridsen, 1985; Kerridge 1988; Jankowski and Sucksdorff, 1996).

3.4.3 Proton precession magnetometer

The total intensity of the field is measured most conveniently with a proton precession magnetometer. PPMs commonly in use have sensitivities of better than one nanoesla. Provided that the frequency standards in the electronics are correctly set and the sensor is non-magnetic, the readings give an absolute measure of the total field. Frequencies should be set for the value of the proton gyromagnetic ratio adopted by IAGA in 1991 — 26751.525581 x 10^4 rad T^{-1} s^{-1} (Rasmussen, 1991). The gyromagnetic ratio will vary slightly depending on the fluid used in the sensor. The value is normally given for water at 25° C. The ratio for commonly used fluids can differ from the above value by up to 10 ppm, resulting in an error of up to 0.5 nT (Hrvoic, private communication).

Each PPM should be compared with a known standard in case a correction is required. Corrections are typically up to a few nanotesla. Often, the PPM sensor becomes slightly magnetic due to magnetic dust particles that become imbedded in the sensor casing. If a large correction is determined during a comparison session, clean the sensor and carry out a second comparison.

The output of a PPM may depend slightly on the orientation of the sensor, possibly due to magnetization effects. If so, the instrument should always be used with the sensor in the same orientation, and always upright (connectors down) or always inverted (connectors up).

Proton precession magnetometers based on the Overhauser effect (Overhauser, 1953) are becoming more widely used. They can be cycled more rapidly than a conventional PPM; they are potentially more sensitive; and they consume less power. Overhauser-effect instruments are used in exactly the same way as conventional PPMs.

Many commercial manufacturers supply instruments suitable for repeat station use. One of the instruments used by the Geological Survey of Canada is shown in Fig. 3.3. More details on the theory and operation of proton magnetometers are given by Jankowski and Sucksdorff (1996).

Figure 3.3
Proton precession magnetometer with solid state memory, used for measuring and recording total intensity.

3.4.4 Variometers

A three-axis variometer may be used to record temporal variations of the geomagnetic field in the vicinity of the repeat station. A fluxgate magnetometer is by far the simplest type of instrument to use for this purpose. Its basic theory and operation are described by Jankowski and Sucksdorff (1996). Several commercially-manufactured instruments are available, some incorporating ring-core technology in the sensor construction (Narod and Bennest, 1990). The three-axis magnetometer used by the Geological Survey of Canada is shown in Fig. 3.4. It was designed and constructed in-house using commercially available components.

Fluxgate magnetometers are subject to drift due to temperature variations, and some instruments in common use have temperature coefficients in excess of 1 nT/°C. It is advisable to determine the temperature characteristics of the instrument (both the sensor and the electronics) before carrying out a survey (§ 3.4.6). Insulated boxes for both the sensor and the electronics can be used to minimize temperature fluctuations when the magnetometer is set up outdoors. These boxes can serve as protective cases for the instruments during transportation. Burial of the sensor is effective for reducing diurnal temperature variations.

The variometer output should be available in digital form, if possible. One-minute mean values, similar to the standard output of most digital magnetic observatories, are ideal. The digital data are often recorded with a personal computer, but other forms of recording are in use (magnetic tape, diskette, or directly into solid state memory for later retrieval by a computer). If digital recording is not possible, data can be re-

Figure 3.4
Three-axis magnetometer with ring-core fluxgate sensors and internal solid-state memory, used for recording variations in the magnetic field elements (**X,Y,Z**, or **D,H,Z**). Shown here, clockwise from the bottom left, are the fluxgate sensor, battery power supply, magnetometer electronics, portable computer used for controlling magnetometer functions and retrieving data, and chart recorder.

corded on a multi-channel chart recorder. The analog records may be digitized later for digital processing, or hand-scaled in the same manner as standard photographic magnetograms.

Either the variometer or the recorder must be equipped with an accurate clock that will put time marks on the output record at appropriate intervals. The internal clock in a PC seldom has the required accuracy for time labels, and must be properly calibrated if used.

Even when the primary method of recording is digital, a small, single-channel chart recorder is useful to allow the observer to check the state of disturbance of the magnetic field. Alternatively, the field variations may be plotted on the computer screen.

It is useful, but not essential, to record the total field, **F**, as well as the three orthogonal components of the field. This provides a cross-check on the drift and baselines of the three-axis variometer (§ 6.2.1), and also provides a backup in case of failure of one of the recording channels. A recording proton precession magnetometer with digital output or with solid state memory can be used for this purpose. Such instruments are widely used by the mineral exploration industry and are commercially available. The PPM shown in Fig. 3.3 is of this type.

Many magnetometer systems use a large amount of power and require either access to a commercial AC power supply, or the use of a portable generator or solar panels. A system that can be operated on batteries has the advantage of flexibility in the location of the installation.

3.4.5 Calibration of instruments

The DIM, PPM, and three-axis variometer should each be checked thoroughly and calibrated at a magnetic observatory before and after a repeat station survey.

Check the theodolite to ensure that it is non-magnetic and that its optics are properly aligned. Test the alignment of the fluxgate sensor parallel to the axis of the telescope and adjust if it is misaligned by more than about 10 minutes of arc. The procedure for making DIM observations is designed to cancel the effects of fluxgate misalignment, but it is unwise to use the instrument in such a state. One method of adjusting the alignment is as follows.

Level the theodolite and adjust the vertical circle to read 0° (telescope pointing vertically upwards). Adjust the offset control on the fluxgate electronics to obtain a finite signal on the most sensitive range. Rotate the theodolite about a vertical axis and observe the fluxgate output. If this changes by no more than a few nanoteslas, then the fluxgate is correctly aligned. If not, then use a non-magnetic (brass) screwdriver to adjust the screws on the fluxgate mounting to achieve correct alignment. Do this systematically by orienting the sensor so that the adjustment is made in the magnetic N-S direction. Make one adjustment, then turn through 90° to make the next. Check periodically to ensure that the vertical circle still reads exactly 0°

The DIM should be checked to ensure that the output is zero when the sensor is in zero-field. Adjust the electronic offset as necessary to achieve this. The stability of the electronics should also be checked. Long-term stability is not required if the instrument is to be used in the null-mode, but the electronics must remain stable over the length of time required for an observation. Consult the operator's manual for the DIM, or refer to Jankowski and Sucksdorff (1996), for more details about how to adjust a DIM.

Finally, make comparisons between the DIM and the observatory standard instruments. In principle, the DIM should not require an instrument correction (§ 3.4.2). If the observer finds a significant difference between the field instrument and the observatory standard, further investigation of the source of the difference is warranted. It is possible that the theodolite contains parts that are magnetic.

The proton precession magnetometer should also be calibrated by comparison with the observatory standard PPM. An alternative method is to check the frequencies in the electronics against accurate frequency standards (see Jankowski and Sucksdorff, 1996). Check if the output reading of the PPM is dependent on orientation or inversion of the sensor.

If two PPMs are being used during the survey, they may be intercalibrated quickly on arrival at the station in the following manner. Set up the PPMs at any two fixed points and, with the help of an assistant, make simultaneous observations. Interchange the instruments and repeat the measurements. The instrument difference is half the difference between the two observed station differences.

The three-axis variometer (if used) should be set up and test-run for an extended period of time. Check the sensitivity of each channel by comparing sample outputs with observatory records.

3.4.6 Effects of temperature on fluxgate magnetometers

The output of a fluxgate magnetometer has a temperature dependence that is often too large to ignore. Although some systems have coefficients as low as a fraction of a nanotesla per degree, some popular commercially-manufactured units have temperature coefficients of up to 5 nT/°C.

Unfortunately, it is difficult both to determine and to correct for temperature effects. In theory, temperature coefficients can be determined by placing the magnetometer and sensor in a chamber at a controlled temperature, letting the instrument reach temperature equilibrium, and then taking absolute observations. The procedure is then repeated at a different temperature. The difference in baselines, determined from the absolute observations, divided by the difference in temperature, gives the temperature coefficient.

In practice, there are several difficulties with this method. The sensor and the electronics are unlikely to have equal temperature coefficients. The temperature coefficient of the sensor may depend on the strength of the applied field so that a value determined at a reference observatory may not be applicable in the survey area. Thermal lag in the sensor assembly means that the recorded temperature may not be the same as the sensor temperature. Nevertheless, you should go through the above procedure if only to determine the seriousness of the problem for your equipment.

In the field, the effects of temperature can be partially mitigated by reducing the temperature fluctuations experienced by the sensor. Bury the sensor underground and cover it with an insulated box. Place a tarpaulin over the installation. Place the electronics in an insulated box, and place the box in a shaded location.

If the temperature of the sensor is recorded along with the magnetic elements, it is sometimes possible to calculate an apparent temperature coefficient for the entire variometer system. This is discussed in § 6.2.4.

CHAPTER 4 Siting and Installation of a Repeat Station

A new repeat station must be installed when a network is being established or expanded, a station has been destroyed or contaminated magnetically, or a secondary station is required. Careful siting is important to ensure good results and a long lifetime for the station. Some repeat stations are still being used after nearly 100 years (Fig. 4.1(a)). Airfields often provide a good environment for repeat stations as they usually satisfy most of the criteria listed below (see also § 3.3.1).

4.1 Choice of Location

4.1.1 Choice of absolute station site

A magnetic repeat station is chosen using the same criteria used for establishing a magnetic observatory. These are listed by Wienert (1970, pp. 15-16) and are, in brief:

(i) the values of the magnetic elements should be representative of the region;
(ii) the magnetic field at the site should not be influenced by magnetic anomalies caused by geological structures;
(iii) the subsurface in the surrounding region should be electrically homogeneous (oceans are usually the dominant source of electrical conductivity inhomogeneity);
(iv) the magnetic field should be uniform in the vicinity of the station marker;
(v) the site should be free from sources of artificial disturbances such as electric railways, generating stations, power lines, transmitters, etc.

It is difficult enough to meet these criteria for a magnetic observatory, and often impossible when establishing a repeat station. In practice, a compromise must be reached, bearing in mind additional requirements such as the need for an equally-spaced network of stations, ease of access to the site, good security, and availability of support services. Siting requirements are discussed in more detail below.

Regionally representative field. The criterion for finding a site that is representative of the regional field can be relaxed if the survey data are to be used for determining the secular variation only and not for field mapping. Magnetic anomalies caused by crustal remanence remain relatively constant with time and will not affect the secular variation. However, the presence of large magnetic anomalies may be indicative of non-homogeneous subsurface electrical conductivity properties that can affect repeat station observations. Crustal magnetization induced by the main field will also affect secular variation determinations, but this is usually ignored (the crustal contribution being the difference between the observed secular variation and the "true" secular variation, as defined in the explanation of terms).

Low gradients. The horizontal and vertical gradients of total field at a repeat station should each be less than a few nT per metre. In certain geological provinces, such low gradients may be impossible to find. Gradients pose a particular problem in basaltic regions, such as volcanic islands, where they may exceed several tens of nT per metre. Adequate secular variation determinations can still be made under these circumstances provided care is taken to relocate the instruments very accurately when reoccupying the site (see § 5.3 and § 6.3.2).

Permanence. Repeat station sites should be usable for many decades. Do not choose locations that are likely to be built up in a few years, or places where transient magnetic noise may cause problems (near roads, railways etc.). Sites on government land, such as airports and weather stations, are often suitable. A variometer can be set up anywhere in the vicinity of the repeat station, subject to the important requirement that field variations at the variometer site reflect accurately the field variations at the repeat station.

Access. You will probably wish to drive to the site and commute between the repeat station and the variometer, if one is installed. Is the site accessible at any time of year, and are there any security restrictions on access?

Freedom from artificial disturbances. Avoid sources of man-made magnetic fields, particularly locations near DC railways or DC power lines. The effects are noticeable at distances of more than 20 km (Wienert, 1970). The effects of radio transmitters and radar, which are prevalent at airports, are also of concern. Although fluxgate magnetometers are relatively unaffected by transmitters, proton magnetometers may be affected. Test that your PPM functions normally at a location before installing a station.

Reference marks. Check that several suitable azimuth reference marks are visible from the proposed station (see § 4.1.3). Using reference marks for azimuth determinations eliminates the necessity of taking sun observations each time the site is occupied.

Ease of relocation. Repeat stations should be located where there are landmarks to facilitate relocation of the site. If there are no features nearby, it may be necessary to build a cairn. Station plaques at ground level are easily obscured by vegetation and can become covered by outwashes from rain storms and floods. A metal detector may sometimes be useful for finding a buried plaque.

When installing a new station (§ 2.5), bear in mind the desirability of installing a secondary station. The secondary station must be sufficiently remote from the primary that there is little risk of both stations being destroyed or contaminated at the same time. It is convenient to have the secondary station a few hundred metres from the primary so that each can be used as a reference mark for the other, yet still be within easy walking distance.

Fig. 4.1 (a) shows an example of a well-located repeat station at Suva Vou in Fiji. The site lies at the extremity of a peninsula of land that is occupied by a sacred cemetery. The condition of the site appears to be much the same as when it was established in 1895 by a British Naval party from *HMS Waterwitch*. Fig. 4.1 (b) shows an example of a poorly located repeat station. The site is now surrounded by buildings that were not there when the station was installed some 25 years ago. Magnetic gradients are also extremely large at the site (58 nT/m), but this is unavoidable because of the geological province in which the station is located. Fig. 4.1 (c) shows an example of a site with poor accessibility. The photo shows the station in the spring, when it was originally installed. The ground was frozen and thickly snow-covered, obscuring the fact that the rock in which the station plaque was placed sits in a shallow lake in summer.

Figure 4.1 (a)

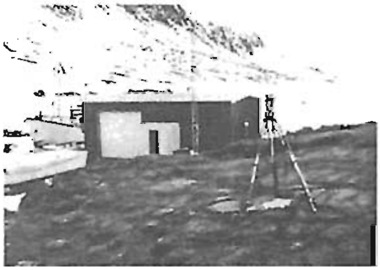

Figure 4.1 (b)

Figure 4.1 (c)

4.1 (a) Repeat station at Suva, Fiji. The station was set up in 1895 by a British naval party on a peninsula of land that is protected from development by a cemetery. The station is still used by the Australian Geological Survey Organisation.

4.1 (b) Repeat station at Pangnirtung, Canada. During the 30 years since the installation of the station, the village has increased in size. Buildings have now been constructed so close to the station that it can no longer be used.

4.1 (c) Magnetic repeat station at Coral Harbour, Canada. The station was originally installed in the spring when the ground was snow-covered. The observer did not realize that the rock in which the plaque was installed is actually located in a small lake, which makes it almost inaccessible in the summer.

4.1.2 Choice of variometer site

The following considerations influence the choice of variometer site.

Access to AC mains power. The power requirements of some variometer and data acquisition systems necessitate access to an AC mains power supply. In remote locations, a portable generator may have to be used, but a reliable AC mains supply is more convenient. The use of low-power equipment operated by batteries (or solar-power devices) allows much greater flexibility when choosing a site.

Security. Choose a site that is not exposed to risks from theft, vandalism, and from curious visitors who might disturb the sensors or cause magnetic contamination.

Ease of access. The variometer site should be easily accessible so that regular visits can be made to check that the clock is functioning correctly, that data are being recorded, and also to monitor the level of magnetic disturbance.

Interference. The site should be free from transient magnetic noise (e.g., vehicles) and interference from electromagnetic signals. Local magnetic contamination (e.g., buildings) is not a problem provided there is no change in the magnetic environment during recording, and there are no transient induction effects.

Proximity to the repeat station. The variometer is best installed within a few hundred metres of the repeat station, but this is often not possible. Distances of up to several kilometres, or even more, may be unavoidable. The acceptable distance is conditional on the electrical conductivity properties of the crust being sufficiently homogeneous that the geomagnetic variation signals at the variometer and repeat station are essentially the same. Some observers prefer to set up a single, centrally located variometer base-station that can be used to reduce the data from several repeat stations in a region. Since the base-station might be 100 km or more from the repeat stations it serves, there is a much greater chance that crustal inhomogeneities will pose a problem (§ 6.3.6)

Uniformity of the geomagnetic variation signals between the repeat station and the variometer site, or the reference observatory, becomes more important as the level of magnetic disturbance increases. Under disturbed conditions, transient induction effects can become large and may vary significantly over distances as short as a few kilometres.

4.1.3 Choice of azimuth marks

Choose at least four azimuth reference marks, preferably more-or-less uniformly spread around 360°. Designate one as the main reference mark (close to magnetic north or south is convenient). Reference marks should be prominent features with sharply defined edges or points, at least 200 m away. Reference marks that are too far away (several km) may be difficult to sight in hot conditions due to atmospheric refraction, or in hazy and misty conditions. It is better to choose reference marks that are not too far above the horizon so that the telescope remains approximately horizontal while they are being observed.

Flagpoles, windsocks, and radio towers do not make good reference marks since they may tilt over a period of time and can sway in the wind. If they must be used, sight their bases. Windsocks are sometimes blown over in regions subject to strong winds; when re-erected they will not be in exactly the same position.

Be wary of using reference marks that may lose their contrast at certain times of day, depending on the direction of the Sun. For example, one edge of a water tower may be in shadow during the morning and clearly silhouetted against the sky, whereas in afternoon sunlight it may be almost invisible. Make allowance for vegetation that may grow to obscure azimuth marks and landmarks. A tripod set up at a secondary repeat station makes a convenient reference mark for the primary station (and vice-versa).

The use of several reference marks, and regular observations of the angles between them, guards against the danger of one or more marks being shifted, obscured, or destroyed.

4.2 Total-field Gradient Measurements

Carry out a quick survey to determine the total-field gradient at a potential new site. If the field varies by more than about 50 nT within a radius of 10 m, an alternative site should be sought. If it is not possible to find a site that meets this standard, then the site with the lowest gradient should be used.

After selecting a site, a more detailed total-field gradient survey should be carried out. There are several ways to do this. For example:

(1) mark the point at which the new station will be installed;

(2) take an initial reading at the mark, preferably at the standard height used for absolute observations;

(3) proceed in a cardinal direction (e.g., north), taking a PPM reading at 0.5 m, 1.0 m and every metre thereafter out to 5 or 10 m;

(4) return to the station marker and take another reading;

(5) proceed in a similar manner in the other three cardinal directions;

(6) take PPM observations vertically above the station marker at 20 cm intervals from 20 cm above ground level up to a height of 200 cm. A graduated rod is useful for this purpose.

The repeated readings at the central point enable the observer to detect temporal variations of the background field. An approximate correction for the time-variation of the field can be made by applying linear interpolation between successive centre-point readings. If the change is more than a few nanoteslas, the gradient survey should be repeated, or the measurements corrected using data from a nearby variometer or reference observatory.

The vertical gradient of **F** can be used to test the magnetic influence of a concrete slab or station marker (the gradient will be non-linear and will be different from the corresponding gradient to the side of the concrete construction). Note that DIM measurements are subject to errors arising from large non-linear vertical gradients (§ 3.4.2).

Document the results of the gradient survey and keep them on file. A possible format is illustrated in Fig. 4.2. During subsequent re-occupations, remeasure the gradients of **F** and compare them with earlier results to check for any change in the magnetic environment. Changes caused by newly-installed underground pipes or cables may not be readily visible (§ 5.2).

4.3 Construction of a Repeat Station

A repeat station must be permanently marked, usually with a pillar, a bronze plaque or plug set in concrete, or a permanent engraving in bedrock. It may be possible to use a triangulation station previously installed by a national geodetic service. This has the advantage that the latitude and longitude are precisely determined, and azimuths of other triangulation stations are available for reference marks. Be certain, however, that the triangulation station and its foundation do not contain magnetic material.

The material used for constructing repeat station pillars or ground markers must be as non-magnetic as possible. Some gravels and sands used for making concrete may contain magnetic minerals and produce unacceptable field gradients. Particular care must be taken with materials used for upgrading an existing repeat station. Not only must the field gradients be low, but the background field must not be changed.

4.3.1 Construction of a pillar

The best form of station marker is a purpose-built pillar, usually made of non-magnetic concrete. Unless installed on bedrock, use a flared base extending at least 50 cm below ground level to ensure stable

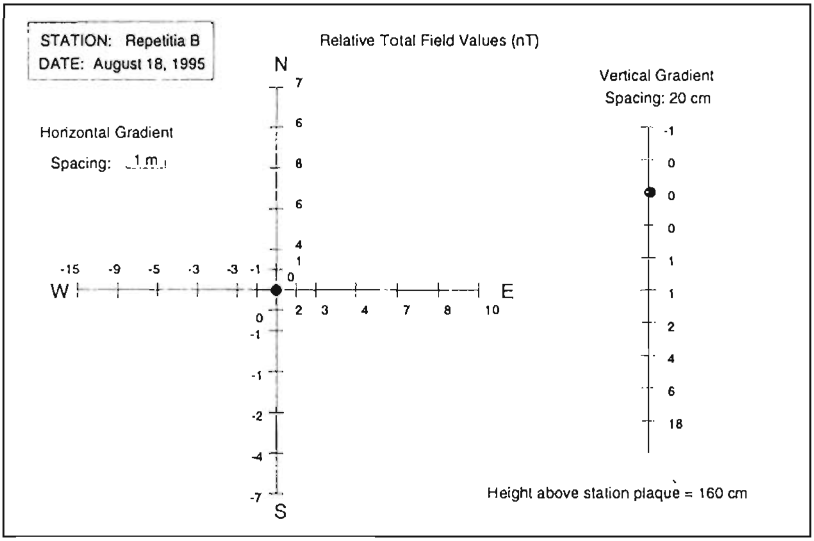

Figure 4.2
Results of a total-field gradient survey at a repeat station. Total field values are specified in nT relative to the central point of the grid (●). This point is 160 cm above the station plaque.

anchorage. In cold climates, the base should be installed below the frost line. The pillar may be cylindrical or square, with a top dimension of about 30 cm. Grooved footplates or sockets of brass, or another non-magnetic material, can be embedded at 120-degree intervals on the top of the pillar to ensure exact placement of the theodolite feet. The theodolite, or PPM sensor, can be placed directly on the pillar, provided a mounting is used to ensure that measurements are made at exactly the same height. Fig. 4.3 shows an example of a pillar installed at a Vietnamese repeat station. The disadvantages of a pillar are that it is costly and time-consuming to build, it may be prone to vandalism, and may have an undesirable impact on the environment. It may not be possible to use pillars on airfields because of the risk to aircraft.

Figure 4.3
Repeat station in Vietnam at which a pillar has been installed.

4.3.2 Construction of a slab

A ground-level slab of concrete provides excellent stability for a tripod and is easier to construct than a pillar. The slab may be triangular or square, approximately 150 cm along a side, and should protrude just above ground level (posing no risk to grass-cutting equipment if located on airfields). The station plaque is placed in the centre of the slab. Avoid placing the slab in a depression where it might become buried by outwash of soil after rainstorms, or overgrown by surface vegetation.

Set three aluminium or brass tubes in the concrete slab for locating the legs of the tripod. The tubes should be about 10 cm

Figure 4.4
French repeat station at Ile Saint Paul, at which a slab has been constructed to support the tripod.

long, placed equidistant from the central marker at 120° intervals, and protrude just above the surface of the slab. Place one of the tubes magnetic north of the central marker, and label it "N" on the concrete slab. When setting the tubes in the slab, use a spirit level to ensure that the tops of the tubes lie in a horizontal plane. Use of a prefabricated template is recommended for installing, centring, and levelling the tubes. It is worthwhile ensuring that the tubes for locating the tripod legs are installed to the same specifications at all repeat stations. This allows the tripod to be oriented and conveniently set up at the same height at all stations. In areas subject to gusts of wind, several non-magnetic eyelets can be set into the slab during construction. These can be used subsequently to secure the tripod legs to the ground. Fig. 4.4 shows an example of a slab installed at one of the French subantarctic repeat stations.

4.3.3 Construction of a benchmark

A benchmark (marker plug) is less satisfactory than a slab, but sometimes used when time and materials do not permit the installation of a slab. The plug is a cylinder of concrete, approximately 30 cm in diameter, set in the ground, flush with the surface. The plug must extend deeply enough into the ground that it will not work loose. The bronze station marker plaque is set in the top surface of the plug. Three footpads for the tripod can also be poured and metal tubes fitted as described in § 4.3.2. If this is not possible, insert 3 brass pipes in the ground as locators for the tripod feet. Use a template to ensure that all installations are identical. Fig. 4.5 shows an example of a concrete plug with separate footpads installed at an Australian repeat station.

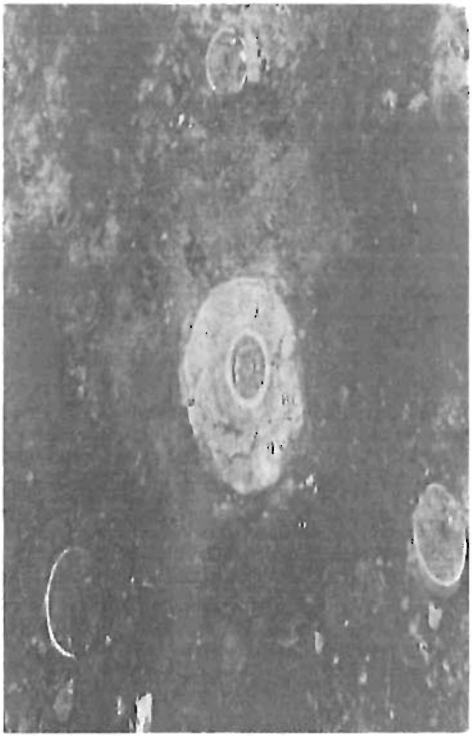

Figure 4.5
Repeat station at Eucla, Australia at which the marker is set in a cylinder of concrete. Separate pads have been made to support the tripod legs.

4.3.4 Construction of a bedrock marker

It may be convenient, or necessary, to install the station plaque in an exposed, stable rock surface (Fig. 4.6). If the plaque is a flat bronze disk, attach it to the flat rock surface using good quality epoxy adhesive. If the plaque consists of a disk with a shaft, insert and fix it in a hole drilled in the rock. In some situations, particularly if vandalism is a serious problem, the centre mark for the station and the 3 locating holes for the tripod can be chiselled directly into the rock.

Figure 4.6
Repeat station at Igloolik, Canada at which the brass plaque is installed in a shale outcrop.

4.3.5 Relocation of a station using GPS

The latitude, longitude, and elevation of the benchmark must be determined from a large scale topographic chart or, preferably, using a GPS unit. The coordinates should be noted on the repeat station description (§ 4.5) to aid in finding the station in the future.

GPS positions obtainable from a hand-held GPS unit are not accurate enough to eliminate the need for a proper station benchmark. Typical positioning errors range from ± 10 to ± 50 m. Even in areas of low gradients, such positioning errors introduce unacceptably large errors in the determination of the secular variation.

The necessary positional accuracy can be obtained by using two high precision GPS receivers in differential mode. This allows the relocation of a station to within 2 cm, which is acceptable except in areas of very high gradients. However, high precision GPS receivers are still expensive, and their use adds another degree of complexity to the repeat station survey. These factors must be weighed against the one-time effort required to install a permanent benchmark, and the advantage of easy, visual relocation thereafter.

There are some circumstances when it is impossible to install a station marker, such as on an ice cap. Under such circumstances, GPS may be the only means of relocating the site for the purpose of making repeat observations. Differential GPS is preferable, but if the region is remote from sources of magnetic anomalies, i.e., the magnetic gradient is very low, acceptable results may still be achieved even using a hand-held GPS unit. A detailed gradient survey of the site would be required to demonstrate this.

4.4 Proton Magnetometer Auxiliary Station

For making absolute measurements of F, the PPM can be interchanged with the DIM on the tripod, or pillar, with care being taken to centre the instruments at the same height. If many sets of absolute measurements are to be made, the interchanging of instruments is time-consuming and can introduce errors. It is then more convenient to make measurements at an auxiliary PPM station set up 5 to 10 meters from the main station. (An auxiliary station, as defined here, is quite distinct from a secondary repeat station.)

A station-difference measurement must be made so that observations at the auxiliary station can be corrected to the main station.

It is useful to mark the auxiliary station permanently using another bronze plaque set in concrete, or, perhaps, an aluminium pipe in which the PPM sensor staff can be inserted. Check the station difference at each reoccupation of the repeat station (§ 5.5.2).

4.5 Station Description

Keep a detailed description of each repeat-station site, and update it after each reoccupation. Information required in the repeat-station description should include the following.

(1) The exact name of the station, with letters (A,B,C,...) to denote different or former stations in the same area.

(2) Names, addresses, and telephone numbers of local contacts, landowners, authorities for permission to access the site, and persons with an interest in the results.

(3) Descriptions of the locations of the primary and secondary stations (and any other stations that may exist in the vicinity). Include geodetic coordinates (latitude, longitude, elevation), photographs, and sketches. Include also a description of the location of the proton magnetomter auxiliary station.

(4) Descriptions of suitable locations for a variometer installation, or the names of suitable reference observatories.

(5) Descriptions of the reference marks and a diagram showing the angles between reference marks and their azimuths. Designate the primary mark. Include photographs and/or sketches.

(6) A table of primary-secondary station differences (all elements) and differences between the auxiliary PPM station and the primary station. Keep a complete record of earlier station differences.

(7) Notes about the condition of the station(s) and any possible sources of magnetic contamination, e.g., proximity to power lines or underground pipes.

(8) A clear statement of the standard height above the station marker at which absolute observations are made — both the height of the top surface of the tripod above the marker and the distance between the secondary axis of the theodolite and the top surface of the tripod (or pillar).

(9) Results of F-gradient surveys, expressed as a table or diagram (see Fig. 4.2) showing distances from the central point and **F** values relative to the centre position (for N, S, E & W and vertical directions). Note the height of the PPM sensor used for the horizontal traverses. Point values, relative to zero at the central point, are more useful than a calculated gradient value because the former can be checked directly against new data.

(10) A geological description of the region. This helps to indicate whether the region may have anomalous magnetic or electrical conductivity properties.

(11) A history of station occupations.

(12) A table and graph of final results (elements of the normal field or mean values vs. time).

A complete station description will encompass several sheets of information. A sample station description diagram is given in Fig. 4.7.

Complete a status report after each visit to a repeat station and file it with the station description documents. A suggested format for a status report is given in Appendix 2.

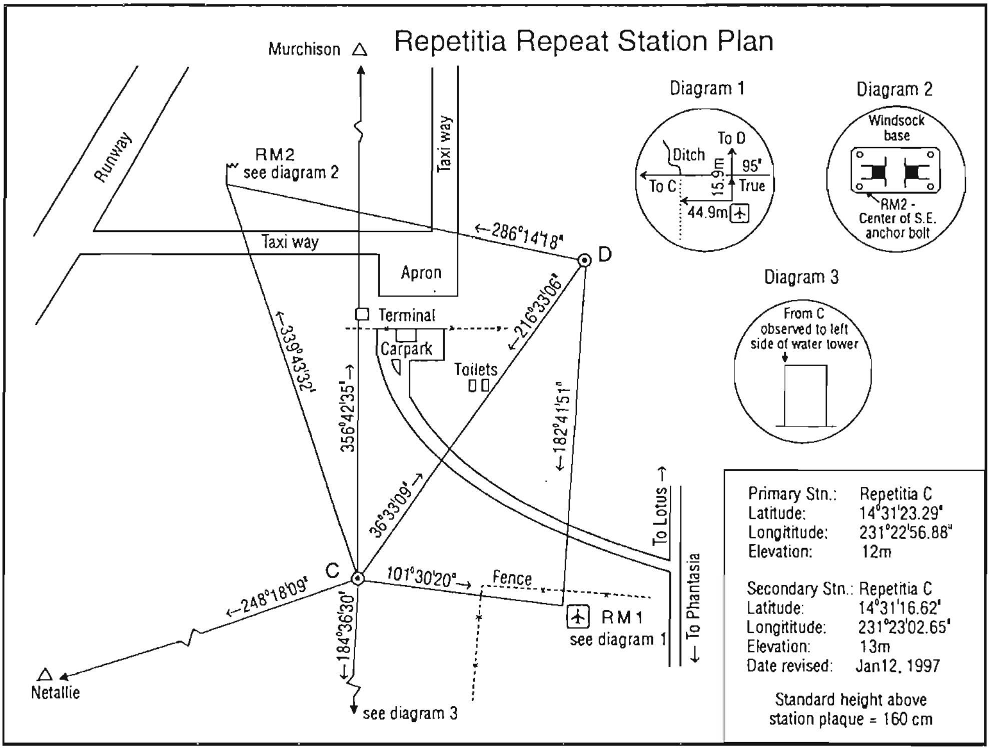

Figure 4.7
Example of a diagrammatic repeat station description; additional information is kept on separate sheets.

CHAPTER 5 Setting up Equipment and Taking Measurements

For the following descriptions, we assume that both a primary and a secondary station already exist, a variometer is being used on-site, and that the station is being occupied for about three days. If a variometer is not used, the same procedure can be followed, except that the variometer steps will be omitted and the duration of the station occupation will be shorter.

Keep a detailed log-book recording all activities and times. Be careful to distinguish between local time and universal time when recording times and dates.

On arrival at a site, conduct any necessary formalities with local authorities. The following sections are presented in the approximate order in which activities would be carried out at the site (§ 5.6)

5.1 Installation of Variometers

Criteria for choosing a variometer site are discussed in § 4.1.2. A variometer will require several hours to equilibrate before stable readings are obtained, so install the variometer before preparing for measurements at the actual repeat station.

The variometer must be set up in a stable physical, thermal, and magnetic environment. Even when this is done, a correction for temperature variations will probably be necessary, and enough absolute observations must be made to quantify any magnetometer drift that may occur (§ 6.2). Include a description of the variometer location in the station description.

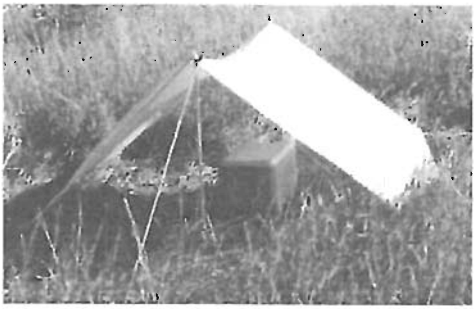

Figure 5.1
Magnetometer sensor installed under a flysheet for protection from direct sunlight; the insulated box is placed over the sensor to reduce temperature variations.

5.1.1 Installation of a three-axis variometer

Mount the variometer sensor on a stable platform, protected from wind and temperature changes by an insulated box, and partly, or totally, buried to reduce diurnal temperature variations. A tent, or flyscreen, can be used to provide protection from direct sunlight and rain (Fig. 5.1). Beware of the effects of magnetic tent pegs and of eyelets in the tent. The instrument electronics should also be protected and insulated, to reduce temperature variations. The electronics and the cable to the sensors will probably have temperature coefficients that differ from that of the sensors (§ 3.4.6).

Carefully level the sensors and orient them in magnetic or geographic coordinates (see below). Check the level a few hours after installation, and again when recording ends. Note any change in level. It is normally better not to re-level the sensor once it has been set up since this results in offsets in the record that may be more difficult to deal with than continuous drifts. Variometer baseline changes can be dealt with provided a sufficient number of absolute observations are made.

Set up an electronic clock to record time marks and reset it accurately to UT using a radio or GPS time-signal. Note the date and time (UT) at which recording starts and ends. One-minute sampling should occur at the start of each minute. Clocks with temperature-compensated crystals are available with accuracies better than 0.5 parts per million, which corresponds to about one second per month. Avoid using the clock inside a personal computer as it is not usually accurate enough for repeat station work.

The axes of the variometer sensor are usually oriented so that either **X**,**Y**,**Z** or **D**,**H**,**Z** are recorded. The geographic system (X,Y,Z) is, in some ways, preferable since it is a fixed reference frame. The alternative, **D**,**H**,**Z** system, i.e., with one of the horizontal axes aligned along magnetic north, is a rotating system; during large field changes, the two horizontal fluxgate sensors will no longer truly register **D** and **H**. This is seldom a problem for repeat station work except at high geomagnetic latitudes. It is convenient to record the same elements as are recorded at the nearest magnetic observatory.

Alignment of the sensors along geomagnetic axes is achieved by levelling the sensors, then rotating about a vertical axis to obtain a null reading on the D-channel. Alignment in the geographic frame is achieved by first aligning along geomagnetic axes, then rotating the sensor about a vertical axis by an amount equal to the expected magnetic declination. Alternatively, a sun compass, theodolite, or gyrotheodolite may be used to determine true north, and the X-axis aligned accordingly using some sighting mechanism.

5.1.2 Installation of a recording PPM

Three-axis variometer data are sufficient for making repeat station measurements, but many observers also record a fourth (F) variation component. Install the sensor of the recording PPM a few metres from the three-axis variometer to insure that the polarizing field of the PPM does not influence the variometer. The sampling interval of the recording PPM should be the same as that of the three-axis variometer, normally one minute. The absolute observations made at the repeat station are used to calibrate both the three-axis and the total-field variometer records.

5.2 Verification of the Station

Use the station description to locate the plaque. Examine the surrounding area and compare it to the station description and photographs. Note any changes that have taken place in a station status report (Appendix 2) and incorporate them later in a revised station description. Take new photographs if required. Do this for both the primary and secondary stations.

Measure the horizontal and vertical gradients of the total field at both the primary and secondary stations to test for magnetic contamination (e.g., new fences, buildings, underground pipes, or cables). If the site is contaminated, several courses of action are possible. It may be possible to remove the source of contamination. If the contamination is large and permanent, for example due to a new building, it will be necessary to abandon the station and adopt the secondary station as the new primary station. A new secondary station must then be installed. The contamination may be permanent, but not large. If further contamination is unlikely in the future, it may be more expedient to continue observing at the station, rather than to install a new one. New station differences between the contaminated primary station (e.g., Mungo-A) and the secondary station (Mungo-B) must be made to determine the corrections to be applied to get continuity between the old and new observations at the primary station. Since the magnetic environment has changed, the primary station must be treated as a new station and should be renamed to avoid confusion (in our example, Mungo-C).

5.3 Setting up a Tripod and Theodolite

You may wish to erect a temporary canopy over the repeat station to protect the observing instruments from Sun and rain. The canopy should permit a view of reference marks and be removable when sun observations are required.

Set up the theodolite on its tripod, or on the pillar. Ensure that the theodolite is centred precisely over the station marker and at the specified standard height (§ 6.3.2). The required accuracy of the centring depends on the magnetic field gradient at the station and the distance to the azimuth reference mark. For example, if the magnetic gradient is 50 nT/m, a positioning error of 2 cm would result in an error of 1 nT in the magnetic observations. If the azimuth reference mark is located 100 m from the station, the same 2 cm (lateral) positioning error could also result in an error of up to 40 seconds of arc in declination.

Accurate levelling of the theodolite is important. If the theodolite is not level, the optical plummet will not point in the vertical direction, leading to a positioning error. In addition, improper levelling will lead to errors in declination readings (§ 5.5.1). A levelling procedure is described in Appendix 3. Avoid direct sunlight on the spirit-levels (bubbles) when levelling.

5.4 Determination of Azimuth

This section describes how observations of the Sun are used to determine the azimuths of reference marks using the theodolite of the DIM, or a similar instrument, set up in the manner described in § 5.3. A similar procedure applies if star observations are used. It is usual practice to determine the true azimuth (with respect to geographic north) of the most prominent, primary, reference mark and then measure horizontal angles between it and the other reference marks to obtain their azimuths. The primary mark is normally numbered "M1"; number and list the others in clockwise order. Keep an updated description, including sketches and photographs, of the reference marks.

Astronomical methods for determining azimuth have several disadvantages: Clear sky is necessary for the observations, the calculations are laborious unless computerized, accurate time keeping is required, and temperature and pressure observations are required to calculate refraction and parallax corrections. We therefore discuss briefly two other methods for determining azimuth: using a gyro-theodolite (§ 5.4.3), and using a GPS receiver (§ 5.4.4). Gyro-theodolites have been available for many years, and are used extensively in Latin America (Barreto, personal communication) and Europe. The use of GPS to determine azimuth is feasible, but the method requires careful consideration of the positional accuracy obtainable with the particular equipment being used.

5.4.1 Verification of existing azimuths

Make routine measurements of the angles between reference marks during each station reoccupation to check that the marks have not shifted and have been correctly identified. Start with the telescope in the normal position (vertical circle to the left).

(1) Sight the primary mark (M1) and record the reading of the horizontal circle (HC). It is convenient, though not essential, to set the HC graduated scale to correspond to the known azimuth of the primary mark.

(2) Sight the next mark (M2) and compare the HC reading (or the difference between M1 and M2 readings) with the value given in the station description.

(3) Return to the primary mark to verify that the value has not changed due to shifting or "cork-screwing" of the tripod.

(4) Proceed in a similar manner with the remaining marks.

(5) Repeat the readings with the telescope in the inverted position (vertical circle to the right) in order to compensate for possible misalignment in the HC graduated circle.

By sighting on several reference marks (typically 4, or more) it is usually easy to identify a mark that has shifted, or an incorrectly recorded angle. If there are any unresolved disagreements between the angles observed and the azimuths of reference marks listed in the station description, it will be necessary to take new sun observations.

As a routine precaution, check occasionally the true azimuth of the primary reference mark by making additional sun observations. Beware of making revisions to the azimuth of a primary reference mark that has been used for many previous station occupations. If the mark has clearly not moved (e.g., the edge of a building) and the old azimuth is found to be in error by a small amount (e.g., several minutes), then it is better to continue using the old azimuth to avoid a step change in the declination record at the repeat station. A careful note of this should be made in the repeat station description. A systematic error in D can be tolerated provided it is not much greater than the range of D over the region represented by the repeat station. If the size of the error is too great to be ignored, then, unfortunately, you will have to revise all earlier results and notify WDC-A, and anyone who may be using the incorrect results.

5.4.2 Determination of azimuth from sun observations

Parameters required in the calculation of azimuth from the Sun's position can either be obtained from tables in the Nautical Almanac, or be calculated by computer. A sample program to do the latter is listed in Appendix 4. Copies of the Nautical Almanac can be obtained from:

Superintendent of Documents
US Government Printing Office
Washington D.C. 20402, USA

or

Her Majesty's Stationery Office
49 High Holborn
London W.C. 1, UK.

The UK/USA Nautical Almanac has been adapted by several other countries for their use. A French almanac is available from:

Annuaire du Bureau des Longitudes
Ephémèrides astronomiques
"Masson", Paris
120 bd Saint Germain
75280 Paris Cedex 06, FRANCE.

The geometry of sun observations is discussed by Roelofs (1950) and many others (e.g., Hazard, 1957; Wienert, 1970; Jankowski and Sucksdorff, 1996). There are two methods for calculating azimuths:

(i) *the hour-angle method*, which requires taking the horizontal circle reading (H) and universal time (UT) of sightings of the Sun;

(ii) *the altitude method*, which requires taking both the horizontal circle reading and the vertical circle reading (V). Temperature and atmospheric pressure should also be recorded, since these are needed to determine corrections for refraction and parallax. Refraction and parallax corrections are found in the front of the Nautical Almanac, or they may be calculated mathematically (e.g., Roelofs, 1950).

If H, V and UT are all recorded, the calculations can be carried out using both methods as a check.

Regardless of the method used, it is good practice to do a series of observations in the morning, and another in the afternoon, symmetric about local noon. If observations are made when the Sun is too close to the zenith it will be difficult to sight accurately and azimuth errors arising from timing errors are a maximum. If the Sun is too close to the horizon, refraction errors due to atmospheric distortion are large. By averaging symmetrical sets of morning and afternoon observations, systematic errors in the latitude and in the hour angle will cancel out. Systematic errors in the Sun's altitude, caused by refraction, are unlikely to cancel because atmospheric conditions normally differ from morning to afternoon. For this reason, it is generally preferable to determine azimuth using the hour-angle method (Roelofs, 1950).

Time of day must be measured to an accuracy of a few tenths of a second, or better, when using the hour-angle method. A timing error of 1 second will result in an error of up to 0.5 minutes of arc in azimuth. It is, therefore, necessary to use a radio receiver or GPS receiver to obtain accurate time signals and a stopwatch with a lap-timer, i.e., a facility to halt the display while the stopwatch continues to run. The observer starts the stopwatch at a known time, then subsequently records the elapsed time when the Sun's disk is aligned with the cross-hairs of the theodolite telescope.

A possible observing procedure is given below. It is assumed that the theodolite is equipped with only a simple vertical and horizontal cross-hair, although some theodolites have circular or twin cross-hairs specifically designed for sun observations. An example of a form for recording observations is included in the comments of program SUNIN in Appendix 4.

(1) Set up the theodolite at the repeat station, as described in § 5.3, and level it (Appendix 3).

(2) Tune the radio receiver to a standard time-signal channel. Start the stopwatch at any of the one-minute signals and note the corresponding time (UT_0). At a subsequent one-minute signal, press the lap-timer button to halt the display; note the timing "error" on the stopwatch. Release the lap-timer and stop it again at another minute-signal from the radio. Do this several times to get an average stopwatch "error". This figure is used to correct all subsequent elapsed times recorded on the stopwatch. As an alternative to a radio receiver, a GPS receiver may be used to obtain a time signal.

(3) Sight on the reference mark (M, which will normally be the primary mark M1) with the telescope inverted (vertical circle right) and record the horizontal circle reading. This reading is arbitrary unless the scale has been referenced to true north. It is convenient to set the horizontal scale to read 0°00′00″ when sighted on M.

(4) Point the telescope towards the Sun and adjust it until an image is cast behind the eyepiece on a piece of paper, or your hand. Use the shadow of the telescope or the foresight as a guide. Place the sun filter on the telescope eyepiece and sight the Sun. <u>Never look at the Sun through the telescope without the filter in place since it will injure your eye.</u>

(5) Set the telescope so that a precise time can be recorded with the stopwatch when one side (e.g., the left limb) of the Sun's disk coincides with the vertical cross-hair. This can only be achieved by presetting the telescope, observing the Sun's disk as it moves across the field of view, and pressing the lap-timer button of the stopwatch when coincidence occurs. Record the elapsed time and horizontal scale reading.

(6) Repeat step 5, being careful to release the lap-timer before commencing.

(7) Reverse the telescope so that it is now in the normal (vertical circle left) position and rotate the theodolite through 180° to resight the Sun. Take two more pairs of readings (elapsed time and horizontal scale reading) with the other limb of the Sun's disk aligned with the vertical cross-hair.

(8) Resight the mark with the telescope still in the normal position, and record the horizontal scale reading.

(9) Repeat steps (3) to (8) in reverse sequence.

A symmetrical set of duplicate observations, such as described above, helps to reduce errors and identify incorrect readings. The readings taken must be averaged appropriately to obtain final horizontal circle readings for the Sun (H), with corresponding universal times, and for the mark (M).

If the altitude method is employed, a procedure similar to that described above can be followed except that the altitude measurements (vertical circle readings at coincidences with the horizontal cross-hair) are made in addition to the azimuth measurements. This requires simultaneous adjustment of both the horizontal and vertical movements of the telescope to achieve joint coincidence of the limbs of the Sun with the horizontal and vertical cross-hairs. It is convenient, but the adjustment is no easier, if the telescope has a central circular cross-hair with the same apparent diameter as the Sun. If the altitude method is used, the time of the sun sighting needs to be recorded only to the nearest minute, since it is required solely for determining the Sun's declination.

The actual times (UT) of the sun sightings are obtained by adding the stopwatch readings to the initial time, UT_0, and making a correction for the stopwatch "error". From the sun observations, the azimuth of the Sun, A_s, (i.e., the Sun's bearing from true north), is calculated from:

$$\tan A_s = \frac{\sin t}{(\sin\theta\cos t) - (\cos\theta\tan\delta)} \qquad (5.1)$$

where $t = 15(\mathrm{UT} + e) + \phi - 180$ in degrees, (5.2)

or $t = \mathrm{GHA} + \phi$. (5.3)

To calculate the azimuth on the basis of the Sun's altitude, use:

$$\cos A_s = \frac{\sin\delta}{(\cos h\cos\theta)} - (\tan h\tan\theta). \qquad (5.4)$$

In the above equations,

δ is the Sun's declination, found in the Nautical Almanac, for the date and time of the observation, or calculated by computer.

h is the Sun's altitude, corrected for refraction and parallax, obtained from the vertical circle reading (V) of the sun observation.

θ is the latitude of the repeat station (°N).

ϕ is the longitude of the repeat station (°E).

t is the Sun's hour angle.

UT is the universal time of the observation (in hours). Note that UT differs by up to a second from UTC (Coordinated Universal Time), which is broadcast by most time services. Some time services, such as WWV, broadcast the corrections; they may also be available from your national geodetic institute.

e is the "equation of time", the difference between local apparent time and local mean time, obtained from the Nautical Almanac. Note that the Nautical Almanac does not give the sign of the equation of time. This may be obtained by noting the meridian passage given in the Almanac. If it is less than 1200, then apparent noon occurs before mean noon and e is positive.

GHA is the Greenwich Hour Angle, found in the Nautical Almanac, for the date and time of the observation, or calculated by computer.

For morning observations, A_s is clockwise from true north, but for afternoon observations, A_s is counterclockwise from true north and should be converted to a clockwise angle, A_s', i.e.,

$$A_s' = A_s \quad \text{in the morning,} \qquad (5.5)$$

$$A_s' = 360^\circ - A_s \text{ in the afternoon.} \qquad (5.6)$$

The azimuth of the mark, A_m, is determined from:

$$A_m = A_s' - (\mathrm{H} - \mathrm{M}), \qquad (5.7)$$

where H is the horizontal circle reading of the Sun and M is the horizontal circle reading of the mark.

The scatter among individual values of A_m

within a series of sunshots should be typically 10 seconds of arc. Differences between mean values derived from different sets of sunshots should be around 20 seconds of arc. Systematic differences in azimuth values derived from morning and afternoon sunshots are an indication of incorrect latitude, longitude, or time.

5.4.3 Determination of azimuth using a gyro-theodolite

Sun observations require good weather. In regions where cloudy conditions are prevalent, delays can be avoided by using a gyro-theodolite (also called a gyro-attachment or north-seeking gyroscope) to determine true north. The use of a gyro-theodolite also eliminates the need for long calculations, astronomical almanacs, and precise time-keeping. The following description, which refers specifically to the Wild GAK-1, is based on notes compiled by Barreto (personal communication), on Schwendener (1966), and on Kerridge (1985b).

A gyro-theodolite consists of a precision theodolite, a gyro-attachment that is rigidly mounted on the theodolite in a fixed position, and a power supply system consisting of a battery, charger, and converter. The gyroscope itself is suspended from a thin metallic tape, like a plumb-bob, so that its spin-axis is always held horizontally. The gyro-rotor, spinning at 22000 rpm, tries to maintain its initial random spin-plane because of its high angular momentum, but is pulled out of the original spin-plane by the Earth's rotation. The spin-axis precesses until it takes up a position in the true meridian plane. Because of its internal mass, the gyro does not stop in the meridian plane immediately, but oscillates about the meridian plane for some time. The north direction is the midpoint of these oscillations.

It can be shown that R, the directional coupling force causing the oscillation about the meridian plane is given by

$$R = J \omega_G \omega_E \cos\theta \sin A, \tag{5.8}$$

where:

J is the moment of inertia of the rotor,
ω_G is the angular velocity of the gyro,
ω_E is the angular velocity of the Earth,
θ is the latitude,
A is the angle of deviation of the gyro spin-axis from the meridian.

Both A and R are zero when the spin-axis lies in the true meridian. It can also be seen that R becomes zero at the poles. Hence, the gyro-theodolite is not suitable for use at high latitudes.

To set up a gyro-theodolite at a repeat station, proceed as follows.

(1) Set up, centre, and level the theodolite in the usual manner.

(2) Fix the gyro-attachment to the theodolite, and connect the battery and converter.

(3) Make certain that the gyro is in the clamped position, and then turn on the power. It will take from 1 to 5 minutes for the gyro to reach running speed.

The direction of true north can be determined using one of several methods. These methods are all variations of two fundamental modes of gyro operation, the tracking mode and the clamped mode. In the tracking mode, the theodolite is turned as the rotor oscillates so that the suspension tape is kept almost free from torsion. In the clamped mode, the theodolite is kept in a fixed position so that, as the rotor oscillates, it is subjected to an additional torque due to the suspension system.

The following three methods are described here — the first two use the tracking mode; the third uses the clamped mode.

(i) Quick orientation by the observation of two reversal points: This provides a determination of north with an accuracy of approximately 3 minutes of arc in a time of 11 to 14 minutes.

(ii) Precise orientation by the reversal point method: This provides an accuracy of from 15 to 30 seconds of arc in a time of 13 to 16 minutes (excluding preorientation).

(iii) Precise orientation by the transit method: This method provides an accuracy of 15 to 30 seconds of arc in a time of 8 to 10 minutes (excluding preorientation) and requires an accurate stopwatch.

The direction of north (N) obtained by observation with the gyro-theodolite must be corrected for the collimation error (E) and the tape zero error ($c\delta$). True north (N_t) is given by

$$N_t = N - E - c\delta. \qquad (5.9)$$

Error E arises from the fact that the gyro-attachment and the theodolite's telescope may not be aligned perfectly. E is determined by comparing known azimuths with those determined using the gyro-theodolite and may be considered constant.

The tape-zero error arises from the fact that, if the gyro-rotor is unclamped while spinning, it will oscillate with a period of about 30 seconds due to the torque in the suspension system. The centre of oscillation may not correspond to the zero of the graduated scale. This offset (δ, in minutes of arc) may be determined by observing repeated oscillations of the gyro-mark. Note that the tape zero error also depends on the parameter c, which is discussed later in the section on the transit method. The tape-zero error is not a constant, and should be measured before and after each true north determination.

Quick orientation by the observation of two reversal points

(1) Pre-orient the telescope to within 30° of north using a magnetic compass, the Sun, or some other means.

(2) Release the gyro, release the horizontal clamp on the theodolite, and rotate the alidade by hand so as to follow the gyro-mark, keeping it within the V-shaped index in the middle of the scale.

(3) As the gyro-mark slows down near the reversal point, tighten the horizontal clamp and follow the gyro-mark by turning the tangent screw until the reversal point is reached. Record the horizontal circle reading, U_1.

(4) Release the clamp and follow the gyro-mark to the opposite reversal point, recording the horizontal circle reading, U_2.

The gyro north direction is $(U_1 + U_2)/2$.

Precise orientation by the reversal point method

(1) Pre-orient the telescope to within 2° of true north by means of a magnetic compass, or by the quick orientation method.

(2) Set the horizontal tangent screw to the middle of its range.

(3) Release the gyro and follow the gyro-mark by turning the tangent screw to keep the mark centred in the V-shaped index in the middle of the scale.

(4) At the reversal point, record the horizontal circle reading, U_1.

(5) Immediately follow the gyro-mark to the opposite reversal point and record the horizontal circle reading, U_2.

(6) Observe the position of 4 to 6 reversal points in total.

The gyro north direction, N, is calculated as follows:

$$N_1 = [(U_1 + U_3)/2 + U_2]/2 \qquad (5.10)$$
$$N_2 = [(U_2 + U_4)/2 + U_3]/2$$
$$\ldots\ldots$$
$$N_i = [(U_i + U_{i+2})/2 + U_{i+1}]/2$$

hence,

$$N = (\sum_{i=1}^{n} N_i).$$

Precise orientation by the transit method

(1) Pre-orient the telescope to within 10′ of true north using the quick orientation method and lock the theodolite in this position. Record this position (N′).

(2) Unclamp the gyro, and, by means of a stopwatch, record the time at which the gyro-mark transits the zero-line of the scale. Record the times of 3 to 5 transits in total.

(3) Record the scale values at the reversal points, a_e (east) and a_w (west). Compute the mean value

$$a = (a_e + a_w)/2.$$

(4) Compute the half-oscillation time, T_e, by differencing consecutive transit times recorded with the stopwatch; this is the time it takes the gyro-mark to transit, reach the easterly reversal point and return to the transit position. In a similar manner, compute T_w for the westerly reversal point. T_w should be recorded as a negative number. Compute

$$\Delta T = T_w + T_e.$$

The correction, ΔN, to be applied to the approximate north value, N′, is then given by

$$\Delta N = c\ a\ \Delta T. \qquad (5.11)$$

This equation is valid over the linear range of the sine curve, corresponding to an amplitude of about 10 scale units. ΔT should not exceed 30″, and ΔN should not exceed 15′. If these limits are exceeded, the observations must be repeated with an improved initial value of N′.

The parameter *c* is a proportionality factor that must be determined experimentally. *c* is determined by making two separate determinations of north with different initial orientations N_1' and N_2'.

Then,

$$c = \frac{N_2' - N_1'}{\Delta T_1 a_1 - \Delta T_2 a_2} \qquad (5.12)$$

Parameter c can be regarded as constant over a latitude range of about 5 degrees.

5.4.4 Determination of azimuth using GPS

The Global Positioning System consists of 18 satellites orbiting at altitudes of approximately 20000 km so that at least four satellites are visible at any time from anywhere on the Earth's surface. Information from these satellites is detected by a ground receiver and used to determine accurate geodetic positions. GPS has revolutionized geodesy and geodynamics, and has found many other uses in fields that relate to navigation and positioning (see Hurn, 1989, 1993; Hofmann-Wellenhof *et al.*, 1992).

The use of GPS for determining the location of repeat stations has already been mentioned (§ 4.3.5). In theory, the use of GPS can be extended to determine the azimuth of a reference mark. If the position of the station bench mark, and the reference mark are both known, it is a straightforward, if somewhat complex, matter to calculate the bearing from one to the other. Whether the resultant bearing is sufficiently accurate depends on the accuracy with which the position of the bench mark and reference mark are determined, and on the distance between them. For an azimuthal accuracy of 1 minute of arc, the following positioning accuracies are required for different separations.

Separation (km)	Positional Accuracy (m)
1.0	0.29
2.0	0.58
3.0	0.87
4.0	1.16
5.0	1.45
30.0	8.78
50.0	14.54

It can be seen that, at practical distances (less than 5 km), positional accuracies must be better than 1.5 m.

There are two types of GPS receivers currently available. The micro-GPS receiver is small, hand-held and relatively inexpensive. With such units, typical accuracies are 10 to 50 m. This is not sufficient to meet the requirements of azimuth determination at a repeat station, but, is sufficient for pre-orienting a gyro-theodolite (§ 5.4.3). The portable GPS station is larger and has an external antenna. When used in "differential" mode, that is, the same satellites are tracked by two GPS receivers simultaneously, relative accuracy of a few millimetres is obtainable. Unfortunately, the cost of a GPS station is approximately US $50 000 (in 1994), but if a system can be borrowed from a geodetic institution, you may wish to consider it.

5.5 Absolute Measurements

This section describes a method of measuring **D**, **I**, and **F** using a DIM and a PPM. Other combinations of instruments are possible (§ 3.4.1), but detailed instructions for their use are not given here. **D** observations are made relative to a reference mark of known azimuth. A set of absolute observations (often abbreviated to a "set of absolutes") is a sequence of absolute measurements of three (or more) elements, required to determine the vector field. The simplest set might be **DIF** or perhaps **DHZ**. Many observers make duplicate measurements, often symmetrically, to produce a set of absolutes such as **FDIIDF** or **FDF IFIFDF**.

Sets of absolute observations are made early in the morning, and late in the evening on each day of the repeat station occupation. This avoids the principal part of the daily variation so that the corrections for temporal variations of the field are less critical. This is particularly important if an on-site variometer is not being used. (It is even better to make observations in the middle of the night [§ 5.5.5]). Early morning is near the coldest time of day, and evening is close to the warmest time of day; thus, depending on the thermal lags within the system, the full amount of temperature drift of the three-axis variometer will be reflected in baselines derived from morning and evening absolute observations (§ 3.4.6 and § 6.2.4).

Quiet daytime values of **D** have an approximately symmetrical distribution about the night-time value; thus the average of morning and afternoon determinations of **D**, equispaced in time about local noon, will be close to the night-time value. The same does not apply to **I**, **Z**, **H**, and **F**. Under disturbed conditions, and at polar latitudes, the pattern of the daily variation is more complicated and such simple rules do not apply.

A set of absolutes, comprising a sequence of measurements of **D**, **I**, and **F**, takes a skilled observer several tens of minutes to complete. This is long enough that consideration must be given to changes in the field elements during the observation period (see below).

In equatorial regions, where **I** is less than 10°, it is advisable to measure **Z** in addition to **D**, **I**, and **F**. This requires the use of a 90° eyepiece to read the vertical circle. Certain instruments of the DIM-type permit the direct measurement of **Z** with an accuracy of better than 1 nT for values of **Z** between 0 and 2000 nT (Cantin *et al.*, 1991). In addition, it may be preferable to use the "residual" method for measuring **D**, **I**, and **Z**, described in § 5.5.3, rather than the "null" method described below. The residual method eliminates certain sources of error under low inclination conditions (Kring Lauridsen, 1991; Jankowski and Sucksdorff, 1996). In addition, the observer produces no interference during sampling since the meter can be read at a distance. The fluxgate output must, however, be linear, with an accurate scale value.

In most cases, absolute measurements at the repeat station will be made for **DIF** whereas, the reference observatory, or on-site variometer, will be recording either **XYZ** or **DHZ**. Ideally, the absolutes would be made simultaneously and instantaneously so that **DIF** could be converted to **XYZ** (or **DHZ**) for direct comparison with the variometer record. In practice, this is not possible. A similar problem arises at observatories when absolute and variometer data are for different sets of elements. Two approaches can be followed.

(i) If a reference observatory is being used for data reduction, then each absolute measurement of an element (E) made at the repeat station can be reduced independently of the others. This produces one estimate (E_n) of the normal field value (either at the nominal date of the station occupation, or an annual mean). Further absolute measurements of **E** give additional estimates of $\mathbf{E}_n$ that are averaged to get the final value for the station occupation. Final values for the other two elements are obtained independently in a similar manner.

(ii) The alternative approach, which must be followed if a variometer record is used for data reduction, requires an observational procedure that corrects for the change of the field while the absolute measurements of three elements are being made. The simplest procedure is to make a symmetrical set of measurement, e.g., **FDIIDF** or **FDF IFIFDF**, distributed symmetrically through time. Averages of the elements are used to estimate the vector field at the mid-time of the observations. This method assumes that any variation of the elements during the observations is linear in time. This simple averaging method will usually be adequate for repeat station measurements made under quiet conditions. For a more rigorous treatment, which is necessary when field variations are larger and non-linear in the elements measured, each absolute observation of each element must be referenced to the variometer record, and a correction made for the change of the element between the time of the observation and the nominal mid-time of the vector-field determination.

It is not essential that a set of absolute measurements be symmetrical, but many observers prefer to use symmetrical sets as this reduces exposure to errors, may simplify the observational sequence (fewer rotations of the theodolite), and permits immediate calculation of provisional results for testing the consistency of sequential sets of absolutes (§ 5.5.4).

5.5.1 Determination of declination and inclination

Remove sources of magnetic contamination from the site before beginning observations. Remove magnetic objects or magnetic parts of clothing from your person and ensure that all cases and tools are placed at least 10 m from the magnetometers. Vehicles should be parked at least 60 m away. The effects of several common ferrous items are given in Table 5.1, reproduced from Jankowski and Sucksdorff (1996). A useful rule-of-thumb is that the distance from a ferrous object at which the influence fall below 1nT is about 20 times the maximum dimension of the object (L. Tomlinson, personal communication). If there are any doubts, a few simple PPM measurements will soon establish the safe clearance distances required for any magnetic object.

Ensure that the cable to the fluxgate is sufficiently free to avoid dragging on the sensor. Check that the fluxgate sensor is aligned parallel to the telescope before embarking on a series of observations (§ 3.4.5). Avoid touching the fluxgate sensor on the theodolite, and never use it as a handle to rotate the telescope since this may change the alignment.

Measuring D and I

Several schemes are in use for measuring declination and inclination using a DIM. The method we outline here is used by French observers.

(1) Position the theodolite, approximately levelled, over the centre of the station marker at the standard height specified in the station description (§ 4.5). Record the height.

Table 5.1 **Distance at which common objects produce a magnetic anomaly of 1 nT**

Safety Pin	1 m
Belt Buckle	1 m
Watch	1 m
Metallic Pen	1 m
Knife	2 m
Screwdriver	2 m
Hammer	4 m
Spade	5 m
Bicycle	7 m
Motorcycle	20 m
Car	40 m

(2) Level the theodolite as described in Appendix 3.

(3) Check the azimuth marks, if this has not already been done. Adjust the horizontal circle scale to read the correct azimuth when the primary mark is sighted. (This step is optional, but it reduces subsequent calculations.)

Make each final null adjustment on the exact minute to correspond to the sampling time of the variometer or reference observatory. Note the time (UT) with each reading.

An individual observation of D

(1) Sight the mark with the telescope in the normal (fluxgate up) position and read the horizontal circle ($M1_u$).

(2) Repeat with the telescope in the inverted (fluxgate down) position ($M1_d$).

(3) Set the vertical circle index to read exactly 270° (telescope horizontal and inverted).

(4) Rotate the alidade until the magnetometer output indicates a null; fine-adjust and read the horizontal circle (D1).

(5) Rotate the alidade by approximately 180°, fine adjust for a null, and read the horizontal circle (D2).

(6) Reverse the telescope back to the normal position; set the vertical circle index to exactly 90°.

(7) Search for a null, fine-adjust and read the horizontal circle (D3).

(8) Rotate the alidade by approximately 180°, fine-adjust for a null, and read the horizontal circle (D4).

(9) Remeasure the mark sightings ($M2_u$, $M2_d$).

Calculate declination, **D**, from the mean value of the mark,

$$\overline{M} = (M1_u + M1_d + M2_u + M2_d - 360)/4, \quad (5.13)$$

the mean of the four horizontal circle readings,

$$\overline{D} = (D1 + D2 + D3 + D4)/4, \quad (5.14)$$

and the true azimuth mark, Az, using the expression:

$$D = \overline{D} - \overline{M} + Az. \qquad (5.15)$$

Note that there may be an error of ±180° in the value of declination calculated using the above formula, depending on the quadrants in which $\overline{D}$, $\overline{M}$, and Az fall. Common sense, and a knowledge of the approximate value of the declination, obtainable from world charts, will tell the observer whether 180° should be added to or subtracted from the calculated value of D. Care should be taken in the vicinity of the magnetic or geographic poles, where the chance of ambiguity is greater.

An individual observation of I

(1) Align the telescope in the magnetic meridian by setting the horizontal circle reading to the appropriate value, $\overline{D}$, determined from the declination observations.

(2) Rotate the telescope about the horizontal axis in the normal (up) position until a null is obtained; read the vertical circle (I1).

(3) Invert the telescope, search for a null, and read the vertical circle (I2).

(4) Rotate the alidade by exactly 180°.

(5) Search for a null (telescope still inverted), and read the vertical circle (I3).

(6) Rotate the telescope to the normal position, search for a null, and read the vertical circle (I4).

Calculate the inclination from the mean of the four readings from

$$I = (I1 + I2 - I3 - I4)/4 + 90 \qquad (5.16)$$

in the northern hemisphere, or

$$I = (I1 + I2 - I3 - I4)/4 - 90 \qquad (5.17)$$

in the southern hemisphere.

5.5.2 Measurement of total field intensity

Set up an auxiliary F-station approximately 10 m from the main station (§ 4.4). This avoids the problem of delays while interchanging instruments at the main station during a set of absolute measurements, but does necessitate the determination of the F-difference between the two stations. Absolute measurements of F can then be made simultaneously with the D and I observations, which reduces errors caused by fluctuations of the field while a set of measurements is being made.

Determination of a station F-difference

The difference in F between the auxiliary PPM station and the main station can be determined using a single magnetometer by taking a sequence of measurements, alternating the instrument between the two platforms. Repeat the measurements several times until you are satisfied that the results are consistent. It is worthwhile preparing special mountings so that the PPM can be clamped rapidly in the required positions. Reducing the time taken for the measurements reduces errors arising from the drift of the field. If necessary, a correction for the drift of the field can be made by referencing a variometer record. The mean difference (main station minus auxiliary station) is the station F-difference that must be added to all F-observations taken at the auxiliary site.

If two PPMs and two observers are available, then a series of simultaneous observations can be made at the two locations. It is good practice to take a second set of simultaneous observations with the two proton magnetometers interchanged. This should result in the same value for the F-difference. If the values differ, one, or both, of the proton magnetometers may need recalibration. Note that the difference between F-differences determined in this manner is twice the difference between the two PPMs.

Measurement of F simultaneously with D or I

It is best to make F-observations simultaneously with observations of D and I to simplify subsequent data reduction. An auxiliary PPM station is required. If there are two observers, the assistant takes an F-reading (or, preferably, several sequential readings to be averaged) at the auxiliary station at the same time as the principal observer nulls the DIM at the main station.

A single observer can make simultaneous F-observations if a recording PPM is set up at the auxiliary station. The recording PPM must be calibrated (§ 3.4.3) and must include a time signal. After the D- and I-observations are completed, the corresponding F-values are obtained from the PPM record.

It is possible to make F-observations after the D- and I-observations without using a recording PPM to correct the F-observations to the time of D and I. The change in the magnetic field that occurs between the time of an individual D- or I-reading and the time of the F-observation can be determined using data recorded by the three-axis variometer. This is a more complicated process since different components are recorded, but reduction can easily be carried out on a laptop computer using equations similar to Eq. 6.5 and Eq. 6.6 in § 6.2.1.

5.5.3 Determination of declination and inclination using the residual method

The residual method of measuring D and I is commonly used at magnetic observatories. The sensor is not turned to the null-field position, but is placed in a fixed position close to the null, and the residual field value is read from the magnetometer.

The residual method has advantages over the null method. Observations are easier to carry out and are more accurate, especially when the magnetic field is unsettled. The requirement that the observer be non-magnetic can be relaxed since the observer can stand a safe distance from the sensor when reading the meter. The method also requires certain precautions. The magnetometer output signal must be linear and must be precisely calibrated. Residuals are often on the order of several tens of nanoteslas, so an error of 1 part in 100 in sensitivity can lead to errors of several tenths of a nanotesla.

The method outlined below is based on Kring Lauridsen (1985), Gilbert (in Kauriste *et al.*, 1990, pp. 67-69), and Jankowski and Sucksdorff (1996).

An observation of D

The instructions pertaining to levelling, positioning, and sighting the azimuth mark, as described in § 5.5.1, apply here. All values are recorded on the exact minute.

(1) Set the vertical circle to read 90°

(normal position), and, with the verti-cal circle facing magnetic north, rotate the alidade until the magnetometer output reads a small value.

(2) Set the horizontal circle reading to a convenient value; record the value, A_1, and the magnetometer output, S_1.

(3) Place the telescope in the inverted position; set the vertical circle to 270°.

(4) Verify that the horizontal circle reading is the same (A_1) and record the magnetometer output, S_2.

(5) Rotate the theodolite exactly 180° ($A_2 = A_1 + 180°$).

(6) Record the horizontal circle reading, A_2, and the magnetometer output, S_3.

(7) Place the theodolite back in the normal position, verify that the horizontal circle reading is the same (A_2) and record the magnetometer output, S_4.

Assuming that the magnetometer gives a positive output when the telescope is pointing north, the declinations in each of the four position are given, in degrees by

$$\begin{aligned}
D_1 &= A_1 + (180/\pi)(S_1/H)\\
D_2 &= A_1 - (180/\pi)(S_2/H)\\
D_3 &= A_2 + (180/\pi)(S_3/H)\\
D_4 &= A_2 - (180/\pi)(S_4/H).
\end{aligned}$$

These four values may be averaged, as in Eq. 5.14, and the declination calculated, taking into account the sighting on the azimuth mark, by Eq. 5.15. Alternatively, baselines may be calculated for each value and the four baselines averaged.

An observation of I

(1) With the telescope in the normal position, set the horizontal circle to the approximate magnetic meridian, $(A_1+A_2)/2$).

(2) Rotate the telescope about the horizontal axis, and set the vertical circle to a convenient value near the null.

(3) Record the vertical reading, B_1, and the magnetometer output, R_1.

(4) Invert the telescope 180°, and set it to a convenient value near the null; record B_2 and R_2.

(5) Rotate the alidade by exactly 180°.

(6) With the telescope still inverted, adjust the vertical circle to a convenient value near the null; record B_3 and R_3.

(7) Invert the telescope back to the normal position; set the vertical circle to a convenient value near the null; record B_4 and R_4.

The inclination in each of the four position is given by

$$\begin{aligned}
I_1 &= B_1 - (180/\pi)(R_1/F)\\
I_2 &= B_2 + (180/\pi)(R_2/F)\\
I_3 &= B_3 + (180/\pi)(R_3/F)\\
I_4 &= B_4 - (180/\pi)(R_4/F).
\end{aligned}$$

I may be calculated from these values by Eq. 5.16 or Eq. 5.17.

5.5.4 A set of absolute observations

A set of "absolutes" is considered to be a sequence of observations of **D**, **I**, and **F** that is used to derive a single value for the vector field. A simple set could be as little as

- an observation of **D** (D1,D2,D3,D4)
- an observation of I (I1,I2,I3,I4)

with simultaneous observations of **F** (§ 5.5.2). An alternative to simultaneous F-observations is to take an F-reading at the mid-point of the D-observation (between D2 and D3) and at the mid-point of the I-observation (between I2 and I3). One assumes that **F** remains constant or varies linearly over the intervals D1 to D4 and I1 to I4. Alternatively, you can take an F-reading one minute before D1 and one minute after D4, and then interpolate linearly over the interval D1 to D4 (and do likewise for **I**).

If corrections for the time-dependence of the field are not being applied to individual observations of **D** and I, then a symmetrical set of observations is recommended. For example

- an observation of **D** (D1,D2,D3,D4), the "out" sequence
- an observation of **I** (I1,I2,I3,I4), "out"
- a reverse observation of **I** (I4,I3,I2,I1), "back"
- a reverse observation of **D** (D4,D3, D2,D1), "back".

Assuming that **D** and I change linearly with time, and that the observations are made symmetrically through time, then the direction of the field at the middle of the observing interval will be given by the mean of the D-observations and the mean of the I-observations.

During such a symmetrical set of observations, make simultaneous F-observations, or, alternatively, F-observations interspersed between the D- and I-observations to produce a sequence such as **FDIFIDF**, **FDDIIF** or perhaps, **FDIIDF**. A precise set of absolutes carried out by French observers at mid-to-low latitudes using simultaneous F-observations at an auxiliary station is the following:

- an observation of **D** (D1,D2,D3,D4)
- an observation of I (I1,I2,I3,I4)
- observations of **D** "out" and "back" (D1,D2,D3,D4,D4,D3,D2,D1)
- observations of **I** "out" and "back" (I1,I2,I3,I4,I4,I3,I2,I1)
- observations of **D** "out" and "back"
- observations of **I** "out" and "back"
- an observation of **D** (D1,D2,D3,D4,)
- an observation of I (I1,I2,I3,I4).

The decision about how rigorously to make the sequence of absolute observations depends on how quiet (and how linear) is the field behaviour at the time of observation. The critical test is the level of consistency that can be obtained between sequential sets of observations. A sufficient number of sets of absolutes must be taken so that consistency can be established. When a variometer is used, it is the consistency of baselines determined from sequential sets of absolutes that should be considered. If a reference observatory is used, then the consistency between sequential determinations of the annual mean values will probably be used. At mid-latitudes the typical errors in the individual field elements derived from a sequence of absolutes will probably be about:

20″ (0.005°)	for **D** and I
1.5 nT	for H
1.0 nT	for **Z**
0.5 nT	for F.

5.5.5 Night-time observations

Absolute observations can be made at night using a DIM and PPM, provided you have an assistant. The inconvenience of operating in the dark is offset by the advantage of observing when the diurnal variation of the field is at a minimum. This is particularly valuable if you cannot obtain accurate variation data for the repeat station site. Night-time conditions tend to be more stable (less wind, smaller temperature variations, and less man-made interference) and may offer excellent observing conditions. The South African observers, for example, make 90% of their absolute observations at night (L. Loubser, private communication).

The main requirement for night-time observations is a reference mark that can be illuminated. This may be either a conventional mark that can be reached with a spot light or car headlights, or, perhaps, a specially designed light mounted on a tripod (perhaps at the secondary station). A hand-held flashlight (torch) is adequate for reading the displays of the DIM and the PPM and can be shone through the illumination port of the theodolite when readings have to be taken. Precautions must be taken to ensure that any magnetic material in the light does not influence the instrument sensors at the critical times when the null settings and PPM readings are made. Use lights that are as non-magnetic as possible, and avoid using batteries with metal casings.

5.6 Schedules for a Repeat-Station Occupation

Some examples are given below of schedules to be followed during a typical repeat-station occupation. The schedule you follow will depend on your particular circumstances and objectives, and will depend on factors such as the instruments available, the data reduction method to be used (on-site variometer vs. reference observatory), the geographical location of the stations, weather conditions, the level of magnetic disturbance, the need for back-up observations at a secondary station, and the number of observers present. In principle, accuracy should not be limited by the time spent on the occupation and observations should be continued until the required level of consistency is achieved. Practical circumstances sometimes make this impossible.

Before the start of the occupation, read all the available literature about the repeat station, particularly previous station status reports, that may indicate problems, remedial work that needs to be carried out, or measurements that may be required. Do any necessary instrument comparisons and calibrations before you set out on the survey, and again when you return.

5.6.1 Schedule with an on-site variometer

The following schedule illustrates a repeat station occupation when variometers are installed on site to record 4 components (**D**, **H**,**Z**,**F**), back-up measurements are made at a secondary station, an auxiliary PPM station is used, two observers are present, and observations are made in daylight. Routine checks of the variometer and time-signal recording are scheduled at the beginning and end of each day, but are best made every few hours and certainly before making a new sequence of sets of absolute observations. If the magnetic field becomes disturbed, observations should be delayed until quieter conditions prevail.

Day 1

0830 Arrive on site; hold discussions with local authorities; bring regional field charts and reports from earlier surveys to give away.

1000 Install the three-axis fluxgate and recording PPM in the vicinity of the repeat station; check the accuracy of the variometer time signals.

1300 Locate the primary and secondary station markers; check the station descriptions; measure F-gradients at the primary station[1]; take photographs; note any changes in the condition of the stations on a status report (Appendix 2).

1400 Set up the tripod and theodolite at the primary station; measure angles between reference marks; note any changes to the reference marks (use sketches).

1430 Make sun observations to check the azimuth of the main reference mark listed in the station description.

1530 Calculate azimuths. Check the variometer installation.

1630 Set up an auxiliary PPM station adjacent to the primary station and determine the F-difference between the two stations.

1730 Do sets of absolutes at the primary station using one of the schemes outlined in § 5.5.4.

1900 Check the variometer and time signal.

Day 2

0700 Check the variometer and time signal.

0730 Do at least two sets of absolutes at the primary station.

0900 Measure F-gradients at the secondary station.

0930 Check angles between reference marks at the secondary station[2].

1030 Do sun observations and azimuth calculations for the secondary station, if required.

1300 Check and enter absolutes into a portable computer; revise the station description.

1600 Do two or more sets of absolute observations at the secondary station.

1730 Do two, or more, sets of absolutes at the primary station.

1900 Check the variometer and time signal. Start consistency checks.

Day 3

0700 Check the variometer and time signal.

0730 Do two, or more, sets of absolutes at the primary station.

0900 Do two, or more, sets of absolutes at the secondary station.

1300 Check and enter absolutes into the computer.

1730 Do two, or more, sets of absolute observations at the primary station.

1900 Check the variometer and time signal.

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[1] If the F-gradients do not agree with results from the previous occupation then the source of contamination must be identified. If the station cannot be returned to its original state then it must be abandoned, or renamed and treated as a new station.

[2] If the angles agree with the station description and the azimuth of the main mark has already been determined, then further sun observations at the secondary station are not necessary.

Day 4

0700 Check the variometer and time signal.

0730 Do two, or more, sets of absolute observations at the primary station.

0900 Check and enter absolutes into the computer. Transfer variometer data to the computer and make back-up copies of all data. Calculate baselines and check that results are consistent and that magnetic activity has not been excessive. Prepare to leave if results are satisfactory; if not, stay another day.

1200 + Pack-up. Say goodbye and thank local authorities.

5.6.2 Schedule with no on-site variometer

The following schedule illustrates a repeat station occupation when an on-site variometer is not used, an auxiliary PPM station is used, and two observers are present.

Day 1

0900 Arrive on site; discussions with local authorities.

1100 Find the station markers, revise station descriptions; take photographs; measure F-gradients at the primary station; note any changes in condition of the station in a status report (Appendix 2).

1200 Set up tripod and theodolite at the primary station; measure angles between reference marks; note any changes.

1300 Set up an auxiliary PPM station adjacent to the primary station; determine the F-difference.

1430 Make sun observations to check the azimuth of the main reference mark.

1530 Calculate azimuths.

1630 Check F-gradients at the secondary station.

1700 Check angles between reference marks at the secondary station.

1900 Do two, or more, sets of absolute observations at the primary station.

Day 2

0700 Do two, or more, sets of absolutes at the primary station.

0830 Do two, or more, sets of absolutes at the secondary station.

1000 Make sun observations and calculate azimuths at the secondary station, if required.

1130 Check observations; enter values into the portable computer; check the level of magnetic activity by telephoning the nearest magnetic observatory.

1300 Check the quality of the observations; if not satisfied, take further sets of observations in the evening.

1500 + Pack up. Say goodbye and thank local authorities.

An even more condensed observing schedule, again assuming that observations will be reduced using data from a reference observatory, is the following.

Day 1

1500 Arrive on site, contact local authorities, check station markers, check reference marks. Do sun observations at primary and/or secondary station, if necessary.

1900 Do an F-gradient survey at both the primary and the secondary station.

Day 2

0600 Telephone the nearest reference observatory to check the level of magnetic activity.
0700 Do absolute observations at the primary station.
0900 Do absolute observations at the secondary station.
1100 Calculate azimuths; check observations; enter values into the computer.
1400 Travel to the next station.

The observing schedule is much simpler and quicker if data from a suitable reference observatory can be used, but care must be taken to establish the validity of data reductions from consistency checks, using the observatory records (refer to § 6.1). For this reason it is unwise to take only a few absolute observations covering a short time span. Sets of absolutes made later in the evening and early in the morning are generally considered to be the minimum requirement unless measurements are made in the middle of the night.

CHAPTER 6 Data Reduction

Absolute observations made at the repeat station must be combined with continuous variation data (from an on-site variometer or from a reference observatory) in order to obtain an estimate of either the normal field, or an equivalent annual mean value at the repeat station.

Several methods of data reduction can be used. A choice should be made according to local circumstances, bearing in mind the following factors:

- is an on-site variometer being used?
- are nearby observatory records available?
- are the variometer outputs digital or analog?
- what elements are being recorded by the variometer?
- what elements are being observed for absolutes?
- was the magnetic field quiet or disturbed during the observation period?
- are data to be reduced to an annual mean value or a normal field value?

All calculations of **D**, **I**, and **F** from the measurements performed, including azimuths from astronomical observations, should be completed on-site. Measurements of **F** at the auxiliary PPM station must be corrected to the site of the repeat station itself (at standard instrument height). Final data reduction is usually done back at the office, but the use of a portable computer allows the observer to do much of the data reduction on-site. Sufficient data reduction should be done on-site in order to check the validity of the observations, paying special attention to the consistency between results from successive sets of absolutes. Try to compare final results with secular variation data from earlier occupations, neighbouring stations, and regional and global model predictions to confirm that your new results are plausible. Completing such checks while still at the repeat station is an essential component of the occupation as it allows an opportunity to rectify any major problems or omissions before the site is vacated.

Reduction of ground-survey data. Ground-survey observations (§ 1.1) may take little or no account of the diurnal variation. They are used principally for vector magnetic field surveys and are not suitable for repeat station work. In remote regions with few facilities and limited opportunities, for example during polar traverses, it may not be possible to achieve better ground-survey quality results. Data reduction amounts to calculating the mean value of the field at a particular time. In some cases, it may be possible to improve the result by correction for diurnal variation of the field by reference to a variometer station or observatory in the region.

Reduction of second-order data. Second-order repeat data (§ 1.2) usually comprise a sequence of daytime, or sometimes night-time, absolute observations of the field. No variometer or observatory data are available to provide a continuous record of the field. The elements of the field should be calculated from the absolute observations and plotted as functions of time in order to estimate the night-time (normal) values. Some prior knowledge of the nature of the quiet daily variation in the region is required to help make this estimate, and also to identify magnetically disturbed conditions from a small set of observations. If night-time observations are possible, the number of absolute observations needed can be greatly reduced and a more accurate final result obtained. Repeat station absolutes that are reduced using a reference observatory (see below) may be deemed to be of second-order standard if the observatory record is thought not to give an accurate estimate of the field variation at the repeat station. This might be because the observatory is too remote, or because of disturbed conditions and crustal induction problems in the region.

Reduction of first-order data. The rest of this chapter describes the reduction of first-order data. Details about the particular methods used by different countries are included in the catalog of regional magnetic survey, chart, and model descriptions that is maintained by IAGA Working Group V-8 and updated periodically (Barton and Newitt, 1995) — see § 8.2.1. Copies of this catalog are available from WDC-A, Colorado or from IAGA Working Group V-8.

6.1 Reduction Using Data from a Reference Observatory

This method is based on the assumption that transient (including diurnal) variations of the magnetic field are identical at both the repeat station and the chosen reference observatory and is usually applied in such a way as to calculate an effective annual mean value at the repeat station. The difference between the instantaneous value of a field element, E(t), and its annual mean value, E, at the repeat station is taken to be the same as the difference between the corresponding values, $E_0(t)$ and E_0, at the reference observatory, i.e.,

$$E(t) - E = E_0(t) - E_0, \tag{6.1}$$

hence

$$E = E_0 + E(t) - E_0(t). \tag{6.2}$$

This relationship is not strictly correct because it also assumes that the secular variation throughout the year for which the annual means are calculated is the same at both the repeat station and the reference observatory. The size of the associated error depends on the distance between the station and the observatory, and on the secular variation gradient (§ 6.3.4). If the difference in secular variation between the repeat station and the reference observatory changes uniformly throughout the year in question, then the error arising from the secular variation assumption can be minimized by conducting the survey near mid-year. In addition, a linear correction can be applied for the difference between the average secular variation at the repeat station (SV) and that at the observatory (SV_0) for the year in question.

Equation 6.2 becomes:

$$E = E_0 + [E(t) - E_0\} + (SV - SV_0)\Delta T, \tag{6.3}$$

where ΔT is the time difference between the mid-year epoch of the annual mean and the time of the repeat station occupation. The linear correction case is discussed in more detail in § 6.3.4, Case B, and is illustrated in Fig. 6.2.

Equation 6.3 involves some circularity since SV is the quantity to be determined. However, it appears only as a correction term so an estimate is adequate. This can be derived by extrapolation from an earlier survey, or from a predictive global field model such as the IGRF (IAGA Division V, Working Group 8, 1996). An example of this correction technique, applied to survey data from West Africa, is given by Vassal and Villeneuve (1987). They estimate that the accuracy of observations reduced by this method to be better than 5 nT in **H** and **Z**.

The reduction need not be made to an effective annual mean value, but may be made to any time when the field at the observatory can be identified as undisturbed. (Equation 6.1 holds equally well when E_0 and E denote the normal values of the element at the observatory and repeat station, respectively.) Errors arising from the secular variation assumption will be negligible in such a case.

Each set of absolute observations made at the repeat station will produce a value for the difference $E(t)-E_0(t)$. These will not be identical, in part due to observational error, but mainly because of failure of the assumption about uniformity of the magnetic field variations (§ 6.3.3). The simplest way to proceed is to average all the instantaneous differences to get an estimate of $E-E_0$, and, hence, determine E.

A better result can usually be obtained by taking a weighted average of the instantaneous differences. Examine the observatory record for the interval spanning the repeat station occupation, and for several weeks before and after, in order to get an approximate measure of the general level of magnetic activity when individual absolutes were made, and also the departure of the field from its normal value at the instant when each set of absolutes was made. Assign weights (W_j) to the N sets of absolutes (j = 1,2,...,N) so as to discriminate in favour of those made under the least active conditions and when the observatory field was nearest to its normal value. The weighted average of the instantaneous differences is given by

$$\frac{\Sigma_{j=1}^{N} W_j \,(E\,(t) - E_o(t))_j}{\Sigma_{j=1}^{N} W_j} . \qquad (6.4)$$

The individual observations and results should be summarized in a table. Table 6.1 shows a highly consistent set of results for the French repeat station of Ploudalmezeau (48° 30′ 36″ N, 04° 38′ 48″ W, altitude 81 m), approximately 500 km from the reference observatory of Chambon-la-Forêt. Results of a similar consistency were recorded for **Z** and **F**. This level of consistency is not always obtained at such large distances from a reference observatory.

It may be possible to improve the accuracy of the data reduction if more than one reference observatory is used. Differences between the repeat station and each reference observatory are calculated, and an interpolation procedure applied to determine the correction to be made at the repeat station. Some sort of weighting is usually applied to reflect the fact that the variation of the diurnal signal with latitude and longitude are somewhat different. (An observatory at the same geomagnetic latitude as the station is more relevant than one at the same longitude at a similar distance.) Such a method has been used successfully in South Africa and Britain, and is described in the IAGA catalog of regional magnetic survey, chart, and model descriptions (Barton and Newitt, 1995).

The attractions of using observatory records for data reduction are:

- no on-site variometer is required; observational procedures are simpler and quicker;
- observatory data are more accurate than on-site variometer data;
- the observatory record will be long

Table 6.1 Reduction of Absolute Field Measurements

Station: PLO Dates of Measurements: 09-10/06/1987

STATION OBSERVATORY DIFFERENCE

UT Day	UT Hour	D_{st}	D_{obs}	D_{st}-D_{obs}	Mean Dif	St. Dev.
160	15:57	-6° 18′ 18″	-3° 26′ 47″	-2° 51′ 31″		
160	16:02	-6 18 12	-3 26 38	-2 51 33		
160	16:14	-6 18 03	-3 26 27	-2 51 36		
160	16:51	-6 17 47	-3 25 51	-2 51 56		
160	17:12	-6 17 42	-3 25 57	-2 51 44		
160	17:35	-6 17 45	-3 25 51	-2 51 53		
161	04:07	-6 13 23	-3 21 45	-2 51 37		
161	04:41	-6 13 06	-3 21 29	-2 51 37		
161	05:08	-6 13 00	-3 21 32	-2 51 29		
161	05:33	-6 12 43	-3 20 39	-2 52 04		
161	06:00	-6 12 46	-3 20 51	-2 51 55	-2° 51′ 43″	0° 00′ 4 ″

Day	Hour	H_{st}	H_{obs}	H_{st}-H_{obs}	Mean Dif	St. Dev.
160	16:27	20725.9	20899.3	-173.4		
160	16:32	20725.3	20899.4	-174.1		
160	16:42	20725.8	20899.3	-173.5		
160	17:01	20726.3	20900.6	-174.3		
160	17:23	20727.9	20901.7	-173.8		
160	17:42	20726.4	20901.0	-174.6		
161	04:22	20730.9	20906.9	-176.0		
161	04:53	20730.9	20906.2	-175.3		
161	05.17	20730.6	20905.5	-174.9	-174.4 nT	0.9 nT

enough to identify any long-term recovery phase after a magnetic storm (easily missed on a 2- or 3-day variometer record);

- it is possible to estimate an annual mean value for the repeat station.

The disadvantage of the method is that the observatory must be sufficiently close to the repeat station to satisfy the assumption of regional uniformity of temporal variations of the geomagnetic field. Where the electrical properties of the crust are highly variable this assumption can be invalid over distances of as little as a few kilometres.

6.2 Reduction Using Data from a Local Variometer

When a three- (or four-) component variometer is used on-site, the repeat station becomes a temporary observatory. Most of the processes normally applied to observatory data are applied to the repeat data.

6.2.1 Preliminary reduction of analog data

If analog (graphical) recording is used for the variometer, preliminary data reduction is straightforward, but laborious. The analog chart must be hand-scaled to give a series of hourly mean values relative to some arbitrary baseline. Spot baseline values are computed for the times of each set of absolute observations. Baseline values are adopted for different intervals of recording and are added to the uncorrected hourly mean values. More details on these basic procedures may be found in Wienert (1970, § 102, pp. 331-337). Values representing the normal field are obtained from the final hourly mean values (§ 6.2.3).

Any drift in the three-component sensor can be identified by regular calculation (every 2 hours, for example) of a pseudo-

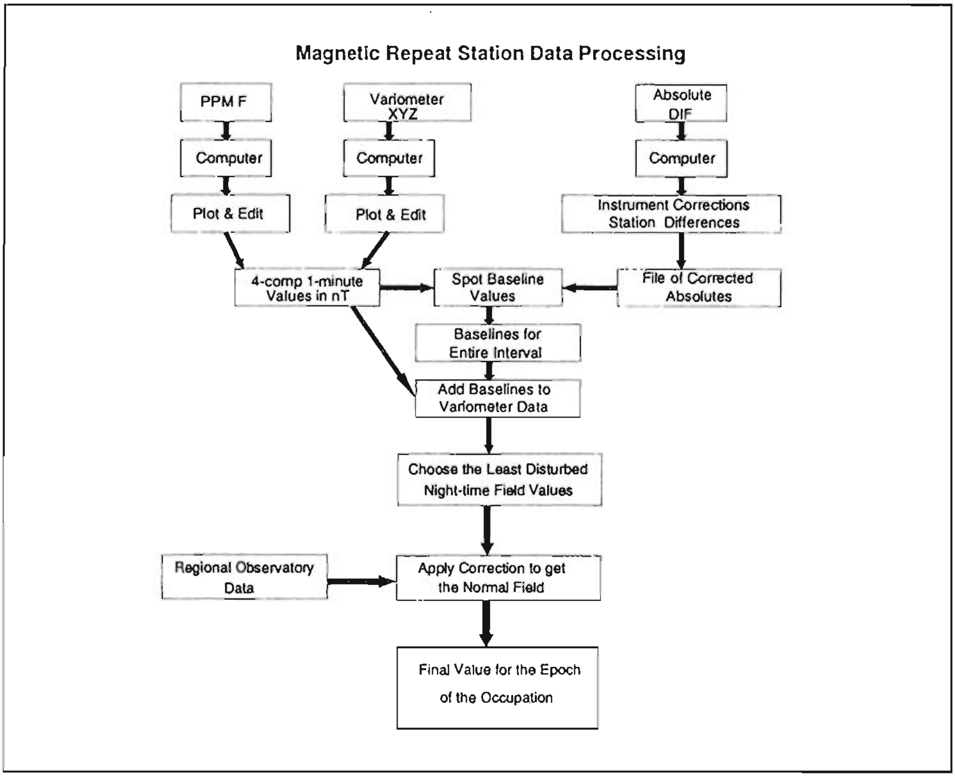

Figure 6.1
Flow diagram showing a typical sequence of steps in processing digital data.

baseline, BF, defined, for D-H-Z orientation by

$$BF = F_a - (\Delta H \cos I + \Delta Z \sin I), \quad (6.5)$$

or, for X-Y-Z orientation, by

$$BF = F_a - \{(\Delta X \cos D + \Delta Y \sin D) \cos I + \Delta Z \sin I\}, \quad (6.6)$$

where

F_a is the total field at the auxiliary absolute PPM station (or at the repeat station itself); ΔH, ΔX, ΔY, ΔZ are the **H**, **X**, **Y**, and **Z** variometer signals measured on the chart recorder relative to any arbitrary baseline; **D** and I are values of declination and inclination observed closest to the time of the calculation.

If BF remains constant over time, it can be assumed that the three-axis variometer has not drifted; if BF changes with time, the variometer baselines must be carefully determined in order to track the drift.

6.2.2 Preliminary reduction of digital data

Digital data must be converted to a usable format and run through various error-checking procedures (including visual scanning of plots of the data). Absolute observations are entered into the computer by hand, calculated and checked, and baselines computed. Baselines are then added to the one-minute values to produce final absolute minute values. It may be possible to use existing observatory data reduction programs, if the raw data are converted to a suitable format.

Any drift of the three-axis variometer can be tested by the consistency of the difference between the total field at the repeat station and the corresponding value determined from the three-axis variometer and a recording PPM, if one is used, in a manner analogous to that involving Eqs. 6.5 and 6.6.

It is recommended that preliminary data reductions be carried out in the field using a portable PC. This allows problems to be detected at an early stage so that, if necessary, further observations and checks can be made before the observer leaves the field site.

It is important to plot the data. This is by far the easiest and safest method of quality checking. Spikes can be removed, and various other corrections made, by using a text editor on the PC. It is not necessary to produce a hard-copy plot since a plot to the computer's screen is normally sufficient to detect major errors such as spikes. Screen plots of the digital data also allow the observer to monitor magnetic activity, and to determine undisturbed intervals that can be used for final data reduction.

6.2.3 Final data reduction

Initial data reduction will leave the observer with either a list of absolute hourly mean values (analog data), or a file of absolute one-minute values (digital data). A value of each magnetic element representative of the normal field or an annual mean is required. There are several ways to proceed depending on the philosophy of the observer, the proximity of permanent observatories, and the availability of the observatory data.

The daily variation of the magnetic field is at a minimum during the night-time hours near, but not necessarily at, local midnight (Table 6.2). Many observers choose the mean of several night-time hours as a first approximation of the undisturbed level of the magnetic field. Whenever possible, recording should be continued over several days so that successive night-time means can be obtained. Close agreement between these values is an indication that they are relatively free from external field effects (and that any drift in the variometer was adequately compensated).

Even if the mean night-time values are in good agreement (within several nanoteslas), they will almost invariably contain some long-term external disturbance effects. For example, magnetic storms can have after-effects that leave the field displaced from its normal level for many weeks, and may pass unnoticed during a two or three day repeat station occupation. (The scatter in typical monthly mean values at observatories demonstrates the nature of the problem.)

A final correction should be applied to estimate either the annual mean or the normal field at the repeat station, which, in the absence of a very long variometer record at the repeat station, can only be done by referring to data from observatories in the region. It must be assumed that the night-time displacement of the field at the repeat station is the same as at the observatory (or observatories, if an interpolation scheme between two, or more, observatories is adopted). The procedure follows that outlined in § 6.1, except that the night-time mean value for the repeat station, E(nt), and for the observatory, $E_0(nt)$, replace the instantaneous values, i.e.,

$$E = E_0 + E(nt) - E_0(nt). \qquad (6.7)$$

E and E_0 may refer to either the annual mean values or to the normal field at the date of the observation (for the repeat station and the reference observatory, respectively). If repeat station annual mean values are calculated by this method, then it is assumed that the average secular change of the geomagnetic field is the same at both the repeat station and the observatory for the year in question (§ 6.1 and § 6.3.4).

In regions where the night-time disturbance at the repeat station cannot be estimated from the nearest observatory (either because the observatory is too remote, or because the field is too inhomogeneous, as in the auroral zones), the final correction for night-time disturbance cannot be made.

Table 6.2 Night-time intervals when the geomagnetic field is likely to be least disturbed

	Geomagnetic Latitude	Local Time
Polar cap	77 - 90	near midnight
Auroral zone	60 - 73	18-19, 04-06 (§ 7.2)
Mid-Latitude	30 - 55	00 - 03 (averaged)
Low-Latitude	05 - 30	00 - 03 (averaged)
Equatorial	00 - 05	near midnight

In such situations, it is equally inappropriate to compute annual means for the repeat station by referencing to observatory data.

6.2.4 Compensation for temperature effects

Problems associated with the temperature drifts to which fluxgate magnetometers are subject were discussed in § 3.4.6. It is sometimes possible to calculate an effective temperature coefficient that allows at least partial correction of temperature effects from the data recorded at the repeat station. We say "effective temperature coefficient" because the coefficient calculated combines several effects that have a diurnal component, such as the temperature drift of the sensor, the temperature drift of the electronics, and sensor tilt.

To calculate an effective temperature coefficient it is necessary to record temperature at one-minute intervals along with the magnetic elements, and to do frequent absolute observations. Calculate and plot baselines for each element. If the baselines show regular diurnal changes it is worthwhile proceeding to calculate a coefficient. If the baseline changes are irregular, or show only a linear drift, coefficients are unlikely to be calculable, or may not be needed.

Calculate the temperature coefficients using the method of least squares. The baseline values for a particular magnetic field element, E_{bl}, determined from each set of absolute observations will form the dependent variable; the temperature values, T, will form the independent variable:

$$(E_{bl} - \overline{E}_{bl}) = \alpha + \beta(T - T_o), \qquad (6.8)$$

where $\overline{E}_{bl}$ is the average baseline value, T_o is an arbitrary reference temperature such as 20° C, and α and β are the regression coefficients to be determined. Also calculate the correlation coefficient between E_{bl} and T to confirm that the variations in the baseline values and temperature values are indeed highly correlated.

Use the coefficients to calculate corrections that are added to the recorded variometer data. Then, calculate baselines again. If the effective temperature coefficient is valid, the newly calculated baselines should exhibit less scatter than those calculated previously.

6.3 Sources of Error

A determination of the error in a repeat station observation is an important but often difficult exercise. By "error" we mean the difference between a repeat station value, after appropriate corrections, and the true annual mean or normal field value at that location. Estimates of overall errors for several mid-latitude repeat station networks were given in § 2.4.

The errors that may affect the final results of a repeat station occupation arise from instrumental and observational limitations, from mis-location of the repeat station, and from assumptions in the data reduction. To get an appreciation of the magnitude of errors that might arise by not fully reducing data, consult the tables produced by Vestine *et al.* (1947a).

6.3.1 Instrumental errors

A proton precession magnetometer will give an accurate absolute output provided the internal frequency standards are correctly adjusted and the sensor is completely non-magnetic. In practice, remanent and induced magnetization can never be eliminated entirely and lead to instrument differences of, typically, up to a few nanoteslas. By making comparisons with known standards (§ 3.4.5) it should be possible to achieve accuracies of better than 0.5 nT.

A Jena Model 010B theodolite has a precision of 1 second of arc, but the actual observational error is considerably larger than this. At mid-latitudes, the errors in a series of careful measurements made with a DIM and a PPM are estimated to be:

D	20″
I	6″
F	0.5 nT.

6.3.2 Positioning errors

If the absolute observations at a repeat station are not made in exactly the same location as previous observations, then an error will be introduced in the estimate of secular variation caused by the spatial variation of the geomagnetic field. Care must be taken to ensure that the absolute instruments are not only centred exactly above the repeat station marker, but are also positioned at exactly the same height as used during previous station occupations. When instruments (DIM and PPM) are interchanged on the tripod or pillar, use suitable mounting adaptors to ensure that the instruments are at the same height. Note this height clearly in the repeat station description for future use.

The effect of the positioning error will depend on both the horizontal and vertical gradients of the geomagnetic field, and the corresponding distance from the true location. For example, in a low gradient environment of 1 nT/m, relocation need be only to within 10 cm, whereas in a gradient of 1000 nT/m, repositioning must be accurate to within one millimetre. It is necessary to know the magnitude of local field gradients to determine the positional accuracy required.

Inexact positioning of the theodolite will also introduce an error in the azimuth of the reference marker, as discussed in § 5.3. Use reference marks that are at least 200 m away to reduce the effect.

Positioning errors can be reduced to a negligible size provided proper procedures are followed, as outlined in § 5.3.

6.3.3 Errors when reducing data using a reference observatory

The main assumption made when correcting repeat station measurements using data from a reference observatory is that the instantaneous difference in any field element between the two sites, $E(t)-E_o(t)$, is constant; that is, the magnetic field variations are the same at the two sites. This assumption must hold both at the time of the observations and during the interval over which an annual mean or normal field value is derived (§ 6.3.4). In general, this will never be the case. (Indeed, if it were, there would be no need for repeat stations.) The errors involved in the assumption depend on several factors.

- *Distance and direction of the station from the observatory*. The patterns of transient and daily variations change with location and change more with latitude than with longitude.
- *Magnetic disturbance*. Slowly varying

changes in the field, such as the quiet solar daily variation, are more homo-geneous than more rapidly varying disturbances.

- *Conductivity anomalies in the Earth's crust*. Electric currents induced in the crust by external field variations can vary significantly over distances of 10 km, or even less, and effect the field variations between sites. This is discussed in more detail in § 6.3.6. A thorough discussion of this problem is also given by Jankowski and Sucksdorff (1996).
- *Location of the station*. Stations located near the auroral zone are much more difficult to correct using a reference magnetic observatory because of the almost continual presence of magnetic disturbances with small scale variability.
- *Differences in local time*. The quiet solar daily variation of the magnetic field and disturbances originating from ionospheric sources are local time phenomena. Thus, the variation at a repeat station several degrees of longitude from an observatory will be out of phase with the variations at the observatory. Magnetic field variations originating from magnetospheric (remote) sources are likely to be near-synchronous at the repeat station and the observatory.

The error in reduction due to these factors is not constant, but will vary from station to station and from observation to observation. It is possible to estimate a lower limit for the error from the scatter in numerous observations made over several successive days. It is also useful to examine the differences in variations between different magnetic observatories and the repeat station to help select the most suitable reference observatory.

6.3.4 Errors in reducing to an annual mean

In reducing to an annual mean it is assumed that

$$E(t) - E_0(t) = E - E_0, \qquad (6.9)$$

where $E(t)$, $E_0(t)$ refer to the elements measured at time t, and E, E_0 refer to the annual mean values at the repeat station and the observatory, respectively. The above expression is not strictly correct since it incorporates additional assumptions about uniformity of the secular variation between the repeat station and the reference observatory. To illustrate the point, consider three cases.

Case A: the secular change at the repeat station and at the observatory are identical at all times throughout the year for which the annual means are calculated. In this case, Eq. 6.9 is exact. Note that the secular change does not have to be uniform throughout the year in question, and the secular change at the repeat station does not have to correspond to that at observatory outside that year. It is usual practice to compute annual means for a calendar year, centred on a mid-year epoch, e.g., 1992.5, but the mean can be centred on any time.

Case B: the secular variation is constant, but different, at both the repeat station and the observatory for the year in question. Equation 6.9 will be in error by an amount equal to the differential change in E between the date of the repeat observations (t) and the mid-year epoch of the annual means. This is illustrated in Fig. 6.2, where the secular change in element E at both the repeat station and the observatory (dE/dt and dE_0/dt, respectively) are constant (but not equal) throughout the

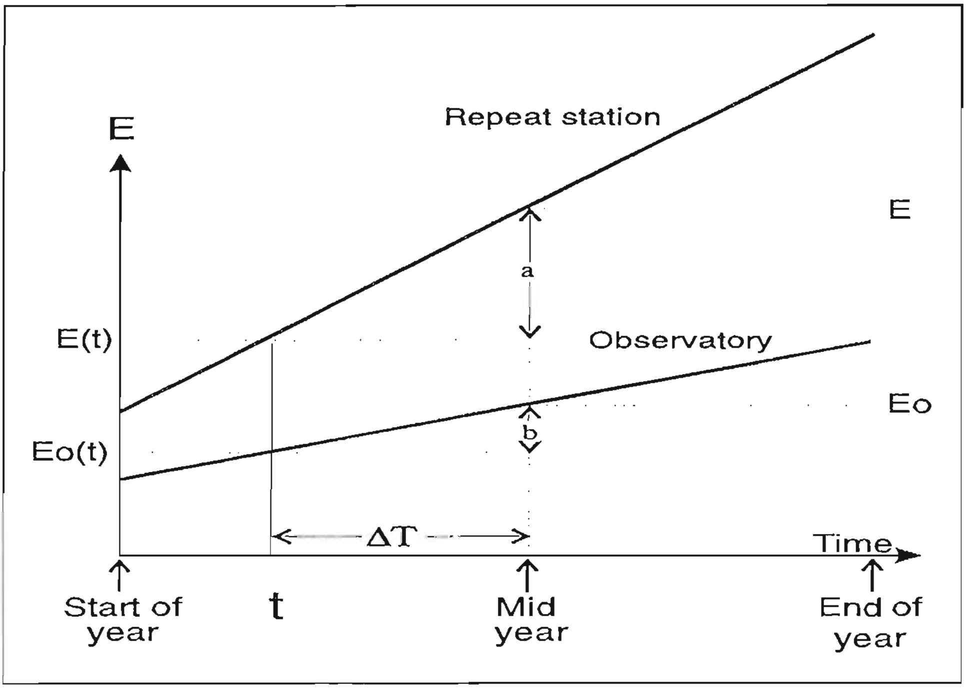

Figure 6.2
Illustration of constant secular variation in element E at both the repeat station and the reference observatory; the secular change at the repeat station is larger than that at the observatory.

year, and the repeat observations are made at a time ΔT before the mid-year epoch.

Then

$$E(t) - E_o(t) = \mathbf{E} - \mathbf{E}_o - (a-b), \qquad (6.10)$$

where

$$(a-b) = (dE/dt' - dE_o/dt)\ \Delta T. \qquad (6.11)$$

The corresponding error in Eq. 6.9 is the quantity (a-b). This can be reduced by making observations near the mid-year epoch, i.e., by reducing ΔT, or by estimating (a-b) as discussed in § 6.1. (Equation 6.10 is equivalent to Eq. 6.3.) An alternative strategy is to compute annual means for the year centred on the time of the repeat observations, t.

Case C: the secular change is non-uniform and different at both the repeat station and the observatory. This is the most likely case in practice, and is illustrated in Fig. 6.3. Without knowing the form of the secular variation functions, it is clearly not possible to calculate the error (a-b), but it is readily apparent that the error will depend not only on ΔT, but also on the difference in secular variation throughout the entire year in question. (There will, of course, be the rare case when the errors cancel out.)

To conclude, when using Eq. 6.9 for data reduction it is assumed that:

(i) diurnal and transient variations are the same at both the repeat station and at the reference observatory for

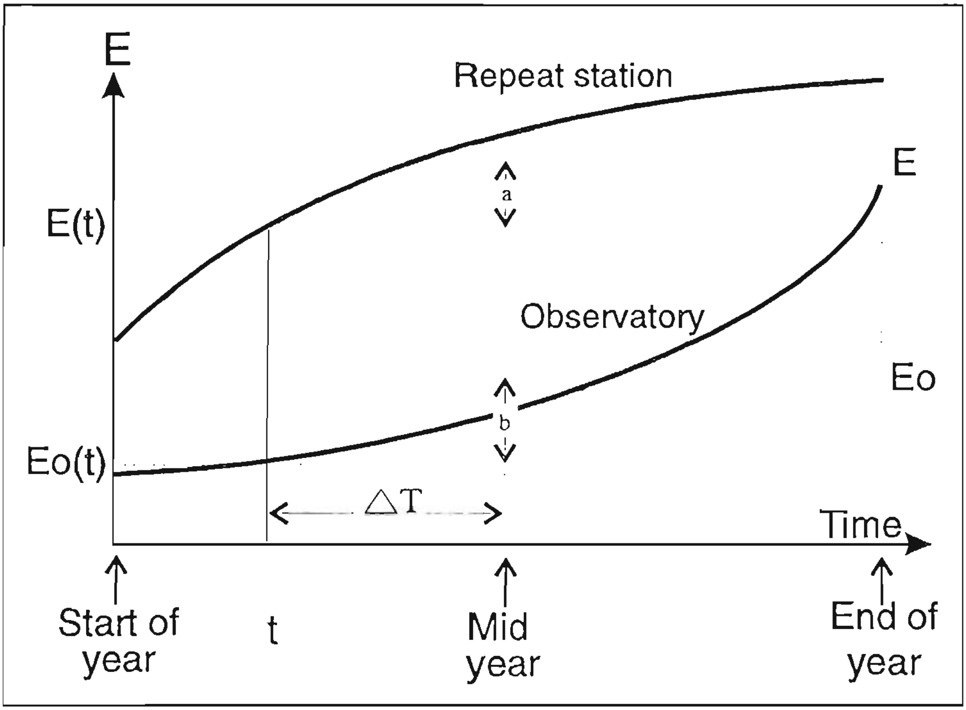

Figure 6.3
Illustration of non-linear and differing secular variation in element E at the repeat station and at the reference observatory. It is not possible to determine the error term (a-b) without knowing the form of the two secular variation functions.

the duration of the repeat station observations,

(ii) there is no difference in secular variation at the two sites between the time of observations and the mid-year epoch of the annual mean, and

(iii) the form of the secular variation is the same at both sites throughout the year for which annual means are calculated, i.e., the difference in the true annual means for the repeat station and the observatory is equal to the difference between the normal field at the repeat station and the observatory at the time of observations.

Precautions can be taken to reduce the errors arising from these assumptions. Assumption (i) is the most important. Making observations during undisturbed times of day (and preferably during the night) will help to satisfy this assumption. Assumption (ii) can be satisfied by observing at, or close to, the mid-year epoch or by calculating annual means for the year centred on the time of observations instead of the mid-year epoch. It is also possible to estimate the correction (a-b) from an approximate knowledge of the difference in secular variation between the observatory and the repeat station based on extrapolation of earlier data or by using a magnetic field model. The correction can be improved by iteration if necessary.

The only way to reduce errors arising from assumption (iii) is to compute mean values for an interval of time less than one year. However, if the interval chosen is too short, the observatory mean value may not be free from the effect of external fields. Regardless of the interval chosen, it is necessary to be selective about choosing quiet days for compiling mean values. The ultimate purpose of the data reduction process is to make an adjustment to the observed values to remove external field effects. If there are grounds for concern about the approximations arising from assumption (iii), then it is still possible to reduce data in the manner described in § 6.2, treating the observatory record as that of an on-site variometer. Note that the secular variation assumptions only apply to the interval during which mean values are computed and not for the entire interval (e.g. 5 years) between repeat station observations.

It is clear from the above that reduction of repeat data using a reference observatory involves a degree of circularity in that it is necessary to make assumptions about the quantity to be measured, namely the secular variation. Despite this, the method is valuable, as it is quick and simple in situations when assumption (i) is satisfied — an essential requirement. The other assumptions are much less important provided a secular variation correction is applied, or the need for a correction is eliminated.

6.3.5 Errors when reducing data using a local variometer

Using a local variometer avoids some of the problems associated with the assumption that transient variations at the reference observatory and the repeat station are identical. However, it is still necessary to use reference observatory data to estimate the displacement of the night-time field from its normal value (§ 6.2.3).

A local variometer is subject to two additional sources of error. First, fluxgate variometers often have large temperature coefficients that cause drifts in the output values (§ 3.4.6 and § 6.2.4). It is more difficult to control temperature variations and apply corrections for a temporary local variometer than for a permanent observatory. Second, the physical stability of the sensor mounting will not be as good as at an observatory; tilting of the sensor will cause a drift in output values. A temporary variometer installation will, therefore, suffer from transient effects as both thermal and physical settling occurs, and it will seldom be possible to wait for these to decay before starting absolute observations. Steady drifts can be accommodated provided frequent absolute observations are made. The scatter in the baseline determinations is an indication of the size of drift problems and associated errors.

Further, very important errors arise when a final correction is applied for the night-time displacement of the field from its normal value. This correction can only be derived from the "nearest" observatory, except in the rare cases when a local variometer can be kept running and calibrated for many months. Part of the error in this final correction is because the night-time displacement estimated for the observatory will not be identical to the corresponding displacement at the repeat station. It is difficult to estimate this difference without a detailed investigation of magnetic variations in the region of interest. An upper limit to the size of the error can be obtained by comparing the night-time displacement corrections from different observatories in the region. The rest of the error in the final correction comes from the estimation of the normal field level at the observatory. This is an extremely difficult problem, which centres around the question of how to identify a truly undisturbed night (or day). A discussion of this question is beyond the scope of this guide, but the scale of uncertainties involved is illustrated in Fig. 6.4, in which the night-time field is plotted for selected extremely quiet days for a mid-latitude observatory, Victoria (J.K. Walker, personal communication, 1994; see also Walker, 1982). A long period signal appears to be present (more evident in **Z** and **Y** than in **X**) on which a scatter of 5 to 10 nT is superimposed. At higher (auroral) latitudes it is even more difficult to pick extremely quiet days and the scatter is typically 10 to 15 nT. Thus, the final night-time correction is likely to be comparable to the uncertainty in making accurate repeat station measurements (Table 2.1).

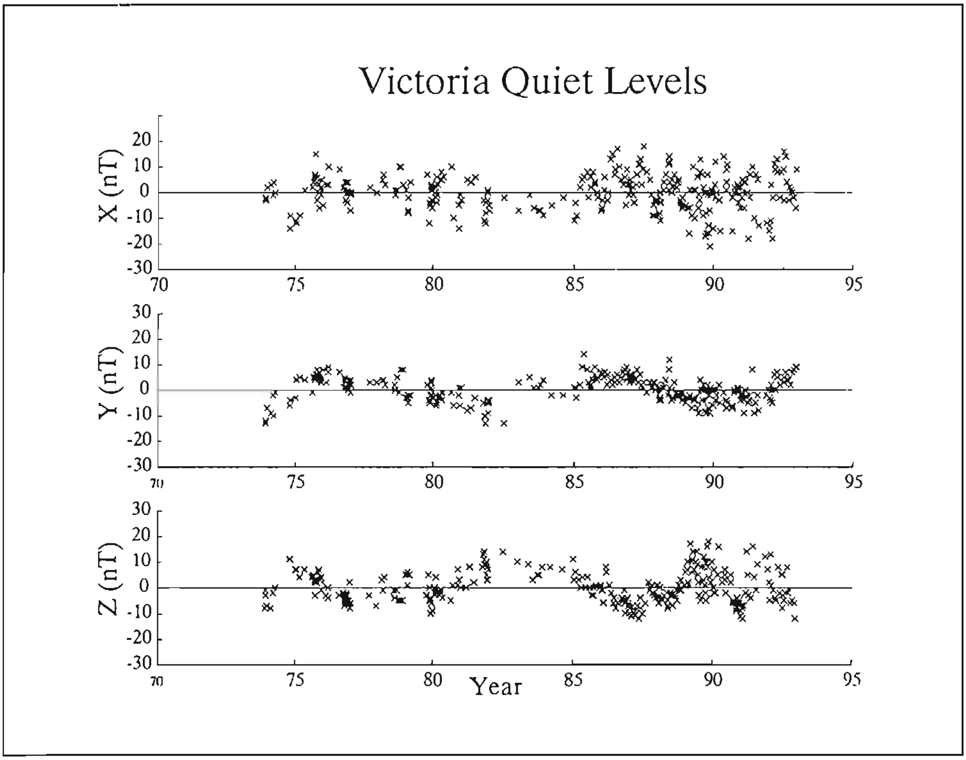

Figure 6.4
Night-time values of the field for selected extremely quiet days at Victoria magnetic observatory, Canada (latitude 48.5°, longitude 236.6°, geomagnetic latitude 54.3°). Victoria is a mid-latitude observatory. Extremely quiet days were selected, first, by choosing days with low Dst and Kp and, second, by careful examination of daily magnetograms. Data provided by J.K. Walker, Geological Survey of Canada.

6.3.6 Crustal induction problems

The scatter in either the baseline values computed for a local variometer from a sequence of sets of absolutes, or the estimates of the repeat station annual mean made using a reference observatory, is sometimes larger than can be accounted for by observational errors or by the expected spatial variation of the external magnetic field. If the observations were not made under quiet conditions, then the possibility of crustal induction problems should be considered.

One way to identify such problems is to make a comparison with results obtained under quiet observing conditions. A lower scatter will indicate that the region is subject to heterogeneity in the electrical conductivity structure of the crust on a scale commensurate with the distance between the repeat station and the variometer or reference observatory. The problem will be greater when the variometer is not installed near the repeat station site, but some distance away at a regional base-station (§ 4.1.2.) A direct method of identifying crustal induction problems is to install a variometer at the repeat station and compare records with the reference observatory or variometer base-station under varying conditions of magnetic disturbance. Differences that are dependent on the level of magnetic disturbance may indicate non-uniformity of the electrical conductivity response of the crust. Variometer records for a disturbed day obtained from stations covering a region containing a large subsurface electrical conductivity anomaly are compared in Fig. 6.5. Stations on opposite sides of the conductor show a reversed Z-response with amplitudes up to a few tens of nanoteslas.

6.3.7 The value of frequent reoccupations

Increasing the duration of a station occupation will increase the probability of observing during a quiet interval and will reduce many of the errors discussed above. In practice, it may be neither possible to extend station occupations beyond several days because of the costs involved, nor desirable because of the diminishing improvements in errors. When greater accuracy in the determination of secular variation is required, then consideration should be given to undertaking repeat station occupations more frequently. This is why IAGA recommends that repeat stations be reoccupied every two years (Vestine, 1950).

There are several benefits to frequent observations. First, frequent reoccupations make it easier to recover from a serious flaw in observations affecting the entire occupation of a station and enable a quick redetermination of SV if it is found that an earlier result suffered from disturbance problems. Second, a source of bias, such as the night-time displacement of the field from its normal value, may affect all the results from a particular occupation but not from successive occupations. Third, frequent observations allow rapid changes in secular variation, such as the 1969 jerk, to be tracked.

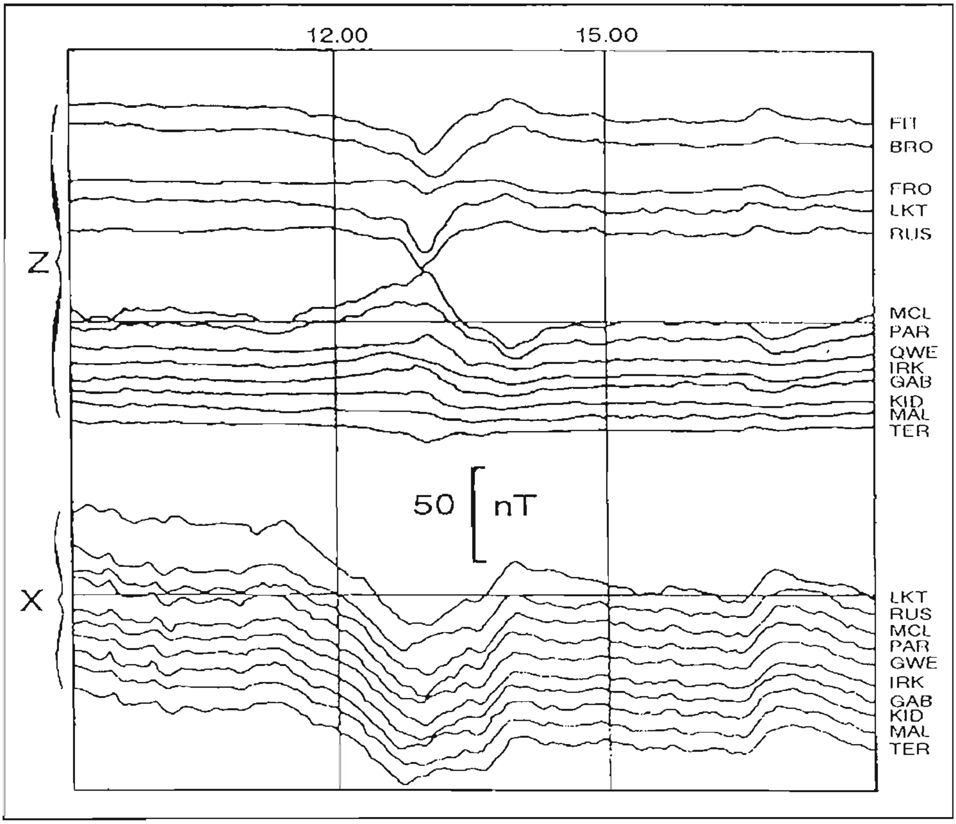

Figure 6.5
Stacked magnetograms for an event on 4 July 1985 obtained from an array of variometers in the Canning Basin, northwestern Australia. The typical spacing between stations is typically 50 km. Notice the reversal in the Z component between station RWS and MCL. Results from Chamalaun and Cunneen (1990).

CHAPTER 7 Special Regions

This chapter covers those regions of the globe where special conditions apply to repeat station observations. Disturbances caused by external fields are both larger and more variable at high and low magnetic latitudes than at mid-latitudes. Special care must be taken in such regions to avoid the contamination of repeat station results by disturbance effects.

7.1 Equatorial Regions

Measurements made in the intertropical zone present special difficulties related both to climatic conditions and, in the neighbourhood of the magnetic equator, to the presence of the equatorial electrojet. Some of the problems caused by climate have been discussed earlier (§ 3.1, § 3.4.2,

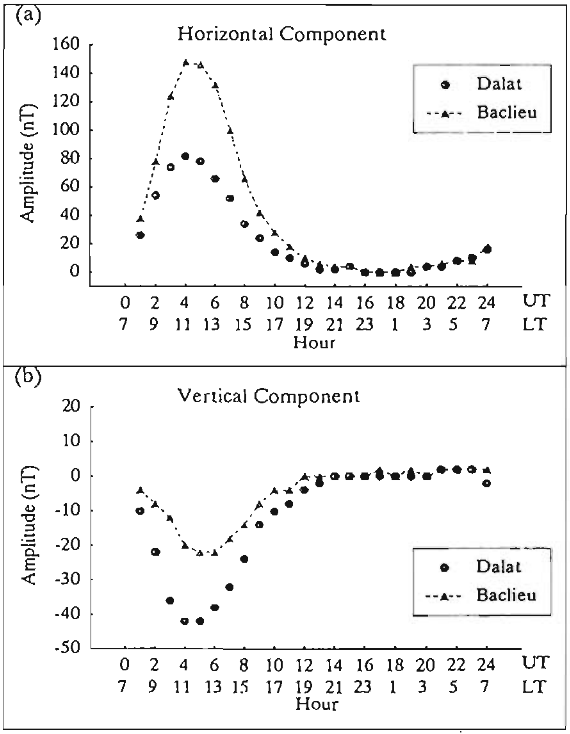

Figure 7.1
Average solar quiet day variation of (a) the H-component, and (b) the Z-component for the year 1990 at Dalat and Baclieu, Vietnam. These sites lie in the equatorial electrojet region.

§ 5.3 and § 5.5). The problems caused by the electrojet are discussed here.

7.1.1 Geophysical conditions related to the equatorial electrojet

The equatorial electrojet can be pictured as a band of electric currents at an altitude of about 105 km, associated with the ionization produced by the Sun. This band, centred on the magnetic equator (I = 0), has a half-width of about 280 km and a thickness of about 10 km (Richmond, 1973). The equatorial electrojet shows distinctive magnetic characteristics at ground level, which appear principally in the horizontal and vertical components of the field as an amplification of the Sq variation. This amplification varies greatly from day to day, and varies strongly both with latitude and as a function of the distance from the centre of the electrojet. The effects may be observed up to 6° from the dip equator (Barreto, personal communication). The amplification occurs between 0900 and 1800 LT and its effect can exceed 100 nT at 1200 LT beneath the centre of the electrojet. The latitude gradient can reach a few tens of nT per degree (Onwumechili, 1967).

The effect of the electrojet is illustrated in Fig. 7.1, which is based on data recorded by Nguyen Thi Kim Thoa and Daniel Gilbert (personal communication) during a magnetic survey of Vietnam carried out in 1990 and 1991. Baclieu is situated at a geomagnetic latitude of 0° 17′ N; Dalat is situated at a geomagnetic latitude of 11° 56′ N, further from the centre of the electrojet so the enhancement of the horizontal component of Sq is less. Fig. 7.1 shows the average Sq over the year 1990; the amplitude of Sq also varies greatly from day to day. Because of the sensitivity of the daily variation, both to day-to-day fluctuations in the equatorial electrojet and to distance from the electrojet, special care must be taken when reducing repeat station observations to ensure that a truly undisturbed normal field, or annual mean value is derived. If data are being reduced using a reference observatory, it is important to establish that the daily variations at the observatory and the repeat station correspond. The reference observatory will usually have to be at a magnetic latitude that is similar to that of the repeat station because of the strong latitude dependence of electrojet effects. If a local variometer is being used, then equal care must be taken to ensure that an accurate correction is applied to remove external field effects from the night-time field in order to obtain the normal field.

7.1.2 Equatorial-zone observations using a local variometer

Because of the low density of observatories in the equatorial zone, use of a local variometer is, in many cases, essential. The procedure, outlined fully in § 6.2, is the same as at a repeat station in any other part of the world, but the following points should be emphasized.

Absolute observations should be made in the morning before 0900 LT and in the evening after 1800 LT, outside the period of enhanced Sq. It is even better to make absolute observations in the middle of the night. Environmental conditions, such as heat, humidity and ground movement cause problems in equatorial regions; their effects can also be reduced by observing outside the main part of the day. Environmental factors that can affect magnetic observations have been discussed in § 3.1, § 3.4.2, § 5.1, § 5.3 and § 5.5.

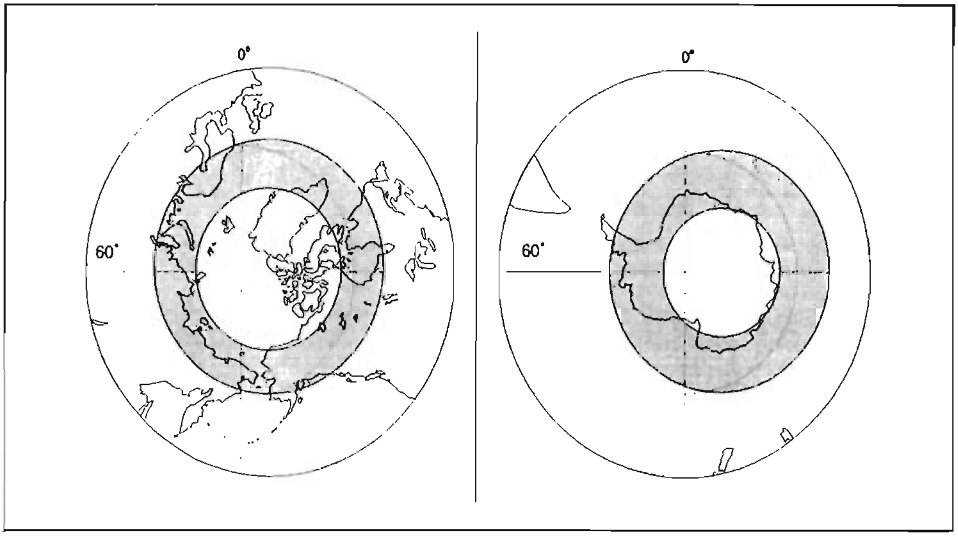

Figure 7.2
The location of auroral zones in the northern hemisphere (left) and southern hemisphere (right). The polar cap is the region poleward of the auroral zone.

7.1.3 Equatorial-zone observations using a reference observatory

In the region of the equatorial electrojet, data reduction using a reference observatory is only feasible if the observatory is at the same magnetic latitude (± 100 km) as the repeat station. If the reference observatory is outside this latitude band, a knowledge of the amplification of the diurnal variation due to the electrojet is essential for data reduction. It is essential to take the absolute measurements at the repeat station outside the main period of diurnal variation, that is, very early in the morning or late in the afternoon, or, if possible, shortly after midnight.

In the earlier example of the magnetic survey carried out in Vietnam between 23° N and 8° N, and thus under the direct influence of the equatorial electrojet, the measurements were reduced with respect to several reference observatories in turn. The final results obtained varied according to the observatory chosen and according to the method of reduction, with differences ranging from 10 nT to 30 nT. These errors are large compared to the errors usually assigned to results from repeat stations at mid-latitudes (Table 2.1).

7.2 Auroral and Polar Regions

Making repeat station measurements in the auroral zones and polar cap regions also presents special difficulties. Both these regions are subject to elevated levels of magnetic activity compared to mid-latitude regions (see Fig. 3.1), but the characteristics of auroral activity and polar activity are quite different, and demand different strategies for repeat station occupations. These are discussed below.

Fig. 7.2 shows the approximate locations of the auroral zones and the polar caps. The boundaries are not distinct. The auroral zones are defined as the regions in which auroras occur most frequently. The instantaneous auroral oval will generally differ in size and position from the auroral zone, with its lowest geomagnetic latitude (about 68°) at local midnight, and its highest geomagnetic latitude (about 78°) at local noon. The auroral zone is the approximate locus of the midnight sector of the auroral oval. Feldstein and Starkov (1967) give examples of the northern auroral oval under a variety of conditions. More recently, nomograms have been produced that give the position of the auroral oval at any local time and for different levels of magnetic activity (Gerson, 1993). The polar caps are the regions around the north and south geomagnetic poles that are enclosed by the auroral zones.

7.2.1 Auroral-zone observations

The auroral zones are characterized by frequent night-time disturbances in the form of auroral substorms. Daytime disturbances are also common (Whitham *et al.*, 1960). This means that it is difficult to obtain recordings spanning a quiet night, even if a variometer is operated for many days. Newitt and Walker (1986) found that, at an auroral zone station, midnight field levels fall within 10 nT of the undisturbed field level only 20% of the time, and daily mean values fall within 10 nT of the undisturbed field value 29% of the time. If the midnight period is disturbed, it is preferable to choose another interval to estimate the normal field. Campbell (1989) recommends the post-midnight-to-pre-dawn period. Loomer (1980) notes that the late afternoon is relatively free of disturbance (see Table 6.1). However, this time of day may not be as satisfactory as the post-midnight period for estimating the normal field since the Sq variation is still present.

Magnetic activity is large in the auroral zone at any time of year. Statistically, it is greatest near the equinoxes (see Fig. 3.1). This means that early summer (May, June, July in the northern hemisphere) is normally the best time of year to carry out magnetic surveys in the auroral zone. There is, however, a large variability from year to year. In some years, the “autumn” maximum shifts forward and occurs in the late summer months (Loomer and Jansen van Beek, 1969).

The morphology of magnetic field variations in the auroral zone is highly complex. Studies show that field variations at an auroral observatory do not correlate at all with variations at sites more than about 250 km from the observatory (Newitt, 1989). Even at distances of less than 250 km, correlations vary greatly from day to day. Thus, correcting observations from repeat stations in the auroral zone can seldom be carried out with any degree of certainty using a nearby magnetic observatory. Indeed, Newitt and Walker (1986, 1990) showed that correcting data from an auroral-zone station using data from an observatory located several hundred kilometres away actually resulted in a value that was further from the normal field than was the uncorrected value.

It is possible to use sophisticated modelling of magnetic field variations to correct observations made under most circumstances (Newitt and Walker, 1990), but the techniques are elaborate and time-consuming and may be beyond the resources of many observers. The most practical advice that can be offered to observers is to carry out the survey in the early summer and to occupy each station for as long as possible, preferably a week or more. This increases the probability of recording a quiet interval. If a quiet interval is not observed, averaging the field values over a long interval of time, excluding the most disturbed periods, especially those with large bay-like features, should reduce the effects of disturbances on the final result.

7.2.2 Polar cap observations

Magnetic activity in the northern polar cap shows a maximum in the summer months (Loomer and Jansen van Beek, 1969), and a minimum in winter (see Fig. 3.1). Unfortunately, observations in the high Arctic (or Antarctic) during the depths of winter are, at best, difficult and, at worst, impossible. The most practical compromise is to observe as late in the autumn as possible.

Polar cap magnetic activity shows a daytime maximum (Loomer and Whitham, 1963). However, during the summer months, there is a great deal of magnetic activity even at night-time, making it difficult to find a quiet interval.

The magnetic field in the polar cap is also subject to the effects of the sector polarity of the interplanetary magnetic field (Loomer, 1979). The result of this is that daily mean values can change drastically from days of positive IMF sector polarity to days of negative sector polarity. In the central polar cap, the effect is most pronounced in the Z-component and can be greater than 60 nT in the summer months. The effect is opposite in sign in the horizontal components and smaller than for the case of the Z-component. Near the edge of the cap, the effect is largest in the X-component.

As a result of the IMF effect, a summertime daily mean value may be a poor estimate of the annual mean value or of the normal field. It will probably be necessary to average over several days and to ensure that an equal number of positive- and negative-sector days are included in the average. The IMF effect is almost negligible in winter, and it is also small at night. However, as previously mentioned, it is difficult to observe in winter, and the generally elevated levels of summertime activity, even at night, create uncertainties in night-time levels.

In contrast to the auroral zones, field variations in the polar caps are fairly uniform spatially. This is especially true if one considers the day-to-day variability of the field. For example, there is an excellent correlation between daily mean values from Resolute Observatory and Mould Bay Observatory, some 700 km away. The errors in estimating a Resolute daily mean using Mould Bay data are 10 nT or less (Loomer, 1979). Therefore, the polar cap is one region where, in the absence of large conductivity anomalies, a neighbouring observatory can be used reliably for data reduction (Newitt and Walker, 1986).

The recommendations for observing in the polar cap can be summarized as follows.

(i) Observe as late in the autumn as possible so that the effects of both magnetic disturbances and the IMF are minimized.

(ii) Record for several days so that the effects of the IMF can be reduced when taking an average value.

(iii) Try using the nearest observatories to correct night-time or daily mean values to a normal field value or annual mean. If recordings are made for several days, the accuracy with which this can be done increases.

CHAPTER 8 Reporting Procedures

When you return exhausted from a repeat station survey, avoid the temptation to neglect the documentation and reporting of results, for these stages are essential if quality standards are to be maintained and your results fully utilized. You will probably keep a file of all the information about one particular survey, but it is valuable to keep a separate file for each individual repeat station site.

A standard report form should be completed by the observer whenever a repeat station site is visited. An example of such a form is given in Appendix 2. Write a field work report for internal use, and revise the repeat station description (§ 4.5) to include any relevant new information. Add the new normal field values or annual means to a plot of earlier data against time. When you are satisfied with the results, report them to WDC-A to be available for others to use for regional or global modelling.

8.1 IAGA Reporting and Station Classification Scheme

A scheme for classifying and reporting magnetic repeat data is coordinated by IAGA Working Group V-8: *Analysis of the Global and Regional Geomagnetic Field and its Secular Variation*. The scheme is designed to ensure regular reporting of repeat data in a standardized form. One of the principal aims is to provide sufficient information to allow repeat data to be assessed accurately so that they can be used for global field modelling. The information given below can also be found in the document "Regional Magnetic Repeat Station Records—Explanatory Notes" issued by IAGA Working Group V-8 and included in the IAGA catalog of "Regional Magnetic Survey, Chart, and Model Descriptions" (Barton & Newitt, 1995). Each agency conducting repeat station surveys is asked to submit the following:

(i) *A Regional Magnetic Survey, Chart, and Model Description* giving general information about the repeat station network, instrumentation, observational methods, data reduction procedures, published products, and other magnetic survey activities.

(ii) *A Magnetic Repeat Station Record Sheet* for each occupation of a station, giving the main results, information about accuracy, and an alphanumeric classification code.

(iii) *A Computer File* summarizing the results of a particular survey (a "**survey file**") or a compilation of results from many surveys (a "**master file**") or both.

8.1.1 Regional survey, chart, and model description

This is a short document summarizing the characteristics of a regional network of magnetic repeat stations, the instruments and observational procedures employed, the data reduction methods used, a list of the models and charts produced, and a list of all previous magnetic surveys. A diagram showing the locations of the stations, and a list of related publications may also be included. An example of a regional magnetic survey, chart, and model description is given in Appendix 5. Please follow the same format if possible, and ensure that your network description is kept up-to-date. One copy should be sent to WDC-A and another copy to IAGA Working Group V-8. The initial compilation of repeat station network descriptions from various national agencies (Barton, 1991) has now been replaced by a more comprehensive catalog issued by IAGA Working Group V-8 (Barton and Newitt, 1995).

8.1.2 Magnetic repeat station record sheets

A record sheet should be completed for each occupation of a repeat station and copies sent to WDC-A, from whom they are available to anyone on request. Working Group V-8 does not keep copies of these record sheets. A blank record sheet and a completed example are given in Appendix 6. The following notes provide information about how to complete a record sheet. It may not be possible to fill in all the information specified, but please complete as much as possible. Include details (such as country) that will be repeated on every sheet. Record sheets should be prepared for old surveys as well as for new ones. The following explanatory notes refer to the record sheet in Appendix 6.

Station name

Do not use the same name for different station markers at the same locality. For example, use names such as Station-A, Station-B to distinguish different station markers. If the magnetic environment has changed, but the station is still usable, treat it as a new station and give it a new name. Ensure that names agree exactly with those given on previous record sheets and data files.

Station coordinates should be given in geodetic coordinates (for a spheroidal Earth). The distinction between coordinates on different spheroids is unimportant. Give coordinates in decimal degrees; latitude positive north, negative south; longitude positive east of the Greenwich meridian. If the height above mean sea level is not known accurately, please enter an approximate value, and indicate that it is approximate (estimates to the nearest 100 metres are still useful).

Classification *(Please pay special attention to this section)*

Assign a classification letter and number (in the range 1 to 3) to the results for each station. The letter denotes the type of diurnal control used for data reduction:

V — local variometer,
M — reference magnetic observatory,
A — absolute observations at the repeat station only.

Classification 1: results for which all the effects of external fields and associated internal induction effects were removed in order to obtain the "normal" field. In most cases, this requires field recordings from a local variometer or nearby magnetic observatory. Unless observations are made under extremely quiet magnetic conditions, a correction for the after-effects of magnetic storms and other long-term transients is necessary.

Classification 2: results for which an approximate correction was made to remove the effects of external fields. For example, if absolute observations are made throughout the day then an approximate diurnal correction can be made. Observations made during the night under magnetically quiet conditions qualify for a "2" classification, or possibly "1" if the observer has reason to believe that the completely undisturbed field was measured. A "2" classification is appropriate if data are reduced using a reference observatory that does not reproduce accurately the variation signal at the repeat station (either because it is too remote, or because of crustal induction anomalies).

Classification 3: spot measurements of the vector field were made when external field effects were small. Spot observations are generally unsuitable for deriving the secular variation and can be used only when the external field contribution is small compared to the secular change of the field between successive epochs.

If an intermediate classification best describes your results, then assign a decimal value as best you can. Some examples of classifications are given below.

V 1 Daytime absolutes were used to provide baselines to calibrate a local variometer; observations were made during quiet magnetic conditions; a final correction was made for long-term transient effects using long records from a representative magnetic observatory.

V 1.5 As above, except that observations were made under moderately disturbed conditions and only an approximate correction for night-time disturbance was possible (the nearest observatory was too far away for an accurate correction).

M 1 Early morning and late evening absolutes were made, and reduced to equivalent annual means by reference to two neighbouring magnetic observatories. Observations were made under quiet conditions and means were centred on the date of the repeat station occupation.

M 2 Absolute observations were made in January under moderately disturbed conditions, and reduced to obtain mid-year annual means via a reference observatory. The poor internal consistency of consecutive results indicated that the observatory was too remote to represent accurately the reduced diurnal variation at the repeat station, and the 6-month gap between the repeat station occupation and the epoch of the annual means probably introduced an additional secular variation error.

A 1.5 Sets of absolute measurements were made in the middle of the night on a magnetically quiet day.

A 2 A good spread of day-time absolutes was recorded, including early morning and late evening, permitting estimation of the night-time field; the nearest reference observatory was too remote to provide effective diurnal control.

A 3 A single determination of the vector field was made early in the morning on a fairly quiet day.

Note the important distinction between the "night-time" value of the field, i.e., when external field effects are at a minimum (which does not necessarily occur at midnight), and the "undisturbed night-time" value. The latter would be the field if there were no external sources, and is referred to here as the normal field. It may be necessary to undertake a special study to establish how accurately records at the nearest observatory represent the geomagnetic variation at the repeat station. This is particularly important if either site is suspected of being influenced by anomalous crustal or coastal induction effects.

Results *(Enter "N/A" if a particular result is not available, or is not applicable.)*

Mid-date of station occupation: enter the date about which the observations are centred either in decimal years or as year, month, day (yyyy mm dd) — e.g., 1995.477 or 1995 06 23 for 23rd June 1995.

Duration of station occupation: enter the time interval spanned by the absolute/ variometer observations, rounded to the nearest day or hour.

Total number of sets of absolutes: enter the total number of sets of absolute measurements made during the entire station occupation. This number need not be exact; it provides a guide to the thoroughness of the observations.

Sequence of elements per set: enter the sequence of individual measurements of the field that comprises a set of absolutes, e.g., **DIFID** or perhaps **FDFIFDFIF**.

Uncertainty in station relocation: enter an estimate of the distance between the points where absolute observations were made and the theoretical centre of the repeat station (at standard height above ground level). This information is important. Errors in relocating the absolute instruments between successive occupations may vary from a few millimetres up to many metres.

Gradient of total field at the station: record the average horizontal gradient of F (e.g., the mean of N-S and E-W gradients) and the vertical gradient of F at the point where absolute measurements were made. These values serve as a test of whether any magnetic contamination has been introduced since the previous station occupation, and are also used to estimate the error associated with non-exact relocation of the observatory instruments.

Field element results: list the three field elements observed. If four elements are observed, enter the three most accurate ones. Conventions are: +**X** northward, +**Y** eastward, +**Z** downward, +**D** east of north, +**I** downward. Enter angles (**D** and **I**) in decimal degrees, to three decimal places if possible, and field strengths in nanoteslas.

(a) Mean night-time value: enter your best estimates of the "night-time" values for each element. You may choose to skip this part if you are using reference observatories to obtain equivalent annual means at the repeat station. "Night-time" refers to the time when diurnal effects are at a minimum, although the field could still be disturbed. Include approximate errors for the results, e.g., the standard deviation of a set of night-time field determinations. It may only be possible to guess the error, taking into consideration the observation and data reduction corrections.

(b) Normal field/annual mean value: if a local variometer base-station is used for data reduction, enter values for the three field elements after a correction has been made to get an estimate of the normal field (i.e. the night-time field under perfectly undisturbed conditions). This correction must be derived from a long variometer or observatory record and not from data recorded only during the repeat station occupation. The correction is important unless observations were made during extremely quiet conditions.

If a reference observatory record was used for data reduction, enter either the normal field values for the repeat station occupation or equivalent annual mean values for the repeat station. In the latter case, give the relevant epoch in decimal years. Enter estimates (guesses if necessary) of the errors in determining the normal field/annual mean values.

Estimated annual changes: enter the old estimates for the annual change of each field element at the repeat station determined for the previous epoch, and your most recent estimates based on the new data. Record the epochs concerned. Estimates might be based on simple differences between final corrected results at successive station occupations, or on the gradient of some curve fitted to a time-series of observations at the repeat station. (It is not essential to complete this section.)

Magnetic disturbance

Give information from the nearest magnetic observatories (or recording stations, possibly the repeat station itself) to illustrate the typical level of magnetic disturbance while absolute measurements were being made. Daily range values are convenient, but any commonly used index or indicator of geomagnetic disturbance is acceptable. State which indicator you use and list the values corresponding to high, medium, and low levels of magnetic disturbance (not necessary if you use a K-index).

8.1.3 Computer files

Provide a computer file summarizing the results of your repeat station surveys. This should be done in addition to completing a regional magnetic repeat station record sheet for each reoccupation of each station. The computer file can be either a **Survey File** of the results from a particular survey, a **Master File** containing a compilation of results from several surveys, or both. It will be assumed that any new revision of a master file replaces earlier versions, unless stated otherwise in the header lines of the file.

Files should be written in ASCII and recorded on any commonly used medium (preferably MS-DOS or Apple Macintosh-formatted diskette). Files should have the format shown in Table 8.1.

Notes

- Upper or lower case lettering is acceptable. Comments can be added to the end of any line.
- There is no restriction on the number of characters per line, or the number of characters per data-field, but each field should be the same size throughout the file.
- Station names must be unique and match exactly those on corresponding record sheets and data files.
- Data-fields should be separated by one or more spaces, or a comma, or a tab character.
- Enter a string of 9's in the appropriate data-field to denote missing values.
- Angles (latitude, longitude, **D**, **I**) should be in decimal degrees; field strength in nT.
- In general, enter the three elements measured although any three elements defining the field vector may be specified, e.g., **D**,**H**,**Z** or **X**,**Y**,**Z**. If a combination such as **D**,**H**,**F** is used, which does not specify the sign of **Z**, then **F** should be given the sign of **Z**.
- It will be assumed that the annual change estimates in Master Files are the original (usually prospective) ones made at the time of each survey. If the annual change values in a Master File have been recalculated retrospectively, then add a note to the file header, and/or at the end of the relevant lines of results.

Table 8.1 Format for computer files

```
HEADER
*STATION   LATITUDE    LONGITUDE   ELEVATION      ESTABLISHED
CLASS    DATE/YEAR   ELT1  ELT2  ELT3  EPOCH   dELT1  dELT2  dELT3
CLASS    DATE/YEAR   ELT1  ELT2  ELT3  EPOCH   dELT1  dELT2  dELT3
 etc....
*STATION   LATITUDE    LONGITUDE   ELEVATION      ESTABLISHED
CLASS   DATE/YEAR    ELT1  ELT2  ELT3  EPOCH   dELT1  dELT2  dELT3
 etc....
```

where:

HEADER = a descriptive header including the revision date, occupying any number of lines.

*STATION = the name of the repeat station, preceded by an asterisk; spaces are not allowed.

LATITUDE = latitude of the station in decimal degrees; positive north, negative south.

LONGITUDE = longitude of the station in decimal degrees; positive east of Greenwich.

ELEVATION = height of the station above mean sea level in metres.

ESTABLISHED = year when this exact station was first used (optional).

CLASS = a 10-character code = R EEE Lm.n (include the spaces).

- where R = D if data are reduced to an undisturbed (normal field) value for a particular day;
  - = Y if data are reduced to an annual mean value.
- EEE = any three of **X,Y,Z,H,F,D,I** to designate the elements reported.
- L = V if local variometer control was used;
  - = M if a reference magnetic observatory was used to obtain normal field or annual means;
  - = A if absolute observations alone were used;
  - = ? if the type of diurnal control is not identified.
- m.n = classification number for the results, e.g., 1.0, 1.5, 2.0, ...

DATE/YEAR = yyyymmdd for data reduced to a particular day (code D above), e.g., 19950717 for 17 July 1995. Enter a pair of 9's if the day or month are unknown;

= yyyy.y for data reduced to an annual mean (code Y above), e.g., 1992.5.

ELT1,...3 = values of the three field elements, reduced to normal field or annual mean values.

EPOCH = the epoch (i.e., decimal year) for the annual change estimates.

dELT1,...3 = best estimates of the annual change in each element at the epoch specified.

Survey File

An example is shown in Table 8.2. Variometer control was used to make a diurnal correction, and a subsequent adjustment for night-time disturbance was applied. Observations were not made strictly under magnetically quiet conditions, hence a classification of V1.2 has been used instead of V1.0. Absolute observations of **D,I,F** were made, but the results have been expressed as **D,H,Z** throughout to be consistent with earlier results. A comment about the approximate elevation for Alice Springs has been added to the line of data.

Master File

An example is shown in Table 8.3. The Albany 1978 results are specified for **D,H,F** so the sign of **Z** has been transferred to **F**. The annual change in **H** at 1980.0 is missing.

Table 8.2 Example of a survey file

```
AGSO repeat station survey 1986-1989  Rev: 17 December 1990
This file contains data from continental Australia.  The file is formatted according to IAGA
specifications.
-----------------------------------------------------------------------------------------------
*Albany_C          -34.945    117.805  075      1965
D DHZ V1.2         19870413   -3.083   21433    -56195   1990.0   0.042    13.4    -1.9
*AliceSprings_B    -23.807    133.897  500      1942     (approx. elevation)
D DHZ V1.2         19891206    5.070   29941    -44697   1990.0   0.027   - 3.0     0.1
*AyersRock_A       -25.348    131.062  560      1947
D DHZ V1.2         19891225    4.322   28877    -46751   1990.0   0.026   -09.7     0.6
         ....etc....
```

Table 8.3 Example of a master file

```
AGSO repeat station master file 1969-1989  Rev: 25 December 1990
This file contains data from continental Australia, surrounding islands, Papua New Guinea and SW
Pacific Islands.  No Antarctic data.  Annual changes are the original forward estimates, not
recalculated.  The file is formatted to IAGA specifications.
-----------------------------------------------------------------------------------------------
*Albany_C          -34.945    117.805  075      1965
D DHF A2.0         19780627   -3.015   21722    -60184   1980.0  -0.016 9999.9      3.60
D DHZ V1.2         19831002   -3.099   21548    -56231   1985.0   0.022  -15.6    -11.5
D DHZ V1.2         19870413   -3.083   21433    -56195   1990.0   0.042  -13.4     -1.9
*AliceSprings_B    -23.807    133.897  590      1942
D DHZ V1.5         19690803   4.720    30463    -44232   1970.0   0.008  -21.6     -5.3
         ....etc....
```

8.2 Archiving and Retrieving Repeat Station Information

World Data Center-A in Boulder, Colorado acts as the primary centre for accumulating and disseminating repeat station information. If you send data to any other World Data Centre then please indicate that copies should be forwarded to WDC-A. Please send completed record sheets and computer files to:

Geomagnetism Services
WDC-A for Solid Earth Geophysics
325 Broadway, Code E/GC1
Boulder, CO 80303-3328
USA

Tel: + 1-303-4976521
Fax: + 1-303-4976513
email: wdcaseg@ngdc.noaa.gov

An up-to-date copy of your regional magnetic survey, chart, and model description should be filed with WDC-A, and a copy sent to IAGA Working Group V-8. The responsible officer is currently:

Larry R. Newitt,
Geomagnetism Program,
Geological Survey of Canada
1 Observatory Crescent
Ottawa, Ontario
CANADA K1A 0Y3

Tel: + 1-613-8377915
Fax: + 1-613-8249803
email: newitt@geolab.nrcan.gc.ca

IAGA Working Group V-8 can also be contacted through:

Dr. Jo Ann Joselyn
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NOAA Space Environment Center
325 Broadway
Boulder, CO 80303-3328
USA

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Fax: + 1-303-4973645
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Requests for repeat data should be addressed to WDC-A. Copies of the IAGA catalog of regional magnetic survey, chart and model descriptions can be obtained from either WDC-A, or from IAGA Working Group V-8. Enquiries and comments concerning the IAGA reporting scheme should be addressed to IAGA Working Group V-8. The chairman is currently:

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APPENDIX 1 Inventory of Repeat Station Equipment

An observer might require the following items during a survey. It is unlikely that all the equipment listed would be necessary. For a single observer travelling by air, the weight of the equipment, including an on-site variometer system and chart recorder, would probably be between 150 kg and 200 kg.

DI fluxgate magnetometer
PPM Magnetometer (2)
QHM absolute magnetometer (backup)
Declinometer
Tripods for instruments
Tripod mounting for PPM sensor

Triaxial variometer
Digital data acquisition system
Recording PPM
Lap-top computer
Digital clock for recorder
Analog chart recorder
Digital thermometer
Recording paper, pens, ink

Magnetic compass
Radio for time signals
Pocket calculator
Stopwatch
Printer for the computer (optional)
Digital wrist watch

Electric generator
12 volt batteries
PPM batteries (spare)
Battery charger
Flashlight (torch)
Spot light (for ref. marks at night)

Graduated 2 m rod
Tape measure (30m minimum)
Spirit level
Plumb line
Camera & spare film
Binoculars
Thermometer
Medical kit

Tent
Canvas fly-sheet (for absolute station)
Tent pegs (non-magnetic)
Canvas fly-sheet (for fluxgate sensor)
Tarpaulin
Rope, cord, string
Umbrella (non-magnetic)
Nylon tape (for markers)
Insect repellent

Spare parts, cables, etc.
Tool kit (instruments)
Tool kit (general purpose)
Connecting cables & spares
Hammer
Rock chisel or drill
Cleaning tissues & rags
Pick, trowel, etc.
Plastic bags
Sponge & towel (if likely to be wet)

Record sheets
Stationery
Clip board (non-magnetic)
Instruction manuals
Nautical Almanac
Station descriptions
Previous data and results
Station status report forms

Theodolite accessories:
90° eyepieces
2 Orange & brown filters
Sunshade
Plumb line
Adjusting tools
Instruction manuals for instruments
Non-magnetic screwdriver

APPENDIX 2 Magnetic Repeat Station Status Report Form

Primary station: .... **Date:**.................

Secondary station: .... **Observer:**......................

Other usable stations...

Local contact/authority..

....

....

Tel: .... **Fax:**...

Condition of stations:

Condition of ref. marks:

Variometer site description:

Gradient determination Station:...

Enter total field values (nT) relative to the station at the following distances (in metres):

S -5.0 -4.2 -3.0 -2.0 -1.0 -0.5 0.0 0.5 1.0 2.0 3.0 4.0 5.0 N

ΔF..0..

W -5.0 -4.2 -3.0 -2.0 -1.0 -0.5 0.0 0.5 1.0 2.0 3.0 4.0 5.0 E

ΔF..0..

DOWN -1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 UP

ΔF..0..

(Standard height of instrument above station marker = 1.6 m)

Local News (e.g. building developments, new magnetic contamination, hurricanes):

Operational and maintenance work carried out during visit:

Future work required:

Recommendations and comments (e.g. need for repairs, new reference marks, new stations, etc.):

APPENDIX 3 Procedure for Positioning and Levelling a Theodolite

Positioning the tripod and theodolite

If footpads have been correctly installed at the station, then place the tripod feet in the pads and adjust the length of the legs to the appropriate length so as to "force-centre" the tripod at the required standard height. Mount the theodolite on the centre of the tripod and roughly level the instrument using the bull's-eye spirit level. Sight the repeat station marker through the optical plummet, and relocate the theodolite on the tripod so that it is centred vertically above the marker. Clamp the theodolite, check the plummet, and level the theodolite accurately as described below.

If there are no footpads, positioning the theodolite is more difficult, especially on uneven ground. Set up the tripod above the marker at the appropriate height, approximately centred using a plumb bob. Ensure that the tripod head is approximately level using a spirit level. Attach the theodolite, level it, and check the centring by sighting through the optical plummet. If the theodolite is not centred, and centring cannot be achieved by sliding the theodolite on the tripod head, it will be necessary to adjust the length of the tripod legs. A movement in a given direction can be achieved by modifying the length of one leg while keeping .the length of the other two legs fixed. A movement in the perpendicular direction can be achieved by simultaneously changing the length of the other two legs in the opposite direction. It will be necessary to relevel the theodolite and to sight through the optical plummet again to recheck the centring. The process may have to be repeated more than once. If, at the end of the levelling process, the height of the tripod is not correct, shorten or lengthen all legs by exactly the same amount.

Levelling the theodolite

Roughly level the instrument using the bull's-eye spirit level. Turn the alidade until the tubular spirit level is parallel to a line joining two foot screws. Centre the bubble by adjusting the two levelling screws. Rotate the alidade through 180° and check that the bubble is still centred. If the bubble is no longer centred, use the levelling screws to bring the bubble to a position halfway between its present position and the centre position. Rotate the alidade back through 180° and verify that the bubble is in the same position. Now turn the alidade through 90° so that the spirit level is pointing towards the third foot screw and use that screw to adjust the level in that direction. When the instrument is level, the bubble will maintain a constant position as the alidade is rotated.

Bubbles in the spirit level wander badly when subjected to strong sunlight. Use a tent or umbrella to shade the level during the levelling procedure.

In the Zeiss-Jena theodolite, the graduated scale of the vertical circle is stabilized by means of a pendulum and can be used to check the level of the instrument. Set the vertical circle to read 90°. Rotate the alidade through 360°, observing the vertical circle reading in various directions. If the theodolite is level, the vertical circle reading will remain at 90° throughout the rotation. Note that for this check to be valid, the initial levelling must be no worse than 5 minutes of arc, the working range of the vertical circle auto-indexing.

APPENDIX 4 Fortran Programs for Reducing Sun Observations

```
      PROGRAM SUNIN                                  !Rev: 05/9/94
C***********************************************************************
C Interactive program for entering sets of Sun observations into a
C data file.  The file is subsequently used as input to program SUNAZ
C for calculating the azimuth of a reference mark. The observational
C proforma (record sheet) and data file format are described below.
C The proforma is similar to that described in K.A. Wienert (1970),
C Notes on Geomagnetic Observatory and Survey Practice, Earth
C Science 5, UNESCO, paragraph 246, page 136.
C
C Programs SUNIN and SUNAZ are based on program SUNSHOT written in
C December 1991 by Andrew Lewis, Geomagnetism Section,
C     Australian Geological Survey Organisation
C     GPO Box 378,  Canberra ACT 2601, Australia
C     Ph +61-6-249 9111  ;  Fax +61-6-249 9986
C
C-----------------------------------------------------------------------
C Subroutines used
C     DMSCHECK: tests for strange deg,min,sec sign combinations
C
C Functions used:
C     DMSDEG  : converts degrees,minutes,seconds to decimal real*4
C
C-----------------------------------------------------------------------
C
C                    NOTES ON OBSERVATIONAL PROCEDURE
C                    --------------------------------
C The proforma is designed for observations made using a theodolite
C with a central vertical cross-hair (some have circular or twin cross-
C hairs specifically designed for making observations centred on the
C Sun). Measurements are made when the cross-hair coincides with
C one or other limb of the sun:
C    O¦  = cross-hair tangential to the right limb of the Sun
C    ¦O  = cross-hair tangential to the left  limb of the Sun
C
C Mark and Sun measurements are repeated with the vertical circle of
C the theodolite on both the right (R) and left (L) of the observer.
C
C A stop watch/clock with a lap-time function is used for timing the
C coincidence of the edge of the Sun's disc with the cross-hair.
C Approximate UT when the stop watch is started is recorded on the
C proforma as the "Watch Time". The difference between this and true UT
C is obtained by checking successive lap times for the pips of a radio
C time-signal. The average difference is noted on the proforma as the
C "correction" to be added to the Watch Time to get the true UT.
C
C-----------------------------------------------------------------------
C
C              EXAMPLE OF A PROFORMA FOR SUN OBSERVATIONS
C              ------------------------------------------
C
C  Place  :                             Date/hr(UT):       /
C  Station:                              Theodolite:
C  Mark   :                                Observer:
C
C  Latitude (degN,min,sec):
C  Longitude(degE,min,sec):
```

```
C
C  Watch Start UT (hr,min,sec):
C  Correction   (decimal secs):
C
C  Vertical   OBJECT        WATCH TIME           HORIZONTAL CIRCLE
C  Circle                                           READING
C                       hour   min    sec       deg    min      sec
C ---------¦---------¦----------------------¦--------------------------
C    R     ¦  MARK   ¦      ---n/a---       ¦
C 1  R     ¦    O¦   ¦                      ¦
C 2  R     ¦    O¦   ¦                      ¦
C 3  L     ¦   ¦O    ¦                      ¦
C 4  L     ¦   ¦O    ¦                      ¦
C    L     ¦  MARK   ¦      ----n/a--       ¦
C ---------¦---------¦----------------------¦--------------------------
C   Mean   ¦         ¦                      ¦
C ==========================================¦==========================
C    L     ¦  MARK   ¦      ---n/a---       ¦
C 5  L     ¦   ¦O    ¦                      ¦
C 6  L     ¦   ¦O    ¦                      ¦
C 7  R     ¦    O¦   ¦                      ¦
C 8  R     ¦    O¦   ¦                      ¦
C    R     ¦  MARK   ¦      ---n/a---       ¦
C ---------¦---------¦----------------------¦--------------------------
C   Mean   ¦         ¦                      ¦
C ==========================================¦==========================
C
C
C            Example of a data file of Sun observations
C            ------------------------------------------
C
C   Warracknabeal
C   Station-C
C   TDC distant silo
C   22 10 1991
C   308887
C   AML
C    -36.0000  19.0000  22.0000   142.0000   25.0000    5.0000
C     23.0000  30.0000  20.0000
C      -.0700
C    336.0000  18.2000    .0000
C       .0000   8.0000  26.3600    53.0000   42.1000     .0000
C       .0000   8.0000  48.0000    53.0000   37.0000     .0000
C       .0000   9.0000  54.5800   232.0000   30.7000     .0000
C       .0000  10.0000  14.0300   232.0000   25.9000     .0000
C    156.0000  18.3000    .0000
C    156.0000  18.5000    .0000
C       .0000  12.0000  22.3900   231.0000   54.3000     .0000
C       .0000  12.0000  41.7700   231.0000   49.8000     .0000
C       .0000  13.0000  31.5000    52.0000   28.4000     .0000
C       .0000  13.0000  53.9500    52.0000   23.0000     .0000
C    336.0000  18.4000    .0000
C    ........
C    Further set of observations can be added to the file
C
C**********************************************************************
      character ans*1,datafile*80,place*40,station*40,mark*79,
     &          theo*12,observer*3
      integer year,month,day,ok,ios
      real*4  timh(4),timm(4),tims(4),sund(4),sunm(4),suns(4),
     &        dlat,dlon,wstart,wcorr,hour,zmin,sec,
```

```
     &          zdmark(2),zmmark(2),zsmark(2),dmsdeg
      luo=30               !unit for output datafile
      write(*,'(//''    Data entry program for Sun observations'')')
      write(*,'(  ''    --------------------------------------''/)')
100   write(*,'(/'' Enter name of a new file to hold data: '',$)')
      read(*,'(a)') datafile
      write(*,*)
      open(unit=luo,file=datafile,status='new',iostat=ios)
      if(ios.gt.0) then
         write(*,*)'***** File already exists - try again'
         goto 100
      endif
C
C Enter the header information
C
      write(*,'('' Enter the location name (a40): '',$)')
      read(*,'(a)') place
      write(*,'('' Enter the station name  (a40): '',$)')
      read(*,'(a)') station
      write(*,'('' Enter mark description  (a79): '',$)')
      read(*,'(a)') mark
120   write(*,'('' Enter the UT date (dd,mm,yyyy): '',$)')
      read(*,*) day, month, year
      if(day.lt.1.or.day.gt.31) then
         write(*,*)'***** illegal day - try again'
         goto 120
      endif
      if(month.lt.1.or.month.gt.12) then
         write(*,*)'***** illegal month - try again'
         goto 120
      endif
      write(*,'('' Enter theodolite ID code (a12): '',$)')
      read(*,'(a)') theo
      write(*,'('' Enter initials of observer(a3): '',$)')
      read(*,'(a)') observer
C
C Display note about formats
C
      write(*,800)
800   format(//10x,'Note on format for time and angle inputs'/,
     &         10x,'----------------------------------------'/,
     &' Times/angles must be entered as hours/deg,mins,secs.'/,
     &' Each value may be entered as integer or real, padded with'/,
     &' zeros as necessary to get three numbers. For example, the'/,
     &' following equivalents are acceptable:'/,
     &'     11.50839,0,0   or  11,30.50333,0   or   11,30,30.2'//,
     &' Latitude  is positive north, negative south.'/,
     &' Longitude is positive east of Greenwich, negative west'/,
     &' Lat/lon angles are signed according to the sign of the'/,
     &' most significant non-zero value, eg. -45,30,0 = -45.5deg'//,
     &' All times are Universal Time (UT)')
C
C Get the rest of the header information
C
150   write(*,'(/'' Enter station latitude  (degN,min,sec): '',$)')
      read(*,*) zlatd,zlatm,slat
      CALL DMScheck (zlatd,zlatm,slat,ok)
      if(ok.eq.0) then
         write(*,*)'***** illegal sign combination - try again'
         goto 150
      endif
```

```
      dlat=dmsdeg(zlatd,zlatm,slat)
200   write(*,'('' Enter station longitude (degE,min,sec): '',$)')
      read(*,*) zlond,zlonm,slon
      CALL DMScheck (zlond,zlonm,slon,ok)
      if(ok.eq.0) then
         write(*,*)'***** illegal sign combination - try again'
         goto 200
      endif
      dlon=dmsdeg(zlond,zlonm,slon)
250   write(*,'(/'' Enter watch start time,UT (hr,min,sec): '',$)')
      read(*,*) hour,zmin,sec
      if(hour.lt.0.0.or.zmin.lt.0.0.or.sec.lt.0.0) then
         write(*,*)'***** negative values not allowed - try again'
         goto 250
      endif
      wstart=dmsdeg(hour,zmin,sec)  !hours
      write(*,'('' Enter watch correction  (decimal secs): '',$)')
      read(*,*) sc
      wcorr=sc/3600.0               !hours
C
C Write all this to the output file
C
      write(luo,'(a40)') place
      write(luo,'(a40)') station
      write(luo,'(a79)') mark
      write(luo,'(i2,i3,i5)') day,month,year
      write(luo,'(a12)') theo
      write(luo,'(a3)')  observer
      write(luo,870) zlatd,zlatm,slat,zlond,zlonm,slon    !lat,lon
      write(luo,870) hour,zmin,sec     !watch start time
      write(luo,870) sc                !watch correction in secs
870   format(3f9.4,3f11.4)
C
C Get the mark and sun observations and write them to the output file
C
1000  write(*,'(/'' Enter mark observation (deg,min,sec): '',$)')
      read(*,*)      zdmark(1),zmmark(1),zsmark(1)
      write(luo,870) zdmark(1),zmmark(1),zsmark(1)
      do 110 i=1,4
         write(*,'('' Enter Sun obs#'',i1,'': h,m,s, d,m,s: '',$)') i
         read(*,*)     timh(i),timm(i),tims(i),sund(i),sunm(i),suns(i)
         write(luo,870)timh(i),timm(i),tims(i),sund(i),sunm(i),suns(i)
110   continue
      write(*,'('' Enter mark observation (deg,min,sec): '',$)')
      read(*,*)      zdmark(2),zmmark(2),zsmark(2)
      write(luo,870) zdmark(2),zmmark(2),zsmark(2)
C
C More?
C
      write(*,'(/'' Process another observation y/[n]? '',$)')
      read(*,'(a)') ans
      if(ans.eq.'y'.or.ans.eq.'Y') goto 1000
      write(*,*)
      write(*,*)'Observations have been stored in file: ',datafile
      close(luo)
      stop
      end
Cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
      real*4 FUNCTION DMSDEG (deg,min,sec)
C
C Converts real*4 deg,min,sec to decimal degrees. If any one of DEG,
```

```
C MIN,SEC is negative non-zero, the whole angle is made negative.
C Pathological inputs (eg. 40,-25,30) are treated as a standard
C negative angle (-40,25,30).  CEB
C Note that FORTRAN reads a negative zero as positive zero.
C - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
      real*4 deg,min,sec
      DMSDEG=abs(deg)+abs(min)/60.0+abs(sec)/3600.0
      if(deg.lt.0.0.or.min.lt.0.0.or.sec.lt.0.0) DMSDEG=-DMSDEG
      return
      end
Cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
      subroutine DMSCHECK (DEG,MIN,SEC,OK)                      !2/9/94
C
C Tests for pathological deg,min,sec sign combinations (eg. 45,-20,30)
C and abnormal values (CEB).
C Returns OK = 1/0 if OK/abnormal
C - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
      real*4 deg,min,sec
      integer OK
      OK=1        !normal
      if(DEG.gt.360.0 .or. DEG.lt.-360.0) then
        write(*,'(/''*** Abnormal DEG warning ***'')')
        OK=0
      endif
      if(MIN.gt.60.0 .or. MIN.lt.-60.0) then
        write(*,'(/''*** Abnormal MIN warning ***'')')
        OK=0
      endif
      if(SEC.gt.60.0 .or. SEC.lt.-60.0) then
        write(*,'(/''*** Abnormal SEC warning ***'')')
        OK=0
      endif
      if(DEG.gt.0.0 .and. MIN.lt.0.0) then
        write(*,'(/''*** Pathological MIN warning ***'')')
        OK=0
      endif
      if(DEG.gt.0.0.and.SEC.lt.0.0.or.MIN.gt.0.0.and.SEC.lt.0.0) then
        write(*,'(/''*** Pathological SEC warning ***'')')
        OK=0
      endif
      return
      end
```

```
      PROGRAM SUNAZ                                  !Rev: 05/09/94
C**********************************************************************
C Reduction of sets of Sun observations to calculate the true azimuth
C of a mark. Input is read from a standard data file, as created by
C program SUNIN. Refer to the comments in program SUNIN for information
C about the observational procedure and the input file format.
C Double precision is used throughout.
C The array of azimuths (AZI) is dimensioned for 64 sets of readings.
C
C Programs SUNAZ and SUNIN are modifications of program SUNSHOT
C written in December 1991 by Andrew Lewis, Geomagnetism Section,
C          Australian Geological Survey Organisation
C          GPO Box 378,  Canberra ACT 2601, Australia
C          Ph +61-6-249 9111  ;  Fax +61-6-249 9986
C
C Subroutines used
C    CRUNCH     : gets obs data into suitable form & calculates azimuth
C    SS         : calculates GHA and Declination of the Sun
C    DDECDMS    : converts real*8 decimal number to degs,mins,secs
C Functions used
C    DDMSDEG    : converts degrees,minutes,seconds to decimal
C    DCIRC      : puts real*8 decimal angle in the range 0 to <360
C
C Note on accuracy of Sun Alamanac Algorithm.
C -----------------------------------------
C The algorithm is based on the equations in G.G.Bennett (1980),
C "A Solar Ephemeris for use with Programmable
C Calculators", The Australian Surveyor, Vol.30, No.3, pp 147-151.
C Bennett claims that errors seldom exceed 0.001 degrees (4" of arc).
C The algorithm is primarily intended for use up to the year 2000.0,
C but it is claimed that reductions to epochs a century removed from
C the present will not be seriousy affected by the approximations made
C in the algorithm.
C Comparisons between this algorithm and Nautical Almanac data (from
C 1970 to 1993) yielded differences no greater than 6" of arc in either
C GHA or Declination. (The Nautical Almanac claims an accuracy of <0.1'
C =6", Nautical Almanac 1993 p 254).
C
C**********************************************************************
      implicit none
      character place*40,station*40,mark*79,theo*12,observer*3,
     &          infile*80
      integer year,month,day,iobs,ios,lui,i,id,im
      real*8 z(6),dlat,dlon,wstart,wcorr,sc,total,sec,
     &       timh(4),timm(4),tims(4),sund(4),sunm(4),suns(4),
     &       zdmark(2),zmmark(2),zsmark(2),AZI(64),DDMSDEG
      common /block1/ zdmark,zmmark,zsmark
      common /block2/ timh,timm,tims
      common /block3/ sund,sunm,suns
      common /block4/ wstart,wcorr,year,month,day,dlat,dlon
C unit for infile
      lui=20
C counts sets of obs
      iobs=0
C
      write(*,'(/''                 program SUNAZ        '')')
      write(*,'( ''           Sun Observation Calculator'')')
      write(*,'( ''           --------------------------'')')
C
C Select an input file (created using program SUNIN)
C
```

```
100   write(*,'(/'' Enter name of input data file: '',$)')
      read(*,'(a)') infile
      open(unit=lui,file=infile,status='old',iostat=ios)
      if(ios.gt.0) then
         write(*,*)'***** File not found - try again'
         goto 100
      endif
C
C Read and display headers
C
      read(lui,'(a)') place
      read(lui,'(a)') station
      read(lui,'(a)') mark
      read(lui,*)     day,month,year
      read(lui,'(a)') theo
      read(lui,'(a)') observer
      write(*,'('' PLACE:      '',a40)') place
      write(*,'('' STATION:    '',a40)') station
      write(*,'('' MARK:       '',a79)') mark
      write(*,'('' DATE:'',i9,''/'',i2,''/'',i4)') day,month,year
      write(*,'('' THEODOLITE: '',a12)') theo
      write(*,'('' OBSERVER:   '',a3)') observer
C
C Read the latitude and longitude, convert to degrees
C
      read(lui,*) (z(i),i=1,6)
      dlat=DDMSDEG(z(1),z(2),z(3))
      dlon=DDMSDEG(z(4),z(5),z(6))
      write(*,'('' Site latitude  ='',f9.4,'' degN'')') dlat
      write(*,'('' Site longitude ='',f9.4,'' degE'')') dlon
C
C Read the watch start time & correction, convert to hours
C
      read(lui,*) (z(i),i=1,3)            !watch hour minute and second
      wstart=DDMSDEG(z(1),z(2),z(3))      !hours
      read(lui,*) sc                      !correction (seconds)
      wcorr=sc/3600.d0                    !hours
C
C Now read next set of observations (M,S,S,S,S,M)
C
1000  read(lui,*,end=2000) zdmark(1),zmmark(1),zsmark(1)            !mark
      do 110 i=1,4
         read(lui,*) timh(i),timm(i),tims(i),sund(i),sunm(i),suns(i) !sun
110   continue
      read(lui,*) zdmark(2),zmmark(2),zsmark(2)                     !mark
C
C Compute the azimuth of the mark and store in array AZI
C
      iobs=iobs+1
      CALL CRUNCH (AZI,iobs)
      goto 1000                             !loop back for next set
C
C All data sets have been processed - now average the azimuths
C
2000  total=0.d0
      do 10 i=1,iobs
         total=total+AZI(i)
10    continue
      total=total/dble(iobs)                   !degrees
      CALL DDECDMS (total,id,im,sec)           !deg,min,sec
      write(*,820) total
```

```
820   format(/' Average Azimuth to mark =',f11.6,' deg')
      write(*,830) id,im,sec
830   format(25x,'=',i4,' deg',i4,' min',f7.2,' sec')
999   close(lui)
      stop
      end
C-------------------------------------------------------------------
      SUBROUTINE CRUNCH (AZI,iobs)
C
C Puts the input data into the desired form, calculates the
C co-ordinates of the SUN, the true north bearing of the SUN, and
C hence the true azimuth of the mark.
C
      integer year,month,day,i,iobs
      real*8 timh(4),timm(4),tims(4),sund(4),sunm(4),suns(4),
     &       wstart,wcorr,timed(4),timav,dsun(4),sunav,
     &       zdmark(2),zmmark(2),zsmark(2),zmark(2),zmarkav,
     &       dlat,dlon,angle,rlat,DtoR,AZI(64),
     &       MINOFD,GHA,LHA,DEC,Z,Z1,Z2,DCIRC,DDMSDEG
      common /block1/ zdmark,zmmark,zsmark
      common /block2/ timh,timm,tims
      common /block3/ sund,sunm,suns
      common /block4/ wstart,wcorr,year,month,day,dlat,dlon
      DtoR=datan(1.d0)/45.d0             !radians per degree
      write(*,'(/,18x,''Observation No.'',i2,/)') iobs
C
C Average the mark readings (in deg, subtracting 180 from the second)
C
      do 20 i=1,2
         zmark(i)=DDMSDEG(zdmark(i),zmmark(i),zsmark(i))
20    continue
      zmark(2)=DCIRC(zmark(2)-180.d0)
      zmarkav=(zmark(1)+zmark(2))/2.d0
C
C Average the four times (as hours)
C
      do 30 i=1,4
         timed(i)=DDMSDEG(timh(i),timm(i),tims(i))
30    continue
      timav=(timed(1)+timed(2)+timed(3)+timed(4))/4.d0
C
C Add watch start time & correction (hours), convert to mins of day
C
      timav=timav+wstart+wcorr
      MINOFD=timav*60.d0
      write(*,840) MINOFD
840   format(5x,'Mean UT of observations =',f11.5,' mins of the day')
C
C Average the Sun circle readings in decimal degrees, subtracting 180
C from the last 2 readings
C
      do 50 i=1,4
         dsun(i)=DDMSDEG(sund(i),sunm(i),suns(i))
50    continue
C
C Check here that a pair of sun circle readings do not traverse 0 on the
C theodolite horizontal circle. It could happen that the first of a pair of sun
C circle readings is (for example) 000 10.2 and the second is 359 58.9,
C which would cause errors in the averaging and hence errors in the final
C azimuth.
C
```

```
C First check dsun(1) and dsun(2), then in the next run of the loop check
C dsun(3) and dsun(4).
       do 55 i=0,2,2
            if (abs(dsun(i+1)-dsun(i+2)).ge.340) then
                write(*,58)
C
C add 360 degrees to the smaller value
C
                if (dsun(i+1).lt.dsun(i+2)) then
                     dsun(i+1)=dsun(i+1)+360.0
                else
                     dsun(i+2)=dsun(i+2)+360.0
                endif
            endif
55     continue
58    format(1x,' Sun circle readings straddle 0.0 on theodolite:',
     &,' Correction applied',/)
C
C Now subtract 180 degrees from the second set of readings and then average
C all four readings.
C
      do 60 i=3,4
         dsun(i)=DCIRC(dsun(i)-180.d0)
60    continue
      sunav=(dsun(1)+dsun(2)+dsun(3)+dsun(4))/4.d0
C
C Calculate the GHA and DEC of the Sun
C
      CALL SS (year,month,day,MINOFD,GHA,DEC)
      write(*,850) GHA,DEC
850   format(' Greenwich Hour Angle of Sun =',f11.6,' deg',/,
     &       '          Declination of Sun =',f11.6,' deg')
C
C Calculate the local hour angle from GHA and station east longitude
C
      LHA=DCIRC(360.d0-GHA-dlon)
      write(*,'(12x,''Local Hour Angle = '',f10.6,'' deg'')') LHA
C
C and find the true north bearing of the SUN (Z in degrees)
C
      rlat=dlat*DtoR
      Z1=dsin(LHA*DtoR)
      Z2=dcos(rlat)*dtan(DEC*DtoR)-dsin(rlat)*dcos(LHA*DtoR)
      Z=DCIRC(datan2(Z1,Z2)/DtoR)
      write(*,880) Z
880   format('   True North Bearing of Sun =',f11.6,' deg')
C
C Calculate the bearing of the mark from the station (in deg)
C
      angle=zmarkav-sunav+Z
      AZI(iobs)=DCIRC(angle)
      write(*,'(13x,''Azimuth to Mark ='',f11.6,'' deg'')') AZI(iobs)
      return
      end
C-----------------------------------------------------------------------
      SUBROUTINE SS (year,month,day,MIN,GHA,DEC)
C Calculates the Greenwich Hour Angle and Declination of the Sun given
C a date and time. The algorithm is based on the equations in
C G.G.Bennett (1980), A Solar Ephemeris for use with Programmable
C Calculators, The Australian Surveyor, Vol.30, No.3, pp 147-151.
C Bennett claims that errors seldom exceed 0.001 degrees (4" of arc).
```

```
C The algorithm is primarily intended for use up to the year 2000.0,
C but it is claimed that reductions to epochs a century removed from
C the present will not be seriousy affected by the approximations made
C in the algorithm.
C
      implicit double precision (a-z)
      integer year,month,day,it2,it3
      DtoR=datan(1.d0)/45.d0
C
C First calculate the variable T, which is the number of Julian centuries
C (of 36525 ephemeris days) since 12:00 UT on January 0 1900
C
      T1=367.d0*dble(year)
      it2=7*(year+int((month+9)/12))/4
      it3=275*month/9
      T4=dble(day)
      T5=MIN/1440.d0
      T=(T1-dble(it2)+dble(it3)+T4-694006.5d0+T5)/36525.d0
C
C Use T to calculate the orbital elements
C
      M=    DCIRC(358.475d0+35999.050d0*T)
      V=    DCIRC( 63.000d0+22518.000D0*T)
      Q=    DCIRC(332.000d0+33718.000d0*T)
      J=    DCIRC(222.000d0+32964.000d0*T)
      OMEGA=DCIRC(101.000d0+ 1934.000d0*T)
C Calculate the constituents in the Apparent Longitude:
C
C the Mean Longitude
      L1=279.69019d0+36000.76892d0*T
      L1=DCIRC(L1)
C
C the equation of centre
      angle=M*DtoR
      L2a=(1.91945d0-0.00479d0*T)*dsin(angle)
      angle=DCIRC(2.d0*M)*DtoR
      L2b=0.02d0*dsin(angle)
      angle=DCIRC(3.d0*M)*DtoR
      L2c=0.00029d0*dsin(angle)
      L2=L2a+L2b+L2c
C
C the lunar perturbation
      angle=DCIRC(261.d0+445267.d0*T)*DtoR
      L3=0.00179d0*dcos(angle)
C
C the perturbations due to Venus
      angle=DCIRC(90.d0+V)*DtoR
      L4a=0.00134d0*dcos(angle)
      angle=DCIRC(90.d0+2.d0*V)*DtoR
      L4b=0.00154d0*dcos(angle)
      angle=DCIRC(258.d0+2.d0*V-M)*DtoR
      L4c=0.00069d0*dcos(angle)
      angle=DCIRC(78.d0+3.d0*V-M)*DtoR
      L4d=0.00043d0*dcos(angle)
      angle=DCIRC((51.d0+3.d0*V-2.d0*M))*DtoR
      L4e=0.00028d0*dcos(angle)
      L4=L4a+L4b+L4c+L4d+l4e
C
C the perturbations due to Mars
      angle=DCIRC(90.d0+Q)*DtoR
      L5a=0.00057*dcos(angle)
```

```
      angle=DCIRC(306.d0+Q-M)*DtoR
      L5b=0.00049d0*dcos(angle)
      L5=L5a+L5b
C
C the perturbations due to Jupiter
      angle=DCIRC(91.d0+J)*DtoR
      L6a=0.00200d0*dcos(angle)
      angle=DCIRC(270.d0+2.d0*J)*DtoR
      L6b=0.00076d0*dcos(angle)
      angle=DCIRC(175.d0+J-M)*DtoR
      L6c=0.00072d0*dcos(angle)
      angle=DCIRC(293.d0+2.d0*J-M)*DtoR
      L6d=0.00045d0*dcos(angle)
      L6=L6a+L6b+L6c+L6d
C
C finally the nutation in longitude
      angle=DCIRC(90.d0-OMEGA)*DtoR
      L7a=0.00479d0*dcos(angle)
      angle=DCIRC(295.d0+2.d0*M)*DtoR
      L7b=0.00035d0*dcos(angle)
      L7=L7a+L7b
C
C Hence find the apparent longitude
      L=L1+L2+L3+L4+L5+L6+L7
C
C the obliquity of the ecliptic
      angle=OMEGA*DtoR
      EPSILON=23.45229d0-0.01301d0*T+0.00256d0*dcos(angle)
C
C the right ascension (in degrees)
      angleL=DCIRC(L)*DtoR
      angleE=DCIRC(EPSILON)*DtoR
      angleN=dsin(angleL)*dcos(angleE)
      angleD=dcos(angleL)
      RA=datan2(angleN,angleD)/DtoR
C
C and the declination (in degrees)
      DEC=dasin(dsin(angleL)*dsin(angleE))/DtoR
C
C Now calculate the GHA from the right ascension
      utobs=MIN/4.d0
      GHA=DCIRC(utobs+99.69130d0+36000.76892d0*T+0.917*L7-RA)
      return
      end
C-----------------------------------------------------------------------
      real*8 FUNCTION DCIRC (R1)
C
C converts a double precision number of degrees to the range 0-359.999
C
      real*8 R1
      DCIRC=dmod(R1,360.d0)
      if(DCIRC.lt.0.d0) DCIRC=DCIRC+360.d0
      return
      end
C-----------------------------------------------------------------------
      SUBROUTINE DDECDMS (angle,id,im,sec)
C
C Converts from double precision decimal degree ANGLE to
C int.deg,int.mins,seconds (dble precision)
C If ANGLE is negative, the first non-zero term is made negative, and
C the others are made positive.
```

```
C e.g., -0.5 deg = (0,-30,0)
C NOTE: FORTRAN reads -zero as +zero
C
      real*8 angle,zmin,dsec,sec
      integer id, im
      id=idint(angle)
      zmin=(dmod(angle,1.d0))*60.d0
      if(id.lt.0) zmin=dabs(zmin)     !make +ve if IDEG is -ve
      im=idint(zmin)
      dsec=(dmod(zmin,1.d0))*60.d0
      if(im.lt.0) dsec=dabs(dsec)     !make +ve if IMIN is -ve
      sec=dsec
      return
      end
C----------------------------------------------------------------------
      real*8 FUNCTION DDMSDEG (DEG,MIN,SEC)
C
C Converts real*8 deg,min,sec to decimal degrees. If any one of DEG,
C MIN,SEC is negative non-zero, the whole angle is made negative.
C Pathological inputs (eg. 40,-25,30) are treated as a standard
C negative angle (-40,25,30).
C Note that FORTRAN reads a negative zero as positive zero.
C
      real*8 DEG,MIN,SEC
      DDMSDEG=dabs(DEG)+dabs(MIN)/60.d0+dabs(SEC)/3600.d0
      if(DEG.lt.0.d0.or.MIN.lt.0.d0.or.SEC.lt.0.d0) DDMSDEG=-DDMSDEG
      return
      end
```

APPENDIX 5 Example of a magnetic repeat station network description

BRAZIL Revised: January 1991

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FIELD SURVEYS (NON-REPEAT)

Type of Survey	**No. stations**	**Date**
Aeromagnetic - F	3000	up to 1980

REPEAT STATIONS AND OBSERVATORIES

Reference observatories

VSS Vassouras	-22.400 °N	316.350 °E	457 m	(1915+)
TTB Tatuoca	-1.200 °N	311.483 °E	010 m	(1957+)

Repeat stations	**Reoccupations**
105 repeat stations	every 5 years, on average

Secondary repeat stations: none in general, but sometimes two.
Repeat stations markers: concrete pillar 40x40x70cm, 10cm above ground level, with a circular aluminum plate marked O.N.
Fieldwork: throughout the year, averaging 20 reoccupations per year.

Comments

The network of magnetic repeat stations has been gradually built up from 1880 onwards. Stations are usually named after the nearest city, with a letter (A, B, C, ...) designating the particular pillar. Many station heights have uncertainties of up to about 50m. Southern Brazil is a basaltic region, hence repeat station data from the south are often influenced by large magnetic anomalies.

Observational Procedures for Repeat Stations

Absolute Instruments

D, I	Fluxgate theodolite (1979+), 3 instruments
F	Proton precession magnetometer (1965+), 3 instruments

Azimuth: gyroscope-theodolite, 2 instruments
Classical instruments were used from 1880 until 1979.

Variometer

Triaxial fluxgate magnetometer (EDA FM-100), 2 instruments

Frequency and Duration of Observations

Stations are reoccupied every 5 years on average (see table below).
Two sets of absolute observations are made.

Comments

Early repeat station observations were made for D,H,F. Measurements are now made for D,I,F.

DATA REDUCTION PROCEDURES FOR REPEAT STATIONS

Up until 1960 no instrumental corrections were applied generally, and no reduction was made to obtain normal (undisturbed) values of the field.

Before 1970 it was usually not possible to obtain local records of diurnal variations. For this reason an interpolative scheme using data from two magnetic observatories was used for epochs 1960.0 and 1965.0. Such a method proved to be acceptable except during perturbed periods or at stations under the influence of the equatorial electrojet.

For epoch models 1960.0, 1965.0 and 1970.0 it has been estimated that the seasonal and solar cycle contributions are generally of the same order as observing errors.

CHARTS AND MODELS

Epoch	Observ.	Cmpts	No.	Corrections		Model	
	Period		Stns	Instr*	Diurnal	Interval	Type
1883.0	1880-85	D,H,I	120	yes	crude	1880-1885	Hand contoured
1904.0	1903-04	D,H,I	25	no	no	1901-1904	Hand contoured
1910.0	1910-11	D,H,I	48	yes	no	1880-1911	Hand contoured
1915.0	1913-15	D,H,I	54	yes	no	1800-1915	Hand contoured
1920.0	1922	D,H,I	14	no	no	1880-1917	Hand contoured
1925.0	1923-24	D,H,I	16	yes	no	1880-1924	Hand contoured
1930.0	1927-32	D,H,I	44	yes	crude		
1935.0	General analysis of all observations					1880-1932	Hand contoured
1940.0	Small corrections to earlier models					1880-1932	Hand contoured
1950.0	1935-49	D,H,I	60	no	no	1880-1949	Hand contoured
1955.0	1950-54	D,H,I	50	no	no	1923-1954	Hand contoured
1960.0	1951-60	D,H,I	80	yes	yes	1880-1960	Polynomial deg=2
1965.0	1960-65	D,H,I	90	yes	yes	1880-1965	Polynomial deg=2
1980.0	1965-79	D,H,I,F	90	yes	yes	1880-1979	Polynomial deg=2
1985.0	1979-85	D,H,F	105	yes	yes	1880-1985	Polynomial deg=4

* Correction applied for instrument calibration

Comments

Prior to 1960 all charts were hand-contoured. For 1960.0, 1965.0 and 1980.0 a parabolic trend (linear in a few cases) was fitted to the observations at each repeat station to permit reduction to a specific epoch. A second degree polynomial (Taylor expansion) in latitude and longitude was then fitted for each field element (D,I,H). Assuming time as an independent variable, secular change values were calculated by finite differences.

For 1985.0 a more elaborate model was produced, using all available repeat station data from 1880 to 1960. Fourth-degree polynomials in latitude, longitude and time were fitted to D,I,F (35 coefficients). Data from anomalous stations (usually those sited on large magnetic anomalies) and very old data were not used in the model. Annual variations for a geomagnetic element (E) at any given points were calculated by finite differences from the 4th degree expansion as follows:

$$\frac{dE}{dt} = E(t + 0.5) - E(t - 0.5)$$

Selected Publications

Barreto, L.M. (1970). Considerações sobre a variação secular e o modelamento do campo geomagnético no Brasil. Publicacação Especial No. 05/87, Observatório Nacional, Rio de Janeiro.

Barreto, L.M. (1988). Reoccupaçã da estação magnética de Fernando de Noronha. Publicacação Especial No.08/88, Observatório Nacional, Rio de Janeiro.

Barreto, L.M. (1988). Secular variation and geomagnetic normal field modelling in Brazil. Paper presented at the Geomagnetism Workshop, Wingst, Germany, April 1988.

Barreto, L.M. (1988). Secular variation and geomagnetic normal field modelling in Brazil. Dt. hydrogr. Z., 41, 199-209.

Barreto, L.M. (1990). Uses and abuses of geomagnetic charts in Latin America. J. Geomag. Geoelectr., 42, 1103-1106.

Constantino de Mello Motta and L.M. Barreto (1986). Campo geomagnético normal e sua variaçã secular no Brasil em 1985.o Publicacação Especial, CNPq-Observatório Nacional, Rio de Janeiro, pp. 51.

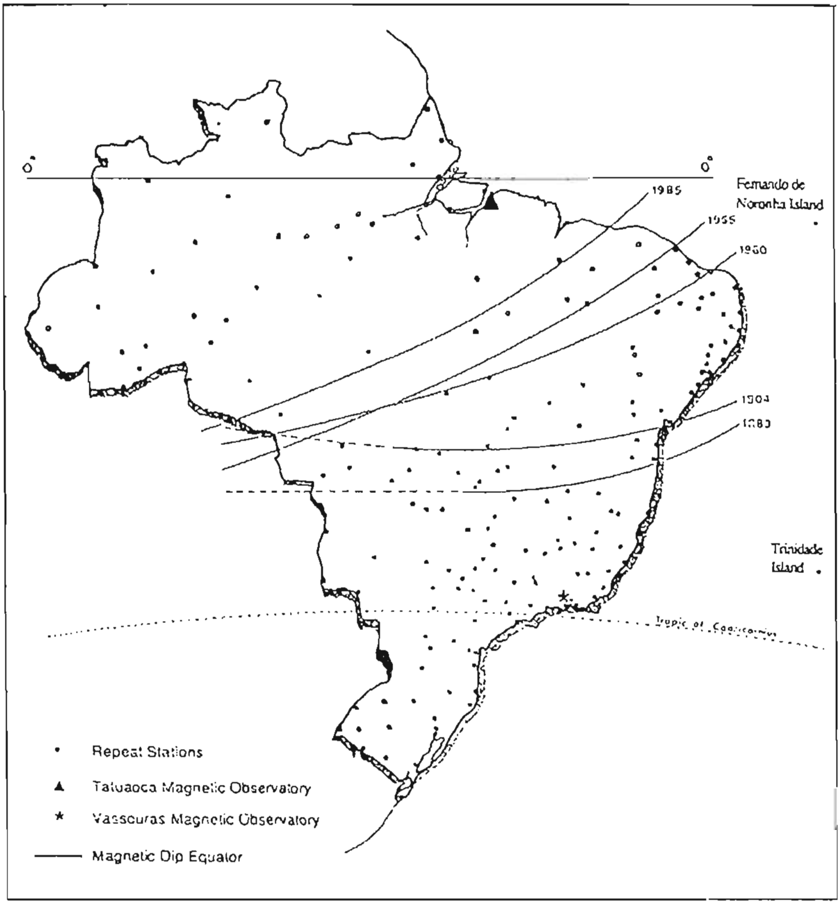

Figure A-1
Locations of magnetic repeat stations and observatories in Brazil.

APPENDIX 6 Regional Magnetic Repeat Station Record Sheet

(Revised: March 1994)

For information on how to complete record sheets refer to the document "Regional Magnetic Repeat Station Records - Explanatory Notes" issued by IAGA Working Group V-4. If the information requested below is inappropriate, please modify the form to suit your situation. Return record sheets to: Geomagnetism Services, WDC-A Solid Earth Geophysics, 325 Broadway, Boulder, CO 80303-3328, USA Fax: +1-303-497-6513

STATION NAME : COUNTRY :

Latitude : Is this a new station? No/Yes*

Longitude : Is this an exact reoccupation? Yes/No*

Height above sea level (m) : Year of previous occupation:

RESULTS CLASSIFICATION (see notes)

Mid-date of station occupation: ....

Duration of station occupation: .... days/hours*

Total number of sets of absolutes: .... Sequence of elements per set: ....

Uncertainty in instrument relocation **Gradient of total field at station**

Horizontal: m: nT/m

Vertical : m: nT/m

....

Element (a) **Mean night-time value** and estimated uncertainty (b) **Normal field † /annual mean value*** @ epoch‡ =........... and estimated uncertainty

1: : ± : ±

2: : ± : ±

3: : ± : ±

....

Estimated annual change (if available)

Element @ previous epoch = ... **@ new epoch = ...**

1: : :

2: : :

3: : :

MAGNETIC DISTURBANCE

Name of reference observatory/station Distance from repeat station Disturbance indicator (state what)

1. : km :

2. : km :

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* circle one † the night-time field when perfectly undisturbed ‡ give mid-year epoch if annual mean is reported

COMMENTS (continue on reverse side if necessary)

Regional Magnetic Repeat Station Record Sheet

(Example of a Completed Sheet)

For information on how to complete record sheets refer to the document "Regional Magnetic Repeat Station Records - Explanatory Notes" issued by IAGA Working Group V-4. If the information requested below is inappropriate, please modify the form to suit your situation. Return record sheets to: Geomagnetism Services, WDC-A Solid Earth Geophysics, 325 Broadway, Boulder, CO 80303-3328, USA Fax: +1-303-497-6513

STATION NAME : ALPHA COUNTRY : AusTRALiA

Latitude : -23.655°

Longitude : 146.587°

Height above sea level (m) : 420

Is this a new station? [✓ No] Yes*

Is this an exact reoccupation? [✓ Yes] No*

Year of previous occupation: 1983

RESULTS

CLASSIFICATION (see notes): V1.1

Mid-date of station occupation: 1986.08.30

Duration of station occupation: 3 days/hours*

Total number of sets of absolutes: 18

Sequence of elements per set: FDIFIDF

	Uncertainty in instrument relocation		**Gradient of total field at station**	
Horizontal:	0.02	m:	5	nT/m
Vertical :	0.01	m:	2	nT/m

Element	(a) **Mean night-time value** and estimated uncertainty		[✓ (b) **Normal field**†] /**annual mean value*** @ epoch‡ =........... and estimated uncertainty	
1: D	8.672	±	8.690	± <0.01°
2: H	30407	±	30430	± <10 nT
3: Z	52483	±	52488	± <5 nT

Estimated annual change (if available)

Element	**@ previous epoch** = 1985.0	**@ new epoch** = 1990.0
1: D	0.042°	0.033°
2: H	-26 nT	-5.1 nT
3: Z	-2.2 nT	-13.0 nT

MAGNETIC DISTURBANCE

Name of reference observatory/station	Distance from repeat station	Disturbance indicator (state what)
1. CHARTERS TOWERS	400 km	45 nT daily RANGE of
2.	km	

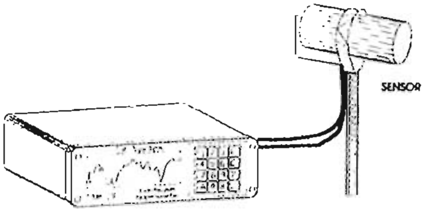
* circle one † the night-time field when perfectly undisturbed ‡ give mid-year epoch if annual mean is reported

COMMENTS (continue on reverse side if necessary)

RANge of H FOR a quiet day is about 35 nT.

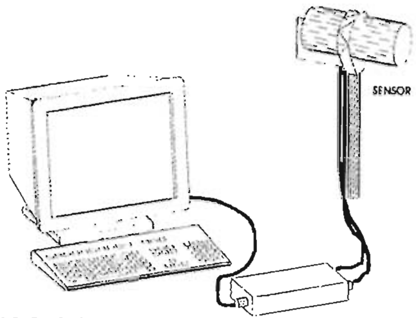
GEM Systems

OBSERVATORY MAGNETOMETERS



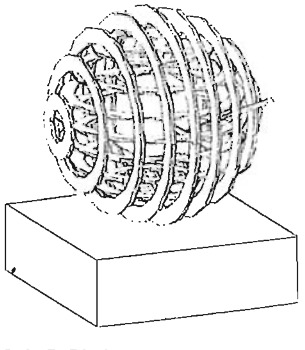
GSM-19

General purpose
Graphic screen
Low power
Large memory
Remote control
High absolute accuracy



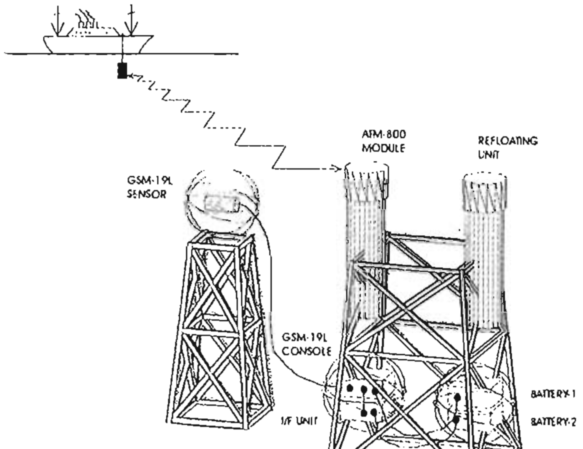
GSM-90

Remotely controlled
Economy model



GSM-19VP

Overhauser
Vector proton magnetometer
High rate of readings
Low power



GSM-19L

Low power magnetometer
6 km. max. depth
1 million readings from 30Ah battery
(10mW power for one reading per minute)

GEM Systems
ADVANCED MAGNETOMETERS

52 West Beaver Creek rd. Unit 14, Richmond Hill, Ontario, Canada L4B 1L9 Tel (905) 764-8008 Fax (905) 764-9329